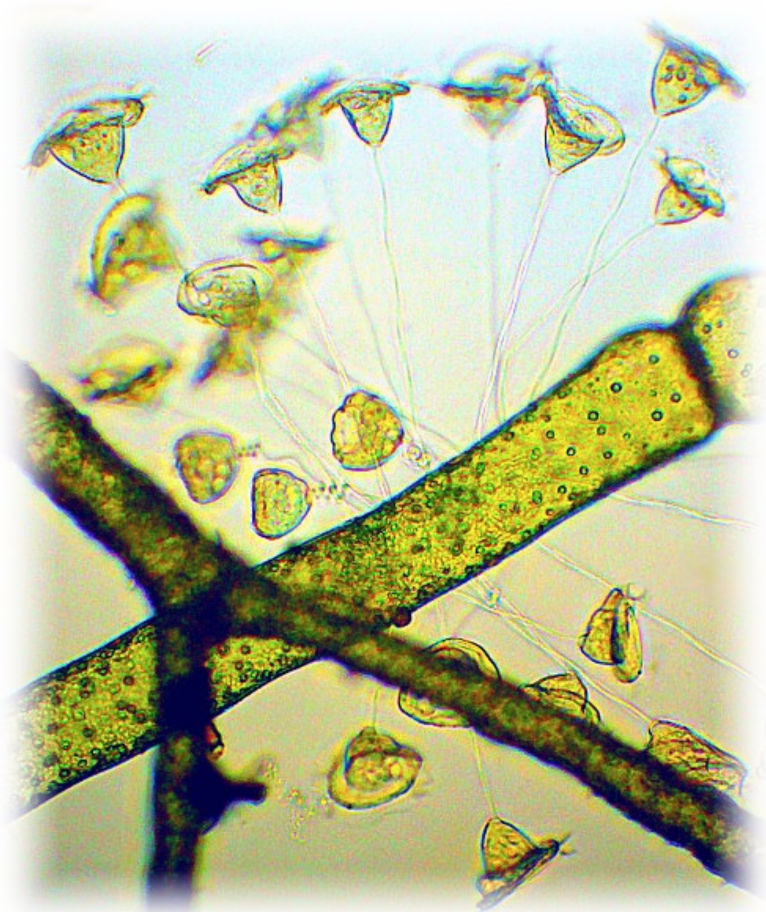
A model for composition-specific life cycle inventories of regionalised wastewater fates



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Title image An impression of micro-organisms, the major agents of removal of organic water pollutants in natural and technical systems, especially in aerobic biological treatment. Photograph is approximately 400 micrometers wide. Depicted is a colony of ciliates, Vorticella microstoma. Microscopy photograph by Andrei Savitsky, January 2019. https://upload.wikimedia.org/wikipedia/commons/2/22/Vorticella_campanula.jpg Creative Commons Attribution 4.0 International license. Editorial changes: Cropped, rotated, colour saturation.

Significant digits Figures in this report often feature several digits. This is not to imply that all the shown digits are really significant or that the data displayed is very precise. Showing several digits helps to minimise the avoidable accumulation of rounding mistakes along the chain of calculations performed here, and in possible future studies referring to this data.

Percent is not a unit A value like 100% is mathematically identical to 1, and "33%" is just a way to write the value 0.33 (which one could also write in yet another different format as "$3.3 \cdot 10^{-1}$". Mere *formatting* does not and should not influence the *magnitude of a value*. There is therefore no need to introduce factors or divisors of 100 in formulas for percentages (see e.g. Eq. 4.11). "Per cent" literally means "per one hundred" and implies the instruction "divide by 100", therefore the mathematical value of the expression "33%" is 33/100 = 0.33 (not 33). In contrast, a formula to calculate a gram value from kilograms must include a factor of 1000, because gram is a *physical unit* (not just a different way to "format" a kilogram value).

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Contents

1 Introduction

The goal of this study is to create a calculation model to inventory the disposal of different types of wastewater. The purpose of this is to be able to supplement other activity inventories with the quantified burdens from the disposal of a specific wastewater compositions, which can be defined by the user. Several already used wastewater compositions from processes are supplied as well.

This work is an update and expansion of the calculation model in (Doka 2003-IV), where only wastewater treatment in Switzerland was modelled. The updated model is regionalised, reflecting the wastewater sanitation and treatment situations in other countries as well. For 251 countries statistical data or estimates were compiled regarding untreated releases, wastewater sewering rates, treatment rates, and treatment stages. The model includes also the pertinent expenditures for sewer and treatment plant infrastructure, as well as the treatment of any secondary waste (treatment sludge) or tertiary waste (for instance landfilling of sludge incineration residues) maintaining the dependency on the initial wastewater input.

The model is implemented in an Excel calculation tool which allows the direct creation of inventory process files (XML) in EcoSpold2 (ecoinvent v3+, 2011–) or EcoSpold1 format (ecoinvent v1–2.2, 2003–2010).

Thanks to Dr. Stephan Pfister, senior research associate at Ecological Systems Design ESD, ETH Zürich, for his helpful comments on chapter 13 'Water balance in treatment plant'.

2 Goal and scope

The goal of the model presented here is to provide inventories for the disposal of a particular wastewater composition. The inventory starts with 1 m^3 of a specific wastewater as it is outputted from a particular wastewater-producing activity with a specific composition.[1] The functional unit is 1 m^3 of untreated wastewater (input).

Depending on the chosen geographic setting, wastewater might not or only partially treated at all. Some countries have widespread lack of sewer networks or wastewater treatment plants. The share of wastewater emitted untreated will be included in the wastewater disposal inventory. A part of sewered wastewater might also be emitted untreated, which results in the same untreated pollutant emissions but requires a sewer network.

Sewered wastewater arriving in a treatment plant will be purified according to the mix of technology stages encountered in a country. Treatment sludge might be digested producing digester gas and subsequently some gross energy outputs, depending on parameters set by the user. The remaining sludge needs to be disposed, and disposal on agricultural fields, in a biologically active landfill, or in municipal waste incineration depending on settings by the user.

[1] Throughout the report the terms "waste-specific" or "wastewater-specific" refer to the fact that inventories are heeding as far as possible the composition of a specific wastewater input, and nor generic, average wastewater.

To save database space and the emissions and exchanges from all these processes are compiled into one single process inventory.[2] This is similar to the scope in the previous wastewater treatment model, where however all wastewater was assumed to be sewered (Doka 2003-IV).

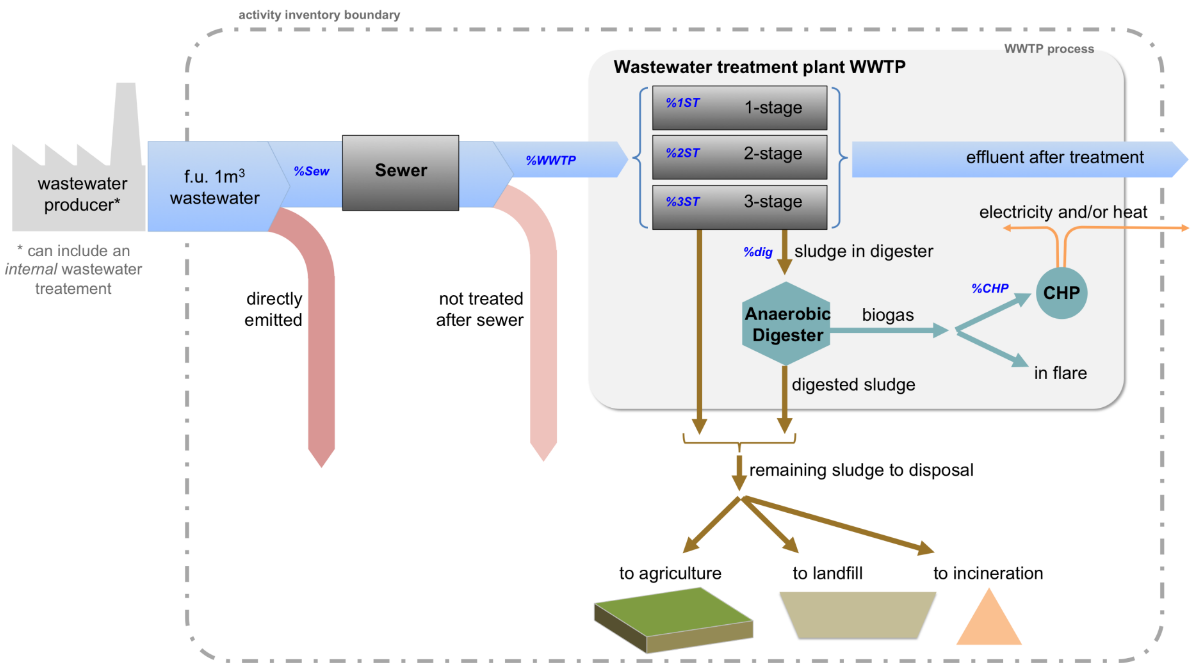

Fig. 2.1 Simplified overview of the possible inventoried processes in the wastewater disposal activity.

2.1 Other wastewater LCAs with different goals

LCA is a procedure with a very flexible approach and usually different goals and purposes can occur even for the same real-world activities.

As outlined above, the purpose of the model presented here is to complement wastewater-producing activities with the caused burdens of the disposal of their specific wastewater output. It can be said, that the model is suited to the needs of the *wastewater producer*, in order to complete LCI process chains.

But this is not the only way how an LCA of wastewater disposal can be targeted. For instance the LCA perspective and information needs of a *wastewater treatment plant operator* will likely be quite different. Here not the treatment of one single *specific* wastewater composition is of interest, but of a generic average wastewater expected at the location, which is the cumulated mix of hundreds or thousands of individual process sources. Variation of the wastewater within expectable bounds could be a topic, but much more granularity will probably be desired in the technical details of the treatment

[2] Without this, the process chain could lead to several very granular process inventories for each individual wastewater and location without them being much use to anyone. For instance, there could be an activity "treatment, landfilling of incineration residues from incineration of sewage sludge from treatment of wastewater from potato starch production" along with "treatment, agricultural spreading of sewage sludge from treatment of wastewater from potato starch production " etc. In the compact version, there will be only one dataset "treatment, wastewater from potato starch production". Different geographical versions of such a dataset would reflect geographically different wastewater disposal mixes.

operation: stages, capacities, residence times, auxiliary demands, etc. and their possible options or variations. Here optimization of the treatment process on the whole—increasing elimination levels, reducing expenditures—would be a fitting goal of an LCA study. Here not the information needs of a particular upstream wastewater producer are relevant, but the those of the treatment plant operator. It is important to realize that an LCA with this focus will not be able to meet the needs of an LCA of the former type.[3]

A yet different LCA approach can be outlined from the perspective of *the producer of a particular chemical compound*. As part of corporate responsibility and product environmental safety guidelines it will be relevant to know how a compound behaves during and after usage. Here the behaviour of a particular compound in wastewater treatment would be of interest. Some LCIA models feature fate calculations of emissions including generic WWTPs. A substance-focused LCA of wastewater treatment would bring those generic fate calculations to the foreground of an LCA study—including indirect burdens like for auxiliaries and infrastructure. Here possible questions would more likely revolve around degradabilities, accumulations, toxicities, ultimate sinks in correspondence to types of wastewater treatment. An example of such an LCA model is (Munoz 2019).

A synopsis of those three different types of LCAs for wastewater or wastewater treatment is shown below. Of course also other goals than shown here are possible.

The takeway from this section is that the model presented here was designed with a specific purpose—calculating burdens of disposal for a particular wastewater composition—and although there will be partial overlaps, is not meant or designed to serve different goals.

For practical reasons of data availability the model's granularity is anticipated to fit the probable level of information available to a wastewater producer. Some aspects of the model are therefore included in a more generic manner, while others are treated in more detail.

If time and resources to research input data were not an issue for a model user, then an overarching and detailed model satisfying various LCA application goals would be appealing. Since this is not so, it is sensible to match models as far as possible with the required model input information a user is likely able to find.

[3] Theoretically, a very detailed model could be conceived, offering the desired granularity regarding wastewater input down to a particular generating source *and* vast details for the treatment process. Here practical problems of data availability ensue, when for instance a wastewater-producer would be asked to set all the WWT operator's bottom-up parameters like residence times, sludge loadings etc., many of which make sense for a single plant, but are not necessarily known in a generic fashion.

Stakeholder or focus:	**1. Wastewater producer**	**2. Treatment plant operator**	**3. Producer of compounds**
Wastewater input: Example:	*Process-specific effluent from wastewater producing activity* *Organic carbon, Nitrogen, Phosphorus, Copper, Zinc*	*Average expected wastewater mixture* *Volatile Suspend Solids, soluble biological oxygen demand, Alkalinity*	*One or several specific chemical compounds in wastewater* *Diethylenetriamine penta(methylene phosphonic acid)*
Granularity of wastewater definition:	*medium (single producer output with available parameters)*	*low (expected inflow average)*	*very high (single compound)*
Granularity of treatment model:	*low (e.g. country average)*	*high (plant specific and variant options)*	*medium to low*
Possible LCA goals:	*LCA burdens for downstream disposal/treatment of wastewater*	*Plant optimisation*	*Substance cradle-to-grave LCA. Degradability and accumulation. Generated burdens from substance(s)*

3 Relevance of unsanitary conditions

The human health damages from unsafe sanitation worldwide are estimated to be 41'500'000 DALYs for 2017 (Murray et al. 2018, p.1940). These damages are from diarrhoeal diseases from unsafe wastewater disposal and include 774'000 deaths for 2017. Of the world population 21.2% are exposed to unsafe sanitation (ibid, p.1927). With a world population of 7548 million in 2017, a total of 1600 million people are exposed to unsafe sanitation. Per capita and year the human health damage from unsafe sanitation in that population part is therefore 0.026 DALY/cap.year.[4]

In the ReCiPe'13 LCIA method, a damage of 0.026 DALY would correspond to 515 burden points[5]. How does this burden from diarrhoeal diseases compare to the burdens already recorded in conventional LCIA from pollutant emissions? If a person's wastewater was emitted directly and untreated into surface water, a total LCIA burden of 3.48 points per year and capita would result (at 120 litres of wastewater daily per capita). So in a situation of unsafe sanitation the diarrhoeal diseases (515 points) outweigh by far the conventional LCIA burdens of untreated emissions into water (3.48 points).

This means that for LCA work in countries with unsafe sanitation, it would be very relevant for a complete picture to include the human health damages from unsafe sanitation, not merely the humanotoxic or ecotoxic effects of its contents.

LCA has developed mainly from an engineering side and seminal activities in LCA are "machines" in a wide sense and their "metabolic" effects (fuels in, emissions out etc.). In conventional LCA today the more situational effects, which affect hygiene of an area, are not considered. But there is conceptually nothing wrong with introducing effects from known risks of disease vectors at least in a

[4] 0.026 DALY /cap.year = 41.5 million DALY/year / 1600 million capita.

[5] 515 points = 0.029 / 0.0202 · 40% · 1000, with normalisation 0.0202 DALY/cap.year, 40% weighting and a convenience factor of 1000.

generic fashion.[6] Ideally, LCIA developers would propose characterisation factors, for instance for 1 kilogram fecal matter emitted to water and soil.

On the other hand, the wastewater activity inventories elaborated here are mainly intended for industrial processes. Those might promote unsanitary conditions as well (e.g. from the food industry). Also animal husbandry produces faeces, which can become problematic to water supply. For many industrial processes though, a new inventory exchange for faecal emissions would not be pertinent.[7] For the time being a new exchange for faecal emissions is not included in the inventory model presented here.

4 Sanitation levels in countries

4.1 The WHO/UNICEF JMP statistics for SDG 6.1.3

The Joint Monitoring Programme—or JMP—of WHO/UNICEF meticulously recorded sanitation levels and technologies in over 200 countries, in most cases for the recent past of 2016 or 2017 (WHO/UNICEF JMP 2019). These statistics are elaborated in connection with the Sustainable Development Goal SDG 6.1.3 on the proportion of wastewater safely treated. Statistics on presence of sewers, and presence of centralised wastewater treatment facilities, technology types of toilet facilities (or absence thereof, i.e. open defecation) etc. are devised in those statistics. In the recorded data, the emphasis is on the situation for households, schools and health services/hospitals. For the treatment situation of *industrial* wastewaters no statistical data was recorded yet, although the SDG 6.1.3 would also include industrial and commercial wastewater (see UN-Habitat 2018).

Sanitation burdens vs. LCA burdens

The statistics for SDG 6.1.3 focus on the *sanitation and human health aspects* for inhabitants, and less the *environmental burdens* as investigated in LCA. For instance, in the SDG framework a wastewater can be categorised as "safely treated" if it is disposed in the ocean with a long outfall pipeline, so as to minimise human contact, while in LCA this would represent a 100% emission to marine water with corresponding burdens (and also possible health damage rebounds e.g. via human consumption of marine fish). Many latrine types that are categorised in SDG as "safely treated" would correspond to 100% emission to soil in LCA. Also important distinctions are made in the SDG statistics whether toilet facilities are shared between several households or not, which is relevant from a perspective of sanitation, hygiene and disease transmission, but in LCA would have no burden signal, or rather possibly an advantageous one from shared infrastructure burdens per capita. So the aim and focus of SDG 6.1.3 and LCA are dissimilar – at least partly. Nevertheless the data gathered contains useful information and its adoption in this project is presented below.

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6 More site-specific assessment is desirable, if possible, but for an initial inclusion a generic approach is fine. If in LCIA it is a common and accepted procedure to express the health damages for instance of an emission of NO_x to air with one single generic characterisation factor—averaging out population densities, climate etc.— then with a similar granularity the average generic health damages from unhygienic conditions can be included as well, at least as a signalling starting point.

7 Unsanitary conditions leading to diarrhoeal diseases are associated with microbial vectors which can occur in faeces, like cholera, noro virus, rota virus, or salmonella.

4.2 Adopting JMP data for industrial wastewater fate

The purpose of the wastewater models elaborated in this project is providing background data for wastewater disposal, see 'Goal and scope' on page 5. This is to complement processes inventories with waste-specific disposal activities. The vast majority of the wastewater-producing processes in the ecoinvent database are industrial or commercial activities, not household activities. Treatment levels and technologies in this project should therefore mainly reflect plausible technologies for disposal of such industrial wastewaters, not household wastewaters. For instance, if in a country like Uzbekistan 77% of the population uses a pit latrine for defecation, it makes little sense to assume that also *industrial* wastewaters, e.g. from a tannery, are also predominantly disposed in pit latrines in Uzbekistan. Pit latrines are rather unsuited to take up industrial wastewater regarding the volume capacity alone.

Fortunately, the JMP statistics detail also many other helpful parameters (WHO/UNICEF JMP 2019). Distinguished are for instance "Population connected to sewers" and "Population with connection to a wastewater treatment plant".[8]

- The first parameter "Population connected to sewers" describes the frequency of occurrence of sewer systems for wastewater transport in a nation. At the end of that sewer an untreated discharge can occur, or a more or less elaborate treatment in a wastewater treatment plant WWTP. Sewers are foremost a means of transport of wastewater away from inhabited areas; they do not unavoidably lead to a treatment plant.
- The second parameter "Population with connection to a wastewater treatment plant" describes the frequency of occurrence of inhabitants being connected to a working wastewater treatment plant in a nation. All WWTPs are fed by sewers so there is an overlap of the previous and this parameter. There is no significant transport of wastewater to WWTPs by trucks.[9,10]

These two parameters are employed here to produce estimates on external treatment of *industrial* wastewaters. The frequency of sewer occurrence in a country as described by the JMP parameter of the share of population connected to sewers is set equal to the proportion of industrial wastewater going into a sewer transport in that country (parameter %Sew in the present model). With this, an equivalence is assumed between a share of *population* and a share of *wastewater generated*. This is not entirely accurate, as not all inhabitants necessarily produce the same annual amounts of wastewater and also because there might be disparities in the geographical distribution of inhabitants and the distribution of industrial activities. Nevertheless the JMP parameters are used to quantify the prevalence of certain wastewater management aspects in a country. It is implicitly assumed that the

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8 See https://washdata.org/data/downloads#WLD → Household Wold File https://washdata.org/data/country/WLD/household/download → JMP_2019_WLD.xlsx → sheet "Sanitation" → Columns "Wastewater treated" and "Sewer connections". Data is given for the national average, for urban and for rural situations. Detailed and unrestrained data is in the hidden sheet "Sanitation Data".

9 But faecal sludge from septic tanks can in some cases be transported by lorry to WWTPs. As septic tanks are not considered for the present model, no lorry transport for WWTP inputs is considered here.

10 In the JMP data, improved sanitary facilities (pit latrine with slab or better) can be shared with other households and then count only as limited service (instead of the better "basic service") due to their inferior sanitation situation. The figure for "wastewater treated" excludes these shared facilities, while the figure for "sewer connections" includes them. This makes the analysis on sewered vs. treated performed for the present project ill-footed, i.e. based on different parts of the population. However the numerical effect is small, as number of improved, but shared facilities (of any kind) are small (cf. total limited service is generally below 15%. At a GNI of 10'000 $/cap.year it is below 2%) and the frequency of sewer-connected facilities which are shared with other households is bound to be even smaller. This effect is neglected in the analysis here.

observed population-percent is a accurate enough indication of the frequency of certain wastewater fates.

The second parameter from JMP describes the frequency of wastewater being treated in wastewater treatment plant. Also this pattern is assumed here to be applicable to industrial wastewater, therefore describing the share of industrial wastewater being externally treated in wastewater treatment plant (parameter %WWTP in the present model).

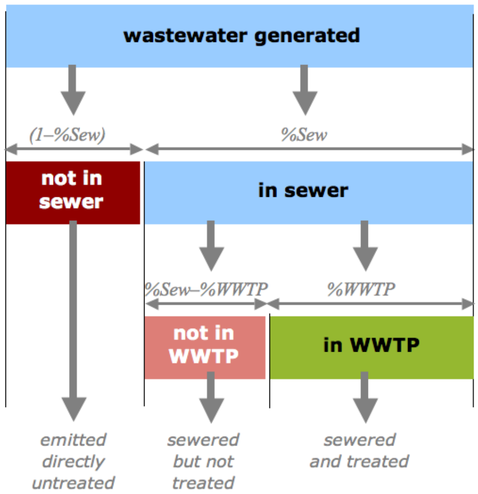

Fig. 4.1 Scheme of the initial wastewater fate employed in the model presented here. Industrial wastewater is either sewered or not, and sewered wastewater can be treated in WWTPs or not. Further differentiation of wastewater treatment in WWTPs is detailed further below.

Since all water into a wastewater treatment plant is assumed to be delivered by a sewer, the *difference* between the sewered wastewater (%Sew) and the treated wastewater (%WWTP) describes the share of wastewater that is being sewered, but not treated, but discharged untreated.

Finally, all wastewater not entering a sewer in the first place is assumed to be discharged without any treatment. This is expressed by (1–%Sew). It is implicitly assumed that in a region with pit latrines and similar levels of sanitation without sewers, no special efforts are made for external treatment of industrial wastewaters. Internal treatment of wastewater might still occur, but this is outside of the system boundaries, cf. Fig. 2.1 on page 6.

So in the derived model, a country's industrial wastewater fates can be summarised as follows:

Tab. 4.1 Description of modelling parameters used for shares of fate of industrial wastewaters

%WWTP	Sewer transport and treatment in wastewater treatment plant WWTP
%Sew – %WWTP	Sewer transport and subsequent direct discharge; not treated
1 – %Sew	Direct discharge without sewer transport

For the all three expressions above, the reference of 100% represents the sum total of wastewater produced per year.

Sanitation for industrial wastewaters

One might prejudge that in industrial operations wastewater treatment is improved and no or little uncontrolled emissions occur. This notion is disproved by statements made in a UN Analytical Brief on Wastewater Management (UN 2015:19):

> *"It is important to note that, in many cases, large volumes of industrial wastewaters which are legally discharged to decaying and/or badly operated sewerage networks, both combined and separate, never actually reach a treatment plant. Much is lost en-route through broken pipes or ends up in surface water drains with consequential pollution of both groundwater and surface watercourses." – UN 2015*

While this statement does not help to support an equality of sanitation rates for population and for industrial wastewater as assumed in the present model, it refutes the notion that industrial wastewater is always treated appropriately.

Geographical coverage of data

The JMP national data has a wide scope giving data for many nations of the world. For 232 listed countries, 221 (95%) have a national average on sewer connections. Most of that data is as recent as 2016 or 2017. For 117 countries (50%), data is available for treatment rates. Most countries without treatment data are those with low incomes, or small states like the Vatican or small island states like Saint Lucia.

4.2.1 National, urban and rural wastewater fate data

In the JMP national data 165 countries (71%) also have some data detailing rural and/or urban situations of sewer connections and treatment rates. So for those counties up to three sets of parameters are available: for the national average, for an average rural setting, and for an average urban setting. The parameters are expressed in the respective setting or territory. So a country might have for instance an average national sewering rate of 70%, a sewering rate in rural setting of 20%, and a sewering rate in an urban setting of 100%. The JMP data also provides values for the share of population in urban areas (%popU) for each country; and the given national, rural and urban rates are compatible with that share.[11]

The rural and urban data can be used in the inventory model presented here to further differentiate wastewater treatment situations. If a wastewater-generating process is known to be situated in an urban setting, more pertinent urban rates of sewering and treatment can be applied instead of the more generic national average. In other situations, a rural rate might be more appropriate, depending on the wastewater-generating process. In an unknown or generic situation the national average rate can be employed. In the inventory model presented here, the split into three different treatment territories (urban, rural, national) replaces the former split into five size classes of WWTPs (Doka 2003-IV:7).

[11] I.e. the national rate %n must be equal to *%r · (1-%popU) + u% · %popU*, where %r is the rural rate and %u is the urban rate.

4.2.2 Augmentation of missing values in JMP wastewater fate data

To avoid data gaps in wastewater fate, an estimation and extrapolation procedure is derived below. Statistical data from JMP is used with priority, but estimates are used to fill missing data. As the estimates are rather coarse, it is better to find pertinent literature data or country statistics, or to estimate parameters based on country-specific sanitation conditions. Future updates of the SDG monitoring programmes as the WHO/UN Joint Monitoring Programme for sanitation would be a premiere source for such data.

For an extended list of 251 nations two rates (%WWTP, %Sew) in three territories (national, rural, urban) are sought, totalling 1506 figures. The original JMP data provides already 834 rates (55%) for 232 countries. The remaining 672 rates need to be estimated.

The sewering and treatment rates are often very dependent on national circumstances, even for countries of similar economic wealth. Therefore, the estimates are based as far as possible on the available statistical data characteristics of a country and extended to missing rates.

1. Complementing rural rates

In a first step, any missing rural rates are completed, when national and urban rates are provided in JMP data. Using the share of urban population (%popU) – also provided in JMP data tables – the rural rate is defined by:

Eq. 4.1
$$\%r = \frac{\%n - \%popU \cdot \%u}{1 - \%popU}$$

where

%r =	Rural rate (e.g. treatment rate %WWTP, sewering rate %Sew)
%n =	National rate (e.g. treatment rate, sewering rate)
%popU =	Share of urban population in that nation
%u =	Urban rate (e.g. treatment rate, sewering rate)

This augmentation is performed where useful for the treatment rate %WWTP and/or the sewering rate %Sew.

2. Using available ratio of treated wastewater

The second augmentation is based on the observation that for available JMP statistics the share of sewered wastewater being treated in a WWTP (expressed by the ratio %WWTP / %Sew) is very often *identical* within one country, whether it is for the national, rural or urban territory.

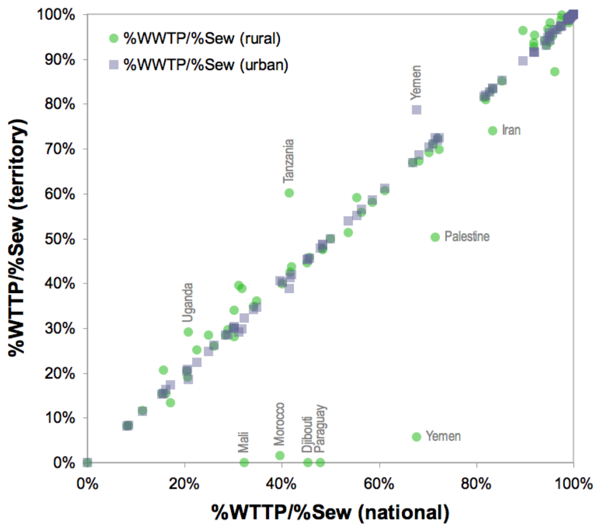

Fig. 4.2 Plot of ratios from available JMP data for (%WWTP/%Sew) of a national average (x-axis) vs. the same ratio in urban territories (blue squares) or rural territories (green circles) of that same nation (y-axis), showing the largely uniform nature of the (%WWTP/%Sew) ratio across different territories of the same nation.

If in one of the three territories of a nation, a ratio for (%WWTP / %Sew) can be derived from available statistical data, it is a fair assumption that this ratio is also a good estimate for that ratio in the other territories of that same nation. For instance the JMP statistics have %WWTP and %Sew data for rural Ethiopia (0.26% and 0.72%), but only %Sew rates for the urban and the national territories (2.79% and 1.14%), while the %WWTP rates are not available in those two territories. In this case, fair estimates for the missing %WWTP rates can be made by assuming the ratio (%WWTP / %Sew) available from the rural territory (0.36 = 0.26% / 0.72%) is also applicable to the other two territories and therefore the missing %WWTP rates can be estimated based on the available %Sew rates. In urban Ethiopia, the estimated %WWTP rate is therefore 1.02% (= 2.79% · 0.36); and the national %WWTP rate can be estimated to be 0.41% (= 1.14% · 0.36).

Tab. 4.2 Exemplary depiction for the calculation chain from available rates (bold) using available %WWTP/%Sew ratios to derive country-specific estimates (grey). Arrows indicate flow of information.

	%WWTP	%Sew	ratio %WWTP/%Sew
rural	**0.26%**	**0.72%**	0.36
national	0.41%	**1.14%**	0.36
urban	1.02%	**2.79%**	0.36

From these first two extrapolation steps 12 additional rates could be added to the data.

3. Extrapolating ratio of treated wastewater

A third extrapolation is again based on the ratio for (%WWTP/%Sew). For nations where no such ratio can be derived from available statistical data for either of the three territories, the ratio is estimated from scratch based on a nation's Gross National Income (GNI in $/capita.year). From available data, the general trend for the median values of the ratio vs. GNI is observable and this forms the base of the derived extrapolation formula.

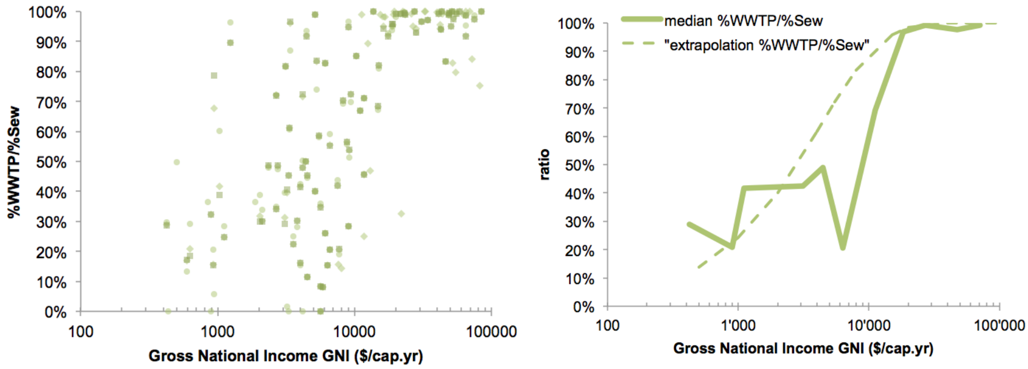

Fig. 4.3 **Plot of ratios of %WWTP/%Sew (x-axis) from available JMP data against the Gross National Income GNI (left, darker points correspond to multiple dots at the same location) and the trend of the median values (right, solid line) and the derived extrapolation (dashed line).**

Eq. 4.2 $$\frac{\%WWTP}{\%Sew} = 1 - e^{\left[c \cdot GNI^{0.9}\right]}$$ **with c = -5.5E-4**

where

GNI = Gross National Income ($/capita.year)

Please note the exponent 0.9 to the GNI variable

Based on a nation's GNI the %WWTP / %Sew ratio can be estimated. The ratio is then used to derive missing %WWTP data from available %Sew data (%WWTP = %Sew · %WWTP / %Sew). So also here the missing data is based as far as possible on available data, but the ratio is estimated based on GNI. Also the obverse were possible at this point—to derive missing %Sew data from available %WWTP data—but this results in no additional data with the 2019 JMP data.

This third estimation step adds 246 rates to the data in all three territories.

4. Extrapolating the ratio of national vs. urban rates

The next estimation involves an extrapolation for the ratio of national vs. urban rates (NU). For mathematical reasons, this ratio cannot be smaller than the share of urban population %popU, and usually is only slightly higher. An estimate for missing NU ratios is based on the share of urban population and the observed median value of the ratio of national vs. urban rates from available data.

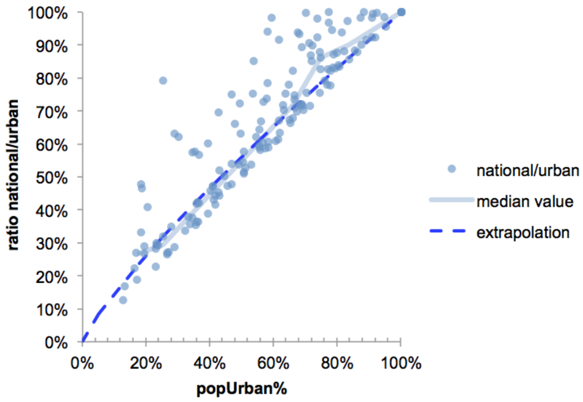

Fig. 4.4 **Plot of the share of a nations urban population %popU (x-axis) against the ratio of national over urban rates from available JMP data, the trend of the median values (solid line) and the derived extrapolation (dashed line).**

Eq. 4.3

$$NU = \left(\frac{\%n}{\%u}\right) = \% popU^{0.83}$$

where

NU = national rate over urban rate

%n = National rate (e.g. treatment rate, sewering rate)

%u = Urban rate (e.g. treatment rate, sewering rate)

%popU = share of urban population in a nation

Please note the exponent 0.83 to the %popU parameter

In countries with available national rate, therefore a urban rate can be estimated from:

Eq. 4.4

$$\% u = \left(\frac{\%n}{NU}\right) = \left(\frac{\%n}{\% popU^{0.83}}\right)$$ **; corrected to ≤ 1**

%u = Urban rate (e.g. treatment rate, sewering rate)

%n = National rate (e.g. treatment rate, sewering rate)

This can be used to estimate additional rates for either missing urban %WWTP or %Sew rates from available national rates. This estimate adds another 114 urban rates to the data.

In nations now possessing data for national and urban rates, the rural rate can be mathematically stringently be derived from Eq. 4.1. This is based on the requirements of the national rate being the weighted average of the rural and the urban rates. This estimate adds another 114 rural rates to the data.

5. Estimation of sewering and treatment rates based on Gross National Income GNI

Up to this point the estimation procedure has added data to countries where JMP statistics had provided *at least* one statistical rate value reflecting country-specific circumstances. Some country gaps remain at this stage where JMP 2019 statistics provide no data at all, for example for Taiwan. In order to be able to provide suggestions for sewering and treatment rates also for these countries, further extrapolations are employed.

