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Determinants of environmental assessment of Polish individual wastewater treatment plants in a life cycle perspective

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Abstract: The article presents results of an input-output data inventory and life cycle assessment (LCA) for individual wastewater treatment plants (IWWTPs), considering their whole life cycle, including the stage of construction, use and end-of-life. IWWTPs located in the area of a medium-sized town in Poland, were assessed from a systemic perspective. The research was conducted basing on actual data concerning performance of 304 individual wastewater treatment plants in Żory. Environmental assessment was conducted with ReCiPe and TRACI methods. Greenhouse gases (GHG) emission, eutrophication, fossil fuel and metal depletion were calculated. The LCA was conducted basing on ISO 14040 standard with SimaPro 8 software and Ecoinvent 3 database. The system boundary ranged from cradle to grave. It was shown that, at the construction stage, GHG emission depends on the amount of used cement, polyethylene, concrete, PVC and polypropylene. At the use stage, the GHG emission is determined by the sewage treatment technology and application of a bio-reactor in IWWTPs. At the construction stage, the fossil fuel depletion is determined by the amount of used polyethylene, PVC, cement, polypropylene and concrete; while the metal depletion is determined by the amount of used stainless steel, copper and cast iron. Data inventory and LCA of IWWTPs are presented for the first time. Conclusions of the work may support decisions taken by local governments concerning wastewater management in their area and promote and support solutions of high ecological standards.

Introduction

Water and sewage management systems in urbanized areas in Poland consist of a few elements, which are: septic tanks, individual wastewater treatment plants, the sewage system and the central wastewater treatment plant. Individual wastewater treatment plants treat sewage in areas without the sewage system (outside the urban agglomeration), then the treated sewage is most often discharged into soil and sewage sludge is transported with vacuum tankers to the central wastewater treatment plant. The central wastewater treatment plant also collects sewage from septic tanks, which collect sewage in areas without the sewage system. The central wastewater treatment plant treats mainly the sewage from the sewage system. The central wastewater treatment plant and the sewage system are located within the area of the agglomeration, while septic tanks and individual wastewater treatment plants are located outside the area. This is the most common configuration solution of the system. Replacing a sewage system and a wastewater treatment plant with septic tanks and individual wastewater treatment plants requires substitute infrastructure to treat sewage sludge from individual wastewater treatment plants and treating sewage collected in septic tanks. Individual wastewater treatment plants (IWWTPs) also known as domestic wastewater treatment plants are installations which treat sewage from one or a few households and then discharge it into soil, waterways or ditches (except roadside ditches as the drainage element). Among the IWWTPs available in Poland the main types are installations with: a subsurface leaching system, a sand filter, a reed bed treatment system, a bio-filter and a bio-reactor (activated sludge). Detailed description of the wastewater treatment plants was presented by Zawartka (2017).

The environmental assessment of systems collecting, transporting and treating sewage is a complex issue. The assessment requires applying various solutions concerning water and sewage management system installations, transporting sewage to a wastewater treatment plant, and the treatment technology. Apart from many organic substances of various biodegradability, wastewater may contain heavy metals which are not biodegradable and can accumulate in the environment leading to irreversible changes (Thomas et al. 2018). Different methods are applied to assess the influence of sewage management on the environment. LCA is the most common method to assess environmental impact which enables a complex analysis of all the elements of the wastewater treatment system (Burchart-Korol et al. 2017a, Lorenzo-Toja et al. 2016, Lorenzo-Toja et al. 2018, Rejman--Burzynska et al. 2014). Opher and Friedler (2016) performed LCA to compare the environmental impacts of alternatives for a city's water-wastewater service system. It was concluded that a decentralized approach to urban wastewater management is environmentally preferable to the common centralized system. In spite of commonness of the method, the works published so far on the application of LCA environmental assessment and natural resources management in sewage systems are limited only to wastewater treatment system (Burchart-Korol et al. 2017b). The state of the art of greenhouse gases from wastewater treatment plants was done by Mannina et al. (2016). Results of environmental analyses conducted with LCA, which are available in the literature, concern mainly comparison between various technologies of treating sewage from the environmental perspective (Bertanza et al. 2016, Buonocore et al. 2016, Corominas et al. 2013, Mellino et al. 2015, Yoshida et al. 2016). Basing on hitherto LCA analyses for wastewater treatment plants, it was emphasized that it is necessary to unify and standardize the methodology of LCA application for wastewater treatment systems.

The conducted review showed that there are few publications concerning LCA analyzes for individual wastewater treatment plants, which would present their potential environmental impact throughout the life cycle. Comparative LCA of vertical flow constructed wetlands and horizontal flow constructed wetlands was done by Fuchs et al. (2011). It was concluded that gaseous emissions, often not included in wastewater LCAs because of the lack of data. The results of LCA of alternative wastewater treatment processes for small and decentralized rural communities were presented by Machado et al. (2007). Options for reduction of life cycle impacts were analyzed including materials used in construction and operational lifetime of constructed wetland, slow rate infiltration and activated sludge process. The low environmental impact of the energy-saving wastewater treatment plants was demonstrated, the most relevant being the greenhouse gas emission indicator. In the study Machado et al. (2007) concluded that the LCA approach can be used as a decision tool in design studies, but information for environmental impact assessment and minimization measures need further improvement. Lopsik (2013) presented results of LCA from two different types of small-scale wastewater treatment systems, a constructed wetland and extended aeration activated sludge treatment system. The results showed that the main negative impact of constructed wetland was caused by the construction phase and use of lightweight expanded clay aggregate to construct the hybrid filter.

