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No Sustainable Future Without the Commitment of Every Individual

For the last ten years, a biennial English language issue of the journal *KA Korrespondenz Abwasser, Abfall* (*Correspondence Wastewater Waste*) of the German Association for Water Management, Wastewater and Waste (DWA) has been published. The occasion for this is usually the IFAT in Munich, the world's leading trade fair for water, sewage, waste and raw materials management, but the magazine is distributed more widely at other trade fairs in Germany and abroad and can be downloaded free of charge from the DWA website (*https://en.dwa.de/en/journals.html*).

The last IFAT in the usual form, as a face-to-face event, before 2022, took place in 2018. More has changed since then than most of us could have imagined in 2018. Two important turning points are the Covid-19 pandemic and then the Russian invasion of Ukraine, which was described by the aggressor as a military special operation.

Against this background, IFAT started again in 2022 as an international trade fair face to face. Pandemics and war are one thing. Protecting the environment, the means of livelihood for us and future generations, and climate change is another – and that requires our ceaseless commitment and action. And international cooperation, not confrontation or power games, is essential if humanity is to survive.

Irrespective of the dark clouds over Europe: It is a step back to normality that trade fairs and congresses are taking place face to face at home and abroad again. A light at the end of the Corona tunnel. In order to be able to meet the challenges in the environmental sector, we need innovation, and these need cooperation, exchange, encounters between people, creativity and imagination. Trade fairs and congresses make this possible and provide the framework for this.

The challenges in the environmental area, the basis of our existence, are ultimately the same everywhere, but vary in strength from region to region. A functioning society requires a stable, sustainable energy supply. An energy supply that uses finite resources is – despite all the convenience – not sustainable and is a strain for the climate, driving up temperatures on earth. Equally necessary are advanced water management systems that give all people access to clean drinking water at a cost they can afford and that ensures hygienic sanitation. Drinking water supply and wastewater disposal use advanced chemical engineering and process technologies. But water management is more than this: it also includes dealing with urban flash floods and other extreme events such as droughts. Another foundation upon which human communities are built is proper waste management. You can find suggestions for all these topics at trade fairs, where the necessary technology is shown and offered.

In this issue, which is a little thinner than usual during the Covid-19 pandemic, there are four articles on selected water management topics that are of international interest: planning instruments for the water balance in settlement areas, an overview of the services of the sewage treatment plants in Germany and Austria to illustrate what is possible in routine operation. This is followed by an article on how to deal with sewage sludge, specifically one climate-relevant aspect: methane emissions from sewage sludge. And finally, a topic that is gaining importance also in Europe: water reuse.

I hope that you can all get through the current crises safely and stay healthy and continue to go about your daily routines including work and social activities. Use the framework of what is possible again responsibly and visit trade fairs and congresses. Our future needs us and our commitment.

Enjoy reading this journal.

Frank Bringewski

Frank Bringewski
Editor

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Standard DWA-A 131E

Dimensioning of Single-stage Acitvated Sludge Plants

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Using the dimensioning values recommended in this Standard, the minimum requirements for municipal wastewater with single-stage activated sludge plants can be met or bettered at national level. In contrast to earlier editions, in which the dimensioning procedure for nitrifying and denitrifying activated sludge plants was based on the measured BOD_5 load, the design is now based exclusively on the COD load. Standard DWA-A 131 deals not only with the description of the process, the design procedure and the design bases, but also with the calculation of the mass of the sludge and the design of the secondary treatment and sludge activation. In addition, planning and operational aspects are dealt with and the possibility of simulation, e.g. scenario comparisons or the consideration and quantification of the effect of further automation functions and operational management concepts, are explained.

The Standard is aimed at operators of wastewater treatment plants, planning engineers and approving authorities.


DWA
DWA Set of Rules
Standard DWA-A 131E

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Planning Instruments for the Water balance in Settlement Areas

Mathias Uhl and Malte Henrichs (Münster/Germany)

Summary

In water bodies dominated by settlements, disturbances of the water balance and hydrological dynamics are present, which are caused by land sealing and the discharge of precipitation runoff. They are the reason for the paradigm shift from the discharge to the retention principle in the planning of rainwater management in settlement areas. Their goal of minimizing the impact on the natural water balance is achieved through measures to evaporate, infiltrate, and delay stormwater runoff instead of the previous complete and rapid discharge. This article summarises the results of the BMBF (German Federal Ministry of Education and Research) joint research project "Water balance of settlement-affected bodies of water" (WaSiG), which make an essential contribution to the professional planning of rainwater management in keeping with the retention principle.

Keywords: drainage systems, rainwater management, retention, water balance, hydrology, soil sealing, precipitation runoff

1 Background and objective

The water balance should be regarded as an essential element of the management of waters in accordance with the Water Resources Management Law (sections 5, 27, 47, 55, 57) [1], as it is one of the basic variables of the good ecological condition of bodies of water. Building development in catchment areas is the most extensive intervention for bodies of water [2]. It is characterised by the sealing of surfaces, by often considerable encroachment on the morphology of waters and on floodplains, as well as by the discharge of runoff and substances from urban drainage systems. Settlement areas change the water balance and the hydrological dynamics of settlement-dominated bodies of water due to their high degree of surface sealing and the mostly still complete, rapid discharge of precipitation runoff. The direct runoff is significantly increased, while the groundwater recharge and in particular the evaporation are reduced correspondingly. Evaporation links the water balance and the energy balance. Its energy requirement causes a lowering of the temperature of the evaporation-active areas. Reduced evaporation is conducive to temperature increases in cities.

Due to these relationships, a paradigm shift in urban drainage from the drainage to the retention principle has developed over a longer period. The technical rules DWA-A 100 [3] and DWA-A 102 [4] introduce the water balance as a planning variable and require the water balance in development and renovation areas to be approximately equivalent to the water balance of the associated cultivated landscape.

Germany's diverse landscape types with their morphological, hydrogeological and climatic characteristics and their cultivated land uses lead to regionally different divisions of the water balance components. The management of settlement-affected bodies of water and precipitation runoffs in settlements must therefore be based on regional water management conditions.

For rainwater management in the settlement area, regional target variables as well as realistic mesoscale and microscale planning instruments are required. The necessary management measures and facilities must be effective, sustainable and resilient.

2 BMBF joint research project WaSiG

In the BMBF (German Federal Ministry of Education and Research) funding measure ReWaM (Regional Water Resources Management for Sustainable Protection of Waters in German), the joint project "Water balance of settlement-affected bodies of water (WaSiG)" was conducted with four sub-topics:

1. Process and efficiency analysis of rainwater management based on water management with regard to the water balance
    - (i) Examination of long-term rainwater management in three different districts
    - (ii) Examination of sub-processes in management systems
    - (iii) Generally available database for the development and validation of simulation models
2. Water balance models for management measures in settlement dominated water catchment areas.
    - (i) Creation and validation of realistic sub-process models for water balance variables in mesoscale and microscale simulation models
    - (ii) Solutions to the scaling problem
    - (iii) Provision of the sub-process models as open-source models
3. Target variables for the water balance of settlement-affected bodies of water
    - (i) Methods for the derivation of target variables for the water balance in settlement-affected catchment areas
    - (ii) Derivation of acceptance measures for planning purposes

Time	Roof	Area	Substrate height	h_N	ET_p	h_A	h_A/h_N	$(h_N – h_A)/ET_p$
		m²	cm	mm	mm	mm		
Year 2017				814	656			
	FHZ 1	80	6			467	57 %	53 %
	Leo 1	3	6			405	50 %	62 %
	Leo 4	3	6			412	51 %	61 %
	Leo 7	3	10			398	49 %	63 %
	Leo 10	3	15			333	41 %	73 %
Summer semester (May–October)				421	487			
	FHZ 1	80	6			150	36 %	56 %
	Leo 1	3	6			138	33 %	58 %
	Leo 4	3	6			146	35 %	56 %
	Leo 7	3	10			130	31 %	60 %
	Leo 10	3	15			91	22 %	68 %
Winter semester (November–April)				393	169			
	FHZ 1	80	6			316	80 %	46 %
	Leo 1	3	6			266	68 %	75 %
	Leo 4	3	6			266	68 %	75 %
	Leo 7	3	10			269	68 %	73 %
	Leo 10	3	15			242	62 %	89 %

Table 1: Water balance of extensive green roof structures in 2017

4. Sustainability and resilience
   (i) Factors influencing current social approval for management measures.
   (ii) Concepts for efficient planning and administrative processes in municipalities
   (iii) Quantification of possible effects of climate change on water balance and flooding behaviour in settlement areas with management measures.

The integrated project approach brought together three municipalities, three service providers from planning and business and research partners from the natural, engineering and social sciences. The participants were the Albert Ludwigs University of Freiburg (Chair of Hydrology; Chair of Human Geography), the state capital Hannover (urban drainage), the city of Freiburg (Environmental Protection Office, Department of Water Management and Soil Protection), the city of Münster (Underground Construction Office), badenova AG & Co. KG, BIT Ingenieure AG (Freiburg) and Ingenieurgesellschaft für Stadthydrologie mbH (Hannover) as well as the Münster University of Applied Science (Institute of Infrastructure·Water·Resources·Environment (IWARU)), which was also responsible for the coordination.

The following chapters provide an overview of the contributions of the WaSiG joint research project to the contemporary planning of rainwater management that meets the requirements of water protection and the urban climate and contributes to the further development of resilient cities.

3 Operation and effectiveness of management measures

3.1 Monitoring of roof greening

The hydrological processes of extensively greened roof structures were continuously examined over about two years in real operation [5–7]. The semi-technical test facility (Leo 1–10) consisted of ten 3 m² test fields with a 3 % incline, different substrates with installation heights of 6 cm, 10 cm and 15 cm as well as associated drainage systems from market-relevant suppliers (Figure 1). The large-scale test facility (FHZ 1+2) is a hall roof with two identical 80 m² roof surfaces, whose substrate height is 6 cm.

The hydrological behaviour of extensive green roofs is primarily influenced by the water reservoir of the substrate layer and the local climatic water balance, as Table 1 shows by way of example. The runoff share is low in the summer semester with 22 % to 36 % and is more dependent on the substrate

Fig. 1: Semi-technical test facility for extensive green roof structures

height than in the winter semester with 62 % to 68 % (80 %). In the long-term balance, the actual evaporation corresponds approximately to the difference $h_N - h_A$. In the summer semester, the actual evaporation is only 56 % to 68 % of the potenzial evaporation, due to a lack of water supply in dry phases. In winter, too, the actual evaporation is only 73 % to 89 % of the potenzial evaporation, probably also due to dry phases. In both semesters, the actual evaporation increases with increasing substrate height.

Extensive green roof structures are likely to reduce the runoff volume significantly in summer, whereas the actual evaporation is only about half of the potenzial evaporation due to the low storage volume. In winter, higher runoff fractions are to be expected as a result of the higher water content in the substrate, which on the other hand also entails a higher share of actual in potenzial evaporation.

3.2 Efficiency of existing systems

When comparing near-natural and conventional rainwater management systems (RWBA), it can be determined that conventional RWBA (i.e., pure retention facilities) are significantly more favorable in terms of investment and operating costs than near-natural facilities (infiltration basins and trenches). With regard to flood protection, multifunctional use, preservation of a near-natural water balance and acceptance by the population, however, clear advantages of near-natural systems can be identified [8]. The differences in the investment and operating costs of near-natural and conventional systems decrease with increasing system size, so that large near-natural systems can also compete with conventional systems in terms of costs. If all aspects are taken into account – ecological (water balance, green areas), economic (costs, maintenance expenditure) and social (multifunctional use, acceptance) – then medium to large M/R/V systems (infiltration basins/infiltration trenches/infiltration areas) with around 20,000 m² of connected drainage-active sealed surface ($A_{b,a}$) have the lowest cost-benefit ratio.

3.3 Operating experiences

As the literature search for operating experience showed, the publications on the subject of the upkeep of near-natural RWBAs usually focus on the naming of necessary or possible maintenance measures for existing facilities [9]. The recommended basic maintenance always consists of a similar or identical pool of work (green maintenance, leaf and refuse removal, etc.), while further measures, in particular for functional checking, are recommended to varying extents depending on the source. The practical analysis showed that the basic maintenance is done as described in the literature, but the scope of inspection is significantly lower, especially for infiltration basins and infiltration trench systems, and appropriate investigations are usually only initiated in the case of obvious failure of an installation. The proven functionality of the existing RWBA (see Chapter 5) confirms that the municipalities are correct in this approach. The vast majority of the systems included in the analysis (98 %) were built less than 25 years ago, and almost two-thirds only after the turn of the millennium. Accordingly, long-term developments, which may suggest a more regular inspection of the systems with increasing design life, cannot be fully estimated at this time.

However, a central finding of the discussion with practitioners does not relate to the maintenance processes themselves, but focuses on system planning. This showed that already including the maintenance in the planning processes can result in significant advantages for later operation. Above all the consideration of green maintenance, which is one of the maintenance priorities and whose effort strongly depends on the conditions (slope inclination, accessibility, etc.), has great potenzial to significantly influence the efficiency and thus the costs for maintenance.

3.4 Costs

With regard to the costs, represented as specific annual costs (€/m²) with the reference value "connected impervious area (A_u)", [8] it was shown that:

- The average costs for central and decentralised system groups decrease with increasing system size (surface of catchment area A_u), although this effect is much more pronounced for M/R/V, so that more decentralised or very small central systems, especially for M/R/V systems, tend to be more expensive than larger, central systems.
- The near-natural M/R/V systems up to a surface of catchment area A_u of about 20,000 m² have significantly higher specific costs per year than retention systems, while the costs seem to converge from more than 20,000 m² A_u, so that, in comparison, conventional near-natural large M/R/V systems can compete with retention systems in terms of cost.
- The cost advantage of large, central systems over small, decentralised systems is due, among other things, to the expenditure for maintenance and operation, since compact, central systems can be maintained more efficiently and better monitored, so that operating costs are reduced.
- There are certain uncertainties regarding the results (methodological weaknesses; uneven size distribution of the systems, quality of the basic data). It may be assumed that the actual costs of M/R/V systems are more likely to be lower than shown here, especially in the case of percolation facilities with an activated soil layer (field ditches, infiltration trenches, tanks).

4 Simulation models

In the planning process, simulation models offer support for the development of measures and making well-founded decisions on preferable solutions. Variably differentiated planning tools are useful, depending on the planning phase.