Further estimates are derived from available national data from JMP for %Sew and %WWTP against a country's GNI, which allow to obtain a trend.

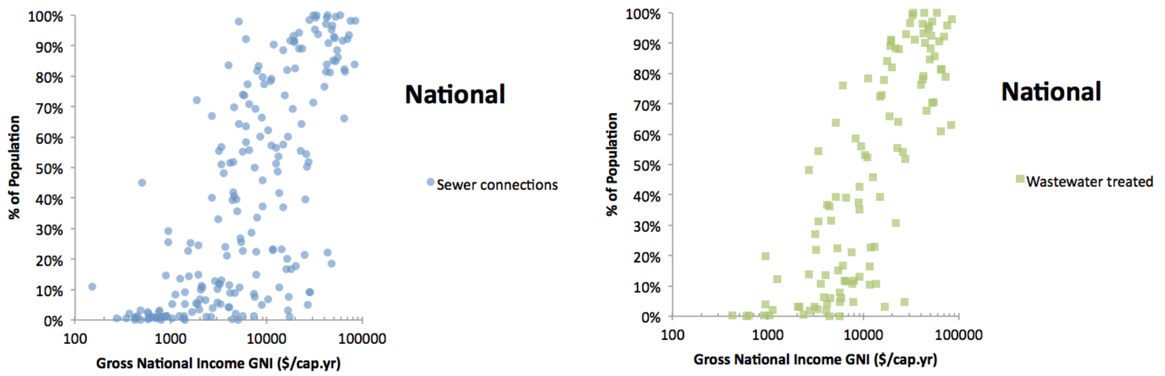

Fig. 4.5 Data values of JMP statistics on national rates of sewer connections (left) and wastewater treated (right).

A general trend of increasing sewering rates and treatment rates with increasing GNI is observable. By calculating tiered median values, the *typical central tendency* can be captured and be used as the basis of a formal extrapolation.

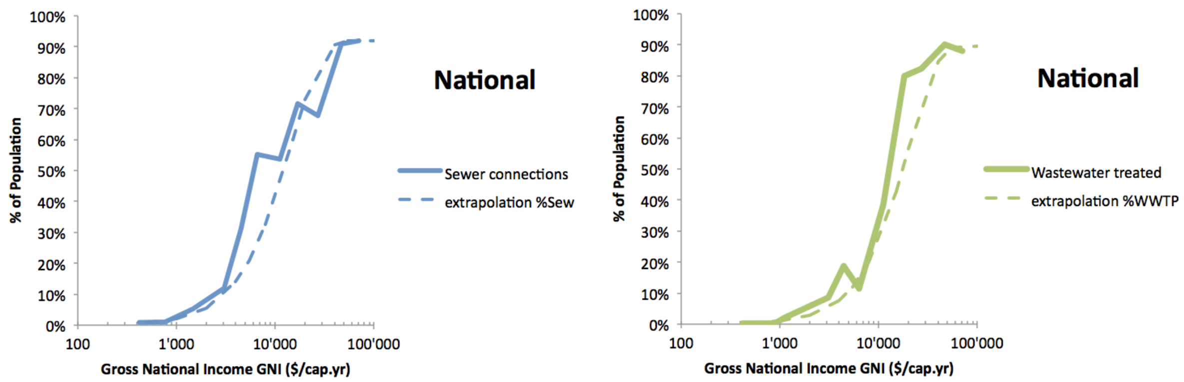

Fig. 4.6 Median values of statistics (solid lines) on national rates of sewer connections (left) and wastewater treated (right) and derived extrapolations (dashed lines).

The derived extrapolations are given in the following formulas.

Eq. 4.5 $$\%Sew = 92\% \cdot \left(1 - e^{\left[c \cdot GNI^{1.4}\right]}\right)$$ **with c = -1.5E-06**

Eq. 4.6 $$\%WWTP = 90\% \cdot \left(1 - e^{\left[c \cdot GNI^{1.5}\right]}\right)$$ **with c = -3.5E-07**

where

GNI = Gross National Income ($/capita.year)

Please note the exponents to the GNI variable

In these extrapolations for national rates the maximal attainable rates are not 100%, but 92% or 90%. This is based on the observable median trend, where even at high GNI some wastewater is emitted untreated, e.g. in available data from Canada, Bermuda or Norway.

With these approximations it is possible to calculate values for %Sew and %WWTP from scratch based on a country's GNI alone. Next, using the approximations used in Eq. 4.3, urban rates can be derived based on the share of urban population in a nation (%popU). And finally, using Eq. 4.4, also rural rates can be added. All this adds another 180 rate values.

Uncertainty

As the employed extrapolations are often rather coarse, an uncertainty parameter (geometric standard deviation GSD) is applied to the extrapolated rates. The estimated GSD is based on observed variability of JMP statistical data and therefore the variability of the derived extrapolations. Care has been taken here to derive GSD values that result in reasonable upper and lower rate values that are within physically sensible realms.[12]

Eq. 4.7 $$GSD_e = 1 + N \cdot \ln(m)$$ **, with N = -0.2171**

where

GSD_e = Geometric Standard Deviation of an extrapolated rate parameter

m = mean value of rate parameter (between 0 and 1)

If m = 0 the GSD is corrected to 100%

Also the original statistical JMP data has some uncertainty attached to it, although much smaller, as the data is based on actual surveys and statistics, rather than extrapolations. For rate parameters coming from original JMP data or from user overrides, the following GSD values are used.

Eq. 4.8 $$GSD_o = 1 + N \cdot \ln(m)$$ **, with N = -0.07422**

where

GSD_o = Geometric Standard Deviation of an original JMP rate parameter

If m = 0 the GSD is corrected to 100%

4.2.3 Treatment level employed in countries

In the sections above it was established, what percentage of the generated wastewater is being treated in a wastewater treatment plant (WWTP). WWTPs can have various levels of sophistication. Some WWTP merely remove the bulky solids (first stage mechanical treatment), while others have also more sophisticated stages of biological or chemical treatments.

In order to be able to capture the encountered level of treatment, the model developed here also differentiates the treatment level of a country's WWTP mix. Data is again available from the WHO/UN joint monitoring programme JMP, but not from the world overview file used in the sections above, but from the individual country files.[13]

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[12] The rates presented here all must remain in the bracket of 0% – 100%. Values larger than 100% make no sense. This also applies to an upper boundary estimate. As the upper boundary in a lognormal distribution is given by upper = mean · GSD^2, GSD values must be set so that all possible upper values remain within the valid bracket and are not exceed 100%. With the used factors this is guaranteed.

[13] See https://washdata.org/data/downloads → see column for Household Files (blue icon) → Open tabs for world regions → download appropriate country file, e.g. https://washdata.org/data/country/AUS/household/download for Australia (JMP_2019_AUS_Australia.xlsx) → then see sheet "Wastewater Data".

In the 2019 JMP country files, some data is compiled for 141 countries regarding their wastewater treatment levels.[14] The data can be from various surveys and is usually recent, but can sometimes be 20 years old (especially notable in several South American countries). The data is often not complete or given in a summary fashion, e.g. by providing a rate value for "at least secondary treatment", which adds up WWTPs with one and two stages, but by itself does not characterise either rates separately. Without further data it is also unclear from such an entry whether the country has any tertiary treatment at all or none. A further difficulty in the presented data is the observation that the identical parameters contain an unhelpful mixture of reference bases. For some countries treatment stage rates are given per wastewater *treated*, while for others the rates are per total wastewater *generated.*[15] It is not always clear or implicit which definition is used for a country.

In this situation, the provided data has been manually redacted in the following way. For each country the *most recent* available national rates for either of the three treatment types were isolated (1-stage, 2-stage, 3-stage).[16] From this resulted 46 countries with explicit data for *all three* treatment types. This data was normalised to 100% to consistently obtain the rates per wastewater *treated,* which is only accurate if all three data items are actually present. So for 46 countries statistical data is available representing the employed treatment levels of WWTPs in this country. The 46 countries represent 14% of the world's population.[17]

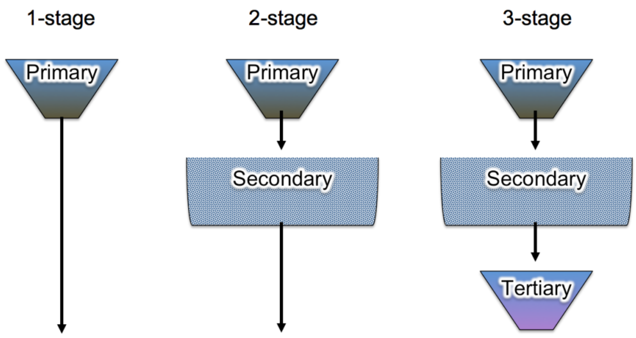

Fig. 4.7 Employed scheme for three generic types of wastewater treatment levels.

[14] Various data can be given: treatment meeting national standards and what those standards are; treatment in plants according to various stages (primary/mechanical, secondary/biological, tertiary, other), data coverage. Also data for faecal sludge treatment plants can be given separately, but only very few countries provide such data.

[15] For instance Zimbabwe reports a treatment rate of 50% in primary stage and 50% in secondary stage, referring to wastewater *treated*, because only less than 5% of wastewater generated are treated in Zimbabwe. But for instance Norway reports stage rates (19%, 3%, 32%) summing up to only 54% and referring to wastewater *generated*, since Norway has considerable untreated releases.

[16] I.e. any of the two available entries "Secondary" or "Secondary with unknown exposure" was taken to represent the rate of treatments in plants with two treatment stages. The other pertinent entries "Secondary with low exposure", "…with medium exposure", "…with high exposure" were not used by any country. Sometimes a rate for two-stage treatment could be calculated by difference, for instance when entries were given for "At least secondary" and "At least primary". An entry for "tertiary or higher" was used for the three-stage treatment rate, as in this project further treatments e.g. for micro-pollutants play no role. Important is also to heed statistical rates given as zero and distinguish them from unavailable rates.

[17] The 46 countries are, in order of increasing GNI: Yemen, Zimbabwe, Egypt, Morocco, Tunisia, Jordan, Albania, Belarus, Serbia, Libya, Turkey, Brazil, Bulgaria, Mauritius, Romania, Croatia, Chile, Poland, Hungary, Latvia, Slovakia, Lithuania, Greenland, Bahrain, Puerto Rico, Portugal, Estonia, Slovenia, Cyprus, Spain, Kuwait, Italy, United Kingdom, France, New Zealand, Israel, Canada, Germany, Netherlands, Sweden, Denmark, Ireland, Iceland, Luxembourg, Norway, Switzerland.

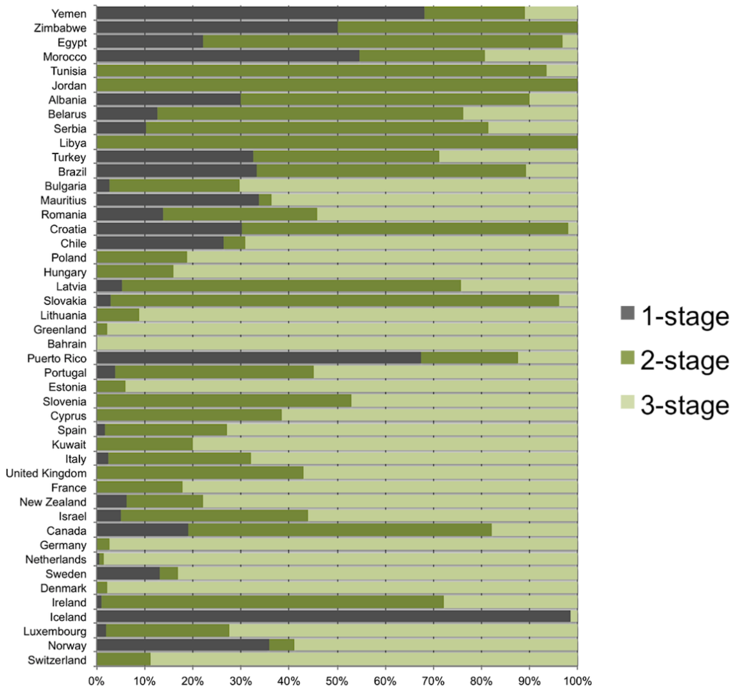

Fig. 4.8 Manually redacted JMP data on wastewater treatment levels in 46 counties, sorted according to Gross National Income GNI. 100% represents the wastewater centrally treated in a country, not all wastewater generated.

The JMP country data list framework would also allow for differentiations for rural and urban territories within a country. Alas only three countries provided rural rates and 9 countries urban rates. This was considered to be too small a foundation to incorporate a differentiation between rural and urban treatment levels. So in the model presented here, no differentiation of treatment is considered in rural or urban WWTPs. Any wastewater treatment—in national, rural or urban territories—is based on the same mixture of treatment stages. In the calculation tool the user can override the values with own data.

Extrapolations for treatment levels

Although the JMP country data provides statistical information on treatment levels in 46 countries, a lot of countries are not covered. For a particular missing country, it would be best to find pertinent literature data or country statistics, or to estimate parameters based on country-specific treatment conditions. In order to be able to suggest at least *estimates* of treatment levels, a coarse extrapolation is performed here, based on the available 46 countries data and their Gross National Income GNI.

The available data covers 46 countries of various economical wealth with incomes between 860 and 85'000 $/capita.year. While in the wealthier countries, statistical data is usually more abundant, the expressed goal of the JMP programme is the Sustainable Development Goal of improvement of sanitation and wastewater treatment, and therefore seeks out to capture the status of wastewater treatment also in less economically wealthy countries. Thus, fortunately the range of available data seems wide enough to attempt also extrapolations for low-income countries.

The plot of the rates of treatment stages vs. GNI shows some coarse trends. Plants with only primary stage treatment are frequent in low-income countries, but usually close to absent in high-income countries. Plants with 3 stages are frequent high-income countries, but rare in low-income countries, especially below 10'000 $/capita.year.

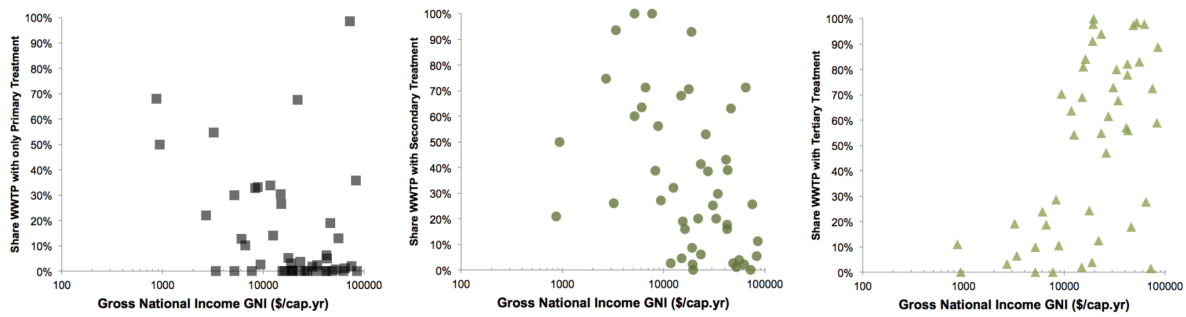

Fig. 4.9 **Manually redacted JMP data on wastewater treatment levels in 46 counties. Share of treatment with only primary stage (left), with primary and secondary stage (middle) and primary, secondary, and tertiary stage (right). 100% represents the wastewater centrally treated in a country, not all wastewater generated.**

For each of the three treatment levels, tiered median values are calculated and extrapolations are fitted onto that central trend.

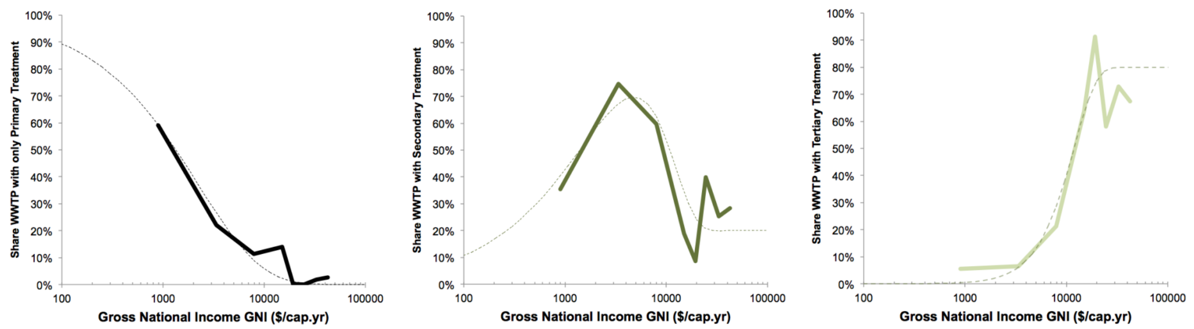

Fig. 4.10 **Tiered median values of the plots in Fig. 4.9 (solid lines) and derived extrapolations (dashed).**

Eq. 4.9 $$\%1ST = e^{\left[c \cdot GNI^{0.7}\right]}$$ **, with c = -4.5E-3**

where

%1ST = Extrapolation for the share of wastewater treatment in plants with only a primary stage

GNI = Gross National Income ($/capita.year)

Please note the exponent 0.7 to the GNI variable

Eq. 4.10 $$\%3ST = 80\% \cdot \left(1 - e^{\left[c \cdot GNI^{2}\right]}\right)$$ **, with c = -4.3E-9**

where

%3ST = Extrapolation for the share of wastewater treatment in plants with a three-stage treatment

Please note the exponent 2 to the GNI variable

Since 100% refers to the sum of wastewater treated, the difference to 100% must be the remaining share of wastewater treatment in plants with a two-stage treatment (primary and secondary).

Eq. 4.11 $$\%2ST = 1 - (\%1ST + \%3ST)$$

where

%2ST = Extrapolation for the share of wastewater treatment in plants with a two-stage treatment

Uncertainty

As can be seen in Fig. 4.9 the variability of treatment levels is quite diverse and the trends with GNI used for extrapolated estimates are therefore quite uncertain. For extrapolated shares a comparatively large geometric standard deviation GSD is attached.

Eq. 4.12 $$GSD_e = 1 + N \cdot \ln(m)$$ **, with N = -0.5**

where

GSDe = Geometric Standard Deviation of an extrapolated share

m = mean value of share (between 0 and 1)

If m = 0 the GSD is corrected to 100%

For share data coming from statistical data or from user overrides the relatively smaller GSD_o calculated from Eq. 4.8 is used.

The resulting country data compiled for wastewater disposal is shown in Appendix B.

5 Modelling concept wastewater treatment

Like with other waste treatment models in ecoinvent (Doka 2003, 2017) the ultimate goal is to obtain process inventories for the disposal of a *specific wastewater*, not merely of an average input of wastewater. Emissions from the treatment as far as possible heed the composition of the specific wastewater under investigation. If a wastewater contains for instance no phosphorus, then no phosphorus emissions will be inventoried for this wastewater.

In order to estimate the burdens specific to a certain waste, a two-step approach has been followed for the disposal inventories in the ecoinvent realm (cf. Doka 2003-IV).

Working point model

In a first step, a so-called working point model of the wastewater treatment plant is created. The aim of this is to describe the typically observed fate of pollutants during disposal and record the average operation inputs of e.g. energy and auxiliaries. Here the typical, average operation conditions in treatment facilities are determined. The "working point" is that state of operation of a disposal facility that can reasonably called typical or average. A facility can also encompass a mix of several technologies to represent a country or regional average. This forms the basis of the second step.

Waste-specific model

With the average facility information, the operation flows are attributed to the components in incoming average waste. Components are usually contents of chemical elements (like cadmium, or nitrogen) but can also encompass other parameters like water content or heating value. This second step can be seen in LCA terms as as *multi-input allocation*: emissions and requirements are distributed onto their causing factors. Some flows also might not be allocated to specific elements, but to the waste input as a whole (so called process-specific flows, as opposed to waste-(composition)-specific flows). The result of this allocation is a largely waste-specific model of the disposal process which can now be combined with any arbitrary waste composition to produce a waste-specific inventory of the disposal of that particular waste. This waste-specific inventory then represents an *allocated fraction* of the average working point expenditures attributed to this specific waste.

6 Average wastewater composition

To derive transfer coefficients for the working point model, the average wastewater input to treatment must be known. As with any waste also wastewater has considerable compositional vagaries, but on average there are more definite trends and relations.

A very extensive analysis of 69 chemical elements is performed in Vriens et al. (2017). Effluents and sludge of 64 Swiss WWTPs of varying sizes were investigated in detail in 2016. Except for elements going into air—carbon and nitrogen—this allows a back-calculation of the input wastewater, which is simply the sum of sludge and effluent. Vriens et al. (2017:Tab S9) gives the mean wastewater input flows per population-equivalent (p.e.) and day. In the measured WWTPs, the mean wastewater input amount per p.e. and day is 0.5576 m^3, which can be used to convert the flows per p.e.-day into a wastewater concentration in mass per m^3, i.e. the sought after concentrations in average wastewater. For definition of average wastewater in the tool input the unit "kg element per kg wastewater" is employed to be consistent with the "kg element per kg wet waste" for solid waste definitions. See chapter 19 'Wastewater composition definition' on page 62.

The wastewater disposal inventory is per m^3 wastewater as a functional unit, and the employed wastewater input composition will be scaled up by a factor 1000.

Tab. 6.1 Mean concentrations in untreated wastewater derived from Vriens et al. (2017). Mostly calculated from their Tab. S9 (see text and footnotes for details).

e	mg e/m^3 WW in	comment	e	mg e/m^3 WW in	comment
Li	9.0204		Cd	0.25107	
Be	0.030486		In	0.014347	
B	55.593		Sn	3.7839	
Na	64560		Sb	1.2553	
Mg	8069.9		Te	0.035866	
Al	10.581		Cs	0.41246	
Si	961.22		Ba	55.593	
P	4483.3		La	2.0444	
S	15602		Ce	5.0392	
K	12374		Pr	0.23313	
Ca	39453		Nd	0.86079	
Sc	1.614		Sm	0.23313	
Ti	25.107		Eu	0.068146	
V	4.4833		Gd	0.62766	
Cr	6.6353		Tb	0.025107	2
Mn	57.386		Dy	0.1345	
Fe	3355.7	1	Ho	0.025107	
Ni	4.6626		Er	0.07532	
Co	1.3988		Tm	0.01076	
Cu	53.8		Yb	0.089666	
Zn	136.29		Lu	0.01076	
Ga	0.52006		Hf	0.071733	
Ge	0.23313		Ta	0.046626	
As	0.68146		W	0.3228	
Se	0.73526		Re	0.0034636	3
Rb	11.657		Os	0.016441	3
Sr	288.72		Ir	0.0029142	3
Y	0.4304		Pt	0.0073497	3
Zr	2.5644		Au	0.025107	
Nb	0.34073		Tl	0.04842	
Mo	1.9906		Pb	6.169	
Ru	0.012044	3	Bi	0.62766	
Rh	0.033178	3	Th	0.14347	
Pd	0.013105	3	U	0.86079	
Ag	1.7754				

1 Wastewater input is back-calculated by (Vriens et al. 2017) from flows in sludge and in effluent. The iron content in wastewater input was corrected here by subtracting the iron added during phosphorus precipitation in the third stage of the WWTPs. 45% of the phosphorus in wastewater is assumed to be removed by precipitation, leading to $FePO_4$ in the sludge, adding to the iron content in sludge. Correcting this leads to a reduction of the Fe content in wastewater by a factor 0.48.

2 The terbium content was reduced here by a factor 1000 over the original. The amount given in Vriens et al. (2017:Tab S9) was at odds with data calculated from sludge and effluent flows, as well as the nationwide flux in Tab S9.

3 No data given in Vriens et al. (2017:Tab S9). Amount calculated by adding the median concentration amount in WWTP effluent and the amount from 0.0002611 kg sludge per litre wastewater, being the median sludge production in the measured 64 WWTPs calculated from (Vriens et al. 2017:Tab S1). If median concentration amounts were given as below detection limit, 71% of the detection limit was used.

Organic carbon in untreated wastewater

From a survey of recent annual reports of Swiss WWTPs, a geometric mean of 124 mg/l organic carbon (TOC) is established. Hydrogen and oxygen in organic matter are derived from typical average molar ratios of H/C of 1.47 and O/C of 0.48, based on measurements of sewage solids and liquids from (Roskosch & Heidecke 2018, Maizel & Remucal 2017, Munoz et al. 2017, Fakkaew et al. 2018, Onabanjo 2016, EC 2001,von Raczeck 1993). This results in 15.19 mg H and 79.37 mg O per litre untreated wastewater.

For BOD in average wastewater a geometric mean of 218.1 mg/L is found in the same survey, and 399.7 mg/L for COD. From these average values typical ratios for COD/TOC 3.22, for BOD/TOC of 1.7587 can be derived, which can be used to convert BOD and COD data into a TOC figure (cf. chapter 19 'Wastewater composition definition' on page 62).

Nitrogen in untreated wastewater

A value of 31 mg N/l is calculated from a Swiss total nitrogen flow in untreated wastewater of 47'900 metric tonnes for the year 2020 (Heldstab et al. 2013:49) and a treated annual wastewater volume in Switzerland of 1544 million m^3.[18]

Mercury in untreated wastewater

Surprisingly, a missing element in the very large scope of investigated chemical elements in (Vriens et al. 2017) is mercury. Data is available from a recent study (Berg et al. 2021). The median amount of total Hg in untreated wastewater going into Swiss 28 WWTPs measured in 2017, was 0.58 microgram per m^3 (Berg et al. 2021:Fig 3a). In the same study also a transfer coefficient to sludge of 95% is specified, which is used in the model.

7 Emissions from sewers

Sewers are infrastructures to transport wastewater away from the wastewater producing location. This is commonly achieved by free flow due to natural inclination and rarely pumps are required to overcome topographies. In poorly planned, constructed or maintained sewers wastewater can become stagnant, i.e. motionless. Under these circumstances it is possible that wastewaters start to degrade in sewers and even to become anaerobic and emit methane.

IPCC (2019:20) has a generic calculation procedure for methane emissions from "stagnant, open and warm sewers", i.e. largely motionless wastewater in *open* sewer ditches in *warm* climates. For these conditions IPCC suggests a generic methane emission of approximately 58 g per m^3 average wastewater.[19] IPCC estimates that 50% of the degraded carbon in stagnant sewers is emitted as methane (MCF=0.5). These figures imply that in stagnant sewers about 70% of the carbon in wastewater is degraded and emitted (half as CH_4 and half as CO_2).[20] This proportion appears rather large. A stagnant sewer in the model of IPCC appears to be largely a *dysfunctional* sewer where wastewater is *stored* rather than transported. Indeed the average emissions factors given for stagnant sewers in IPCC are the same as those for a "communal latrine (with many users) in dry climate with ground water table lower than latrine" (IPCC 2019:21). The IPCC calculation does not heed the length of stagnant sewer sections or a hydraulic retention time, which would be parameters influencing

[18] Calculated from 514 L per cap.day (Binggeli et al. 2011:8) and 8.4 million inhabitants and a 98% sewer connection rate for the year 2020.

[19] IPCC gives two emissions factors for stagnant sewers (0.3 kg CH_4/kg BOD and 0.125 kg CH_4/kg COD). With the average concentration of BOD and COD in Swiss wastewater of 218.1 and and 399.7 mg/L, emissions of 65 and 50 g CH_4 per m^3 are calculated.

[20] 58 grams of CH_4 are 43 grams of carbon (=58/16*12). Another 43 grams of carbon are emitted as CO_2. The removed 86 grams of carbon are 70% of the total organic carbon (TOC) contained in average wastewater of 124 g/m^3 (for Swiss average wastewater).

how long wastewater is exposed to anaerobic sewer conditions. Also the IPCC formulas apply only for stagnant sewers which are also open and warm, while in well flowing sewers zero default emissions are given. It is unclear from this, which default emissions should be applied for stagnant, but *closed* sewers or for stagnant sewers in *colder* climates. IPCC (2019:7) mentions that solar heating in open sewers increases likelihood of emissions in stagnant sewers, but does not specify "warm sewers" with a climate zone or a temperature.

To estimate the frequency of stagnant conditions in a sewer network it would be important to calculate or estimate the velocity distribution of wastewater transport over a typical year and this would require parameters like the capacity of sewer, temporal distribution of wastewater input, distribution of hydraulic retention times, frequency of large leakages in sewer (and loss of volume leading to slow flow), topography and downtimes of any sewer pumps. This modelling can not be performed on a country level in the present model.

No assumptions can be made in the present model, which parts of sewer networks in which countries experience stagnant conditions or how frequently. Emissions from sewers are therefore neglected for the time being. I.e. all sewers are assumed to be functional and non-stagnant.

8 Elimination in wastewater treatment

Several pathways to eliminate pollutants from wastewater exist. In the model the frequently used stages of wastewater treatment are considered. In an preliminary step grit and accompanying waste items like paper and plastic are removed by sieving and sedimentation. In the first mechanical stage a part of solids are removed by sedimentation. In the second biological stage part of the carbon is converted to gaseous CO_2 and nitrogen to gaseous N_2O and N_2. Also on this stage sludge is removed that has formed from biomass growth in wastewater (so called excess sludge). In the third stage (chemical) phosphorus removal is enhanced by addition of precipitation agents.

In the following sections the transfer coefficients for various pollutants in the three stages are described.

8.1 Removal of raw sludge

Raw sludge is the sum of sludges from all three stages (mechanical, biological, chemical). The transfer coefficients to sludge can be derived from extensive measurements on elemental content in treatment sludge and WWT effluent in Vriens et al. (2017). Using the median sludge mass generation of the investigated 64 WWTPs of 0.2611 kg raw sludge dry mass per m^3 wastewater, the transfer coefficients to sludge can be calculated.[21] This calculation is valid for elements not eliminated into air, i.e. where only sludge or treated effluent are output streams. For iron, the iron added with precipitation agents in the third treatment stage needs to be heeded, reducing the transfer coefficient from 99.901% to 99.866%.

[21] In the data from (Vriens et al. 2017) concentration data given as "below detection limit" was replaced with 71% of the detection limit. This affects only a few elements in concentrations below the microgram per litre level in the effluent.

8.1.1 Additional transfer coefficients

Carbon

The transfer coefficient of carbon to sludge is set to 69.9%, which results in a total carbon elimination (including to air) of 94.4%, which is the median average elimination in WWTPs from a literature survey.

Hydrogen

The hydrogen considered here is the hydrogen in organic compounds. The transfer coefficient to sludge is derived from the carbon diverted to sludge and a H/C ratio in sludge of 0.1359 by weight, based on measurements of sewage sludges in (Roskosch & Heidecke 2018, EC 2001, von Raczeck 1993, Munoz et al. 2017, Onabanjo 2016). For average wastewater this results in a transfer coefficient of 77.56%.

Oxygen

The oxygen considered here is the oxygen in organic compounds. The transfer coefficient to sludge is derived from the carbon diverted to sludge and a O/C ratio in sludge of 0.6286 by weight, based on measurements of sewage sludges in (Roskosch & Heidecke 2018, EC 2001, von Raczeck 1993, Munoz et al. 2017, Onabanjo 2016). For average wastewater this results in a transfer coefficient of 68.65%

Nitrogen

The transfer coefficient of nitrogen to sludge is set to 26.3%, which results in a total nitrogen elimination (including to air) of 47%, which is the average nitrogen elimination in Swiss WWTPs (Heldstab et al. 2013:49).

Phosphorus

For phosphorus the total elimination is set to 92% based on measurements in European WWTPs (EEA 2020) and the elimination in stages 1+2 only is set to 50%. Phosphorus is the only element where the elimination in a three stage plant is *not* equal to the elimination in a two stage plant.

Mercury

A transfer coefficient of mercury to sludge of 96% is adopted from (Berg et al. 2021).

Tab. 8.1 Transfer coefficient to raw sludge in a two-stage WWTP, based on data from (Vriens et al. 2017).

e		e	
Li	12.756%	Cd	97.079%
Be	98.677%	In	65.975%
B	8.0065%	Sn	99.06%
Na	0.79698%	Sb	43.924%
Mg	8.0065%	Te	93.635%
Al	46.534%	Cs	56.625%
Si	55.898%	Ba	85.475%
P	50%	La	99.987%
S	4.1702%	Ce	99.992%
K	5.2985%	Pr	99.979%
Ca	20.704%	Nd	99.941%
Sc	49.804%	Sm	97.998%
Ti	92.972%	Eu	96.311%
V	97.589%	Gd	66.196%
Cr	98.326%	Tb	99.851%
Mn	95.942%	Dy	99.847%
Fe	99.866%	Ho	99.851%
Ni	53.083%	Er	99.745%
Co	85.9%	Tm	99.618%
Cu	95.157%	Yb	98.385%
Zn	92.229%	Lu	99.683%
Ga	90.444%	Hf	88.739%
Ge	92.092%	Ta	94.842%
As	67.625%	W	80.479%
Se	71.623%	Re	1.6057%
Rb	21.031%	Os	0.67652%
Sr	18.177%	Ir	2.5446%
Y	99.405%	Pt	60.393%
Zr	92.157%	Au	63.97%
Nb	97.761%	Tl	78.621%
Mo	62.561%	Pb	99.499%
Ru	8.6712%	Bi	99.653%
Rh	12.592%	Th	98.219%
Pd	45.823%	U	63.8%
Ag	99.405%		

8.2 Transfer coefficients primary treatment

Elimination to primary raw sludge

The composition of traces in primary sludge and secondary sludge is given in (Guillemet et al. 2008). The compositions are—within the variability ranges—very similar. This implies that sludge transfer coefficients to primary sludge and to secondary sludge are essentially proportionate to each other. For this reason the transfer coefficients to primary sludge are taken to be a constant fraction of the total raw sludge.

For the transfer coefficients to primary sludge a fraction of 30% of the transfer coefficients of primary and secondary sludge is used (Kalbar et al. 2018:33). I.e. 30% of the values given in Tab. 8.1 are the transfer coefficients to primary raw sludge. This determines the elimination in 1-stage WWTPs.

8.3 Transfer coefficients secondary treatment

Elimination to excess sludge

The remainder 70% of the values given in Tab. 8.1 are the transfer coefficients to secondary sludge (excess sludge), while 30% are eliminated to primary raw sludge.

Carbon to air as CO_2

During aeration in the biological stage, carbon in wastewater is partially metabolised to CO_2, which is emitted to air. In the model this transfer coefficient is set to 24.5%. Together with the 69.9% elimination of carbon to raw sludge a total carbon elimination for a two and three stage plant of 94.4% results.

Nitrogen to air as N_2 and N_2O

During aeration in the biological stage, carbon in wastewater is partially metabolised to molecular nitrogen, N_2, and emitted to air. A fraction of 20.7% if the nitrogen input in wastewater is assumed to be removed via this route. With this transfer to air, the complementary transfer to sludge results in an appropriate N/C ratio of 0.1 in the generated excess sludge.

During this denitrification process also some gaseous nitrous oxide (N_2O) can be formed, which is a greenhouse gas and depletes stratospheric ozone. In the model 0.68% of the nitrogen removed in denitrification to air is assumed to be N_2O-N (Doka 2003-IV, based on Maurer 2002).

For an average wastewater with 31 g N/m^3 and a TK_N to air of 20.7%, the N_2O emissions are 0.137 g/m^3 and around 28 g per capita and year. IPCC gives a range of 3–60 g per capita.year (Hobson et al. 2000), which fits well with amount calculated here.