The aim of the research was to assess potential influence on the environment of all the life stages of individual wastewater treatment plants (construction, use and end-of-life) with life cycle assessment (LCA) technique. The article is the first one to present results of both data inventory in the life cycle of individual wastewater treatment plants and LCA analyses for the element of water and sewage management system.

Materials and methods

Goal and scope of analysis

The paper presents analyses of the life cycle of wastewater treatment plants with a subsurface leaching system and plants with a bio-reactor as the most commonly-applied solutions for individual wastewater treatment plants in Poland.

A wastewater treatment plant with a subsurface leaching system is the simplest type of an individual wastewater treatment plant. The sewage flows to a septic tank and after primary treatment goes to a subsurface leaching system or a seepage pit. The drain system consists of parallel pipes which evenly distribute primarily treated sewage over a percolation area. The filtering layer beneath is made of 16–32 mm gravel. A percolation area consists of layers protected with geo-textile from overgrowing and silting the system resulting from surface run-off after heavy rains or snowmelt. A seepage pit is to discharge sewage into soil after primary treatment with the filter layer; sewage seeps into soil through the weep holes. The top approximately 0.5-metre-thick filtering layer is made of sand. The approximately 1-metre-thick filtering layer beneath (actual filtering layer) is made of fine gravel. Septic tanks consist of one, two or three chambers. The volume ratio of chambers in two-chamber tanks is usually 2:1, and in three-chamber ones 2:1:1. The sewage is retained in a tank between 3 and 4 days for mechanical treatment. Treatment efficiency for BOD_5 is within 30÷40% and for suspension it is approximately 50%. Wastewater treatment plants with a subsurface leaching system are a very common solution due to low costs of construction and use.

Wastewater treatment plants with activated sludge technology are a miniature version of the technology applied in large-scale wastewater treatment plants. Individual installations most often employ the method of low-load activated sludge or a sequential batch reactor (SBR). The components of such a wastewater treatment plant are: a septic tank, a chamber with activated sludge, a secondary settling tank, and either a seepage pit or a subsurface leaching system or an outlet discharging into waterways. A septic tank, like in other systems, most often serves as a primary settling tank, where, during the decantation process, mineral parts, fats and oils and, to a limited degree, organic parts are removed. The next component is a bio-reactor where sludge is activated and which receives sewage from the primary settling tank. Activated sludge is continuously suspended by air bubbles from diffusers on the bottom. Wastewater treatment plants employing activated sludge are more and more commonly applied in Polish conditions due to their good treatment efficiency and more and more competitive prices. Treatment efficiency in a wastewater treatment plant with an activated sludge reactor is: suspension approx. 90%, COD and BOD_5 within the range of approx. 80÷90%, total nitrogen is approx. 40% and total phosphor between 50 and 60% (Zawartka 2017). Wastewater treatment plants employing activated sludge technology are a common solution as they have good operating parameters and preferential conditions of financing with subsidies.

Basic function of the analyzed water and sewage management system is neutralization of sewage produced within a given area through treatment before it is discharged into the environment. The area where the system operates includes an administrative unit with an urban agglomeration covering part of the area. A basic unit of the system's function, i.e. a functional unit (FU), is population-equivalent (1 PE), which, following point 6 of Article 2 of Council Directive of 21 May 1991 concerning urban waste-water treatment (EUR-Lex 1991) and point 2 paragraph 2 of Article 43 of Water Law Act of 18 July 2001, is defined as load of biodegradable organic substances expressed as 5-day biochemical oxygen demand (BOD_5) of 60 g oxygen per day (ISAP 2001). The functional unit of the analysis is 1 PE as a parameter which is universal for each urban wastewater system considering its diversity. The assumed functional unit enables comparative analyses with other facilities, and is the foundation to create universal models to assess water and sewage management.

The research was conducted for an operating system of collecting, transporting and treating sewage in the city of Żory, Poland; including the area of the agglomeration of Żory with the central wastewater treatment plant (WWTP Żory) located in the catchment area of the Ruda river. The system consists of individual wastewater treatment plants which were analyzed.

The location of the research objects in the city map of Żory is presented in Figure 1. The research objects are marked green.

At the end of 2015, in Żory, there were 304 (UM Żory 2016) individual wastewater treatment plants: 290 in septic tank technology (203 with a subsurface leaching system of treating sewage and 87 with a seepage pit playing the same role), and 14 in activated sludge technology with a bio-reactor (10 with subsurface leaching system of treating sewage and 4 with seepage pits). In Żory, individual wastewater treatment plants serve 912 PE and like septic tanks are located mainly in the suburbs, in the area of detached houses, where there is no sewerage system. Sewage from wastewater treatment plants is discharged into the soil, and sewage sludge from septic tanks is transported in vacuum tankers to central wastewater treatment plant Żory for treatment. The average distance between an individual wastewater treatment plant and wastewater treatment plant Żory is approximately 8 km. System boundaries were determined and inputs/outputs for a given life cycle stages were identified for the life cycle of individual wastewater treatment plant. The system boundaries are presented in Figure 2.

Data inventory

For a given life cycle stages of individual wastewater treatment plant, including construction, use and end-of-life, Life Cycle Inventory (LCI), necessary to conduct life cycle assessment, was conducted. The sources of data were:

- actual data concerning use of individual wastewater treatment plants (e.g. consumption of materials, fuels, energy to transport and treat sewage, qualitative and quantitative parameters of sewage) – obtained from the operator (PWiK Żory 2015),
- actual data from registers of individual wastewater treatment plants obtained from the City Hall of Żory (UM Żory 2016),
- actual data from manufacturers of the equipment and technology providers,
- research and own analysis data concerning construction and use of individual wastewater treatment plants,
- supplementary literature data,
- Ecoinvent 3 database in SimaPro 8.

