Combining the production of renewable energy with innovative urban drainage systems - The KREIS Project

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Abstract
The KREIS project has researched resource based concepts and methods of supply and disposal for urban quarters and has prepared the implementation in the quarter Jenfelder Au in Hamburg, accommodating 2500 residents. Results of the preparatory phase are presented in this paper. In regard to the discharge of waters, the elimination of micro-pollutants from blackwater, the treatment concept for liquid digestate and greywater and the concept of using treated greywater for the augmentation of urban waters are important. The initial trial phase of the project is under construction and will start its operation in 2016.

Keywords
New Alternative Sanitation Systems, NASS, resource oriented sanitation, energy recovery, nutrient recovery, vacuum drainage

INTRODUCTION

Separation of stormwater and the use of separate sewerage systems are commonly accepted but not yet put into practice. All waste design concepts presume require rainwater separation and management. Focussing on water, energy and nutrient reuse, it is advantageous to keep sewage flows separate at the source. New Alternative Sanitation Systems (NASS) are based on not mixing faeces, urine and greywater with the aim of recovering these separated resources and selling products originating from wastewater. Concepts for future urban material flows in regard to sewage and organic waste can be elaborated (Fig. 1).

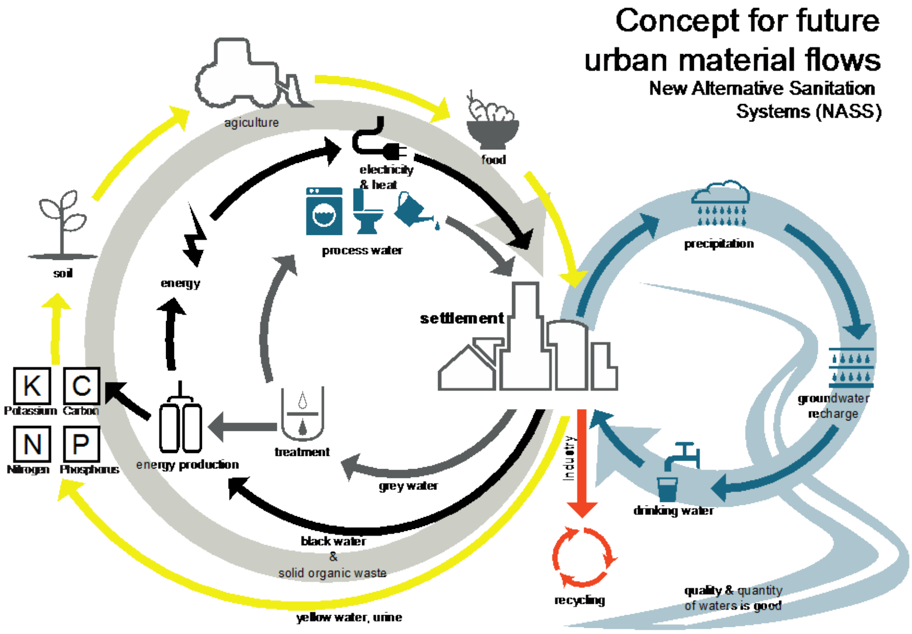

Figure 1: Concept for future urban material flows (translated from Rost et al. 2015)

An example of such a NASS with flow separation of greywater is shown in figure 2.

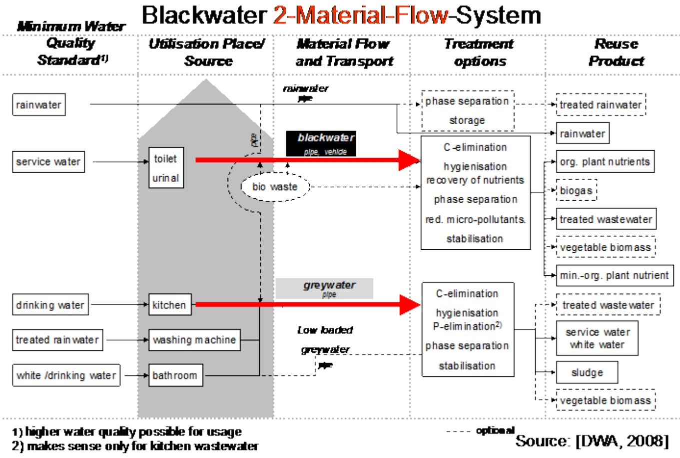

Figure 2: Blackwater 2-Material-Flow-System (based on DWA (2008))