8.4 Transfer coefficients tertiary treatment

The tertiary treatment stage removes phosphorus from wastewater by adding precipitation agents. In the model, a third stage removes 42% of the phosphorus of the initial untreated wastewater. The first two stages already remove 50% of the phosphorus. Thus the total elimination of a three stage plant in the model is 92%.

The third stage removes phosphorus as $FePO_4$. The chemical sludge removed in the third stage is added to the raw sludge flow from the primary and secondary stages and therefore adds iron to the sludge. Per kg of phosphorus removed to sludge in the third stage 1.8 kg of iron are added. The precipitation agent is added in excess. The excess amount of the agent is added to the WWT effluent, leading to increased amounts of iron and sulfur.

Inventoried demand of precipitation agents is described in chapter 11.1 'Phosphate precipitation' on page 35.

8.5 Synopsis transfer coefficients wastewater treatment

Element	Transfer coefficients primary sludge	Transfer coefficients secondary sludge	Transfer coefficients to air in secondary stage	Transfer coefficients chemical sludge	Transfer coefficients final effluent
O	20.596%	48.056%	–	–	31.348%
H	23.268%	54.291%	–	–	22.441%
C	20.97%	48.93%	24.5%	–	5.6%
S	1.2511%	2.9191%	–	–	95.83%
N	7.89%	18.41%	20.7%	–	53%
P	15%	35%	–	42%	8%
B	2.402%	5.6046%	–	–	91.993%
Cl	–	–	–	–	100%
Br	–	–	–	–	100%
F	–	–	–	–	100%
I	–	–	–	–	100%
Ag	29.822%	69.584%	–	–	0.59468%
As	20.287%	47.337%	–	–	32.375%
Ba	25.643%	59.833%	–	–	14.525%
Cd	29.124%	67.955%	–	–	2.9213%
Co	25.77%	60.13%	–	–	14.1%
Cr	29.498%	68.828%	–	–	1.6737%
Cu	28.547%	66.61%	–	–	4.8431%
Hg	28.8%	67.2%	–	–	4%
Mn	28.783%	67.16%	–	–	4.0578%
Mo	18.768%	43.793%	–	–	37.439%
Ni	15.925%	37.158%	–	–	46.917%
Pb	29.85%	69.649%	–	–	0.50141%
Sb	13.177%	30.747%	–	–	56.076%
Se	21.487%	50.136%	–	–	28.377%
Sn	29.718%	69.342%	–	–	0.94024%
V	29.277%	68.312%	–	–	2.4114%
Zn	27.669%	64.56%	–	–	7.7711%
Be	29.603%	69.074%	–	–	1.3228%
Sc	14.941%	34.863%	–	–	50.196%
Sr	5.4532%	12.724%	–	–	81.823%
Ti	27.892%	65.08%	–	–	7.0279%
Tl	23.586%	55.035%	–	–	21.379%
W	24.144%	56.335%	–	–	19.521%
Si	16.769%	39.129%	–	–	44.102%
Fe	29.96%	69.906%	–	–	0.13365%
Ca	6.2112%	14.493%	–	–	79.296%
Al	13.96%	32.574%	–	–	53.466%
K	1.5896%	3.709%	–	–	94.701%
Mg	2.402%	5.6046%	–	–	91.993%
Na	0.23909%	0.55789%	–	–	99.203%

9 Sludge digestion

9.1 Country-specific digestion rates

Country data on occurrence of digestion of wastewater treatment sludge and digester gas utilization is compiled in (Munoz 2019).

Two parameters are generated from the given data.

1. Share of raw sludge into anaerobic digestion, %dig
2. Share of digester gas into energy utilisation, %CHP (combined heat and power)

The first parameter %dig refers to which fraction of the generated raw sludge of the WWTP is digested anaerobically, either on-site or—usually for smaller plants—at another facility. The remainder not going into a digestion is assumed to go into sludge disposal undigested, i.e. without generating any digester gas.

The second parameter refers to the fate of the generated digester gas going into an energy utilization—frequently an on-site conversion into heat and/or electricity (CHP). The remainder of the digester gas is assumed to be flared without energy use. A third option would be upgrading of digester gas (~65 volume% methane, ~35 V% CO_2) into biomethane (~100% methane) and further utilisation in third party heating or transport combustion engines, but this is not regarded in the present model. As the utilised digester gas reduces on-site energy demand of the WWTP, the advantage of digester gas energy utilisation is included in the inventory.

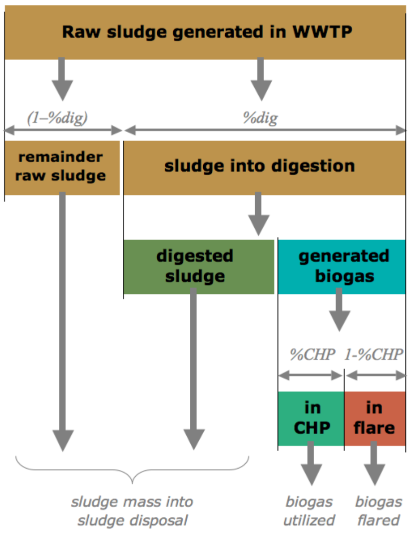

Fig. 9.1 Scheme of the parameters describing the fate of the raw sewage sludge generated in the wastewater treatment plant, which are employed in the model presented here. Raw sludge is either digested anaerobically or not. Remaining digested sludge mass joins the disposal fate for sewage sludge. Biogas generated in digestion can be utilized energetically (CHP) or go to a flare without energy utilisation.

The available data covers 69 countries, which encompass approximately 82% of the world's population. Some populous countries which have significant shares of municipal wastewater treatment are missing, like Tunisia, Jordan, Belarus, or the United Arab Emirates. To avoid data gaps in the assessment, extrapolations for the two parameters %dig and %CHP were derived based on available data plotted against Gross National Income (GNI). These provide at least some qualified estimates, although actual statistical country data would be preferable.

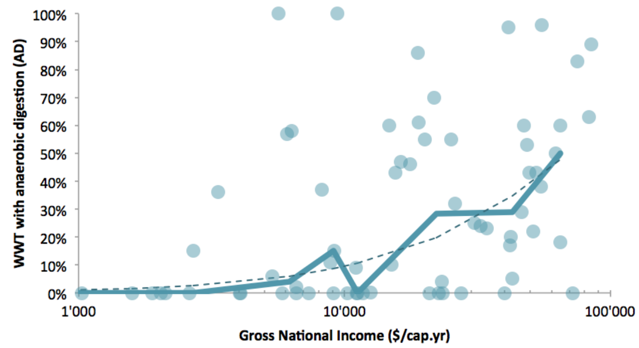

Fig. 9.2 **Plot of a country's share of WWTPs with anaerobic digestion (%dig) against the Gross National Income GNI (dots), the central trend as the tiered median values (solid line) and the derived extrapolation (dashed line).**

Based on the central trend as observed from the available country data versus the Gross National Income, an extrapolation for %dig is derived, which is an exponential function:

Eq. 9.1 $\%dig = 1 - e^{[c \cdot GNI]}$ **with c = -1E-5**

where

%dig = A country's share of WWTPs with anaerobic digestion

GNI = Gross National Income ($/capita.year)

The available data for %CHP plotted against GNI data is shown in Fig. 9.3. The central trend of the median shows unsurprisingly the more frequent use of CHP in countries with larger GNI. The spike at low GNI (~2300) is based on two data points and not very reliable. The observable dip in %CHP in countries with GNI >50'000 $/cap.yr is possibly an effect of increased conversion of digester gas being converted to a biomethane fuel product.

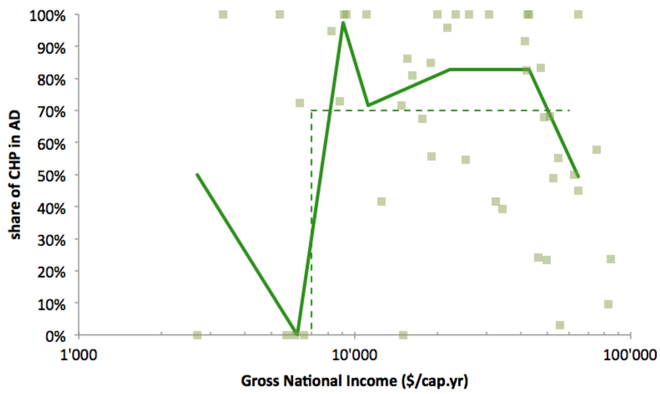

Fig. 9.3 **Plot of a country's share of sewage sludge anaerobic digestion with energy utilization (%CHP) against the Gross National Income GNI (dots), the central trend as the tiered median values (solid line) and the derived extrapolation (dashed line).**

For missing data a simple bi-value approximation was made, where for any country with a GNI over 7000 $/cap.yr a fixed %CHP of 70% is assumed, and 0% for countries with lower GNIs.

Eq. 9.2 $$\%CHP = \begin{cases} if\ GNI < 7000 : \%CHP = 0 \\ if\ GNI \geq 7000 : \%CHP = 70\% \end{cases}$$

where

%CHP= A country's share of sewage sludge anaerobic digestion with energy utilization

GNI = Gross National Income ($/capita.year)

9.2 Modelling of sludge digestion

Transfer coefficient carbon to digester gas

During digestion it is assumed that 60.3% of the carbon in input sludge is transferred to digester gas. The methane content in digester gas is assumed to be 35 V%, and 65 V% CO_2. Thus 1 kg of carbon in sludge leads to 0.7739 kg methane and 0.5226 kg $_{CO2}$, heeding the weight increases of the compounds.

Methane leakage

Kägi (2019) inventoried a sewage sludge digestion process with a digester gas leakage rate of 0.75%.[22] This leakage is applied here to derive air emissions of uncombusted methane CH_4.[23] The carbon balance is heeded: carbon in emitted methane is subtracted from the carbon emitted as CO_2 after combustion.

Transfer coefficient nitrogen to digester gas

Nitrogen in sludge is mostly associated with organic matter of the sludge. Nitrogen can go to digester gas as gaseous ammonia (NH_3) or elemental nitrogen gas N_2. The N/C ratio in raw and digested sludge is roughly constant and therefore the total nitrogen removal must be in proportion to the carbon removal. The nitrogen transfer coefficient is therefore the same as the carbon transfer coefficient (60.3%). Most of the nitrogen in digester gas will be elemental N_2. Some nitrogen will be in reactive ammonia NH_3. A literature source indicates an emission factor of digester gas burning of 732.5 mg N per m^3 digester gas (Notter & Graf 2016).[24] This flow refers to nitrogen in a reactive form, which will later lead to NO_x emission in burning.[25] In the working point model a share of 1.51% NH_3-N in total nitrogen in digester gas results in 732.5 mg N per m^3 digester gas. The complement of 98.49% is converted to unreactive elemental N_2.

[22] In the comment to the methane exchange. This is a *weight*-percentage rate, referring to an emission of 0.003366 kg methane from 1 m^3 of biogas containing 0.449 kg methane.

[23] The leakage could equally be applied to NH_3, H_2S, and CO_2. For CO_2 the leakage emission will not be different from the emission after an energy utilization or flare. Emissions of NH_3 and H_2S are converted in the inventory to NO_x and SO_2, reflecting the spontaneous atmospheric oxidation reactions these pollutants would undergo rather promptly, and also aiding LCIA, as some LCIA methods don't cover NH_3 and H_2S, but NO_x and SO_2.

[24] Figure 18 of (Notter & Graf 2016) indicates 139 tons of NOx are generated from burning of 1.4 petajoules of sewage gas. Using those study's own parameters (heating value 20.2 MJ/kg, Density 1.2 kg/m^3, p.54) this can be converted to 732.46 mg N/ m^3 digester gas ($= 139 \cdot 10^9 / (1.4 \cdot 10^9 / (20.2 \cdot 1.2)) /(14 + 2 \cdot 16) \cdot 14$).

[25] This approach neglects formation of thermal NO_x from N_2 in combustion air.

Transfer coefficient sulfur to digester gas

Sulfur can go to digester gas as gaseous hydrogen sulfide, H_2S. Treyer (2018) gives a value of 300 mg Sulfur per m^3 biogas from sewage sludge or manure. In the working point model for the average WWTP operation a transfer coefficient for sulfur of 4.69% during digestion leads to that concentration. During digester gas combustion, the sulfur in digester gas will be emitted as sulfur dioxide SO_2.

Volatile (semi-)metals to digester gas

Certain metals can form volatile metalorganic compounds in anaerobic environments, for instance trimethyl antimony $Sb(CH_3)_3$. Based on measurements by Feldmann & Hirner (1995), transfer coefficients to digester gas were established in (Doka 2003:29) for As, Cd, Hg, Pb, Sb, and Sn. These transfer coefficients are used in the model to calculate transfer of metals to digester gas. Upon gas utilisation or flaring the metals are assumed to be emitted to air.

Tab. 9.1 Transfer coefficient of volatile elements to digester gas.

Element	Transfer coefficient sludge to digester gas
As	0.13%
Cd	0.000045%
Hg	0.00024%
Pb	0.0000037%
Sb	0.01%
Sn	0.000017%

10 Digester gas utilization

In the model presented here, digester gas produced can either be converted on-site for energy or be flared without energy utilisation (see previous chapter). The share of energy utilisation can be overwritten by the user. The possibility of upgrading digester gas to biomethane and off-site utilisation in gas-consuming processes (heating, road transport, or other) is not included for simplicity's sake.

In the energy utilisation a conversion to electricity and/or useful heat is possible. The user can set the gross efficiencies of the generation of those energy products individually. The produced energy is used by the WWTP internally to reduce any external energy input for the wastewater treatment. This means that the inventory will not include any energy *outputs*, but the energy inputs required to treat a specific wastewater will be *reduced* in accordance to the wastewater's contents transferred to energy-rich digester gas (carbon in methane, sulfur in hydrogen sulfide, nitrogen in ammonia) and the average utilization of that digester gas. Even in wastewaters with very high carbon loads and therefore large digester gas energy, the net energy balance is negative, since wastewaters with large carbon loads also require large amounts of energy to process for the aerobic treatment stage and sludge handling.

10.1 Digester gas combustion emissions

Emissions are calculated waste-specifically from chemical elements. E.g. if wastewater contains sulfur, some of it ends up in digester gas and will lead to SO_2 emissions. If a wastewater contains no sulfur, then no SO_2 emissions will be attributed from digester gas combustion.

As noted in section 'Transfer coefficient nitrogen to digester gas' on page 33, only 1.51% of the nitrogen in digester gas is assumed to be converted to NO_x air emissions, while the remainder is emitted as elemental N_2.

The volume of digester gas generated is calculated waste-specifically for the components ending up in digester gas. A specific particulate emission factor is attached to the produced and combusted volume of digester gas. Per m^3 digester gas combusted or flared and emission of 46.75 mg $PM_{<2.5}$ is inventoried. This is based on Swiss data for sewage gas motors (Notter & Graf 2016).[26]

10.2 Energy production efficiencies

In Switzerland 271 municipal wastewater treatment plants produced 433 TJ of electricity, 780 TJ of usable heat, and 665 TJ of biomethane from 2295 TJ digester gas in 2019 (BFE 2020:36). Disregarding the biomethane production (as this utilisation is not heeded in this model), this results in gross efficiencies of 26.56% and 47.85% for electricity and heat.[27]

11 Treatment auxiliaries

11.1 Phosphate precipitation

In the third stage of a WWTP some of the phosphorus still remaining in solution after the first two stages is precipitated by adding precipitation chemicals. Here iron sulphate ($FeSO_4$) is considered. Addition of $FeSO_4$ precipitates much of phosphorus as $FePO_4$, but it is usually dosed in excess.

From a literature survey of current Swiss WWTPs a typical mean value of 57.7 g $FeSO_4$ per m^3 wastewater treated is found. In the working point model 1.88 g of phosphorus is removed in the third stage. So per kilogram of phosphorus removed in the third stage, an amount of 30.65 kg of $FeSO_4$ is required.

This specific demand is employed to derive a *waste-specific $FeSO_4$ demand* in the inventory, depending on the conditions that a wastewater contains phosphorus, that wastewater is sewered to any WWTPs and whether those WWTPs have a third treatment stage.

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26 In Notter & Graf (2016: Fig 18) an annual emission of 2.7 tonnes of PM from the combustion of 1.4 Petajoule sewage digester gas are given. Notter & Graf use a LHV 20.2 MJ/kg and density 1.2 kg/m^3 digester gas, and thus 46.75 mg PM/m^3 = 2.7 /(1.4/20.2/1.2).

27 26.56% = 433/(2295-665); 47.85% = 780/(2295-665);

11.2 Sludge flocculation

To aid secondary sludge dewatering, a flocculant is added. For the model a polymer flocculant of poylacrylamide is considered.[28] From a literature survey of current Swiss WWTPs a typical mean value of 2.63 g flocculant per m^3 wastewater treated is found. In the working point model 139 g of secondary sludge dry matter (DM) is generated. Thus the flocculant use is 18.86 kg per kilogram of DM.

This specific demand is used to calculate a *waste-specific flocculant demand* in the inventory, depending on the conditions that a wastewater is sewered to any WWTPs and the secondary sludge generated in them.

The flocculant composition $(C_3H_5NO)_n$ is added to the generated sludge composition. In that way, even specific wastewaters without any carbon can generate sludges with carbon and subsequently also digester gas.[29]

12 Treatment energy demand

The energy demand for a three-stage WWTP is derived from a literature survey of annual reports of Swiss WWTPs for the years 2010–2019. The geometric mean of total electricity demand is 0.333 kWh per m^3 wastewater treated. From the same survey the typical relative shares of the energy demand for different parts of the facility were derived.

The electricity demands in the working point model are allocated to various flows to derive specific electricity demands. For instance the electricity demand in the biological stage is largely associated with pumping air into the pools for aerobic degradation. This electricity demand is therefore allocated to the actual oxygen uptake required for degradation.

Tab. 12.1 Electricity demand calculation for WWTPs

Contribution	Share of electricity demand	Allocand	Electricity demand, in kWh per allocand unit
1st stage mechanical	17.23%	m^3 wastewater input	0.0574
2nd stage biological	56.65%	kg oxygen uptake in 2^{nd} stage	1.3278
Sludge digestion	12.28%	kg raw sludge dry mass into digestion	0.1796
Sludge dewatering	8.10%	kg final sludge dry mass	0.2376
Other	5.74%	m^3 wastewater input	0.01912 *

* For 1-stage WWTP this contribution is multiplied by a factor 0.233, representing the lower expenditure expected in 1-stage plants (derived from shares for 1^{st} and 2^{nd} stage, 0.233 = 17.23% / (17.23%+56.65%)

[28] Poylacrylamide has the formula $(\text{-}CH_2\text{-}CH(CO\text{-}NH_2)\text{-})_n$

[29] The flocculant polymer is assumed to contribute fossil carbon. This addition of fossil carbon can influence the properties of the inventoried emissions. For instance TOC emissions to water after the WWT have the share of biogenic carbon specified by the user for the wastewater. But in the inventory also further downstream TOC emissions to water from the incineration of sewage sludge can be added and the sludge can have a different share of biogenic carbon due to the flocculant. The appropriate share of biogenic carbon in the inventoried TOC emission depends on the weighted mean of the contributing parts. This calculation is performed in the model and the resulting properties are written into the EcoSpold2 inventories.

The geometric mean of total heat demand is 0.19148 kWh per m^3 wastewater treated. The vast majority of the heat demand (90%) is associated with sludge digestion. This part of the heat demand is allocated to the raw sludge dry mass into digestion. In the working point model this leads to a specific heat demand of 2.725 MJ per kg dry matter into digestion. The remaining 10% of the heat demand are simply allocate to each m^3 of wastewater input, leading to 0.06893 MJ per m^3 wastewater.

12.1 Economy of scale

In the present model, the wastewater treatment plants are discerned into urban, rural, and national average plants for inventories with the corresponding territory setting, see chapter 4.2.1 'National, urban and rural wastewater fate data' on page 12. WWTPs display an economy-of-scale trend that larger plants have lower energy demand per m^3 treated. The question arises, whether for rural plants a larger energy demand should be considered in the model.

Fig. 12.1 shows the specific energy demands from 152 WWTPs in the Canton of Vaud (Switzerland) for 2017 versus their treated daily volumes (DIREV 2018).

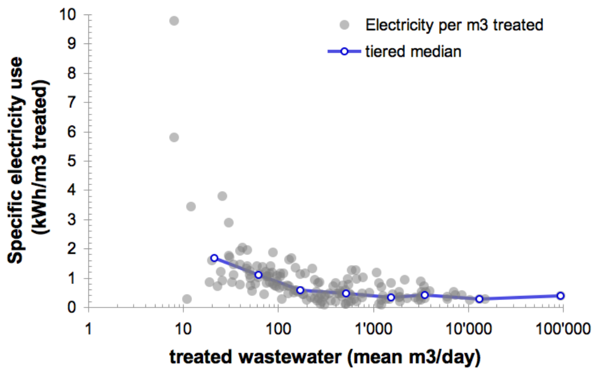


Fig. 12.1 Plot of the specific electricity demands per m^3 treated from 152 WWTPs in the Canton of Vaud (Switzerland) for 2017 versus their respective treated daily volumes (derived from data in DIREV 2018).

The line in Fig. 12.1 represents the tiered median of the data. A trend of larger electricity demands in smaller plants is visible, but this only sets in below a daily volume of 1000 m^3. The generic rural plant in the present model is much larger (4400 m^3/day, 1.6 Mio m^3/year) and thus will have on average the same electricity demand as the larger urban plant. No economy-of-scale for energy demand is therefore considered in the present model.

13 Water balance in treatment plant

In the ecoinvent database water losses to air are inventoried. These can be pertinent in Impact Assessment, for instance in consumptive water losses. For wastewater treatment one would surmise that most wastewater in a treatment plant is ultimately released to a river or lake, as it was assumed in (Doka 2003-IV). In 2014 the ecoinvent Association added a 10% water loss to air in all wastewater treatment datasets from that work, with only 90% of the water being returned to a river. This change was not officially documented by the ecoinvent Association. It was based on a range of 5% – 17% given by the company Veolia in France, depending on the climate and type of technologies (Levova 2014).

The water loss percentage in WWTPs is re-investigated for the present model. Two principal components of evaporation in WWTPs can be distinguished. On one hand, the open pools of the treatment plant allow passive evaporation. On the other hand, aeration pools allow for more intensive evaporation than passive evaporation. Water is also removed with the humidity in disposed sewage sludges, which is also investigated.

The passive evaporation depends chiefly on the water temperature, the wind speed, and the air's relative humidity. Also relevant to express a percentage loss are the hydraulic retention time, i.e. the time during which the wastewater resides in WWTP pools and the depth of pools.

In a generic WWTP the hydraulic retention time is around 17 hours. A medium sized WWTP processes on average around 80'000 m^3 wastewater per day. With a hydraulic reserve capacity of 20% and a generic depth of 3.5 m, assumed for all kinds of pools and stages, the required total surface of all pools A can be calculated to be around 20'000 m^2.[30]

Passive evaporation from pools

McJannet et al. (2012) derived an approximation formula for the specific evaporation from reservoirs and pools, based on a literature survey. The following formalism was found for water evaporated per meter squared and per day.

Eq. 13.1 $$m_p = (2.36 + 1.67 \cdot v) \cdot A^{-0.05} \cdot (1 - RH) \cdot p_{sat}$$

where

m_p = Specific mass of water passively evaporated in kg/day.m^2 = mm/day

v = Wind speed 2 m above surface, m/s

A = Area of the water pool surface, m^2

RH = Relative humidity of air, % of 100% saturation

p_{sat} saturated vapour pressure at the water surface temperature, kPa

Although this describes a specific rate loss per area, the pool area A appears in the formula: The term $A^{-0.05}$ depicts a saturation effect over larger surfaces of water, where not every part of a water surface is equally good at evaporating water, because upwind pool areas have already begun to humidify the air with water vapour. Even for WWTP-sized pools, this effect alone reduces pool evaporation by about 40%.

The saturated vapour pressure p_{sat} depends on the temperature of the water. The Tetens approximation is used here to calculate p_{sat} from the water temperature (Monteith & Unsworth 2013:13):

Eq. 13.2 $$p_{sat} = 0.61078 \cdot \exp\left(\frac{17.27 \cdot T_w}{T_w + 237.3}\right)$$

where

p_{sat} Saturated vapour pressure at the water surface temperature, kPa

T_w = Temperature of wastewater in pools, °C

In the disposal model, the mean annual temperature of the site climate is available (MAT), but that is a parameter for the ambient air. It is assumed here that the wastewater temperature is affected by the environmental air temperature and following formalism is used to derive an estimate for the

30 20'000 m^2 = 80'000 m^3/day · (1+20%) / 3.5 m / 24 h/day · 17 h

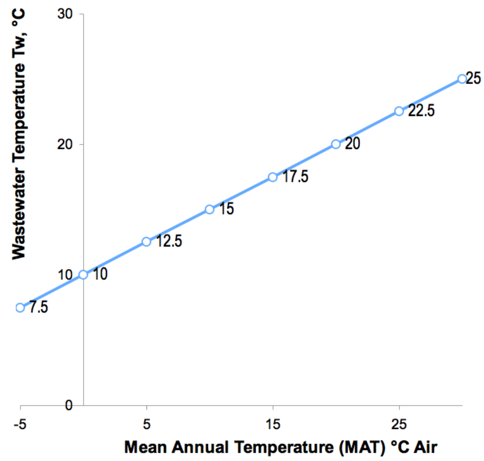
wastewater temperature T_w required above (original). This reflects that in climates with MAT ≤ 20°C, wastewater is thought to be warmer than the outside coming from buildings and that wastewater should remain above freezing temperatures.

Eq. 13.3 $$T_w = \frac{1}{2} \cdot (MAT + 20)$$

where

T_w = Temperature of wastewater in pools, °C

MAT = Mean Annual Temperature (air) of site



The typical relative humidity of ambient air RH is coarsely estimated from available site data of mean annual precipitation MAP and actual evapotranspiration ETa.[31] Following formalism is employed (original):

Eq. 13.4 $$RH = 0.4562 \cdot \left(\frac{ETa}{MAP}\right)^{-0.8267}$$, **corrected to ≤ 100%**

where

RH = Relative humidity of air, % of 100% saturation

ETa = Actual evapotranspiration of the site, mm/year

MAP = Mean Annual Precipitation of the site, mm/year

This approximation for RH can fail, if humidity is influenced by sea air, but as we will see this is ultimately of little relevance.

For wind speed *v* a generic average value of 2 m/s is assumed. This is for 2 m above surface.

With the above, all parameters are available to calculate the passive evaporation in a WWTP. For a Swiss climate[32] the specific water mass evaporated according to Eq. 13.1 is 1.06 kg/m^2.day.[33] The assumed generic WWTP has pool areas A of around 20'000 m^2 and treats 80'000 m^3 wastewater per day. Thus the percentage of wastewater lost to passive evaporation is **0.026%** (= 1.06 · 20'000 / 1000 kg/m^3/ 80'000).

31 The actual evapotranspiration refers to evaporation from solid surfaces, not water areas, and is used in the landfill models to estimate leachate generation.

32 MAT 8°C, MAP 1000 mm/day, ETa 500 mm/day. Thus RH 80%.

33 This amounts to an evaporation rate of 390 mm/year. This is thus in the same order of magnitude as the evaporation from vegetated surfaces of 500 mm/year (=ETa).

Eq. 13.5 $$r_p = \frac{\mathrm{m_p} \cdot \mathrm{A} \cdot 1000}{V_w}$$

where

r_a = Percentage of passive evaporation loss per wastewater input, kg passive loss/kg wastewater

m_p = Specific mass of water passively evaporated in kg/day.m^2 = mm/day

A = Area of the water pool surface, m^2

V_w = Volume of water treated daily, m^3/day

Variations to this calculation yield different results. Most notably for instance in a dry and hot climate (RH=10%, MAT = 25°C) the percentage of passive evaporation can rise to 0.2%. Keeping a Swiss climate, but increasing the average annual wind speed to a breezy 8 m/s increases the loss percentage to 0.11%. Smaller WWTP can have higher loss rates which is chiefly an effect of less deep pools and consequently larger required pool areas per m^3 wastewater treated. Constructing an extreme case of a small WWTP in a arid, hot and windy climate, the loss percentage is 0.9%.[34]

So the passive evaporation in WWTP seems to be around two orders of magnitude below the 5–17% range previously applied by (Levova 2014). But passive evaporation is only one part of the evaporation losses. A second part is the evaporation in agitated aerated pools.

Evaporation in aerated pools

In the secondary, biological stage of WWTPs air is blown into the pool, usually from the bottom. It is reasonable to assume that this intense mixing facilitates evaporation. For the calculation here it is assumed that the air blown trough the aeration pools initially has the same relative humidity RH as the ambient air, but in the pool becomes *fully saturated* with water vapour (i.e. RH = 100%) and thus can carry water vapour from the pools. During aeration, a maximal amount of air used per m^3 wastewater treated is 10.8 kg air/m^3.[35] It is assumed here that the air upon outgassing has achieved the same temperature as the wastewater T_w. The saturation amount of water vapour in air depends on that temperature and is given by following approximation (original).

Eq. 13.6 $$m_{sat} = 0.044 \cdot e^{(0.0591 \cdot T_w)}$$

where

m_{sat} = Specific amount of water per kg of completely saturated air, kg H_2O/kg air

Tw = Temperature of wastewater = temperature of aerated air, °C

The capacity of air to take up water vapour is limited by the original relative humidity RH of the entering air, i.e. if the air blown in is already very humid, the additional evaporation loss is diminished. Initial air RH is set equal to that of ambient air, which was already derived in Eq. 13.4.

The using the 10.8 kg maximal amount of air used per m^3 wastewater treated derived above, the maximal percentage of aeration evaporation loss r_a is thus:

[34] Risch et al. calculate the passive evaporation loss from WWTPs in a French climate (Toulouse) based on monthly measured data to be on average 2.56 mm/day (Risch et al. 2014: SI "Evaporation"). With the generic average WWTP dimensions used above (80'000 m^3 wastewater per day, pool areas 20'000 m^2) this results in an percentage of passive evaporation loss of 0.064% (= 2.56 · 20'000 / 1000 kg/m^3 / 80'000). This matches well the results from the calculations used above when setting a French climate with 50% RH.

[35] Based on a maximal aeration rate of 6000 m^3/h in a WWTP with 16'000 m^3 treated per day (Schuhmacher 2012), and an air density of 1.2 kg/m^3 , thus 10.8 kg/m^3 = 6000 · 1.2 / (16'000/24).

Eq. 13.7 $$r_a = (10.8/1000)\cdot m_{sat}\cdot(1-RH)$$

where

r_a = Maximal percentage of aeration evaporation loss per wastewater input, kg aeration loss/kg wastewater

m_{sat} = Specific amount of water per kg of air, kg H_2O/kg air

RH = Relative humidity of air, % of 100% saturation

In a Swiss climate[36] the maximal aeration loss percentage r_a is **0.002%**. This is around one order of magnitude lower than the passive loss percentage. Since r_a is a maximal percentage, the typical percentage will be even lower. For the wastewater inventory model it is assumed that the typical aeration rate is 80% of the maximal rate. The aeration loss percentage is less dependent on WWTP size, assuming biological stages have similar air requirements per m^3 wastewater treated.

Water loss via sewage sludge

After wastewater treated the remaining sludge is disposed. Three disposal types are considered in the inventory model.

Sludge disposal	Assumed water content in disposed wet sludge
to agriculture	97%
to landfill	75%
to incineration	70%

Sludges are assumed to be partly dried at the WWTP site and the abstracted water is recirculated into the WTWP. The sludges disposed in landfill and incineration are assumed to be dried to a larger degree in order to save disposal costs. In agriculture disposal a high water content facilitates spreading on the field.

If all wastewater is treated in a WWTP (i.e. %WWTP=100%), sludge dry matter in the range of 0.1-0.2 kg is produced per m^3 of average wastewater. Depending on the sludge mass disposal type, between 0.2 and 6 kg of water are removed. Thus the water removal by the sludge route is on average between **0.02% and 0.6%.** In incineration this water will be transferred mostly to the air, but incinerated sludge carries little humidity away from the WWTP. In agricultural disposal, the water in sludge is returned to the soil and not lost.

In the inventory model, the sludge masses and disposal routes are calculated waste-specifically, and the sludge water fate is inventoried accordingly.

Water generation from mineralization of organic compounds

Some amounts water can be generated during decomposition of organic compounds in the WWTP. An aerobic decomposition during the secondary biological stage, can create water, as well as CO_2.

Eq. 13.8 $$C_xH_yO_z + n\,O_2 \rightarrow x\,CO_2 + y/2\,H_2O$$, **with n = (x + y/4 + z/2)**

But is this generated water relevant? An average m^3 of wastewater contains around 100 g of organic carbon with an approximate formula $C_1H_{1.47}O_{0.48}$ (data from chapter 6 on page 23). Approximately 25% of TOC is converted to CO_2 in the biological stage. Thus per 1000 kg of wastewater

[36] MAT = 8°C, T_w = 14°C, RH = 81%.

approximately 0.219 kg of water will be generated.[37] So the water mass increases by **0.02%**. This amount appears negligible, but it compensates partly the water lost by evaporation and sludge removal. In order to have an accurate water balance the waste-specific amount of generated water during the biological stage is included in the model, i.e. will increase the amount of water emitted to river after treatment.

Conclusion water evaporation loss

The above calculations demonstrate that the water evaporation loss in wastewater treatment plants is practically always well below 1 mass-% of the treated wastewater volume and 0.03% is a typical value for Swiss climate. The above calculations of passive and where appropriate aeration evaporation loss are included in the inventory model for the part of wastewater in WWTPs. The calculations are based on the site climate data provided by the user.

14 Process-specific burdens in treatment

Process-specific burdens are burdens in the treatment plant which are not assigned to one specific component of the wastewater but to the whole treated wastewater and are always constant for each m^3.

Grit waste

Grit is large pieces of solid waste that are removed from the wastewater at the very start. Grit consists of packaging, plant leafs and other coarse waste that is typically washed from road surfaces to the sewers. So grit mainly stems from vegetation, littering and road surfaces. It is a technical necessity to remove these waste materials before treatment, and for this reason their disposal is assigned to the treatment process, although the source of these materials is usually not the wastewater-producing process. Grit waste can be thought of as a result of the way sewers are constructed.

From a literature survey of Swiss treatment plants a mean value of 19.59 grams per m^3 treated is found. Their disposal is inventoried as 50% biomass waste and 50% mixed plastic waste.

Sand waste

Sand waste is separated from an initial sedimentation. It can originate from natural sources from waterways or cracked sewer pipes, or from wastewater producers, when they illegally dump unsuitable waste like the contents of cat litter boxes into the toilet.

From a literature survey of Swiss treatment plants a mean value of 4.81 grams per m^3 treated is found. Its disposal is inventoried as inert material, since the pollutant content is probably low.

Uncertainty

Based on the variability of the encountered literature data, for both specific waste flows a geometric standard deviation of 160% is assumed. This uncertainty will be combined with the uncertainty of wastewater mass arriving in treatment, see section on uncertainty of treatment rates on page 22.

[37] 0.219 kg = 100g / 12g/mol · 1.47mol/mol / 1.008g/mol · (1.008 · 2 + 16) g/mol / 1000g/kg.

