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The use of multi-criteria analysis for selection of technology for a household WWTP compatible with sustainable development

Krzysztof Jóźwiakowski[1]*, Zbigniew Mucha[2], Agnieszka Generowicz[2], Stanisław Baran[3], Jolanta Bielińska[3], Włodzimierz Wójcik[4]

[1]University of Life Sciences in Lublin, Poland
Faculty of Production Engineering
Department of Environmental Engineering and Geodesy
[2]Cracow University of Technology, Poland
Faculty of Environmental Engineering
Institute of Water Supply and Environmental Protection
[3]University of Life Science in Lublin, Poland
Faculty of Agrobioengineering
Institute of Soil Science, Engineering and Environmental Engineering
[4]Krosno State College, Poland
Department of Civil Engineering

*Corresponding author's e-mail: krzysztof.jozwiakowski@up.lublin.pl

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Abstract: This paper presents the use of multi-criteria analysis as a tool that helps choosing an adequate technology for a household wastewater treatment plant. In the process of selection the criteria of sustainable development were taken into account. Five municipal mechanical-biological treatment plants were chosen for the comparative multi--criteria analysis. Different treatment technologies, such as sand filter, activated sludge, trickling filter, a hybrid system – activated sludge/trickling filter and a hybrid constructed wetland system VF-HF type (vertical and horizontal flow) were taken into account. The plants' capacities were 1 $m^3 \cdot d^{-1}$ (PE=8) and they all meet the environmental regulations. Additionally, a solution with a drainage system was included into the analysis. On the basis of multi-criteria analysis it was found that the preferred wastewater treatment technologies, consistent with the principles of sustainable development, were a sand filter and a hybrid constructed wetland type VF-HF. A drainage system was chosen as the best solution due to the economic criteria, however, taking into consideration the primary (ecological) criterion, employment of such systems on a larger scale disagree with the principles of sustainable development. It was found that activated sludge is the least favourable technology. The analysis showed that this technology is not compatible with the principles of sustainable development, due to a lack of proper technological stability and low reliability.

Introduction

According to the Polish Standard PN-EN 12566, household wastewater treatment plants (WWTPs) are defined as those serving up to 50 inhabitants. According to the Water Law (Prawo wodne 2001), the maximum throughput of objects of the type is 5 $m^3 \cdot day^{-1}$, and according to the Building Law (Prawo budowlane 2003) – 7.5 $m^3 \cdot day^{-1}$. Objects of this type, in Poland and worldwide, are installed primarily in areas with scattered housing, where the construction of a sewerage system and a collective wastewater treatment plant is not economically viable.

Data from the Central Statistical Office (GUS 2014) indicate that by the year 2013 in Poland 154,944 household wastewater treatment plants were built. Current estimates and projections (Jóźwiakowski 2012a) indicate that in the coming years over 555 thousand new household wastewater treatment plants can be built in Poland. In the case of building such a great number of objects it is necessary to use technologies that have been tested in practice and that are characterised by a high efficiency of operation, and that are easy to build and to operate.

Household wastewater treatment plants are characterised by specific features that set them apart from large collective wastewater treatment plants (Lundin et al. 1999, Mucha and Mikosz 2009, Roeleveld et al. 1997). Small wastewater treatment plants are characterised by highly fluctuating influx of wastewater and by a chemical composition that is significantly different from that encountered in typical municipal wastewater flowing into medium and large WWTPs. Therefore, the technology of wastewater treatment used in a household WWTP should be chosen in such a way as to ensure adequate ecological effects combined with low requirements relating to maintenance and with minimal costs of operation.

The decision concerning the application of a specific technological solution for a household WWTP should by based on an analysis of the local conditions and the technological and environmental factors. Moreover, a careful economic analysis needs to be performed. In practice, decisions on the choice of wastewater treatment technology applied in household WWTP are most often taken irrationally and contrary to the principles of sustainable development – solely on the basis of the lowest investment costs. The effect of that situation is the use of technological solutions which are not suitable for the amounts and composition of inflowing wastewater, unreliable and difficult in operation, and in consequence do not ensure the required effects of wastewater treatment.

The process of selection of technology for both a collective and a household WWTP must involve the participation of an experienced process engineer able to correctly evaluate the suitability of various technologies and technical solutions under specific local conditions (Mucha and Mikosz 2009). The technological solutions applied in household wastewater treatment plants include systems with drainage systems, sand filters, activated sludge systems, trickling filters systems, hybrid systems (activated sludge + trickling filters), constructed wetlands (Jóźwiakowski 2012b).