4.1 Water balance model WABILA

Rainwater management measures must be integrated into urban planning at an early stage. Urban hydrological simulation models are not flexible and fast enough for these rather fast and variable planning processes. For that reason, the simple water balance model WABILA was developed for the urban space as part of the BMBF joint research project SAMUWA [9]. Based on extensive simulation calculations and non-linear, multiple regression approaches, it was possible to determine easily and quickly the three main components of the water balance as a function of the local characteristic data for built-

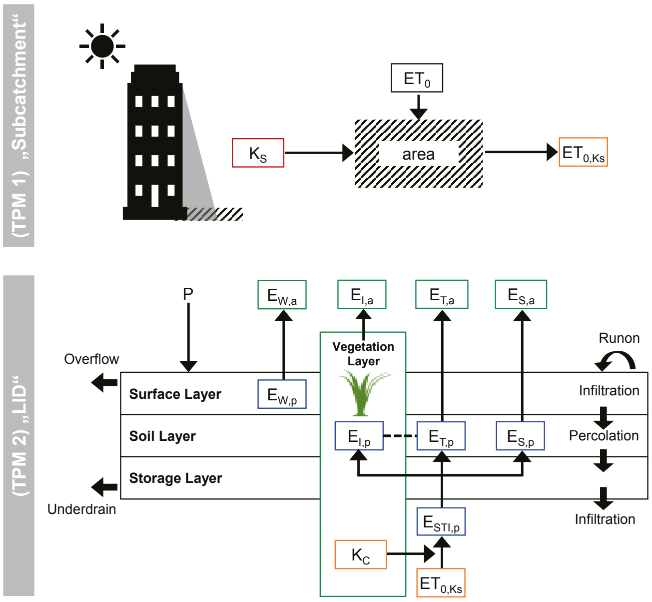


Fig. 2: Integration of SWMM-UrbanEVA into SWMM (modified according to [12])

up areas, systems and measures for rainwater management as well as hydrogeological and meteorological data The calculation approaches are published in full in the new DWA-M 102-4 [4]. WABILA is provided in a user-friendly version as a “DWA Water Balance Expert”.

4.2 Evaporation model UrbanEVA

Evaporation is an essential water balance component for which no realistic sub-model has been available in urban hydrological models so far. This gap was closed in the BMBF joint research project WaSiG.

Evaporation in urban streetscape has been experimentally studied by Koelbing et al. [10] with high spatio-temporal resolution. The measurements focused on the space up to about 2 m above the top edge of the road surface, which also shapes the quality of life in the city in terms of the urban climate. It was proven that evaporation is highly variable and depends primarily on the net radiation. Shading from buildings and deciduous trees significantly reduces evaporation in the lower streetscape. A model relationship was derived between the data of an unshaded main climate station and the local climate measurements, and this relationship also takes into account the local shading situation. In addition to evaporation in the lower street space, the evaporation of the street trees at the height of the treetops acts as a second level of evaporation. The dynamics of water vapour transport from the lower evaporation level in and through the upper evaporation level depend on microclimatic boundary conditions and especially on the canopy density of the street trees.

Hörnschemeyer [6, 7] selected proven approaches to the calculation of evaporation and coupled them using the transfer approach of Koelbing et al. [10] with a freely available, dynamic shadow-casting model for generally available three-dimensional data in the urban space. The UrbanEVA evaporation model developed was integrated as a partial model into the urban hydrological simulation model “Storm Water Management Model (SWMM)” of the US Environmental Protection Agency (EPA) [11]. As an open-source model with many years of expertise and quality-assured further development, SWMM is the “mother model” of urban hydrology. The new sub-model eliminates the deficits of the previous SWMM evaporation model and is particularly suitable for the modelling of blue-green infrastructure.

SWMM-UrbanEVA illustrates different vegetation types according to the location and with component accuracy (interception evaporation E_I, transpiration E_T, evaporation E_S) (Figure 2). The interactions of the soil – plant – atmosphere system as well as the shading by buildings or trees are integrated realistically. SWMM-UrbanEVA makes it possible to calculate simplified and detailed variants for greening and evaporation in the building and district planning.

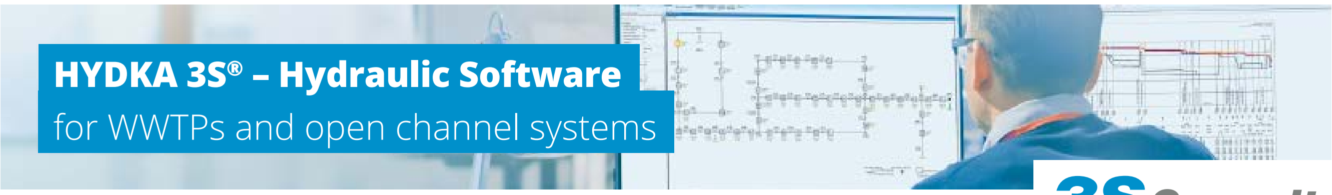
5 WaSiG model for reference values of the urban water balance

The planning goal of rainwater management is to keep the changes in the natural water balance through settlement activities as low in terms of quantity and material as is technically, ecologically and economically justifiable (DWA-A 100) [3]. In the future, the water balance in settlement areas will be regarded as the emission criterion for the water volume, which should be as close as possible to that of the undeveloped reference condition (DWA-A 102-2, DWA-M 102-4) [4]. The water balance of a landscape area of the same natural region with current cultivated land use serves as the reference condition.

The Hydrological Atlas of Germany (HAD) [13] provides the first helpful information for orientation here. To obtain a more spatially precise differentiation, a GIS-based method (WaSiG method) was developed to calculate the small-scale non-urban water balance based on data generally available in the federal territory.

5.1 Procedure

Natural regions, ground overview maps, land usage data as well as precipitation and climate data from the German Weather Service are used as databases. One of the proven water balance models is used to calculate the small-scale water balance of non-urban areas. In the WaSiG project, the water balance model RoGeR WHM was used, which was further developed in the project from the event-based precipitation-runoff model RoGeR



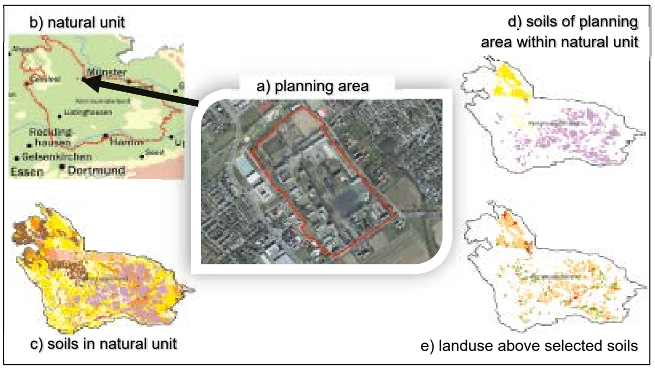


Fig. 3: Procedure for determining the databases for the planning and reference area

[14]. The determination of the reference state of the water balance is divided into eight steps (see Figure 3 for 1–4):

1) Starting from the planning area, the natural region where the planning area is located is determined. The Natural regions of the Hydrological Atlas of Germany serve as a data source.
2) The determination of the soils occurring in the planning area is based on the Soil Mapping Guide 5 (2005) [15].
3) The soils occurring in the planning area are selected in the Natural regions.
4) On these soils, non-urban land usage is determined from the Corine data.
5) Area shares of the same combination of soil and land use are determined to simplify the simulation.
6) The model parameters are determined on the basis of soil properties (Soil Map of Germany – BÜK), land usage, topography and geology.
7) A representative climate station (e.g. a station of the German Weather Service) is selected for the planning area.
8) By using a validated water balance model for this purpose (e.g. RoGeR WHM [14]), the shares for direct runoff, groundwater recharge and evaporation are calculated on an area-weighted basis.

5.2 Results

As an example, the reference conditions for five non-urban areas in Germany with different characteristics of warm and humid temperate climatic conditions were investigated [9] with annual precipitation P between 550 mm/a and 1100 mm/a and potenzial evapotranspiration ETp between 600 and 700 mm/a. The surface runoff was 2 % to 4 % of the annual precipitation and the direct runoff between 9 % and 18 %. The evaporation showed a pronounced differentiation with 44 % to 88 % of the annual precipitation, as did the groundwater recharge with 19 % to 49 % (Figure 4).

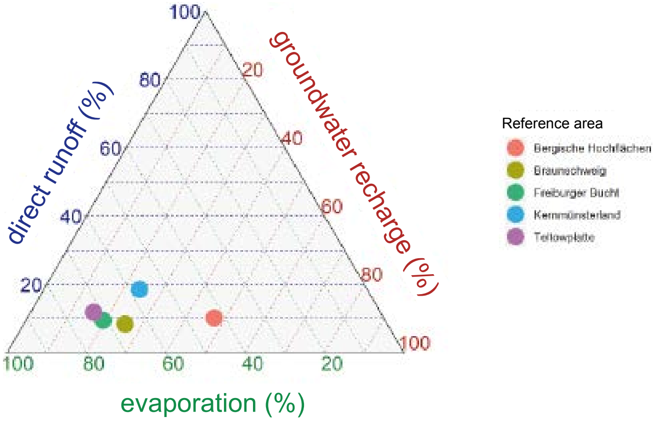


Fig. 4: Percentages of the components of the water balance for the reference areas studied.

The simulation calculations and further considerations from a hydrology, landscape ecology, and data management perspective lead to the following conclusions and recommendations:

- The natural region represents the characteristics of a planning area better than, for example, a hydrological catchment area.
- The cultivated landscape of a natural region without urban areas is well suited for determining the reference state of the water balance and is a more realistic parameter than a potenzial natural state.
- The proposed method can be used uniformly throughout Germany on the basis of freely available data and is well suited for determining the long-term average water balance as a reference state.
- The local differentiation of the reference states for the settlement areas is primarily characterised by the groundwater recharge and evaporation.

6 Planning processes

6.1 Acceptance

An essential element of today's planning processes is the participation of citizens. The level of knowledge about stormwater management and the acceptance of its measures was surveyed and analysed in a representative survey in the cities of Freiburg, Münster and Hannover [16–19]. Overall, there was a good level of knowledge and a consistently high level of acceptance of rainwater management measures. The perceived beneficial evaluations outweighed the concerns expressed, which are also a reason for improvement and clarification. The frequent criticism of the poor aesthetic quality of measures should be a welcome incentive for landscape architecture.

6.2 Success factors

An analysis of the planning processes in Freiburg, Münster and Hanover summarises the currently still existing obstacles and highlights success factors for successful planning processes. Detailed explanations have been published [16–19]. Bannert et al. [19] point out that it will only be possible to realise water-sensitive urban development and exploit the potenzials of multifunctional land use in the coming years if, above all, the willingness to innovate and cooperate on the part of the various political, planning, economic and social actors involved increases. Kramer [20] and Hörnschemeyer et al [6, 7] name further success factors with regard to the consideration of evaporation in the planning process.

7 Conclusion

The most important key messages of the project are summarised below:

1) Rainwater management measures (RWBM) are reliable in the long term and are consistently rated positively by citizens. The space requirements for the RWBM must be considered early on in the urban land use planning process. Experts from Freiburg, Hanover and Münster have compiled their experiences in recommendations on administrative and operational practice.
2) Simulation models for rainwater management measures were improved, supplemented by a newly developed module for calculating evaporation in urban areas and validated on measurement data. They are freely available as open-source software for users and providers of specialist software.
3) The water balance is an important and suitable target variable in the planning. Based on generally available data and a generally accepted water balance model, a new GIS-based calculation approach is available to determine a reference condition for the near-natural water balance (undeveloped state).

Acknowledgement

The joint research project “Water balances of settlement-affected waters” (WaSiG) was funded by the German Federal Ministry of Education and Research (BMBF) as part of the funding measure “Regional Water Resources Management for Sustainable Protection of Waters in Germany” (ReWaM). For this, the team would like to thank the project partners mentioned in chapter 2.

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33. Performance Report for Municipal Wastewater Treatment Plants

Trends of Energy Consumption

DWA Working group BIZ-1.1 “Wastewater Treatment Plant Neighbourhoods”

1 Aims, principles and limits of the national performance report

The DWA performance report (DWA: German Association for Water Management, Wastewater and Waste) shows the quality of the wastewater treatment and the power consumption used for it as well as the energy generated at the sewage treatment plants, in particular by digester gas power generation. The performance report is a reflection of the qualified work of the operating personnel, which was characterised by the ongoing pandemic situation in the report year. It should be particularly emphasised that, especially in the smaller wastewater treatment plants, which often have to struggle with a very thin staffing level anyway, it has nevertheless been possible to maintain wastewater treatment without sacrificing the effluent quality. In most cases, this was only possible through deferred maintenance and repair work and gnawed at the substance of “man and machine”. Overall, it is a testimony to the great commitment and dedication that the operating personnel show day after day, even under difficult conditions.

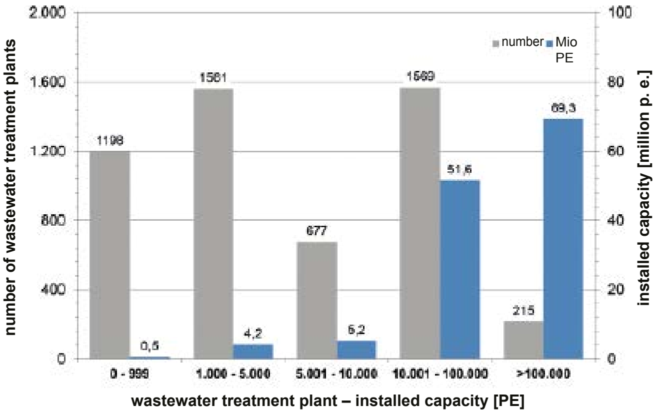

Fig. 1: Number and design capacities of the wastewater treatment plants taking part in the DWA performance report in 2020 by plant size

The data for the performance report was collected and evaluated by the DWA federal state associations and the Austrian Water and Waste Management Association. According to the Federal Statistical Office, the level of connection of the inhabitants to municipal wastewater treatment plants was 97.1 % in 2016. Of the total of 9105 municipal wastewater treatment plants in Germany with a design capacity of 151.8 million inhabitants, 5220 wastewater treatment plants with a


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design capacity of 130.8 million inhabitants participated in the 33rd DWA performance report. With a participation rate of 86.2 %, the results for 2020 can be considered representative for Germany. This is based on the more than 3.6 million spot measurements taken by operating personnel as part of self-monitoring, which are included in the assessment as annual mean values.

As in the past, the evaluation is grouped by DWA regional groups and size range (SR) of the wastewater treatment plants. Figure 1 shows the distribution of wastewater treatment plants in terms of design capacity and number. Only 4 % of the wastewater treatment plants have a design capacity > 100,000 inhabitants (SC 5), but at the same time these plants represent 45 % of the total capacity.