The blackwater 2-Material Flow-System according to DWA (2014) has been elaborated in more detail by HAMBURG WASSER and is referred to as Hamburg Water Cycle® (HWC). The implementation of the HWC in the quarter Jenfelder Au in Hamburg for 2500 residents has been prepared within the KREIS project. KREIS (meaning “cycle” in German) is a transdisciplinary research project that investigates the combination of supply and disposal with an intelligent integration of wastewater management based on source control with energy generation (Augustin et al, 2014). For transportation of black water, a sewer network based on vacuum technology has been constructed. Apart from blackwater, other bio-resources like fats, food residuals, grass clippings or fractions of these substances, which can be collected in the immediate surroundings of the quarter, may also be treated in the blackwater digestion plant and can supply additional heat and electricity as well as increased process stability. The electricity can then be fed into the public grid. The heat is partly used to temper the digestion plant. The excess heat will be applicable for the heat supply of the quarter.
This realisation of the HWC is the largest demonstration of a resource oriented sanitation concept working with vacuum technology for the collection of concentrated blackwater in Europe.

The advantages of the new system are almost no discharge of toilet water, the potential to reuse the energy and nutrients from black water, the CO_2 neutral local heat supply and water savings of about 30% compared to the conventional system.

Many stakeholders with different interests, obstacles regarding the legal framework for NASS as well as organizational boundaries made the implementation a special challenge.

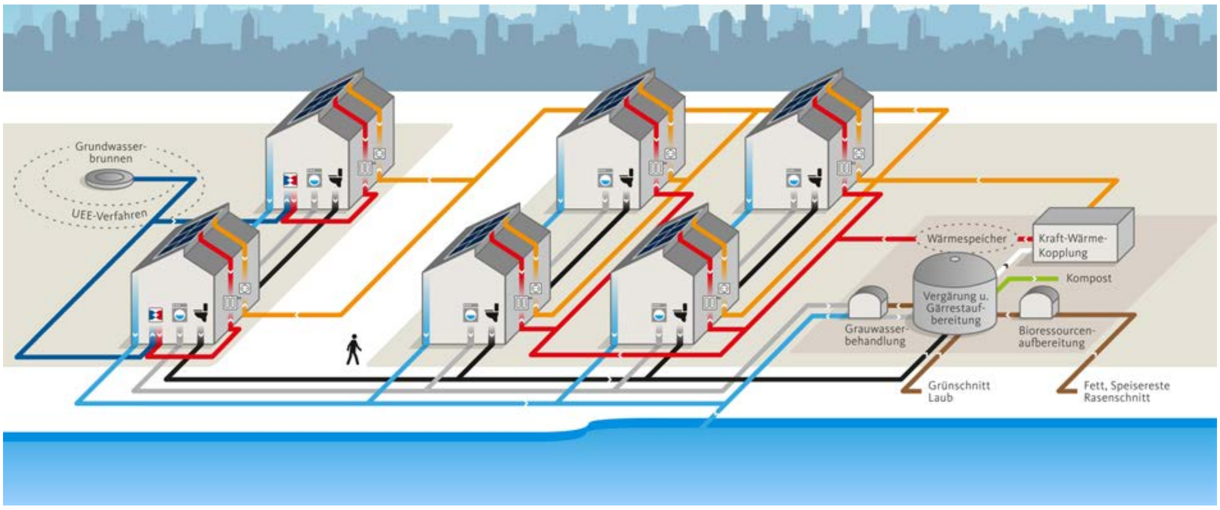

Figure 3: KREIS Concept

Often, biological treatment is a good approach to reduce the concentration of micro-pollutants without increasing toxicity because it generally produces fewer transformation products than Advanced Oxidation Processes (AOP) due to selective enzymatic reactions (Kümmerer, 2013). The elimination of micro-pollutants from blackwater, the treatment concept for liquid digestate and greywater and the concept of using treated greywater for the augmentation of urban waters will be addressed in the following chapters.

