Deliverable D1.2
Report on opportunities for nutrient reduction and recycling in water reuse schemes

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Abstract	This document summarizes the structure, the content and the functionalities of the website developed in the scope of the DEMOWARE project.

Versioning and Contribution History

Version	Date	Modified by	Modification reason
v.01	31/03/2016	Emmanuel Van Houtte	Initial draft
v.02	31/03/2016	Xavier Martinez	Correct format to match DEMOWARE template
v.03	13/06/2016	Emmanuel Van Houtte, Martina Sukupova, Christian Remy and Ulf Miehe	Answering the comments of reviewer

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Executive Summary

Nutrients, phosphorus and nitrogen, from municipal and industrial water streams contribute to the pollution or reduce the ecological potential of receiving water bodies. Recovering or reducing the nutrient content of waste streams, thus reducing the amounts of phosphorous and nitrogen that ends up in the water bodies, will contribute to a better environment.

The first part of this report describes two tests performed to treat the concentrate of the reverse osmosis process at the Torreele facility. The first test used a natural system based on willows; the second test was based on post-denitrification MBBR. The willows proved able to remove nutrients for more than 30%, resulting in a substantial cost benefit for discharge which could make it economical feasible when installed at full-scale to treat the total volume of RO concentrate. Contrary to the willows, that even remove part of the nitrogen in winter, the post-denitrification MBBR was only efficient when N-NO_3^- concentrations exceeded 30 mg/L. The variable N-NO_3^- concentration and salinity of RO concentrate seemed to be limiting factors for a good performance.

The second part of this report summarizes the activities regarding the optimization of water and nutrient (nitrogen and phosphorus) management at the reuse site Braunschweig, Germany. A detailed analysis of supply and demand of both, water and nutrients, for the reuse site was conducted. The optimization potential is especially high for nitrogen management, since the simultaneous supply via the Braunschweig wastewater treatment plant and additional conventional nitrogen fertilizer application by farmers result in an oversupply of nitrogen, losses to environment and a low efficient reuse compared to the total potential of renewable nitrogen in wastewater or sludge. Following this analysis, two possible solutions are discussed (fertigation and technical nutrient recovery), which are practically relevant for the Braunschweig reuse scheme in mid- and long-term timescale. Results indicate a high potential to increase the efficiency of nitrogen recycling. Simultaneously irrigation adopted on water demand of plants can be achieved.

1 Experiments with nutrient removal from RO concentrate

1.1 Introduction

One of the most pervasive problems affecting people throughout the world is inadequate access to clean water and problems with water are expected to grow worse in the coming decades (Shannon et al., 2008). Today there are already many examples of water recycling systems in the world (http://www.water360.com.au/) as this is one of the ways to address these problems. In the near future it is expected that wastewater effluent will become more and more important as a source for the production of potable water. In many of these water recycling schemes, reverse osmosis (RO) filtration is and will be deployed as a key process to remove inorganic salts and trace organic chemicals (Verliefde et al., 2008). The removed substances end up in a contaminated concentrate, which in most cases is discharged to nature (e.g. surface water) without any treatment at all.

The Intercommunale Waterleidingsmaatschappij van Veurne-Ambacht (IWVA)[1] is one of the pioneers in indirect potable reuse (Figure 1). At the Torreele facility, the municipal wastewater effluent from the adjacent wastewater treatment plant (WWTP) of Wulpen[2], is treated using ultrafiltration (UF) prior to RO. After RO, the water recharges the unconfined dune aquifer of St-André (Van Houtte and Verbauwhede, 2011). This water reuse/infiltration scheme is operational since July 2002.

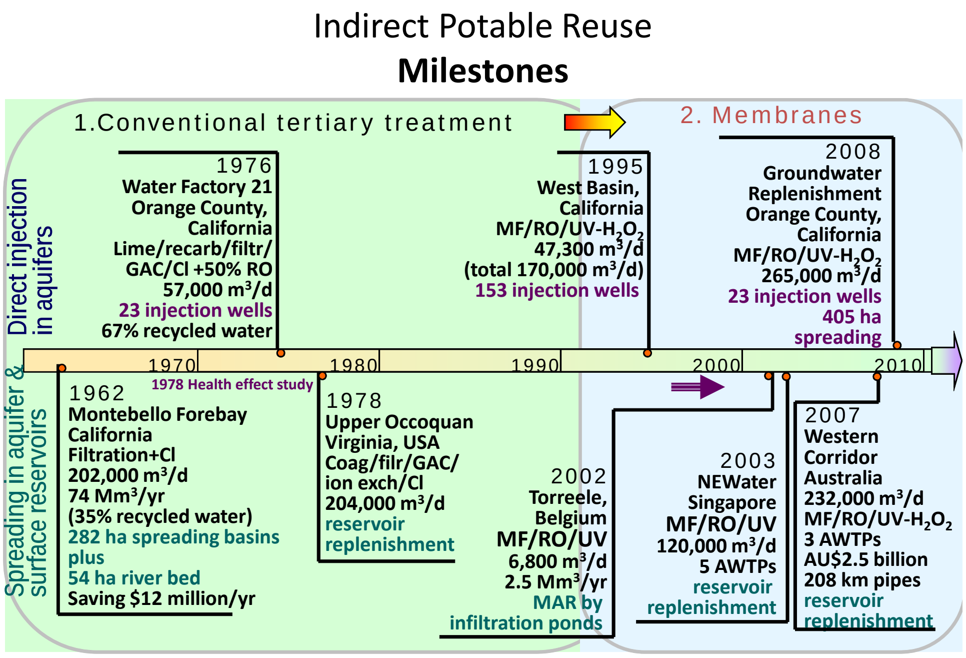

Figure 1 Milestones in indirect potable water reuse with selected cornerstone projects (Lazarova, 2011)

The main issues concerning membranes are the high energy consumption and the concentrate. Up to the end of February 2016 the average energy consumption to produce 1 m³ of infiltration water (RO filtrate), was 0.58 kWh for RO and 0.20 kWh for UF thus 0.78 kWh in total. The discharge of the mixed concentrates,

[1] Could be best translated as 'Intermunicipal Water Company of The Veurne Region'

[2] This WWTP is operated by Aquafin; 83.000 p.e.

35% is UF backwash and 65% is RO concentrate, is into the adjacent canal, together with the part of WWTP effluent that has not been treated (Van Houtte and Verbauwhede, 2013). As the canal is brackish, the salinity does not have a major negative effect on the quality and regular sampling showed that the quality downstream the Torreele facility is only negatively affected after longer dry periods.

The IWVA will start reuse of UF backwash water in June/July 2016 meaning that only RO concentrate will be discharged.

Almost from the start-up of the scheme in Torreele IWVA performed tests using natural systems to treat the discharged water and mitigate the effect of discharge. From October 2003 until 2009 the IWVA performed a test using a subsurface flow reed bed (constructed wetland). It proved not to be tolerant for higher salinity. In April 2007, a first test using willows (Salix) was performed under the same conditions as reed (Van Houtte and Verbauwhede, 2012).

In 2010 10 different willow species were tested for their salt tolerance and in 2011 a test field of 28 m² containing 70 willows of 9 different species was installed and put into operation (Van Houtte et al., 2012). The set-up was considered as a Short Rotation Coppice (SRC), a crop of wooden species planted at very high density with the intention to produce wood (appendix 1). 'Short Rotation' reflects to the frequency of harvesting which is in the order of 2 to 3 years and the biomass produced is considered a renewable energy source. It can be used for heating.

The mechanisms of treatment are discussed in appendix 1.

Besides the willows a conventional post denitrification pilot was installed in June 2015. The goal of it was to evaluate de-nitrification rates of RO concentrate. The test ended at the end of March 2016.

1.2 Experiments on nutrient removal

1.2.1 Use of willow

IWVA started experiments with willows to treat the wastewater from the membranes (both UF and RO) of the wastewater effluent reuse facility of Torreele in 2007. In 2010 10 different species were tested for its salt tolerance (Table 1) and in 2011 a test field (3 m wide, 9.5 m long and 70 cm deep, 4 rows in line with 70 cuttings in total, 9 species randomly planted) was prepared to treat RO concentrate (Table 2). It was the first time willows were tested to treat RO concentrate, thus treating a more brackish water. No soil is used as the cuttings are planted in calibrated sand[3]. After few months it was obvious that not all plants grew and they were replaced. Beginning of 2012, a first evaluation was made and 36 plants remained in two rows. The third row was totally removed and in the fourth row 17 new cuttings were planted.

[3] Calibrated quartz sand (0,7 to 1,25 mm) was used from an old sand filter

Table 1 Overall assessment after visual examination of 10 willow species after salt tolerance test (Ghyselbrecht et al., 2012) and performance in the first years of the pilot.

Willow species	Overall assessment	Number of stems 2011 (initially/after 5 months)	Number of stems 2012
Salix viminalis 'Orm'	Very positive	10/11	8 + 4
Salix nigra '44'	Very positive	10/10	5 + 5
Salix x rubens var. Basfordiana 'BR56'	Very positive	9/8	5 + 4
Salix x rubens var. Basfordiana 'BR60'	Very positive	9/11	10 + 4
Salix tiandra 'Noir de Vilaine'	Positive	7/5	0
Salix tiandra 'Noir de Touraine'	Positive	7/7	4
Salix viminalis 'Ulv'Salix purpurea	Positive	10/8	2
'Helix'	Positive	8/4	0
Salix viminalis 'Rap'	Negative	0/6	2
Salix nigra '108'	Negative	0/0	0

Table 2 Characteristics of the willow test field

Length 9.55 m; 8.70 m since August 2013 Width 3.00 m Depth 0.7m; filled with calibrated sand (0.7 – 1.2 mm)	Surface 28.3 m2; 26.1 m2 since August 2013 Volume 19.8 m3; 18.3 m3 since August 2013
Feed flow 500 l/h (2011 – 2012) 250 l/h (2013 – 2015)	Quality RO concentrate

The 36 plants of the 2 first rows were harvested in December 2012. The plants with the greatest salt tolerance also obtained the greatest average weight (Table 3).

Table 3 Weight of plants after harvesting in December 2012

Type of plant	number of plants	weight (kg/plant)			
		average	median	min	max
Nigra 44	5	11.4	14.0	1.7	16.2
BR56	5	9.7	8.4	8.0	15.0
BR60	10	8.9	8.1	5.1	15.0
RAP	2	7.6	7.6	6.8	8.3
Orm	8	6.2	6.4	2.0	10.0
ULV	2	5.1	5.1	4.6	5.6
Noir de Touraine	4	4.4	4.6	1.9	6.4

The removal rate in 2012, based on 22 samples, was the highest for phosphorous and zinc, respectively 24.3 and 20.2%. Total nitrogen was removed by 16.1% and the chemical oxygen demand (COD) was lowered by 9.4%.

In the first half of 2013 it was observed that 'BR 56' and 'BR 60' were the best to re-sprout. Unfortunately, in the summer of 2013, due to unexpected works at the WWTP, IWVA had to cut part of the willow field. It was shortened (Figure 2) and due to the fact that the field was not fed with water during 2 weeks many plants suffered.

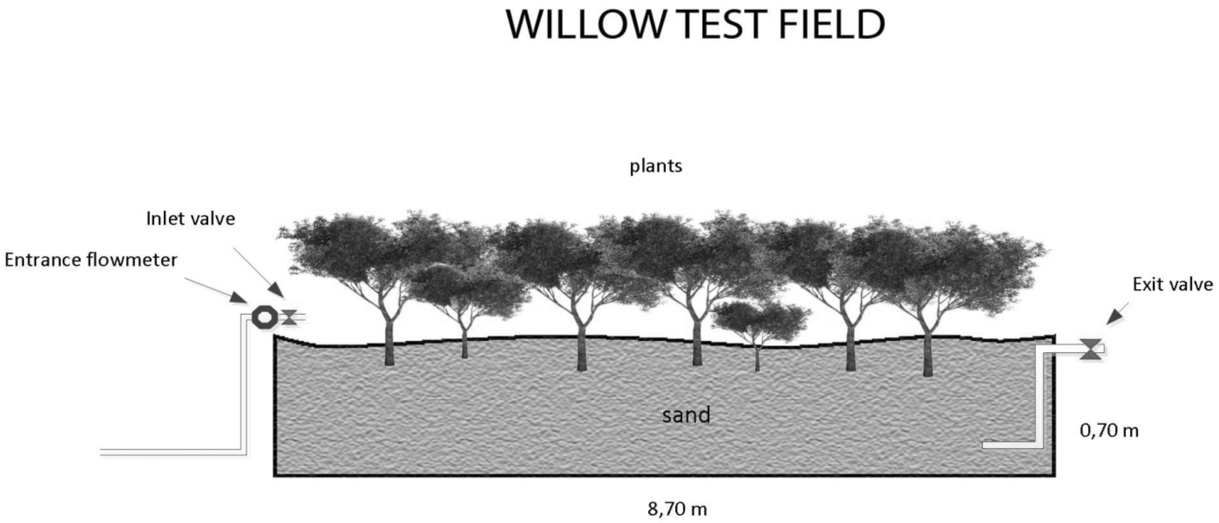

Figure 2 Scheme of the willow-test field (Sept. 2013 – 2015)

The removal rate in 2013 was better compared to 2012. This was due to the lower flow rate which was initially 500 l/h. In 2013 it was lowered to 250 l/h. Phosphorous and zinc were still removed the best, respectively by 33.2 and 26.0%. Total nitrogen content dropped by 25.4% after the willow treatment and COD by 18.9%. All these results were based on 22 samples, approximately every 2 weeks.

All plants were cut the 14th of February 2014, the good examples remained at place and new cuttings were placed at vacant places. On the exception of 2 specimens of Salix nigra '44' only species of Salix x rubens var. Basfordiana, Dutch cultivated types, 'BR56' and 'BR60' were kept as they proved the best to re-sprout and regrow after harvesting.

In 2014 and 2015 the evaluation of the willow test field was part of the DEMOWARE project. The results are discussed in 2.3.

1.2.2 Use of denitrificator

Biological system for post-denitrification was applied in Torreele site in regard to remove nitrates from reverse osmosis concentrate. The post-denitrification pilot-plant was planned as a fixed-bed technology according to Annex I. Although this technology has many advantages e.g. capable of handling high variability and high NOx removal and is a proved technology, fixed-bed technology is demanding for design and scale-up, manufacturing and operation. Fix-bed requires frequent backwash, a special filtration media and large filtration area. All partners contributing to this task agreed to use Moving Bed Biofilm Reactor (MBBR) as it is easy to build, transport, operate and scale up. MBBR is a biological reactor; the biomass present in the biofilm is responsible for the denitrification process. Biofilm is grown on plastic carriers and the biomass is thus retained in the reactor. MBBR is also valued for smaller footprint and easy control of the process.

Design and manufacturing of the pilot-plant was started by a review of existing technologies, operational parameters and efficiencies. The main limiting parameter of post-denitrification is COD/ N-NO_3^- ratio. COD/N-NO_3^- ratio is specific for each different substrate and can vary from 3 g/g up to 8 g/g.

Bench scale testing with real water was performed in order to evaluate denitrification rates for different conditions and several external substrates as a carbon source. Bench scale experiments were performed with suspended biomass because the growth of attached biomass on carriers takes several weeks. Based on bench scale results the pilot post-denitrification reactor was designed.

1.2.2.1 Pilot-plant (Figure 3) (Table 4)

Wastewater (RO concentrate) is pumped from an equalization tank to the reactor by gear-pump. This pump enables reverse operation, influent and effluent flow is performed by the same pump. The frequency converter is applied for more sensitive operation. Motor load both for standard and reverse operation is adjustable via control unit. Three-port valve is installed in front of the pump to open and close appropriate way. Effluent flow measurement is provided by flowmeter installed on the effluent pipe. There is a stainless steel suction basket at the suction of the pump inside the reactor. This basket is installed to retain carriers in the basin. pH adjustment consists of: pH probe, controller, pump for hydroxide dosing, pump for acid dosing and equipment. The motor load of chemical pumps is adjustable manually. pH adjustment is provided continuously during the reaction and is limited in sedimentation and drainage processes purposely. N-NO_3^- is measured by ion selective electrode installed in the reactor. For signal utilization, controller SC200 installed at Torreele treatment plant was used. Signal from this controller was lead to the control unit for process control. Both pH and N-NO_3^- probes were installed with the use of PVC pipe, whereas manipulation (cleaning, calibration or removing probes) was easier with using collar pipe clamps. External substrate was dosed by peristaltic pump into the reactor. This pump is suitable for any suitable substrate for post-denitrification. The motor load of the pump is adjustable as well.

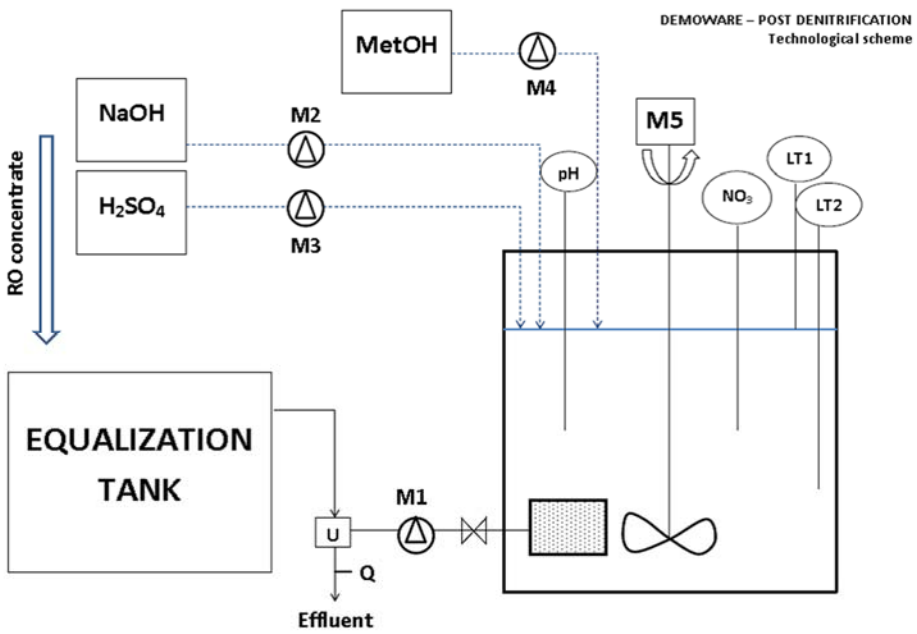

Figure 3 Technological scheme of post-denitrification MBBR

The reactor is mixed by vertical hyperboloid stirrer with stainless steel shaft. The stirrer requires low revolutions per minute (rpm). The motor is connected with gear box with final maximal 50 rpms. The motor is equipped by frequency converter for lowering the motor load. Some process phases are limited by minimal and maximal water level in the reactor. Water level is measured by ultrasound probe and the output was used for process control.