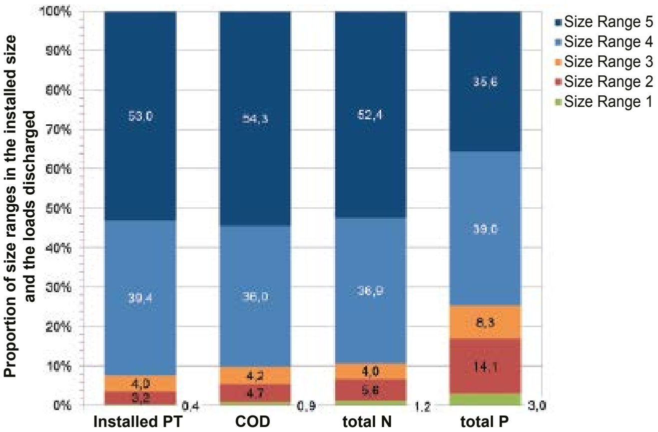


Fig. 2: Percentage proportions of capacity (PT) and introduced load by size of wastewater treatment plant

2 Results

2.1 Cleaning performance results

Table 1 summarizes the results of the in and outflow measurements (freight-weighted mean values), the elimination performances, further characteristics and information about participation. As in previous years, the results of the Austrian Water and Waste Management Association performance report for

DWA Federal State Association		**Baden-Württemberg**	**Bavaria**	**Hesse/Rhineland-Palatinate/Saarland**	**North**	**North East**	**North Rhine-Westfalia**	**Saxony/ Thuringia**	**DWA**	**ÖWAV**)**
wastewater treatment plants [number]		880	1456	1234	398	312	480	460	5220	780
annual sewage amoung [million m^3]		1476	1382	1243	716	478	2025	407	7727	1075
installed volume [millon residents]		21.6	24.5	16.4	18.9	13.3	28.3	7.8	130.8	21.9
mean p. e. loading [million residents]		15.5	17.0	15.8	14.3	11.7	21.7	6.3	102.2	15.1
installed p. e./mean p. e. loading		1.39	1.45	1.04	1.32	1.13	1.31	1.24	1.28	1.45
specific resultant wastewater [$m^3/(p. e. \cdot a)$]		95	81	79	50	41	93	65	82	71
COD	inflow [mg/L]	462	546	511	887	1075	470	674	575	616
	discharge [mg/L]	19	26	23	37	37	24	27	25	29
	elimination [%]	96.0	95.2	95.5	95.8	96.6	94.9	95.9	95.6	95.3
total nitrogen*)	inflow [mg/L]	42.5	51.9	48.5	74.7	88.9	43.6	58.7	52.1	49.1
	discharge [mg/L]	9.1	10.9	7.9	8.2	10.4	7.2	9.5	8.7	8.9
	elimination [%]	78.7	79.1	83.7	89.0	88.3	83.5	83.9	83.2	81.8
P_{tot}	inflow [mg/L]	5.9	7.4	7.1	10.4	13.6	6.0	8.8	7.4	7.1
	discharge [mg/L]	0.36	0.73	0.57	0.49	0.51	0.39	0.80	0.51	0.59
	elimination [%]	93.9	90.1	92.0	95.3	96.2	93.5	91.0	93.1	91.8
NH_4-N	discharge [mg/L]	0.59	1.53	1.56	1.29	0.79	0.62	1.07	1.02	1.15
NO_3-N	discharge [mg/L]	7.0	7.7	5.0	5.3	7.6	5.1	6.5	6.2	6.2
N_{inorg}	discharge [mg/L]	7.6	9.2	6.5	6.6	8.4	5.7	7.6	7.2	7.3

*) Total nitrogen = $N_{inorganic} + N_{organic}$
**) Austria and South Tyrol

Table 1: Average intake and discharge values, elimination performances and characteristics

wastewater treatment plants for the facilities in Austria and South Tyrol were also shown.

There were hardly any changes compared to the previous year. The nationwide high level of nutrient elimination already achieved in previous years has again increased slightly with regard to phosphorus elimination. Significant, as compared to the results of the other regional groups, are the higher N and P-elimination levels in the north and north-east regional groups. This is due to the significantly higher concentrations in the inflow. One of the reasons for this is probably the separation systems that are more widespread in these states.

Overall, the requirements of the EU Urban Wastewater Directive were again met or significantly exceeded on a national average in 2020. Nevertheless, some facilities still need to be adapted to the state of the art (sewer network and wastewater treatment plant).

As a reference value for calculating the specific wastewater generation and the specific electricity consumption, the average load of the plants was determined from the average COD (chemical oxygen demand) influent load. A specific COD load of 120 g/(p. e. · d) was assumed here.

The specific resultant wastewater is 82 m^3/(p. e. · a) in the national average. In the north and north-east regional groups the specific resultant wastewater is far lower due to the widespread separate system. In the other state associations, drainage is predominantly performed in a combined system, and the rainwater makes for a considerably higher specific resultant wastewater on the treatment plants.

The COD and total nitrogen loads introduced into the bodies of water correspond largely to the respective proportions of the design capacities, grouped into size ranges (Figure 2). Plants sizes 1 to 3, however, have an above-proportional share of phosphorus at about 25 %, although, taking their design capacity into account, these plants only represent a proportion of 8 %. The reason for the high proportion of size classes 1 to 3 are those plants that are not required by law to implement targeted phosphorus elimination measures.

2.2 Results for power consumption and power generation

Data on electricity consumption, likewise, was collected in all regional groups. The specific electricity consumption (kWh/PT) was calculated for 4835 wastewater treatment plants. Table 2 shows the total energy consumption of the municipal wastewater treatment plants in Germany included in the performance report (coverage 84.7 %) at 3148 GWh/a. This lies within the order of magnitude of approx. 2 % of the domestic power consumption (129 TWh in 2017). Specific electricity consumption varies little among the state associations. The lowest values were for Austria and South Tyrol and for the northeast state association, while the higher values tended to be in the north and Baden-Württemberg regional groups.

The sewage treatment plants' own power generation, whose data has not yet been recorded in the performance report, amounts to a total of 1118 GWh/a. It can be seen that in state associations with predominantly large sewage treatment plants, such as North Rhine-Westphalia, energy generation is over 50 %, while in a state association such as Hesse/Rhineland-Palatinate/Saarland with many smaller plants without anaerobic sludge digestion, only less than 30 % of the consumed energy is generated at the sewage treatment plants.

DWA Federal State Association	Baden-Württemberg	Bavaria	Hesse/Rhineland-Palatinate/Saarland	North	North East	North Rhine-Westfalia	Saxony/Thuringia	DWA	ÖWAV*)
sewage treatment plants [number] with data on electric power consumption	856	1263	1180	341	286	472	437	4835	733
installed capacity [million residents]	21.6	23.4	16.2	18.5	13.1	28.2	7.7	128.7	21.5
mean loading [million residents]	15.5	16.5	15.6	14.1	11.5	21.5	6.2	100.9	14.8
total electric power consumption [GWh/a]	524	527	460	453	320	674	191	3148	417
specific power consumption [kWh/(resident · a]	33.8	32.0	29.4	32.2	27.8	31.3	30.7	31.2	28.2
Sewage treatment plants [number] with datan on electric power generation / power consumption	268	n. r.	202	84	68	214	62	898	338
installed capacity [million residents]	16.7	n. r.	9.3	11.3	9.8	23.1	5.4	75.7	18.4
mean loading [million residents]	11.9	n. r.	8.1	8.7	9.5	18.0	4.5	60.7	12.8
total energy generation [GWh/a]	209	n. r.	125	185	158	360	82	1118	172.5
specific electric power generation / energy consumption [kWh/(resident a]	17.6	n. r.	15.4	21.2	16.6	20.0	18.0	18.4	13.5
proportion of installed capacity (p. e.) of plants with own power supply of installed p. e. total [%]	77	n. r.	57	61	75	82	70	59	8.6
proportion of own electrical power supply of total elecitric power consumption [%]	40	n. r.	27	41	49	53	43	36	41

*) Austria and South Tyrol
n. r.: not recorded

Table 2: Power consumption and self-generation

This is also evident that there the share of design capacities of plants with power generation is only 57 % compared to the total design capacity of plants with data on power consumption. In regional groups with a percentage of over 80 %, the potenzial of self-generation of power is likely to be largely exhausted, apart from individual cases in which no digester gas power generation has yet been implemented. In addition to increased co-fermentation and more efficient digester gas power generation, a further increase in self-generated power requires the construction of photovoltaic or wind power plants and, as far as the hydraulic conditions exist, the integration of a hydro-electric plant.

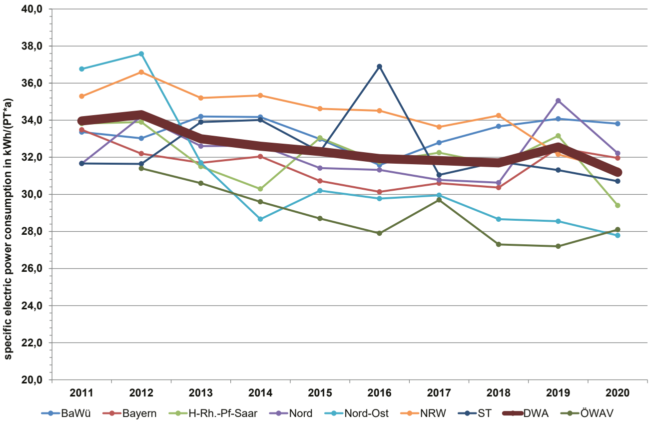


Fig. 3: Development of the specific power consumptions from 2011 to 2020

3 Development of the power consumptions and cleaning performances in the last ten years

In 2011, the power consumption of municipal wastewater treatment plants was recorded for the first time in the DWA performance report for all federal state associations (Figure 3). The data of the Austrian Water and Waste Management Association are also available since 2012. All DWA state associations show a trend towards slightly decreasing power consumptions from 34.0 kWh/(p. e. · a) to currently 31.2 kWh/(p. e. · a). Values at a slightly lower level, but also decreasing, can be

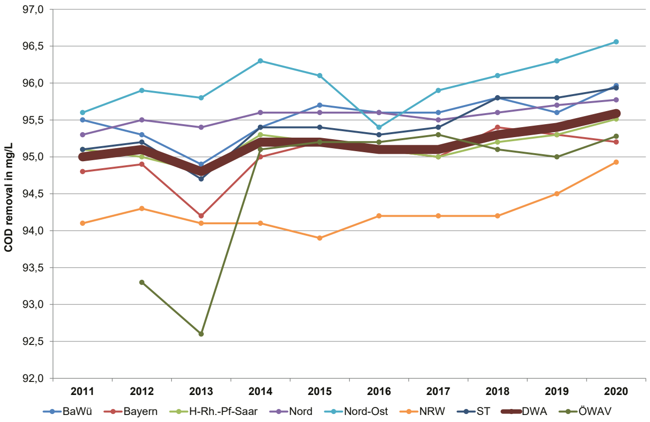


Fig. 4: Development of the COD removal from 2011 to 2020 (calculated from the COD loads)

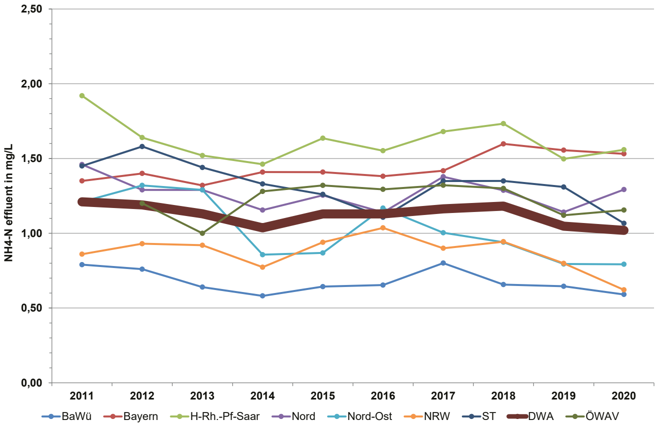


Fig. 5: Development of the NH_4-N effluent concentrations from 2011 to 2020

observed in the sewage treatment plants of the Austrian Water and Waste Management Association. Nevertheless, there was a slight but steady increase in the COD removals and especially in the P_{tot} removals during the period considered. There is a dip in 2013 (Figures 4, 6, and 7), which was characterized by lower inflow concentrations. The nitrogen removal and the NH_4-N effluent concentrations have remained at almost the same but high level over the past decade (Figure 5). Thus, it can be stated that the power savings achieved at the sewage treatment plants were not at the expense of wastewater treatment.

Compared to the first survey of power consumption in 2011, the number of wastewater treatment plants involved has increased by almost 500 (approx. + 11 %) (Table 3). In the current survey, the recorded design capacity has increased to over 128 million inhabitants (approx. + 7 %). This is 84.7 % of the design capacity of all wastewater treatment plants in Germany. Although the number and design capacities of the wastewater treatment plants covered have increased, power consumption has decreased from 3217.7 GWh/a to 3148.1 GW/h. Extrapolated to the total capacity of all wastewater treatment plants, power consumption is likely to have decreased from around 4000 GWh/a in 2011 to around 3600 GWh in 2020.

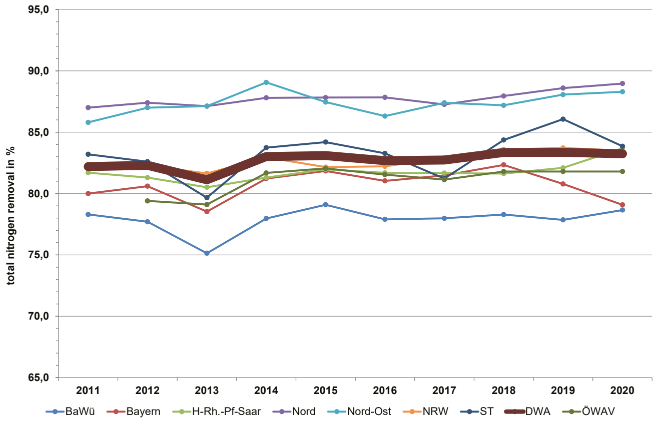


Fig. 6: Development of the total nitrogen removal from 2011 to 2020 (calculated from the total N loads)

	number		installed capacity [million p. e.]		mean loading [million p. e.]		power consumption [GWh/a]		specific power consumption [kWh/(p. e. ·a)]	
	2011	2020	2011	2020	2011	2020	2011	2020	2011	2020
SC 1	811	938	0.4	0.5	0.4	0.4	22.7	22.5	54.1	56.1
SC 2	1292	1484	3.6	4.0	3.1	3.4	128.6	145.2	41.5	42.1
SC 3	610	644	4.7	5.1	4.0	4.1	152.6	161.7	38.1	39.8
SC 4	1415	1538	46.1	50.6	36.0	39.5	1229.3	1235.1	34.1	31.3
SC 5	203	211	66.0	68.5	51.2	53.5	1684.6	1583.6	32.9	29.6
total	4331	4835	120.8	128.7	94.7	100.9	3217.7	3148.1	34.0	31.2

Table 3: Electric power consumption by size class (SC) in 2011 and 2020

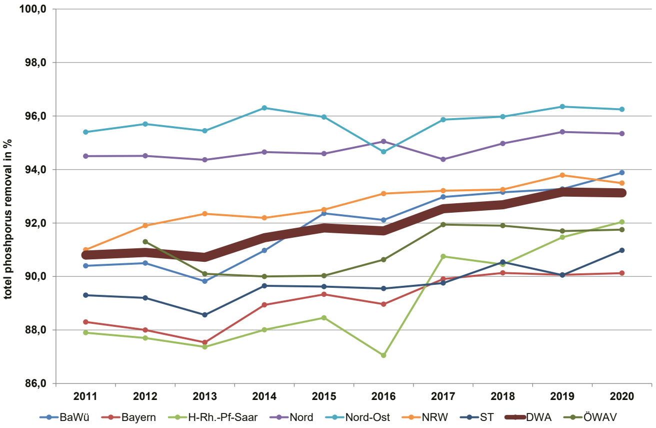


Fig. 7: Development of the P_{tot} removal from 2011 to 2020 (calculated from the P_{tot} loads)

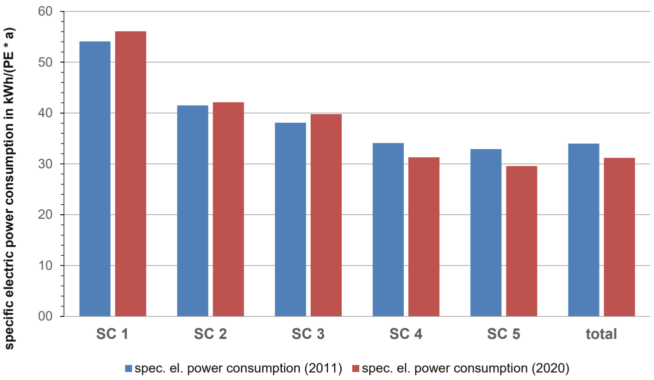


Fig. 9: Specific power consumptions by size class for the years 2011 and 2020

The wastewater treatment plants of size classes 4 and 5 account for about 90 % of the total power consumption (Figure 8). In contrast, plants with a design capacity of less than 10,000 inhabitants account for only a small share of total electricity consumption (approx. 10 %). It is therefore obvious that the plants of size classes 4 and 5 have the greatest potenzial for power savings in absolute terms.