15 WWTP infrastructure

15.1 Extrapolation of WWTP infrastructure with plant size

The infrastructure of WWTPs was already included in former wastewater treatment inventories (Zimmermann et al. 1996, Doka 2003-IV). There, a postulated linear extrapolation versus plant size, expressed in the nominal design PCE capacity, was used to derive infrastructure materials per plant. Linear extrapolations with plant size have also been used in other studies (e.g. Morera et al. 2020).

For the present work, the linear infrastructure extrapolation is abandoned and replaced with a scaling approach using a power law.[38] Also the former distinction of plants into 5 sizes is abandoned, and replaced with a more coarse classification for urban, rural, and national average sites. The reason for this simplification of size classes is that the availability of five size classes was not a much used feature of the former inventory tool and most datasets were simply created for a generic median plant size.

An examination of several papers devising WWTP infrastructure is presented in Appendix A on page 78. For the reappraisal of the infrastructure materials, a parameter for comparison is formed. This parameter is the Specific Concrete Mass SCM given in (kg concrete / wastewater treated annually). Here, "kilogram concrete" is the mass of concrete that is used for the construction of the whole plant, without reinforcement steel. This figure does not (yet) heed any material lifetimes of the plant, but is simply the total mass of concrete present in the plant, i.e. mass standing. "Wastewater treated annually" expresses the size of the WWTP. This is not a nominal design capacity, but the typical average of actual volume of wastewater treated annually, given in m^3/yr. So the physical unit of the SCM parameter is (kg/(m^3/yr)), or "mass per size". The SCM parameter allows a meaningful comparison of various plants, avoiding issues of different lifespans that different authors have applied.[39] Concrete is the largest part by mass of a WWTP.

Three different sources for WWTP concrete masses were compiled for WWTPs from France, Switzerland[40], and the United States. See Appendix A for details.

Tab. 15.1 Data for three different WWT plants for wastewater treated per year, total concrete mass, and Specific Concrete Mass SCM.

	Wastewater treated per year m^3/yr	**Concrete mass per whole plant** kg	**Specific concrete mass SCM** kg/(m^3/yr)	Source
Olwisheim, France	332'930	9'393'100	28.21	Risch et al. 2015
Ergolz, Switzerland	4'000'000	56'582'240	14.15	Fahner et al. 1995
Mill Creek, Cinncinati, United States	157'618'869	840'549'906	5.33	Xue et al. 2019

38 A good introduction and application of scaling laws in LCA using power law functions can be found in (Caduff et al. 2012).

39 For instance (Xue et al. 2019) chose a 100 year lifespan for concrete parts, (Risch et al. 2015) and (Doka 2007-IV) used 30 years.

40 Fahner et al. (1995) is the same source that was already used in (Zimmermann et al. 1996) and (Doka 2003), but this study has been re-examined for the present work.

As can be seen the SCM decreases with increasing plant size. Plotting the SCM against plant size, reveals the characteristics of this trend, see Fig. 15.1. A power law fits well the observed data, see dashed regression line. The exponent of –0.2689 agrees well with Fermi-style, ad hoc estimates.[41]

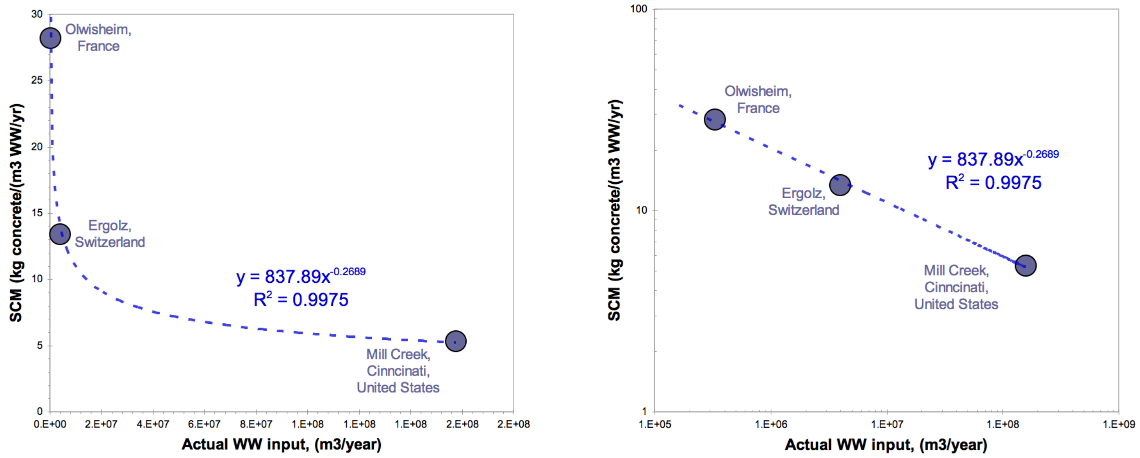


Fig. 15.1 Plot of specific concrete mass SCM against the WWTP plant size with linear axes (left) and double-logarithmic axes (right).

The extrapolation exponent of –0.2689 is applied to all expenditures, except the specific excavation work (m^3 excavation per (m^3/yr) plant size), which is assumed to be constant, i.e. unaffected by plant size.

15.2 Infrastructure expenditures

The WWTP infrastructure expenditures are taken from (Fahner et al. 1995) which was reassessed and expanded for the present work. The data is for the Swiss plant Ergolz, which treats 4 Mio m^3 per year.

Tab. 15.2 shows the infrastructure expenditures used as the basis for extrapolation, reassessed from (Fahner et al. 1995). A land use area of 17'500 m^2 for the whole plant was added. Disposal of materials is included, equal to the amounts inputted. Concrete density is 2470 kg/m^3. Column A in Tab. 15.2 shows the materials and expenditures of the plant standing, e.g. 22'908 m^3 of concrete are 56'582'240 kg, which is the figure in Tab. 15.1. These figures do not yet heed any lifetimes, but are simply the present masses in the standing WWTP. In column B the values from column A are divided by plant size. The plant size is expressed in (m^3/yr), which is the volume of wastewater actually treated annually (not a nominal capacity), here 4 Mio m^3/yr (BL 2009). The figures in column B are then used to perform the extrapolations to other plant sizes as described in the previous chapter.

41 Assuming identical treatment times (hydraulic retention time HRT) and plant reserve capacities, the reservoir volumes of a plant will be proportionate to the treated wastewater Volume $\propto V$. Assuming similar pool geometries and wall thicknesses, the required concrete for those pools will be proportionate to the *surface* of the pool volumes, i.e. $\propto V^{(2/3)}$. The SCM expresses the mass of concrete per treated wastewater, which is $\propto V^{(2/3)} / V = 1 / \sqrt[3]{V} = V^{-1/3}$, i.e. an exponent of -0.333. Some concrete parts of the plant can be expected to be not or less dependent on plant size, so a larger exponent like the observed -0.2689 is sensible.

Tab. 15.2 WWTP infrastructure vector for Ergolz plant used for the extrapolation of WWTP infrastructure expenditures. A: masses and expenditures as of the standing plant (not heading lifetimes). B: specific amounts per plant size, which is expressed as m^3 treated/yr. B is used for extrapolation. C: infrastructure per m^3 wastewater treated, heeding material lifetimes.

		A per plant (standing)	B per actual m^3 treated annually	lifetime yr	C per m^3 treated
excavation, hydraulic digger	m3	86'000	0.0215	40	0.0005375
electricity, medium voltage	kWh	935'000	0.23375	40	0.00584375
concrete, exacting	m3	22'908	0.005726946	40	0.000143174
reinforcing steel	kg	1'957'200	0.4893	40	0.0122325
tap water	kg	3'022'222	0.755555556	40	0.018888889
aluminium, cast alloy	kg	15'750	0.0039375	25	0.0001575
limestone, crushed, washed	kg	530'000	0.1325	40	0.0033125
chromium steel 18/8	kg	128'250	0.0320625	25	0.0012825
flat glass, uncoated	kg	48'400	0.0121	40	0.0003025
copper	kg	19'000	0.00475	25	0.00019
synthetic rubber	kg	23'200	0.0058	40	0.000145
rock wool mat, packed	kg	21'600	0.0054	40	0.000135
chemicals organic	kg	130'800	0.0327	40	0.0008175
bitumen	kg	12'400	0.0031	40	0.0000775
chemicals inorganic	kg	16'400	0.0041	40	0.0001025
polyethylene, LDPE, granulate	kg	400	0.0001	40	0.0000025
polyethylene, HDPE, granulate	kg	77'200	0.0193	40	0.0004825
extrusion, plastic pipes	kg	77'600	0.0194	40	0.000485
Transformation, from pasture and meadow	m2	17'500	0.004375	40	0.000109375
Occupation, construction site	m2a	35'000	0.00875	40	0.00021875
Transformation, to industrial area, built up	m2	10'500	0.002625	40	0.000065625
Transformation, to industrial area, vegetation	m2	7'000	0.00175	40	0.00004375
Occupation, industrial area, built up	m2a	420'000	0.105	40	0.002625
Occupation, industrial area, vegetation	m2a	280'000	0.07	40	0.00175

To arrive at the expenditures attributed to a single m^3 of treated wastewater for this plant, in column C the lifetime of materials is now heeded. I.e. column C is column B divided by the lifetime given. The lifetimes assumed in the original source (Fahner et al. 1995) are used here. Materials with long lifetimes will serve longer and therefore their burden will distributed over a larger mass of treated wastewater.

The data from the Ergolz plant are extrapolated to other WWT plant sizes, by heeding their size S and using the power law approach derived above.

Eq. 15.1
$$SCM = SCM_0 \cdot \left(\frac{S}{S_0}\right)^{-0.269}$$

where

SCM = Specific Concrete Mass of target plant, kg/(m^3/yr)

SCM_0 = Specific Concrete Mass of Ergolz plant, =0.005726946 kg/(m^3/yr)

S = Size of target plant, in (m^3/yr)

S_0 = Size of Ergolz plant, in (m^3/yr)

The specific amounts per plant size (column B in Tab. 15.2) can thus be converted into the infrastructure expenditures for a three-stage plant of an arbitrary size (with excavation being the exception).

15.3 Infrastructure of plant with different stages

The expenditures derived above are for a 3-stage WWTP. Depending on the technology mix of WWTPs used in a particular activity inventory, also 2-stage and 1-stage WWTPs can occur. For 2-stage plants the infrastructure is assumed to be roughly identical to a 3-stage WWTP. For a 1-stage WWTP the infrastructure demand is reduced overall by 65%.

Not all wastewater in an inventory will necessarily be treated in a WWTP, since some can be emitted untreated. WWTP infrastructure is only ascribed to that part of wastewater being treated, i.e. %WWTP. This factor is used to modify the infrastructure requirements of the wastewater disposal activity.

15.4 Application of extrapolation to three types of territory

The wastewater activities can not only be modelled for national average, but also a rural situation or an urban situation, and the required national wastewater fate data for this is derived in chapter 4.2.1 'National, urban and rural wastewater fate data' on page 12.

In rural situations, the WWTPs will tend to be smaller ones and in urban situations the WWTPs will tend to be larger ones, and this has consequences for required infrastructure demands for treated wastewater. The following sections describe how the WWTP size for the extrapolation is derived.

Rural situation WWTP size

For inventories defined to occur in a rural territory, a WWTP with a size of 1.6 Mio m^3 wastewater treated per year is assumed (SW_r). This is based on a typical small-scale WWTP in Switzerland. In other countries different sizes might apply—and indeed even within any country—but due to lack of country-specific data on WWTP size distribution, this single size is used as a generic rural WWTP size here and used for the infrastructure extrapolation.

Urban situation WWTP size

For inventories in an urban territory, a WWTP with a size of 120 Mio m^3 wastewater treated per year is assumed (SW_u). This is based on a large-scale WWTP. Also here this size is used as a generic urban WWTP size and used for the infrastructure extrapolation.

National average WWTP size

For the national average, the typical mean plant size must be determined that represents the national average plant size wastewater is treated in. For this it is helpful to look at the structure of wastewater treatment in a country, with the help of the wastewater fate parameters derived in chapter 'Adopting JMP data for industrial wastewater fate' on page 10.

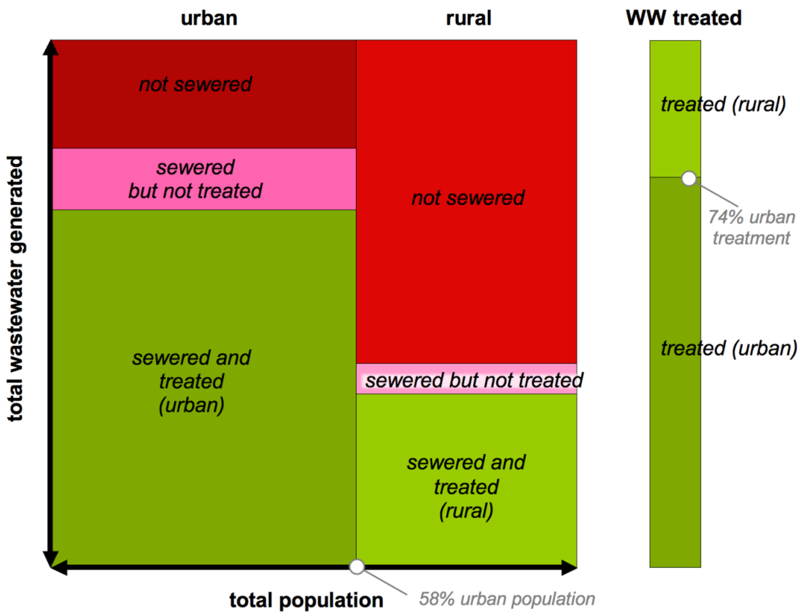


Fig. 15.2 Structure of a nation's wastewater fate (y-axis), differentiated into urban and rural territories (x-axis).

In Fig. 15.2 the structure of a country's wastewater fate is shown, differentiated into rural and urban territories.[42] The whole square area corresponds to the wastewater generated in a country per year. The green areas are the wastewater that is treated in WWTPs. The darker green areas are wastewater treated in urban areas, the light green areas wastewater treated in rural areas.[43] Treatment is usually more frequent in urban areas[44], which means that the fraction of all treated wastewater that is treated in an *urban* WWTP (%Tu) surpasses the share of urban population (%popU).[45] The fraction %Tu can be calculated from the JMP data:

Eq. 15.2 $$\%T_u = \frac{\%popU \cdot \%WWTP_u}{\%popU \cdot \%WWTP_u + (1 - \%popU) \cdot \%WWTP_r} = \frac{\%popU \cdot \%WWTP_u}{\%WWTP_n}$$

where

%Tu = Fraction of all treated wastewater that is treated in an urban WWTP

%popU = Share of urban population in that nation.

%WWTPu = Treatment rate of wastewater generated in urban territories only.

%WWTPr = Treatment rate of wastewater generated in rural territories only.

%WWTPn = National treatment rate of all national wastewater generated.

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42 The example of JMP data for China is shown. China was chosen because its parameters are not concentrated in the 0% or 100% edge, but are midway and result in a meaningful chart.

43 The underlying simplification is made again here that wastewater volumes generated per capita are identical in rural and urban territories, cf. chapter 4.2 'Adopting JMP data for industrial wastewater fate' on page 10.

44 Indonesia is the only exception to this, where JMP data gives—surprisingly—slightly higher rates of sewer connections in rural areas (13.5%) compared to urban areas (9.5%), and this results also in higher treatment rates for rural territories (8.4%) than in urban territories (5.9%).

45 The fraction of treated wastewater in urban treatments %Tu must not be confused with the rate of wastewater treatment in urban areas (%WWTPu). For %Tu, the reference of 100% refers to all wastewater treated in a country, while for %WWTPu the reference of 100% refers to all wastewater generated in an urban territory.

In the example picture the urban population is 58% but the fraction of wastewater treated in urban WWTPs (%Tu) is 74%. The appropriate WWTP size for the national average infrastructure S_n can now be calculated using this latter fraction.

Eq. 15.3 $$SW_n = \%T_u \cdot SW_u + \left(1 - \%T_u\right) \cdot SW_r$$

where

%Tu = Fraction of all treated wastewater that is treated in an urban WWTP

SW_n Size of the national average WWTP (in m^3 treated per year)

SW_u Size of a generic urban WWTP (120 million m^3 treated per year)

SW_r Size of the generic rural WWTP (1.6 million m^3 treated per year)

In the example, the appropriate national average WWTP size S_n is 89 million m^3/yr.

The so calculated national average WWTP size S_n is then used to derive the infrastructure needs for wastewater treatment using the extrapolations derived in chapters 15.1 and 15.2.

If the required data is not available for the calculation of %Tu, the generic global average of 68.08% is used.

16 Sewer Infrastructure

Detailed data on sewer infrastructure is available from (Labhardt 1996). This data encompasses the construction of a new sewer, which lasts 70 years and after that is renovated to last another 30 years. So in total the data covers more or less *two* constructions over 100 years. The data is given per m^3 sewered wastewater for five size class types of sewer networks. The data is nonlinear with size of the network, i.e. small capacity, rural networks tend to have higher material demands.[46] This is used below do derive extrapolations of sewer infrastructure with network size.

Labhardt (1996) was the basis of sewer infrastructure data used in (Doka 2003), where it was converted to five separate datasets per *kilometre of sewer length* (similar to pipeline transport infrastructure). For the present study, the concept of size classes is abandoned, and wastewater fate datasets can encompass a gradual, country-specific mixture of rural and urban sewer networks depending on the urban population share and wastewater fates, which affects the infrastructure demands in a nonlinear fashion. The separate sewer infrastructure datasets are therefore abandoned.

To check the validity of the data in (Labhardt 1996) it was compared to other literature sources. The entire Swiss sewer network was coarsely estimated in (BFS 2005) and for a total sewer network of 57'638 km a total mass of 74 Mio tonnes was estimated. This encompasses all kinds of sewer networks, urban and rural. The Specific Sewer Mass (SSM)—the total standing mass divided by the length—is 1280 kg/m. The source (BFS 2005) is likely to underestimate the total sewer mass as the mass was estimated by applied geometry from length, pipe cross-sections, and material densities, while additional materials like manholes, fittings, connectors etc. were neglected. The figure however includes pipe bedding materials.

[46] The data also reflects the characteristic of rural sewer networks that due to the lower population density, the necessary length of piping per m^3 treated is larger than in more densely populated urban areas.

Another detailed sewer inventory is in (Risch et al. 2015)[47] where the sewer network of Grabels, near Montpellier, France, was inventoried based on detailed, modular construction data. For a sewer network of 46.3 km length a total mass of 86'635 tonnes is necessary (standing mass). The Specific Sewer Mass (SSM) is 1871 kg/m. Risch et al. include not only pipes, manholes, connectors, bedding materials, but also cleanfill/gravel to bury the sewers.

In the data of Labhardt (1996) the Specific Sewer Mass is between 1630 kg/m for rural networks and 1920 kg/m for urban networks. This concurs well with the literature values given above.

16.1 Sewer infrastructure extrapolations

The sewer data given in Labhardt per m^3 wastewater treated shows some strong nonlinear dependencies, which are used here to derive extrapolations to sewer network of different sizes. The size of a network is characterised here by the amount of wastewater it transports annually, i.e. m^3/yr. For most materials and expenditures, the logarithm of sewer size and the material per m^3 sewered result in an excellent fit. I.e. the extrapolation has following general form.

Eq. 16.1
$$\left(\frac{expenditure_i}{m^3\ wastewater\ sewered}\right) = slope_i \cdot \ln\left(sewer\ size\left[\frac{m^3}{yr}\right]\right) + intercept_i$$

where

ln = natural logarithm

For different expenditures and materials different slope factors and intercepts are used.

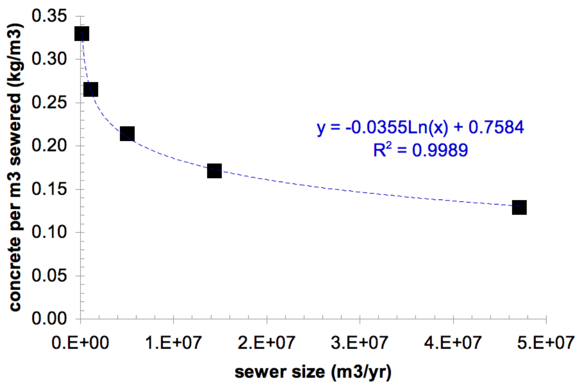

Fig. 16.1 Plot of the concrete demand per m^3 wastewater sewered (from Labhardt 1996) versus to size of the sewer network in (m^3/yr). The size of the five networks is 162'812, 1'074'842, 5'022'730, 14'368'866, 47'111'450 m^3/yr.

The only exception to the single-logarithmic extrapolation is the excavation work. Excavation work is almost constant per m^3 sewered with slight trend to lower numbers for larger networks. Here a simple linear regression was used, which essentially omits the LN-function used in Eq. 16.1.

Tab. 16.1 shows the parameters used in the extrapolation to derive the sewer expenditures per m^3 sewered for sewer networks of different sizes. For instance in a sewer network with a size of 10 Mio

[47] In Supplemental Material No.3, sheet "LCI construction Sewer".

m^3/yr, the cement demand per m^3 wastewater transported is 0.01394 kg/m^3 = -0.005656327· LN(10'000'000)+0.118141687.

Tab. 16.1 Parameters for the extrapolation of sewer expenditures per m^3 sewered depending on sewer size in (m^3/yr)

Expenditure	unit	Type of extrapolation	Slope	Intercept
Transport lorry [1]	tkm	x-LN	-0.008647046	0.204376275
Excavation	m^3	linear	-2.6885E-12	0.00117
Diesel in building machine	MJ	x-LN	-0.001192333	0.024796922
Electricity	kWh	x-LN	-0.000273705	0.007256364
Concrete	kg	x-LN	-0.035528546	0.75839406
Cement	kg	x-LN	-0.005656327	0.118141687
Mortar	kg	x-LN	-9.50608E-05	0.001932586
Iron	kg	x-LN	-0.002313145	0.047026254
Steel	kg	x-LN	-0.000802735	0.016319613
Cast Iron	kg	x-LN	-0.000390805	0.007945075
Pvc	kg	x-LN	-5.33044E-05	0.001187738
Pe	kg	x-LN	-0.000653887	0.017137028
Pp	kg	x-LN	-5.6514E-05	0.001259854
Rubber	kg	x-LN	-2.11246E-05	0.000429464
Sand	kg	x-LN	-0.0162412	0.345728159
Gravel	kg	x-LN	-0.027869267	0.598476158
Water	kg	x-LN	-0.243788136	7.139705237

16.2 Sewer sizes extrapolation in three types of territory

Sewer infrastructure is inventoried in the wastewater disposal inventories only for the part of wastewater that actually enters a sewer, which is described with the parameter %Sew (cf. Fig. 4.1 on page 11).

The sizes of the inventoried sewers determines the specific material demand per m^3 sewered: in smaller networks the specific demand is higher than in larger networks as exemplified in Fig. 16.1 above. In rural territories the sewer networks tend to be smaller, as a re the treatment facilities, while in urban territories the sewer networks tend to be larger. The following sections describe how the sewer network sizes are derived for the three different territories.

Rural situation sewer network size

The size of the treatment plant in a rural situation was previously set to a generic figure of 1.6 Mio m^3 wastewater treated per year (see page 46). The sewer network for such a rural plant will match the size of that plant. So the sewer network size in a rural territory (SS_r) is set to 1.6 Mio m^3 wastewater sewered per year.

Urban situation sewer network size

In an urban situation a generic treatment plant size of 120 Mio m^3 wastewater treated per year was assumed (see page 46). Correspondingly the sewer network size in an urban territory (SS_u) is set to 120 Mio m^3 wastewater sewered per year.

National average sewer network size

For the national average, the typical mean sewer size must be determined that represents the national average sewer size wastewater is sewered in. This is determined by establishing the share of sewered wastewater that is sewered in urban sewers %Su. This can be derived from the fate parameters derived in chapter 'Adopting JMP data for industrial wastewater fate' on page 10. Similar to Eq. 15.2 the parameter %Su is determined by following equation.

Eq. 16.2 $$\%S_u = \frac{\%popU \cdot \%Sew_u}{\%popU \cdot \%Sew_u + (1 - \%popU) \cdot \%Sew_r} = \frac{\%popU \cdot \%Sew_u}{\%Sew_n}$$

where

%Su = Fraction of all sewered wastewater that is sewered in an urban sewer

%popU = Share of urban population in that nation.

%Sewu = Sewering rate of wastewater generated in urban territories only.

%Sewr = Sewering rate of wastewater generated in rural territories only.

%Sewn = National sewering rate of all national wastewater generated.

If the required data is not available for the calculation of %Su, the generic global average of 72.17% is used.

If a nation's share of sewered wastewater sewered in an urban sewer is known, the appropriate size for the national average sewer SSn can be determined.

Eq. 16.3 $$SS_n = \%S_u \cdot SS_u + (1 - \%S_u) \cdot SS_r$$

where

%Su = Fraction of all sewered wastewater that is sewered in an urban sewer

SS_n Size of the national average sewer (in m^3 sewered per year)

SS_u Size of a generic urban sewer (120 million m^3 sewered per year)

SS_r Size of the generic rural sewer (1.6 million m^3 sewered per year)

The so calculated national average sewer size S_n is then used to derive the infrastructure needs for sewer networks using the extrapolations derived in chapter 16.1.

16.3 Residential sewer

The sewer networks inventories above are the public sewers usually maintained by the municipality. Between the public sewer and a building a residential sewer is required, connecting a building's water outflow pipes and the public sewer. Depending on how infrastructure of a building is inventoried it can be important to include or exclude the residential sewer, to avoid data gaps or double counting. Inclusion or exclusion can be selected in the user's definition of the disposal site (see Calculation Manual document, chapter 4 'Creating a new disposal site entry', point 109).

The residential sewer infrastructure will be added to sewered share of wastewater. If for instance only 70% of wastewater is sewered (%Sew), the residential sewer pipe infrastructure will only be added to those 70%.

The material inventory of the residential sewer is taken from (Labhardt 1996). The inventory figures are already calculated per m^3 sewered heeding lifetimes.

Tab. 16.2 Infrastructure for residential sewer inventoried per m^3 wastewater sewered, based on (Labhard 1996).

Expenditure	Unit	per m^3 sewered
excavation, hydraulic digger	m3	0.001852148
concrete, exacting	m3	6.93848E-05
cement, unspecified	kg	0.007476563
cast iron	kg	0.001472656
sand	kg	0.057773438
gravel, round	kg	0.091757813
extrusion, plastic pipes	kg	0.007589844
polyethylene, LDPE, granulate	kg	0.005550781
polyvinylchloride	kg	0.002039063
tap water	kg	0.90625
electricity, medium voltage	kWh	0.001689779
diesel, burned in building machine	MJ	0.012121094
disposal, building, reinforced concrete, to sorting plant	kg	0.166523438
disposal, building, polyethylene/polypropylene products, to final disposal	kg	0.005550781
disposal, building, mineral plaster, to sorting plant	kg	0.007476563
disposal, polyvinylchloride, 0.2% water, to municipal incineration	kg	0.002039063
iron scrap, unsorted	kg	0.001472656

17 Sludge Disposal

The remaining sludge after wastewater treatment must be disposed. This can be raw sludge or digested sludge or a mixture (see Fig. 9.1). In the present model also this disposal is included in the inventory in a waste-specific manner.

Three sludge disposal fates are considered in the model:

- Spreading on agricultural fields
- Disposal in landfills
- Disposal in waste incineration

Other disposal routes are possible, like composting, but are disregarded for the moment.

17.1 Country-specific sludge disposal pathways

Depending on circumstances and legislations, different sludge disposal pathways can be employed in various countries. Spreading on agricultural fields is widespread, but prohibited in some countries. Incineration is only possible in countries with corresponding disposal infrastructure.

Data for European countries on sludge disposal could be compiled from the EEA Waterbase (EEA 2020). Rates can be quite variable over the years, which is why the weighted mean over three different years was calculated (2018, 2016, 2014).[48,49,50]

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[48] From the versions 8, 7 , and 6 of the EEA Waterbase UWWTD released 2020, 2019, and 2017.

The available country rates are included in the model. The provided rates can be overridden by the user, if more pertinent data is available. No trends or extrapolations from the available countries could be derived for sludge disposal data. Disposal data for non-European countries must be provided by the user.

If no statistical data is available and no override data is provided by the user, an error value results. The given sludge disposal fates must add up to 100%. If the sludge fates contain an error or do to add up to 100%, the model will issue a warning before inventory export.

17.2 Treatment sludge to agriculture

Sludge from wastewater treatment can be used on agricultural fields. In the wastewater model the most elements in sludge diverted to agriculture can be inventoried directly as emissions on agricultural soil. In inventories of agricultural production of ecoinvent, inputs of fertilizer nitrogen and phosphorus are converted with local fate factors into emissions to air and water, while their majority is taken up as intended by the cultivated plants. For compatibility, these local fates are applied here, but in a simplified fashion. Nemecek & Schnetzer (2011) describe the employed methodologies to calculate emissions factors to arrive at emissions per *hectare and year* (ha.yr). For the present wastewater model not the *annual* emissions are of interest, nor the emissions in the first year after application, but the ultimate, *time-integrated* sum of emissions occurring from a particular deposition, i.e. transfer coefficients. These local transfer coefficients can be obtained by looking at the flows on an agricultural plot in a *dynamic equilibrium*, i.e. where per element the annual inputs are equal to the annual outputs.

The correspondence to agricultural production inventories is not absolute. In agricultural production inventories often only the *net* emission or uptake is inventoried, i.e. input to field minus plant uptake, for example for heavy metals.[51] For the wastewater model the *gross* input to agricultural fields is inventoried. Further fate of pollutants—into environmental media or into human food chains—is heeded in a generic fashion in the LCIA stage in methods with fate and exposure modelling.

17.2.1 Nitrogen species emissions from agricultural fields

The nitrogen flows on an agricultural field, as modelled in Nemecek & Schnetzer (2011), consists of nitrogen inputs from fertilizer, nitrogen uptake from the plant, emissions of nitrate (NO_3^-) to water, of ammonia (NH_3) to air, of nitrous oxide (N_2O) to air, and of nitrogen oxides (NO_x) to air. Based on this, the local fate factors are calculated here partly based on site-specific parameters and in an equilibrium flow situation (cf. chapter 'Equilibrium condition' on page 55 below).

Nitrate loss

After plant uptake the nitrate loss represent the largest nitrogen loss. Nemecek & Schnetzer (2011) present a formula that depends on the precipitation rate. In the wastewater model the nitrogen fate calculation is attached to the precipitation rate provided for the disposal site (mean annual

49 Country-wide disposal of WWT sludges are listed in table "MSLevel". For the data compiled here, all data given as 'sludge reuse' other were added to agricultural spreading. 'Disposal other' and 'discharge into water' were added to disposal landfill.

50 Missing data for Germany were added from (Eurostat 2020).

51 For instance if fertilizer application adds 123 grams of cadmium to a field and the net plant uptake of cadmium is 50 grams, then only the net remainder of 73 grams will be inventoried in agricultural production inventories as emission to soil.

precipitation, MAP). This makes the calculation of the equilibrium flow situation site-specific. As agricultural production is not in the primary focus for the wastewater model, some required parameters for the nitrate loss are filled with generic values.

Eq. 17.1 $$NO_3N = 21.37 + \frac{P}{c \cdot L} \cdot \left(0.0037 \cdot S + 0.0000601 \cdot N_{org} - 0.00362 \cdot U\right)$$

where

NO_3N = leached NO_3-N in kg N/(ha.yr)

P = precipitation and irrigation in mm/year

c = clay content in kg/kg

L = rooting depth in mm

S = Nitrogen supply through fertilizer in kg N/(ha.yr)

N_{org} = Organic nitrogen in soil in kg N/ha

U = Nitrogen uptake by plant in kg N/(ha.yr)

The required precipitation rate is taken from the user-specified mean annual precipitation (MAP) for the site. Irrigation is neglected and set to zero. A generic clay content of 0.2 and a generic rooting depth of 1000 mm is assumed (based on Imbeault-Tétreault 2013). The nitrogen supply through fertilizer S is calculated recursively heeding all losses to obtain an equilibrium situation with stable input and output flows. For the organic nitrogen in soil N_{org} a generic value of 772.7 kg N/ha is used.[52] For the plant uptake U a generic value of 120.3 kg N/ha is assumed (based on Imbeault-Tétreault 2013).

This allows to calculate the nitrogen losses as nitrate, depending on the site's precipitation rate. Since the equilibrium depends on all losses and outputs, also the following emissions play a role in establishing the equilibrium fertilizer input S.

Ammonia to air

The emissions of ammonia to air is calculated based on the fertilizer input and some modifying factors.

Eq. 17.2 $$NH_3N = S \cdot AN \cdot \left(er + c_{app}\right) \cdot c_x$$

where

NH_3N = Ammonia-N emitted to air in kg N/(ha.yr)

S = Nitrogen supply through fertilizers in kg N/(ha.yr)

AN = Fraction of ammonia-N in total fertilizer N, kg/kg

er = Ammonia emission fraction to air, kg/kg

c_{app} = correction factor that influences the emission rate, kg/kg

c_x = correction factor for the crop production system

The fraction of ammonia-N in fertilizer AN is set to 0.04839, based on Imbeault-Tétreault (2013). The ammonia emission fraction to air *er* is only available for animal manures in Nemecek & Schnetzer (2011). A generic value of 0.8 is used for *er* based on Imbeault-Tétreault (2013). The correction factor

52 Based on a generic soil carbon mass of 10'000 kg C/ha (estimated from Lugato et al. 2014), a C/N ratio of 11 and a N_{org} fraction in N_{tot} of 0.85 (both from Nemecek & Schnetzer 2011:15), thus 772.7 kg N/ha = 10'000/11·0.85.

c_{app} is set to zero, and the correction factor for the crop production system c_x is set to 0.8712, both based on Imbeault-Tétreault (2013).

Nitrous oxide N_2O to air

The emissions of nitrous oxide are estimated based on three other flows: the fertilizer N input, the nitrate emissions, and the ammonia emissions. The calculation does not mean that nitrate is assumed to be converted to N_2O, i.e. transfer coefficients, but the magnitude of the other calculated emissions and flows are used to estimate the magnitude of the N_2O emissions.

Eq. 17.3 $$N_2ON = 0.01 \cdot (S + cr) + 0.01 \cdot NH_3N + 0.0075 \cdot NO_3N$$

where

N_2ON = nitrous oxide-N emitted to air in kg N/(ha.yr)

S = Nitrogen supply through fertilizers in kg N/(ha.yr)

cr = Nitrogen in crop residues left on field in kg N/(ha.yr)

NH_3N = Ammonia-N emitted to air in kg N/(ha.yr)

NO_3N = leached NO_3-N in kg N/(ha.yr)

The nitrogen in crop residues cr is assumed to be zero, all other parameters are determined in the recursive calculation of the equilibrium situation and will be determined from that.

Nitrogen oxides NOx to air

The magnitude of the emissions of nitrogen oxides are based on the magnitude of nitrous oxide emissions. Also here it is not implied that N_2O will subsequently be converted to NO_x—which would reduce the net N_2O emissions—but that nitrogen oxide emissions and N_2O emissions are in proportion to each other.