1.2.2.2 Operation

Operation of post-denitrification pilot-plant was prepared for automatic control and distant access. The control algorithm enabled two modes of operation – semi-continuous or sequencing batch reactor (SBR). Semi-continuous operation ensured pumping and draining of defined volume into and from the reactor in short, but adjustable intervals. The reactor was mixed constantly meaning that the carriers with attached biomass were moving continuously. This movement of carriers was necessary for distribution of nutrients to the attached biomass. Different approach was applied for SBR process. The process was divided into several parts: filling, reaction, sedimentation and drainage. Filling is the period when wastewater was pumped into the reactor while mixing. Mixing continued another 10-15 minutes in order to release all dissolved oxygen from the water. Reaction process was time defined and was initiated by adding of external substrate into the reactor. Sedimentation served to separate carriers with biomass from water. Clean water was drained from the reactor afterwards. All processes were adjustable concerning time or operational parameters (table 4). Advantage of this system was easier control of effluent quality, since $N\text{-}NO_3^-$ concentration in influent varied substantially.

Table 4 Operational parameters setup

Name	Mean	Unit
Type of operation	Semi-continuous/SBR	[-]
Operational conditions	COD/N ration	[-]
	Volume to change (different for SBR and continuous operation)	[L]
Motor lead	Agitator	[%]
	Influent	[%]
	Effluent	[%]
Time of operation	Mixing	[min]
	Semi-continous/SBR process	[min]
	Sedimentation in SBR process	[min]

The pH and $N\text{-}NO_3^-$ concentration were continuously measured and actual $N\text{-}NO_3^-$ concentration was used for calculation of external substrate dosage based on chosen COD/N ratio. Dissolved oxygen concentration, which could be limiting factor of anoxic denitrification, was daily measured by mobile device.

1.3 Results using willow treatment

At the end of the experiment the evaluation is performed in several ways:

- Chemical analysis of influent (RO concentrate) and effluent from the test field;
- Composition of the leaves;
- Weight of biomass of the plants.

The willow field is followed daily by the IWVA: flow, in- and outgoing conductivity, pH and temperature. Regular samples have been taken for analysis, both of the in- and effluent of the willow field (figure 4).

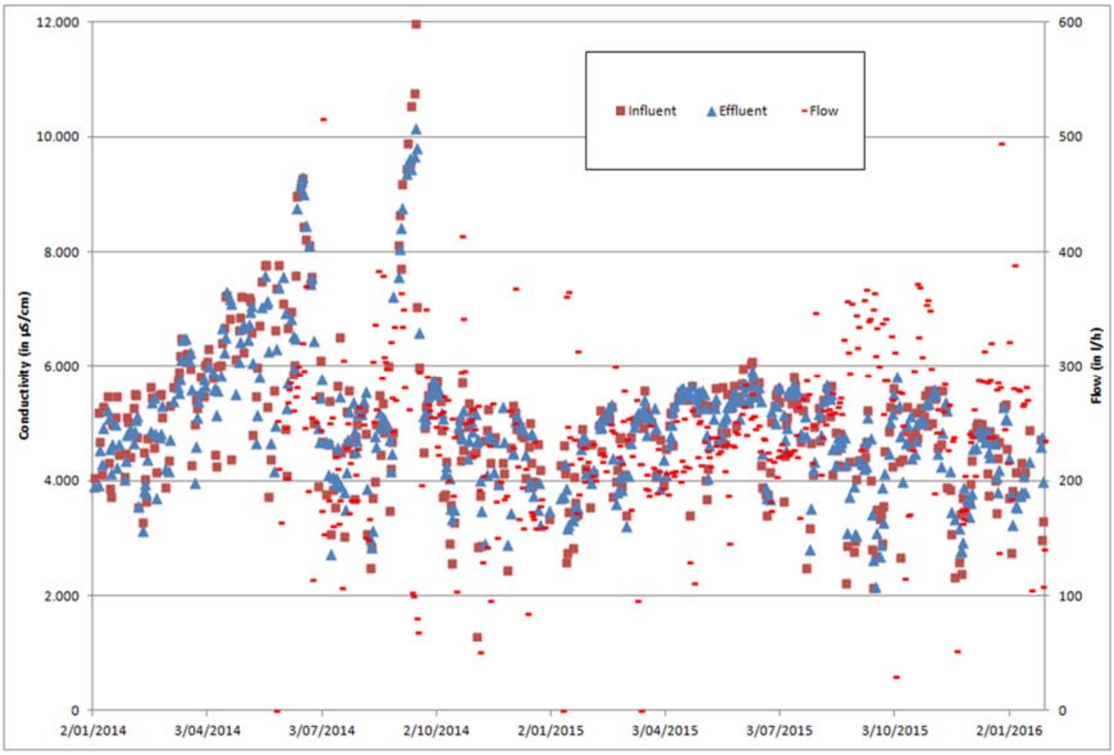

Figure 4 Average daily conductivity of in- and effluent of willow field and flow of the field

The samples from the effluent of the willow field are taken 24 hours after the influent (sampling period of 16 hours) due to the calculated residence time of the RO concentrate in the willow field. To have more accurate data late May 2014 a flow meter[4] was installed on the influent in order to measure the flux within the willow field at every sampling event. The flow was adjusted daily around 250 l/h[4]. As can be seen in Figure 5 there is a good correlation between the conductivity of the influent and the effluent one day later. The samples were analysed by a certified lab[5].

From the beginning of 2014 up to the end of 2015, samples of the in- and effluent were taken every 2 weeks. The results are given in Table 5 (2014) and Table 6 (2015). A longer evolution is shown in Figure 6.

4 Initially only a tube flow meter was used to adjust the flow; in May 2014 a Paddle-wheel type mechanical flow meter was added to the system.

5 From January 2014 until the end of June 2015 samples were analyzed by Eurofins in Nazareth (Belgium); from July 2015 on it was performed by ECCA in Merelbeke.

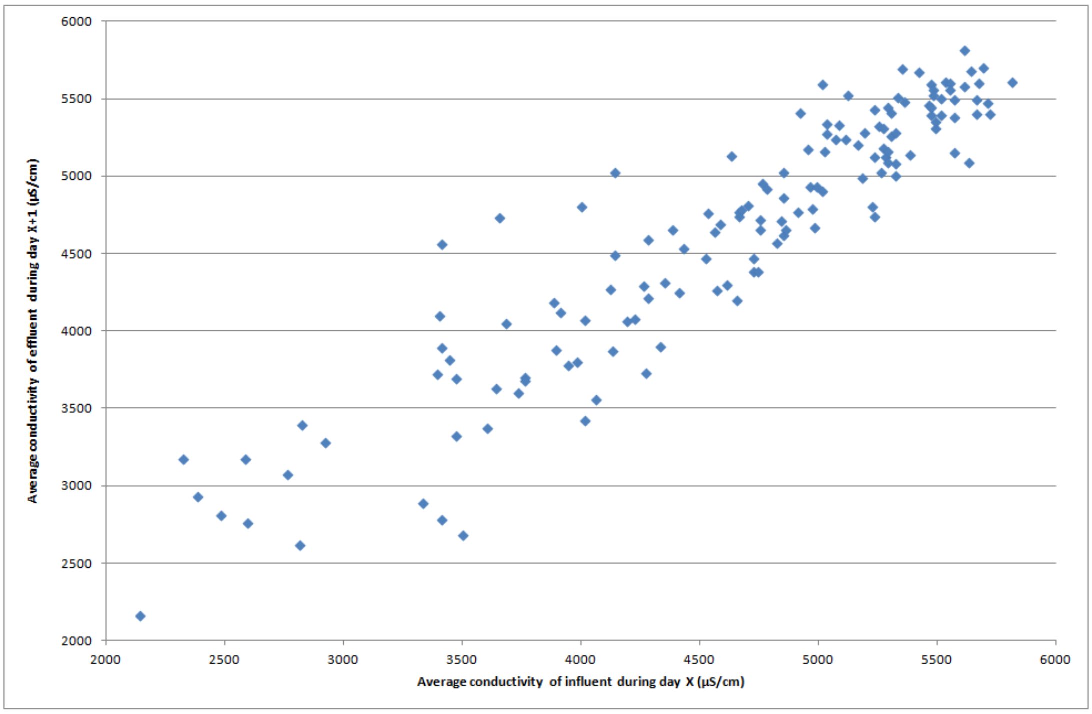

Figure 5 Relation between daily conductivity of influent and effluent the day after

Table 5 Results of sampling in 2014

	2014	Conducti-vity	pH	COD	tN	tP	Zn
Influent of willows	avg	5.509	8,0	99	26,1	4,1	51,7
	stdev	1.210	0,1	17,2	7,6	1,3	12,9
	median	5.500	7,9	100	26,0	3,9	50,0
	number of samples	11	10	23	23	23	23
	min	3400	7,9	62	14,0	1,7	32,0
	max	7900	8,1	130	45,0	6,9	85,0
Effluent of willows	avg	5.509	8,0	92	18,7	2,8	40,8
	stdev	1.007	0,1	16,1	4,1	0,5	10,1
	median	5.400	8,0	93	20,0	2,8	39,0
	number of samples	11	11	23	23	23	23
	min	4.200	7,8	62	11,0	1,8	21,0
	max	7.600	8,1	120	26,0	4,2	59,0
	removal based on average			-7,2%	-28,5%	-32,6%	-21,0%
	removal based on median			-7,0%	-23,1%	-28,2%	-22,0%

Table 6 Results of sampling in 2015

	2015	Conducti-vity	pH	COD	tN	tP	Zn
Influent of willows	avg	4.611	8,0	112	32,8	4,0	58,9
	stdev	780	0,1	21,6	14,0	1,9	16,2
	median	4.840	7,9	120	31,1	4,0	53,0
	number of samples	23	10	23	22	23	23
	min	2590	7,9	53	17,0	1,1	33,0
	max	5510	8,1	150	74,5	8,6	100,0
Effluent of willows	avg	4.644	7,9	98	22,3	2,9	45,7
	stdev	744	0,2	20,8	12,1	0,7	11,5
	median	4.780	8,0	98	20,7	2,9	43,0
	number of samples	23	18	23	22	23	23
	min	2.760	7,2	44	5,2	0,9	28,0
	max	5.590	8,1	150	65,0	4,5	70,0
	removal based on average			-12,3%	-32,1%	-27,6%	-22,4%
	removal based on median			-18,3%	-33,3%	-27,5%	-18,9%

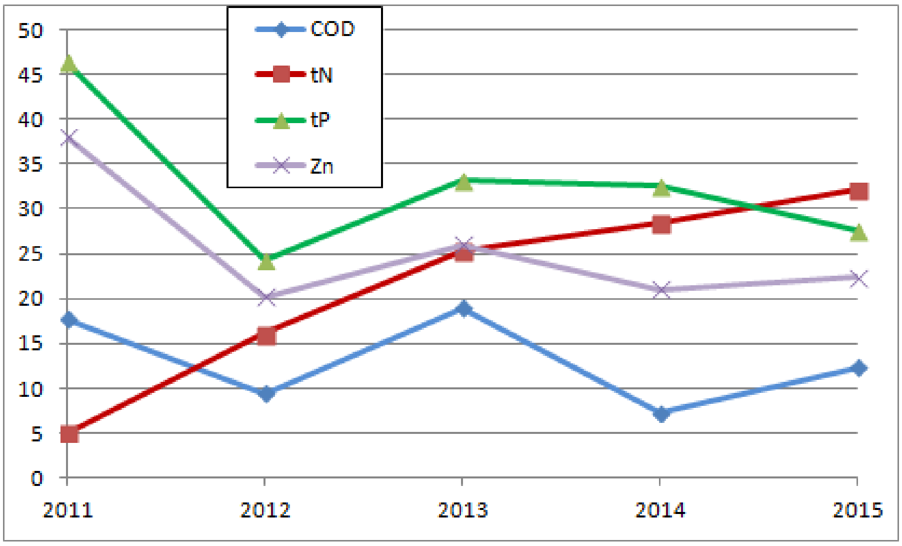

Figure 6 Yearly removal based on average concentrations of in- and effluent of willow field

1.3.1 Chemical Oxygen Demand

As is shown in Figure 7 in most of the campaigns COD is removed between 0 and 25% with a yearly average from 5 to 20% (Figure 6). As the average COD content is below the discharge limit for wastewater in Flanders (125 mg O_2/l) COD is of less concern compared to nitrogen and phosphorous. The COD is used as an energy source for the chemical processes involving nitrogen.

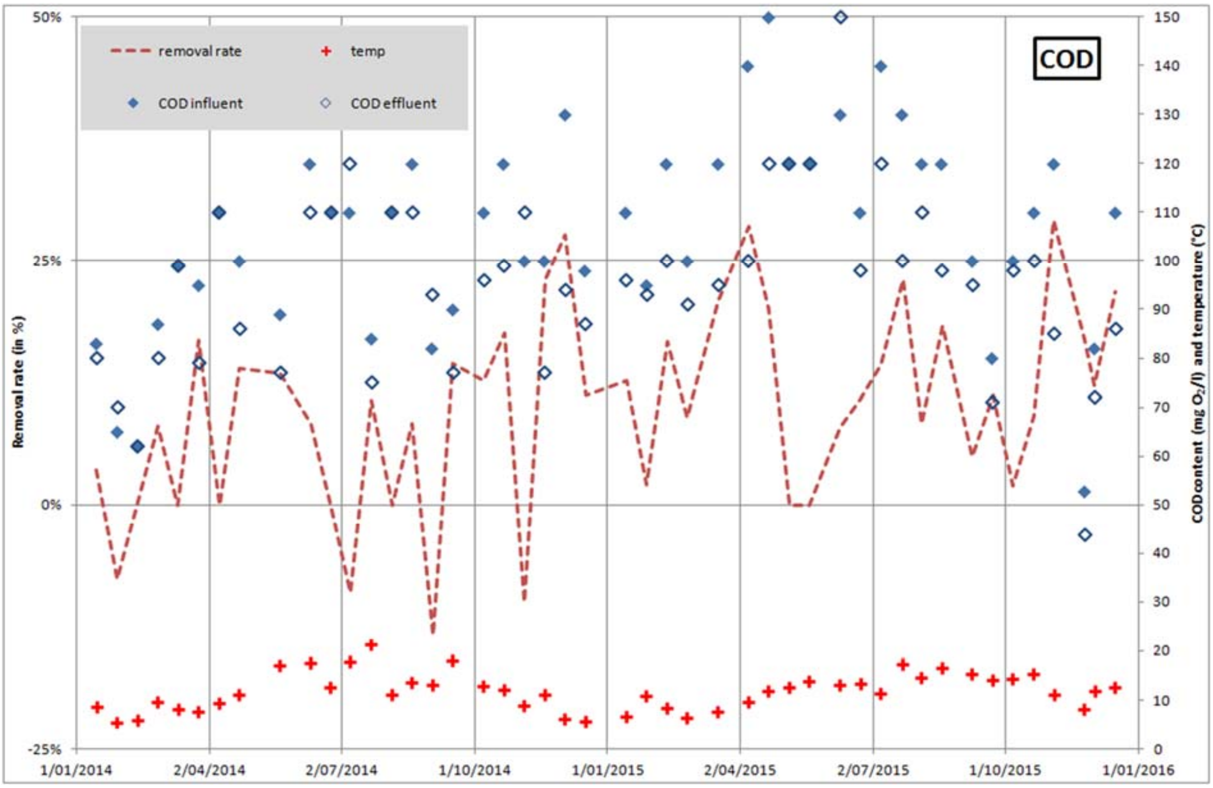

Figure 7 COD concentration in in- and effluent of willow field during 2014-2015

1.3.2 Total Nitrogen

The total nitrogen content[6], respectively 26.1 and 32.8 mgN/l in 2014 and 2015 is above the discharge limit set for wastewater effluent in Flanders (15 mgN/l). This is due to concentration with reverse osmosis. Based on a recovery of 75 to 77% (RO) the initial concentration is increased by a factor 4. Reduction of total nitrogen was the main objective of the willow test set-up.

As can be seen in Figure 6 the removal of nitrogen increased from year to year probably because the plants are cultivating a more abundant root system. The results from the Demoware test period are consistent: on 45 samples 43 show nitrogen removal (Figure 8). From April to October the nitrogen removal is higher than 25% but even during winter nitrogen is slightly removed. The explanation is that most of nitrogen removal is based on bacteriological activity in the root system which remains up to 5°C. As the willows are fed with concentrate after treatment of wastewater effluent the temperature is always above 5°C.

The average removal rate of 2015, higher than 30%, is very promising.

6 In 2013, in all samples (23) the individual nitrogen parameters were measured: on average 64% of the nitrogen content was nitrate, 2% nitrite and 33% Kjeldahl.

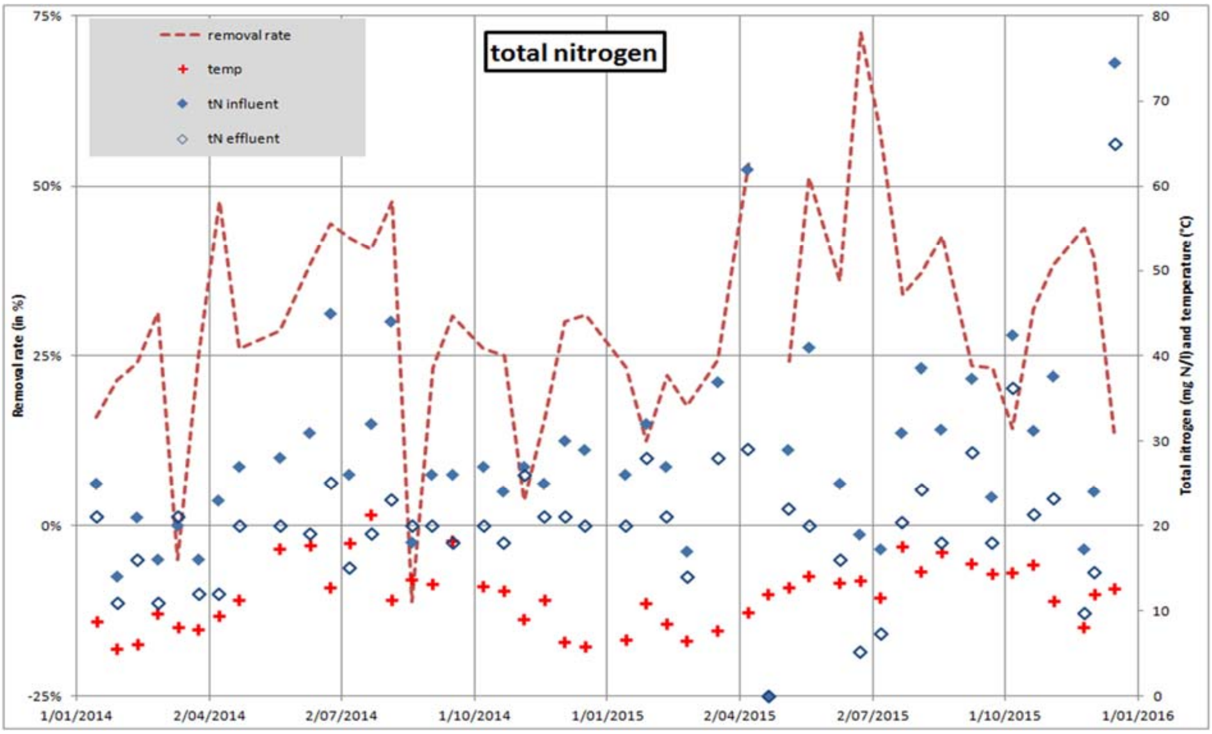

Figure 8 Concentration of total nitrogen in in- and effluent of willow field during 2014-2015

1.3.3 Total phosphorous

As for nitrogen the highest removal of phosphorous, essentially phosphate, is achieved from April to October (Figure 9) but contrary to nitrogen the phosphorous content can slightly increase during willow passage in winter. This is probably due to desorption of phosphorous from sand grains as filter media was used from old sand filters and thus coated with an iron layer. This presence of iron on the sand grains is also the explanation why the phosphorous removal was around 45% in the first year of operation (Figure 6 and Figure 9). Since then the yearly average phosphorous removal is between 25 and 35%. As the average phosphorous content was around 4 mg P/l, 2 mg P/l being the discharge limit for wastewater effluent, the average could be reduced to 3 mg P/l and lower.