However, greater savings are possible in individual cases for the small size classes with higher specific electricity consumption, which can then even have a reducing effect on the wastewater taxes.

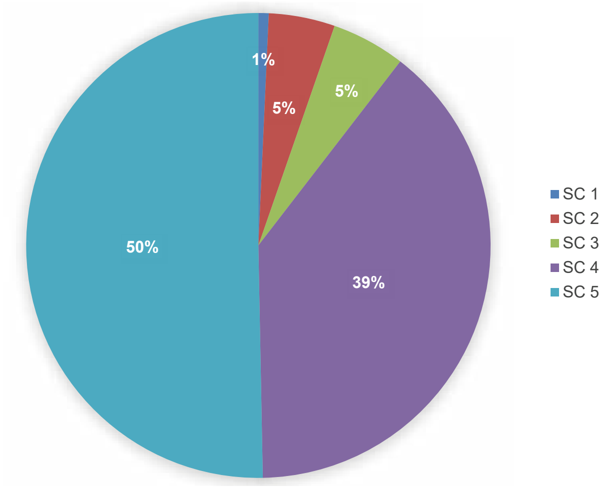


Fig. 8: Share of size classes in power consumption in 2020

The first nationwide survey in 2011 already showed that the specific power consumptions at the wastewater treatment plants decrease with increasing design capacity. In principle, that has not changed to this day; in fact, the differences are even more apparent (Figure 9). While specific electricity consumption has risen at wastewater treatment plants with a design capacity below 10,000 inhabitants (size classes 1-3), facilities with a design capacity above 10,000 inhabitants have been able to reduce their already lower specific electricity consumption even further. Since the wastewater treatment plants of size class 4 and 5 represent more than 90 % of the design capacity in total, this results in a decrease in the specific power consumption calculated for all wastewater treatment plants.

4 Summary

Participation in the nationwide DWA performance report was maintained at a high level in 2020 despite the ongoing pandemic situation and the limited exchange among operating personnel. We would like to offer our sincerest thanks to the operating personnel at the municipal wastewater treatment plants for their dedicated cooperation.

The results provide a representative overview of the cleaning performance of wastewater treatment plants in Germany. In 2020, 5220 wastewater treatment plants with a design capacity of 130.8 million inhabitants participated. As in the previous year, the corresponding data from Austrian Water and Waste Management Association for Austria and for South Tyrol are included for comparison. The results correspond largely to the data for German wastewater treatment plants.

Overall, the requirements of the EU Urban Wastewater Directive were again met or significantly exceeded on a national average in 2020. Whereas there were no great differences between the various size classes in respect of the COD and the total degree of nitrogen decomposition, the wastewater treatment plants with a design capacity of less than 10,000 inhabitants achieved lower values for the phosphorus removal. These wastewater treatment plants represent a proportion of about 8 % of the total design capacity, but are responsible for about 25 % of the phosphorus load introduced into the bodies of water. The polluters are those plants that do not implement targeted phosphorus elimination measures due to a lack of legal requirements.

The wastewater treatment plants recorded in the performance report (recording quota 84.7 %) have a total power consumption of 3148 GWh/a. The specific power consumption amounts to 31.2 kWh/(E · a). Many sewage treatment plants already generate energy. The total self-generation of power amounts to 1118 GWh/a. The plants with self-generation of power account for 59 % of the recorded design capacity of 120.8 million inhabitants. There is still potenzial to be exploited here by further expanding digester gas power generation, but this depends on the prevailing plant structure in the federal state associations. Currently, 36 % of the power required for wastewater and sludge treatment at the sewage treatment plants is already covered by self-generation of power nationwide. In the future, photovoltaic systems, wind power and hydropower will also gain in importance to digester gas power generation.

Compared to the first survey in 2011, the power consumption of municipal wastewater treatment plants has decreased from about 4000 GWh/a to about 3600 GWh in 2020. Approximately 90 % of the power is consumed by wastewater treatment plants with a connection capacity of more than 10,000 inhabitants. Therefore, the focus is particularly on these systems with regard to further optimisation measures. Although smaller wastewater treatment plants have a higher specific power consumption, they only contribute to a lesser extent to the total power consumption. Nevertheless, unnecessary power consumption should also be stopped here.

COD and P_{tot} removals developed positively overall during the report period and increased slightly. The high level of nitrogen removal and in particular the low NH_4-N effluent concentration could also be maintained. This proves that power savings and efficient wastewater treatment are compatible with the current requirements. In this context, the importance of the operating staff, who must first recognise optimisation potenzial and then implement it expertly and with dedication, must be particularly highlighted. The DWA performance report and further training in the wastewater treatment plant neighbourhoods can make an important contribution.

A further, general need for action in respect of sewage treatment plants may be triggered in coming years as a result of statutory requirements for the construction of a further wastewater treatment stage to remove trace substances from the wastewater. Extensive research is currently being conducted in this area.

The DWA working group BIZ-1.1 “Sewage Treatment Plant Neighbourhoods” would like to thank all the participants, teachers and representatives of the sewage treatment plant neighbourhoods for their support in the collection and evaluation of the data, without which this nationwide performance report would not be possible.

Methane in the Storage and Dehydration of Sewage Sludge

Albert Heindl (Berching/Germany) and Daniel Dobslaw (Stuttgart/Germany)

Summary

Methane is released unintentionally at some points in the sewage sludge treatment process, such as during dewatering after digestion, storage of dewatered sludge or its further use. This article provides an overview of methane emissions during sewage disposal and in particular during the storage and dehydration of dewatered sewage sludge. It also describes processes for methane cleavage and oxidation, and relates to the practice of storage and drying of dewatered sewage sludge.

Keywords: sewage sludge, dewatering, storage, dehydration, methane, emission, Technical Instructions on Air Quality Control, removal, oxidation

1 Introduction

Methane is produced by anaerobic decomposition processes during wastewater treatment. This process is deliberately promoted in the case of sludge digestion, firstly to reduce the amount of sludge produced and secondly to generate digester gas with a high methane content, which can be used for both electricity and heat generation. Methane is inadvertently emitted at other points, such as the dewatering of sludge after digestion, the storage of dewatered sludge or its further use. In addition to methane, other long-chain hydrocarbons are also emmited from the dewatered sewage sludge. However, they usually represent only 2–8 % by mass of the methane content.

Since the organics of dewatered sewage sludges consist of different proportions of fats (triglycerides with carboxylic acids as building blocks), proteins (amino acids as building blocks) and carbohydrates (various sugars, starch, cellulose as building blocks), which are metabolised to different degrees by microorganisms into digester gas with deviating methane contents, the methane gas produced per kg of organic dry mass (oDM) will be subject to certain fluctuations under otherwise constant conditions.

Emission location	Percentage of total emission
Primary treatment	11.4 %
Primary sludge thickening	8.6 %
Digestion tank loss	37.1 %
BHW slip	14.3 %
Dewatering collection container	17.1 %
Sludge dewatering	2.9 %
Stack container for dewatered own sludge	8.6 %

Table 1: percentage emission of methane at a 50,000 PT sewage treatment plant

2 Methane emissions at sewage treatment plants

According to Parravicini and Svardal, the specific methane emission of 0.50 kg (PT · a) results for a model wastewater treatment plant with 50 000 PT according to Table 1 [1]. Figure 1 illustrates this distribution. However, it must be emphasized that there may be deviations in the magnitude of the methane emission and in the distribution depending on the plant implementation and the practical operation of the sewage treatment plant. It is interesting to note that especially the digester, the storage tank for dewatering and the motorised digester gas utilisation have comparatively high shares of the total emission, while the stacking tank for dewatered sludge only has a share of 8.6 %. An increase in the methane emissions attributable to storage can occur both with increasing storage time of the dewatered sludge and if sludge dehydration is installed at the wastewater treatment plant site and sludge from other

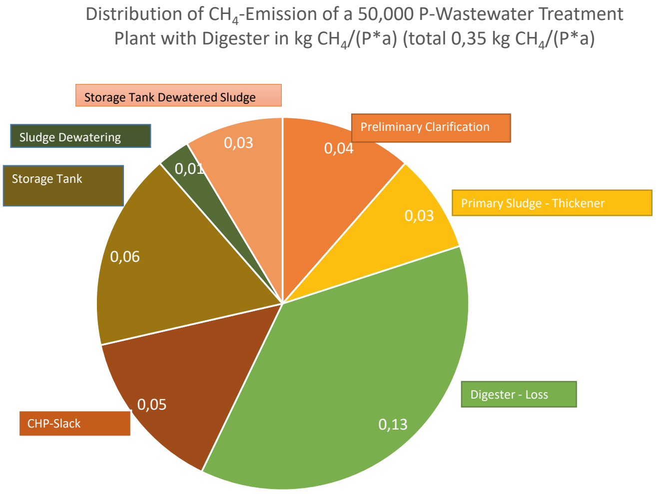


Fig. 1: Distribution of the methane emission of a sample 50 000 PT sewage treatment plant with digestion (according to [1])

wastewater treatment plants is delivered and also dried. In the latter case, the different compositions and the different degrees of stabilisation of the sewage sludges can lead to increased methane production.

Methane is mainly produced by the anaerobic decomposition of organics in the liquid sludge feed and in the dewatered sludge, i.e. around 74 % of the total methane emission results from the sludge treatment [1].

3 Methane emission from sewage sludge drying and preceding sludge storage

The situation is entirely different in the case of drying large quantities of sludge at a power plant site that provides sufficient waste heat for drying delivered sludges. The situation is comparable to the power plant sites for mono-incineration plants for sewage sludge, which obtain the dewatered sewage sludge from the near and wider surroundings. In these cases, sludge storage quantities of several thousand tonnes with storage times of several days are provided for and correspondingly larger amounts of methane are emitted by secondary anaerobic decomposition processes on site. In addition, intermediate storage or handling times must be expected if the sludge is delivered via disposal companies or if the power plant is only used to supply local heating for peak loads in the cold season. Due to the long storage times and renewed formation of anaerobic zones in the sludge body, anaerobic decomposition with associated methane emissions occurs to a greater extent in these sludges than in freshly dewatered sludges. Since prior sludge stabilisation at the treatment plants degraded bioavailable structures by up to 90 % and more, the anaerobic decomposition processes occurring here are not comparable to those known from digesters, and sludge bunker temperatures rarely exceed 30 °C. The resulting emissions are temperature-related and continue to be dominated by methane.

The situation is different in the exhaust air volume flows in sewage sludge belt dehydration plants, where the relative methane content of the VOC load (Volatile Organic Compounds) usually falls below 3–10 % by mass – calculated as carbon – in relation to the total C content due to drying temperatures of up to approx. 125 °C. When drying the sewage treatment plant’s own sludge, the carbon share of the methane in the emissions may rise to more than 20 % with generally significantly lower VOC loads in the exhaust air. This is caused by the fact that – due to the temperature-induced rapid surface drying with warm air – microbial activity is stopped in a minimum of time. Furthermore, the high temperature level leads to an increase in the specific vapour pressures of longer-chain hydrocarbons, alcohols, fatty acids, ammonia and organosulphur compounds, which are transferred to the dryer exhaust air together with evaporated water vapour and dominate the emission spectrum. The specific flow of total carbon passing into the exhaust air depends on various factors such as

- composition of the organic substance
- sludge temperature during storage and dehydration
- mechanical stress on the dewatered sludge before dehydration and mixing of atmospheric oxygen into the sludge mass
- degree of stabilisation of the sludge
- duration of storage and transport between dewatering and drying

and usually varies in a wide range from 60 to 1000 mg C/kg dry mass for dehydration of own sludge and 1500 to 6000 mg C/kg dry mass for drying of intermediately stored foreign sludge. Accordingly, methane levels also vary widely.

For solar dehydration of sewage sludge, it is necessary to turn sludge sufficiently to reduce methane formation and subsequent emissions due to the anaerobic decomposition of organic matter during several weeks of drying. However, these increased methane emissions mainly occur only in the temporal/spatial phase of the dehydration with a damp sewage sludge surface. Therefore, methane emissions can be significantly reduced if dry sludge is mixed into the delivered wet sludge, thereby drying the surface faster. It must also be taken into account that solar dehydration plants in most cases only dry freshly dewatered proprietary sludge,

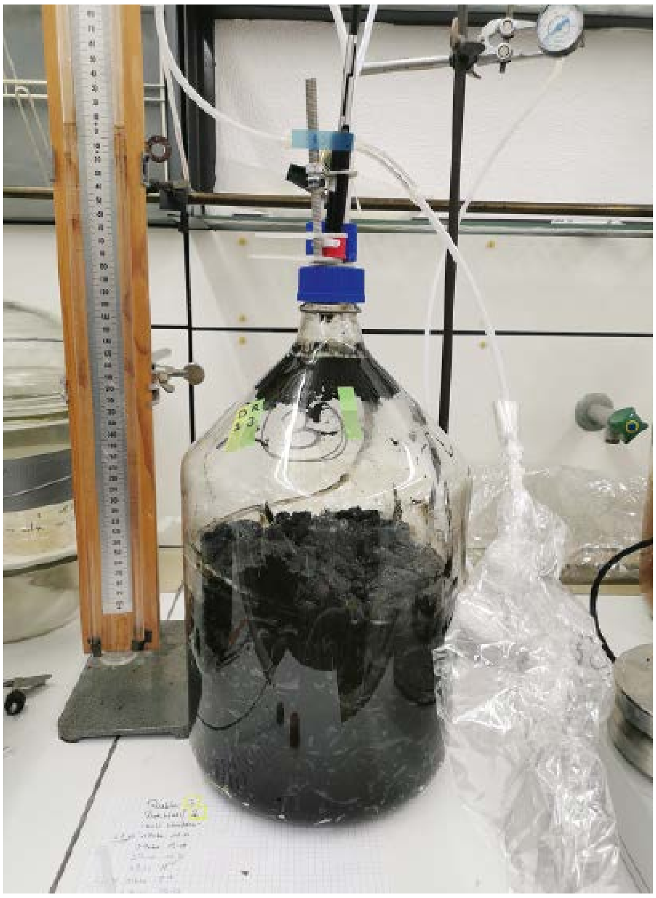


Fig. 2: Measurement of gas emission from dewatered sewage sludge at the ISWA at the University of Stuttgart

which has a much lower tendency to emit VOCs compared to sewage sludge that has been in intermediate storage for a longer period.