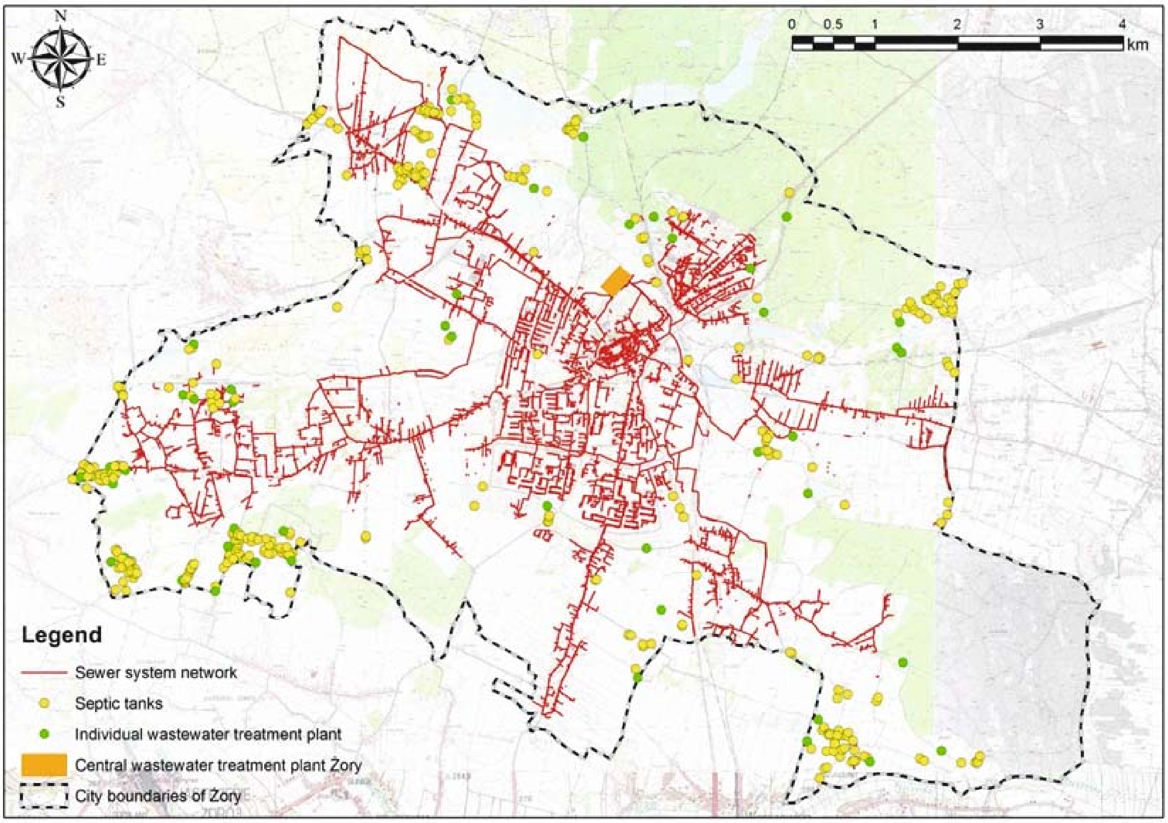

Fig. 1. Location of research object in the city map of Żory (PWiK Żory 2015, UM Żory 2016)

Data identification and inventory concerned the whole life cycle of individual wastewater treatment plants. It was assumed that, in accordance with the facts, the EU's regulations (EUR-Lex 2014) and common practice in the water and sewage sector, the objects are built for a life span of 30 years and within this period their operating as intended is guaranteed.

Data analysis for construction stage

Data analysis for the construction stage of individual wastewater treatment plants (IWWTPs) considers the processes of consumption of materials and resources for necessary infrastructure and machinery, including a section of Ø160 PVC pipe transporting sewage from a building to IWWTPs and earthworks. The range of necessary data for all the IWWTPs in the system is presented in Table 1. Data inventory of construction stage was developed based on the data of producers of Polish individual wastewater treatment plants and technical characteristics of bio-reactors.

Data analysis for use stage

Maintaining the infrastructure, e.g. replacing mechanical equipment (pumps, diffusers, air blower) in IWWTPs with bio--reactors, as well as replacing a subsurface leaching system in treatment plants with only a septic tank, is an important process associated with the use stage. In hitherto analyses the process was ignored in environmental aspects of using IWWTPs.