1.3.4 Zinc

Zinc is not a parameter of concern but is was used to evaluate the behaviour of metals. The removal is continuous: on 46 samples only 3 showed an increase of Zn after the willows. The removal rates vary between 0 and 50% and no seasonal variation could be observed (Figure 10).

There is a parallel with phosphorous: higher removal during the first year of operation and a stabilisation since then between 20 and 25% on yearly average.

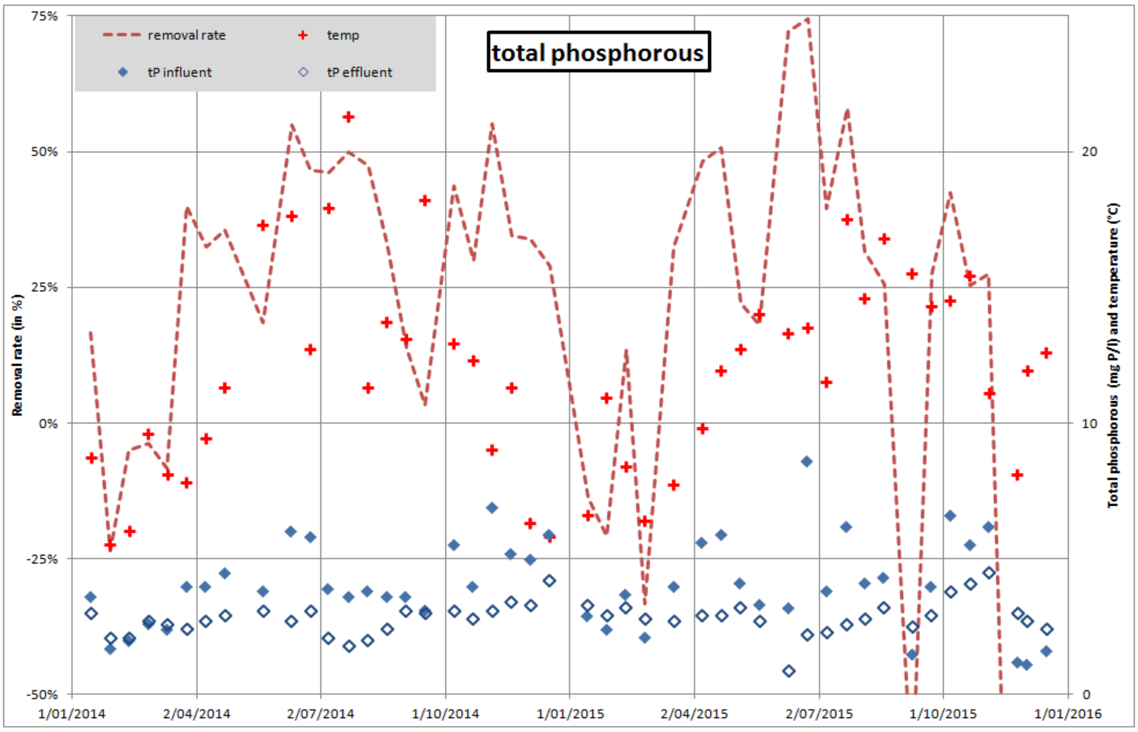

Figure 9 Concentration of total phosphorous in in- and effluent of willow field during 2014-2015

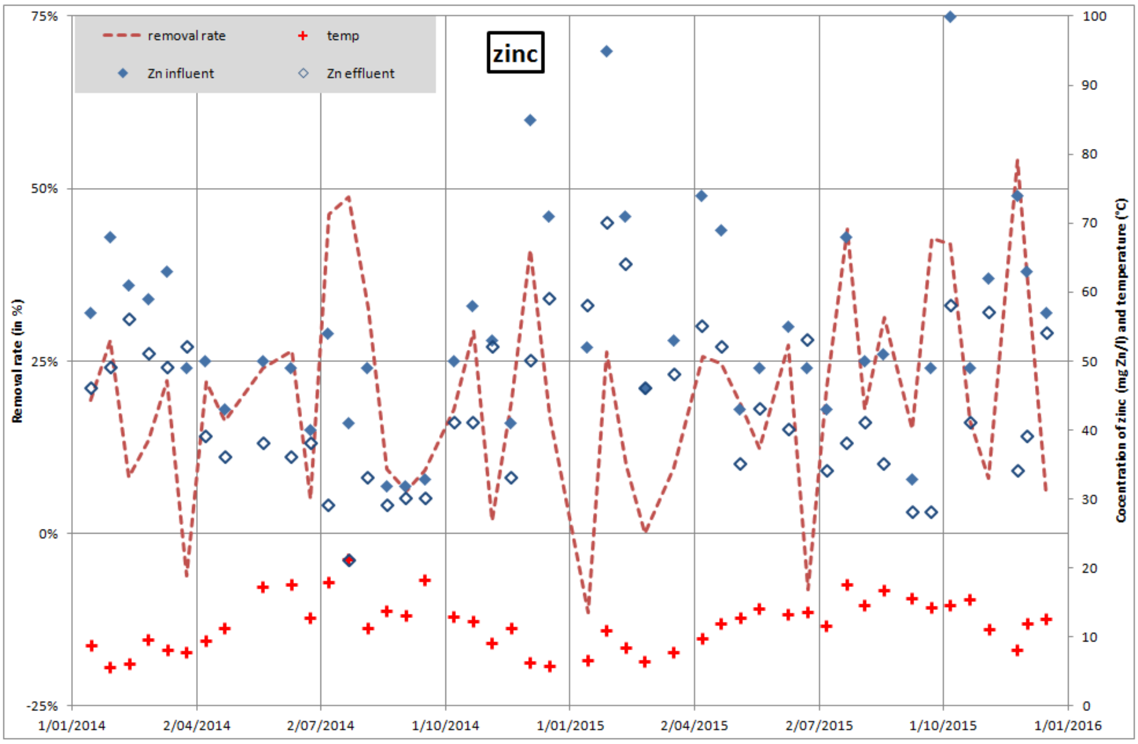

Figure 10 Concentration of zinc in in- and effluent of willow field during 2014-2015

1.3.5 Composition of plants

In September 2014 and 2015 leaves of 10 different plants were sampled and analyzed. Six were original plants (placed at the start of the test in 2011) and 4 were placed later. The dry matter content was around 28% on average for both years.

The results for C, N and P and their ratios are shown in Table 7 and Table 9Table 9 and for other parameters in Table 8 and Table 10.

Table 7 Results of leave analysis (C, P and N) 10 selected plants in 2014

	mg P/g plant	%N	%C	C/N	C/P	C/S	N/P	$\delta^{15}N$	$\delta^{13}C$
1	1,82	3,22	45,14	14,0	2,48	125,2	1,77	26,45	-28,86
2	2,15	2,62	44,13	16,9	2,05	104,6	1,22	17,81	-28,02
3	1,76	2,94	45,94	15,6	2,61	129,9	1,67	21,78	-27,52
4	2,15	3,29	44,66	13,6	2,08	98,4	1,53	26,15	-29,33
5	2,27	3,19	44,81	14,1	1,98	85,8	1,41	23,08	-29,34
6	2,27	3,60	43,82	12,2	1,93	109,5	1,58	26,64	-29,48
7	2,05	3,21	44,90	14,0	2,19	113,6	1,57	16,13	-29,17
8	1,64	3,01	45,10	15,0	2,75	115,7	1,84	20,96	-28,41
9	1,98	2,97	44,94	15,1	2,27	143,4	1,50	18,23	-28,49
10	2,03	2,87	43,48	15,2	2,14	100,4	1,41	18,51	-29,89

Table 8 Results of leave analysis (metals) on 10 selected plants in 2014

		mg/kg DM	g/kg DM				mg/kg DM					µg/kg DM	
Reference	%DM	S	Ca	K	Mg	Na	Al	Cu	Fe	Mn	Zn	Cd	Pb
1	27,0	3.605	12,2	31,2	2,55	0,661	49,2	4,63	106	150	43,5	97,6	507
2	27,7	4.219	11,1	31,7	2,68	0,402	40,2	3,50	107	115	39,0	34,3	398
3	29,1	3.536	9,66	33,7	2,57	0,389	30,2	2,90	84,5	122	43,3	29,6	345
4	27,1	4.540	15,9	24,4	3,11	0,681	49,3	4,17	119	125	143	34,6	491
5	26,6	5.224	14,7	25,3	2,79	0,819	55,4	2,85	132	198	110	41,2	519
6	26,1	4.004	12,2	28,2	3,29	0,592	47,4	3,61	123	70,5	73,3	44,6	403
7	27,6	3.954	13,7	27,9	3,09	0,552	44,1	3,44	121	122	65,7	29,2	448
8	28,3	3.898	10,8	30,2	2,46	0,518	32,0	3,62	93,9	68,4	50,4	26,8	360
9	30,9	3.133	9,38	35,0	2,23	1,58	54,2	2,52	109	83,9	78,7	29,7	492
10	27,2	4.332	13,9	23,4	3,13	0,426	39,1	4,90	257	105	22,5	35,4	355

Table 9 Results of leave analysis (C, P and N) 10 selected plants in 2015

	mg P/g plant	stdev	%N	%C	C/N	C/P	C/S	N/P	$\delta^{15}N$	$\delta^{13}C$
1	2,04	0,02	2,99	45,56	15,2	2,23	120,3	1,46	18,13	-28,59
2	2,03	0,03	2,51	46,91	18,7	2,31	110,3	1,23	18,91	-28,68
3	2,28	0,02	2,90	47,06	16,2	2,06	121,0	1,27	17,29	-28,54
4	1,94	0,08	2,41	47,83	19,8	2,46	161,9	1,24	21,24	-29,06
5	3,25	0,00	4,44	48,15	10,8	1,48	95,1	1,37	32,91	-29,10
6	2,69	0,09	3,42	47,17	13,8	1,75	119,9	1,27	28,96	-29,00
7	2,17	0,05	2,47	46,00	18,6	2,12	125,2	1,14	18,63	-28,93
8	2,00	0,01	2,64	45,91	17,4	2,30	106,5	1,32	16,88	-29,59
9	2,30	0,02	2,26	46,36	20,5	2,01	157,8	0,98	21,44	-27,08
10	2,62	0,15	3,29	45,30	13,8	1,73	88,7	1,25	23,06	-29,67

Table 10 Results of leave analysis (metals) on 10 selected plants in 2015

		mg/kg DM	g/kg DM				mg/kg DM					µg/kg DM	
Reference	%DM	S	Ca	K	Mg	Na	Al	Cu	Fe	Mn	Zn	Cd	Pb
1	27,6	3.786	17,0	17,7	2,36	0,610	31,3	1,51	78,2	211	47,2	35,7	1.151
2	28,0	4.253	17,1	16,7	2,67	0,404	24,0	2,06	64,5	183	67,8	25,7	845
3	29,1	3.889	14,5	20,4	2,20	0,191	20,5	1,80	52,8	190	49,6	20,5	661
4	28,6	2.954	15,2	17,7	2,73	0,532	41,2	1,35	86,4	145	95,0	29,8	926
5	26,1	5.062	9,53	18,2	2,05	0,557	16,6	4,36	77,3	153	107	22,3	933
6	26,4	3.934	9,75	17,9	1,98	0,417	23,9	3,22	76,2	124	116	47,6	694
7	29,9	3.673	21,0	12,6	3,33	0,504	37,8	1,84	95,8	166	96,1	33,2	667
8	26,9	4.309	16,2	21,4	2,15	0,329	24,8	1,88	54,4	242	85,7	23,8	540
9	31,4	2.938	11,5	17,4	1,51	0,375	17,4	0,736	40,9	143	43,2	18,3	448
10	25,9	5.107	11,1	20,1	2,17	0,344	19,3	4,52	59,9	101	48,8	39,3	415

The difference in ratios in 2014 and 2015 is minor:

- The C/N ratios of 14.56 and 16.49 are comparable with the average results of 4 leave samples of the same species taken in 2011 and 2012, respectively 15.04 and 15.35; there is no significant difference between older and newer plants; according to Schrama et al. (2014) the C/N ratio of willows is lower compared to other energy crops which means that willows tend to take up more nitrogen;
- The C/P ratios of 2.25 and 2.05 are also in the same range with no significant difference between older and newer plants;
- The variation of the N/P ratio is greater, with values of 1.55 in 2015 and 1.25 in 2014 with no difference between older and younger plants; in 2011 the ratio was comparable but in 2012 the ratio of 0.71 proved to be significant lower thus more P was taken up by the plants.

Concerning the other parameters, the C/S ratio is comparable for 2014 (112.6) and 2015 (120.7) with no difference between older and younger plants; this is higher compared to 2011 (82). Other parameters that were analysed (Table 8 and Table 10) show more significant variations. The differences can be as high as 69%, e.g. lead. There is no explanation for that. It can be noticed that the amount of heavy metals is low and does not limit any potential use of the harvested biomass.

1.3.6 Yield of plants

The 18th of December 2015 all remaining 26 plants were harvested. The 11 plants still present since 2011 had an average yield of 6.3 kg/plant after 2 years of growing varying between 0.7 kg and 24.3 kg. If we do not consider the 0.7 kg plant the average raises to 7.5 kg which is close to the average weights when the BR56 and BR60 plants were harvested at the end of 2012 (Table 6). The average weight of the stems that were placed beginning of 2014 amounted 1.9 kg/l which was far below the yield of older plants. This proved that new stems placed in an existing field, where roots were already well developed, do not grow very well. It proved better to start with all stems in the same condition.

The yield for the whole willow test field amounted 90.6 kg after 2 years of growing. Upgrading this result to 1 ha would mean a yearly production of 17.4 ton/ha/year. If we calculate with the average yield of the initial stems (6.8 kg), and this is more realistic, with 20,000 stools/ha, the average yield would be 67.9 ton of harvested biomass/ha/year. Taking into account a dry matter content of 30% the average yearly production would amount 20 tons of dry wood chips/ha/year. This is in line with the results of experiences in Canada where polluted groundwater was treated and where it was observed that irrigated plots, and the willow test field here has comparable conditions, produced more than unirrigated plots. The woody biomass yield after 2 years of cropping amounted 32.6 Odt/ha[7] (Nissim et al., 2014). Also a test in Flanders (Schrama et al., 2014) obtained an average crop yield of 18.5 ± 3.8 ton dry matter/ha/year. According to De Somviele et al. (2009) there is a tendency to place the stems in higher density even up to 30,000 stools/ha. As in the IWVA case the field is constantly irrigated, and the plants thus constantly fed, this seems technically feasible. De Somviele et al. also mentioned that 1 ton of dry willow biomass amounts 18 GJ of energy and 2.5 kg of dry biomass values 1 l of fuel. Calculating with a yearly yield of 20 tons it could mean that 8.000 l of fuel could be replaced when treating the RO concentrate of Torreele with willows.

1.4 Results using denitrification plant

1.4.1 Bench scale experiments

Bench scale testing was performed in order to evaluate denitrification rates for different conditions and several external substrates as a carbon source. Bench scale experiments were performed with suspended biomass because the growth of attached biomass on carriers takes several weeks. Activated sludge used for the bench scale experiments was taken from a municipal WWTP.

First, the RO concentrate and sludge were analyzed for the parameters: pH, dissolved oxygen, COD, $N\text{-}NO_3$, N_{tot}, $P\text{-}PO_4^{3-}$, MLSS. The activated sludge was mixed and aerated for one day to achieve endogenous respiration. Sludge concentration was kept at 3 g/L for all tested variants. Tested COD/N ratios were: 3, 5, 6, 8. Different external substrates were tested: methanol, ethanol, sodium acetate, citric acid, commercial KEM-DN7 (Kemira). Concentration of dissolved oxygen, COD, $N\text{-}NO_3^-$, $N\text{-}NO_2^-$ and pH were analyzed during the two-hours testing period. Decrease of $N\text{-}NO_3^-$ concentration was evaluated and the denitrification rate was calculated for comparison of different substrates and COD/N ratios.

Although the results showed overall low denitrification rates for suspended biomass, the highest nitrate removal was achieved with methanol (0.153 g $N\text{-}NO_3^-$/g VSS·day), followed by ethanol (0.088 g $N\text{-}NO_3^-$/g VSS·day) and citric acid (0.085 g $N\text{-}NO_3^-$/g VSS·day). Commercial product KEM-DN7 achieved denitrification rate only 0.065 g $N\text{-}NO_3^-$/g VSS·day. Regarding the applicability of external substrates, methanol is recommended for its best performance and the lowest operating costs, citric acid for its available amount from chemical membrane cleaning. Minimal COD/N ratio necessary for proper denitrification process is 5.

Although no tests were performed with attached biomass, AnoxKaldnes carriers were chosen for pilot-plant operation. Suggested volume of 50% was applied.

1.4.2 Pilot-plant testing

Post-denitrification pilot was installed in June 2015. The first part of operation was biomass growth. Activated sludge concentration of 3 g/L was put into the post-denitrification reactor. Organic loading rate was kept at 75 g COD per day (0.124 g COD/g biomass per day). RO concentrate was daily added in small amounts (13 liters) into the reactor to ensure adaptation of biomass to RO concentrate. Some chemicals were added in order to achieve assumed ratio COD:N:P=100:5:1. COD in RO concentrate was considered as non-biodegradable, thus external substrate was also added (46% citric acid).

The pilot was always running in SBR mode, therefore time and operational conditions had to be set. According to bench scale experiments, we recommended mixing time (in order to reach anoxic conditions) for 15 minutes, minimal SBR time for 90 minutes and COD/N ratio at least 5.

[7] Odt/ha refers to Oven Dried Tonnes per hectare.

Several technical issues occurred during operation, especially regarding the water level control. Deficiencies in water level measurement caused incorrect process control, resulting in problematic performance. Water level sensors were changed three times; the final solution was ultrasound water level control. Another problem was caused by pH probe breakdown. Considerable hardness of RO concentrate created a strong crust at pH probe after few weeks of operation, that couldn´t been removed. This, however caused overdosing of the reactor by hydroxide up to pH 12. The biomass was killed and the process had to be started again. Since static pH probe was no longer in operation, the operator provided measurement by portable probe regularly.

Regarding the testing, maximal $N\text{-}NO_3^-$ concentration was very dependent on influent concentration. Influent concentration was on the other hand independent on the weather. Proper function of post-denitrification unit was characterized by $N\text{-}NO_3^-$ concentration below 5 mg/L in the effluent. Values around 3 mg/L $N\text{-}NO_3^-$ were achieved during months September and October. High values were monitored in November and December, when maximal concentration achieved in the reactor was 30 and 45 mg/L, respectively. High concentrations were decreased after 2-3 days in all cases. After changing the water level control, reliable operation was monitored, meaning maximal $N\text{-}NO_3^-$ concentrations in the reactor 7 mg/L from January to the end of March 2016 and again, those concentrations were max. in two days decreased. Average concentrations were around 3 mg/L, which indicates well adapted biomass and working denitrification processes. Influent and effluent MBBR parameters are shown in Table 11.