4 Measurement of the emission of methane from dewatered sewage sludges

4.1 Measurements and results by Drescher/Kapp

More extensive measurements were carried out by Drescher and Kapp in the mid-1990s [2]. These covered both a test plant with three cylindrical tanks of 700 mm diameter and a maximum usable volume of 1.4 m³ each of dewatered sewage sludge. Further measurments were executed on dewatered sludge receiving bunkers with a volume of 30 m³ and silo plants with a volume of 300 m³ at the Weiher site of a sewage sludge dehydration plant in Saarland [2].

Sludge stabilised according to the state of the art at thar time – cold-digested over 100 days, mesophilic digested over 25 days and simultaneously aerobically stabilised over 25 days – were stored in the exhausted test facility. VOC losses of the sludges laid between 41 and 58 %, on average around 50 %. The dry residue of the dewatered sludge samples covered a range of 22 to 34 %. The sludge was heated to a temperature of 25 to 30 °C and the storage duration was between 13 and 28 days.

In summary, the following results were achieved and conclusions drawn:

- The methane emission is virtually independent of the organic content.
- The specific methane emission increases as the temperature rises. 0.7 L CH_4/(kg oDM · h) at 25 °C was given as the maximum peak value for a dormant sludge filling (oDM: organic dry mass). Standardised, this means about 0.64 NL CH_4/(kg oDM · h). The most common values lay within the range of 20 to 80 % of the given peak value, i.e. around 0.14 to 0.56 L CH_4/(kg oDM · h), assuming a comparable methane content in the digester gas.
- Peak values for the methane emission are only reached for a short time if the sludge mass is moved after a certain rest period of one to two days, thus creating deeper crevices in the sludge interior. This can be the case, for example, when dumping sludge masses from a truck into a bunker or by drawing off sludge from the lower bunker area via screw conveyors or pumps.
- Higher sludge temperatures cause higher average and peak emissions of methane. However, it should be kept in mind that this only applies if the methane bacteria present in the dewatered sewage sludge are active over a wide temperature range.
- As the storage period becomes longer, organic acids are released to an increased extent, which were measured in the operating waste towards the end of the storage period. Anaerobically cold stabilised sludge tend to develope organic acids. This clearly shows the effect of intermediate storage of dewatered sewage sludge, which leads to the formation of organic acids and a pH drop of the sludge accompanied by a DM loss.
- On average, an organic decomposition of 5 % of the primary stored organic dry mass was observed over the storage period.

4.2 Measurements at the University of Stuttgart

At the Institute of Sanitary Engineering, Water Quality and Waste Management (ISWA), Department of Biological Waste Air Treatment, University of Stuttgart, gas emissions from digester sludges in 10-litre glass containers were examined on behalf of Huber SE as part of a student's master's thesis. Figure 2 shows a sample bottle with sludge filling and connections for the gas analysis.

Digested sludges with a dry residue (DR) of 20.2 and 21.4 % as well as an oDR (organic dry residue) of 55.5 to 64.4 % were tested. For one digested sludge, a change in the ratio of sludge surface area to sludge volume was investigated. The test had a duration of seven days in each case. The following results were determined:

- The emission of methane and non-methane components increases in the case of periodic movement of the sludge, simulating the withdrawal of sludge from a bunker, for example.
- Aliphatics and terpenes as well as mono and bicyclic aromatics degas in addition to methane.
- An increase in temperature does not always cause an increase in degassing if the existing microorganism population cannot adapt to a different temperature level, or can adapt only poorly. In one experiment, an increase of up to 50 % of the total carbon emitted and thus also of the

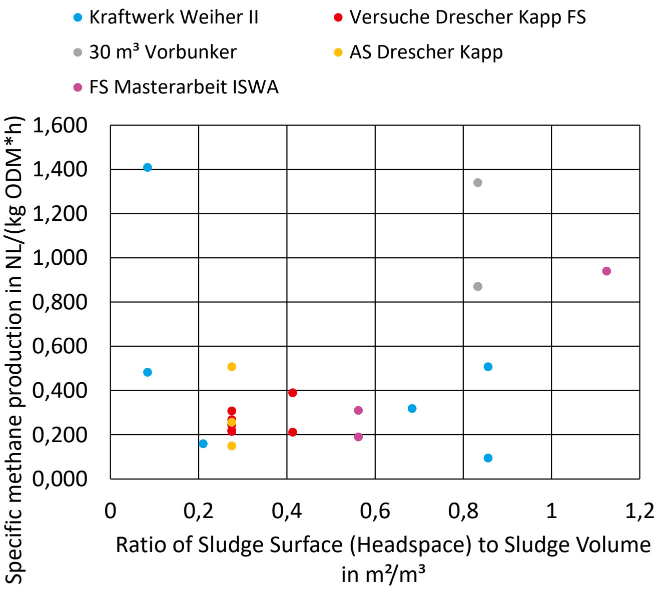


Fig. 3: Test values for methane degassing during the storage of dewatered sewage sludge as a function of the ratio of sludge surface area to sludge volume (FS: digested sludge, AS: aerobically digested sludge)

methane can occur if the sludge temperature increases from 20 to 30 °C.

- A larger ratio of surface area to volume usually leads to increased degassing in relation to the dry mass of the sludge (see Figure 3).
- The level of organic dry mass in the dewatered sewage sludge examined has only a minor influence if any on the amount of methane produced in the range of 50 to 65 % organic dry mass.
- The specific emission spectrum depends strongly on both the origin of the sludge and the sludge history (sludge stabilisation, storage time and sludge temperature during storage).

In the case of the sewage sludge shown in Figure 3, it is sewage sludge from the Stuttgart-Büsnau teaching and research wastewater treatment plant (LFKW), which is located on the ISWA site. The sludge used here is predominantly municipal and, based on the results of recurring long-term test series, exhibits a high stability in the sewage sludge composition with regard to wet chemical parameters such as TOC, TKN, sulphate and total sulphur content as well as the pH value. Furthermore, transport and storage effects could be ruled out due to the geographical proximity.

4.3 Measurements by Huber SE on a 30 m³ sewage sludge bunker with extraction

A measurement of emissions from an extracted, free-standing 30-m³ steel bunker for dewatered digested sludge – set up in a hall – made it possible to determine the influence of sludge temperature and the rupturing of the sewage sludge bed on the level and type of gas emissions. The DR of the digested sludge was 26.9 %, the oDR 55.6 %. An extraction ball was used on the surface of the sludge; the measuring instrument was the Dräger X-am 7000 gas measurement equipment. The specific exhaust air flow rate was 62.5 m³ exhaust air/(m² sludge surface area · h). Normally, methane, carbon dioxide and ammonia escape from the surface of a resting backfill. However, if the sludge heap is moved and ripped open by withdrawing sludge from the bunker, small amounts of carbon monoxide and hydrogen sulphide are also released from the interior into the headspace. The measurements took place in midsummer at extreme sludge temperatures of around 29 °C and ambient temperatures of more than 30 °C. On average, a methane emission of 0.87 NL/(kg oDM · h) was determined. The influence of the sludge temperature becomes clear here.

The annual average sludge temperature is about 15 °C, especially as the heating remains limited in the case of bunkers bedded deep in the ground which are not subject to direct solar radiation even in summer.

4.4 Summary

In a summarising diagram, the specific methane emission in NL CH_4/(kg oDM · h) is plotted from measurements of the ratio of sludge surface area to sludge volume in m²/m³. A trend can be seen where, with an increasing ratio of surface area to volume, the specific methane emission increases and roughly covers the range between 0.2 and 0.5 NL CH_4/(kg oDM · h). Figure 3 shows the evaluation of the tests described above in the form of a diagram. Extreme values that occurred due to rupturing of the sludge layer due to sludge removal are also listed. In this case, a methane measurement in the free bunker space above the sludge filling must lead to an increase in air exchange rates by the bunker extraction. High silos with a small ratio of sludge surface area to volume produce a smaller specific average methane degassing compared to shallow bunker systems.

In principle, it must be noted that different degrees of residual decomposition of the organic dry mass are possible depending on the degree of stabilisation:

- sufficiently stabilised digested sludge: further decomposition of around 15 % of the readily biodegradable oDM supplied
- partially stabilised sludge: further decomposition of around 30 % of the readily biodegradable oDM supplied

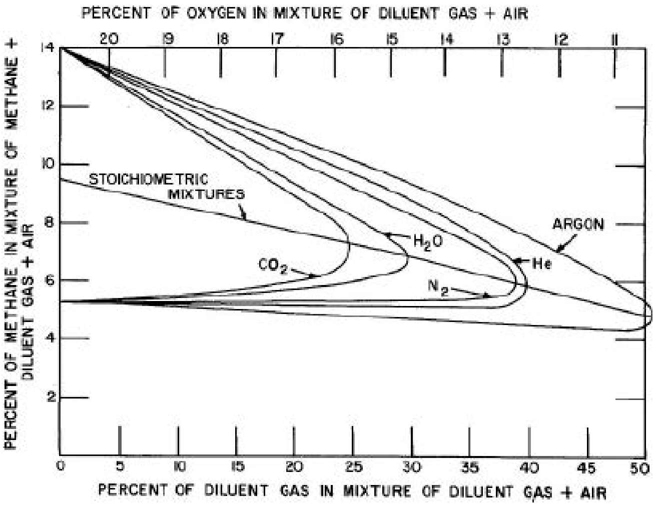


Fig. 4: Inertisation of a methane/air mixture by addition of an inert gas [17]

<table>
<tr><td>Chemical formula</td><td colspan="3">CH_4</td></tr>
<tr><td>Chemical group</td><td colspan="3">Hydrocarbons: paraffins</td></tr>
<tr><td>Molecular structure</td><td colspan="3">Hydrogen atoms arranged tetrahedrally to the carbon atom</td></tr>
<tr><td>Molar volume at 0ºC</td><td colspan="3">22.3621 l/mol</td></tr>
<tr><td>Molar mass</td><td colspan="3">16.043 g/mol</td></tr>
<tr><td>Molecular diameter [10]</td><td colspan="3">~ 0.39 nm</td></tr>
<tr><td>Standard density (0 °C, 101 325 Pa)</td><td colspan="3">0.7174 kg/Nm^3</td></tr>
<tr><td>Density ratio to air</td><td colspan="3">0.5548 : 1</td></tr>
<tr><td>Critical temperature</td><td colspan="3">– 82.5 °C (methane always exists as a supercritical gas at ambient temperature)</td></tr>
<tr><td>Gas constant</td><td colspan="3">518.271 J/(kg · K)</td></tr>
<tr><td>Diffusion of methane in air (20 °C, 101 325 Pa)</td><td colspan="3">0.21 cm^2/s</td></tr>
<tr><td>Specific thermal capacity at constant pressure</td><td colspan="3">2,230.27 J/(kg · K) (27 °C)
2,156.00 J/(kg · K) (0 °C)</td></tr>
<tr><td>Global heating potenzial for 100 years in comparison to CO_2 [12]</td><td colspan="3">21</td></tr>
<tr><td>Heating value</td><td colspan="3">35 880,9 kJ/Nm^3
802 358 kJ/kmol</td></tr>
<tr><td>Calorific value</td><td colspan="3">39 816,5 kJ/Nm^3
890 365 kJ/kmol</td></tr>
<tr><td>Minimum air requirement for combustion at an air ratio λ of 1.1</td><td colspan="3">9.472 m^3 air/m^3 methane</td></tr>
<tr><td>Maximum carbon dioxide content in combustion gas at an air ratio λ of 1.1</td><td colspan="3">10.56 % by vol.</td></tr>
<tr><td>Lower Explosive Limit LEL at 20 °C
Upper Explosive Limit UEL at 20 °C [13]
0.1 MPa = 1 bar or approx. ambient pressure</td><td colspan="3">4.4 % by vol. (44 000 ppm) at 0.1 to 1 MPa
16.5 % by vol. (165 000 ppm) at 0.1 MPa and 22 % by vol. (220 000 ppm) at 1 MPa</td></tr>
<tr><td>Ignition temperature in air</td><td colspan="3">595 °C (535–645 °C)</td></tr>
<tr><td>Minimum ignition energy at 8.5 % by vol. in air</td><td colspan="3">0.5 mJ</td></tr>
<tr><td>Maximum explosion pressure in mixture with air (20 °C, 101 325 Pa)</td><td colspan="3">8.3 bar at 10.5 % by vol.</td></tr>
<tr><td>Inertisation with nitrogen/carbon dioxide to residual oxygen content</td><td colspan="3">11.6/14.1 % by vol. O_2</td></tr>
<tr><td>Partial and complete inertisation with nitrogen/carbon dioxide</td><td colspan="3">partial: 9.9/13.7 % by mol O_2
complete: Ratio of the mole fractions N_2/CH_4: 11 and CO_2/CH_4: 5</td></tr>
<tr><td>Segregation energy in kJ/mol [14]
1 mol CH_4 is equivalent to 16.043 g</td><td colspan="3">CH_3 … H: 439.6$^{*)}$
CH_2 … H: 420.8
CH … H: 259.6
C … H: 335.0
Sum: 1455 kJ/mol CH_4 or 90.69 kJ/g CH_4
$^{*)}$ The first reaction level is decisive for the further splitting of the methane through the formation of a free H radical.</td></tr>
<tr><td>Ionisation energy
$CH_4 \rightarrow CH_4^+ + e^-$ [15]</td><td colspan="3">13.1 ± 0.4 eV</td></tr>
<tr><td>Temperature for free formation enthalpy = 0 [5]</td><td colspan="3">From about 550 °C, the CH_4 molecule becomes unstable and can be split into its elements and oxidised. This corresponds to the minimum ignition temperature of 595 °C.</td></tr>
<tr><td>Standard molar Gibbs formation energy at 25 °C
Negative value means stability.</td><td colspan="3">– 50.5 kJ/(mol · K)</td></tr>
<tr><td>Oxidation speed v_{oxid} of methane as a function of the mol concentration of oxygen and methane [9]</td><td colspan="3">400 °C: $v_{oxid} \sim (C_{O2})^{0.5}$ and $\sim (C_{CH4})^{2.3}$
650 °C: $v_{oxid} \sim (C_{O2})^2$</td></tr>
<tr><td rowspan="6">Henry coefficient of methane in bar · mol/mol in relation to the temperature [16]</td><td>Temperature</td><td>Henry coefficient</td><td>Solubility in water (Bunsen coefficient) at 1 bar (0.1 MPa)</td></tr>
<tr><td>°C/K</td><td>bar · mol/mol</td><td>g/L</td></tr>
<tr><td>25/298.15</td><td>43 250</td><td>0.029</td></tr>
<tr><td>40/313.15</td><td>58 689</td><td>0.021</td></tr>
<tr><td>55/328.15</td><td>77 447</td><td>0.016</td></tr>
<tr><td>70/343.15</td><td>99 753</td><td>0.012</td></tr>
<tr><td>Limit value for TOC emissions according to Technical Instructions on Air Quality Control TA Luft 2021 (TOC: Total Organic Carbon, of which methane is a part)</td><td colspan="3">contained in TOC: ∑20 mg C/Nm^3</td></tr>
<tr><td>Conversion of methane content to C-content in the exhaust air</td><td colspan="3">$C_{carbon\ (mg/m^3)} = C_{methane\ (mg/m^3)} \cdot 0.749$</td></tr>
</table>

Table 2: Physical and chemical properties of methane

5 Removal of methane from exhaust air streams

5.1 Physical and chemical properties of methane

The basic physical and chemical properties of methane are important for an understanding and evaluation of the possibilities to remove methane from exhaust air streams. They are listed in Table 2 [3–11]. The methane molecule is characterised by a high stability, which is expressed by the listed properties. This shows that a high amount of energy has to be supplied for an oxidation or segregation of hydrogen atoms. Also, removal of the methane molecule by absorption in a scrubber or adsorption on activated carbonate ambient pressure is neither technically nor economically feasible.