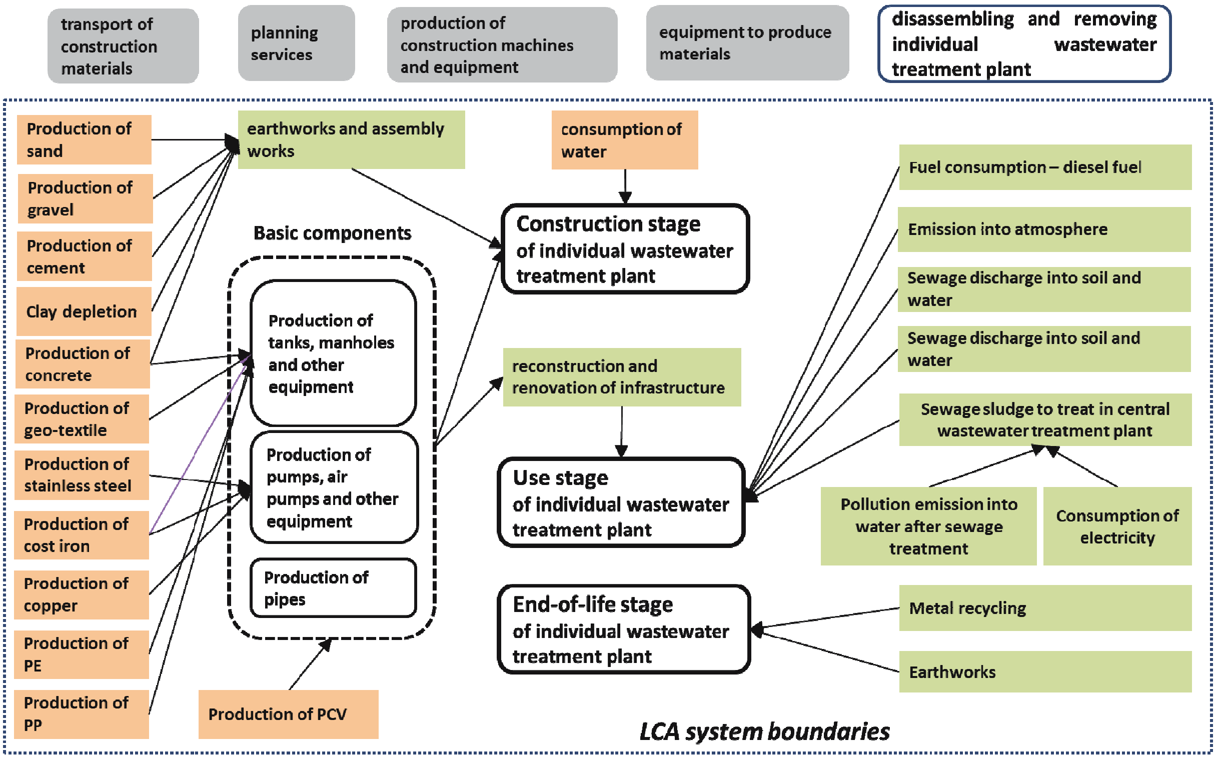

Fig. 2. System boundaries of life cycle assessment of individual wastewater treatment plant

Table 1. Data inventory for individual wastewater treatment plants, stage of construction

Process	Inputs/Outputs	Value	Unit
Consumption of materials and resources	Production of sand	1,172.808	kg
	Production of gravel	1,212.241	kg
	Production of clay	29,201	kg
	Production of cement	116,345	kg
	Production of concrete	140	m^3
	Production of geotextile	160	kg
	Production of stainless steel	448	kg
	Production of cast iron	2,093	kg
	Production of copper	28	kg
	Production of PVC	13,478	kg
	Production of PP	1,960	kg
	Production of PE	31,358	kg
	Consumption of water – leakproofness test	694,302	kg
Earthworks	Excavations	7,281	m^3

Technical wear period of mechanical equipment and subsurface leaching system is assumed to be approx. 15 years at the level of depreciation, depending on specific type of equipment, of 5÷10%. The work assumes 7%, i.e. the discussed elements of IWWTPs are replaced once. Data collected for IWWTPs are presented in Table 2. Data inventory of usage stage was developed based on the data of producers of Polish individual wastewater treatment plants, data of water and sewage management utility companies in Poland and technical characteristics of bio-reactors (Leverenz et al. 2010, PWiK Żory 2015).

Environmental impact associated with the use of IWWTPs results from the following processes: transporting sewage sludge from IWWTPs to WWTP Żory and maintenance of certain types of IWWTPs (indispensable for proper use), emission of pollutants into the atmosphere, emission of pollutants into water after the sewage and sewage sludge treatment process, consumption of energy necessary to treat sewage in an individual wastewater treatment plant with a bio-reactor and in the wastewater treatment plant, as well as replacing infrastructure of IWWTPs. During data inventory conducted for the stage, it was considered that the central wastewater treatment plant also consumes electricity from biogas to treat sewage sludge transported from IWWTPs. Direct GHG emission (CO_2, CH_4, N_2O) was estimated according to (Leverenz et al. 2010).

Emission into water after the sewage treatment process was calculated basing on the expertise of users presented by Zawartka (2017). It was difficult to assess the environmental impact of treating sewage sludge in WWTP Żory, due to the fact that in the system there are no records of received sewage sludge and its composition is not analyzed. Instead, the results of quantitative research into sludge conducted by Błażejewski (2003) and qualitative research conducted in recent years in selected wastewater treatment plants in Poland (Lublin, Rzeszów) were applied. For the analyses, the following pollution indices in unsettled sewage from IWWTPs (MPWiK Lublin 2016) were assumed: BOD_5 – 12,000 g/m^3; COD – 24,000 g/m^3 and suspension – 12,000 g/m^3.

Data analysis for the end-of-life stage

The end-of-life stage of IWWTPs most often occurs when a household is connected to the sewage system. The processes associated with the end-of-life stage involve recycling metal from mechanical installations and conducting earthworks – backfilling a septic tank. The infrastructure in form of a subsurface leaching system, seepage pits and septic tanks or reactors remains buried in the ground. Data for the end-of-life stage are presented in Table 3.