Table 11 Influent and effluent MBBR characteristics

	Unit	MBBR Influent	MBBR effluent	Removed (%)
BOD	mg/L	3.67	3.00	18.2
COD	mg/L	106.33	96.33	9.4
N_{tot}	mg/L	22.30	18.80	15.7
TKN	mg/L	10.13	7.80	23.0
$N\text{-}NO_3^-$	mg/L	11.67	9.57	18.0
P_{tot}	mg/L	3.07	3.10	-
Cond	µS/cm	3663.3	3966.7	-

On-line measurement of $N\text{-}NO_3^-$ gave us valuable data. The best results showed correlation between $N\text{-}NO_3^-$ concentration in the reactor and influent to the reactor. We can see two different scenarios: in case of higher concentration in RO concentrate compared to the reactor, there is fast step increase of $N\text{-}NO_3^-$ in the reactor (Figure 11) On the contrary, we can see step decrease of $N\text{-}NO_3^-$ concentration along with every draining (Figure 12). This indicated both dilution by RO concentrate and denitrification process.

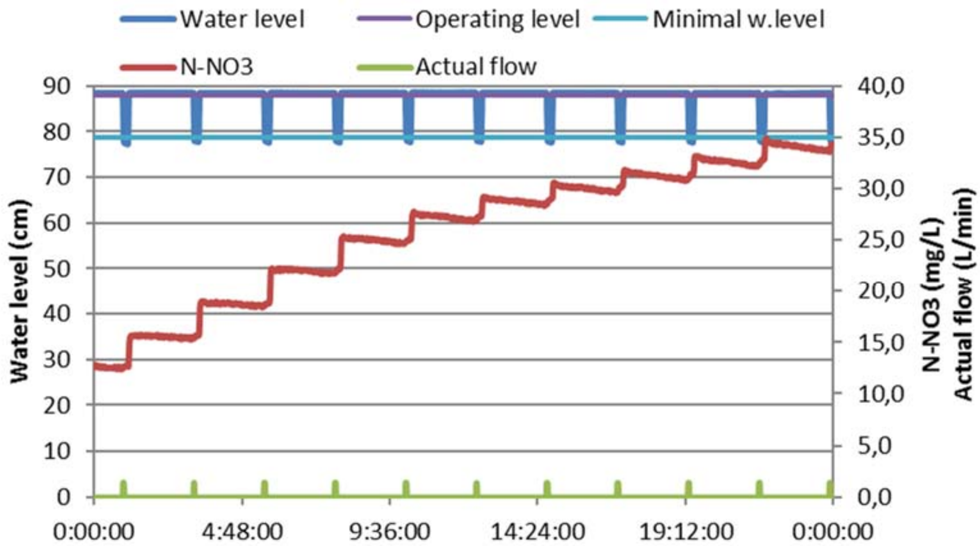

Figure 11 Nitrogen concentration, flow and water level of pilot MBBR – 13th December 2015

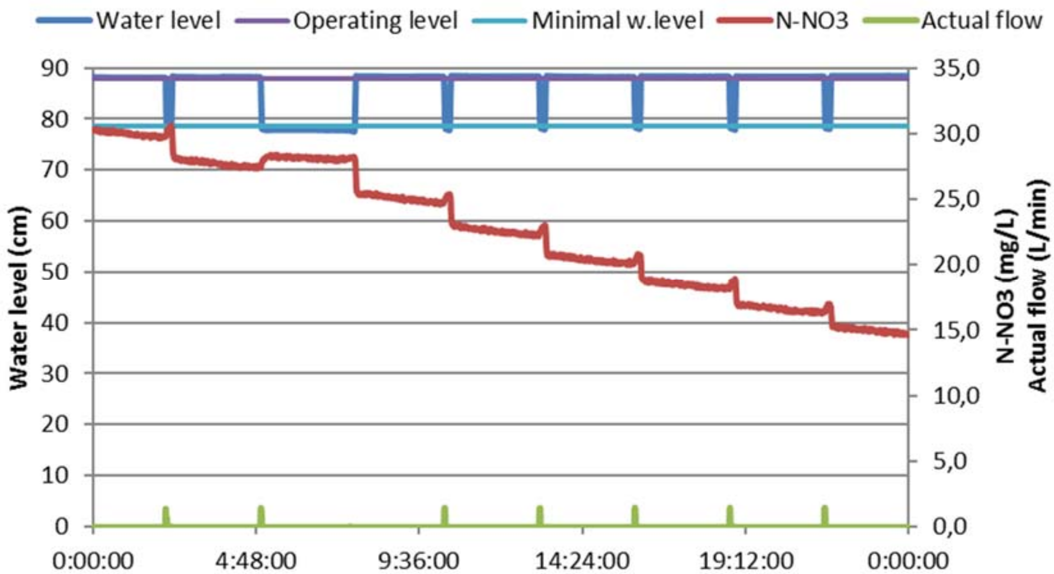

Figure 12 Nitrogen concentration, flow and water level of pilot MBBR – 16th December 2015

The main evaluating parameter of post-denitrification MBBR is NOx-N removal rate. This parameter defines the amount of nitrogen removed by 1 square meter of carrier per day. This value can be easily compared with other MBBRs or technologies, as listed in Table 12. It should be mentioned, that presented removal rates were achieved when $N\text{-}NO_3^-$ concentrations in the reactor exceeded 30 mg/L. With average N concentration in RO concentrate below 10 mg/L removal rates were around 0.01 g $N/m^2 \cdot d$ or less. Maximum achieved denitrification rate was 0.11 g $N/m^2 \cdot d$. It can be concluded, that efficient denitrification requires

$N\text{-}NO_3^-$ concentrations higher than 30 mg/L. This is in accordance with literature where the lowest recommended $N\text{-}NO_3^-$ concentrations are around 50 mg/L (Hamlin *et al.*, 2008). Dependence of influent $N\text{-}NO_3^-$ concentration on N-NOx removal rate detected in our research is presented in Figure 13.

Table 12 Typical MBBR Loading Rates for Tertiary Denitrification

Flow, m3/d	Media Fill, %	NOx-Removal Rate, g N/m2/d	Effl. TN-N, mg N/L	External substrate	Downstream Clarification	Reference
126,000	50	1.05	6.8	Methanol	DAF	Täljemark et al., 2004
23,800	36	1.05	5.8	Ethanol	Filtration	Täljemark et al., 2004
8,700	23	-	<1i	Methanol	Filtration	Wilson et al, 2008
6.7ii	30	-	<2	-	Filtration	Pilot testing, Washington, D.C. (Stinson et al., 2009)
0.4	50	0.11	<1i	Citric acid	none	DEMOWARE

Notes:

i Effluent NOx-N

ii Gallons per minute

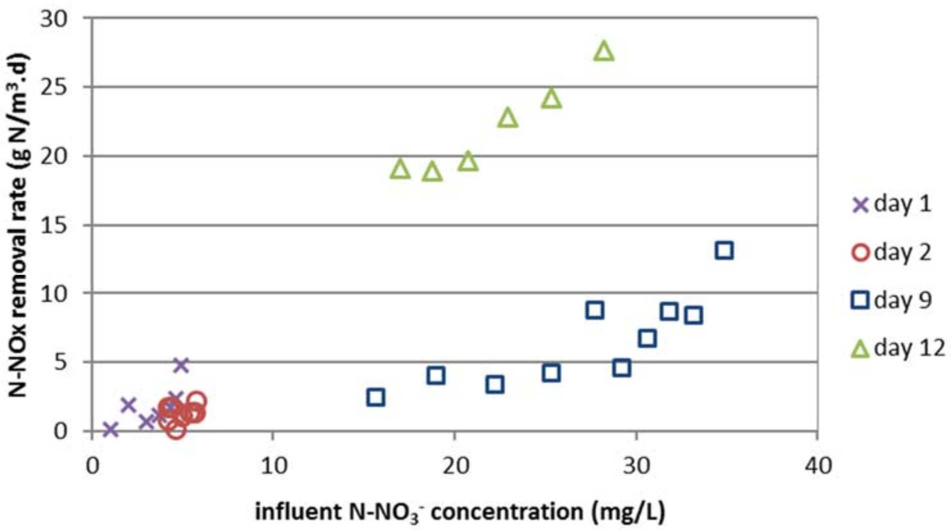

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Figure 13 Dependence of influent $N\text{-}NO_3^-$ concentration on N-NOx removal rate

Dependence shown in Figure 13 also showed a big difference between N-NOx removal rates in day 9 and 12, although influent $N\text{-}NO_3^-$ concentrations were very similar. Nitrate concentration was continuously increasing from day 1 (0-4 mg $N\text{-}NO_3^-$/L), to day 9 (13-35 mg/L), and then finally decreasing during day 12 (30-15 mg/L). We assume, that higher $N\text{-}NO_3^-$ concentration kept for 4 days had a positive effect on denitrification performance, resulting in higher N removal. According to our results, post-denitrification MBBR is not suitable for applications where nitrate content fluctuates too much.

Several tests were made also for another external substrates and different COD/N ratios. External substrates tested were methanol and citric acid with COD/N ratios 5 and 6. No differences in denitrification rates or N removal were achieved during the testing. We can declare, that similar results were obtained for different external substrate adjustment. The only parameter that affected the performance was lowering of pH caused by citric acid dosing. To adjust pH to optimal range, big amount of NaOH was dosed into the reactor. This resulted in even higher conductivity in the reactor. Although citric acid was chosen as an external substrate for pilot operation, since it is waste material produced ibidem, it is not suitable for long-term operation.

Another important parameter of post-denitrification was the conductivity of RO concentrate which varied between 3200-6700 µS/cm. Higher salinity required high initial concentration of suspended biomass and a longer adapting phase for biomass. The conductivity was increasing continuously in the reactor; therefore, sequential adapting of biomass was assured. Growth of attached biomass was complete after ca. four weeks and the same time was sufficient for adaptation of microorganisms to high conductivity. We can generally conclude, that for adapting biomass to abnormal conditions, slow increasing of deteriorative parameter in combination with high biomass concentration is sufficient. Furthermore, no dependence of conductivity variation on denitrification performance was observed. Since the tests were performed with real RO concentrate, we did not evaluate minimal conductivity that could limit the process itself.

Although the MBBR installation was successful, there are some factors that have an influence on the performance. Those are especially variable $N\text{-}NO_3^-$ concentration and salinity of RO concentrate. Another important factor is biofilm occupancy. No biological analyses were provided during MBBR operation. Analyses of microbial population could be further applied for process optimization.

1.5 Economic evaluation

There are different aspects in the economic evaluation of willow treatment. On the ‘income’ side there are:

- reduced taxes for discharge due to lower nutrient content;
- income from yearly yield of woodchips.

On the cost side there are:

- investment costs for installing a full-scale plantation;
- Maintenance and harvest costs.

The IWVA pays taxes to discharge the wastewater from the Torreele facility. The taxes are based on 3 groups:

- Organic load calculated on BOD and COD content and suspended solids;
- Content of metals (As, Ag, Cr, Zn, Cu, Cd, Pb, Hg and Ni);
- Nutrient content (N and P).

Currently IWVA discharges both UF backwashwater and RO concentrate but in the near future this will be limited to only RO concentrate as UF BW water will be recovered using sand filtration.

The tax was calculated using the average data for 2014 and 2015 taking into account a total yearly production of 2.0 and 2.5 Mm³/yr[8] respectively, being the current yearly production capacity and the maximum permitted. In 2014 the benefit using willows would have been respectively 22.000 and 25.000 euro; in 2015 this would have been 28.000 and 34.000 euro.

8 In 2014 a project was started to enlarge the infiltration capacity using ‘infiltration boxes’. From 2016 on, 300.000 m³/year should be Infiltrated this way. Currently the IWVA is also planning to extend the infiltration ponds so that the full permitted capacity could be infiltrated from 2018 on.

The potential yield of woodchips was discussed earlier. The Austrian Standards Institute has set up a classification for woodchips for energy regeneration (Önorm M7 133). They are based on size, moisture content, material density and ash content. There is also a New European Pellets Standard (EN 14961-1) and a standard on solid biofuels e.g. wood chips for non-industrial use (EN 14961-4). 'Woody biomass' is defined as 'biomass from trees, bushes and shrubs'. In the Önorm the moisture content goes from <20%, described as 'air dry' (W20) to 40-50%, described as 'green' (freshly harvested) (W50).

The current price for dry woodchips is 100 euro/ton which means that the yearly income would be not more than 2.000 euro.

The costs for installing the full-scale field comprises investment costs: the purchase of land, preparing and installing the field (impermeable clay math, sand, pipe work) and placing the first generation of stools. These costs were calculated based on what Aquafin had recently to pay for ground nearby and on information from a local company active in wastewater treatment (www.ecoz.be)[9]. There are yearly operational costs for maintenance of the field and harvesting half of the plants. In Table 13 the results are shown for a 20-year lifetime. This shows that installing and operating a willow field for the treatment of RO concentrate is economically feasible mainly due to the reduced discharge cost.

Table 13 Price calculation of the willow field based on a 20 year lifetime

INVESTMENT	*Cost* (EUR)	*Depreciation period* (years)	*Yearly cost* (EUR/jr)
Preparation cost	25.000	20	1.381
Construction cost	200.000	20	11.046
Purchuse of land	100.000	33	3.347
Plants	20.000	20	1.105
Total	**345.000**		**15.774**
OPERATIONAL COSTS			
Maintenance	5.000		5.000
Harvest	5.000		5.000
Total	**10.000**		**10.000**
Discharge	30.000		-30.000
Biomass production	2.000		-2.000
Total	**32.000**		**-32.000**
TOTAL			**-6.226**
Period of loan	*10*	*Interest rate (in %)*	*1,0*

There is a safe margin in the calculation and as in this test the willows were fed with the same flow through the whole year the removal rates are probably underestimated as in normal circumstances flows in winter will be lower resulting in higher removal capacities. Also inflation will lead to higher discharge costs and thus greater savings when treating the concentrate.

1.6 Conclusions

The use of willows to treat RO concentrate is technically feasible. Two specimens of Salix x rubens var. Basfordiana, Dutch cultivated types, 'BR56' and 'BR60', were salt tolerant and proved the best to re-sprout

9 This information was double-checked.

and grow. Based on the experiences with the test and other related experiences, a production of 20 ton dry matter/ha/year seems feasible. In this way minimum 30% of the total phosphorous and nitrogen is removed from the concentrate and this would benefit to the canal where the water is drained and the yearly tax for discharge would be reduced by 30.000 euro yearly. Based on these results this seems to be economically feasible. This system does no use energy during its operation and it produces carbon neutral energy when using the woodchips for heating or energy production.

The test with post-denitrification MBBR showed that the variable and mainly low nitrate content of the concentrate in combination with high salinity limits the performance. And contrary to willows energy and chemicals are needed to run the MBBR.

2 Decoupling nutrient and water management in CAS-systems targeting agricultural reuse of municipal wastewater

The most common way to reuse municipal wastewater after treating it in a wastewater treatment plant (WWTP) is the direct irrigation of agricultural land with WWTP effluent. In agriculture not only the treated wastewater is of interest for water supply to the plants, but also the plant nutrients (e.g. nitrogen (N) and phosphorus (P)) which are present in the WWTP effluent. In modern WWTPs with biological or chemical nutrient removal, N and P are removed to a wide extent from the effluent into sewage sludge in order to protect receiving surface waters from eutrophication.

The following section of this report gives an overview and assessment on possible options for optimized water and nutrient management in large-scale wastewater treatment plants targeting reuse of water and nutrients in agriculture, focussing on WWTPs with conventional activated-sludge (CAS) processes. The different management options will be demonstrated with particular focus on the existing reuse site in Braunschweig, Germany. For optimisation of water and nutrient management, two separate objectives will be prioritized:

- Decoupling of water reuse and nutrient recycling in Braunschweig
- Decoupling of nitrogen recycling and sewage sludge valorisation in agriculture

2.1 Background on water reuse and nutrient recycling

2.1.1 Situation of water reuse in agriculture: status and challenges in management

Many applications of water reuse in agriculture can be found in arid and water scarce regions of the world, with Israel being the country with the highest share of reused water worldwide (Asano, Burton et al. 2007). In such regions with high water scarcity, a permanent demand for irrigation water can be expected during the vegetation period.

In countries such as Germany however, sufficient precipitation for agriculture can be expected in many areas due to the positive climatic water balance , so that even in summer only a small percentage of the agricultural area is irrigated at all (2.2%) (Destatis 2014). Hence, only two large scale schemes for water reuse exist in Germany, located in the neighbouring cities of Braunschweig and Wolfsburg in Lower Saxony. Both reuse schemes have been historically developed in the 1950s due to suitable conditions and respective water demand in agriculture (deficit in climatic water balance in summer, poor sandy soils). For Braunschweig, stabilized sewage sludge is directly mixed to the irrigation water during the summer period (March-October) to supply additional nutrients to the plants. Within this specific setting of water and nutrient supply through water reuse, an optimised management of both water and nutrients throughout the year poses various challenges (see Figure 14 as example the reuse site in Braunschweig):

- The main period where an additional water supply for agriculture is recommended is mid-summer (May-July). The actual nitrogen demand of plants during their growth period can be estimated for early summer (Apr-June) (Beegle and Durst 2003) (see Figure 14), but in fact common agricultural practices recommend nitrogen fertilizer application in spring (Mar-May). Given the different timing of water and nitrogen demand, a decoupling of water and nitrogen management is mandatory in Braunschweig for a demand-driven supply of both, water and nitrogen. The target of water and nitrogen decoupling is useful for both traditional nitrogen dosing strategies (i.e. in spring) as well as if demand-driven strategies for N dosing are applied.
- At the beginning of the vegetation period, which is also the period when famers usually apply major amounts of nitrogen fertilizers, the amount of precipitation which will be delivered throughout the

entire vegetation period is still unknown. Since the demand for treated wastewater for irrigation depends on the effective amount of rainfall during the summer period (excess irrigation has to be avoided in order to prevent leaching of nitrogen into groundwater) both the volume of required irrigation water and the corresponding loads of nutrients applied with the water cannot be predicted easily in advance (i.e. in spring time, when the farmers decide on the main fertilizer application).

- The fluctuation between dry and wet years has to be considered in case of a demand-driven water supply of plants. Therefore, the decoupling of nutrients from water is important, to apply also nutrients to arable land, even when no additional water supply is needed.