Eq. 17.4 $$NO_xN = 0.21 \cdot N_2ON$$

where

NO_xN = Nitrogen oxide-N emitted to air in kg N/(ha.yr)

N_2ON = nitrous oxide-N emitted to air in kg N/(ha.yr)

Equilibrium condition

The equilibrium flow condition requires that all outputs equal all inputs. In equilibrium, the flows represent the time-integrated fates from which the sought transfer coefficients can be derived. The conditions for nitrogen is:

Eq. 17.5 $$S = U + NO_3N + NH_3N + NO_xN + N_2ON$$

I.e. the annual nitrogen input from fertilizer supply S must equal all nitrogen outputs, be it to plant (U) or any emissions. With this condition the equilibrium can be calculated recursively. Since all flows except U depend directly or indirectly on the precipitation rate, the equilibrium situation depends on the mean annual precipitation of the site.

For a precipitation of for instance 1000 mm/year the following nitrogen equilibrium flows and fates result:

	Annual equilibrium flow, kg/ha	Transfer coefficient
Fertilizer N input	149.61	
Outputs		
Plant uptake	120.3	80.41%
NO3-N loss	22.193	14.83%
NH3-N loss	5.0458	3.373%
N2O-N loss	1.713	1.145%
NOx-N loss	0.35973	0.24%

The resulting site-dependent transfer coefficients are applied to the nitrogen mass in sludge transferred to agricultural fields for disposal, i.e. output = input · transfer coefficient. Plant uptake is not recorded as an inventory exchange, but the emissions are included, heeding their molecular weights. These are then the waste- and site-specific nitrogen emissions from applying nitrogen in sewage sludge on agricultural fields.

17.2.2 Phosphorus emissions from agricultural fields

Also for phosphorus applied to an agricultural soil, the time-integrated fates of a phosphorus addition are of interest for the wastewater inventory. Nemecek & Schnetzer (2011) distinguish three different emissions of phosphorus from the agricultural field.

1. Leaching out to groundwater
2. Surface run-off to surface water
3. Water erosion of soil particles

The calculation is simplified here using generic values and results in fixed rates independent of climate. Assuming an equilibrium situation (cf. 'Equilibrium condition' on page 57), relating those loss rates to the input of phosphor results in the phosphorus transfer coefficients. The latter can then be used to calculate the emissions resulting from a sludge spreading containing phosphorus.

Phosphorus leaching to groundwater

Nemecek & Schnetzer (2011) have a generic leaching rate P_{gw} of 0.07 kg P/(ha.yr) for arable land, which is used here. There is also a correction factor for increased losses for application by slurry, which however has hardly any influence using generic values.[53]

Phosphorus emission to surface water

Nemecek & Schnetzer (2011) have a generic emission rate P_{ro} of 0.175 kg P/(ha.yr) for arable land, which is used here. Also here a correction factor for increased losses for application by slurry is applicable, but turns out to have practically no numerical influence.[54]

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53 With an average P_2O_5 content in sewage sludge of $9.5 \cdot 10^{-6}$ kg per kg dry matter, an estimated sludge application rate of 3000 kg dry matter per ha, a correction factor of 1.00007089 results ($=1+0.2/80 \cdot 9.5 \cdot 10^{-6} \cdot 3000$), which would increase the emission by less than one tenth of a permille.

Phosphorus lost by soil erosion

Nemecek & Schnetzer (2011) present a formula for estimation of loss of phosphorus to surface water by soil erosion P_{er}. Only water erosion is meant here, not wind erosion. Soil erosion rates depend on a multitude of conditions such as type of crop, soil type, climate, land management practices etc. For the wastewater model, a generic annual soil erosion rate S_{er} of 3000 kg soil per ha is used, which is the average erosion rate of agricultural land in Europe (Eurostat 2020:Fig 2).

Eq. 17.6 $$P_{er} = S_{er} \cdot P_{cs} \cdot F_r \cdot F_{erw}$$

where

P_{er} = Phosphorus eroded to surface water in kg P/(ha.yr)

S_{er} = Soil erosion rate in kg dry matter/(ha.yr)

P_{cs} = P concentration in soil in kg P /kg dry matter

F_r = Enrichment factor for P, -

F_{erw} = Fraction of eroded soil reaching surface water, -

The enrichment factor F_r heeds the fact that eroded soil particles contain more phosphorus than the average soil matter. Nemecek & Schnetzer (2011) use following values for their calculations: Phosphorus concentration in soil P_{cs} = 0.00095 kg P/kg soil; enrichment factor F_r = 1.86; fraction reaching river F_{erw} = 0.2. Together with the generic soil erosion rate S_{er} of 3000 kg/(ha.yr) an erosion loss P_{er} of 1.06 kg P/(ha.yr) results.

Equilibrium condition

Nemecek & Schnetzer (2011) provide no data for plant uptake of phosphorus. For the wastewater inventory this is unimportant, since the emission losses of phosphorus are of interest here. The emissions must however be related to an input of phosphorus to obtain transfer coefficients. A generic input of phosphorus on agricultural land of 12 kg P/(ha.yr) is used here.[55] Assuming the emissions derived above and the input are in a steady state equilibrium—or reasonably close to it—the transfer coefficients can be derived.

Tab. 17.1 Generic annual flows of phosphorus on an agricultural field and derived transfer coefficients

Phosphorus annual flows	kg P/(ha.yr)	Transfer coefficient for phosphorus
Phosphorus fertilizer input	12	100%
Phosphorus leaching to groundwater P_{gw}	0.07	0.583%
Phosphorus emission to surface water P_{ro}	0.175	1.458%
Phosphorus lost by soil erosion P_{er}	1.06	8.835%

54 The correction factor depends on the P_2O_5 content in sludge and the applied sludge mass per ha. Using the same values as in footnote 53 above, a correction factor of 1.000248 results (=1+0.7/80 · 9.5·10^{-6} · 3000), which would increase the emission by less than one fourth of a permille.

55 Taken from (Lu & Tian 2017:Fig 3) as 1.2 g P/(m^2.yr) representing the world average phosphor input on cropland from fertilizer application in 2013.

For any phosphorus in sludge applied on agriculture the waste-specific emissions of phosphorus can be calculated. The last two emissions are combined into one emission to surface water. The not emitted amount (89.12%) can be assumed to be crop plant uptake.

17.2.3 Water balance

Sewage sludge to agricultural fields is assumed to be applied with a high water content of 97%. To close the water balance, the water contained in sludge is inventoried as water emissions. Based on the climate data given for the inventoried site, a share of evaporated water is calculated.[56] The evaporated water is inventoried as emission to low population air, while the remainder is inventoried as emission to groundwater.

17.2.4 Fertilizer function

Treatment sludge spreading provides nutrients to agricultural crops, which is a chief motivation for this type of disposal. So apart from detrimental emissions outlined above also a beneficial fertilizer function is provided, as well as a disposal service. The fertilizer can be seen as a by-product of the disposal on agricultural fields, similar to a net energy production in municipal incineration.

For allocation schemes where such by-products are relevant the provided fertilizer functions are inventoried. The amounts of nitrogen, phosphorus, and potassium are inventoried with the exchanges for organic fertiliser.[57]

Assuming an maximal case of 100% 3-stage WWTP treatment and 100% agricultural disposal of sludge, per cubic meters of average residential wastewater, 6.2 grams of N, 9.45 grams of P_2O_5, and 0.79 grams of K_2O of fertilizer is provided. This maximal case corresponds to a transfer from the original wastewater onto the agricultural field of 20% for nitrogen, of 92% for phosphorus, and 5% for potassium, reflecting the limited retention potential of wastewater treatment for the frequently soluble species of potassium and nitrogen.

17.2.5 Sludge spreading

A process for spreading liquid waste on agricultural field exists in ecoinvent "liquid manure spreading, by vacuum tanker". This includes the machine use for the spreading of 1 m^3 of sludge or manure, but not the sludge emissions. The wet mass of the treatment sludge is converted to a m^3 figure by using an assumed density of 1030 kg/m^3.

17.3 Sludge disposal in landfill

To include the emissions and expenditures for landfilling of sludge, the model for the sanitary landfill is employed here (Doka 2017). Also with this disposal, the inventory is calculated as waste-

56 From Actual Evapotranspiration (ETa) and Mean Annual Precipitation (MAP) the ratio ETA/MAP defines how much water will be evaporated into air. On arid and dry sites with reversed hydrology (ETA ≥ MAP) 100% evaporation is assumed.

57 Exchanges "organic nitrogen fertiliser, as N", "organic phosphorus fertiliser, as P2O5", and "organic potassium fertiliser, as K2O" each with the unit kg. "Organic" is used here as the antonym of "mineral" or "inorganic", not to denote a kind of agricultural practice.

specifically as possible, heeded the particular flows in sludge generated from the treatment of a particular wastewater, and not simply assuming average sludge.

The same concept as in (Doka 2003-IV) is employed here: Static inventory factors are derived from the landfilling of average sludge, and then these inventory factors are applied to the specific sludge amounts and flows to obtain a waste-specific inventory. In the future it is intended to dynamically integrate sludge disposal into the Excel calculation tools of the landfill model to obtain results also reflecting the chosen technology parameters of a site or country (so-called full integration). With the present solution the landfill model is fixed in the state as it was when the inventory factors were derived.

17.3.1 Water balance

Sewage sludge to landfill is assumed to be disposed with a water content of 75%. To close the water balance, the water contained in sludge is inventoried as water emissions. The sludge is buried in the landfill and no evaporation to air is assumed. The water in sludge is assumed to be removed to landfill leachate and to surface water.

17.4 Sludge disposal in waste incineration

To include the emissions and expenditures for landfilling of sludge, the model for the sanitary landfill is employed here (Doka 2013). Similar to the disposal in landfills above, static inventory factors are derived from the incinertaion of average sludge. These inventory factors are applied to the specific sludge amounts and flows to obtain a waste-specific inventory of incineration.

Also here a dynamic integration of the disposal calculation into the Excel calculation tools of the incineration model is intended, which then would dynamically reflect the technology parameters of a site or country.

17.4.1 Water balance

Sewage sludge to incineration is assumed to be disposed with a water content of 70%. To close the water balance, the water contained in sludge is inventoried as water emissions. From the water balance of the working point calculation of average sewage sludge incineration, a share of 92.7% of water is released to air, while 7.3% is emitted to the incinerators effluent and to surface water. This division is applied to all water in incinerated sludge.

18 Wastewater disposal dataset names

In the new wastewater disposal model, various dissimilar fates of wastewater can be contained in one single activity dataset, representing a mixture of disposal and treatment of that wastewater, for instance in a country average. This might encompass direct emission, sewering, minimal treatment, and/or elaborated treatment, as well as disposal of any generated sludge. Depending on the user choices, one single wastewater dataset can contain one or several different wastewater fates.

All waste disposal activities are being consistently called "treatment" in ecoinvent. This creates a potential for misunderstandings here, since in the activities modelled here not all wastewater is necessarily really *treated* in a wastewater treatment plant, but direct emission with or without sewering of untreated wastewater can be included to a large degree. Nevertheless, the phrasing is maintained here, as it represents the way wastewaters are handled and disposed in the specified geography.

For Ecopsold2

To be as consistent as possible to previous activity datasets following general structure of wastewater treatment activities is introduced:

Tab. 18.1 Activity name structure for ecoinvent v3.8+ (EcoSpold2)

start	wastewater name	comma , territory (optional)
"treatment of …	*…wastewater from maize starch production…*	*, rural"*

The start phrase "treatment of…" denotes a waste disposal process as is customary in ecoinvent v3+. This is immediately followed by the waste name (no comma). The waste name is the specific wastewater exchange. The same words as for the actual exchange shall be use to minimise misunderstandings. Most wastewater exchanges start with the phrase "wastewater from..." followed by a descriptor of the originating process, e.g. "wastewater from maize starch production".[58]

The optional last part of the name describes the type of territory the activity occurs: rural, urban or national average. Since "national average" is the default territory for any ecoinvent country-specific dataset, the suffix is omitted in this case.[59]

Depending on the chosen site, the name might also include a phrase ", from residence" if the sewer pipes from the building to the public sewer are included.

If from a certain process two or more different wastewaters originate and are to be inventoried separately, make sure the activity names and wastewater names are clear, unambiguous and understandable to practitioners not necessarily familiar or even interested with your specific wastewater-producing activity. Consider, that users of the database who might have to search through a large list of disposal activities to find an appropriate one are not necessarily interested in or knowledgable about your activity as a foreground. If two or more wastewaters originate from a process, it is also possible to define two or more waste materials as wastewaters and let an activity treatment a mixture of these, i.e. analogous to a complex solid waste.

In ecoinvent v3-3.7 (2011-2020) wastewater treatment datasets were representing exclusively treatment in a three-stage wastewater treatment plant, based on Swiss average performance.[60] The activity name used to include a suffix, signifying the size of the treating plant, e.g. "capacity 1E9l/year". Five different size classes were distinguished like this. As in the new model not all wastewater is necessarily treated in a wastewater treatment plant of a certain capacity and mixtures of various treatment types may apply within the same dataset, the suffix "capacity ###l/year" is removed. Also the former ending phrase "to wastewater treatment" is discontinued, as not all wastewater is necessarily treated in these inventories.

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58 Some historic exceptions to this exist ("treatment of wastewater, average…", "treatment of wastewater, from residence….", "treatment of wastewater, unpolluted…", "treatment of condensate from light oil boiler…", "treatment of heat carrier liquid, 40% C3H8O2…", "treatment of rainwater mineral oil storage…"). It is advised to start any novel wastewater exchange names with "wastewater from" (for EcoSpold2).

59 Also datasets can be created for global regions, like "Asia" or "Northern America" and there a suffix "national average" would be a misnomer.

60 Which included some combined sewer overflow as direct emission of sewered, but untreated wastewater.

For Ecospold1

For inventories in the original Ecospold1 format (2003-2010), slightly different naming conventions apply than in EcoSpold2. The initial phrase is separated by a comma before the wastewater name. A similar structure is used for the local language German.

The optional suffix of the name may denote the territory (rural/urban). The national average is not denoted especially.

Tab. 18.2 Activity name structure for Ecospold1 for activities adhering to ecoinvent v1.0-2.2 (2003-2010)

	start, comma	**wastewater name**	**comma, territory (optional)**
EN	*"treatment,*	*wastewater from maize starch production*	*, rural"*
DE	*"Behandlung,*	*Abwasser Maisstärkeproduktion*	*, ländlich"*

Depending on the chosen site, the name should also include a phrase ", from residence" if the sewer pipes from the building to the public sewer are included.

As explained in the previous chapter these inventories comprise several activities in one dataset and therefore the former ending phrase "to wastewater treatment" is discontinued, as is noting the size class ("Gr.Kl.") of the treating plant.

Different naming conventions are used in EcoSpold1 compared to EcoSpold2, e.g. *"treatment,…"* vs. *"treatment of…"*. This can help to discern different database sources.

It is advised though to *harmonise the names of the wastewater exchanges* themselves, to ease correspondence of datasets. For instance in ecoinvent v1.0-2.2 the wastewater from maize starch production was called "maize starch production effluent". It is advised to generally use the "wastewater from..." phrasing for any new wastewaters. A correspondence of the old legacy wastewater names and their new correspondences in ecoinvent v3.7.1 (2020) is shown in Tab. 18.3.

Tab. 18.3 Corresponding names of specific wastewaters in ecoinvent v1.0-2.2 (2003-2010) and ecoinvent v3.7.1 (2020)

Legacy wastewater names in ecoinvent v1.0-2.2	Corresponding wastewater names in ecoinvent v3.7.1 (2020)
black chrome coating effluent	wastewater from black chrome coating
ceramic production effluent	wastewater from ceramic production
concrete production effluent	wastewater from concrete production
condensate from light oil boiler	condensate from light oil boiler
CRT tube production effluent	wastewater from cathode ray tube production
glass production effluent	wastewater from glass production
heat carrier liquid, 40% C3H8O2	heat carrier liquid, 40% C3H8O2
LCD backlight production effluent	wastewater from liquid crystal display backlight production
LCD module production effluent	wastewater from liquid crystal display production
liquid crystal production effluent	wastewater from liquid crystal production
lorry production effluent	wastewater from lorry production
maize starch production effluent	wastewater from maize starch production
pig iron production effluent	wastewater from pig iron production
plywood production effluent	wastewater from plywood production
potato starch production effluent	wastewater from potato starch production
PV cell production effluent	wastewater from PV cell production
rainwater mineral oil storage	rainwater mineral oil storage
sewage grass refinery	wastewater from grass refinery
sewage whey digestion	wastewater from anaerobic digestion of whey
tube collector production effluent	wastewater from tube collector production
wafer fabrication effluent	wastewater from wafer fabrication
soft fibreboard production effluent	wastewater from soft fibreboard production
fibre board production effluent	wastewater from hard fibreboard production
wastewater from medium density board production [1]	wastewater from medium density fibreboard production
particle board production effluent	wastewater from particleboard production
wastewater from particle board production [1]	wastewater from particleboard production
sewage	wastewater, average
sewage, unpolluted	wastewater, unpolluted
sewage, from residence	wastewater, from residence
sewage, unpolluted, from residence	wastewater, unpolluted, from residence
n.a.	wastewater from ammonium paratungstate production
n.a.	wastewater from ground granulated blast furnace slag production
n.a.	wastewater from vegetable oil refinery
wastewater from NF3 production	n.a.

1 The KBOB database contains some datasets whose names are styled according to the structure in EcoSpold2, but with slight variations, i.e. "board" vs. "fibreboard" and "particle board" vs. "particleboard".

19 Wastewater composition definition

In past models of wastewater treatment a range of various parameters was used to characterise the input wastewater, like for instance "particulate phosphorus" or "soluble Kjeldahl nitrogen" (Doka 2003-IV). This allowed for a differentiated description of input wastewater. In actual practice this granularity was hardly ever useful, as the literature data providing data on produced wastewaters from activities almost never had those detailed parameters.

In the present model the definitions of wastewater is integrated in the framework of definition of *solid* waste, with its vector of chemical elements. So instead of characterising carbon with between one and four parameters like COD, BOD, DOC, TOC, simply the carbon content is used.

Solid wastes are characterised as a wet mass composition, i.e. kg element per kg wet mass. This is now also employed for the wastewater definition. For instance a concentration like 5 mg per litre will be entered as 0.000005 kg per kg wet mass. I.e. one litre of wastewater is assumed to be 1 kg of wet waste. Water content of wastewater will consequently be usually very large.

These decisions affect only the wastewater *definition*. The functional unit of a wastewater disposal activity will be based on 1 m^3 wastewater input (not one wet kilogram). Resulting output emissions in the calculated inventory will still be listed with the required granularity of the ecoinvent methodology (e.g. COD, BOD, DOC, TOC for carbon emissions to water).

19.1 Appropriate wastewater pollutant parameters

19.1.1 Nitrogen species

In the previous wastewater inventory model (Doka 2003-IV), the fate of nitrogen species like ammonia (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) or organic-bound nitrogen though a treatment plant was modelled substance-specifically, and wastewater inputs could be specified with four different levels of detail.[61] The resulting water emissions were also inventoried in detail. For LCA results, the precise nitrogen species of a water emission is however not important, since all LCIA methods have characterisation factors which are *simply proportionate to the nitrogen content* of an emission.[62] Also in practice hardly ever more than one input parameter was available to specify production effluents (usually nitrate and/or ammonia). So the previous granularity for nitrogen species seems rather too large for LCA applications. For engineering questions and WWT plant operators the former granularity is of course often crucial and very relevant, but in the LCA world, modelling five different nitrogen species is rather excessive on the inventory side and currently entirely irrelevant on the impact assessment side. For this reason the present modelling considers simply total nitrogen as an input and does not discern different species. The treatment can lead to different outputs (to water, to air as N_2 or N_2O, to sludge biomass) and these differences are of course heeded. This reduction in granularity reduces modelling complexities and which are instead enlarged to allow diverse international wastewater fates.[63]

To characterise the initial wastewater, the user shall as best as possible compile a value for total nitrogen. This is a sum of any organic or inorganic nitrogen (merely discounting any dissolved N_2 gas). Wastewater parameters are usually given as nitrogen equivalents, e.g. "Nitrate as N". In case compound weights are given, they need to be converted into elemental weight. Which nitrogen species are likely to be included to cover the total nitrogen load, depends on the wastewater-producing activity. Some activities might produce for instance an ammonia-heavy wastewater with little nitrate nitrogen, and other process might produce a wastewater dominated by nitrate nitrogen.

19.1.2 Organic carbon

In previous models, four different parameters could be used to characterise the content of organic pollutants in the initial wastewater (Doka 2003-IV).

61 The four levels were A. (coarsest) total nitrogen, B. Total Kjeldahl Nitrogen, nitrate and nitrite, C. Soluble Kjeldahl Nitrogen, particulate nitrogen, nitrate and nitrite, D. ammonia, particulate nitrogen, nitrate, nitrite, soluble organic-bound nitrogen.

62 They can be dissimilar for single emissions compartments, e.g. ocean water vs. fresh water, but within one emission compartment the characterisation factors are in proportion to the nitrogen content of the emitted molecule.

63 Also keeping the former granularity would also necessitate to create a *separate* location in the inventory calculation tools to define input wastes: one for solid wastes and one for the more granular wastewaters, with for instance five different types of nitrogen species. On a superficial level this would be trivial, but in order to fulfil the requirements of creating EcoSpold2 datasets—especially the need to keep new, uncanonised technosphere exchanges distinguishable from already existing exchanges—this would introduce several awkward parallelisms. Being able to input a wastewater composition at the same location as solid wastes is a clearly more efficient solution.

Abbrev.		*Parameter remarks*
TOC	Total organic carbon	Carbon mass in organic compounds. This could be biogenic or fossil carbon, but not inorganic carbon like carbon in carbonates (CO_3-C)
DOC	Dissolved organic carbon	The fraction of TOC that is dissolved in the liquid phase. Consequently (TOC – DOC) is the carbon in solids of the wastewater
BOD	Biological oxygen demand	Mass of oxygen used up to degrade the more easily degradable part of organic carbon. Usually measured over 5 days (BOD_5).
COD	Chemical oxygen demand	Mass of oxygen used up to degrade all of the organic carbon. Therefore COD ≥ BOD

BOD and COD are important parameters for WWTP operators, since they represent the "work load" of a treatment plant and the reduction of either parameter is a good and a relatively easily measured indicator of the operational performance of the plant. However, for performing a mass balance of carbon through the WWTP both parameters are less useful.[64] The amount of TOC is the most relevant parameter here. In the following sections, prioritised suggestions are made on how to convert the various literature parameters for an input wastewater into a unique TOC figure.[65]

1. Priority: TOC of wastewater is known

Use TOC parameter to define carbon in wastewater (kg C/kg WW). Make sure the TOC value from your source is for the *whole wastewater composition* and does not represent a part, e.g. other TOC besides specified components.

2. Priority: DOC of wastewater is known

Depending on the wastewater source, you can assume TOC=DOC. If a wastewater also contains undissolved carbon, convert with a share of the dissolved fraction. In absence of data a generic value of 68% (Doka 2003-IV:14) for Swiss residential wastewaters can be used, i.e. TOC = DOC/0.68.

3. Priority: COD of wastewater is known

Convert COD with a generic TOC/COD ratio of 0.2565, i.e. TOC = COD · 0.2565 , based on

4. Priority: BOD of wastewater is known

Convert BOD with generic TOC/BOD=0.53034, i.e. TOC = BOD · 0.53034

If several of the parameters are available, use the highest priority. Try to find literature sources for the higher priority parameter. The conversion factors are taken from a literature survey for Swiss average wastewater. If more pertinent conversion factors can be found, they can be used. The goal should be to find a representative value for TOC for the specific wastewater under investigation.

After this procedure, you should have a organic carbon concentration of the input wastewater with the unit kg C/kg wastewater.

64 Similar things can be said about other WWTP parameters like total suspended solids TSS, volatile suspended solids VSS, volatile fatty acids (VFA), or readily biodegradable COD (rbCOD) and similar summary parameters.

65 In the inventory model from (Doka 2003-IV) the parameters were converted in-model in parallel and the largest value resulting from those conversions was selected to represent the TOC value. This is replaced here by a staged selection sequence using priorities performed by the user (ex-model).

19.1.3 Phosphorus

In literature on wastewater pollutants, phosphorus is characterised as total phosphorus and/or as Phosphate-P (PO_4-P). For the present wastewater model the total phosphorus is required (inorganic and organic). Whether a value for phosphate-P reasonably covers total phosphorus depends on the wastewater-producing activity. The user must be diligent to cover the entirety of the pollutant load in the characterised wastewater.

19.2 Uncertainty of input composition

The uncertainty of the wastewater composition is calculated from composition data in a generic fashion. As with solid waste it is considered that major constituents by mass will likely have a smaller variability than small trace constituents. Following formalism is employed.

Eq. 19.1

$$GSD = 1 + N \cdot \left[\ln(c)\right]^3$$

where

c = Concentration of element in kg element per kg wastewater

ln natural logarithm (base e)

N = -0.000166667 = -1/6000

Please note the exponent 3

The formalism is built on the basic uncertainties in the pedigree approach for water emissions from processes (DQG 2013, p.75).

19.3 Relevance of emissions of organic compounds

In the model presented here, organic compounds emitted in the wastewater effluent will simply be denoted with the sum parameter TOC (total organic carbon).[66] For wastewater plant operators this and similar sum parameters like COD, BOD, or DOC represent valuable information. In view of the goals of an LCA application however, a shortcoming arises that such sum parameters can comprise a very large range of very different compounds with very different ecotoxic or humanotoxic effects. Another practical problem of those parameters as an emission in LCA is that only very few LCIA methods actually have characterisation factors for TOC, COD, or BOD. The organic compounds emitted to water—either as direct untreated emission or after treatment—will therefore often not lead to any burden signal in LCIA, not even in a very generic or cursory way.

Single compound fates are not heeded in the model presented here, due to common lack of granular data availability in wastewater compositions for specific process wastewaters and also due to the resulting large model complexity requiring substance-specific behavioural parameters.

Nevertheless, it is valuable to investigate what a possible characterisation factor a TOC emission might have in LCIA, and what relevance that would have to the LCIA burdens currently described in the current wastewater model.

[66] And also—as required by ecoinvent methodology—in parallel the sum parameters COD, BOD, and DOC will be inventoried, using generic ratios measured in wastewater effluents.

19.3.1 An estimated characterisation factor for TOC emissions

One way to home in on a possible characterisation factor for TOC emissions is to select some compounds that would conceivably occur in wastewater in considerable amounts. The assumption being that a characterisation factor for TOC will be chiefly be dependent on the compounds that are common by mass and not on the compounds that are scarce.

A selection of common single compounds that could occur as contributions to TOC or as degradation products of biomass is compiled here. This excludes man-made compounds designed for particular purposes, e.g. lubricants. Also only compounds with an available characterisation factor are selected. The characterisation factors of the ReCiPe'13 (HA) endpoint LCIA method is used, as being one with a very large range of over 2600 characterised organic compounds. For each compound the carbon content is derived from their molecular formula. Dividing the characterisation factor for the (whole) compound by the carbon content, results in a value for a characterisation factor per kg TOC *for this compound*.

Tab. 19.1 TOC characterisation factors calculated for single compounds, in descending order

Compound	Carbon content, kg C / kg compound	ReCiPe characteri-sation per kg TOC	Ratio to median value
naphthalene	60%	0.111607744	167
PAH, polycyclic aromatic hydrocarbons [1]	94%	0.083593748	125
benzene	92%	0.026808597	40.1
styrene	92%	0.020633725	30.8
aldehydes, unspecified [1]	75%	0.010881868	16.3
acetaldehyde	54%	0.008610189	12.9
ethylbenzene	90%	0.007899022	11.8
n-hexane	84%	0.007067139	10.6
ethylene glycol, monobutyl ether	61%	0.006467394	9.66
m-cresol	78%	0.005567683	8.32
decanoic acid	70%	0.005031277	7.52
hydrocarbons, aromatic [1]	92%	0.004647671	6.94
undecanoic acid	71%	0.003915237	5.85
benzoic acid	69%	0.003328064	4.97
phenol	77%	0.003325651	4.97
dodecanoic acid	72%	0.002333678	3.49
nonanoic acid	68%	0.001774352	2.65
maleic acid	41%	0.001598578	2.39
diethylene glycol	45%	0.001597297	2.39
octanoic acid	67%	0.001187881	1.78
salicylic acid	61%	0.001047544	1.57
pentanoic acid	59%	0.00078945	1.18
toluene	91%	**0.000693521**	**1.04**
o-xylene	90%	**0.000672201**	**1**
malonic acid	35%	**0.00067218**	**1**
p-xylene	90%	**0.000666255**	**0.996**
m-xylene	90%	**0.000629113**	**0.94**
cyclododecane	86%	0.00058092	0.868
heptanoic acid	65%	0.000574225	0.858
hydrocarbons, aliphatic, alkanes, cyclic [1]	86%	0.000554364	0.828
fumaric acid	41%	0.000542228	0.81
acetic acid	40%	0.000490728	0.733
carboxylic acids, unspecified [1]	40%	0.00044609	0.667
hexanoic acid	62%	0.000396852	0.593
formic acid	26%	0.000377848	0.565
propionic acid	49%	0.00037334	0.558
oleic acid	76%	0.000324117	0.484
butyric acid	54%	0.000305358	0.456
cyclohexane	86%	0.000305064	0.456
methanol	37%	0.000251273	0.375
citric acid	37%	0.000242438	0.362
L-lactic acid	40%	0.000235253	0.352
oxalic acid	27%	0.000223698	0.334
ethyl acetate	54%	0.000170967	0.255
ethanol	52%	0.000166272	0.248
methyl acetate	49%	0.000116111	0.174
isobutyric acid	54%	9.25813E-05	0.138
cyclooctane	86%	8.81981E-05	0.132
cycloheptane	86%	3.26376E-05	0.0488
triethylene glycol	48%	3.20299E-06	0.00479

1 PAH considered as phenanthrene $C_{14}H_{10}$. Unspecified aldehydes as octyl aldehyde $C_8H_{16}O$. Aromatic hydrocarbons as benzene C_6H_6. Cyclic alkanes as $C_{15}H_{30}$. Carboxylic acids as acetic acid $C_2H_4O_2$.

From the list of derived values a median of 0.0006692 points per kg TOC can be calculated. In absence of information on the concentration of compounds in a generic wastewater TOC emission, this value can serve as a preliminary estimate. As can be seen in the table for individual compounds the characterisation can deviate from this median, e.g. TOC from naphthalene is a factor 167 more damaging than the median value. But the goal here was to find a suitable first estimate for the characterisation of a plant's generic TOC emission as a whole, not for single compounds.

How would the inclusion of this estimated characterisation factor for TOC change the LCIA results of wastewater disposal? The ReCiPe score for the average national wastewater disposal in Switzerland is 0.0288 points per m^3 wastewater input. The total TOC emissions to water are 8.27 grams per m^3. If the TOC emissions were considered with the characterisation factor derived above, the additional burden would be 0.00000554 points, or plus 0.01920% . So, from this first estimate the contribution from TOC emissions seems negligible.

But this estimate was based on the assumption of considering common hydrocarbon decay products as compounds to estimate a characterisation factor for TOC. What if we looked at individual and more industry-specific compounds?

19.3.2 Relevance of single organic compounds in wastewater

To exemplify the relevance of single organic compounds in wastewater, firstly concentrations in wastewater of those compounds needs to be known. Then those compounds require a characterisation factor to include their damaging effects into LCIA results. A measurement of various specific industrial chemicals in municipal wastewater was performed in (Abeggelen et al. 2009:Tab.14) during a 16-month campaign at the Swiss WWTP Regensdorf. A range of typically problematic 50 micro-pollutants and the dynamics of their elimination across the treatment plant was quantified. It is assumed in the exploration made here that those concentration values found in wastewater are also approximate for other locations.

Looking at substances, which could occur in industrial processes, initially pharmaceuticals and agrochemicals are excluded as being unlikely to be used in industrial processes. Compounds with large concentrations are benzotriazole and methyl-benzotriazole (both anti-corrosion agents) and bisphenol A. Of these compounds only bisphenol A has a characterisation factor in the ReCiPe'13 LCIA method (0.0646 points per kg). Abeggelen et al. (2009) recorded concentrations after the first mechanical stage, after the second biological stage, after ozonisation, and after a sand filter. Looking for an upper estimate and thus using the concentration after first-stage treatment only, a concentration of 4.5 micrograms bisphenol A per litre is found, leading to a burden of 0.294 *micro*points per m^3 wastewater. Average wastewater disposal in Switzerland creates a burden of 0.0288 points per m^3 wastewater. Thus the upper expected contribution of bisphenol A is only around a negligible 0.001%.

Opening up the scope and looking also at pharmaceuticals and agrochemicals paracetamol, diuron, carbendazim, and atrazin are selected here as examples. Paracetamol, a popular analgesic, is the pharmaceutical with the largest concentration of all substances in Abeggelen et al. (2009), 38 microgram per liter after first-stage treatment. With a low characterisation factor of 0.003 points per kg, an upper estimate burden of 0.12 micropoints per m^3 wastewater results, which would increase the burden in average Swiss wastewater disposal by 0.0004%.

The three agrochemicals have in part higher characterisation factors than the other substances.[67] Their concentrations are however low, below 0.2 micrograms per litre. Also here, these substances would increase the burden in average Swiss wastewater disposal only in negligible amounts < 0.0002%, even smaller than of the substances calculated before.

Conclusion

These explorations are obviously not comprehensive. But while it was aimed to maximise the burdens from single substances (by selecting substances of concern with high average concentrations and using concentrations after only mechanical treatment with little elimination), none of the investigated substances could really be called a relevant contribution.

But this exploration only looked at the approximate relevance for *average* wastewater. For a particular industrial activity it is possible that concentrations are different by orders of magnitude and individual organic compounds could play a relevant role in the LCIA of wastewater disposal. This is likely to happen, if the concentrations in wastewater are high, elimination in treatment is low (or there is little treatment), or characterisation factors are high.

Also the list of compounds in Abeggelen et al. (2009) is not comprehensive, although they focused on substances of concern. The inventories created with the Excel tools implementing the model presented here can be augmented, if a particular process is known to produce particular wastewater pollutants. This can become relevant, especially if the elimination is low and the toxicity is high. An effect on the LCIA result will however only be observable, if the compounds possesses available characterisation factors. To include these emissions, the concentration in wastewater must be researched, as well as the compound's elimination in the wastewater treatment. The latter must be applied in accordance with the share and level of wastewater treated (and the treatment levels (%WWTP, %1ST, %2ST, see chapter 4.2 'Adopting JMP data for industrial wastewater fate' on page 10).

19.4 Wastewater degradability

Wastewater comprises a vast conglomerate of different compounds with differing biodegradability. The BOD parameter symbolizes the sum of organic compounds that are relatively easy to biodegrade – usually measured as oxygen uptake within a time frame of 5 days. The ratio of BOD/COD of a wastewater roughly characterises the share of easily biodegradable organic compounds compared to their total amount. A wastewater with large BOD/COD ratio can be considered better biodegradable than a wastewater with small BOD/COD ratio.

It might be tempting to incorporate this degradability characterisation into the WWT model. Intuitively, larger elimination would be expected from wastewaters with large (BOD/COD) through better mineralization, especially in the biological stage. BOD will also be eliminated through sludge, but more easily degradable compounds should lead to faster and better mineralization and subsequently air emissions as CO_2.