LCA method

Environmental impact assessment of individual wastewater treatment plants was conducted with LCA technique, as it enables performing environmental assessment considering the whole life cycle and many different influence categories. LCA was conducted following the requirements of ISO 14040:2006 International Standards. The phases of the LCA comprised:

- Goal and scope definition phase which included determination of system functions, a functional unit, system boundaries and basic assumptions of the analysis,

Table 2. Data inventory for individual wastewater treatment plants, stage of use

Process	Inputs/Outputs	Value	Unit
Transport of sewage sludge to WWTP Żory and maintenance of IWWTP	Consumption of diesel fuel	1,483	kg/year
GHG and pollution emission from IWWTP into atmosphere	CO_2	335.9	kg/year
	CH_4	19.79	kg/year
	N_2O	0.187	kg/year
Pollutant emission into water after treating IWWTP sewage sludge in WWTP Żory	BOD_5	112.96	kg/year
	COD	886.70	kg/year
	Suspension	251.18	kg/year
Pollutants emission from sewage treated in IWWTPs	BOD_5	7,787	kg/year
	COD	15,574	kg/year
	Suspension	11,356	kg/year
	TN	2,498	kg/year
	TP	350	kg/year
Consumption of electricity in WWTP Żory to treat sewage sludge transported from IWWTPs	Total consumption of energy	571	kWh/year
	Consumption of energy from grid	283	kWh/year
	Consumption of energy produced from biogas	288	kWh/year
Consumption of electricity in wastewater treatment plants with bio-reactor	Consumption of energy from grid	4,855	kWh/year
Replacing IWWTP infrastructure	Production of gravel	776,475	kg
	Production of geotextile	152	kg
	Production of stainless steel	448	kg
	Production of copper	28	kg
	Production of PVC	3,343	kg

- Life Cycle Inventory (LCI) which included inventory of all data necessary to conduct LCA analyses,
- Life Cycle Impact Assessment phase (LCIA) which included calculating values of environmental influence categories following the selected assessment methods,
- Interpretation phase.

LCA was carried out using LCA software package SimaPro v.8 and Ecoinvent 3 database within the program. The study performed an environmental evaluation following ReCiPe method (Goedkoop et al. 2013). The results of LCA were calculated and the main sources of environmental burdens according to circular economy requirements were identified. The results of the LCA consider the stages of classification and characterization, which are obligatory. Four categories were selected for environmental assessment: GHG emission, eutrophication, depletion of metals, and depletion of fossil fuel. The categories were selected following the analyses of results which were standardized in relation to the volume of environmental load occurring around the world, following ReCiPe method. The standardized analyses showed that the categories are the most significant environmental issues for individual wastewater treatment plants.

Influence category of GHG emission expresses radiative forcing of emitted greenhouse gases, converted into kilograms of carbon dioxide equivalent (kg CO_2 eq). GHG emission is calculated basing on the Global Warming Potential (GWP). Influence category of eutrophication is associated with excessive growth of vegetation in lakes and seas under the influence of emission of e.g. sewage and fertilizers (especially increased concentration of phosphorus and nitrogen) into water. Eutrophication is expressed in kg N eq unit. Influence category of fossil fuel depletion includes such fuels as methane, oil and coal. The influence of fossil fuel depletion is assessed basing on the increase in costs of acquiring fuels in the future, resulting from their lowered quality. The fuels were converted into oil equivalent (kg oil eq) basing on the lower calorific value of 42 MJ/kg. Influence category of metal depletion includes lower availability of metals and an increase in the costs of acquiring metals resulting from depletion and lowering quality. Metal depletion is converted into iron equivalent (kg Fe eq) (Goedkoop et al. 2013).

A detailed analysis of life cycle assessment results and of given substances which influence category of eutrophication, showed that ReCiPe Midpoint method does not consider the influence of 5-day biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) on eutrophication. Due to the fact that for individual wastewater treatment plants analyses the parameters are significant from the perspective of their influence on the environment, there were conducted analyses with another method to assess their influence in the life cycle. Basing on the comparative analyses of LCIA methods, it was concluded that TRACI (Tool of Reduction and Assessment of Chemical and other environmental Impacts) method considers the influence of BOD_5, COD, nitrogen and phosphorus on the influence category of eutrophication (EPA 2013), hence detailed analyses of the influence category of eutrophication for given elements of the system were conducted with TRACI method. The method was developed by the US EPA (United States Environmental Protection Agency) (EPA 2013).

Results and discussion

GHG emission assessment

Table 4 presents the main sources of GHG emission for IWWTPs at all the stages of the life cycle. Basing on a detailed analysis of the life cycle of IWWTPs, the factors which determine the result of GHG emission assessment and main greenhouse gases are presented.

It was shown that the main greenhouse gas from IWWTPs is CO_2 with 91% share in the total emission (54% at the construction stage and 46.4% at the end-of-life stage). It was concluded that the volume of GHG emission is also affected by methane emission (8%) and to a much lesser extent by nitrous oxide (approx. 0.5%). Basing on life cycle assessment of IWWTPs, it was concluded that at the construction stage the volume of GHG emission is determined by the amount of used cement (38%), polyethylene (30%), concrete (14%), PVC (10%) and polypropylene (3%). Cement is applied for bedding and backfilling of individual wastewater treatment plant and

Table 3. Data inventory for individual wastewater treatment plants, end-of-life stage

Process	Inputs/Outputs	Value	Unit
Recycling	Recycling cast iron	2,093.00	kg
	Recycling stainless steel	448.00	kg
	Recycling copper	28.00	kg
Earthworks	Backfilling	1,456.00	m^3

Table 4. GHG emissions for individual wastewater treatment plants, kg CO_2 eq/FU

Greenhouse gases	Stages			Total
	Construction	Use	End-of-life	
CO_2	277.00	218.25	-3.09	492.16
N_2O	0.78	2.34	0.00	3.12
CH_4	13.90	29.70	-0.26	43.34
Other gases	1.09	0.76	-0.01	1.84
Total GHG emission	292.77	251.05	-3.36	540.46

polyethylene to build it. Share of other factors (including: geotextile, stainless steel, copper, cast iron earthworks, gravel, clay and water) constitutes 5%. Determinants of GHG emission at the stage of construction of an individual wastewater treatment plants are presented in Fig. 3.