GREYWATER, BLACKWATER AND BIO-RESOURCES CHARCTERISATION

A literature review of Meinzinger & Oldenburg (2009) describes that the composition of **greywater** varies widely depending on factors such as water source, quality of water supply, water use, household activities and socio-economic and cultural factors. It is obvious that sampling and analysis methods influence the results. Therefore, a new sampling method was tested in several campaigns allowing separate assessment of the liquid and solid phase of the greywater flow (see figure 4 and 5). These measurements and a systematic literature review improved the design database remarkably. (Sievers et al., 2014)

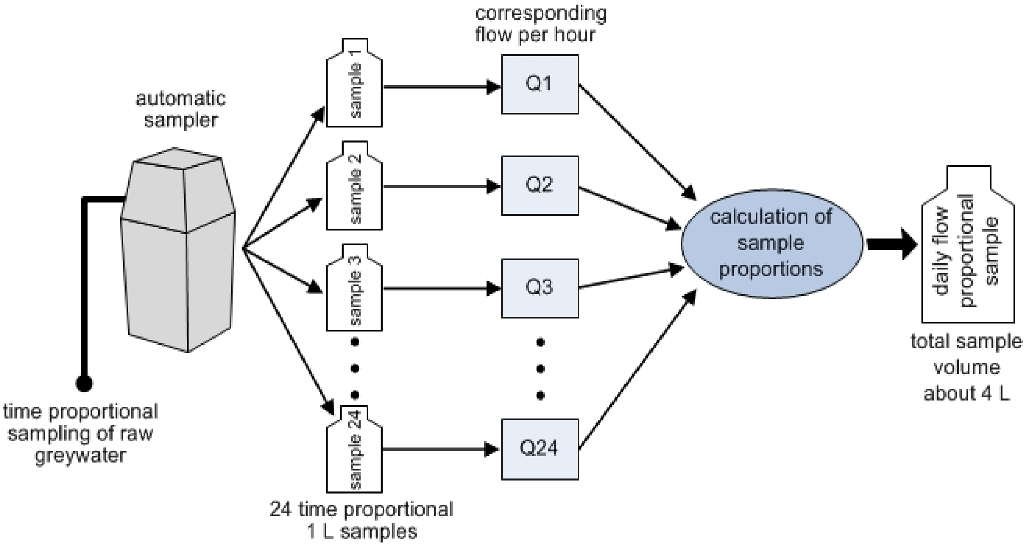

Figure 4: Sampling procedure and compilation of daily flow proportional samples (Sievers et al., 2014)