The objective of the paper is to present a method for the use of multi-criteria analysis as an auxiliary tool for the selection of correct technology for a household wastewater treatment plant. Such a technology must conform with the principles of sustainable development which, in recent years, has been referred to more and more frequently, both in Poland and in the world (Baryła 2013, Pawłowski 2008, Pawłowski 2009, Pawłowski 2011). Sustainable development was the leading idea of the report of the World Commission for the Environment and Development established in 1983 by the UN General Assembly. It was defined there as "*such a development that satisfies the needs of the present generation without restricting the possibility of satisfying the needs of future generations*". This is a general definition. It does not provide answers to the engineer's questions as to which of the possible technologies conforms to that concept, whether it leads to permanent development and how it can be measured. There have appeared the first approximations of the concept of sustainable development in the form of Daly's three rules, or practical guidelines concerning environmental management. They do approximate the concept, but not sufficiently. Therefore, there is a need to develop easier--to-apply measures for the estimation of technologies, policies or systems which will indicate sustainable development in a more practical way and which will be easy to understand both for the decision makers and for the society.

Methods

Selection of evaluated variants of technologies for household WWTPS

For the comparative multi-criteria analysis 5 variants of mechanical-biological household WWTPs were selected, with throughput of $1 m^3 \cdot d^{-1}$ (PE=8), meeting the requirements of the environmental protection regulations (Regulation of the Ministry of the Environment 2006), and additionally a drainage system. The systems selected for the analysis included the following: 1) a drainage system, 2) a sand filter, 3) an activated sludge, 4) a trickling filter, 5) a hybrid system (activated sludge + trickling filter), 6) a hybrid constructed wetland system, VF-HF type.

It was assumed that in the first case the receiver of the treated wastewater was the ground, and in the other cases flowing surface waters. In each case the technological system of the household WWTPs included a septic tank with volume of $4 m^3$. It was assumed that the sediments from the septic tanks will be transported out for dewatering and stabilisation in a collective WWTP. The sizes of the biological treatment units were selected on the basis of the parameters and indices given by Heidrich et al. (2008). The calculations of investment costs were made based on unit cost indices from data concerning installations built in recent years and quotation cost estimates of companies building objects of this size, for average ground-water conditions, and on the basis of the literature data (Mucha 2005, Mucha 2008, Mucha and Iwanejko 2012). The cost of sludge transport was adopted at the level of 125 PLN/disposal, while the costs of operation of the wastewater treatment plants were based on a unit index of 2.0 PLN/m^3 of wastewater (including costs of maintenance, electric power, and consumable materials).

Criteria for the selection of technology for household WWTP and adopted assumptions

When determining the criteria for multi-criteria analysis it is necessary to apply individual approach to every decision problem. So far various criteria were used in studies of this type, depending on the size of the object, the technology applied, and on the purpose of the analysis (Lundin et al. 1999, Mucha and Mikosz 1999, Roeleveld et al. 1997). A comprehensive system of criteria for use in the evaluation of various systems of wastewater treatment was presented by e.g. Balkema et al. (1998). The selection of optimum engineering solutions is usually made on the basis of economic, environmental, technical and social-cultural criteria. The most numerous group is that of environmental criteria, concerning primarily the use of natural resources and the emission of pollutants to the environment, as well as counteracting the generation of pollutants, and technical criteria (Balkema et al. 1998, Generowicz et al. 2012, Korizi 2008).

In accordance with the fundamental principles of sustainable development, the overriding criterion for the selection of technology for domestic WWTPs should be the ecological criterion, i.e. the effectiveness of wastewater treatment (Mucha and Mikosz 2009). Other criteria include the following:

- environmental criteria (effect on the natural environment and aesthetics)
- technical criteria (ease of operation and maintenance and modern solutions),
- economic criteria (costs of investment and operation),
- reliability criterion (reliability of operation) (Fig. 1).

Characterisation of multi-criteria analysis applied for evaluation of technologies for household WWTP

Multi-criteria analysis is a mathematical method of decision analysis, evaluating solutions according to adopted criteria and indicating the most favourable solution at pre-defined