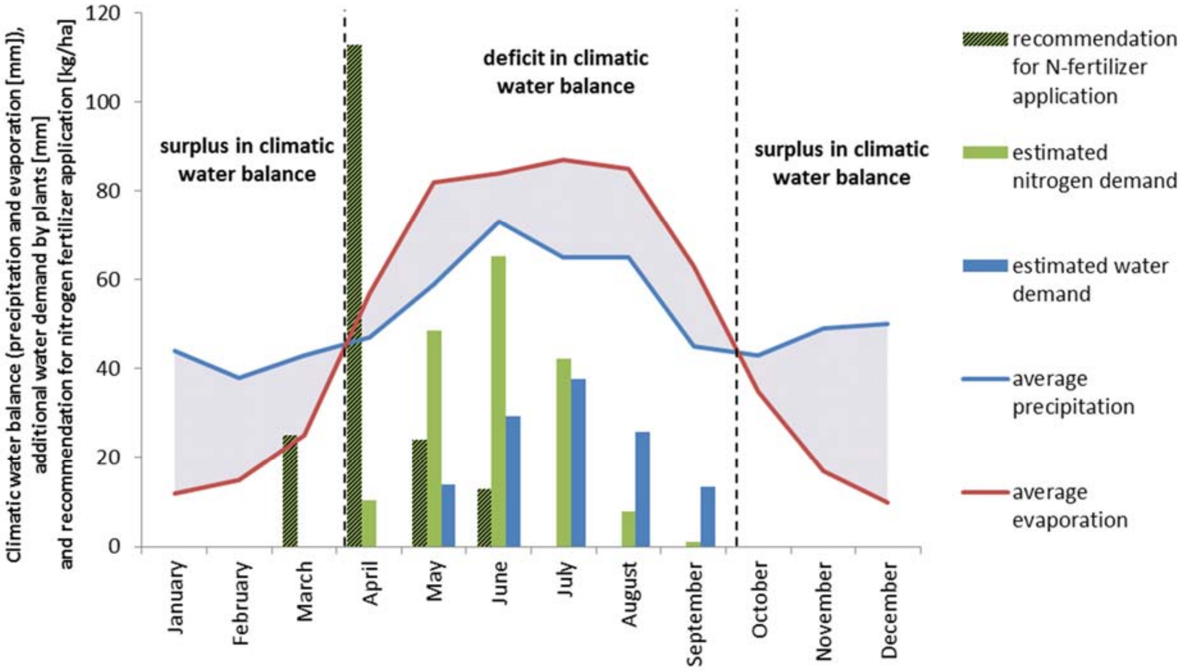

Figure 14 Climatic water balance (precipitation and evaporation), additional water demand recommendation for nitrogen fertilizer application and estimated nitrogen demand by plants at the reuse site Braunschweig
(Teiser 2013), (Deutsches Institut für Normung 2012), (Landwirtschaftskammer Niedersachsen 2010), (Beegle and Durst 2003)

As a consequence, farmers in Braunschweig cannot adequately adapt, i.e. minimize, the amount of applied fertilizer, since water and nutrients are applied as one phase, which is a special feature of the Braunschweig reuse scheme. Thus, the decoupling of nutrient and water flows, more specific the demand-orientated supply of plants with nitrogen and water decoupled from a wastewater treatment plant operating year-round is an ongoing challenge if water reuse is practiced in temperate climate and nutrients shall be recycled in the same system. Alternatively the concept of "fertigation" (= fertilizer application with water via an irrigation system) can be a better option for supplying the plant with nutrients when they are actually needed (see Chapter 2.2.3).

2.1.2 Nutrient recycling via agricultural application of sludge

In general, recycling of nutrients from wastewater or sewage sludge on arable land is a long-time tradition. In contrast to application of conventional fertilizers with defined composition of nutrients, a demand-orientated fertilizer application by agricultural valorization of complex matrices like sewage sludge is difficult:

- The problem of nutrient distribution is a central element for disposal (recycling) of organic fertilizers on agricultural land. Transportation of organic fertilizers to arable land with an actual nutrient demand competes economically with thermal disposal schemes. A local valorization of these biowastes in areas with local nutrient (especially nitrogen) surplus is also limited due to legislative issues (e.g. Nitrates directive and their national interpretations).
- Sewage sludge and other organic fertilizers contain hazardous substances like heavy metals. Depending on sewage sludge quality and the concentration of these hazardous substances the agricultural valorization can be prohibited due to legislation (EU or national fertilizer regulations).

Nonetheless the traditional nutrient valorization via sewage sludge application to arable land is and will be (with exception of a few EU member states) one important option of nutrient recycling. Thereby nutrient recycling and water reuse are already decoupled in those systems that apply water and sewage sludge to agriculture in two phases (contrary to the Braunschweig model).

2.1.3 Nutrient recovery technologies

Additionally to this traditional recycling route, various technical recovery options for nutrients are available to close the nutrient cycle between sewage sludge and agriculture. Typical distribution of water, nitrogen and phosphorus flows in CAS-based WWTP are shown in Figure 15 related to 100 % in the influent.

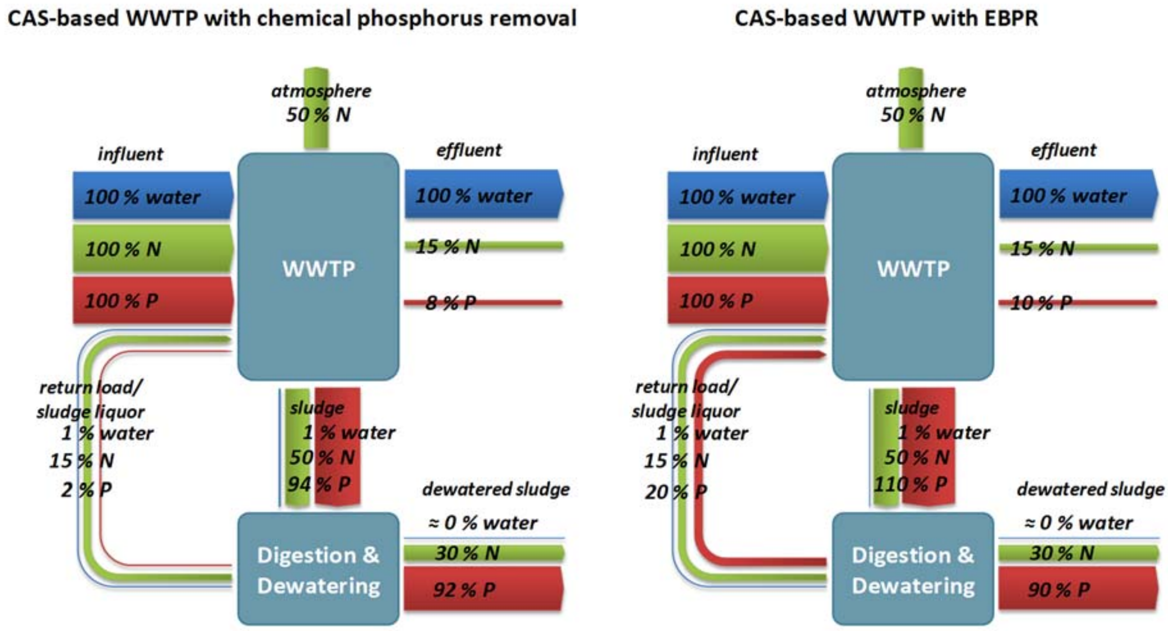

Figure 15 Averaged distribution of water, nitrogen and phosphorus flows in CAS-based WWTP with chemical phosphorus removal and EBPR (% relate to 100 % in WWTP influent)

The distinction between WWTP with chemical phosphorus removal and with enhanced biological phosphorus removal (EBPR) is of importance regarding the phosphorus balance of the WWTP: Due to higher release of phosphorus in digestion of EBPR-plants the return load regarding phosphorus and the phosphate concentrations in sludge liquor is at least 10-fold higher compared to a plant using chemical agents for phosphorus removal (Remy and Jossa 2015). Consequently, the total phosphorus load which has to be removed in wastewater treatment increases in EBPR plants.

Technical options for nitrogen recovery are limited, whereas many different options for phosphorus recovery from sludge liquor, sludge, dewatered sludge and ash (mono-incinerated dewatered sludge) had been demonstrated so far (see also EU-FP7-Project P-REX). Up to know only recovery technologies working in/with sludge liquor (in EBPR plants) had been implemented in full-scale. This results from operational and economic benefits for the operator (e.g. reduction of return load of nutrients) and high dissolved concentrations of nutrients in this stream.

Nitrogen:

Regarding nitrogen recovery, ammonia stripping is the only current known technical option to recover nitrogen from sludge into a fertilizer. The stripping-process takes place in sludge liquor, and its efficiency is related to the pH-dependent NH_3-NH_4^+-equilibrium. To reach a combined stripping and harvesting efficiency of 80-90 %, the equilibrium has to be shifted to NH_3 by raising pH and/or temperature (e.g. > pH 9, > 70° C). The actual stripping process can be achieved via air or steam or using gas-permeable membranes, taking up the gaseous NH_3. To capture the NH_3 again, the air/steam with ammonia is passed into an acid (e.g. sulfuric acid). The liquid product (e.g. ammonium-sulfate) can be directly reused as N fertilizer. The recovery rate related to the nitrogen in sludge is directly dependent on the quantity of NH_4 in sludge liquor.

Phosphorus:

In principle phosphorus recovery is possible from liquid phase (sludge liquor) or solid phase (sludge or ash). Some technologies also aim to promote an increased transfer of phosphorus from solid into liquid phase to enhance process efficiency. From all available concepts for P recovery, only struvite[10] precipitation (from liquid sludge phase) in WWTPs with EBPR has been established in full-scale so far due to considerable operational and economic benefits (Kabbe, Kraus et al. 2015). In principle, struvite precipitates in the presence of magnesium, ammonium and phosphate and high pH conditions. Since the magnesium concentration is normally limiting the formation of struvite, magnesium is dosed and the pH-value is adjusted to approx. 8, so phosphate is the limiting substance and is thereby efficiently removed from sludge liquor. The crystalized struvite product is harvested e.g. in a hydro cyclone or via sedimentation, and the product is washed to remove sand and organics from the end product which can be directly reused as fertilizer. Although struvite contains nitrogen and phosphorus, struvite recovery is usually focused on phosphorus recovery, since the N:P ratio in struvite is 1:2 and does not fit the actual nutrient demand ratio of plants. Therefore, struvite is often not considered as NP fertilizer, but rather as P fertilizer with additional N-value. Current drawbacks of the struvite technologies are the limited applicability (only WWTP with EBPR) and the low overall nutrient recovery rates (5-20 % phosphorus recovered and 1-3 % nitrogen recovered related to total sludge input) (Stemann, Ewert et al. 2014). Both aspects are related to harvesting efficiency and dissolved phosphorus concentrations (ammonium is not limiting) in sludge liquor. Harvesting efficiency depends on the matrix where harvesting takes place (sludge or liquor) and to the design of precipitation and harvesting reactor. Latest reactors with a combined precipitation and harvesting efficiency about 80-90 % related to the phosphorus concentration in sludge liquor have been implemented in full-scale (Stemann, Ewert et al. 2014, Remy and Jossa 2015).

[10] Struvite = ammonium-magnesium-phosphate: $(NH_4)Mg[PO_4]\cdot 6H_2O$

Optimizing nutrient recovery from sludge:

Some technologies aiming to transfer more N and P from solid sludge into the liquid phase can increase recovery rates, since 80-90 % harvesting efficiency from liquor can be reached with the currently available technologies. For this purpose, two main treatments of sludge can be considered: acidification and/or thermal disintegration. The thermal disintegration of excess sludge prior digestion is favored due to its beneficial effects on sludge treatment, i.e. increased biogas production, improved sludge dewatering, and higher release of nutrients into the liquid phase (Bormann, Sievers et al. 2009, Stemann, Ewert et al. 2014, Ewert 2015). Contrary to these benefits many drawbacks by acidification of sewage sludge emerge (e.g. high consumption of acid and disadvantages in sludge disposal via incineration). The combined process design of thermal disintegration and nutrient recovery is also planned for the WWTP in Braunschweig.

Summary:

A limited number of economically feasible techniques are available to recover nitrogen and phosphorus from wastewater, more specific from sludge liquor (for phosphorus mainly for WWTP with EBPR) with simultaneous benefits in operation. This is currently an important economic precondition towards actual recycling of these recovered nutrients from wastewater stream.

2.2 The Braunschweig model of water reuse and nutrient recycling

2.2.1 Current status

The “Braunschweig model” of water and nutrient management is shown in Figure 16.

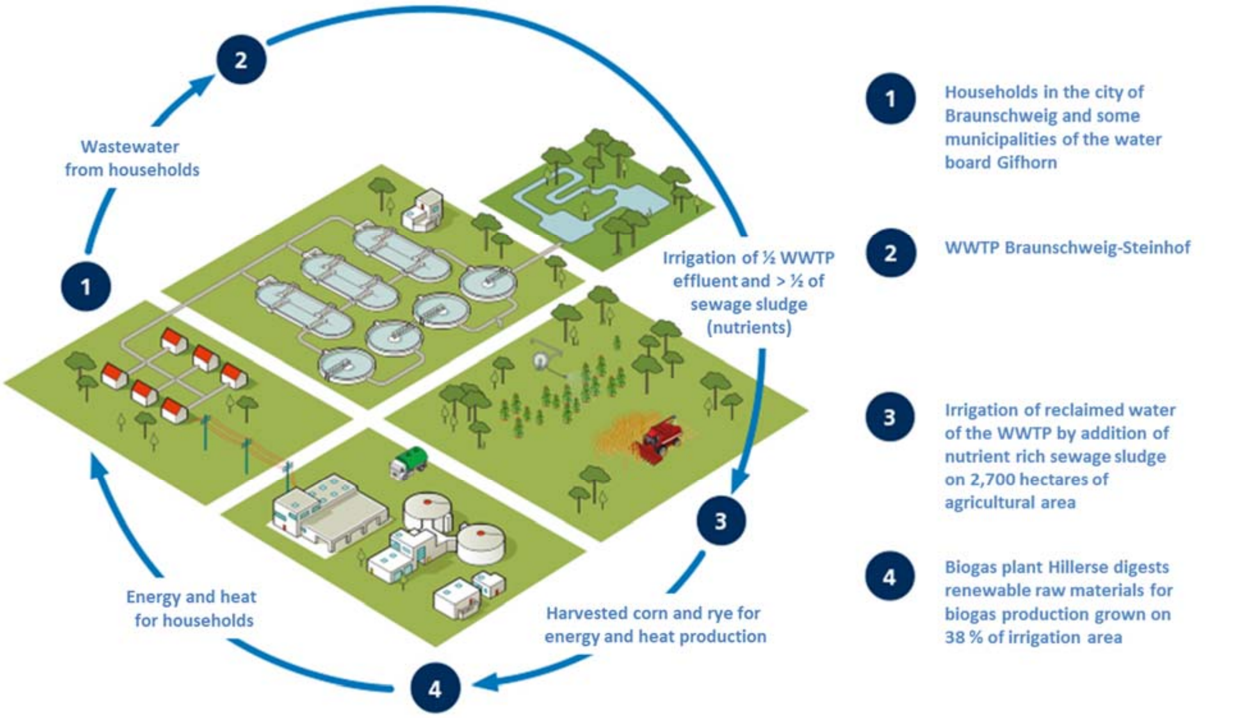

Figure 16 The Braunschweig model of local water and nutrient recycling (simplified)
(Abwasserverband Braunschweig 2016)

The Braunschweig reuse scheme is characterized by simultaneous water reuse and recycling of digested sludge during the vegetation period (March-October), where the latter contains nutrients for agricultural purposes (Klein, Dockhorn et al. 2013). Thus, approximately 50% of the annual effluent water of the WWTP is mixed with digested sludge during summer season and spread on arable land of the wastewater association Braunschweig (AVB). Part of the crops grown on arable land are energy crops which are digested and converted to biogas, producing energy and heat in a CHP which is used in the city of Braunschweig.

2.2.2 Challenges of the Braunschweig management scheme

Besides the operational benefits of the Braunschweig model (direct recycling of water and nutrients for the local agriculture, but also reduced disposal costs for sewage sludge in summer), some challenges have emerged for this type of coupled water and nutrient management (see also Chapter 2.1.1). This section provides a deeper analysis regarding the actual supply and demand patterns of water and nutrients (especially nitrogen) for the Braunschweig reuse site and estimates the amount of water and nutrients which effectively substitute alternative sources (e.g. groundwater, mineral fertilizer), but also potential oversupply which can be optimized in the future.

Water management:

Basic data for the agricultural area of AVB regarding crops and water demand are shown in Table 14. Major plants are corn (mostly as energy crop), winter wheat, sugar beets, and winter rye. In this simplified assessment, the average demand or irrigation water is assumed equal for each crop and amounts to an annual additional water demand of 120 mm (Klein, Dockhorn et al. 2013) via irrigation in the Braunschweig climatic conditions.

Table 14 Crop, crop area and related water demand (estimated to 120 mm/a for all crops and period of water demand) (Klein, Dockhorn et al. 2013), (Deutsches Institut für Normung 2012)

Crop	Crop area [ha]	Annual water demand via irrigation [m³]	Period of water demand
Corn	889	1’066’800	Mid-June – Mid-September
Winter wheat	500	600’000	Early-May – Mid-July
Sugar beet	448	537’600	Mid-June – Mid-September
Winter rye	258	309’600	Early-May – Mid-July
Other breeds	605	726’000	-
All crops	2700	3’240’000	-

Figure 17 shows total effluent volume of the WWTP per month in 2014 and the volume of water supplied for irrigation, together with the total estimated water demand of the plants in the irrigation area according to Table 14. It is obvious that the applied volume of water is higher than the actual demand of the plants for each month. However, water supply and demand are more aligned during summer (June – August) than in the other seasons. If irrigated water is not used by the plants, the remaining water supply will contribute only to artificial groundwater recharge.

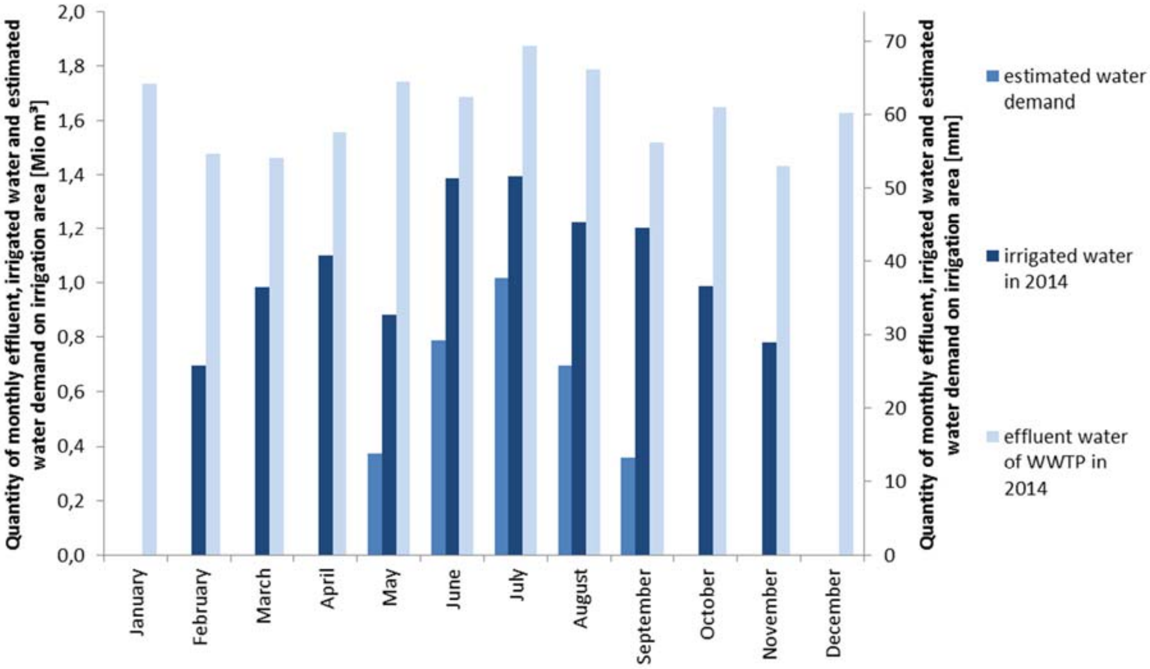

Figure 17 monthly distribution of effluent water from WWTP, water supply to agriculture and projected water demand in the irrigation area of Braunschweig
(Klein, Dockhorn et al. 2013), (Siemers 2015), (Deutsches Institut für Normung 2012)

The actual water demand is estimated to 3.24 Mio m³/year (120 mm on 2700 ha; see Table 14) (Klein, Dockhorn et al. 2013), while the water supply accounted for 10.6 Mio m³/year in 2014 (Siemers 2015). Hence, almost 70 % of the water spread on arable land is not really used by the plants, revealing a high potential for optimization. Energy costs for pumping water to agriculture could be significantly reduced when demand-driven water supply would be targeted. Furthermore, oversupply of irrigation water may also lead to additional leaching of nitrogen and trace organic contaminants into the groundwater.