To eliminate the explosion hazard caused by methane, for example in a silo system for dewatered sewage sludge, an inert gas such as CO_2, H_2O, N_2, He or Ar can be added to the methane-air mixture. Figure 4 shows the areas of explosion within the curves and inertisation outside the curves. It can clearly be seen that the individual inert gases have different inertisation effects. Of the gases shown, CO_2 exhibits the highest degree of inertisation, as the explosive zone is compressed to the smallest area. The concentrations shown are given in % by volume at a pressure of 101 325 Pa. In the case of the water vapor curve instead of steam curve, the temperature of the mixture was adjusted so that the necessary water vapor pressure was reached [17].

The Henry cofficient of methane assumes extremely high values, which is reflected by a very low solubility of methane in water. That is the reason why a segregation of methane in scrubbers at ambient pressure is not technically and economically feasible. An adsorption of hydrocarbons on activated carbon at ambient pressure only occurs to any appreciable extent starting from five carbon atoms in the molecule; due to the high vapour pressure of short-chain components, methane is adsorbed in quantities that are irrelevant for practical purposes. At 15 °C, ambient pressure and for the pure methane gas with no competing auxiliary gases, Hene gives an adsorption of around 12.3 mg CH_4/g activated carbon, i.e. only 1.2 % by mass [18]. It can be assumed that longer-chain hydrocarbons displace the small, already adsorbed methane molecules from the surface of the activated carbon pores due to their higher adsorption energy for attachment to the activated carbon surface. Furthermore, water vapour condensation in the pores of the activated carbon can significantly reduce the adsorption of methane.

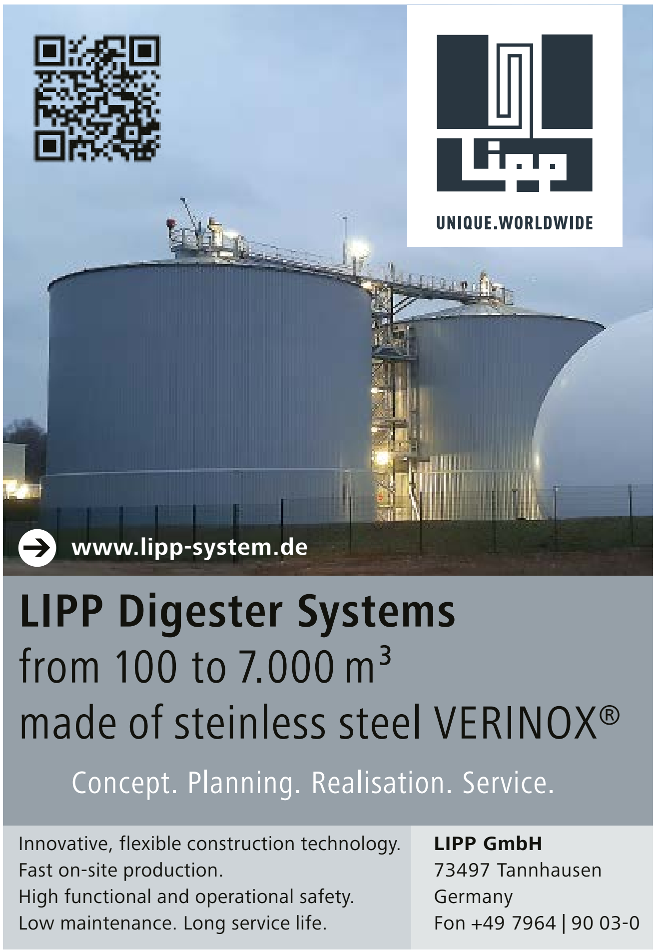
The described chemical and thermodynamic properties of methane have consequences with regard to the separation or conversion of the CH_4 in process apparatuses. A direct ionisation of methane by UV-C photons with a wavelength of 185 nm – typical for odour removal from exhaust air streams – is theoretically impossible, since the ionisation energy of methane is 12,6 eV [21] and the energy of the photon is only 6.70 eV.

Biodegradability of methane is also practically not possible, since decomposing times for methane of up to 20 minutes [19] would require unrealistically large biofilters.

5.2 Systems for methane splitting and oxidation

Various systems for methane splitting and oxidation are available on the market, but their efficiency varies greatly:

- RTO: Regenerative thermal oxidation
  The methane-containing air is heated up to combustion temperature and part of the energy used is fed back into the process via regenerative heat recovery. Virtually complete methane oxidation can be assumed. Normal reaction temperatures lie between 800 to 850 °C, while specific power consumptions are around 0.20 to 0.35 kWh per 1000 m³/h exhaust air. If we calculate that the air is heated from 10 to 850 °C, around 450.7 kJ/kg or 582.7 kJ/Nm³ must be expended per Nm³ of dry air, neglecting the other gases in relation to heating. Allowing a maximum concentration of methane in the bunker exhaust air of 40 % of the lower explosion limit, corresponding to 1.76 % by vol. or 0.0176 Nm³ methane, this results in a heating value of 631.5 kJ/Nm³. This would provide sufficient energy in continuous operation in the exhaust air to bring it to the appropriate temperature. However, design-related heat losses would still have to be taken into account. At lower methane concentrations below 37 % of the LEL, additional heating with natural gas, for example, would be necessary. In industrial practice, the air containing methane is preheated by the heat recovery system. Assuming that the temperature difference for heating is halved on average, only 291.4 kJ/Nm³ need to be expended without waste heat losses. A methane content of only 20 % of the LEL in the exhaust air would thus be necessary. In fact, in industrial plants with regener-



ative heat recovery, the CH_4 content is limited to 25 % of the LEL for explosion protection reasons and thus leads to self-sustaining combustion. While the methane concentrations occurring in the bunker make it seem possible to treat the exhaust air there, the low methane concentration in the dryer exhaust air, on the other hand, leads to very high operating costs when implementing an RTO. The required use of natural gas for autothermic operation can be around 1.1 to 1.7 m^3 per 1000 m^3 of exhaust air, depending on the exhaust air temperature and the heating value of the VOCs (Volatile Organic Compounds) contained in the exhaust air.

- Non-thermal plasma
  Plasmas induced in the exhaust air by resonators (microwave plasmas) or high-frequency alternating electric fields (dielectrically impeded discharge, corona discharge) generate radicals that can be used to split the methane molecule. Catalysts immobilised on carriers such as Al_2O_3 or silica gel (precious metals or mixed metal oxides) are intended to improve efficiency. However, it should be taken into account that the necessary reaction time for the oxidation of methane is around 260 seconds and this time is far beyond the lifetime of the hydroxide radicals or ozone produced [19]. By using carrier materials with an adsorptive effect (zeolites, activated carbons), the catalytic oxidation of the methane can be facilitated by the parallel adsorption of the methane and the reactive gas components with catalytic activation of the carrier material. It should also be taken into account that the plasma process is sensitive to high humidity and that electrical flashovers can occur.
- Photoionisation
  Photons from UV-C lamps produce O radicals from the oxygen in the air, which react either with O_2 to form ozone, according to the reaction $O_2 + O \rightarrow O_3$, or directly with methane. Only in the latter case a splitting of the methane molecule can occur according to the reaction $CH_4 + O \rightarrow CH_3 + OH$. Ozone formation dominates, but the ozone either hardly reacts with the stable methane or the reaction time is usually not sufficient. Therefore, methane splitting in this process is well below 10 % of the initial value and cannot be used economically with regard to methane removal. The design of the electrical UV lamp output must be based on the VOC mass flow, especially in the case of high VOC loadings in the dryer exhaust air, which can result in significantly higher energy inputs per 1000 m^3 exhaust air than the usual 1.8 to 2.0 kWh per 1000 m^3 exhaust air.

In principle, the relative energy expenditure for the splitting or oxidation of methane increases sharply with decreasing methane content, since reaction probabilities of methane and reactive gas molecules decrease sharply with decreasing methane concentration and thus the economic efficiency decreases. When evaluating the different processes, it must also be taken into account that the manufacture of the apparatus itself also causes CO_2 emissions and that additional electrical energy and, at least for start-up processes in the case of the RTO, thermal energy is expended due to primary energy carriers causing CO_2 emissions. Only regenerative thermal oxidation can be considered as a procedure for the complete removal of methane from the exhaust air, but it usually requires the use of primary energy for autothermic operation and their use must be critically subjected to the objectives of global warming restrictions.

6 Practical references for the storage and dehydration of dewatered sewage sludge

Since the processes referred to in Section 5 have insufficient cleaning efficiency with respect to methane or require the cost-intensive use of primary energy carriers, a process-integrated approach to methane reduction is preferable to the end-of-pipe solution, i.e. potential emissions are to be minimised through intelligent sewage sludge storage management. The temporal methane emission in relation to the oDM of the dewatered sewage sludge depends on the type of sewage sludge and the composition of the organics, on the stabilisation of the sewage sludge, on the duration of storage and handling, on the sludge temperature as well as on the ratio of surface area to volume of the sludge filling and on the movement of the heap. The microorganisms in the sludge and their activity temperature range may also play a role. Therefore, only areas for the specific methane formation can be specified. In this respect, analyses of gas emissions by gas chromatography and mass spectrometry of sludges that are stored and dried are recommended, especially for projects with a large number of different external sludges with a strongly deviating age of the dewatered sludge.

Basically, the methane escaping at the sludge surface rises due to its low density (density ratio to air ~ 0.554) and continuously mixes with the air in the headspace of the bunker [6].

At wastewater treatment plants that store and dry their own sludge, methane emission from various process stages occurs at varying intensities, with storage of dewatered sludge playing only a minor role.

Whether methane removal from the bunker or silo exhaust air, for example via an RTO, is ultimately considered necessary for larger sewage sludge dehydration plants on power plant sites or sewage sludge mono-incineration plants, depends on whether a standard or normal operation or a short-term incident is involved. At power plant sites, the bunker exhaust air is usually used as combustion air and thus present methane is converted into carbon dioxide and water vapour. During combustion downtimes or revision times, the methane emission from the sewage sludge storage can be minimised by emptying the bunker in time.

According to BGR 104 [6], the minimum exhaust air volume flow $V_{\text{exhaust air}}$ in m^3/h is calculated under the condition of a constant methane emission from a backfill of dewatered sewage sludge according to:

$$V_{\text{exhaust air}} = G \cdot f \cdot T\ (K)/293K/(k_{\text{perm}} \cdot UEG)$$

where G is the gas emission per unit of time in g/h, f is a quality factor for the quality of the air flow (f = 1 with even extraction), T is the air temperature in K, k_{perm} is a safety factor by which the concentration of the combustible gas must lie below the LEL (usually $k_{\text{perm}} = 0.5$) and LEL is the lower explosion limit in g/m^3 at 20 °C (= 293 K) [6].

In practice, since the amount of sewage sludge in a bunker varies over time, an air exchange rate is defined in relation to the total bunker volume without taking into account the sewage sludge filling [6]. VGB bulletin sheet M 116 [20] recommends at least a two-fold air exchange for the extraction of the methane produced in the sewage sludge bunker, and the bunker must be equipped with a methane warning system. The air exchange rate is to be increased to 6 if a methane concentration of 20 % of the LEL is reached. Ventilation is provided, for example, by redundantly arranged fans monitored via pressure differential measurement. Since methane rises upwards due to its low density compared to air, the extraction of the air/methane mixture must take place at the highest possible position in the headspace of the bunker. A flow simulation of the bunker extraction is recommended, as an uneven ventilation of the headspace can lead to locally higher methane concentrations and thus change the quality factor f for the calculation of the exhaust air flow rate from 1 to higher values. Peak values in methane formation, which only occur for a short time, can be reacted to either by a short-term increase in the exhaust air flow rate or by temporarily shutting down the drives in the area of the bunker (for example, the hall crane).

Storage in a bunker or silo plant is always upstream of the drying of dewatered sewage sludge. If the bunker or silo exhaust air is used as drying air, it is possible to separate odorous substances and VOCs in the conventional exhaust air treatment plants, consisting of scrubbers and biofilters or active carbon filters. However, the methane as part of the VOCs cannot be removed from the exhaust air by the techniques mentioned and is included in the limit value of the Technical Instructions on Air Quality Control 2002 and 2021 as part of the TOC. Depending on the size of the sludge storage facility, this can cause exceeding of the legally binding value in the Technical Instructions on Air Quality Control (German TA Luft). However, the use of regenerative thermal oxidation for exhaust air treatment involves an extremely high cost relative to the benefit of methane removal from the collected storage and dryer exhaust air. In the light of these facts, practitioners aks themselves the question of the failed reassessment of the limit value for the TOC in the new Technical Instructions on Air Quality Control excluding methane in sewage sludge drying.

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Recommendations for Non-Potable Water Reuse

Implementation of projects for the reuse of treated wastewater

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Abstract

From 2023, new minimum standards for the reuse of treated wastewater will apply in the EU. Internationally, water reuse has already been a relevant issue for some time. Rising water demand worldwide, also as a result of global climate change, is increasing the scarcity of freshwater resources in some areas. Reclaimed water is increasingly considered as a valuable substitute for natural water resources. Even before the new EU regulation came into force, DWA has published an extensive report covering a variety of aspects to be considered within the scope of non-potable water reuse. This article provides an overview of that DWA Topics issue "Non-Potable Water Reuse – Development, Technologies and International Framework Conditions for Agricultural, Urban and Industrial Uses"[*].