This assumption can be tested. A larger total BOD elimination would be expected in plants treating wastewater with a high BOD/COD ratio. So in a plot of BOD elimination against BOD/COD ratio, a larger elimination would be expected at the high end of BOD/COD. This plot was created from available data of actual loads and eliminations from over 5700 individual European WWT plants for the year 2018 (EEA 2020) and is shown in Fig. 19.1. No pronounced trend can be observed. The BOD

[67] For diuron, a herbicide, 0.314 points per kg; for carbendazim, a fungicide, 0.0617 points per kg; for atrazin, a herbicide, 0.3387 points per kg.

elimination is typically high across the whole observed range of BOD/COD ratios – with a median value between 95 and 98% (red line). At relatively high BOD/COD ratios > 0.7 rather *lower* BOD eliminations are observed than in the more frequent BOD/COD range of 0.4–0.6. In a similar plot for COD elimination (not shown) the effect, if any, is also merely slight and even the opposite of the expected: a slight tendency for lower COD eliminations are found at the high end of BOD/COD rather than at the low end.

Therefore the BOD/COD ratios seem to influence the *actually observed* WWT elimination performance only to a very limited degree, if at all. Other circumstances have more relevant influence on elimination than the relative biodegradability expressed in BOD/COD. On average, plants seem to be able to eliminate the carbon mass in wastewater roughly equally well, regardless of its overall biodegradability.[68]

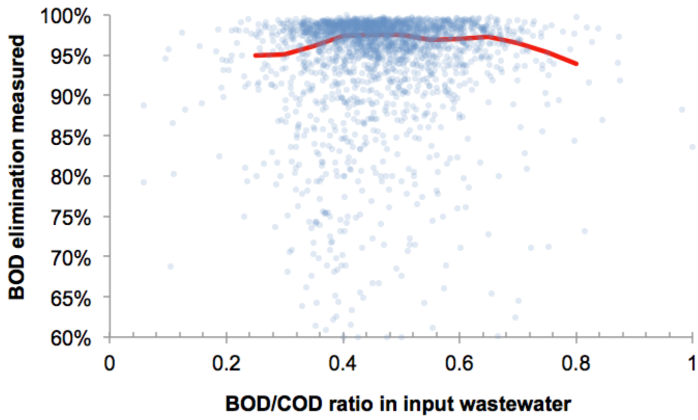

Fig. 19.1 Measured BOD elimination against the BOD/COD ratio of incoming wastewater in 5700 European WWT plants for 2018. The red line is the central tendency given as median per consecutive segment.

For this reason, no degradability parameter for wastewater is introduced in the present model. Eliminations are derived as technological characteristics of treatment plants and not modified based on the degradability of any specific wastewater.

20 Corrections in wastewater composition

20.1 Wastewater from particle board production (2014)

Instead of pollutants per m^3 wastewater, the pollutants *per m^3 of produced particle board* were falsely entered in 2014 (Werner 2014-a). Old wrong figures were 0.00044 kg COD /m^3 and 0.0000616 kg BOD /m^3. Heeding the 0.0711 m^3 of wastewater produced per m^3 particle board, the concentrations

68 This statement refers to the *bulk sum of organic compounds* processed in a WWTP as measured here. For *individual* compounds, e.g. hexane or ethylene glycol, it is reasonable to maintain that clear differences in degradability exist and such differences can also measured, see for instance (Fahlenkamp et al. 2008:Tab 2.2).

would be a factor 14 higher (Werner 2020). But even those figures are very minute and represent practically unpolluted water.[69]

The intended wastewater concentrations are then 0.00619 kg COD/m^3 and 0.000866 kg BOD/m^3. TOC content was then derived from COD. These new, corrected figures are however also four orders of magnitude lower than the legacy values from ecoinvent 2000, which seems odd. But it's possible that advancements in in-house wastewater treatment lead to such changes in production effluents.

20.2 Wastewater from medium density fibreboard production (2014)

Instead of pollutants per m^3 wastewater, the pollutants *per m^3 of MDF board* were falsely entered in 2014 (Werner 2014-b). Heeding the 0.407 m^3 of wastewater produced per m^3 MDF board, the concentrations are a factor 2.457 higher (Werner 2020). The corrected figures are thus (all in kg/m^3) 0.015995 BOD, 0.149386 DOC, 0.01671 N_{tot}, 2.56511E-05 PO_4 as P, 0.000164373 Cr, 8.20639E-05 Cu, 0.000117936 Zn. TOC content was then derived from DOC.

20.3 Wastewater from hard fibreboard production (2014)

Instead of pollutants per m^3 wastewater, the pollutants *per m^3 of MDF board* were falsely entered in 2014 (Werner 2014-c). Heeding the 2.23 m^3 of wastewater produced per m^3 hard fibreboard, the concentrations are a factor 2.23 *lower* (Werner 2020). The corrected figures are thus 0.560538 kg COD/m^3, 0.0028296 kg N_{tot}/m^3, and 0.000713 kg P_{tot}/m^3. TOC content was then derived from COD.

20.4 Plywood production effluent (2003)

The original COD value was 0.7 kg/m3 and the BOD is 4.23 kg/m3, i.e. COD < BOD, which should not occur. This data is from the source (Werner et al. 2003). Another source suggests the ratio for BOD/COD in plywood effluent is 0.65, with 4.1317 kg COD per m^3 and 2.684 kg BOD per m^3 (Sunny et al. 2017). The used COD value was therefore augmented to 6.508 kg/m^3 (=4.23 / 0.65), while the original BOD value of 4.23 kg/m^3 was retained. TOC content was then derived from COD.

20.5 LCD module production effluent

In the datasets by (Hischier et al. 2007:93), the BOD value (3.37 kg/m^3) is larger than the COD value (2.6 kg/m^3), which should not happen, as COD is the more complete oxidation than BOD. BOD and COD values were originally adopted from Socolof et al. (2001). And already in Socolof et al. (2001) BOD is larger than COD. To remedy this, it was assumed that the COD value is meant to represent an *additional* oxygen demand beyond BOD. TOC content was then derived from COD.

[69] For comparison, the total organic carbon in precipitation is in the range 300–1900 µg C/L (from five European background sites in Cerqueira et al. 2010). Using a TOC/COD ratio of 0.27, the COD concentration given in (Werner 2014) world equate to 1663 µg C/L, i.e. similar to unpolluted rainwater.

20.6 Heat carrier liquid, 40% propylene glycol ($C_3H_8O_2$)

This wastewater is for a 40% propylene glycol solution which acts as heat carrier liquid in solar collector plants. For small amounts from domestic plants, disposal via sewer is tolerated in Switzerland.

For the inventories a (Jungbluth 2003) an unsourced composition of 650 kg COD per m^3 wastewater was assumed. Since the formula of propylene glycol is known and C, H, O can now explicitly be entered as composition, the former COD value was now replaced with 0.20834 kg C, 0.185 kg O, 0.04663 kg H per litre of wastewater.[70]

21 New exchanges for environmental scarcity LCIA

The method of environmental scarcity (a.k.a. eco-scarcity, or MOeK, or UBP) is a Swiss LCIA method (ÖBU 2013). This method has some special characterisation factors for certain exchanges that occur within the technosphere. Relevant for disposal processes are the characterisation factor for **organic carbon placed in landfill** and **total waste mass placed in landfill**. These flows relate to mass *going into* a landfill, not its emissions coming out of the landfill, and are therefore not covered by the usual biosphere exchanges of conventional inventory work.

In order to asses these two material flows for ecoscarcity accurately, new exchanges were introduced in 2020, which accurately represent the targeted mass flows (Doka 2020-M). These exchanges were discussed and defined with the ecoscarcity authors (Fredy Dinkel, Thomas Kägi, Rolf Frischknecht) prior to their introduction in the suite of Excel disposal tools.

With regard to wastewater treatment, flows into landfills occur only downstream after processing of wastewater and generation of sewage sludge as a secondary waste. Sewage sludge might be landfilled or incinerated. After incineration, solid residues as tertiary waste can be landfilled. The wastewater treatment inventory model includes all these higher order disposal processes in a wastewater-specific manner and are therefore also able to detail the required technosphere flows into landfill.[71]

22 Calculation Manual

The wastewater disposal model is implemented into an Excel calculation workbook and integrated into the suite of disposal Excel workbooks, which can export EcoSpold1 and EcoSpold2 process inventory files. The tools include a centralised repository for waste composition definitions, site parameters like

[70] Based on a 40 V-% solution, density of propylene glycol of 1100 kg/m^3, sum formula of $C_3H_8O_2$ with a molecular weight of 76.1 g/mol.

[71] One of the motivations of the "landfill ecofactors" is to penalise not recycled material; another is to penalise the risk of undesired landfill reactions by introducing organic carbon into landfills and possible other motivations. It could be argued that wastewater emitted directly into water represents also unrecycled matter and could be included. On critical examination, it is obvious that the same argument would also hold for water emissions *after* wastewater treatment and in fact for any kind of emission into any environmental media. The over-generalisation from flows into landfill to emissions in general is therefore not carried out here.

climate, EcoSpold2 Master Data etc. The usage of the tools is described in updated report (Doka 2021).

23 Results

23.1 An example for two countries

With the model and calculation tools elaborated here a large range of different inventories of wastewater disposal of specific wastewaters can be created. A complete result presentation is therefore not possible. As an exemplary examination the results for average wastewater disposal in Switzerland and Zambia is presented here. Zambia is chosen for being a country with exceptionally high share of untreated wastewater: 97%, based on JMP data, therefore representing a country with a poor national average wastewater sanitation. Only an estimated 2.86% of wastewater in Zambia is treated and for subsequent sludge disposal 100% agricultural spreading is assumed. The average wastewater derived in chapter 6 is used as input for both countries. So the difference in results reflects the difference in wastewater disposal and technologies, not differences in input.

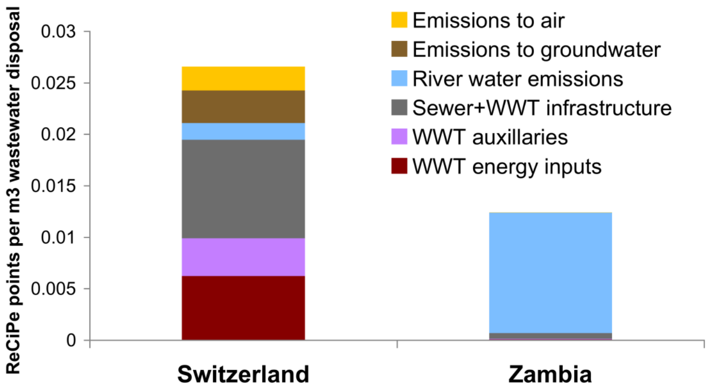

Fig. 23.1 LCIA results for wastewater disposal in Switzerland and Zambia with ReCiPe'13 (HA) endpoint method.

Fig. 23.1 shows the LCIA results of average wastewater disposal in Switzerland and Zambia per m^3 wastewater. In Switzerland rates of sewering and treatment are high leading to large burden contributions for infrastructure as well as WWT energy and auxiliaries inputs. The emissions to river water are low. They are comprised of emissions of untreated wastewater, emissions after treatment, and effluents of the waste incinerator disposing of sewage sludge. The emissions to groundwater are larger than river water, which reflects the fact that many pollutants removed from wastewater end up in incineration residues, which subsequently partially leach to groundwater in landfills. Two thirds of the groundwater burden are caused by the heavy metal zinc. Air emissions come from direct emissions of the treatment plant and from sludge incineration. The largest contributions here are emissions of NO_x and N_2O from sludge incineration.

By comparison the burden in Zambia appear overall smaller. With low sewering and treatment rates, infrastructure burdens are minute. Emissions to river water are large and reflect the low treatment rates and direct emissions from untreated wastewater. Some small emissions to groundwater and air also occur, here mainly from agricultural sludge spreading.

23.2 The unheeded utility of wastewater treatment

The conventional total LCIA burden of wastewater disposal in Zambia in Fig. 23.1 is about half as large as in Switzerland. This might seem surprising, as treatment rates in Switzerland are much higher. Is wastewater treatment actually detrimental for the environment? Is the significant expenditure for infrastructure not over-compensated by beneficial effect from reduced emissions? As explained in chapter 3 'Relevance of unsanitary conditions' on page 8, the burden on human health due to unsanitary conditions from untreated or insufficiently treated wastewater is not contained in these results. Inclusion of these effects would increase the burden of wastewater disposal causing unsanitary conditions, due to the safeguard subject "Human Health" in LCIA methods. But with conventional LCIA methods one of the chief reasons to perform wastewater treatment—better sanitation to prevent diseases—is not reflected in their human health effects.

How large are those burdens from unsanitary conditions and, if included, are they large enough to change to relative outcome in this example? The reasons to not (yet) include burdens from unsanitary conditions in these inventories were given in chapter 3. Here a generic first estimate of those burdens is attempted.

In chapter 3 a worldwide average damage for people exposed to unsafe sanitation of 0.026 DALY/cap.year was calculated. A simplifying assumption is made here now that unsanitary conditions are very local, i.e. people *suffering* from unsanitary conditions are the same people *causing* unsanitary conditions.[72] To connect the damage from unsafe sanitation to the LCIA results per m^3 wastewater, the annual rate of wastewater generation per person needs to be calculated. The wastewater input in Fig. 23.1 contains 124 mg TOC/l and 399.7 mg COD/l. The generic output of COD per person is 120 grams daily. Thus, the one cubic metre wastewater f.u. corresponds to the pollutant load one person produces during 3.3 days.[73]

If *all* the wastewater would lead to unsanitary conditions, this would result in a damage of 0.000237 DALYs per m^3 wastewater.[74] Converted into ReCiPe points, this is 4.695 points per m^3.[75] While a lot of wastewater in Zambia is not treated, not all of that untreated water necessarily leads to unsanitary conditions.[76] The statistics from JMP detail the kinds of toilets used, which play an important role in the sanitary situation (WHO/UNICEF JMP 2019). In Zambia the average national rate of open defecation (no toilet facilities used at all) is 19.3%, and 36.6% of the inhabitants use unimproved facilities. It is assumed here that only open defecation and unimproved facilities are causing unsanitary conditions, and that other, improved facilities do not. Thus of one m^3 wastewater disposed in Zambia

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72 This assumption might be an underestimation or an overestimation. It is possible, that the unsanitary behaviour of a community affects only *a part* of that community, but it is also possible that the community is fully affected as well as additional outside communities. The answers depend on local circumstances.

73 3.3 capita.days = 399.7 grams COD/m^3 wastewater / 120 grams COD/capita.day.

74 0.000237 DALYs per m^3 = 0.026 DALY/capita.year /365.25 days/year · 3.3 days/m^3 wastewater.

75 Normalisation of 0.0202 DALY/year, weight 40%, scaling factor 1000.

76 Generally speaking, the occurrence of unsanitary conditions is influenced by the local population density. A collection of people living in close proximity are potentially more at risk to cause sanitation problems than those same people living scattered over a large area. The risk is obviously also influenced by levels of sewering and wastewater treatment as well as the sources and technologies of drinking water purification and supply.

only 0.56 m^3 lead to unsanitary conditions.[77] So the additional burden from unsanitary conditions in Zambia is 2.63 points per m^3 wastewater.[78]

For Switzerland no unsanitary conditions are assumed, as they are very unlikely.[79] In Zambia the damage from unsanitary conditions calculated above (2.63 points) absolutely dominate the burdens compared to the conventional LCIA burdens shown in Fig. 23.1 (0.0126 points). The total damage in Switzerland is 0.0288 points per m^3 and thus a factor of 92 below that of Zambia. This factor to a large degree represents the utility of wastewater sewering and treatment by avoiding unsanitary conditions and disease in humans. So the initially asked question can be answered: Wastewater treatment is beneficial regarding environmental damages mainly due to avoidance of human health damages.[80]

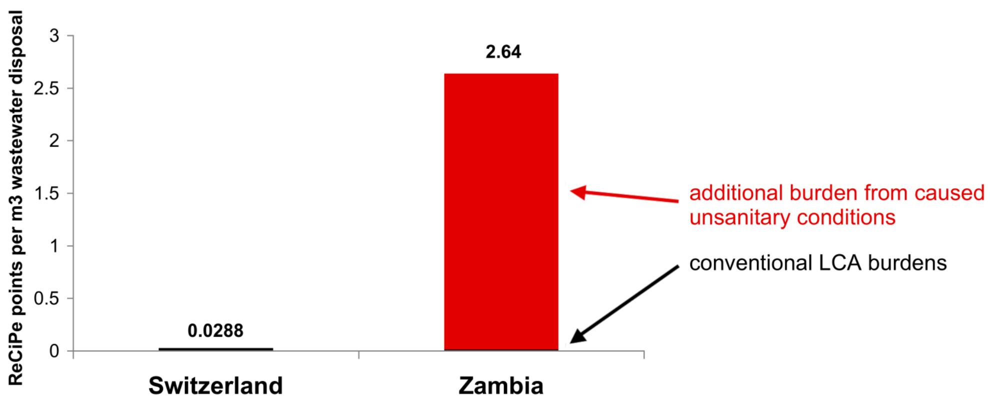

Fig. 23.2 LCIA results for wastewater disposal in Switzerland and Zambia as in previous figure, but including estimate for burdens from unsanitary conditions in Zambia.

24 Outlook

The waste disposal model for wastewater in ecoinvent have developed over the years since their first inception in 1996 (Zimmermann et al. 1996). They have grown in scope and details, but owing to the goal of delivering background data on the fate of wastewater from industrial processes, also contain several simplifications and generalisations.

A simplification is for instance the breakdown of wastewater treatment sophistication into merely three kinds of plants. For instance oxidation lagoons[81] are disregarded here. Also treatment of sewage sludge is simplified to include merely three different fates (agriculture, landfill, incineration). Drying

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77 0.56 = 0.193 + 0.366. Again, an approximate equivalence of rates for *population* and rates for *wastewater generated* is assumed here, as in chapter 4.2 'Adopting JMP data for industrial wastewater fate' on page 10.

78 2.63 points = 4.695 points /m^3 · 0.56 m^3.

79 Rare and temporary sanitary problems in Switzerland are usually associated with cattle manure excess.

80 Not everywhere in LCA is it proper to include the *utility* of an assessed product or process in the LCIA outcome, or, as here, to include the *absence* of an utility as an additional burden. But in wastewater treatment the process itself deliberately improves the environmental conditions not only in the conventional pollutant load of the water, but also regarding the microbial load, leading to unsanitary conditions.

81 Lagoons are basically artificial open ponds, in which the wastewater is allowed to settle and degrade for days before discharge. Periodically accumulated bottom sludge is removed.

and utilization in cement kilns is not considered, neither is composting or dedicated mono sludge incinerators. In the future such technology fates could be added.

New in the present model is the widening of the scope to include wastewater fate in developing countries, where neither treatment plants nor sewers might be commonly available. This was based on data recorded for household situation from the WHO/UN monitoring of Sustainable Development Goals SDG, which was taken to be representative for the level of wastewater management sophistication in a country. In the future, a validation, refinement and update of wastewater fate based on recorded data for industrial sources of wastewater would be desirable.

The present model covers all water emissions of organic compounds with the sum parameter TOC. In chapter 19.3 'Relevance of emissions of organic compounds ' on page 65 an exemplary selection of certain organic compounds were found to be of little relevance. But for particular production process and activities single compounds could become relevant and would need to be added to the inventory to be more complete. To help calculate a compound's fate, data on elimination and degradation in WWTP stages are important. In the future generic information on single compound elimination per WWTP stage could be compiled to assist the addition of single compounds in wastewater disposal inventories. For general application, it is expected that inclusion of single compounds will remain a rare purpose, but for some particular processes it could be important.

In Switzerland a new waste law of 2016 "VEVA" tasks the WWTPs with introducing a form of phosphorus recycling by January 2026. Similar legislation is also in effect in some other European countries. The goal is to replace imported mineral phosphorus fertilizer with recycled, secondary phosphorus. As direct agricultural use of sewage sludge is prohibited in Switzerland, other solutions are sought. For instance isolation of phosphorus from the ash of separate sludge incinerators, or alternatively procedures that work with flows within the WWTP. At the moment no Swiss WWTP has yet installed beyond phosphorus recycling beyond trials and demonstrations (PXCH 2021). The present wastewater disposal does not model the possibility of phosphorus recycling. In future updates this can be added, when the selected technologies become clear.

The performance of wastewater treatment was based on Swiss plants. Swiss WWTPs have comparatively low elimination for nitrogen. The national average of nitrogen elimination in WWTPs is only 47% (Heldstab et al. 2013:49). This rate has increased since the 1985 due to international agreements like the OSPAR (Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic). But compared to the level of nitrogen elimination in other European countries, where the weighted mean elimination is 80%[82], the Swiss rate is low. This means that for some countries the modelled nitrogen elimination even for a 3-stage plant is underestimated. In the future, this might be refined, if more country data becomes available. But presently, asking the user of the tools to provide a country-specific elimination rate (not only for N, but also P, and organics) will in many cases be unfeasible, especially for low-income countries.

The disposal of treatment sludge in the model is based in fixed inventory factors used to derive waste-specific disposal inventories for landfilling and incineration. This does not necessarily reflect the technical parameters of a particular site currently chosen by the user, e.g. landfill gas capture rates in landfilling. In the future it is intended to integrate the landfilling and incineration model calculations with the sludge disposal inventory calculation. This would heed the parameters of a particular site for landfilling and incineration also in sludge disposal.

[82] Calculated from 4772 European WWTPs with data on nitrogen elimination, weighted by nitrogen input, based on data from (EEA 2020).

In EcoSpold1-Files the *disposal route* of infrastructure materials is constant and is not adapted to the country set by the used. It is therefore possible that for instance a disposal of PVC in a waste incinerator is inventoried in countries where there are no incinerators at all. In EcoSpold2/ecoinvent v3+ this issue is solved with market datasets establishing a country's technology mixes.

25 Glossary

Combined sewer Sewers that transport wastewater as well as rainwater from sealed built-up areas.

Combined sewer overflow (CSO): In combined sewers the hydrological capacity of treatment plants at the end of the sewer can be exceeded during intense rain events. To avoid sewer overflows and flushing wastewater onto streets or even back into households, relief structures divert excess untreated wastewater into rivers. This excess relief is the combined sewer overflow, which emits untreated wastewater into rivers.

ES1 EcoSpold1 (sometimes also named "EcoSpold 2000"). A file format for Life Cycle Assessment data. Within the context of this project, ES1-files refer to process inventory files. EcoSpold1 files were defined and used in the ecoinvent 2000 project (2003-2010) which released the ecoinvent database versions 1.0-2.2. Subsequent ecoinvent versions (3+) used EcoSpold2 (ES2). After 2010, non-canonical versions or dialects of the EcoSpold1 format (i.e. not strictly adhering to the original ecoinvent nomenclature) were created by various consulting firms (e.g. Pre, ESU-services, treeze).

ES2 EcoSpold2. A file format for Life Cycle Assessment data. Within the context of this project, ES2-files refer to process inventory files. ES2 is the updated format of EcoSpold1 (→ ES1). EcoSpold2 is used by the ecoinvent database versions 3+ since 2010.

PCE Per-capita equivalent (German: *EGW, Einwohnergleichwert*). Also p.e. for "population equivalent" is used. A measure of wastewater amounts. PCE can be based on pollutant contents (BOD, COD, N_{tot}, or P_{tot}) or volume (hydraulic equivalent). For instance, one adult human is roughly producing 120 grams of COD daily. A wastewater flow with a certain COD content, can be converted to a PCE figure, E.g. 50'000 m^3 wastewater per day with a COD content of 300 mg/L would equate to 125'000 PCE_{COD}. Different conversions to PCE are possible simultaneously. Since not only people, but also industrial activities can produce wastewater pollutants, the PCE treated in a WWTP does not necessarily equal the *actual number of inhabitants* connected to that WTWP. Alternatively PCEs can also be used to express the nominal design capacity of a plant (PCE_{dim}) , which needs to be discerned from the statistical data of PCEs actually treated. PCE characterizes wastewater before treatment and does not contain any information about pollution elimination efficiency of a WWTP.

Sanitation Sanitation refers to public health conditions related to clean drinking water supply and adequate treatment and disposal of human excreta and sewage.

Sewage or domestic/municipal wastewater, is a type of wastewater that is produced by a community of people. It consists mostly of grey water (from sinks, bathtubs, showers, dishwashers, and clothes washers, including soap and detergents), black

	water (the water used to flush toilets, combined with the human waste that it flushes away and toilet paper). I this report the more encompassing term "wastewater" is used.
Sewer	Collection and transport system for wastewater. Often in underground pipes, but also open sewers exist.
Sewerage	Term that in American English can signify the municipal wastewater itself (→ sewage), but in British English and professional technical American English means the *infrastructure* network transporting the wastewater → sewer. Due to this ambiguity the term is best avoided altogether, and "wastewater" and "sewer" are used with advantage. In the ISIC classification of industrial activities the term "sewerage" (No. 3700) is used for any wastewater related activities lumping together sewer transports and wastewater treatment plants.
sewering	Term used in this report to describe the service or action of transporting wastewater in sewers.
STP	Sewage treatment plant. Facility to remove pollutants and nutrients from wastewater. In this report the more encompassing term wastewater treatment plant WWTP is used.
Wastewater	Generic term for liquid waste from domestic, municipal or industrial sources. Can include grey and black wastewater from households. In combined sewers wastewater can also include relatively unpolluted rainwater.

26 Appendix A

26.1 Papers with information on WWTP infrastructure data

Various papers could be found which contain information on WWTP infrastructure expenditures, which can be used for LC inventories.

26.1.1 Risch et al. 2015 for Olwisheim, France (912 m^3/day)

Risch et al. (2015) set out to assess the wastewater sewering and disposal services for Grabels, a town belonging to the metropolitan area of Montpellier in the south of France. Grabels represents 5200 PCE and this wastewater is sewered into the large, central WWTP of Montpellier-Lattes which treats a total of 470'000 PCE from the whole Montpellier metropolitan area. For the *sewers*, Risch et al. (2015) make a detailed evaluation of the 40 km of sewers built in Grabels. The WWTP infrastructure however they approximate with planning data for a small WWT plant with 5200 PCE capacity located in Olwisheim in the Alsace region in the east of France. Taking proxy data from another region is acceptable, but it is erroneous to inventory a plant of much smaller total capacity than the actually much larger plant used. The correct way to inventory the WWTP infrastructure used in Grabels would be to inventory an appropriate *fraction* of a 470'000 PCE plant. A convenient way to do this would be to calculate an infrastructure inventory for Montpellier-Lattes *per PCE treated annually*, and then multiply with the 5200 PCE produced in Grabels.[83] The Olwisheim plant is 90 times smaller in terms of treated wastewater than the actually used Montpellier-Lattes plant. There is considerable "material

[83] Alternatively also the volume of wastewater treated annually can be used for scaling.

economy of scale" in WWTP infrastructure as shown in Fig. 15.1 on page 44. I.e. a large plant uses much less infrastructure materials per m^3 treated than a small plant. Assuming the exponent of -0.2689 in the regression of Fig. 15.1 is suitable, it can be estimated that Risch et al. overestimated the WWTP infrastructure in their study by a factor of 3.4.[84]

Regardless of this shortcoming for the goal of the paper in Risch et al. (2015), the data compiled for the Olwisheim plant is valuable as a data source for a 5200 PCE plant. According to Risch et al. this is for an activated sludge plant with physico-chemical sludge conditioning taken from a planning technical report.[85] A daily wastewater flow of 911.5 m^3 per day (332'930 m^3/yr) in Olwisheim was estimated based on the average ratio of measured daily pollutant flow and concentration data available for the year 2011 (SIERM 2021).

26.1.2 Fahner et al. 1995 for Ergolz, Switzerland (10'951 m^3/day)

Fahner et al. (1995) made an LCA of the Ergolz WWTP in Switzerland, comprising a detailed inventory of the WWTP infrastructure needs per year.

The data from Fahner et al. was used together with other sources in (Zimmermann et al. 1995) as a basis for extrapolation of WWTP infrastructure to other plant sizes. The same extrapolation was also used in (Doka 2003-IV). A problem with that extrapolation was that a purely linear dependency with plant size was assumed, while a concave trend is more likely (cf. Fig. 15.1 on page 44). A linear extrapolation tended to overestimate the infrastructure of mid-sized plants. The linear approach also implied that in plants the at the intercept of about 700'000-800'000 PCE, the infrastructure needs would become zero, and while this did not affect the application in (Zimmermann et al. 1995) or (Doka 2003-IV) it is nevertheless clearly unrealistic. Another problem in (Zimmermann et al. 1995) was that the plant size of Ergolz was underestimated to be 25'000 PCE. The Ergolz plant was extended from 1991-1994, and the inventory data from Fahner et al. referred to this extended plant with 40'000 PCE. Using a smaller plant size and material data from a larger plant overestimated the specific material input in the extrapolation. This error was also included in (Doka 2003-IV).

The data from (Fahner et al. 1995) is re-examined for this study, cf. Tab. 15.2 on page 45. The plant size of Ergolz is now based on the actually treated volume of wastewater of 4 million m^3 annually (= 10'951 m^3/day).

26.1.3 Xue et al. 2019 for Mill Creek, USA (431'537 m^3/day)

Xue et al. (2019) made an LCA and cost accounting of the urban water system of the Greater Cincinnati region. This includes the large WWTP Mill Creek, servicing that area. In part 2 of the publication (Arden et al. 2019) they publish in their supplementary material (sheet 'T-S6' of the Excel workbook) a granular inventory of the WWTP with materials and inputs used per m^3 treated, differentiated into nine plant parts[86] and five categories (tanks and buildings, motors, pumps, internal

[84] $3.4 = (5200^{-0.2689}) / (470'000^{-0.2689})$

[85] It is unclear whether this is planning data for the now existing Olwisheim plant, or planning data for a future replacement plant.

[86] The nine parts are 1. Pumping at Wastewater Treatment Plant; 2. Screening and Grit Removal; 3. Primary Sedimentation; 4. Aeration; 5. Secondary Clarifiers; 6. Sludge Thickening and Dewatering; 7. Sludge Incineration; 8. Primary disinfection; 9. Release wastewater effluent.

pipes). Xue et al. (2019) also list the lifetimes of the different parts (Tab S14), which allows to calculate masses of the standing plant and the Specific Concrete Mass SCM.

The data has some peculiarities. For the plant parts primary sedimentation, aeration and secondary clarifiers the volume of concrete used for tanks and buildings is factors larger than the volume of excavation work inventoried there. This seems only feasible, if the tanks had significant volumes aboveground. Considering available online photographs of the Mill Creek plant, this seems not to be the case. It is possible though, that the construction benefited from pre-existing ground depressions, reducing the excavation work required. Or that excavation work was used as a proxy for other construction energy used, as the inventory does not feature any corresponding energy inputs. The original concrete masses are used to calculate the Specific Concrete Mass SCM in Tab. 15.1 on page 43. The excavation figures have no bearing on the present work.

26.1.4 Morera et al. 2020, four WWTPs in Spain

Morera et al. investigate four different existing WWTPs in Spain.

Tab. 26.1 Data for three different WWT plants for wastewater treated per day and per year, and calculated Specific Concrete Mass SCM.

Plant	Capacity in m^3/day	Capacity in m^3/year	SCM kg/(m^3/yr)
Navàs (Bagès)	1'500	547'500	4.97
Balaguer (La Noguera)	3'750	1'368'750	4.21
Manlleu (Osona)	14'400	5'256'000	3.27
L'Escala (Alt Empordà)	21'000	7'665'000	4.06

They derive the plant's material inventories from construction budgets and have a very detailed inventory vector with 73 different materials and energy inputs. They have 13 different entries for mineral building materials.[87] The Specific Concrete Mass shown in Tab. 26.1 was calculated by heeding all four different concrete material types in their inventory. Compared to the correlation of SCM vs. treatment volume in Fig. 15.1 on page 44 the resulting figures seem (a) low and (b) have diminished economy-of-scale. Compared to the regression in Fig. 15.1 the SCM figures calculated for these plants is a factor 2.4 to 4 lower. This could partly be explained by the use of a capacity figure in Tab. 26.1, while in Fig. 15.1 actually treated annual volumes are used. Capacity figures are likely to be larger and therefore SCM calculated with actual volumes would become somewhat larger, maybe around 10–30%, making them still comparatively low by factors between 2 and 3. The Spanish plants in Morera et al. seem much smaller in occupied area compared to their treatment size. Possibly, the hydraulic reserve capacities in Spain need not be as large as in the wetter climates of the plants used in Fig. 15.1, which would be a reason for smaller SCM, especially when considering combined sewering of wastewater and urban runoff. Also the four plants inventoried by Morera et al. appear to have no sludge treatment on-site, while those in Fig. 15.1 do. While in Fig. 15.1 the economy-of-scale of plants lead to an exponent of –0.2689 in the power law regression, this exponent is clearly lower in the four Spanish plants at around –0.1. It is unclear why these plants would not have as pronounced

87 The 13 entries are concrete, lime mortar, cement mortar, adhesive mortar, plaster, concrete high requirements, precast concrete, lightweight precast concrete, brick, gypsum plasterboard, sand, crushed rock, gravel.

economy-of-scale as observed in other data, seeing that the fundamental driver of economy-of-scale here is lower concrete inputs due to larger volume pools.

Since the data of Morera et al. appears to be not comparable to the plants in Tab. 15.1 on page 43, owing to the various possibilities of discrepancies mentioned above, their data was not used for the present work, although their wide scope of materials appears an attractive feature.

26.1.5 Foley et al 2010 for two WWTPs, Australia (10'000 m^3/day)

Foley et al. investigate nine scenarios for hypothetical wastewater treatment, and two of those have plants with a conventional activated sludge stage. They derive the required concrete on the engineering design data of the plant scenarios. The Specific Concrete Mass SCM calculated from their data is only 0.61 and 0.9 kg/(m^3/year) for the two conventional plants.[88] This is about a factor 13 to 19 lower than expected based on the correlation in Fig. 15.1. One part of the explanation here is that the plants are designed to have only very short hydraulic retention time of 1.5 hours in the aerobic pool (see Foley et al. 2010:Tab 2). This is considerably lower than usual where hydraulic retention time in the activated sludge stage is between 6 and 24 hours, even when excluding the secondary settler. A low hydraulic retention time also makes the Specific Concrete Mass SCM smaller.

Since the data of Foley et al. appears to be not comparable to the plants in Tab. 15.1 on page 43, their data was not used for the present work.

27 Appendix B: Country data

This appendix contains the available country-specific data to be used with the wastewater disposal model. These are suggested values. The user of the inventory calculation tool can override these figures.

The data is presented in three parts:

1. Tab. 27.1 contains the Gross National Income GNI data used for extrapolations, the share of urban population, and the national average of the share of wastewaster treated (%WWTP), the share of wastewaster not sewered (1-%Sew), and the share of wastewaster sewered but not treated (%Sew – %WWTP). Details to these parameters are in chapter 4.2 'Adopting JMP data for industrial wastewater fate' on page 10.
2. Tab. 27.2 contains the same three wastewater fate parameters, but for the rural respectively the urban territory of the country.
3. Tab. 27.3 contains parameters for wastewater treatment, i.e. treatment levels (%1ST, %2ST, %3ST. See chapter 4.2.3), share of WWTP with anaerobic digestion (AD), share of energy utilization (CHP) in AD (see chapter 9) , and disposal mix of sewage sludge (agriculture, landfill, or incineration. See chapter 17).