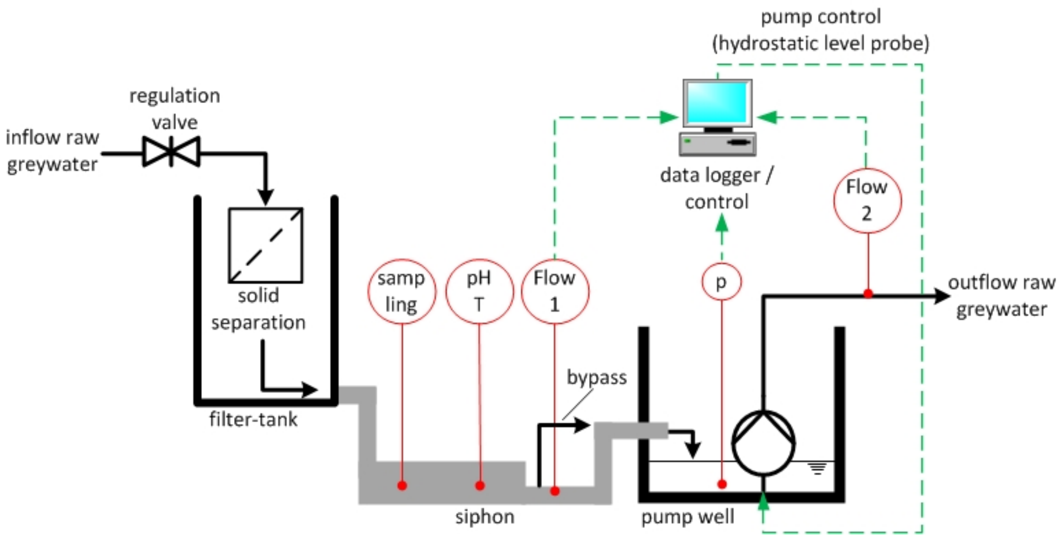

Figure 5: Sampling device for sampling campaigns (Sievers et al., 2014)

Table 1: Average loads of greywater (Sievers et al., 2014)
Sampling campaign Berlin "Block 6"

Parameter		n	Unit	Mean	STD	Median	Range
Volume	Q	17	L/(c*d)	77	16	76	62 -114
org. Matter	TSS	16	g/(c*d)	9	3.1	8	6 - 16
	VSS	16	g/(c*d)	7	2.9	6	5 - 14
	BOD_5	15	g/(c*d)	35	11	32	19 - 54
	COD	17	g/(c*d)	66	21	59	46 - 105
Nutrients	TP	17	g/(c*d)	0.4	0.2	0.3	0.2 - 0.8
	PO_4-P	17	g/(c*d)	0.1	0.1	0.1	0.1 - 0.3
	TN	17	g/(c*d)	1.3	0.3	1.1	0.8 - 2.1
	NH4-N	17	g/(c*d)	0.2	0.1	0.2	0.1 - 0.4

Sampling campaign Lübeck "Flintenbreite"

Parameter		n	Unit	Mean	STD	Median	Range
org. Matter	TSS	12	mg/L	68	27.00	73	23 - 102
	VSS	11	mg/L	54	23.00	57	18 - 87
	BOD_5	11	mg/L	467	81.30	464	340 - 631
	COD	12	mg/L	805	80.10	815	673 - 982
Nutrients	TP	12	mg/L	7.4	1.80	7.1	3.6 - 10.8
	PO_4-P	12	mg/L	1.7	0.50	1.5	1 - 2.6
	TN	12	mg/L	13.4	2.20	13.3	9.8 - 16.9
	NH4-N	12	mg/L	2.1	0.76	2.0	1.1 - 3.8

The measurements showed that the greywater concentrations of BOD and COD are nearly in the same range as calculated on basis of the literature review, but differ completely concerning suspended solids and nutrients concentrations. The specific loads of nutrients are significantly lower than suggested by previous publications.

Table 2 summarises the concentrations measured in **blackwater** from the pilot site Lübeck "Flintenbreite", which was used for the experiments in the KREIS project. The characteristics in

"Flintenbreite" are comparable to published data (Wendland, 2009; de Graaff et al., 2010).

Table 2: Average concentrations of blackwater in Lübeck "Flintenbreite" (Wätzel et al., 2013)

Parameter		n	Unit	Mean	SD	85%-
org. matter	acetic acid	10	mg/l	429.6	244.8	690
	propionic	10	mg/l	168.9	123.5	295.4
	DOC	11	mg/l	1027	314	1420
	DIC	11	mg/l	918	94	1332
	TOC	7	mg/l	2510	1100	3645
nutrients	TP dissolved	7	mg/l	74.1	7.6	82.2
	TN dissolved	7	mg/l	1412	108	1486

Special focus was given to the elimination of pharmaceuticals present in blackwater. The concentrations of those substances, which were investigated in the KREIS-project, are presented in table 3.