1 Introduction

In June 2020, EU Regulation 2020/741 on minimum requirements for water reuse [1] came into force. After a three-year transitional period, it sets binding standards for all EU Member States with regard to water quality and risk management, among other things. This regulation standardises the requirements for water reuse, which is already widespread especially in southern Europe, across the EU and sets out framework conditions for future applications.

But internationally, water reuse has already long been an issue. Along with the world population growth, the need for increased food and energy production, both with significant associated "water footprints," also rises [2]. Scarcity of locally available water supplies, competition for water with agriculture and energy, climate change impacts, rising energy prices, environmental restoration, and economics will require communities to reuse far more water. Thus, water reclamation and water reuse will play an important role in future water management.

Types of Water Reuse

Unplanned reuse of municipal wastewater – untreated or treated – has been practiced for many centuries with the objective of diverting human waste outside of urban settlements [3], but also by farmers in many arid and semiarid regions to irrigate their fields. Planned water reuse is defined as the benefi-

Figure 1: Water reuse for drip irrigation of public green spaces in Bahrain (source: p2m berlin)

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[*] DWA Topics issue "Non-Potable Water Reuse" (2019) was prepared by the following members of the DWA Working Group BIZ-11.4 "Water Reuse": Prof. Dr. Peter Cornel (Darmstadt), Prof. Dr. Jörg E. Drewes (Garching), Edgar Firmenich (Frankfurt a. M.), Dr. Tim Fuhrmann (Essen), Dr. Stefan Gramel (Frankfurt a. M.), Prof. Dr. Jens Haberkamp (Münster), Andreas Hartmann (Braunschweig), Dr. Wolfgang Jendrischewski (Köln), Volker Karl (Bad Nauheim), Prof. Dr. Steffen Krause (Neubiberg), Dr. Josef Lahnsteiner (Vienna), Dr. Manfred Lübken (Bochum), Dr. Ingmar Obermann (Eschborn), Dr. Florian Schmidtlein (Essen), Jochen Sinn (Darmstadt), Prof. Dr. Dörte Ziegler (Koblenz); the following guests have contributed: Dr. Tamara Avellán (Dresden), Dr. Serena Caucci (Dresden), Emily Fokin (Münster), Alexander Grieb (Frankfurt a. M.), Roland Knitschky (Hennef), Veronika Zhiteneva (Garching).

cial use of treated wastewater and can either serve non-potable or potable applications. Non-potable water reuse comprises agricultural and urban landscape irrigation (Figure 1), as well as water use for cleaning purposes (e. g., street cleaning, car washing), for fire-fighting, recreational applications (e. g., golf courses), environmental protection measures (e. g., stream flow augmentation), intrabuilding applications (such as toilet-flushing), and groundwater recharge (also as a barrier against seawater intrusion) [4].

Need for safe application of water reuse

Multiple planned non-potable reuse projects for agricultural and landscape irrigation, but also potable reuse applications, have demonstrated that the use of reclaimed water for such applications can be practiced in a safe manner. The total volume of municipal wastewater produced per day worldwide is estimated to be about 684 million m^3. However, only about 30 million m^3 ($\sim$4.4 %) receive tertiary or advanced treatment. The largest application of water reuse globally is for agricultural irrigation [5].

Water reuse practices have to be safe for users, groundwater, surface water, and soil. Thus, it is critical that the provided effluent quality is suitable for the desired use (fit for purpose) and assures safe practices. In order to ensure proper risk management, appropriate technological and administrative measures are also necessary, taking into account the individual case-specific circumstances. Their long-term financing and social acceptance must be ensured at an early stage.

The German DWA Topics issue on Water Reuse

To address such issues, the DWA Topics issue “Non-Potable Water Reuse – Development, Technologies and International Framework Conditions for Agricultural, Urban and Industrial Uses” [6] provides recommendations on the selection of suitable treatment processes, as well as the consideration of planning, regulatory, socio-cultural, ecological, agricultural, and economic aspects that need to be taken into account in connection with water reuse. The report is intended to provide general guidance for water utilities, consulting engineers and regulatory agencies in planning and expanding non-potable water reuse.

The following sections provide an overview of the report’s contents, focusing especially on aspects regarding the development and implementation of water reuse projects.

2 Regulations and Risks

Conventionally treated municipal wastewater effluents include pathogenic microorganisms, antibiotics including antibiotic resistant bacteria and antibiotic resistance genes, as well as residual nutrients, dissolved solids, remaining levels of heavy metals, and a wide range of natural and synthetic trace organic chemicals. Their presence is generally concerning due to potential adverse impacts on human and environmental health, particularly from pathogens and chemicals (Figure 2). To minimise health and environmental risks, sufficient elimination of potentially harmful water constituents through efficient barriers and their monitoring is therefore an essential part of water reuse.

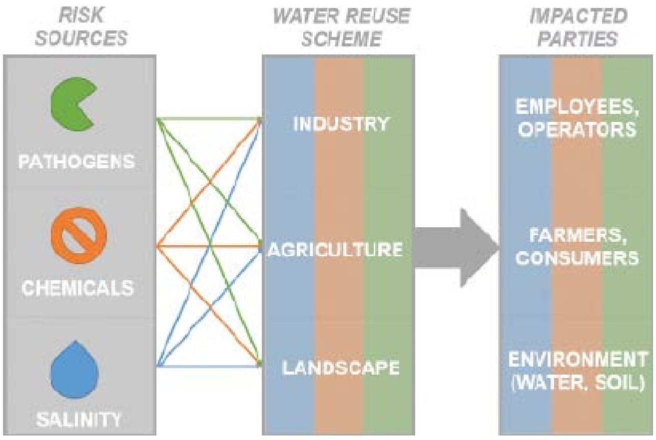


Figure 2: Risk sources and exposure in water reuse schemes

Risk Management

Risk management plays a major role in the new EU regulation. To manage risks related to water reuse, government regulations have to go beyond the definition of technical standards and requirements but must also cover additional aspects such as source control programmes (discharger control), water quality monitoring, and the responsibilities and rights of the parties involved (implementation organizations, operators, consumers), as well as a proper rate or fee structure for reclaimed water.

In many countries there is no lack of legally binding sets of rules and standards or of recommendations for minimum standards for water reuse. The problem in most areas with scarce water resources is rather, above all, an implementation deficit with a lack of compliance and insufficient monitoring by governmental and/or private regulatory institutions. Often, the capacities and resources of those institutions are not appropriate to guarantee a functioning and trustworthy regulatory system.

International Guidelines

In 1992, the Food and Agriculture Organization (FAO) published recommendations for the agricultural application of reclaimed water being based on previous WHO guidelines [7] and considering health aspects as well as requirements in terms of crops and soil [8]. Extensively revised guidelines for non-potable water reuse were published by the World Health Organization (WHO) in 2006 [9]. These represent a specific framework for the development of individual national directives and standards for the reduction of microbiological health hazards associated with water and provide information regarding monitoring procedures to assure microbiological safety. Fundamentally, the quality requirements should be adopted to the respective use of the water and consider, for example, salt and nutrient contents for agricultural water uses, in addition to those of pathogens.

The WHO approach to managing risk associated with water reuse is based on the Hazard Analysis and Critical Control Point (HACCP) system for analysis and control of hazards in any treatment train, and the Stockholm framework for preventive risk assessment. Risk management frameworks feature the same steps: identify the problem, determine the hazard in the system, quantify the hazard (exposure, dose-response), assess and characterize the risk, and manage the risk (Figure 3). Risk assessment can range from a straightforward risk matrix to an extensive quantitative microbial risk assessment.

The main guideline for addressing risk in non-potable water reuse is the Sanitation Safety Planning (SSP) Manual for Safe Use and Disposal of Wastewater, Greywater and Excreta [11]. SSP is a participative approach involving all stakeholders. Risks are followed from wastewater generation through the various reuse applications (agriculture, irrigation) to their individual end points (environmental discharge, crop production). It serves to maximize benefit of wastewater or greywater reuse while minimizing illness and contamination. Responsibility for SSP implementation is shared across numerous stakeholder agencies, depending upon the reclaimed water application purpose. Due to the broad nature of SSPs, their implementation can be difficult to coordinate, particularly in developing countries. Difficulties are encountered due to lack of or incompletely established improvement plans, supporting programmes, and management procedures. Additionally, the chances of success might be reduced by problems such as lack of training for workers and farmers, lack of monitoring programmes, lack of local community education on behavioural changes needed for compliance, and lack of governmental initiative and stakeholder support.

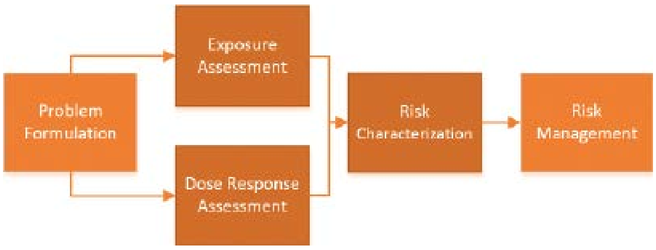


Figure 3: Risk management framework for determining whether a system meets tolerable risk levels (adapted from [10])

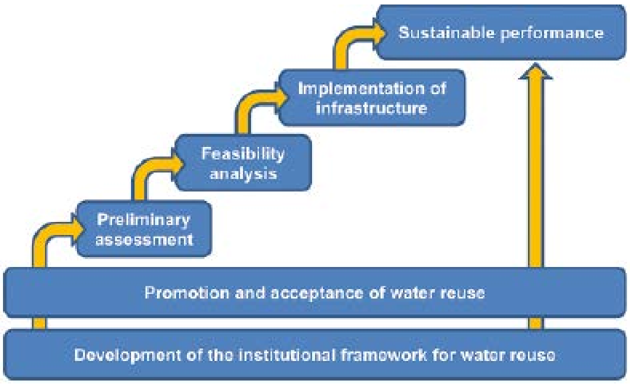


Figure 4: Steps of the development of water reuse schemes

3 Development of Water Reuse Schemes

In most cases, the development of water reuse schemes follows a typical order of development steps. These steps should be supported by qualified consulting experts (Figure 4). These steps are briefly described in the following. More detailed information is given in the DWA Topics issue [6].

Preliminary Assessment

The implementation of water reuse must be rooted in an adequate institutional framework and in sufficient acceptance by relevant stakeholders (e. g., the regulatory authority, the operator, the water user as well as the consumer of produced products). Therefore, within the preliminary assessment an initial analysis is required to determine existing regulatory frameworks for water reuse. Adequate means of public engagement for acceptance of water reuse should also be compiled. Thus, once a water reuse opportunity is proposed, a preliminary assessment of the existing local water resources and infrastructure as well as economic, institutional, legal, and social conditions should be conducted to determine whether the project is practical and necessary. If so, an in-depth feasibility analysis is carried out.

The preliminary assessment includes a rough analysis of the main elements of a potential reuse project, clarifying the need and crucial aspects for water reuse. It mainly includes the following tasks:

- Assessing the need for reclaimed water use
- Quantity and quality of potential reclaimed water
- Options for infrastructure
- Rough economic assessment
- Screening of institutional and regulatory framework

- Screening of environmental and social impacts
- Overall analysis, support of decision process

Feasibility Analysis

Based on the results of the preliminary assessment, a decision process of mainly authorities and political decision-makers sets the basis for the further steps of development. In case of a positive decision, a feasibility analysis is carried out. Occasionally, the preliminary assessment and the feasibility analysis are integrated into one study. The aim of the feasibility study is mainly to analyse thoroughly all relevant aspects and to develop a concept which can be taken as basis in further development steps (design, implementation phase). Crucial aspects of the feasibility study are:

- Water quality and water quantity aspects
- Technology and infrastructure
- Economic analysis
- Environmental and social impact assessment (ESIA)
- Public involvement and public awareness
- Monitoring system
- General institutional and organizational aspects related to the use of reclaimed water
- Relevant aspects on the water user's side

In the case of reclaimed water being used in agriculture, there is a range of additional topics to be analysed in this subject area, mainly:

- Institutional analysis and concept for development
- Extension and advisory activities
- Support of farmers in day-to-day work
- Information systems

Based on the results of the feasibility analysis, a concluding decision is taken. This decision is based on positions of the relevant stakeholders and other key aspects of a large infrastructure project (such as the cost-benefit ratio, interests of the user groups, options for financing and environmental criteria).

In the case of confirmation of the feasibility, an appropriate water reuse infrastructure is installed, and measures for sustainable performance, including continuous promotion of acceptance and updates to regulatory and institutional frameworks, can be implemented.

Implementation of Water Reuse Facilities

The steps of implementation (preliminary and detailed design, tendering, and infrastructure implementation including supervision works) are basically the same as in all larger infrastructure projects.

Also, the first phase of operation is basically similar to other infrastructure projects in the water sector. Nevertheless, special reuse-related topics have to be focused upon, such as trainings of the operational staff, support in the operation of the special treatment steps and the water quality control system, as well as support of the farmers (if related to agriculture).

Operation of Water Reuse Facilities

When the effluent of a wastewater treatment plant is used by third parties, the operation of the plant changes its established role. The plant now enters the water supply market as a “water seller”. Thus, the offered product – reclaimed water – requires reliable quality and introduces new, additional stakeholders into the management and operation of the plant. In general, the plant must consider at least the following reuse-specific issues in addition to the operation of conventional wastewater treatment plants:

- Water quality requirements: The production of reclaimed water places more emphasis on pathogen removal with absolute limits. Higher nutrient concentrations may be allowed when the water is used for irrigation purposes.
- Continuous availability of reclaimed water supply: The plant must guarantee quality and quantity at any time and in the long term.
- Reliable, independent quality control: A stringent internal monitoring structure as well as an external monitoring by independent supervisory bodies must be implemented.
- Additional facilities: Facilities for further treatment, storage, and distribution of reclaimed water are necessary. They might be controlled by a separate operator.
- Additional stakeholders: Since the use of the reclaimed water results in several additional processes for treatment, transport, and storage, the need for contractual clarification of responsibilities arises between the operation of the treatment plant, the operation of the subsequent facilities, and the use of the water. Hence, the number of involved stakeholders significantly increases (e. g., operators of storage and distribution systems, water users, water user associations, regulators and supervisory authorities, both from the water sector as well as the sectors the reclaimed water is used for).
- Form of organization: To ensure sustainable and coordinated operation of the related facilities, the organizational structures and, more precisely, the chosen operator model are to be adopted, particularly in the context of the regional logistical, institutional, and legal conditions.