[88] These are cases 2 and 3. And even the scenario with the largest concrete input to treat the 10'000 m^3 per day – Case 9 with Bardenpho biological nutrient removal, activated sludge and sludge stabilisation lagoon – only gets to a SCM of 1.7 kg/(m^3/year).

A suffix 'e' indicates that the figure was extrapolated using the procedures described in the chapters referenced above.

All the figures are also tabulated in the Excel workbook 'Central Repository' in the sheet 'GNIWWT'.

The countries in the tables are sorted by (1.) global region and (2.) country population, with small islands and sub-territories appended at the end. The global regions are in following order: Central and Eastern Europe; Commonwealth of Independent States; East Asia; Latin America and Caribbean; Middle East and North Africa; North America and Australia/New Zealand; Other Oceania; South Asia; Southeast Asia; Sub-Saharan Africa; Western Europe; Small Islands; Additional sub-territories already included above.

Tab. 27.1 Country data for Gross National Income GNI, urban population, and wastewater disposal parameters on a national average level. A suffix 'e' denotes extrapolated data.

		GNI $/cap.yr	% urban population	Wastewater treated (NATIONAL)	not sewered (NATIONAL)	sewered but not treated (NATIONAL)
Poland	PL	15'492	60.105%	73.012%	26.219%	0.76915%
Romania	RO	12'524	53.936%	45.785%	48.752%	5.4633%
Czech Rep.	CZ	21'682	73.675%	88.376%	10.85%	0.77386%
Hungary	HU	16'233	71.062%	77.928%	18.093%	3.979%
Serbia	RS	6'580	55.942%	11.396%	44.36%	44.244%
Bulgaria	BG	9'374	74.669%	55.864%	22.771%	21.365%
Slovakia	SK	18'870	53.751%	65.881%	30.677%	3.4421%
Croatia	HR	14'772	56.667%	39.352%	42.367%	18.281%
Bosnia Herzegovina	BA	5'656	47.876%	4.6441%	44.692%	50.664%
Lithuania	LT	18'953	67.516%	89.157%	6.7837%	4.0591%
Albania	AL	5'134	59.383%	39.229%	2.0153%	58.756%
Latvia	LV	17'598	68.075%	84.19%	8.4015%	7.4082%
North Macedonia	MK	5'852	57.748%	6.041%	26.264%	67.695%
Slovenia	SI	25'951	54.273%	54.041%	45.473%	0.48552%
Estonia	EE	23'343	68.717%	88.124%	10.95%	0.92581%
Montenegro	ME	9'060	66.477%	13.026%	54.161%	32.813%
Russia	RU	11'015	74.292%	52.433%	21.636%	25.931%
Ukraine	UA	3'347	69.246%	31.272%	48.918%	19.809%
Uzbekistan	UZ	1'512	50.55%	7.479%e	77.305%	15.216%e
Kazakhstan	KZ	9'094	57.336%	35.247%	62.819%	1.9339%
Belarus	BY	6'087	78.134%	76.131%	7.9319%	15.937%
Azerbaijan	AZ	4'436	55.343%	36.119%	60.682%	3.1994%
Tajikistan	TJ	896	26.982%	3.2365%e	85.348%	11.415%e
Kyrgyzstan	KG	1'245	36.135%	12.126%	86.465%	1.4088%
Turkmenistan	TM	6'987	51.153%	22.808%e	71.318%	5.8741%e
Georgia	GE	4'491	58.231%	5.9044%	48.21%	45.886%
Moldova	MD	3'130	42.557%	27.065%	66.869%	6.0657%
Armenia	AM	4'532	63.103%	31.551%	30.23%	38.219%
China	CN	10'281	57.96%	52.997%	37.819%	9.1845%
Japan	JP	39'899	91.535%	76.327%	23.547%	0.12575%
South Korea	KR	32'375	81.503%	99.269%	0.73082%	0%
North Korea	KP	500	61.678%	22.436%e	54.912%	22.652%e
Taiwan	TW	20'925	78.5%	58.801%e	25.165%e	16.034%e
Hong Kong	HK	50'753	100%	88.297%	7.1276%	4.575%
Mongolia	MN	3'818	68.363%	6.3656%	78.909%	14.726%
Macao	MO	79'821	100%	89.966%e	8.0016%e	2.032%e
Brazil	BR	8'853	86.309%	37.524%	33.544%	28.932%
Mexico	MX	9'124	79.867%	42.72%	20.389%	36.891%
Colombia	CO	6'343	80.446%	11.82%	22.699%	65.481%
Argentina	AR	11'130	91.749%	52.086%e	42.78%	5.1338%e
Peru	PE	6'576	77.72%	39.177%	29.243%	31.58%
Venezuela	VE	11'780	88.183%	22.64%	9.6427%	67.717%
Chile	CL	15'035	87.49%	72.522%	11.579%	15.899%
Ecuador	EC	6'101	63.67%	16.603%	36.376%	47.02%
Guatemala	GT	4'445	50.68%	27.332%e	58.077%	14.59%e
Cuba	CU	7'480	76.977%	20.974%	50.097%	28.929%
Bolivia	BO	3'568	69.08%	10.802%	51.879%	37.319%
Dominican Rep.	DO	7'754	80.277%	4.605%	77.719%	17.676%
Haiti	HT	775	54.346%	0.12988%e	99.34%	0.53006%e
Honduras	HN	2'679	56.457%	13.72%	59.863%	26.417%
Paraguay	PY	4'166	61.3%	4.2199%	91.184%	4.5961%
El Salvador	SV	4'589	71.275%	26.895%e	59.405%	13.7%e
Nicaragua	NI	1'936	58.299%	9.5857%e	75.618%	14.796%e
Costa Rica	CR	11'711	78.56%	10.494%	77.022%	12.485%
Puerto Rico	PR	21'924	93.587%	30.67%	5.6589%	63.672%
Panama	PA	14'856	67.365%	35.457%e	62.916%	1.6267%e
Uruguay	UY	16'562	95.24%	58.278%e	39.808%	1.9146%e
Jamaica	JM	5'631	55.378%	7.9084%	77.339%	14.753%
Trinidad & Tobago	TT	16'362	53.205%	19.449%e	79.887%	0.66419%e
Guyana	GY	4'756	26.538%	1.4444%e	97.858%	0.69782%e
Suriname	SR	5'586	66.041%	0.96334%e	98.674%	0.36266%e
Cabo Verde	CV	3'696	65.261%	14.094%e	76.151%	9.7554%e
Guadeloupe	GP	25'479	98.463%	39.427%e	60.326%	0.24659%e
Belize	BZ	4'653	45.601%	5.9369%e	91.1%	2.9629%e
Bahamas	BS	25'054	82.925%	21.305%e	78.551%	0.1439%e
French Guiana	GF	16'000	85.042%	43.586%e	54.817%	1.5972%e
Curacao	CW	20'350	89.203%	17.404%e	82.317%	0.2787%e
Grenada	GD	10'307	36.164%	6.0526%e	93.234%	0.71311%e

		GNI $/cap.yr	% urban population	Wastewater treated (NATIONAL)	not sewered (NATIONAL)	sewered but not treated (NATIONAL)
Palestine	PS	3'695	75.894%	36.836%	48.506%	14.657%
Egypt	EG	2'694	42.705%	48.227%	33.061%	18.712%
Turkey	TR	8'230	74.644%	58.52%	16.724%	24.756%
Iran	IR	5'341	74.394%	22.364%	73.182%	4.4547%
Algeria	DZ	4'022	72.052%	13.435%	16.326%	70.239%
Morocco	MA	3'211	61.908%	21.97%	44.608%	33.423%
Iraq	IQ	5'465	70.278%	15.008%	74.374%	10.618%
Saudi Arabia	SA	22'669	83.622%	55.504%	44.496%	0%
Yemen	YE	864	36.016%	19.822%	70.727%	9.451%
Syria	SY	1'860	53.5%	27.599%e	27.822%	44.579%e
Tunisia	TN	3'374	68.642%	54.543%	43.26%	2.197%
Israel	IL	42'736	92.336%	93.263%	0.84488%	5.8925%
Jordan	JO	5'126	90.747%	63.681%	35.58%	0.73878%
Libya	LY	7'659	79.817%	10.769%	30.688%	58.543%
Emirates	AE	43'951	86.248%	90.216%	9.0696%	0.71473%
Lebanon	LB	7'988	88.429%	11.664%	18.282%	70.054%
Oman	OM	13'646	83.56%	10.772%	89.228%	0%
Kuwait	KW	32'916	100%	100%	0%	0%
Qatar	QA	69'282	99.078%	92.063%	7.9369%	0%
Bahrain	BH	19'566	89.186%	91.11%	8.8896%	0%
United States	US	64'811	82.058%	81.166%	17.749%	1.0849%
Canada	CA	46'244	81.35%	67.756%	18.681%	13.563%
Australia	AU	54'687	85.904%	70.479%	11.5%	18.021%
New Zealand	NZ	42'290	86.466%	79.055%	16.243%	4.7017%
Fiji	FJ	5'629	55.742%	12.368%e	78.433%e	9.1998%e
French Polynesia	PF	15'990	61.784%	15.985%e	83.428%	0.5869%e
New Caledonia	NC	14'020	70.256%	39.66%e	43.283%e	17.056%e
Vanuatu	VU	3'230	25.163%	6.6014%e	87.932%	5.4666%e
Samoa	WS	4'393	18.452%	0.11533%	99.769%	0.11533%
Micronesia FSM	FM	3'476	22.608%	7.4968%e	86.866%	5.637%e
Nauru	NR	14'230	100%	21.956%e	76.903%	1.141%e
Antarctica	AQ		0%	0%e	100%e	0%e
India	IN	2'120	33.6%	3.1842%	89.438%	7.378%
Pakistan	PK	1'596	36.442%	8.649%e	74.768%	16.583%e
Bangladesh	BD	1'890	35.858%	1.9063%e	94.76%	3.3341%e
Afghanistan	AF	575	25.25%	0.40061%e	97.402%	2.1978%e
Nepal	NP	1'040	19.336%	1.2733%e	94.874%	3.8532%e
Sri Lanka	LK	4'026	18.384%	2.594%e	95.811%	1.5955%e
Bhutan	BT	3'037	40.167%	2.9673%e	94.371%	2.6613%e
Maldives	MV	8'549	39.38%	51.152%e	39.866%	8.9819%e
Indonesia	ID	4'061	54.659%	7.0561%e	88.657%	4.2868%e
Philippines	PH	4'043	46.682%	1.7896%	95.709%	2.5011%
Viet Nam	VN	2'612	35.213%	0.47903%e	99.002%	0.51873%e
Thailand	TH	7'332	49.2%	6.9673%e	91.389%	1.6441%e
Myanmar	MM	1'447	30.322%	0.0063723%e	99.98%	0.0136%e
Malaysia	MY	11'225	75.447%	78.444%	20.818%	0.73809%
Cambodia	KH	1'530	22.98%	4.7614%e	85.679%	9.5593%e
Laos	LA	2'347	34.368%	0.53818%	98.886%	0.57541%
Papua New Guinea	PG	2'205	13.102%	1.8963%	96.078%	2.0255%
Singapore	SG	58'780	100%	100%	0%	0%
Timor-Leste	TL	2'095	30.212%	4.689%e	88.703%	6.6085%e
Brunei	BN	28'389	77.312%	94.948%e	4.7%	0.35239%e
Nigeria	NG	2'040	49.519%	3.1809%	89.983%	6.8363%
Ethiopia	ET	850	20.31%	0.41485%e	98.861%	0.72403%e
Congo (Kinshasa)	CD	480	43.88%	0.0087844%e	99.934%	0.057399%e
South Africa	ZA	6'074	65.85%	43.933%e	41.648%	14.419%e
Tanzania	TZ	1'028	33.053%	0.25031%	99.398%	0.35164%
Kenya	KE	1'823	26.562%	2.0301%e	94.615%	3.3554%e
Sudan	SD	645	34.37%	0.17112%e	98.99%	0.83882%e
Uganda	UG	627	23.196%	0.14059%	99.322%	0.53729%
Ghana	GH	1'966	55.407%	1.3007%e	96.727%	1.972%e
Mozambique	MZ	436	35.455%	0.1089%e	99.11%	0.7809%e
Madagascar	MG	446	36.522%	0.16251%e	98.699%	1.1387%e
Cote d'Ivoire	CI	2'316	50.326%	2.8853%e	93.501%	3.614%e
Cameroon	CM	1'356	55.777%	0.12394%e	99.592%	0.28358%e
Angola	AO	2'879	64.839%	6.4827%e	87.296%	6.2216%e
Burkina Faso	BF	704	28.743%	0.14363%e	99.211%	0.64561%e
Niger	NE	423	16.35%	0.19415%	99.328%	0.47792%
Malawi	MW	371	16.714%	0.22323%e	97.911%	1.8661%e
Mali	ML	897	41.572%	0.38115%	98.82%	0.79933%
Zambia	ZM	1'393	42.976%	2.8598%e	90.785%	6.3552%e
Senegal	SN	1'111	46.74%	2.0536%	91.739%	6.2079%

		GNI $/cap.yr	% urban population	Wastewater treated (NATIONAL)	not sewered (NATIONAL)	sewered but not treated (NATIONAL)
Zimbabwe	ZW	934	32.237%	4.0079%	74.423%	21.569%
Rwanda	RW	773	17.125%	0.22187%e	98.87%	0.90774%e
Chad	TD	700	22.858%	0.077761%e	99.571%	0.35129%e
Guinea	GN	583	35.793%	0.31215%e	97.999%	1.6892%e
South Sudan	SS	790	19.346%	0.020516%e	99.897%	0.08214%e
Burundi	BI	275	12.706%	0.036277%e	99.56%	0.4034%e
Somalia	SO	150	44.391%	0.53665%e	88.993%	10.47%e
Benin	BJ	881	46.768%	0.30332%e	98.609%	1.0873%e
Togo	TG	572	41.162%	0.044083%e	99.713%	0.24314%e
Eritrea	ER	480	39.451%	0.40504%e	96.948%	2.6469%e
Sierra Leone	SL	596	41.636%	0.082712%	99.514%	0.40306%
Cent. Afr. Rep.	CF	420	40.98%	0.0057834%e	99.951%	0.042966%e
Congo (Brazzaville)	CG	1'217	66.459%	0.35678%e	98.728%	0.91569%e
Liberia	LR	345	50.697%	0.051219%e	99.49%	0.45883%e
Mauritania	MR	1'274	52.824%	0.76569%e	97.362%	1.8725%e
Namibia	NA	4'943	49.005%	24.499%e	64.337%	11.165%e
Botswana	BW	7'344	68.7%	1.1074%e	98.632%	0.26051%e
Lesotho	LS	1'266	27.73%	0.3484%e	98.794%	0.85799%e
Gambia	GM	514	60.599%	0.356%e	97.465%	2.1785%e
Guinea-Bissau	GW	762	42.945%	0.60298%e	96.894%	2.5034%e
Gabon	GA	7'946	88.976%	27.947%e	66.386%	5.667%e
Eswatini	SZ	3'087	23.625%	3.1759%	89.796%	7.0284%
Mauritius	MU	11'722	40.841%	16.509%	76.768%	6.723%
Djibouti	DJ	3'310	77.648%	2.3274%	94.875%	2.7973%
Comoros	KM	742	28.784%	1.0042%e	94.716%	4.2794%e
Equatorial Guinea	GQ	5'219	71.646%	7.4774%e	89.388%	3.1348%e
Western Sahara	EH	2'500	86.622%	3.8526%e	92.44%e	3.7072%e
Mayotte	YT	12'820	46.395%	17.282%e	81.523%	1.1953%e
Sao Tome & Principe	ST	2'079	71.968%	6.1193%e	85.179%	8.7019%e
Germany	DE	48'508	77.261%	95.535%	3.4352%	1.0297%
France	FR	42'029	80.18%	78.034%	18.384%	3.5819%
United Kingdom	GB	41'395	83.143%	96.318%	2.9742%	0.70756%
Italy	IT	34'335	70.144%	91.069%	6.3417%	2.5892%
Spain	ES	30'690	80.08%	96.62%	0.015625%	3.3642%
Netherlands	NL	52'486	91.077%	97.256%	0.43431%	2.3094%
Portugal	PT	23'251	64.652%	63.962%	35.801%	0.2373%
Greece	GR	19'990	78.724%	81.901%	17.361%	0.73819%
Belgium	BE	47'302	97.961%	94.714%	4.7966%	0.48906%
Sweden	SE	55'281	87.146%	85.604%	13.788%	0.6078%
Austria	AT	51'163	58.094%	92.483%	7.5174%	0%
Switzerland	CH	84'925	73.761%	98.011%	1.8906%	0.098232%
Denmark	DK	62'362	87.757%	90.651%	8.4381%	0.91112%
Finland	FI	49'524	85.325%	84.6%	14.93%	0.47023%
Ireland	IE	64'798	62.947%	60.905%	33.814%	5.2812%
Norway	NO	82'763	81.871%	63.13%	16.168%	20.702%
Cyprus	CY	27'418	66.836%	51.775%	48.225%	0%
Luxembourg	LU	75'070	90.727%	95.762%	1.7997%	2.4388%
Malta	MT	25'243	94.546%	92.984%	1.5%	5.5159%
Iceland	IS	72'153	93.773%	78.811%	6.4405%	14.748%
Andorra	AD	43'270	88.15%	100%	0.0000037%	0%
Greenland	GL	19'290	86.574%	90.651%	8.4381%	0.91111%
Liechtenstein	LI	115'530	14.315%	98.7%	1.3%	0%
San Marino	SM	52'140	97.072%	70.372%	15%	14.629%
Monaco	MC	186'710	100%	100%	0%	0%
Vatican	VA	137'010	100%	90%e	8%e	2%e
Bonaire, Sint Eustatius & Saba	BQ	23'000	74.838%	0.34815%e	99.648%	0.0034171%e
Martinique	MQ	29'090	89.018%	46.495%e	53.352%	0.15231%e
Barbados	BB	16'596	31.159%	3.0536%	96.887%	0.059381%
St Lucia	LC	8'982	18.612%	4.3354%e	94.976%	0.68819%e
Aruba	AW	26'810	43.293%	4.6721%	95.082%	0.2459%
Virgin Is. (US)	VI	13'660	95.603%	39.329%e	58.379%	2.2921%e
St Vincent & Grenadines	VC	7'510	51.784%	6.0559%e	92.578%	1.3665%e
Antigua & Barbuda	AG	17'225	24.713%	1.0839%e	98.885%	0.03134%e
Dominica	DM	7'845	70.181%	12.311%e	85.131%	2.5582%e
Bermuda	BM	123'770	100%	1.5%	95%	3.5%
Cayman Is.	KY	47'320	100%	18.597%e	81.4%	0.0026152%e
St Kitts & Nevis	KN	16'904	30.773%	7.2469%e	92.53%	0.22287%e
Turks & Caicos	TC	28'340	92.817%	9.1657%e	90.8%	0.034313%e
Sint Maarten (NL)	SX	27'680	100%	9.0936%e	90.868%	0.038299%e
Virgin Is. (Brit)	VG	43'366	47.337%	22.222%e	77.771%	0.0061071%e
St Martin (Fr)	MF	15'400	0%	43.895%e	38.839%e	17.266%e

		GNI $/cap.yr	% urban population	Wastewater treated (NATIONAL)	not sewered (NATIONAL)	sewered but not treated (NATIONAL)
Anguilla	AI	29'493	100%	1.1964%e	98.8%	0.0036485%e
St Barthelemy	BL	9'000	0%	23.249%e	62.955%e	13.796%e
Montserrat	MS	12'384	9.048%	13.201%e	85.8%	0.99902%e
US Minor Outlying Is.	UM	46'381	0%	87.271%e	8.5518%e	4.1768%e
Solomon Is.	SB	2'010	23.286%	2.7715%e	93.132%	4.096%e
Guam	GU	30'500	94.699%	71.218%e	28.6%	0.18173%e
Tonga	TO	4'736	23.169%	0%e	100%	0%e
Kiribati	KI	3'224	53.262%	6.4426%e	88.209%	5.348%e
Marshall Is.	MH	5'296	76.634%	28.041%e	60.471%	11.488%e
American Samoa	AS	13'000	87.17%	22.842%	51.34%	25.818%
Northern Mariana Is.	MP	13'300	91.53%	50.432%e	46.407%	3.1618%e
Palau	PW	12'501	79.365%	52.562%e	43.556%	3.8825%e
Wallis & Futuna	WF	12'640	0%	35.269%e	48.158%e	16.573%e
Tuvalu	TV	6'884	61.53%	0%	26.171%	73.829%
Cook Is.	CK	20'722	74.835%	58.317%e	25.561%e	16.122%e
Norfolk Is.	NF	35'852	0%	81.637%e	10.596%e	7.7673%e
Tokelau	TK	6'275	0%	14.371%e	75.41%e	10.218%e
Niue	NU	5'800	44.057%	5.169%e	93%	1.831%e
Pitcairn Is.	PN	3'125	0%	5.3375%e	89.827%e	4.8352%e
Bouvet Is.	BV		0%	0%e	100%e	0%e
Heard & McDonald Is.	HM		0%	0%e	100%e	0%e
British Indian Ocean Territory	IO		0%	0%e	100%e	0%e
Christmas Is.	CX	46'364	100%	87.266%e	8.5532%e	4.1804%e
French Southern Territories	TF		0%	0%e	100%e	0%e
Reunion	RE	26'369	99.503%	49.948%e	49.786%	0.2661%e
Seychelles	SC	17'881	56.261%	16.348%e	83.235%	0.41694%e
St Helena, Ascension & Tristan da Cunha	SH	11'275	39.696%	47.556%e	47.9%	4.5441%e
Aland Is.	AX	55'829	39.723%	89.111%e	8.1211%e	2.7683%e
Jersey	JE	62'009	31.2%	89.595%e	8.0424%e	2.3623%e
Isle of Man	IM	79'595	52.458%	89.965%e	8.0017%e	2.033%e
Guernsey	GG	71'875	31.2%	89.894%e	8.0073%e	2.0987%e
Faroe Is.	FO	51'375	41.914%	88.472%e	8.251%e	3.2773%e
Gibraltar	GI	92'843	100%	100%e	0%	0.000008607%e
Svalbard & Jan Mayen	SJ	59'364	0%	89.43%e	8.0668%e	2.503%e
Falkland Is.	FK	96'962	77.206%	100%e	0%	0.0000045016%e
Cocos Is.	CC	7'632	75.3%	18.731%e	69.114%e	12.155%e
St Pierre & Miquelon	PM	31'548	89.901%	77.339%e	12.659%e	10.003%e
South Georgia & South Sandwich Is.	GS		0%	0%e	100%e	0%e
Kosovo	XK	4'634	41%	9.4085%e	83.064%e	7.5277%e
Channel Is.	GB-CHA	65'430	30.914%	81.5%	18.5%	0%

Tab. 27.2 Country data for wastewater disposal parameters for rural and urban territories. A suffix 'e' denotes extrapolated data.

	Wastewater treated (RURAL)	not sewered (RURAL)	sewered but not treated (RURAL)	Wastewater treated (URBAN)	not sewered (URBAN)	sewered but not treated (URBAN)
Poland	32.352%e	65.72%e	1.9279%e	100%e	0%e	0%e
Romania	9.903%e	88.915%e	1.1817%e	76.43%e	14.45%e	9.12%e
Czech Rep.	67.813%	31.7%	0.48686%	95.724%	3.4%	0.87641%
Hungary	59.947%	38.877%	1.1754%	85.251%	9.6287%	5.1207%
Serbia	4.1748%	79.616%	16.209%	17.083%	16.593%	66.324%
Bulgaria	21.032%	69.898%	9.0709%	67.68%	6.55%	25.77%
Slovakia	51.706%	44.84%	3.4538%	78.078%	18.49%	3.4322%
Croatia	19.658%	70.74%	9.6022%	54.412%	20.67%	24.918%
Bosnia Herzegovina	2.4501%	70.828%	26.722%	7.0328%	16.237%	76.73%
Lithuania	76.687%	19.36%	3.9531%	95.157%	0.7328%	4.1101%
Albania	38.022%	4.4735%	57.505%	40.055%	0.33394%	59.611%
Latvia	72.237%	22.163%	5.6004%	89.796%	1.9478%	8.2561%
North Macedonia	3.0901%	62.16%	34.75%	8.2%	0%	91.8%
Slovenia	11.662%e	88.233%e	0.10478%e	89.747%e	9.4465%e	0.80631%e
Estonia	64.864%	34.514%	0.62222%	98.713%	0.22341%	1.064%
Montenegro	4.2646%	85.028%	10.708%	17.444%	38.595%	43.96%
Russia	31.526%	52.882%	15.592%	59.667%	10.824%	29.509%
Ukraine	1.5572%	97.435%	1.0078%	44.47%	27.371%	28.16%
Uzbekistan	0.12358%e	99.625%	0.25142%e	14.674%e	55.47%	29.855%e
Kazakhstan	2.0169%	97.914%	0.068978%	59.973%	36.705%	3.3216%
Belarus	60.217%	27.122%	12.661%	80.585%	2.5615%	16.854%
Azerbaijan	5.685%	93.925%	0.39041%	60.677%	33.857%	5.466%

	Wastewater treated (RURAL)	not sewered (RURAL)	sewered but not treated (RURAL)	Wastewater treated (URBAN)	not sewered (URBAN)	sewered but not treated (URBAN)
Tajikistan	0.046094%e	99.791%	0.16258%e	11.87%e	46.263%	41.867%e
Kyrgyzstan	0.19178%	99.801%	0.0072332%	33.22%	62.894%	3.8861%
Turkmenistan	1.316%e	98.345%	0.33894%e	43.332%e	45.509%	11.16%e
Georgia	0.56608%	95.111%	4.323%	9.7335%	14.568%	75.699%
Moldova	2.842%	96.509%	0.64864%	59.761%	26.861%	13.378%
Armenia	8.7567%	80.358%	10.886%	44.879%	0.91983%	54.201%
China	32.749%	61.503%	5.7486%	67.683%	20.64%	11.677%
Japan	13.457%e	86.521%e	0.022169%e	82.142%e	17.723%e	0.13532%e
South Korea	96.049%e	3.951%e	0%e	100%e	0%e	0%e
North Korea	4.7273%	90.5%	4.7727%	33.439%e	32.8%	33.761%e
Taiwan	11.026%e	85.967%e	3.0067%e	71.885%e	8.5127%e	19.602%e
Hong Kong	88.297%	7.1276%	4.575%	88.297%	7.1276%	4.575%
Mongolia	0.87356%	96.886%	2.2409%	8.9072%	70.59%	20.503%
Macao	89.966%e	8.0016%e	2.032%e	89.966%e	8.0016%e	2.032%e
Brazil	4.749%	91.492%	3.7589%	42.723%	24.352%	32.925%
Mexico	18.112%	64.751%	17.136%	48.923%	9.2063%	41.87%
Colombia	2.1305%	86.143%	11.726%	14.175%	7.2781%	78.547%
Argentina	4.3516%e	95.219%	0.42891%e	56.448%e	37.988%	5.5637%e
Peru	10.247%	82.641%	7.1124%	47.471%	13.936%	38.593%
Venezuela	4.0524%e	81.6%e	14.348%e	25.131%e	0%e	74.869%e
Chile	16.651%	79.408%	3.9406%	80.511%	1.88%	17.609%
Ecuador	6.9558%	73.198%	19.846%	22.108%	15.366%	62.526%
Guatemala	6.6993%e	89.724%	3.5762%e	47.411%e	27.28%	25.309%e
Cuba	6.5166%	85.085%	8.3987%	25.298%	39.633%	35.07%
Bolivia	1.3116%	94.768%	3.92%	15.05%	32.682%	52.268%
Dominican Rep.	0.93284%	95.092%	3.9752%	5.5073%	73.45%	21.043%
Haiti	0.035803%e	99.818%	0.14611%e	0.20891%e	98.938%	0.85259%e
Honduras	2.1282%	93.884%	3.9877%	22.659%	33.624%	43.716%
Paraguay	0%	100%	0%	6.884%	85.618%	7.4977%
El Salvador	0.46103%e	99.304%	0.23485%e	37.548%e	43.325%	19.127%e
Nicaragua	0.21537%e	99.452%	0.33245%e	16.288%e	58.57%	25.142%e
Costa Rica	2.7225%	94.056%	3.2215%	12.614%	72.373%	15.013%
Puerto Rico	5.3583%e	83.518%e	11.124%e	32.404%e	0.32366%e	67.272%e
Panama	3.6404%e	96.193%	0.16701%e	50.871%e	46.796%	2.3339%e
Uruguay	2.3861%e	97.535%	0.078391%e	61.071%e	36.922%	2.0064%e
Jamaica	2.5456%	92.927%	4.5275%	12.23%	64.778%	22.993%
Trinidad & Tobago	4.2276%e	95.628%e	0.14438%e	32.836%e	66.042%e	1.1214%e
Guyana	0%e	100%	0%e	5.4429%e	91.928%	2.6295%e
Suriname	0.5546%e	99.237%	0.20878%e	1.1735%e	98.385%	0.44178%e
Cabo Verde	0.66408%e	98.876%	0.45965%e	21.243%e	64.054%	14.704%e
Guadeloupe	6.7458%e	93.212%e	0.04219%e	39.938%e	59.813%e	0.24978%e
Belize	0.39117%e	99.414%	0.19522%e	12.553%e	81.183%	6.2646%e
Bahamas	3.909%e	96.065%e	0.026401%e	24.887%e	74.945%e	0.16809%e
French Guiana	7.9165%e	91.793%e	0.29009%e	49.86%e	48.313%e	1.8271%e
Curacao	3.1008%e	96.85%e	0.049654%e	19.136%e	80.558%e	0.30643%e
Grenada	1.5055%e	98.317%e	0.17738%e	14.079%e	84.262%e	1.6588%e
Palestine	4.525%	91.012%	4.4631%	47.099%	35.006%	17.895%
Egypt	32.638%	54.835%	12.527%	69.141%	3.8498%	27.009%
Turkey	30.258%	56.273%	13.469%	68.12%	3.29%	28.59%
Iran	1.0717%	98.553%	0.37518%	29.692%	64.449%	5.8588%
Algeria	9.1618%	40.594%	50.244%	15.093%	6.913%	77.994%
Morocco	0.053604%	96.712%	3.2346%	35.455%	12.548%	51.998%
Iraq	3.4702%	94.026%	2.5036%	19.887%	66.063%	14.05%
Saudi Arabia	10.15%e	89.85%e	0%e	64.387%e	35.613%e	0%e
Yemen	0.38942%	93.102%	6.5087%	54.345%	30.977%	14.678%
Syria	17.207%e	55%	27.793%e	36.631%e	4.2%	59.169%e
Tunisia	7.3943%	91.51%	1.0962%	76.082%	21.218%	2.6998%
Israel	89.354%	5%	5.6455%	93.587%	0.5%	5.9129%
Jordan	12.506%	87.378%	0.11644%	68.9%	30.298%	0.80223%
Libya	2.0061%e	87.088%e	10.906%e	12.985%e	16.426%e	70.589%e
Emirates	28.852%e	65.951%e	5.1973%e	100%e	0%e	0%e
Lebanon	2.0854%e	85.39%e	12.525%e	12.917%e	9.501%e	77.582%e
Oman	1.5085%	98.491%	0%	12.595%	87.405%	0%
Kuwait	100%e	0%e	0%e	100%e	0%e	0%e
Qatar	15.711%e	84.289%e	0%e	92.774%e	7.2264%e	0%e
Bahrain	17.795%e	82.205%e	0%e	100%e	0%e	0%e
United States	30.59%	69.001%	0.40888%	92.224%	6.5432%	1.2327%
Canada	48.154%	42.207%	9.6391%	72.25%	13.287%	14.462%
Australia	12.749%e	81.583%e	5.6672%e	79.952%e	0%e	20.048%e
New Zealand	14.263%e	84.888%e	0.84829%e	89.197%e	5.4982%e	5.3049%e
Fiji	2.6429%e	95.391%e	1.966%e	20.089%e	64.968%e	14.943%e
French Polynesia	3.2876%e	96.592%e	0.12071%e	23.839%e	75.286%e	0.87526%e