Table 3: pharmaceutical products in blackwater (20 samples each, measuring period 370 days) (Wätzel & Kraft, 2014)

	Diclofenac	**Ibuprofen**	**Metformin**	**Metoprolol**	**Amoxicillin**	**Carba-mazepine**
mean [µg/l]	11.6	290.2	1082.4	42.1	596.5	119.3
standard deviation [µg/l]	13.3	111.3	934.8	10.6	451.1	32.2
median [µg/l]	3.35	305	835	41	460	120

TECHNICAL WATER CONCEPT AND RESULTS OF RESEARCH

Greywater was treated by trickling filters lab-scale experiments. Only artificially produced greywater could be used as a natural source for greywater was unavailable at the lab. The method of preparing artificial greywater is described in Giese and Londong (2015). In first trials with natural greywater, the former results could not be reproduced. Therefore, it is strongly recommended to use original greywater for elimination experiments only.

The **vacuum drainage** of blackwater was thoroughly examined. Advice on construction and operation of the system was fully investigated and published by Rohde (2015). Due to its high content of organic substances, **blackwater** is suitable for anaerobic digestion and thus for the production of biogas. Completely stirred reactors (CSTR) as well as up-flow anaerobic sludge blanket reactors (UASB) were operated for 2,5 years. Both types of reactors proved to be suitable for blackwater treatment. Although the concentration of nitrogen (about 1700 mgTN/L) was high, inhibition of the digestion process did not occur. The majority of organic carbon (70% COD and 80% DOC) could be converted into biogas (in average 68% methane). The CSTR operated in stable conditions with volumetric loadings of up to 5 kg COD/m^3 reactor volume*d. For the UASB, it was possible to increase the volumetric loading to 12 kg COD/m^3 reactor volume*d.

The **decomposition of pharmaceutical products** during anaerobic digestion differed depending on reactor system, substrate mixture, and volumetric loading. A summary of the results in comparison with published results for aerobic treatment is shown in figure 6.