Nitrogen management:

In Braunschweig, the actual spreading practice of digested sludge in summer is directly connected to the generated amount of sludge, because digested sludge cannot be stored over a longer period if it is not dewatered. Hence, digested sludge has to be mixed to irrigation water at all times during summer, which is not reflecting the actual nutrient demand of the plants. In contrast, recommended doses for nitrogen fertilizer application (Landwirtschaftskammer Niedersachsen 2010) on arable land are especially high in spring to ensure N supply to the growing plants during the following vegetation period. However, these recommended doses of N fertilizer cannot be supplied in March and April with the mixture of water and sludge, leading to high quantities of additional conventional nitrogen fertilizer that are applied by farmers in the irrigation area (Klein, Dockhorn et al. 2013).

Table 15 shows the recommendations (Landwirtschaftskammer Niedersachsen 2010, Landwirtschaftskammer Niedersachsen 2015) for nitrogen (and phosphorus) fertilizer application for the plants on arable land for the AVB. It has to be underlined that the current fertilizing recommendations do not reflect the timing of the actual nitrogen demand by plants, but they are rather related to practical reasons (e.g. application with heavy machinery before plants grow too high, limiting the annual fertilizer doses to 2-3 times to minimize work for farmers, etc.). The estimated demand period for nitrogen in Table

15 according to effective plant growth period and water demand indicates that nitrogen as nutrient is mostly needed in early summer (Beegle and Durst 2003), more in-line with the actual growth of the plant.

Table 15 Crops, crop area and maximal recommendation for nitrogen according to N_{min}-method, estimated demand period for nitrogen and recommendation for phosphorus fertilizer application for sites with average-good phosphorus supply
(Landwirtschaftskammer Niedersachsen 2010), (Beegle and Durst 2003)

Crop	Crop area [ha]	Nitrogen [kg N/ha]					Phosphorus[11] [kg P/ha a]
		Mar	Apr	May	Jun	Estimated demand period[12]	
Corn	889		180			May – early September	35-50
Winter wheat	500	50	60	50	70	April-July	20-35
Sugar beet	448		160			May – early September	30-45
Winter rye	258	50	50	40		April-July	20-35
Other breeds	605	50	50	50		-	20-50

Figure 18 shows the recommendation for nitrogen fertilizer application, the estimated effective nitrogen demand of the plants, and the supplied nitrogen via water and sludge irrigation in the current Braunschweig reuse scheme in 2014.

[11] Assuming concentration class C – average-good phosphorus supply by soils

[12] Estimated nitrogen demand according to growth period of plants and water demand

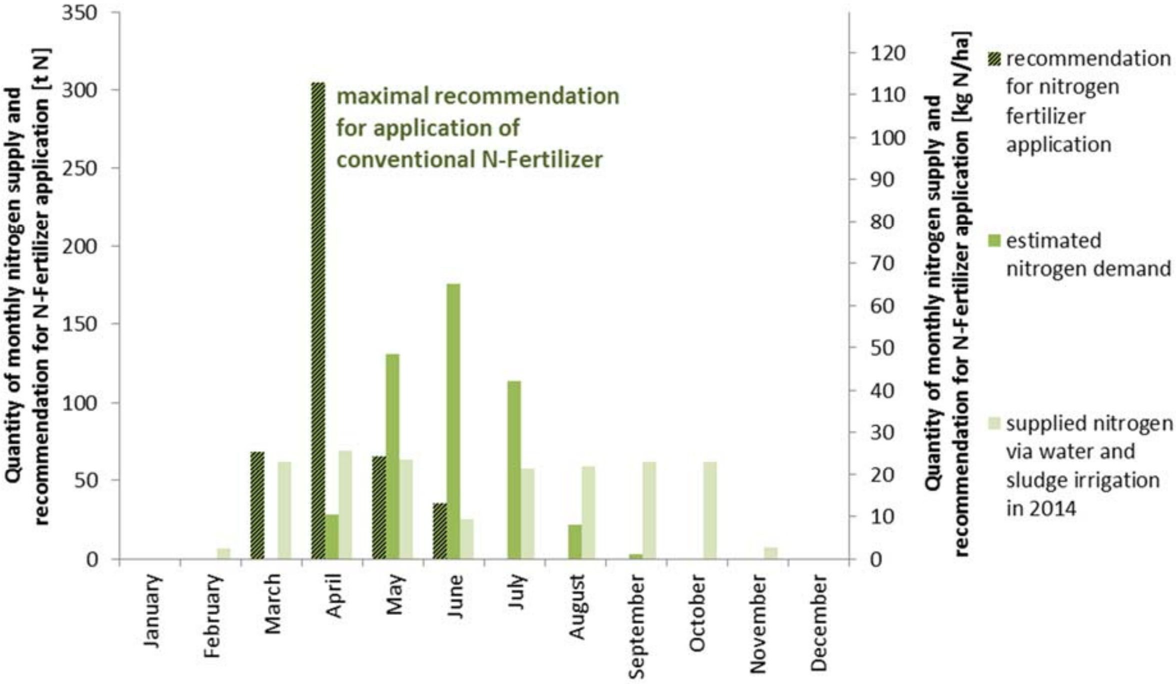

Figure 18 Quantity of supplied nitrogen with water/sludge, actual nitrogen demand of the plants and recommendation for N fertilizer application
(Siemers 2015), (Beegle and Durst 2003), (Landwirtschaftskammer Niedersachsen 2010)

An in-depth analysis of the current fertilizing practice in Braunschweig concludes that farmers effectively substitute around 20% of the annual recommended nitrogen demand with nutrients from water and sludge, meaning that 80% are still supplied as mineral N fertilizer (Klein, Dockhorn et al. 2013). However, the total applied N dose with water and sludge is significantly higher, because farmers tend to account only a fraction of total N in water/sludge as being available in short-term to plants. Finally, the annual amount of nitrogen supplied with water and sludge is near the annual recommended total N dose, but farmers add mineral N fertilizer in spring to realize the recommended fertilizing practice at this time of the year. Hence, the arable land is effectively oversupplied with nitrogen by the combination of conventional fertilizer and sewage sludge, because the farmers do not fully account the N load applied with the sludge in their fertilizing practice.

These calculations are based on the assumption that N fertilizer application reflects the actual maximum recommended N dosing throughout the year. In fact, long-term application of organic fertilizer (= sewage sludge) should be taken into account in the recommended N doses by accounting a part of the accumulated organic N in soil as being mineralized during the vegetation period ("N_{min} method"), reducing the total amount of N fertilizer by 40 kg N/ha for corn (Landwirtschaftskammer Niedersachsen 2010) and by 20 kg N/ha for other crops (Landwirtschaftskammer Niedersachsen 2010) (see Table 16). This reduction of total N fertilizer requirements results in an even lower substitution potential of sludge N of only 5% if current N fertilizing practices of farmers are counted. Finally, it can be concluded that the current practice of N management in the Braunschweig irrigation area is sub-optimal, because farmers are applying large amounts of conventional N fertilizer despite an overall high supply of N (both inorganic and organic) with water and sludge.

Table 16 Annual target value for N fertilizer application according to N_{min}-method, corrected target value for N fertilizer application considering long-term application of organic fertilizer (= sewage sludge) and supplied nitrogen via sludge/water and conventional N fertilizer resulting in total supply of N
(Landwirtschaftskammer Niedersachsen 2010), (Siemers 2015), (Klein, Dockhorn et al. 2013)

Crop	Recommended N dose [kg N/ha a]	Recommended N dose with N_{min} [kg N/ha a]	Supply via sludge/ water [kg N/ha a]	Additional supply via mineral N fertilizer [kg N/ha a]	Total supply of nitrogen [kg N/ha a]
Corn	180	140	mean value for irrigation area: 176 kg N/ha a	148	324
Winter wheat	230	210		170	346
Sugar beet	160	140		153	329
Winter rye	140	120		98	274

Phosphorus management

In contrast to nitrogen, phosphorus is a “pool nutrient” which can be accumulated and bound in soil in case of excess supply, making the management of P between seasons and years less complicated. The substituted amount of mineral P fertilizer is about 80% of the currently applied P with sludge (Klein, Dockhorn et al. 2013) (comparatively low substitution rate for sugar beet and especially corn, but high substitution rate for cereal crops), so the P content is used efficiently. Pot-trails with this sludge showed a relative fertilizer effect of 80 % regarding the total phosphorus content (Wilken, Gerhardt et al. 2015). It has to be underlined that the effectiveness of the applied phosphorus is strongly related to the phosphorus storage and supply of soil.

Summary:

In summary, the seasonal distribution of water and nitrogen supply in Braunschweig is sub-optimal. Depending on the specific assumptions regarding nitrogen supply, the reuse scheme in combination with current N fertilizing practices of farmers does not reflect a demand-orientated operation. The current practice results in inefficient supply of water and nitrogen, resulting in high losses of nitrogen into the environment and also increased efforts for water. Phosphorus is more efficiently used in the system due to immobilization and remobilization of P in soil. The nutrient flows for nitrogen and phosphorus of the WWTP Braunschweig and the irrigation area are shown in Figure 19 for the current operation following the assumptions that the nitrogen demand is maximized according to N_{min}-method and maintaining current fertilizer practices by farmers.

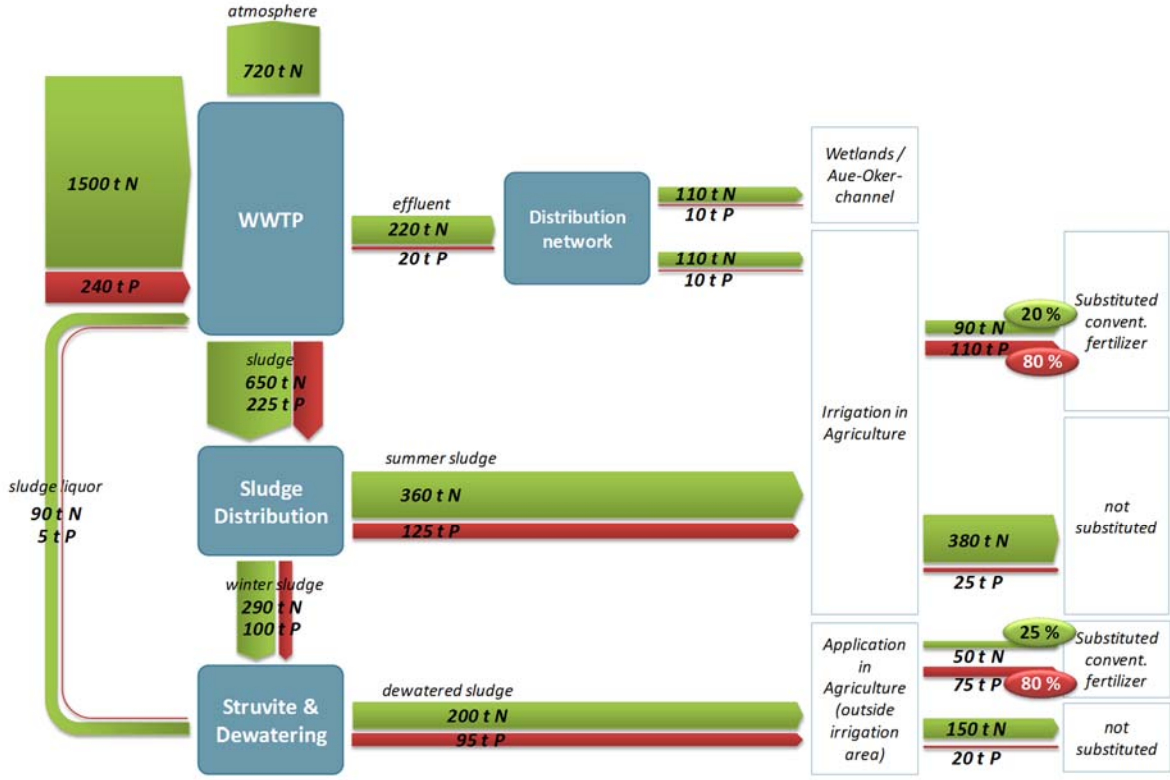

Figure 19 annual nutrient flows of the Braunschweig reuse scheme and currently substituted fertilizers

2.2.3 Optimized nitrogen management by adopting the "fertigation" concept

The principle of "fertigation" is related to direct fertilizer application with the irrigation water via an irrigation system, so this concept is actually realized on the supply side in Braunschweig by the WWTP operators. However, the fertigation practice is not fully effective on the demand side of the system, since farmers apply a high additional amount of conventional nitrogen fertilizers in parallel to the reuse system, not taking into account the total potential of nitrogen supplied to their fields.

By adapting the conventional fertilizer application practice and raising acceptance of the "fertigation effect", the efficiency of the current reuse scheme could increase up to 40 % for nitrogen, reducing the amount of required conventional nitrogen fertilizer by around 30 %. This estimation results from following conditions:

- The estimated nitrogen demand of the plants (see Figure 18) is reasonably accurate
- Inorganic nitrogen from sludge/water and conventional N fertilizer are fully plant available

Figure 20 illustrates one possible option to adapt the fertilizing practice of farmers according to the fertigation concept. In detail, the following aspects are important:

- The inorganic nitrogen from sludge/water is fully accounted by the farmers at all times of the year.
- The organic nitrogen in sludge applied before the vegetation period can be mineralized in summer (higher temperatures promote mineralization of biowaste); therefore, the applied organic N from sludge applied in spring will be plant available in summer.
- Conventional nitrogen fertilizer is only used to cover the difference between supply and demand in early summer (including a reasonable buffer); application via fertigation is favored (see Figure 20), since nitrogen is applied more accurate on demand with the fertigation concept. Alternatively,

nitrogen could be applied in spring ("normal fertilizer application"), but in reduced amounts compared to current practices.

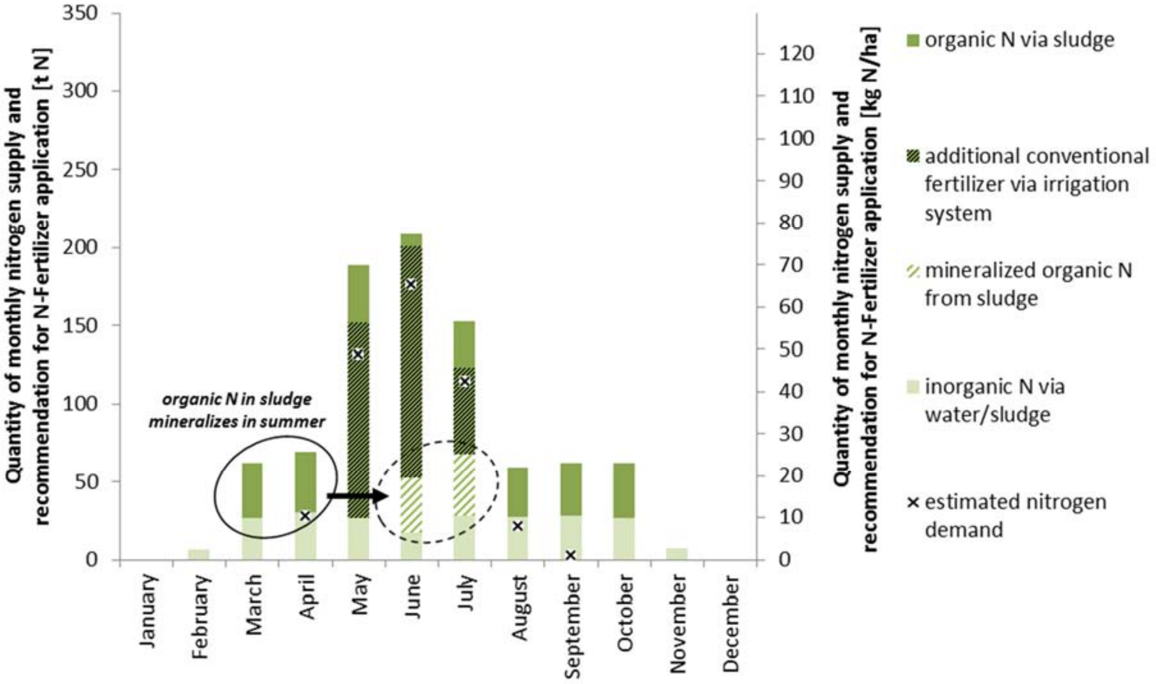

Figure 20 Adapted management of nitrogen fertilizer in the fertigation concept (data from 2014, and estimates)

Figure 21 gives a comprehensive overview of the annual nutrient flows in Braunschweig if the current concept of fertigation operated by the WWTP/AVB would be fully adopted. This acceptance of the fertigation concept would lead to a +70% increase of mineral N fertilizer substituted by the overall Braunschweig system, accounting for 240 t N/a and 185 t P/a (including sludge valorization outside of the irrigation area). Recommended strategies for promoting the fertigation concept include the close cooperation with farmers and an increased awareness raising for the full potential of the reuse system.