Environmental assessment of the use stage of individual wastewater treatment plant showed that the volume of GHG emission is determined by wastewater treatment technology and application of a bio-reactor in an individual wastewater treatment plant, and hence the amount and type of electricity consumed to treat sewage in IWWTPs (74%), mount of diesel fuel consumed to transport sewage sludge to the WWTP (10%), and also direct emission of gases – methane (6%), carbon dioxide (4%) and nitrous oxide (1%) (Fig. 4).

Basing on an electricity consumption analysis at the use stage, it was concluded that electricity consumption in bio-reactors of IWWTPs has a decisive influence on GHG emission, in spite of the fact that their share in wastewater treatment plants with reactors is only approx. 5% of all the IWWTPs in the system. Use of biogas to produce electricity in the central wastewater treatment plant for treating sewage sludge transported from IWWTPs has little influence on lowering GHG emissions (4%).

Life cycle analysis of the end-of-life stage of IWWTPs showed that earthworks (GHG emission is 0.85 kg CO_2eq/FU) and recycling metals, i.e. cast iron from manhole covers, stainless steel and copper from bio-reactors, which is an environmental benefit in the form of avoided emission (GHG emission is – 4.21 kg CO_2eq/FU). The share of the end-of-life stage of IWWTPs, both negative and positive influence, in GHG emission is insignificant.

Abiotic resources depletion assessment

Basing on a detailed life cycle analysis of IWWTPs, factors determining fossil fuel and metal depletion indicators at the stage of construction and use are presented. It was shown that individual wastewater treatment plants contribute to fossil fuel depletion with the total of 210.59 kg oil eq/FU (at the stage of construction 100.97 kg oil eq/FU, at the stage of use 110.28 kg oil eq/FU, while at the end-of-life stage fossil fuel depletion indicator is -0.65 kg oil eq/FU (environmental benefit). It was shown that at the stage of construction, fossil fuel depletion indicator is determined by the amount of used polyethylene (62%), which is directly involved in constructing a septic tank, PVC (16%) to transport sewage from a building to IWWTPs, cement (10%), as well as polypropylene (5%) and concrete (4%). The share of other factors (including: earthworks, geotextile, stainless steel, cast iron, copper, clay, water and gravel) is 4%.

Individual wastewater treatment plants contribute to depletion of metals of 5.38 kg Fe eq/FU, at the construction

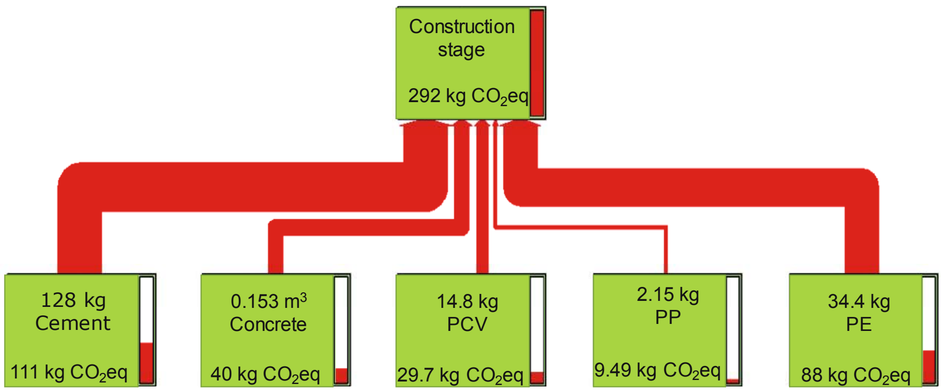

Fig. 3. Determinants of GHG emission for individual wastewater treatment plants, stage of construction, kg CO_2 eq/FU

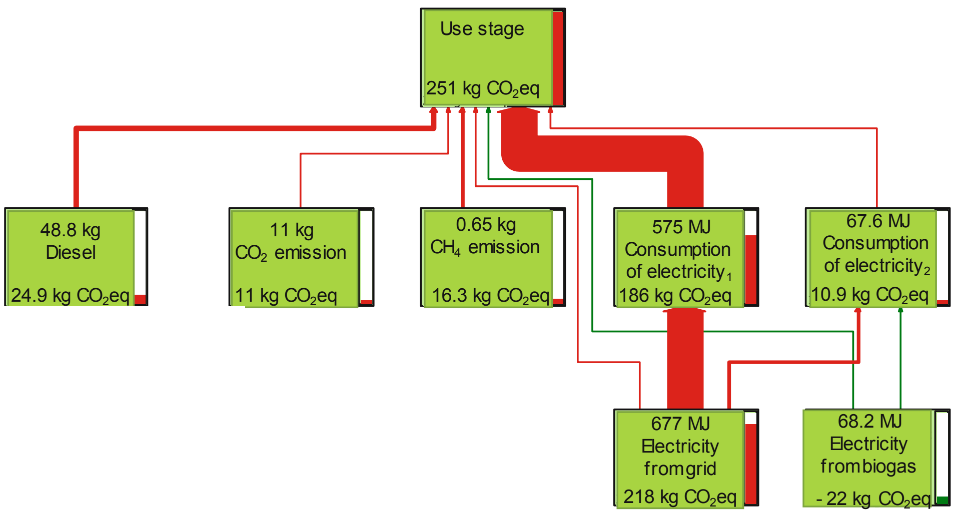

Fig. 4. Determinants of GHG emission for individual wastewater treatment plants, use stage, kg CO_2 eq/FU

stage with 9.47 kg Fe eq/FU (Tab. 5), at the use stage with 1.79 kg Fe eq/FU, while at the end-of-life stage fossil fuel depletion indicator is -5.88 kg Fe eq/FU. Metal depletion indicator at the construction stage is determined, most of all, by the amount of stainless steel (approx. 27%) and copper (14%) in bio-reactors and cast iron for manhole covers (22%). It has to be emphasized that metal depletion at the construction stage of IWWTPs is low.