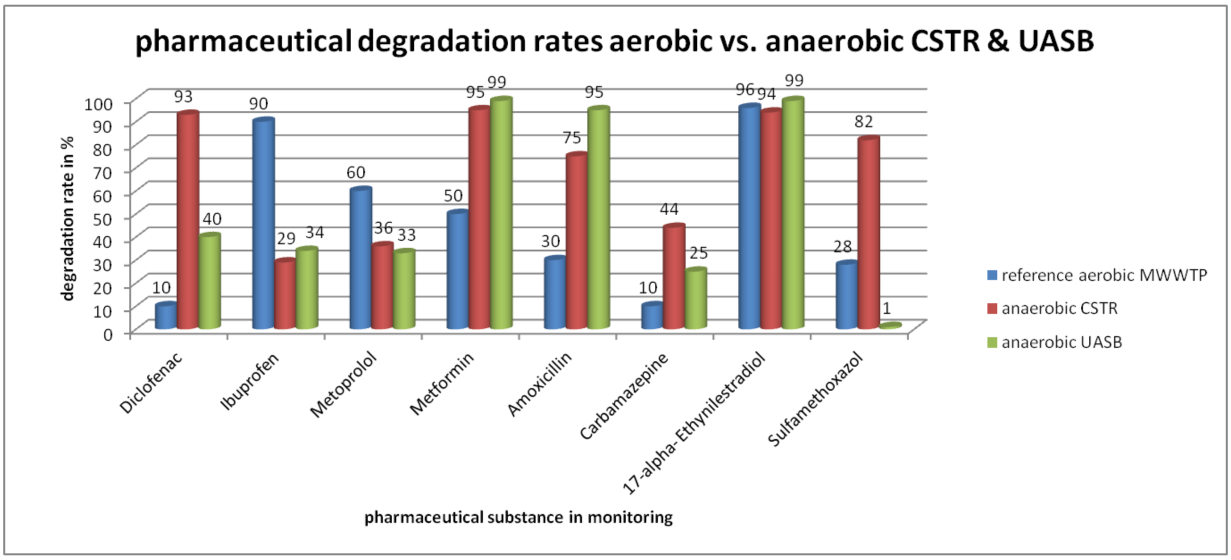

Figure 6: Results of degradation rates of pharmaceutical substances

The results shown were generated over an experimental duration of approximately 2 years. The blue columns represent the published treatment performance of European municipal wastewater treatment plants (MWWTP). The red columns show the KREIS-data using anaerobic CSTR during an experimental setup of 2 years. The green columns express the anaerobic degradation performances of UASB reactors over an experimental setup of 1 ½ years. The percentage of degradation (degradation rate) was calculated by comparing input and output flow, in this case blackwater and blackwater digestate using average concentrations, building a global mean as well as calculating the differences between untreated and treated blackwater.

Overall, it can be concluded that the anaerobic digestion technology is able to degrade a high amount of pharmaceutical substances and is partly more efficient than the classical activated sludge process. Feeding various co-substrates to the blackwater digester showed positive effects (process stability, increased pharmaceutical degradation rates) (Wätzel et al., 2014). To produce digester gas as well as a pharmaceutically reduced digestate, which could be used for further nutrient recovery, anaerobic treatment provides a major advantage over classical wastewater treatment systems. For Diclofenac, Metformin, Amoxicillin, as well as Sulfamethoxazol, the anaerobic digestion technology shows higher rates of degradation performance than MWWTP´s.

The KREIS-consortium has developed the following **treatment concept.**

The **digestate** leaves the fermentation with a very high water content. Recycling possibilities in close proximity to the place of production are rare and transportation to dewatering facilities would be cost intensive. In order to generate usable products, the digestate must therefore be separated into a low-solids phase and a muddy, solids and phosphate-rich phase. For the dewatering of the digestate, mechanical methods will be required.

To avoid transportation costs and annoyance of residents, the liquid phase should be treated and recycled locally. A treatment together with the greywater after prior removal of nitrogen and phosphorus will be investigated in further research projects.

Nitrogen should preferably be removed from the low-solids phase by deammonification. Stripping has a high potential of odour nuisance and the small amounts of usable nitrogen makes recycling unprofitable.

The thickened digestate can be processed together with structural material (green cuttings and leaves) into compost. The extracted phosphate (precipitate of the liquid digestate) can be composted with the dewatered digestate.

The heat potential of greywater should be used (see chapter Energy) before advanced treatment.

Trickling filters with AOP and filtration are proposed for the treatment of greywater, because the legal requirements for augmentation of the urban creek that possesses a very low flow rate are very strict. In figure 8 the comprehensive concept is presented.