Further optimization of the nutrient management scheme via fertigation could be achieved by the following procedure, targeting further minimization of N losses in the system:

- Applying sludge only in (early) spring, since the organic nitrogen of the sludge can be mineralized until the vegetation period when nitrogen is effectively required by plants
- Targeted mixing of sludge liquor with high nutrient content with irrigation water in summer to enhance the concentration of inorganic N and P in the distributed water

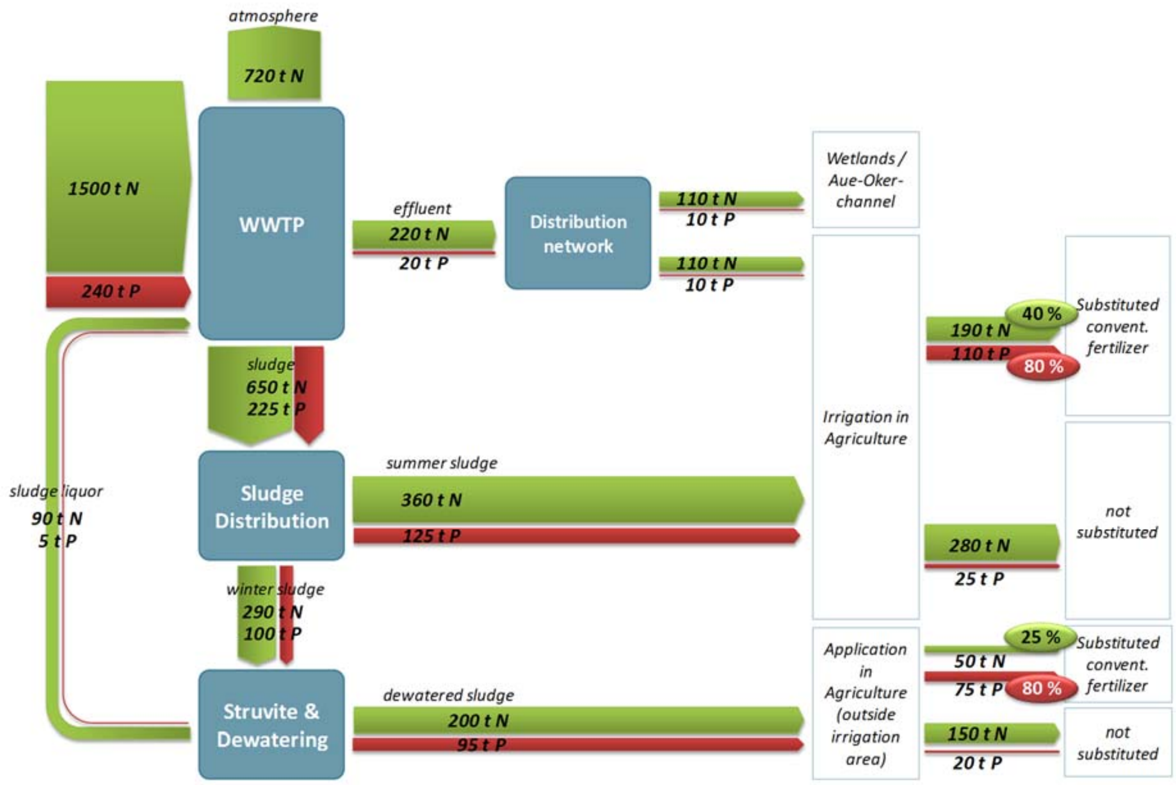

Figure 21 annual nutrient flows of the Braunschweig reuse scheme and substituted fertilizers in the fertigation concept

2.2.4 Legal challenges and solutions for an optimized water and nutrient management

In the near future, a new concept for sludge management is mandatory in the Braunschweig system, as changing legislation for sewage sludge application in agriculture in Germany is going to set new restrictions to the current practice:

- The proposed Fertilizer Application Ordinance (German interpretation of the EU Nitrates Directive; Düngeverordnung – DüV (BMEL 2015)) sets strict limits for valorization of nitrogen in organic fertilizers (Umweltbundesamt 2014).
- The proposed German Sewage Sludge Ordinance (Klärschlammverordnung – AbfKlärV (BUMB 2015)) aim to ban sewage sludge valorization on arable land for larger WWTP starting in 2025.

Besides the legal situation, energy efficient nutrient recovery concepts have been developed in the last years, so there are other options available for the Braunschweig reuse scheme to increase energy efficiency and provide more environmental benefits with the reuse system.

Decoupling of water reuse and nutrient recycling and optimized water management

Decoupling of water reuse and nutrient recycling is mandatory for irrigation on demand, since water is used as a “carrier” for nutrients (digested sludge) in the current practice of the Braunschweig reuse scheme. So excess irrigation is partly an operational result in periods when nutrients are needed on arable land but water is not. The following options could be considered for the Braunschweig WWTP:

- Year-round dewatering of digested sludge to decouple water and nutrient flows
- Irrigation on demand to adjust the water supply to the actual water demand by plants
- Nutrient recovery (struvite precipitation and ammonia stripping) combined with thermal disintegration to increase both biogas production and nutrient recovery rates

Year-round dewatering of sludge and irrigation on demand

A simple option of decoupling nutrients and water without much additional infrastructural effort can be realized by year-round sludge dewatering. Consequently, the annual nutrient load in sludge liquor of the return load as well as in dewatered sludge increases by a factor of 3. The increase of nutrients in return load leads to higher annual loads for nitrogen and phosphorus in the WWTP influent, effluent and sludge, but also in higher nitrogen emissions into the atmosphere. In combination with year-round dewatering for sludge, more precise irrigation "on demand" is possible. Reducing the total volume of irrigation water to the actual water demand of the crops simultaneously reduces the nutrients delivered on arable land. The effects on the annual nutrient flows for (1) year-round sludge dewatering and (2) irrigation on demand are shown in Figure 22.

Following this approach, an improved decoupling of water reuse and nutrient management can be realized. The reclaimed water can be reused demand-orientated (in summer, May-September, see Figure 17), avoiding excess water supply and high pumping costs. Nutrient recycling could be realized via valorization of dewatered sludge on arable land of the AVB. Nonetheless, this option would not result in a fully sustainable nitrogen management strategy.

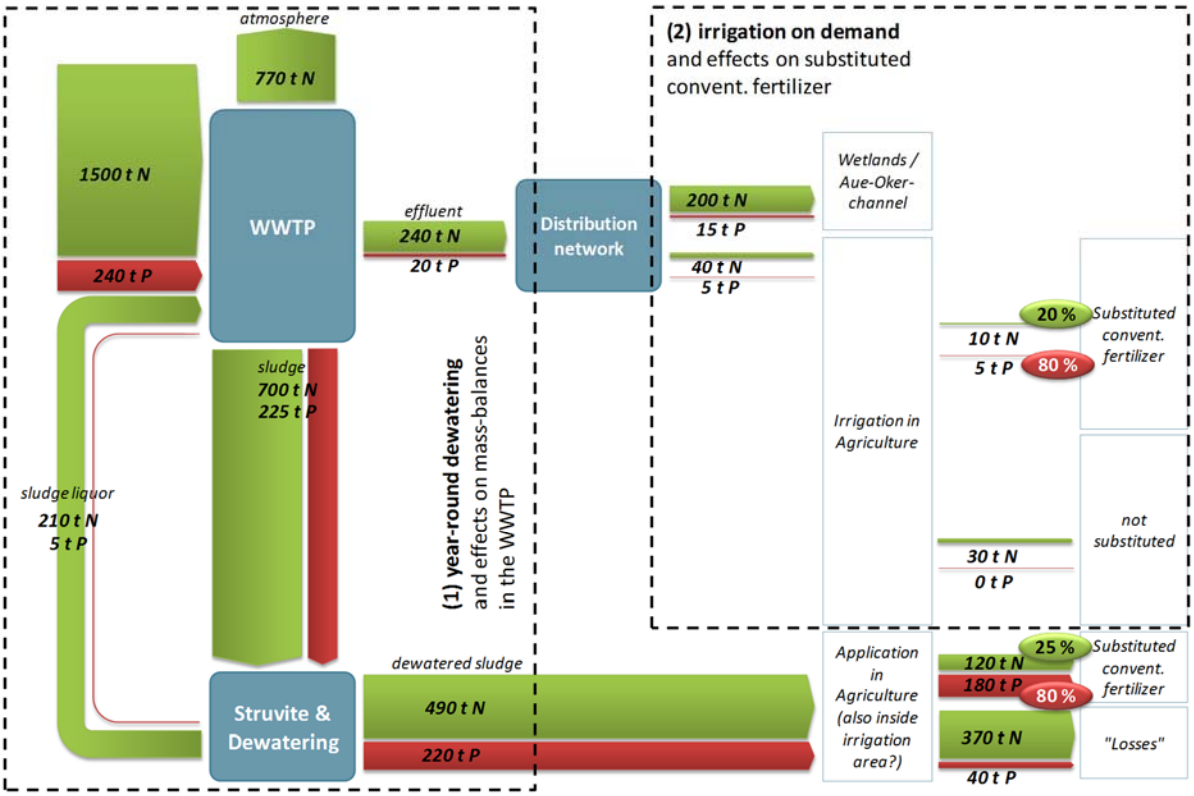

Figure 22 Annual nutrient flows of the Braunschweig reuse scheme for year-round dewatering and irrigation on demand

Optimized nutrient management by introducing technical nutrient recovery

If sludge is dewatered year-round, the N and P loads in sludge liquor would respectively increase up to 230 t/a N and 45 t P/a (without current struvite precipitation before dewatering), respectively. This effect could be used to introduce technical processes for nutrient recovery from sludge liquor. This will reduce the return load to the WWTP mainstream process and improve operational flexibility of the plant, and simultaneously generate valuable fertilizer products for both N and P fertilizer. In addition, the planned implementation of a thermal hydrolysis step in sludge digestion will further increase nutrient loads in the liquor by dissolving N and P from sludge into the water phase. Depending on actual performance of the proposed thermal disintegration of sewage sludge (DLD[13] configuration), the selected process for excess sludge lysis[14] and the operation of the digestor (mesophilic/thermophilic), this effect of mobilising N and P into the liquor is difficult to prognosticate. Since the nutrient recovery technologies are implemented in sludge liquor, the recovery rates for N and P in relation to their total amount in sludge will be directly related to the concentration of both nutrients in the liquid phase of sludge. Full-scale data of this mobilization effect is not available, so that pilot-scale data is used to extrapolate potential effects of this configuration on the nutrient recovery scheme. The estimated annual nutrient flows of the Braunschweig system including thermal hydrolysis and dedicated nutrient recovery are shown in Figure 23 (based on up-scaled lab-data of DLD (Fülling 2016)). For nutrient recovery in sludge liquor (nutrients are mainly dissolved), recovery rates are assumed to 80 % for P via struvite precipitation and 80 % for N via ammonia stripping.

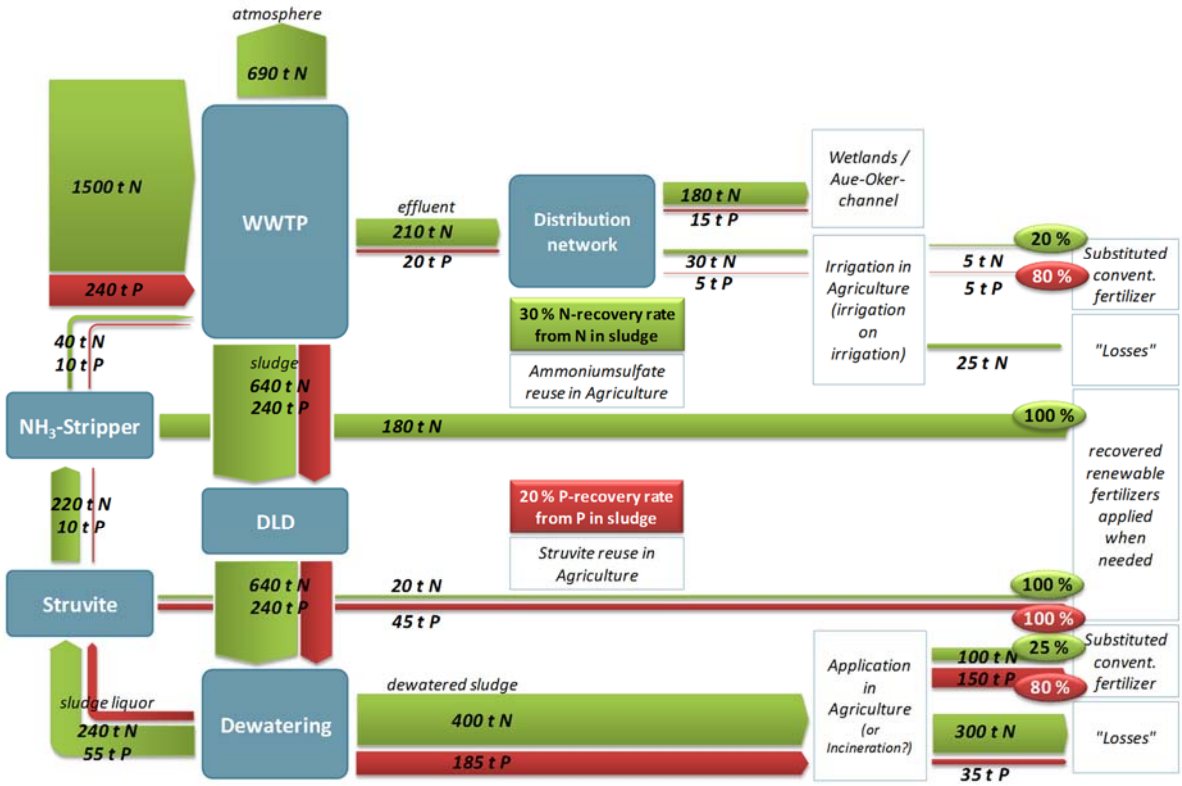

Figure 23 Annual nutrient flows of the future Braunschweig reuse scheme with nutrient recovery
According to data from (Fülling 2016)

2.3 Results and Discussion

Perspective of AVB (only for farmland irrigated with reused water):

[13] excess sludge Digestion and pre-dewatering & thermal Lysis of excess sludge & combined Digestion of primary and excess sludge

[14] Various differences between thermal hydrolysis processes in process parameters (pH, pressure, temperature), performance (batch or continuous) and effluent parameters of lysis (transformation to degradable COD, formation of hard COD and N- and P-release from solid phase into sludge liquor)

Figure 24 summarizes the total N and P loads to agriculture and the respective amount of substituted mineral fertilizer for the status-quo in Braunschweig in 2014 (with and without adopting the concept of fertigation) and for the system with dedicated nutrient recovery. The results reflect the perspective of the AVB and account only nutrients applied in the irrigated area of AVB, not accounting dewatered sludge from the winter period which is usually applied on arable land outside the irrigated area.

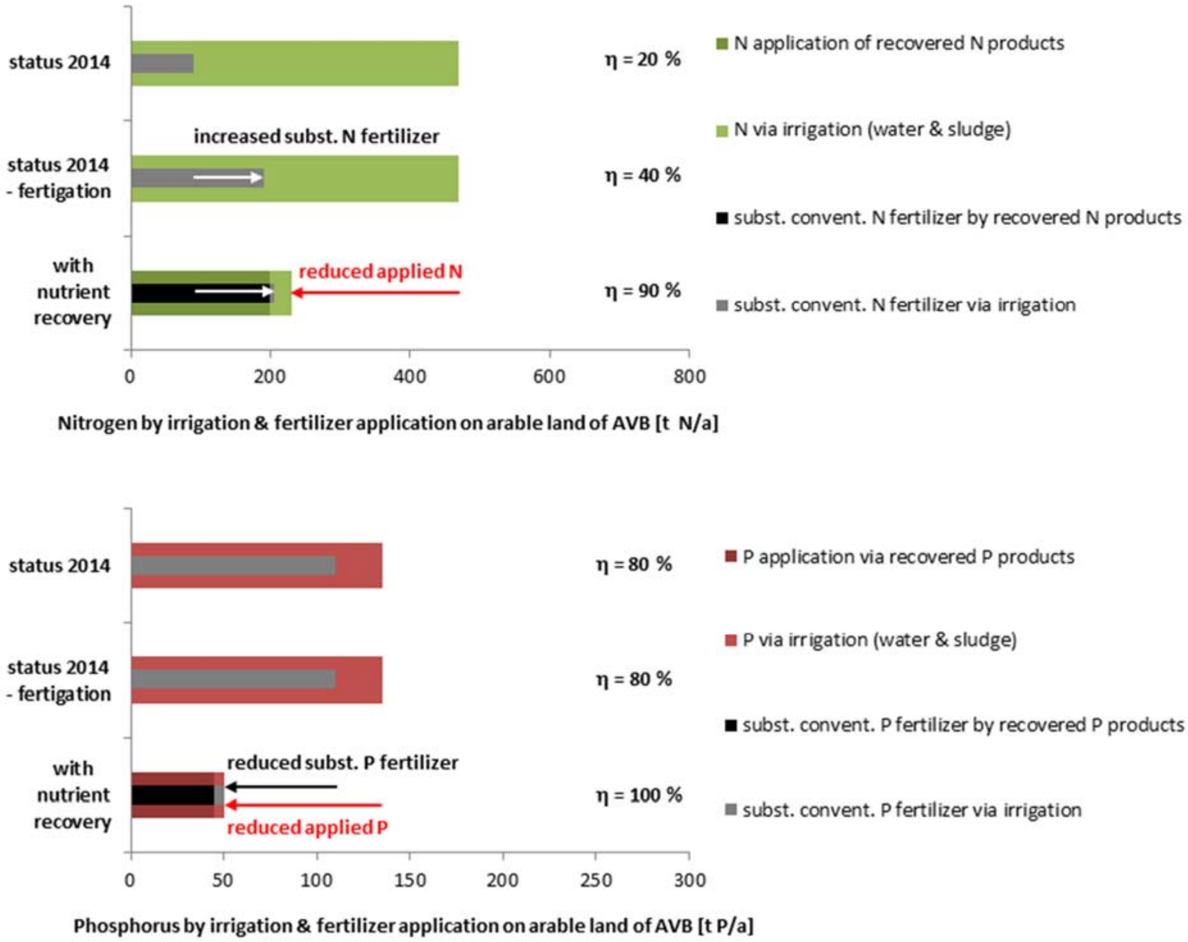

Figure 24 Total nitrogen and phosphorus input by irrigation and secondary fertilizer application on arable land of the AVB and effectiveness of applied nutrients regarding mineral fertilizer substitution (reuse-site perspective)

Following the concept of fertigation, the applied nitrogen load via sludge and water irrigation remains constant, but the dosing of additional mineral N fertilizer would decrease significantly. Hence, the calculated amount of substituted mineral N fertilizer increases by more than 100%, improving the efficiency of nitrogen management from 20% (status 2014) to 40% (fertigation).

Implementing a technical nitrogen recycling scheme to decouple water and nutrient management will reduce the total nitrogen input from WWTP on arable land by 50% (from 470 t N/a to 230 t N/a), with most N coming from secondary fertilizer products now which can be applied more precisely to meet N demand. Thus, the quantity of substituted conventional N fertilizer increases by more than 100% to a total of 205 t N/a. As a consequence, the efficiency of the applied nitrogen increases from 20 % (status 2014) to 90 % for the proposed technical nutrient recovery system.

Phosphorus is already used quite efficiently in the Braunschweig system (80 % of applied P). An increase of mineral P fertilizer substitution by reducing total P input into agriculture is not achievable with the struvite technology if compared to the status-quo. Figure 24 shows a reduction of the phosphorus loads on arable land by 63% for the nutrient recovery scenario compared with the status-quo, but the amount of substituted mineral P fertilizer also decreases by 55%. Hence, the implementation of a nutrient recovery strategy will enhance the relative efficiency of P management to 100%, but it will also reduce the total amount of P which is recycled into agriculture in the AVB area.

Perspective of total Braunschweig reuse system:

Figure 25 illustrates the results for the nutrient recycling scheme from a more general perspective, taking the entire system of Braunschweig into account. This perspective gives information on the overall concept of Braunschweig in terms of nutrient valorization from sewage sludge.