Environmental assessment of the use stage of individual wastewater treatment plants showed that fossil fuel depletion indicator is determined by the amount of diesel fuel consumed to transport sewage sludge to the central wastewater treatment plant (54%) and the amount and type of electricity used in IWWTPs (43%). Other factors like electricity used by the WWTP, replacing bio-reactors contribute merely 3%.

As far as metal depletion is concerned, the opposite is true – electricity consumed by IWWTPs is 48% and diesel fuel to transport sewage sludge is 37%. Additionally, grid electricity consumption to treat sewage sludge has 5% share, and stainless steel associated with replacing bio-reactors has 5% share. It also has to be emphasized that the share of use stage in metal depletion is negligible. Determinants of fossil fuel depletion for individual wastewater treatment plants at the use stage are presented in Figure 5.

Life cycle assessment of the end-of-life stage of IWWTPs showed that there are environmental benefits associated with the stage obtained through recycling metals (cast iron, stainless steel and copper), -5.92 kg Fe eq/FU and -0.93 kg oil eq/FU, which outweigh fuel and metal depletion as a result of earthworks by respectively 0.04 kg Fe eq/FU and 0.28 kg oil eq/FU.

Eutrophication assessment

Water eutrophication is mainly influenced by sewage introduced into the environment, hence presentation of the results of the LCA analysis for IWWTPs was limited to the use stage. Basing on a detailed analysis of the factors contributing to the influence category, it was shown that sewage treated in IWWTPs, discharged into soil with a subsurface leaching system or a seepage pit, has the biggest influence on eutrophication (204 kg N eq/FU i.e. 98%). Sewage sludge

Table 5. Fuel and metal depletion, construction stage of IWWTPs

Factors	Fossil fuel depletion		Metal depletion	
	kg oil eq/FU	share, %	kg Fe eq/FU	share, %
Gravel	1.16	1.15	0.7871	8.308
Cement	9.79	9.69	0.9040	9.542
Concrete	3.73	3.69	0.7434	7.846
PP geotextile	0.31	0.31	0.0004	0.004
Stainless steel	0.27	0.27	2.5471	26.885
Cast iron	0.89	0.88	2.0698	21.847
Copper	0.02	0.02	1.3687	14.447
PVC	15.70	15.55	0.0693	0.732
Polypropylene	5.05	5.00	0.0065	0.069
Polyethylene	62.55	61.95	0.7573	7.993
Earthworks	1.41	1.40	0.2035	2.148
Clay	0.03	0.03	0.0025	0.026
Water	0.06	0.06	0.0145	0.153
Total	100.97	100.00	9.4741	100.000

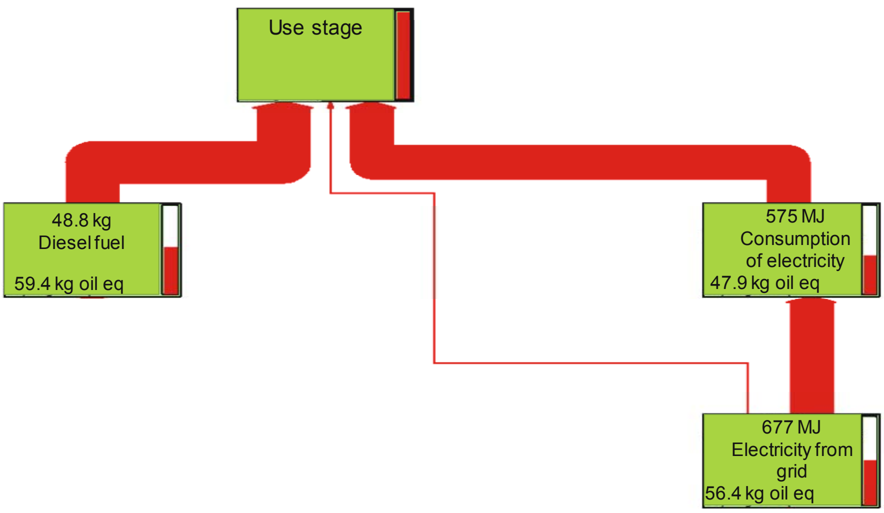

Fig. 5. Determinants of fossil fuel depletion for IWWTPs, use stage, kg oil eq/FU

treatment in the central wastewater treatment plant has little influence (1.64 kg N eq/FU i.e. 1%), while diesel fuel to transport sewage sludge and electricity are 1% share. By using individual wastewater treatment plants, the influence on eutrophication caused by phosphor is 84.1 kg N eq/FU (41% share), by nitrogen is 81.1 kg N eq/FU (40% share), by COD is 25.6 kg N eq/FU, (13% share) and by BOD_5 is 12.8 kg N eq/FU (6% share). Substances discharged into the environment after treating sewage sludge in the central wastewater treatment plant have minimal influence on eutrophication when compared with sewage discharged from IWWTPs which results from little sewage sludge produced and high efficiency of sewage treatment in the central wastewater treatment plant. All the most significant sources of eutrophication in IWWTPs are presented in Fig. 6.

The conducted analysis show that sewage treated in IWWTPs has significant influence on eutrophication, which results from low efficiency of the installations, especially the ones with only a septic tank and subsurface leaching system (or a seepage pit). Low share of IWWTPs with a bio-reactor in the system means that individual wastewater treatment plants are not able to provide a measurable scale effect of the whole analyzed system and eutrophication influence.

Conclusions

The work addresses important problems associated with the assessment of sewage management. Environmental assessment of an individual wastewater treatment plant was conducted, considering life cycle of the elements, which was possible thanks to the life cycle assessment.