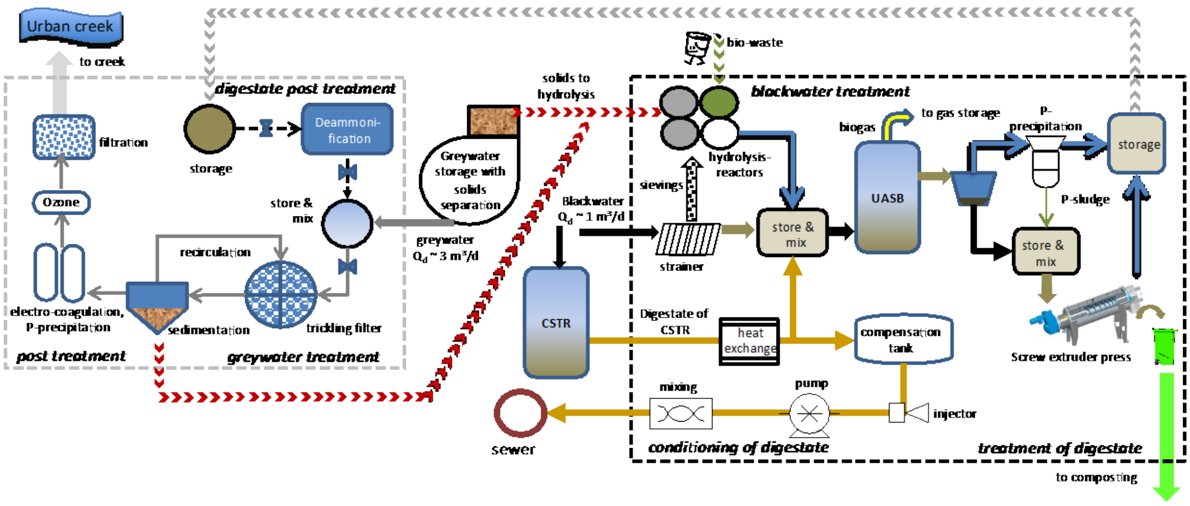

Figure 7: Blackwater and greywater treatment concept at Jenfelder Au

TECHNICAL ENERGY CONCEPT AND RESULTS OF RESEARCH

A model was designed that dynamically simulates the temporal development of the energy need and energy supply, and shows optimal configurations, including modes of operation and combinations of individual system components at the quarter Jenfelder Au. Various energy supply concepts were taken into consideration especially with regard to their behaviour in terms of primary energy. The comparison of the systems showed that the system of reference had the highest need for primary energy. The system realised at Jenfelder Au will be able to save about 22 % of primary energy. The system optimized in the KREIS project would save more than 50 % of the necessary primary energy in comparison to the implemented concept. (Stübler, 2014)

ECONOMY

The economy of decentralized sanitation in an urban context has been analysed in order to identify the prospects of future implementations. Net present value method, cost-benefit analysis, and cost-utility analysis were used to assess and calculate the economic efficiency. Using an economic evaluation and decision model, various centralized and decentralized infrastructure models of supply and disposal systems could be compared. Based on calculations using the developed model, it will be possible to examine the influence of decentrality and to identify cost-relevant factors. By varying the size of the project area, the economic capability of different project area sizes can be determined. Based on these studies, the optimal degree of decentrality with regard to size can be derived. (Alfen and Lück, 2012)

ECOLOGY

Balancing negative and positive ecological consequences was the basis for the ecological evaluation of the concept and a comparison to other infrastructure systems. The HWC system shows advantages in the evaluated ecological impact categories in comparison to the conventional system.
There is a difference between emissions which have a global, or at least transregional effect, and the local environmental effects. These might put a strain on local population and the local ecosystem. Relevant factors occur in the form of noises and odours. (Giese and Londong, 2015)
Sources of emissions with local environmental effects are the vacuum toilets, the vacuum system, garbage disposal units, and the digestion plant with the block heat and power plant or micro gas turbines located on the site. During the operating phase, the local environmental effects will be

measured according to the concepts and methods as established by the KREIS project. (Giese and Londong, 2015)

ORGANISATIONAL AND INSTITUTIONAL QUESTIONS

The KREIS project has determined the necessary coordination that is to be expected during the realization and operation on the quarter level. Early cooperation management is necessary. The acceptance of the system and of its compounds will be evaluated during the operation phase starting in 2017, based on methodologies developed in the KREIS-project. (Schramm et al., 2015)

CONCLUSIONS

Extracting recyclable materials and elimination of pollutants in source separated municipal wastewater of an urban quarter will be demonstrated in Hamburg Jenfelder Au. In the preparatory research project KREIS, knowledge about volumetric quantity, concentrations and specific loads of grey- and blackwater was generated. On the basis of these data and lab-scale experiments, valuable information for the large-scale implementation of the HWC could be gained. Methods for cost analysis and investigations of acceptance were adapted to the project boundaries.

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