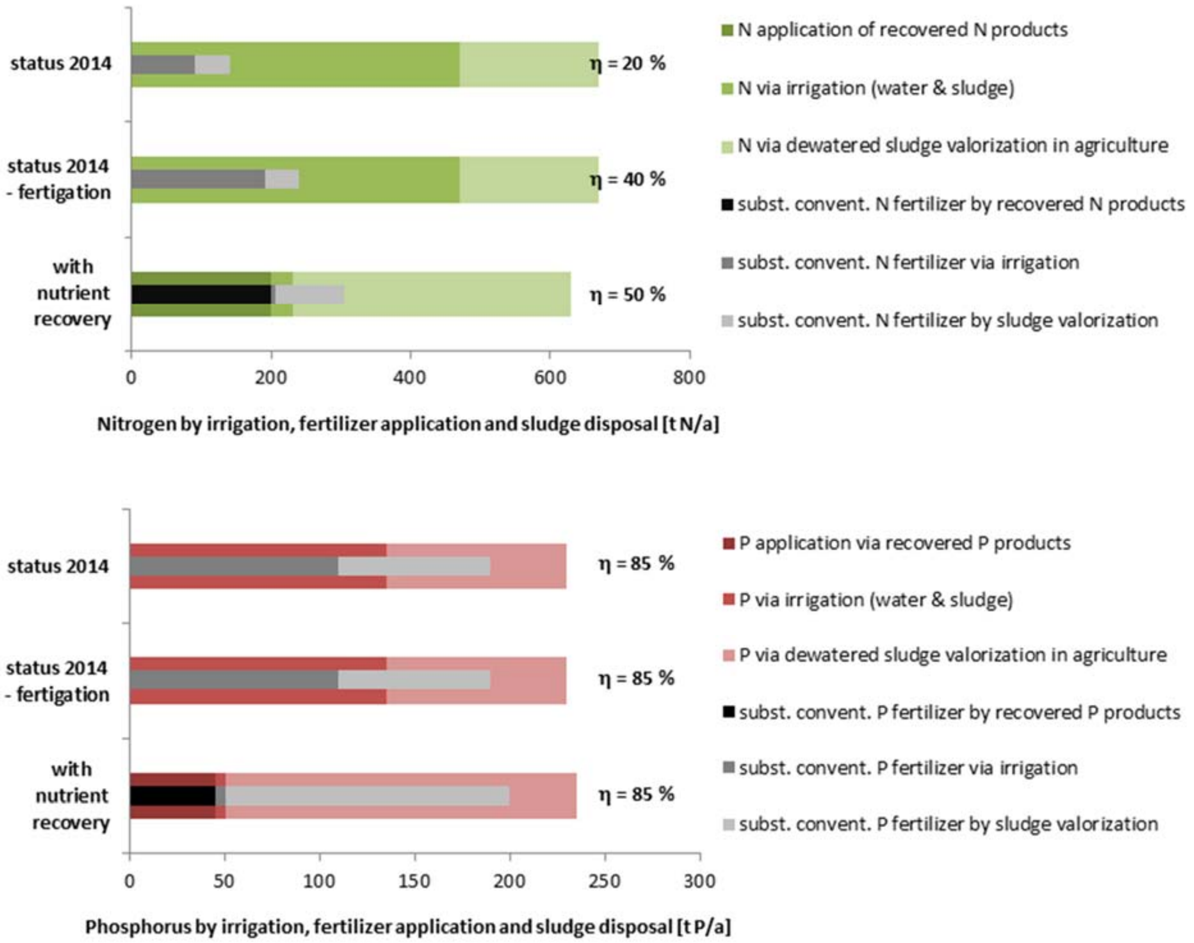

Figure 25 Total nitrogen and phosphorus input by irrigation and secondary fertilizer application on arable land of the AVB, nitrogen and phosphorus by agricultural valorisation of sewage sludge and effectiveness of applied nutrients regarding mineral fertilizer substitution (total perspective on nutrient valorisation)

This perspective indicates an increase of nitrogen efficiency from 20 % currently up to 50 % for the future Braunschweig system with dedicated nutrient recovery. The entire amount of sludge is still applied in agriculture, but the efficiency of substitution is improving due to the targeted application of the secondary fertilizer products (struvite, ammonium sulfate). Contrary to nitrogen the efficiency of phosphorus use is constantly about 85 % as agricultural sludge valorization is still maintained. The total input loads of nitrogen and phosphorus to farmland are similar for all three scenarios, but nitrogen losses can be reduced by implementation of nitrogen recovery techniques (due to lower N loads in sludge).

In summary, the technical nutrient recycling scheme as proposed in Braunschweig will recycle less amounts of phosphorus, but with a similar efficiency than in 2014. However, nitrogen input to agriculture will be reduced while significantly increasing the effectiveness of nitrogen recycling. If current fertilizer application practices are followed, the farmers will need less mineral N fertilizer, but more mineral P fertilizer compared to the status-quo in 2014.

2.4 Conclusion

Concluding from the investigated scenarios in Braunschweig, a decoupling of water and nutrients management is reasonable to achieve a demand orientated supply of both water and nutrients. An adapted management strategy (e.g. according to the fertigation concept) within existing reuse and recycling schemes can improve the net efficiency in nitrogen recycling, but this approach will demand precise application of nutrient doses per field area and hence a close cooperation between farmers and operators of the reuse system.

If agricultural valorization of sludge is not an option, stand-alone technical options for nutrient extraction or phosphorus recovery from ash can improve the net efficiency in nitrogen recycling and mitigate reduced net efficiency in phosphorus recycling. An overview of all scenarios in terms of nutrient recycling efficiencies and important aspects to consider is provided in Table 17.

Table 17 Overview on recycling efficiencies[15] and major benefits and drawbacks for the investigated scenarios from the AVB operator perspective (and with additional valorization of dewatered sewage sludge on arable land)

Scenario	Water management	Nitrogen management	Phosphorus management
status 2014	$\eta_{recycled}$ = 50 % $\eta_{effective}$ = 30 % **η_{total} = 15 %** + Low hydraulic pressure on wetlands and river – Excess irrigation	$\eta_{recycled}$ = 30 % $\eta_{effective}$ = 20 % **η_{total} = 6 % (9 %)** + Cost efficient disposal and valorization of sewage sludge and N – Low efficiency of N recycling	$\eta_{recycled}$ = 55 % $\eta_{effective}$ = 80 % **η_{total} = 45 % (75 %)** + Cost efficient disposal and valorization of sewage sludge + Highly efficient way of P recycling
fertigation	$\eta_{recycled}$ = 50 % $\eta_{effective}$ = 30 % [16] **η_{total} = 15 %** + Lower hydraulic pressure on wetland and river – Excess irrigation – Increased management and communication complexity between irrigation team and farmers	$\eta_{recycled}$ = 30 % $\eta_{effective}$ = 40 % **η_{total} = 12 % (16 %)** + Increased efficiency of applied N on arable land + Increased substitution of conventional N fertilizer – additional complexity of management and communication between irrigation team and farmers	$\eta_{recycled}$ = 55 % $\eta_{effective}$ = 80 % **η_{total} = 45 % (75 %)** + Cost efficient disposal and valorization of sewage sludge + Highly efficient way of P recycling
nutrient recovery	$\eta_{recycled}$ = 50 % $\eta_{effective}$ = 30 % [16] **η_{total} = 15 %** + Reduced energy demand for pumping to fields (savings up to 2 GWh/a) + Decrease of operational efforts for a future disinfection scheme + Demand orientated water supply on arable land is possible	$\eta_{recycled}$ = 15 % $\eta_{effective}$ = 90 % **η_{total} = 13.5 % (20 %)** + Reduction of total N emissions on arable land + Reduction of N losses causing eutrophication + Increased efficiency of applied N on arable land + Increased substitution of conventional N fertilizer	$\eta_{recycled}$ = 20 % $\eta_{effective}$ = 100 % **η_{total} = 20 % (85 %)** + Increased efficiency of applied P on arable land, struvite application according to good agricultural practice – Reduced substitution of mineral P fertilizer (less P recycled)

[15] $\eta_{recycled}$: recycling quota as “amount spread on AVB fields related to amount in WWTP influent”; $\eta_{effective}$: utilisation quota of recycled material as “plant available amount related to applied amount”; η_{total}: total efficiency ($\eta_{recycled}$ x $\eta_{effective}$) on AVB fields (in brackets: total efficiency including agricultural valorization of sludge outside of AVB fields)

[16] Effectiveness can be increased by irrigation on demand

	– Higher hydraulic pressure on wetlands/river	– Storage capacity needed for year-round storage of liquid N fertilizer	

Since the Braunschweig system with combined delivery of water and nutrients is differing from most water reuse sites in Europe, proper decoupling between nutrient recycling and water reuse is already realized on most reuse sites. This is achieved by separated reuse of effluent water for irrigation purposes and sewage sludge valorization for nutrient application purposes.

At least in the Braunschweig system sewage sludge valorization in agriculture is an efficient way of phosphorus recycling[17]. Nonetheless a technical phosphorus recovery scheme might be beneficial in operation of the WWTP and may increase the efficiency of the phosphorus applied on arable land. But, as this study showed, sewage sludge valorization is not exclusively an efficient way of nitrogen recycling. Especially if the additional conventional N-fertilizer application is not sufficiently adapted on nutrient irrigation or sewage sludge valorization, high "N-losses" will result. Technical nitrogen recovery and demand-orientated recycling can reduce the nitrogen losses on arable land compared to sewage sludge valorization or even fertigation. The usage of conventional nitrogen fertilizers can be reduced by implementation of nitrogen recovery technologies. Consequently a stronger focus on sustainable nitrogen management, recovery and recycling strategies is mandatory for the European Union's circular economy and low carbon economy target (3 % contribution to the total EU-28 CO_2-Eq emissions by conventional N fertilizer production via Haber-Bosch process [21-23]).

Reflecting these issues and the results of this study, three levels of decoupling water and nutrients could be derived (see Figure 26). In this order they are recommended for decision making regarding water and nutrient management for water reuse sites, but also valid for WWTPs without water reuse.

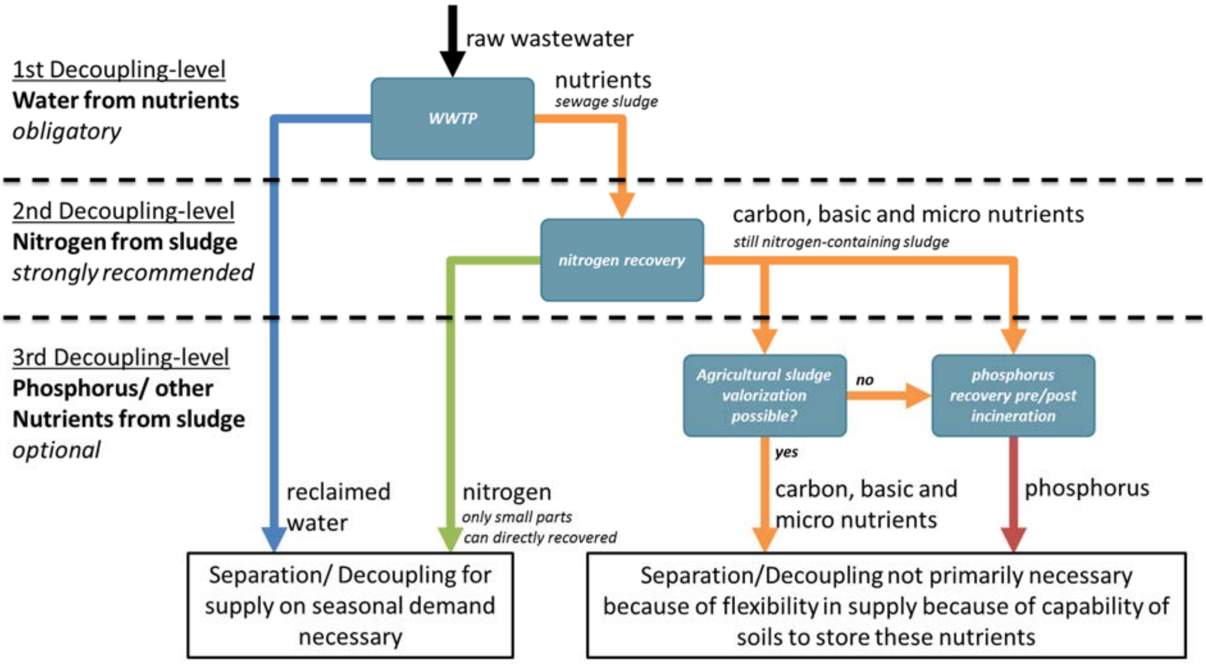

Figure 26 Three levels of decoupling nutrient and water management

[17] Phosphorus availability from sludge is normally related to the use of Fe/Al in the WWTP, the use of chemicals reduces also the applicable technologies for technical phosphorus recycling.

The 1st decoupling-level (Decoupling water from nutrients or common nutrient removal) is obligatory according to EU Water framework directive and implemented in many European WWTP so far.

Since sewage sludge contains carbon, nitrogen and other basic and micro nutrients, valorization to arable land is a disposal route achieving the target of recycling. This study precisely showed that the effectiveness of this route is particular low for nitrogen (η = 20-40 %) depending on practices of farmers. Current nitrogen recovery schemes are unable to remove/recover the major quantities of nitrogen; nonetheless they can increase the effectiveness of nitrogen valorization from sewage (2nd decoupling level – partly recovery of nitrogen from sludge).

Finally enhanced technical recovery of phosphorus or other nutrients from sludge or ash is optional (3rd Decoupling-level). Alternatively, sewage sludge valorization on arable land can be considered as an effective way of recycling for carbon, basic and micro nutrients, since technical recovery of all the valuable ingredients in sewage sludge is from the current perspective unrealistic.

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APPENDIX 1. SHORT ROTATION COPPICE AND WILLOWS

Short Rotation Coppice (SRC)

Short Rotation Coppice (SRC) is a crop of woody species planted at very high density (> 15,000 stools/ha) intended for energy wood production. The term "Short Rotation" is derived from the frequency of harvesting: every 2-3 years. The biomass produced is a renewable energy source which could be used as a substitute for fuel oil for heating. Biomass is considered an important source of renewable energy with applications in both heating and power, and in the near future woody biomass could become a major contributor to achieve renewable energy targets in the European Union. The general lifetime of the plants amounts 20 to 25 years (AILE, 2007).

SRC is used in many different ways. In agricultural areas it could replace traditional crops. It is also used to treat wastewater (e.g. Sweden) and for phytoremediation of polluted solids (e.g. metals). Poplars ('Populus') and willows ('Salix') are the most common plants used.

Willows

The genus Salix originated in the mountains of Eastern Asia and spread into parts of temperate and Arctic regions of the northern hemisphere (Newsholme 1992). The trees thrive in temperate, wet conditions and produce strong, light wood. Traditionally, willows have been used in basket making and as garden plants, and more recently for energy production (Pei and McCracken 2005). Willow cultivation can be dated back to the Roman Empire in the second century BC, where varieties of willow such as Salix caprea, Salix alba and others were used for the production of baskets, fences, medicine, and as framing for shields.

The genus Salix comprises approximately 400 species and more than 200 listed hybrids (Newsholme 1992); these are mainly deciduous trees and shrubs and all show a significant variation in growth rate and size. There are three main subgenera. Willows used in energy production belong to the subgenera known as Salix or true willows (Larsson and Lindegaard 2003).

Interest in willow as a SRC energy crop has evolved over the last 30 years. Willow for energy production has a number of inherent benefits both as a crop and in the wider environment and community, including (only those mentioned of importance for concentrate treatment) :

- Fast-growing perennial plant with the ability to coppice after harvest.
- Particularly suited to climatic conditions at Torreele.
- Greenhouse gas emission savings – the end market being developed for willow is renewable heat and power, and as a dedicated energy crop it can provide a long term, sustainable replacement for fossil fuels (Smart et al. 2005).
- Environment – low environmental impact when compared with conventional crops due to reduced chemical input (Mitchell et al. 1999).
- Local supply chain – SRC plantations located at a short distance from potential users may meet their heating demands.

The biomass yield from a plantation is typically measured in oven dry tonnes per hectare per year (odt $ha^{-1} \cdot yr^{-1}$). The productivity of a plantation is site specific but average commercial yields of 8-10 odt ha^{-1} yr^{-1} are attainable in Europe. Trials in the UK have shown that up to 15-18 odt ha^{-1} yr^{-1} can be achieved under certain conditions; and through specialised breeding, targets of 25 odt ha^{-1} yr^{-1} may be achievable (Karp 2009). Yields are generally greater in the second harvest rotation compared to the first. This may be attributed to an overall increase in shoots per stool and stem diameter between harvests (Danfors et al. 1998) (Wickham et al., 2010).

Treatment mechanisms

The cuttings are generally placed in sand with a high planting density. The plants are often placed at 60 cm distance in the row and the rows are 75 cm apart. The willows root shallowly : around 80% of the root hairs of willow are found at depths of less than 40cm (RYTTER & HANSSON, 1996; CROW & HOUSTON, 2004).

Commonly the willows are planted in double rows. The two rows in a double row were spaced 75cm apart and the double rows were spaced 1.5 m apart. According to Jossart et al. (1999) the willow system can be considered a “biological reactor”, the location of many ecological processes. The most important of which are:

- Stabilisation and retention of suspended matter and other nutrients in the concentrate by the filter media;
- Decomposition of organic matter by the fauna (macro- and micro-organisms, bacteria, fungi) re-sent in the filter media;
- Absorption, by the willow roots, of nutrients (supplied in directly assimilable form by the concen-trate or produced by organic matter decomposition).

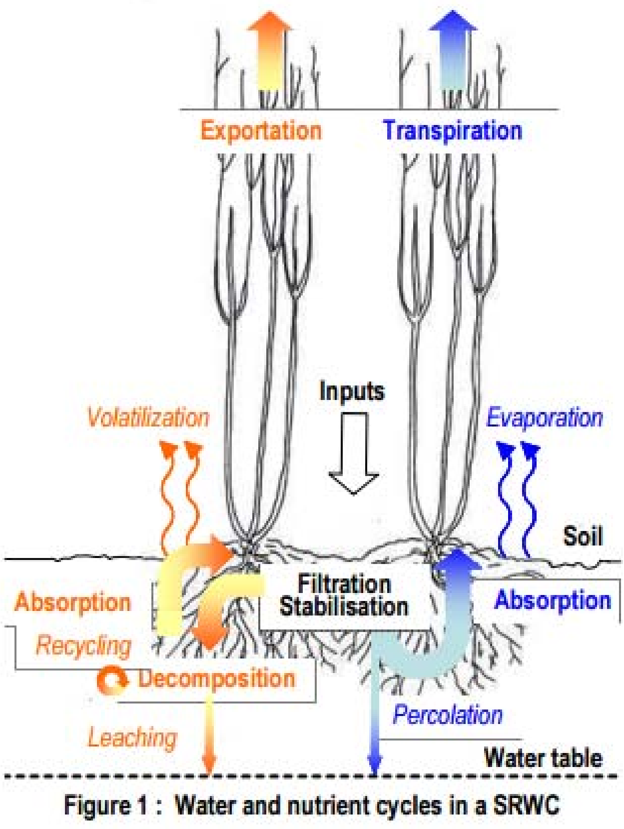

Figure 27 Water and nutrient cycles in a short rotation willow coppice
Source : www.aile.asso.fr/wp-content/uploads/2007/11/4-WW-GB-PurificationResults.pdf

Willow offers a number of advantages when grown in coppice under constant flow. The main advantages are:

- A long growing season (temperatures >5°C) and therefore a long season for nutrient treatment;
- A perennial root system which restricts winter leaching of nitrogen (ARONSSON and Perttu, 2001).

- High evapotranspiration and a root system which tolerates slight, long-term anoxia (JACKSON & ATTWOOD, 1996).
- The ability to resort to luxury consumption of some minerals, including nitrogen (; KLANGWESTIN & PERTTU, 2002).