	Wastewater treated (RURAL)	not sewered (RURAL)	sewered but not treated (RURAL)	Wastewater treated (URBAN)	not sewered (URBAN)	sewered but not treated (URBAN)
New Caledonia	7.7669%e	88.893%e	3.3402%e	53.163%e	23.974%e	22.863%e
Vanuatu	6.0201%e	88.995%	4.9853%e	8.33%e	84.772%	6.8981%e
Samoa	0.0868%	99.826%	0.0868%	0.2414%	99.517%	0.2414%
Micronesia FSM	2.1636%e	96.21%e	1.6268%e	25.754%e	54.882%e	19.365%e
Nauru	21.956%e	76.903%	1.141%e	21.956%e	76.903%	1.141%e
Antarctica	0%e	100%e	0%e	0%e	100%e	0%e
India	0.32375%	99.045%	0.63162%	8.837%	70.453%	20.71%
Pakistan	1.8415%e	94.628%	3.5307%e	20.522%e	40.131%	39.347%e
Bangladesh	0.051472%	99.859%	0.090021%	5.2243%e	85.639%	9.137%e
Afghanistan	0.11193%e	99.274%	0.61407%e	1.2552%e	91.859%	6.8862%e
Nepal	0.43402%e	98.253%	1.3134%e	4.7745%e	80.777%	14.448%e
Sri Lanka	1.4225%e	97.703%	0.87496%e	7.7946%e	87.411%	4.7943%e
Bhutan	0.60625%e	98.85%	0.54375%e	6.4843%e	87.7%	5.8157%e
Maldives	29.123%e	65.763%	5.1137%e	85.064%e	0%	14.936%e
Indonesia	8.4197%e	86.465%	5.1153%e	5.925%e	90.475%	3.5996%e
Philippines	1.2897%	96.958%	1.7524%	2.3605%	94.283%	3.3563%
Viet Nam	0.28841%e	99.399%	0.31231%e	0.82975%e	98.272%	0.89852%e
Thailand	4.3789%e	94.588%	1.0333%e	9.6398%e	88.085%	2.2747%e
Myanmar	0.0091454%e	99.971%	0.019518%e	0%e	100%	0%e
Malaysia	14.941%e	84.787%e	0.27142%e	99.11%e	0%e	0.88996%e
Cambodia	1.1399%e	96.572%	2.2885%e	16.899%e	49.173%	33.928%e
Laos	0.32568%	99.32%	0.35475%	0.94397%	98.059%	0.99679%
Papua New Guinea	0.47465%	99%	0.52535%	11.325%	76.7%	11.975%
Singapore	100%	0%	0%	100%	0%	0%
Timor-Leste	3.457%e	91.671%	4.8722%e	7.5347%e	81.846%	10.619%e
Brunei	77.731%e	20.716%e	1.5532%e	100%e	0%e	0%e
Nigeria	1.6594%	95.722%	2.6188%	4.732%	84.132%	11.136%
Ethiopia	0.26182%	99.281%	0.45694%	1.0153%e	97.213%	1.772%e
Congo (Kinshasa)	0.015653%e	99.882%	0.10228%e	0%e	100%	0%e
South Africa	3.5332%e	95.307%	1.1596%e	64.884%e	13.82%	21.296%e
Tanzania	0.070221%	99.883%	0.046574%	0.61506%	98.415%	0.96954%
Kenya	0.038761%e	99.897%	0.064065%e	7.5357%e	80.009%	12.455%e
Sudan	0.023092%e	99.864%	0.1132%e	0.45378%e	97.322%	2.2244%e
Uganda	0.054839%	99.812%	0.13333%	0.42451%	97.701%	1.8748%
Ghana	0.17311%e	99.564%	0.26246%e	2.2081%e	94.444%	3.3479%e
Mozambique	0%	100%	0%	0.30714%e	97.49%	2.2025%e
Madagascar	0.091377%e	99.268%	0.6403%e	0.28614%e	97.709%	2.005%e
Cote d'Ivoire	0.4396%e	99.01%	0.55062%e	5.2994%e	88.063%	6.6378%e
Cameroon	0.0113%e	99.963%	0.025856%e	0.21325%e	99.299%	0.48792%e
Angola	0.69525%e	98.638%	0.66725%e	9.6211%e	81.145%	9.2336%e
Burkina Faso	0%e	100%	0%e	0.49969%e	97.254%	2.2461%e
Niger	0.063981%	99.785%	0.15131%	0.86009%	96.991%	2.1489%
Malawi	0.10175%e	99.048%	0.85059%e	0.82857%e	92.245%	6.9266%e
Mali	0%	100%	0%	0.91684%	97.16%	1.9228%
Zambia	0.15453%e	99.502%	0.34341%e	6.4494%e	79.218%	14.332%e
Senegal	0.08771%	99.691%	0.22098%	4.2937%	82.676%	13.03%
Zimbabwe	0.32482%	98.426%	1.2488%	11.75%	23.967%	64.283%
Rwanda	0.024767%e	99.874%	0.10133%e	1.1757%e	94.014%	4.8103%e
Chad	0%e	100%	0%e	0.34019%e	98.123%	1.5368%e
Guinea	0.070404%e	99.549%	0.381%e	0.7458%e	95.218%	4.036%e
South Sudan	0.0083968%e	99.958%	0.033618%e	0.071042%e	99.645%	0.28443%e
Burundi	0%e	100%	0%e	0.28551%e	96.54%	3.1748%e
Somalia	0.11151%e	97.713%	2.1755%e	1.0692%e	78.07%	20.861%e
Benin	0.075169%e	99.655%	0.26946%e	0.56301%e	97.419%	2.0182%e
Togo	0.003231%e	99.979%	0.01782%e	0.10248%e	99.332%	0.56521%e
Eritrea	0%e	100%	0%e	1.0432%e	92.14%	6.8171%e
Sierra Leone	0.0068527%	99.949%	0.04455%	0.18905%	98.905%	0.90561%
Cent. Afr. Rep.	0.0013114%e	99.989%	0.0097425%e	0.012321%e	99.896%	0.091538%e
Congo (Brazzaville)	0.10069%e	99.641%	0.25842%e	0.48603%e	98.267%	1.2474%e
Liberia	0.001796%e	99.982%	0.016089%e	0.099283%e	99.011%	0.88939%e
Mauritania	0.025239%e	99.913%	0.061723%e	1.427%e	95.083%	3.4897%e
Namibia	4.2799%e	93.77%	1.9505%e	45.538%e	33.708%	20.753%e
Botswana	0.16191%e	99.8%	0.03809%e	1.5381%e	98.1%	0.36185%e
Lesotho	0.09769%e	99.662%	0.24058%e	1.0018%e	96.531%	2.4671%e
Gambia	0.0039318%e	99.972%	0.024061%e	0.58491%e	95.836%	3.5794%e
Guinea-Bissau	0.18317%e	99.056%	0.76046%e	1.1607%e	94.02%	4.819%e
Gabon	7.199%e	91.341%	1.4598%e	30.517%e	63.294%	6.1883%e
Eswatini	1.0048%	97.453%	1.542%	10.195%	65.041%	24.765%
Mauritius	3.845%	94.585%	1.5696%	34.852%	50.96%	14.188%
Djibouti	0%	100%	0%	2.9974%	93.4%	3.6026%
Comoros	0.76735%e	95.963%	3.2699%e	1.5903%e	91.633%	6.7768%e
Equatorial Guinea	4.6504%e	93.4%	1.9496%e	8.5962%e	87.8%	3.6038%e

	Wastewater treated (RURAL)	not sewered (RURAL)	sewered but not treated (RURAL)	Wastewater treated (URBAN)	not sewered (URBAN)	sewered but not treated (URBAN)
Western Sahara	0.69459%e	98.637%e	0.66836%e	4.3403%e	91.483%e	4.1765%e
Mayotte	3.9459%e	95.781%e	0.27291%e	32.691%e	65.048%e	2.2609%e
Sao Tome & Principe	3.3527%e	91.88%	4.7677%e	7.1968%e	82.569%	10.234%e
Germany	84.79%	14.088%	1.1222%	98.698%	0.3%	1.0024%
France	14.511%e	84.823%e	0.66607%e	93.736%e	1.9611%e	4.3027%e
United Kingdom	83.706%	16.041%	0.25264%	98.875%	0.325%	0.7998%
Italy	90.332%	7.1%	2.5681%	91.383%	6.019%	2.5982%
Spain	96.713%	0%	3.2872%	96.597%	0.019506%	3.3834%
Netherlands	95.014%	4.8673%	0.11861%	97.476%	0%	2.524%
Portugal	30.983%	68.954%	0.063555%	81.993%	17.675%	0.33229%
Greece	36.888%	62.415%	0.69731%	94.067%	5.1842%	0.74924%
Belgium	16.239%e	83.677%e	0.083853%e	96.348%e	3.1548%e	0.4975%e
Sweden	75.172%	24.564%	0.26402%	87.143%	12.199%	0.65851%
Austria	84.328%	15.672%	0%	98.365%	1.6352%	0%
Switzerland	92.702%	7.2054%	0.092981%	99.9%	0%	0.1001%
Denmark	23.636%e	68.922%e	7.4419%e	100%e	0%e	0%e
Finland	19.577%	80.316%	0.1075%	95.783%	3.6842%	0.53262%
Ireland	21.182%	77.772%	1.0455%	84.287%	7.9387%	7.7745%
Norway	11.642%e	84.54%e	3.8178%e	74.532%e	1.0275%e	24.441%e
Cyprus	9%	91%	0%	73%	27%	0%
Luxembourg	79.865%	19.163%	0.97151%	97.386%	0.025%	2.5888%
Malta	93.025%	0%	6.975%	92.982%	0.046547%	6.9718%
Iceland	13.758%e	83.668%e	2.5746%e	83.131%e	1.3122%e	15.557%e
Andorra	100%	0%	0%	100%	0%	0%
Greenland	30.365%e	62.849%e	6.7862%e	100%e	0%e	0%e
Liechtenstein	98.483%e	1.5172%e	0%e	100%e	0%e	0%e
San Marino	12.111%e	85.371%e	2.5176%e	72.129%e	12.877%e	14.994%e
Monaco	100%	0%	0%	100%	0%	0%
Vatican	90%e	8%e	2%e	90%e	8%e	2%e
Bonaire, Sint Eustatius & Saba	0.066523%e	99.933%e	0.00065294%e	0.44283%e	99.553%e	0.0043465%e
Martinique	8.2906%e	91.682%e	0.027158%e	51.209%e	48.624%e	0.16774%e
Barbados	0.79763%e	99.187%e	0.015511%e	8.0377%e	91.806%e	0.1563%e
St Lucia	3.1943%e	96.299%	0.50706%e	9.3249%e	89.195%	1.4802%e
Aruba	1.093%e	98.85%e	0.057524%e	9.3602%e	90.147%e	0.49264%e
Virgin Is. (US)	6.8113%e	92.792%e	0.39697%e	40.825%e	56.796%e	2.3793%e
St Vincent & Grenadines	1.3294%e	98.371%e	0.29998%e	10.457%e	87.184%e	2.3596%e
Antigua & Barbuda	0.30451%e	99.687%e	0.0088045%e	3.4583%e	96.442%e	0.099993%e
Dominica	2.4119%e	97.087%e	0.50119%e	16.517%e	80.051%e	3.4322%e
Bermuda	1.5%	95%	3.5%	1.5%	95%	3.5%
Cayman Is.	18.597%e	81.4%	0.0026152%e	18.597%e	81.4%	0.0026152%e
St Kitts & Nevis	1.9006%e	98.041%e	0.058451%e	19.274%e	80.133%e	0.59276%e
Turks & Caicos	1.6068%e	98.387%e	0.0060152%e	9.7507%e	90.213%e	0.036503%e
Sint Maarten (NL)	9.0936%e	90.868%e	0.038299%e	9.0936%e	90.868%e	0.038299%e
Virgin Is. (Brit)	5.0379%e	94.961%e	0.0013845%e	41.34%e	58.648%e	0.011361%e
St Martin (Fr)	43.895%e	38.839%e	17.266%e	43.895%e	38.839%e	17.266%e
Anguilla	1.1964%e	98.8%	0.0036485%e	1.1964%e	98.8%	0.0036485%e
St Barthelemy	23.249%e	62.955%e	13.796%e	23.249%e	62.955%e	13.796%e
Montserrat	4.8669%e	94.335%e	0.79764%e	96.977%e	0%e	3.0233%e
US Minor Outlying Is.	87.271%e	8.5518%e	4.1768%e	87.271%e	8.5518%e	4.1768%e
Solomon Is.	0.80054%e	98.016%	1.1831%e	9.2646%e	77.043%	13.692%e
Guam	12.382%e	87.586%e	0.031596%e	74.512%e	25.298%e	0.19013%e
Tonga	0%e	100%	0%e	0%e	100%	0%e
Kiribati	1.3999%e	97.438%e	1.1621%e	10.868%e	80.111%e	9.0212%e
Marshall Is.	1.881%e	97.348%	0.7706%e	36.017%e	49.227%	14.756%e
American Samoa	4.1077%e	91.249%e	4.6429%e	25.599%e	45.466%e	28.935%e
Northern Mariana Is.	8.8913%e	90.551%e	0.55744%e	54.276%e	42.322%e	3.4028%e
Palau	11.175%e	88%	0.82541%e	63.323%e	32%	4.6773%e
Wallis & Futuna	35.269%e	48.158%e	16.573%e	35.269%e	48.158%e	16.573%e
Tuvalu	0%	37%	63%	0%	19.4%	80.6%
Cook Is.	11.143%e	85.776%e	3.0807%e	74.181%e	5.3117%e	20.508%e
Norfolk Is.	81.637%e	10.596%e	7.7673%e	81.637%e	10.596%e	7.7673%e
Tokelau	14.371%e	75.41%e	10.218%e	14.371%e	75.41%e	10.218%e
Niue	1.2019%e	98.372%e	0.42572%e	10.206%e	86.178%e	3.6154%e
Pitcairn Is.	5.3375%e	89.827%e	4.8352%e	5.3375%e	89.827%e	4.8352%e
Bouvet Is.	0%e	100%e	0%e	0%e	100%e	0%e
Heard & McDonald Is.	0%e	100%e	0%e	0%e	100%e	0%e
British Indian Ocean Territory	0%e	100%e	0%e	0%e	100%e	0%e
Christmas Is.	87.266%e	8.5532%e	4.1804%e	87.266%e	8.5532%e	4.1804%e

	Wastewater treated (RURAL)	not sewered (RURAL)	sewered but not treated (RURAL)	Wastewater treated (URBAN)	not sewered (URBAN)	sewered but not treated (URBAN)
French Southern Territories	0%e	100%e	0%e	0%e	100%e	0%e
Reunion	8.5087%e	91.446%e	0.04533%e	50.155%e	49.578%e	0.2672%e
Seychelles	3.4817%e	96.43%e	0.088794%e	26.351%e	72.977%e	0.67204%e
St Helena, Ascension & Tristan da Cunha	13.034%e	79.431%e	7.5353%e	100%e	0%e	0%e
Aland Is.	81.934%e	13.473%e	4.5926%e	100%e	0%e	0%e
Jersey	84.877%e	11.69%e	3.4336%e	100%e	0%e	0%e
Isle of Man	78.893%e	16.831%e	4.2763%e	100%e	0%e	0%e
Guernsey	85.311%e	11.638%e	3.0505%e	100%e	0%e	0%e
Faroe Is.	80.153%e	14.205%e	5.6421%e	100%e	0%e	0%e
Gibraltar	100%e	0%	0.000008607%e	100%e	0%	0.000008607%e
Svalbard & Jan Mayen	89.43%e	8.0668%e	2.503%e	89.43%e	8.0668%e	2.503%e
Falkland Is.	100%e	0%	0.0000045016%e	100%e	0%	0.0000045016%e
Cocos Is.	3.5705%e	94.113%e	2.3169%e	23.704%e	60.914%e	15.382%e
St Pierre & Miquelon	13.735%e	84.488%e	1.7764%e	84.483%e	4.5898%e	10.927%e
South Georgia & South Sandwich Is.	0%e	100%e	0%e	0%e	100%e	0%e
Kosovo	2.2428%e	95.963%e	1.7945%e	19.72%e	64.502%e	15.778%e
Channel Is.	73.222%e	26.778%e	0%e	100%e	0%e	0%e

Tab. 27.3 Country data for wastewater treatment parameters and the sewage sludge disposal mix. A suffix 'e' denotes extrapolated data. An empty cell denotes not available data.

	Primary Treatment	Secondary Treatment	Tertiary Treatment	WWT with anaerobic digestion (AD)	Share of CHP in AD	Sewage sludge in agriculture	Sewage sludge in landfill	Sewage sludge in incineration
Poland	0%	18.87%	81.13%	43%	43%	39.829%	40.24%	19.931%
Romania	13.91%	31.96%	54.13%	0.1%	41.7%	11.316%	87.822%	0.86112%
Czech Rep.	0.76%e	22.22%e	77.02%e	70%	95.7%	88.532%	5.7299%	5.7381%
Hungary	0.13%	15.86%	84.01%	47%	80.9%	75.021%	24.602%	0.37723%
Serbia	10.22%	71.11%	18.67%	0%	0%e			
Bulgaria	2.68%	27.06%	70.26%	100%	100%	58.542%	41.458%	0%
Slovakia	3%	93%	4%	86%	84.9%	86.31%	13.648%	0.041937%
Croatia	30.25%	67.86%	1.89%	60%	71.7%	33.159%	66.841%	0%
Bosnia Herzegovina	14.88%e	69.07%e	16.05%e	100%	0%			
Lithuania	0.14%	8.61%	91.25%	61%	55.7%	61.781%	36.762%	1.4569%
Albania	30%	60%	10%	5%e	0%e			
Latvia	5.22%	70.52%	24.26%	46%	67.4%	96.529%	3.471%	0%
North Macedonia	14.21%e	68.74%e	17.05%e	0%	0%e			
Slovenia	0%	52.95%	47.05%	32%	100%	3.7019%	54.991%	41.307%
Estonia	0%	6.02%	93.98%	0%	70%e	89.18%	10.82%	0%
Montenegro	7.07%e	57.97%e	34.96%e	0%	70%e			
Russia	4.79%e	49.42%e	45.78%e	9%	100%			
Ukraine	26.72%e	67.24%e	6.03%e	36%	100%			
Uzbekistan	46.92%e	51.81%e	1.27%e	1.5%e	0%e			
Kazakhstan	7.02%e	57.82%e	35.16%e	8.7%e	70%e			
Belarus	12.63%	63.45%	23.92%	5.9%e	0%e			
Azerbaijan	20.04%e	69.66%e	10.29%e	4.3%e	0%e			
Tajikistan	59.18%e	40.37%e	0.45%e	0.9%e	0%e			
Kyrgyzstan	51.66%e	47.47%e	0.86%e	1.2%e	0%e			
Turkmenistan	10.98%e	65.86%e	23.16%e	6.7%e	0%e			
Georgia	19.76%e	69.7%e	10.53%e	4.4%e	0%e			
Moldova	28.39%e	66.31%e	5.3%e	3.1%e	0%e			
Armenia	19.56%e	69.73%e	10.71%e	4.4%e	0%e			
China	5.53%e	52.64%e	41.83%e	0%	70%e			
Japan	0.06%e	19.94%e	80%e	0%	70%e			
South Korea	0.16%e	19.9%e	79.95%e	24%	41.7%			
North Korea	70.56%e	29.3%e	0.14%e	0.5%e	0%e			
Taiwan	0.86%e	22.88%e	76.27%e	0%	70%e			
Hong Kong	0.01%e	19.99%e	80%e	39.8%e	70%e			
Mongolia	23.53%e	68.71%e	7.76%e	3.7%e	0%e			
Macao	0%e	20%e	80%e	55%e	70%e			
Brazil	33.21%	56.13%	10.66%	11%	72.7%			
Mexico	6.98%e	57.69%e	35.33%e	15%	100%			
Colombia	12.69%e	67.68%e	19.64%e	58%	72.4%			
Argentina	4.69%e	48.92%e	46.39%e	0%	70%e			
Peru	12.04%e	67.07%e	20.89%e	2%	0%			
Venezuela	4.14%e	46.14%e	49.72%e	11.1%e	70%e			
Chile	26.4%	4.58%	69.02%	10%	0%			
Ecuador	13.41%e	68.24%e	18.35%e	5.9%e	0%e			
Guatemala	20%e	69.67%e	10.33%e	4.3%e	0%e			
Cuba	9.86%e	64.22%e	25.92%e	7.2%e	70%e			
Bolivia	25.16%e	68.02%e	6.82%e	3.5%e	0%e			
Dominican Rep.	9.29%e	63.23%e	27.48%e	7.5%e	70%e			
Haiti	62.25%e	37.41%e	0.34%e	0.8%e	0%e			
Honduras	32.33%e	63.75%e	3.92%e	2.6%e	0%e			
Paraguay	21.48%e	69.37%e	9.15%e	4.1%e	0%e			
El Salvador	19.28%e	69.75%e	10.96%e	4.5%e	0%e			
Nicaragua	40.67%e	57.25%e	2.07%e	1.9%e	0%e			
Costa Rica	4.2%e	46.44%e	49.37%e	0%	70%e			
Puerto Rico	67.5%	20.1%	12.4%	19.7%e	70%e			
Panama	2.36%e	34.7%e	62.93%e	13.8%e	70%e			
Uruguay	1.76%e	29.97%e	68.27%e	15.3%e	70%e			
Jamaica	14.97%e	69.11%e	15.92%e	5.5%e	0%e			
Trinidad & Tobago	1.82%e	30.46%e	67.72%e	15.1%e	70%e			
Guyana	18.5%e	69.79%e	11.72%e	4.6%e	0%e			
Suriname	15.13%e	69.18%e	15.7%e	5.4%e	0%e			
Cabo Verde	24.3%e	68.4%e	7.29%e	3.6%e	0%e			
Guadeloupe	0.42%e	20.43%e	79.15%e	22.5%e	70%e			
Belize	18.98%e	69.77%e	11.25%e	4.5%e	0%e			
Bahamas	0.45%e	20.54%e	79.01%e	22.2%e	70%e			
French Guiana	1.93%e	31.4%e	66.67%e	14.8%e	70%e			

	Primary Treatment	Secondary Treatment	Tertiary Treatment	WWT with anaerobic digestion (AD)	Share of CHP in AD	Sewage sludge in agriculture	Sewage sludge in landfill	Sewage sludge in incineration
Curacao	0.94%e	23.47%e	75.59%e	18.4%e	70%e			
Grenada	5.5%e	52.53%e	41.97%e	9.8%e	70%e			
Palestine	24.31%e	68.4%e	7.29%e	3.6%e	0%e			
Egypt	22.01%	74.73%	3.27%	15%	0%			
Turkey	32.61%	38.69%	28.71%	37%	94.6%			
Iran	16.03%e	69.48%e	14.48%e	6%	100%			
Algeria	22.3%e	69.14%e	8.56%e	3.9%e	0%e			
Morocco	54.6%	26.13%	19.27%	3.2%e	0%e			
Iraq	15.57%e	69.34%e	15.09%e	5.3%e	0%e			
Saudi Arabia	0.65%e	21.54%e	77.81%e	0%	70%e			
Yemen	68.04%	20.9%	11.06%	0.9%e	0%e			
Syria	41.7%e	56.39%e	1.91%e	1.8%e	0%e			
Tunisia	0%	93.47%	6.53%	3.3%e	0%e			
Israel	5.04%	38.93%	56.03%	5%	100%			
Jordan	0%	100%	0%	5%e	0%e			
Libya	0%	100%	0%	7.4%e	70%e			
Emirates	0.03%e	19.97%e	80%e	35.6%e	70%e			
Lebanon	8.84%e	62.34%e	28.82%e	7.7%e	70%e			
Oman	2.93%e	38.79%e	58.27%e	12.8%e	70%e			
Kuwait	0%	20%	80%	28%e	70%e			
Qatar	0%e	20%e	80%e	50%e	70%e			
Bahrain	0%	0%	100%	17.8%e	70%e			
United States	0%e	20%e	80%e	60%	45%			
Canada	19.05%	63.1%	17.86%	29%	24.1%			
Australia	0.01%e	19.99%e	80%e	38%	55.3%			
New Zealand	6.3%	15.9%	77.8%	20%	100%			
Fiji	14.97%e	69.11%e	15.91%e	5.5%e	0%e			
French Polynesia	1.94%e	31.42%e	66.64%e	14.8%e	70%e			
New Caledonia	2.74%e	37.47%e	59.79%e	13.1%e	70%e			
Vanuatu	27.6%e	66.76%e	5.63%e	3.2%e	0%e			
Samoa	20.26%e	69.63%e	10.11%e	4.3%e	0%e			
Micronesia FSM	25.79%e	67.72%e	6.49%e	3.4%e	0%e			
Nauru	2.64%e	36.75%e	60.61%e	13.3%e	70%e			
Antarctica	100%e	0%e	0%e	0%e	0%e			
India	38.34%e	59.18%e	2.48%e	0%	0%e			
Pakistan	45.57%e	53.01%e	1.41%e	0%	0%e			
Bangladesh	41.29%e	56.74%e	1.98%e	0%	0%e			
Afghanistan	68.07%e	31.74%e	0.18%e	0.6%e	0%e			
Nepal	55.86%e	43.53%e	0.6%e	1%e	0%e			
Sri Lanka	22.27%e	69.15%e	8.58%e	3.9%e	0%e			
Bhutan	29.14%e	65.85%e	5%e	3%e	0%e			
Maldives	7.85%e	60.11%e	32.04%e	8.2%e	70%e			
Indonesia	22.07%e	69.21%e	8.72%e	0%	0%e			
Philippines	22.17%e	69.18%e	8.65%e	0%	0%e			
Viet Nam	32.98%e	63.29%e	3.73%e	0%	0%e			
Thailand	10.18%e	64.74%e	25.08%e	0%	70%e			
Myanmar	48.01%e	50.82%e	1.16%e	1.4%e	0%e			
Malaysia	4.6%e	48.51%e	46.88%e	0%	70%e			
Cambodia	46.63%e	52.07%e	1.3%e	1.5%e	0%e			
Laos	35.72%e	61.25%e	3.03%e	2.3%e	0%e			
Papua New Guinea	37.33%e	59.99%e	2.68%e	2.2%e	0%e			
Singapore	0.01%e	19.99%e	80%e	44.4%e	70%e			
Timor-Leste	38.65%e	58.93%e	2.42%e	2.1%e	0%e			
Brunei	0.28%e	20.01%e	79.72%e	24.7%e	70%e			
Nigeria	39.33%e	58.37%e	2.3%e	0%	0%e			
Ethiopia	60.31%e	39.28%e	0.4%e	0%	0%e			
Congo (Kinshasa)	71.25%e	28.62%e	0.13%e	0.5%e	0%e			
South Africa	13.5%e	68.3%e	18.21%e	57%	0%			
Tanzania	56.13%e	43.28%e	0.59%e	0%	0%e			
Kenya	42.21%e	55.95%e	1.84%e	1.8%e	0%e			
Sudan	65.92%e	33.85%e	0.23%e	0.6%e	0%e			
Uganda	66.46%e	33.32%e	0.22%e	0.6%e	0%e			
Ghana	40.28%e	57.59%e	2.14%e	1.9%e	0%e			
Mozambique	72.84%e	27.05%e	0.11%e	0.4%e	0%e			
Madagascar	72.48%e	27.41%e	0.11%e	0.4%e	0%e			
Cote d'Ivoire	36.07%e	60.99%e	2.95%e	2.3%e	0%e			
Cameroon	49.6%e	49.37%e	1.02%e	1.3%e	0%e			
Angola	30.49%e	65%e	4.51%e	2.8%e	0%e			
Burkina Faso	64.2%e	35.52%e	0.28%e	0.7%e	0%e			
Niger	73.33%e	26.57%e	0.1%e	0.4%e	0%e			
Malawi	75.35%e	24.57%e	0.08%e	0.4%e	0%e			

	Primary Treatment	Secondary Treatment	Tertiary Treatment	WWT with anaerobic digestion (AD)	Share of CHP in AD	Sewage sludge in agriculture	Sewage sludge in landfill	Sewage sludge in incineration
Mali	59.15%e	40.4%e	0.45%e	0.9%e	0%e			
Zambia	48.95%e	49.98%e	1.08%e	1.4%e	0%e			
Senegal	54.34%e	44.97%e	0.69%e	1.1%e	0%e			
Zimbabwe	50%	50%	0%	0.9%e	0%e			
Rwanda	62.31%e	37.36%e	0.33%e	0.8%e	0%e			
Chad	64.32%e	35.41%e	0.27%e	0.7%e	0%e			
Guinea	67.82%e	31.99%e	0.19%e	0.6%e	0%e			
South Sudan	61.86%e	37.79%e	0.35%e	0.8%e	0%e			
Burundi	79.49%e	20.46%e	0.04%e	0.3%e	0%e			
Somalia	86.06%e	13.93%e	0.01%e	0.1%e	0%e			
Benin	59.55%e	40.02%e	0.43%e	0.9%e	0%e			
Togo	68.17%e	31.65%e	0.18%e	0.6%e	0%e			
Eritrea	71.25%e	28.62%e	0.13%e	0.5%e	0%e			
Sierra Leone	67.41%e	32.39%e	0.2%e	0.6%e	0%e			
Cent. Afr. Rep.	73.44%e	26.46%e	0.1%e	0.4%e	0%e			
Congo (Brazzaville)	52.2%e	46.97%e	0.83%e	1.2%e	0%e			
Liberia	76.42%e	23.52%e	0.07%e	0.3%e	0%e			
Mauritania	51.11%e	47.99%e	0.9%e	1.3%e	0%e			
Namibia	17.66%e	69.76%e	12.58%e	4.8%e	0%e			
Botswana	10.15%e	64.69%e	25.16%e	7.1%e	70%e			
Lesotho	51.26%e	47.85%e	0.89%e	1.3%e	0%e			
Gambia	70.08%e	29.77%e	0.15%e	0.5%e	0%e			
Guinea-Bissau	62.6%e	37.07%e	0.32%e	0.8%e	0%e			
Gabon	8.92%e	62.5%e	28.58%e	7.6%e	70%e			
Eswatini	28.73%e	66.1%e	5.16%e	3%e	0%e			
Mauritius	33.7%	2.59%	63.71%	11.1%e	70%e			
Djibouti	27%e	67.1%e	5.91%e	3.3%e	0%e			
Comoros	63.15%e	36.55%e	0.31%e	0.7%e	0%e			
Equatorial Guinea	16.51%e	69.6%e	13.89%e	5.1%e	0%e			
Western Sahara	34.1%e	62.48%e	3.42%e	2.5%e	0%e			
Mayotte	3.41%e	41.91%e	54.68%e	12%e	70%e			
Sao Tome & Principe	38.86%e	58.76%e	2.38%e	2.1%e	0%e			
Germany	0%	2.62%	97.38%	53%	67.9%	35.191%	0.3549%	64.454%
France	0.12%	17.76%	82.11%	17%	82.4%	78.202%	4.8245%	16.973%
United Kingdom	0%	43%	57%	95%	91.6%	82.404%	0.065866%	17.53%
Italy	2.46%	29.73%	67.81%	23%	39.1%	53.41%	40.68%	5.9102%
Spain	1.8%	25.26%	72.94%	25%	100%	83.587%	8.8916%	7.5217%
Netherlands	0.6%	1%	98.4%	43%	48.8%	0.51783%	3.48%	96.002%
Portugal	3.78%	41.34%	54.88%	4%	100%	97.05%	2.9496%	0%
Greece	0.99%e	23.88%e	75.12%e	55%	100%	20.689%	45.531%	33.78%
Belgium	0.02%e	19.98%e	80%e	60%	83.3%	44.007%	2.326%	53.667%
Sweden	13%	4%	83%	96%	3.1%	97.07%	1.447%	1.4829%
Austria	0.01%e	19.99%e	80%e	22%	68.2%	39.497%	8.2291%	52.273%
Switzerland	0%	11.22%	88.78%	89%	23.6%	10%	0%	90%
Denmark	0%	2.2%	97.8%	50%	50%	76.878%	0.89973%	22.222%
Finland	0.02%e	19.98%e	80%e	43%	23.3%	99.294%	0.40005%	0.30592%
Ireland	1.03%	71.13%	27.84%	18%	100%	99.664%	0.33619%	0%
Norway	35.75%	5.4%	58.85%	63%	9.5%	91.366%	5.9151%	2.7189%
Cyprus	0%	38.59%	61.41%	0%	70%e	95.965%	0%	4.0355%
Luxembourg	1.93%	25.69%	72.39%	83%	57.8%	81.97%	0%	18.03%
Malta	0.44%e	20.49%e	79.08%e	55%	54.5%	0%	100%	0%
Iceland	98.48%	0%	1.52%	0%	70%e	15.883%	82.41%	1.7078%
Andorra	0.04%e	19.96%e	80%e	35.1%e	70%e			
Greenland	0%	2.2%	97.8%	17.5%e	70%e			
Liechtenstein	0%e	20%e	80%e	68.5%e	70%e			
San Marino	0.01%e	19.99%e	80%e	40.6%e	70%e			
Monaco	0%e	20%e	80%e	84.5%e	70%e			
Vatican	0%e	20%e	80%e	74.6%e	70%e			
Bonaire, Sint Eustatius & Saba	0.62%e	21.35%e	78.03%e	20.5%e	70%e			
Martinique	0.25%e	19.97%e	79.79%e	25.2%e	70%e			
Barbados	1.75%e	29.89%e	68.36%e	15.3%e	70%e			
St Lucia	7.18%e	58.3%e	34.52%e	8.6%e	70%e			
Aruba	0.35%e	20.18%e	79.48%e	23.5%e	70%e			
Virgin Is. (US)	2.92%e	38.74%e	58.33%e	12.8%e	70%e			
St Vincent & Grenadines	9.79%e	64.11%e	26.09%e	7.2%e	70%e			
Antigua & Barbuda	1.57%e	28.46%e	69.97%e	15.8%e	70%e			
Dominica	9.11%e	62.89%e	28%e	7.5%e	70%e			
Bermuda	0%e	20%e	80%e	71%e	70%e			

	Primary Treatment	Secondary Treatment	Tertiary Treatment	WWT with anaerobic digestion (AD)	Share of CHP in AD	Sewage sludge in agriculture	Sewage sludge in landfill	Sewage sludge in incineration
Cayman Is.	0.02%e	19.98%e	80%e	37.7%e	70%e			
St Kitts & Nevis	1.66%e	29.17%e	69.18%e	15.6%e	70%e			
Turks & Caicos	0.28%e	20.01%e	79.71%e	24.7%e	70%e			
Sint Maarten (NL)	0.31%e	20.07%e	79.63%e	24.2%e	70%e			
Virgin Is. (Brit)	0.04%e	19.96%e	80%e	35.2%e	70%e			
St Martin (Fr)	2.15%e	33.06%e	64.79%e	14.3%e	70%e			
Anguilla	0.23%e	19.95%e	79.82%e	25.5%e	70%e			
St Barthelemy	7.15%e	58.22%e	34.62%e	8.6%e	70%e			
Montserrat	3.7%e	43.65%e	52.66%e	11.6%e	70%e			
US Minor Outlying Is.	0.02%e	19.98%e	80%e	37.1%e	70%e			
Solomon Is.	39.71%e	58.06%e	2.23%e	2%e	0%e			
Guam	0.2%e	19.92%e	79.88%e	26.3%e	70%e			
Tonga	18.59%e	69.79%e	11.62%e	4.6%e	0%e			
Kiribati	27.65%e	66.74%e	5.61%e	3.2%e	0%e			
Marshall Is.	16.21%e	69.53%e	14.26%e	5.2%e	0%e			
American Samoa	3.3%e	41.21%e	55.49%e	12.2%e	70%e			
Northern Mariana Is.	3.12%e	40.07%e	56.81%e	12.5%e	70%e			
Palau	3.62%e	43.17%e	53.21%e	11.8%e	70%e			
Wallis & Futuna	3.52%e	42.62%e	53.86%e	11.9%e	70%e			
Tuvalu	11.23%e	66.18%e	22.59%e	6.7%e	0%e			
Cook Is.	0.88%e	23.08%e	76.04%e	18.7%e	70%e			
Norfolk Is.	0.1%e	19.91%e	79.99%e	30.1%e	70%e			
Tokelau	12.89%e	67.84%e	19.27%e	6.1%e	0%e			
Niue	14.38%e	68.83%e	16.78%e	5.6%e	0%e			
Pitcairn Is.	28.43%e	66.29%e	5.29%e	3.1%e	0%e			
Bouvet Is.	100%e	0%e	0%e	0%e	0%e			
Heard & McDonald Is.	100%e	0%e	0%e	0%e	0%e			
British Indian Ocean Territory	100%e	0%e	0%e	0%e	0%e			
Christmas Is.	0.02%e	19.98%e	80%e	37.1%e	70%e			
French Southern Territories	100%e	0%e	0%e	0%e	0%e			
Reunion	0.37%e	20.24%e	79.38%e	23.2%e	70%e			
Seychelles	1.41%e	27.13%e	71.47%e	16.4%e	70%e			
St Helena, Ascension & Tristan da Cunha	4.56%e	48.3%e	47.14%e	10.7%e	70%e			
Aland Is.	0.01%e	19.99%e	80%e	42.8%e	70%e			
Jersey	0%e	20%e	80%e	46.2%e	70%e			
Isle of Man	0%e	20%e	80%e	54.9%e	70%e			
Guernsey	0%e	20%e	80%e	51.3%e	70%e			
Faroe Is.	0.01%e	19.99%e	80%e	40.2%e	70%e			
Gibraltar	0%e	20%e	80%e	60.5%e	70%e			
Svalbard & Jan Mayen	0.01%e	19.99%e	80%e	44.8%e	70%e			
Falkland Is.	0%e	20%e	80%e	62.1%e	70%e			
Cocos Is.	9.54%e	63.68%e	26.79%e	7.3%e	70%e			
St Pierre & Miquelon	0.18%e	19.9%e	79.92%e	27.1%e	70%e			
South Georgia & South Sandwich Is.	100%e	0%e	0%e	0%e	0%e			
Kosovo	19.07%e	69.77%e	11.17%e	4.5%e	0%e			
Channel Is.	0%e	20%e	80%e	48%e	70%e			

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Web addresses indicate the source of electronic documents. The subsequent (date in brackets) refers to the date of retrieval.

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