4 Technical Barriers for Pathogens

Multi-Barrier Treatment Approach

To achieve reliable protection against harmful microorganisms, disinfection procedures must significantly reduce pathogens through removal, destruction, or inactivation processes. Also considering possible by-product formation, a multi-barrier treatment approach should be utilized in all water reuse applications. The various barriers include wastewater load control, appropriate wastewater treatment, disinfection, bacterial regrowth prevention, reclaimed water quality control, occupational safety measures, as well as monitoring of soil, groundwater, and final effluent quality in water reuse systems. Following the above-mentioned Hazard Analysis and Critical Control Points (HACCP) approach to risk management, relevant parameters (or control points) such as disinfectant concentration, integrity of membranes or seals, and water quality parameters influencing pathogen removal efficacy are to be defined. Appropriate operational ranges for these identified parameters must be documented within a monitoring programme based on existing national and local regulations, as well as international recommendations.

Assessment Matrix of Treatment Technologies

Treatment technologies for pathogen removal or inactivation include membrane filtration, microscreening, cloth filtration, sand filtration, as well as additional disinfection processes, such as UV disinfection, ozonation, or chlorination.

In order to support planners and decision-makers with the selection of appropriate treatment processes for safe water reuse, an assessment matrix of various wastewater treatment processes has been compiled. The matrix included in [6] provides a general evaluation of technological options, which may serve as a basis for further detailed investigations considering site-specific conditions. Each process step is assessed with regard to aspects such as water quality, costs, consumption of materials and energy, and expenditure for preventive maintenance, among others. The assessment matrix is intended to provide fast and simple support for an initial evaluation of treatment options. It is not exhaustive and will not replace the engineering investigation for site-specific decisions. However, it should be applicable for most cases and enable reasonable decisions, even when access to expert knowledge is limited.

5 Ecological and Agricultural Aspects

Substitution of Freshwater

Consuming around 70 % of total available freshwater, the global agricultural water demand exceeds private and industrial consumption. The specific irrigation water demand depends on factors like the type of crop grown, climate, soil moisture content, and the crop’s growth stage. According to an exemplary calculation included in [6], the crop water demand of an agricultural area of about 25-30 m^2 per capita can be covered by reclaimed water (assuming a rather high specific wastewater production of 200 litres per capita and day). However, although water reuse can only cover a limited proportion of the agricultural water demand, it contributes to the substitution of valuable freshwater resources.

Substitution of Fertilizers

The use of reclaimed water for irrigation provides nutrients free of charge for farmers. In the context of steadily increasing fertilizer prices over the past years, substitution of fertilizers by wastewater nutrients may play a more pronounced role in the future.

The most important nutrients in wastewater irrigation are nitrogen, phosphorus, and potassium. The nutrient concentrations in reclaimed water depend on the degree of the wastewater treatment. Efficient nutrient management depends on the type of crop grown, the soil structure, the expertise and training of the farmer, as well as the awareness about marginal-quality water as a nutrient source. A systematic and targeted nutrient supply by reclaimed water is sophisticated, since the crops’ nutrient demand shows strong seasonal differences for both perennial plants, such as those grown in orchards, and field crops, which have different nutrient demands depending on their growth phase. In the context of water reuse, it is therefore recommended to count on only partial nutrient application and avoid applying in excess. In the case of partial supply, the farmers may additionally fertilize with mineral fertilizer. In case of excess application, the groundwater can possibly be impacted.

Suitable Irrigation Methods

In addition to the substitution of irrigation water and fertilizer, further agricultural aspects regarding different irrigation methods, as well as the risk and management of salt accumulation in the soil are discussed in [6].

Increased salinity of reclaimed water often requires measures for minimizing the risk of salt accumulation in the soil. This includes the selection of appropriate irrigation methods, e. g., drip or sub-surface irrigation, which can also provide an additional barrier against the microbial contamination of farmers and crops.

6 Energetic Aspects

Water and energy are inevitably interlinked. Water is required for exploring and processing conventional primary energy sources and for cooling when converting them into electric power, as well as in hydropower or biomass generation. On the other hand, energy is needed for running the water cycle.

Water reuse can reduce energy demands in the water cycle, especially where energy consumption for conveyance, transport, treatment and distribution of freshwater is high. Comparing the energy demands associated with conventional freshwater production and distribution with the potential energy demands for provision of reclaimed water allows decision-making bodies to determine whether water reuse is feasible, from an energetic point of view, for specific applications.

Figure 5 exemplarily summarizes energy demands for all stages of the urban water cycle from water supply to wastewater treatment and discharge, taken from experiences in California and other locations. Utilization of reclaimed water (pink boxes) can be more energy efficient than supplying freshwater (blue boxes). In California, energy consumption associated with recycling (0.11-0.32 kWh/m³) is comparable to that one associated with water extraction, treatment, and distribution, which ranges from at least 0.21 (= 0.18 + 0.026) kWh/m³ to more than 4.5 kWh/m³, when assuming either long distance transport or desalination for treatment.

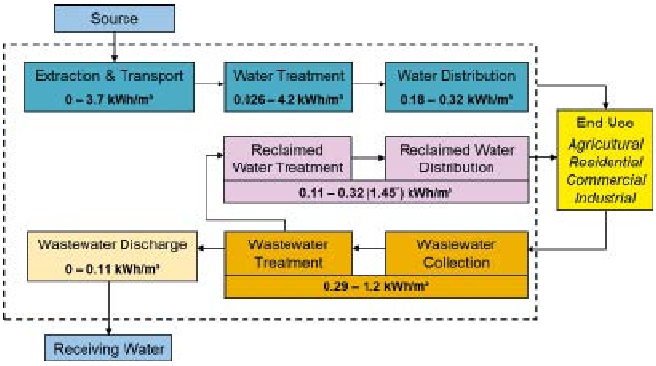
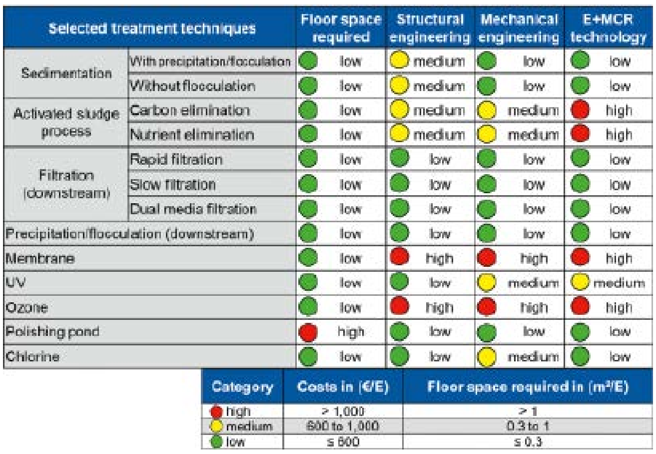


*Figure 5: Range of energy consumption for segments of the water use cycle, based on values from California (blue: freshwater; pink: recycled water, brown: wastewater; adapted from [12]; values converted in metric units; *[13]: energy consumption for direct potable reuse including microfiltration, reverse osmosis and advanced oxidation)*

Energy consumption for adequate reclaimed water generation varies considerably depending on the raw water source (e. g., treated or untreated wastewater) as well as on the required quality of the reclaimed water. Tertiary treated, disinfected wastewater, especially after membrane bioreactors, often needs almost no additional treatment for agricultural irrigation or non-potable intra-urban uses, like street cleaning, irrigation or even toilet flushing. The more stringent the effluents standards are (i.e., the more energy is already embedded in the wastewater treatment), the less energy is required to produce reclaimed water.

7 Economic Aspects

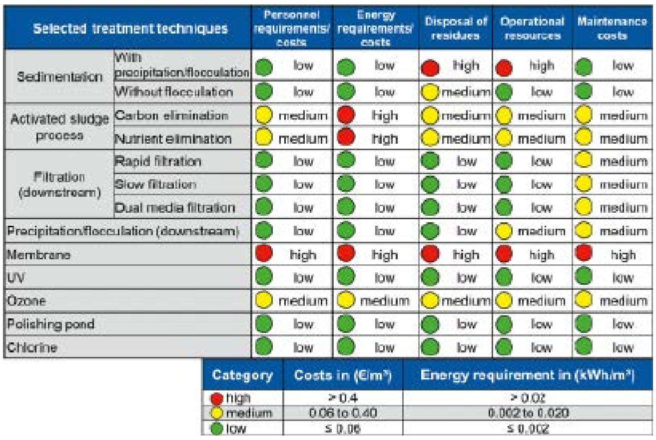
As crucial step of the preparation of a reuse project, an economic analysis has to be carried out. In the context of the detailed analysis of a reuse project (cf. chapter 3), a cost estimation based on potential alternatives of a reuse scheme is required. The cost estimation represents the basic data for an economic analysis. Tables 1 and 2 categorize the costs for investment as well as for operation and maintenance.



Selected treatment techniques		Floor space required	Structural engineering	Mechanical engineering	E+MCR technology
Sedimentation	With precipitation/flocculation	🟢 low	🟡 medium	🟢 low	🟢 low
	Without flocculation	🟢 low	🟡 medium	🟢 low	🟢 low
Activated sludge process	Carbon elimination	🟢 low	🟡 medium	🟡 medium	🔴 high
	Nutrient elimination	🟢 low	🟡 medium	🟡 medium	🔴 high
Filtration (downstream)	Rapid filtration	🟢 low	🟢 low	🟢 low	🟢 low
	Slow filtration	🟢 low	🟢 low	🟢 low	🟢 low
	Dual media filtration	🟢 low	🟢 low	🟢 low	🟢 low
Precipitation/flocculation (downstream)		🟢 low	🟢 low	🟢 low	🟢 low
Membrane		🟢 low	🔴 high	🔴 high	🔴 high
UV		🟢 low	🟢 low	🟡 medium	🟡 medium
Ozone		🟢 low	🔴 high	🔴 high	🔴 high
Polishing pond		🔴 high	🟢 low	🟢 low	🟢 low
Chlorine		🟢 low	🟢 low	🟡 medium	🟢 low

Category	Costs in (€/E)	Floor space required in (m²/E)
🔴 high	> 1,000	> 1
🟡 medium	600 to 1,000	0.3 to 1
🟢 low	≤ 600	≤ 0.3

Table 1: Assessment of investment costs



Selected treatment techniques		Personnel requirements/ costs	Energy requirements/ costs	Disposal of residues	Operational resources	Maintenance costs
Sedimentation	With precipitation/flocculation	🟢 low	🟢 low	🔴 high	🔴 high	🟢 low
	Without flocculation	🟢 low	🟢 low	🟡 medium	🟢 low	🟢 low
Activated sludge process	Carbon elimination	🟡 medium	🔴 high	🟡 medium	🟡 medium	🟡 medium
	Nutrient elimination	🟡 medium	🔴 high	🟡 medium	🟡 medium	🟡 medium
Filtration (downstream)	Rapid filtration	🟢 low	🟢 low	🟢 low	🟢 low	🟡 medium
	Slow filtration	🟢 low	🟢 low	🟢 low	🟢 low	🟡 medium
	Dual media filtration	🟢 low	🟢 low	🟢 low	🟢 low	🟡 medium
Precipitation/flocculation (downstream)		🟢 low	🟢 low	🟢 low	🟡 medium	🟡 medium
Membrane		🔴 high	🔴 high	🔴 high	🔴 high	🔴 high
UV		🟢 low	🟢 low	🟢 low	🟢 low	🟢 low
Ozone		🟡 medium	🟡 medium	🟡 medium	🟡 medium	🟡 medium
Polishing pond		🟢 low	🟢 low	🟢 low	🟢 low	🟢 low
Chlorine		🟢 low	🟢 low	🟢 low	🟢 low	🟢 low

Category	Costs in (€/m³)	Energy requirement in (kWh/m³)
🔴 high	> 0.4	> 0.02
🟡 medium	0.06 to 0.40	0.002 to 0.020
🟢 low	≤ 0.06	≤ 0.002

Table 2: Assessment of costs for operation and maintenance

In the economic analysis, quantitative methods, such as dynamic cost calculation (mainly the prime cost) and cash flow analysis, are applied. In comparison with other projects in the water sector, reuse projects face two specific obstacles:

- A high range of uncertainty of the input data: Methods such as sensitivity analysis, Monte Carlo method, and scenario analysis are usually applied to develop results considering the uncertainty.
- An unclear situation for the reference of the costs: The reference for a comparison of reclaimed water is difficult because tariffs (in particular for irrigation) are often much lower than the level required for cost-coverage. Therefore, it is recommended to compare the costs of the envisaged reuse project (e. g., prime cost) with different existing values, mainly the real costs of existing water production, the costs of other new water resources, and the tariffs.

For the financing of investment costs of reuse projects, besides existing financial resources of an authority or a company, also normal bank loans, loans from development institutions (such as development banks), subsidies, and BOT models play an important role.

For the financing of operation and maintenance (O/M), tariffs, taxes, and subsidies play the predominant role. The financing completely by tariffs is often seen as the ideal solution. Nevertheless, in reality subsidies play a major role particularly in developing countries, but also in industrialized countries. During the analysis of the feasibility, the stability of the O/M-financing has to be analysed, including a partial financing through subsidies.

8 Conclusion and Outlook

The implementation of water reuse projects is a complex undertaking. Therefore, a structured approach including comprehensive risk management and the early participation of all relevant stakeholders as well as the consideration of socio-cultural conditions are necessary to stimulate acceptance. Moreover, the permanent coverage of all costs for investment, operation and maintenance of water reuse systems has to be ensured in order to attain sustainable success.

Regarding the quality of the reclaimed water, microbial risks are of major concern in terms of water reuse. A variety of established processes for advanced wastewater treatment is available for pathogen removal in order to ensure the required effluent quality. Regulations and standards for water reuse have often been limited to the definition of quality requirements for reclaimed water. Recently, the multi-barrier approach focusing on health-based targets for risk management in water reuse recommended by the WHO has increasingly been adopted by standardization institutions (cf. [14]) as well as legislative bodies, e. g., the European Commission, which published the European minimum standards for agricultural water reuse in 2020 [1].

Water reuse can significantly contribute to the substitution of freshwater resources, reduce the demand for mineral fertilizer, and help minimizing the energy embedded in the water cycle, thus reducing greenhouse gas emissions.

Use of reclaimed water, especially for irrigation purposes, has been practised for a long time in regions suffering from water scarcity. With regard to changing rainfall patterns in consequence of the global climate change and an increasing need for seasonal irrigation, it is expected that water reuse will further gain relevance also in regions with rather high average water availability. Not least, the substitution of freshwater resources by reclaimed water contributes to securing future drinking water supply especially in arid and semi-arid regions, and therefore also to the realization of the United Nations' Sustainable Development Goals.

The DWA Topics issue [6] provides general recommendations for the international application of water reuse. For the implementation of the EU regulations [1] coming into force in 2023, in Germany a new specific set of regulations and technical rules is being developed, covering planning tasks and detailed requirements for the risk management of water reuse schemes as well as for the official approval procedures. These regulations and rules will be available by 2023 in the form of the new three-part DWA Guideline "Water reuse for agricultural and urban purposes in Germany" (DWA-M 1200-1 to 1200-3).

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