1. Results of an inventory and life cycle assessment of individual wastewater treatment plants in urban wastewater system are presented for the first time.
2. Basing on LCA of individual wastewater treatment plants, it was concluded that at the construction stage, GHG emission factor is determined by the amount of used cement, polyethylene, concrete, PVC and polypropylene. Cement is used for bedding and backfilling of a septic tank, and polyethylene to construct the tank itself.
3. Environmental assessment of the use stage of individual wastewater treatment plant showed that the volume of GHG emission is determined by the treatment technology and application of a bio-reactor in an individual wastewater treatment plant. It is associated with the amount and type of electricity consumed to treat sewage in IWWTPs, the amount of diesel fuel consumed to transport sewage to IWWTPs, as well as direct emission of gases – methane, carbon dioxide and nitrous oxide.
4. It was shown that at the stage of construction fossil fuel depletion indicator is determined by the amount of used polyethylene, which is directly associated with the construction of a septic tank; PVC, cement, polypropylene and concrete.
5. Individual wastewater treatment plants contribute to metal depletion mostly at the construction stage, where metal depletion indicator is determined by the amount of stainless steel and copper in bio-reactors and cast iron for manhole covers.
6. Fossil fuel depletion and metal depletion indicators at the use stage of individual wastewater treatment plants are determined by the amount of diesel fuel consumed to transport sewage sludge to the central wastewater treatment plant and consumption of electricity from the grid in bio-reactors.
7. Basing on detailed analysis of factors contributing to eutrophication influence, it was determined that sewage treated in IWWTPs, discharged through a subsurface leaching system or a seepage pit directly into soil, has the biggest impact. Electricity consumption and diesel fuel depletion to transport sewage sludge and treat sewage sludge in the central wastewater treatment plant have minimal influence.

Recommendations and perspectives

The problem addressed in the research is significant concerning assessment of actions aimed at water protection.

The object of the research was a system functioning on a local scale, which was selected in such a way that due to its specificity (Fig. 1) it could correspond to systems functioning at least on a national scale. Technological solutions in the analyzed system are commonly found on a global scale (septic tanks with a subsurface leaching system of treating sewage, seepage pits, bio-reactors with activated sludge), therefore it should be recognized that the test results can be universally applicable. The results obtained in the research can be used to assess wastewater management in order to comply with European Commission's legal regulations and guidelines.

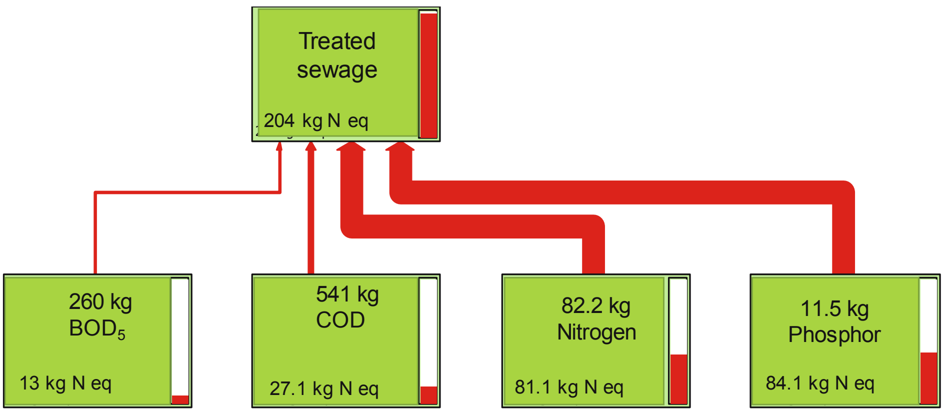

Fig. 6. Main sources of eutrophication resulting from using IWWTPs

The obtained results can be used as the basis for further development of environmental assessment towards selection of environmentally friendly materials at the construction stage, and limiting the influence of individual solutions to neutralize sewage on eutrophication, at the use stage. The results are important for practical approach of using individual wastewater treatment plants in e.g. single-detached residential zones. The solutions became popular in Poland leading to a significant increase in the number of IWWTPs with a subsurface leaching system, which, considering their low sewage treatment efficiency results in a significant influence on eutrophication. Conclusions of the work may support decisions taken by local governments concerning wastewater management in their area and promote and support solutions of high ecological standards.

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Determinanty oceny środowiskowej krajowych indywidualnych oczyszczalni ścieków uwzględniając perspektywę cyklu życia

Streszczenie: W artykule przedstawiono wyniki inwentaryzacji danych oraz środowiskowej oceny cyklu życia (LCA) indywidualnych oczyszczalni ścieków (IWWTP), z uwzględnieniem całego ich cyklu życia, w tym etapu budowy, użytkowania i wycofania z eksploatacji. IWWTP zlokalizowane na terenie średniej wielkości miasta w Polsce, zostały ocenione z perspektywy cyklu życia. Wykazano, że na etapie budowy IWWTP emisja gazów cieplarnianych jest zależna od ilości użytego cementu, polietylenu, betonu, PCV i polipropylenu. Na etapie budowy zużycie paliw kopalnych zależy od ilości zużytego polietylenu, PCV, cementu, polipropylenu i betonu; natomiast zużycie metali zależy od ilości użytej stali nierdzewnej, miedzi i żeliwa. Na etapie użytkowania determinantami emisji gazów cieplarnianych są technologia oczyszczania ścieków i zastosowanie bioreaktora w IWWTP. Dane inwentaryzacyjne i analiza cyklu życia IWWTP są prezentowane po raz pierwszy w literaturze. Wnioski z pracy mogą służyć do podejmowania decyzji przez samorządy dotyczących gospodarki wodno-ściekowej na ich terenie oraz promowania i wspierania rozwiązań proekologicznych.