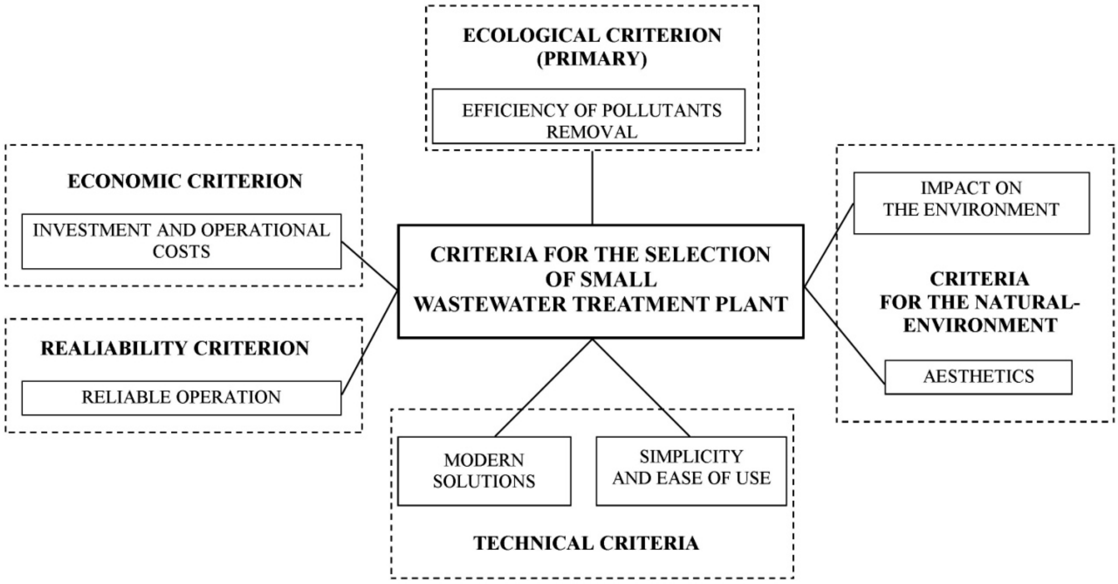

Fig. 1. Selection criteria for small WWTPs according to sustainability principles (Mucha, Mikosz, 2009)

boundary conditions. Correct methodology of the analysis is based on developing a set of measurable criteria evaluating individual strategies. Therefore the variants should be extensively described and measured, while the selection itself is a compromise choice, depending on the importance of particular criteria (Mucha et al. 2012). So far, the multi-criteria analysis has been applied e.g. in studies (Brechet and Tulkens 2009, Generowicz et al. 2011a, Generowicz et al. 2011b, Generowicz et al. 2012, Georgopoulou et al. 2008).

In this study, for a full description of the technologies under evaluation we proposed their assessment in compliance with the principles of sustainable development, based on criteria in the groups of ecological, economic and social evaluation. The mathematical description of the decision process is the co-called normalised decision matrix, the formal notation of which is a table of numerical values that represent the evaluated criteria for the particular technologies. Their measure is the realization of the assumed target. In this decision problem, the variants under evaluation are the technologies for household WWTPs with uniform technological parameters: Q=1 $m^3 \cdot day^{-1}$ and PE=8.

Results and discussion

Multi-criteria analysis and selection of the most favourable technology

The notation of the decision matrix is presented in Table 1. All the criteria were evaluated in such a way as to allow the comparison of all technologies between one another. Since the easiest to evaluate were the costs and the size of the area occupied, those criteria were valued in specific measurable units, while the remaining criteria were assigned values with the expert method, using a point scale from 0 to 10 (where: 0 – the lowest rating, 10 – the highest rating).

The technologies under evaluation were annotated with successive numbers, i.e.: 1 – drainage system, 2 – sand filter, 3 – activated sludge, 4 – trickling filter, 5 – hybrid systems (activated sludge + trickling filter), 6 – constructed wetlands (hybrid), VF-HF type (vertical flow – horizontal flow).

For the solution of the decision problem the method of compromise programming was applied (Aragonés-Beltrána et al. 2009, Generowicz et al. 2011a, 2011b). The mathematical notation of the decision method is described by the equations (1 and 2):

$$L_\alpha(s_n) = \sum_{m=1}^{M} w_m^\alpha \cdot (x'_m - r'_{NM})^\alpha \qquad [1]$$

$$s_j = \bar{s} \Leftrightarrow L_\alpha(s_j) = \min L_\alpha(s_n); n = 1, 2, ..., N \qquad [2]$$

where:
L (s_n) – measure of divergence of a strategy s_n from the ideal point
$\bar{s}$ – selected strategy,
w_m – criterion weight coefficient m,
x_m' – m-th (coordinate of ideal point),
r_{NM}' – normalised value of criterion,
M – number of evaluation criteria,
α – index exponent measuring the divergence of a strategy from ideal point X', assumed in practice as 1, 2 and ∞.

The adopted methodology permits to assume a hierarchy of weights of the particular evaluating criteria. This is an additional advantage of the decision method, allowing the decision maker to estimate criteria more or less important for him. In these calculations, the weights of the criteria were adopted by the authors. Their broad range permitted the analysis of sensitivity of particular sequences, dependent on the adopted weights.

Table 2 presents the solution of the decision problem, i.e. the sequences of the evaluated technologies, from the most to the least advantageous, taking into account the evaluation criteria from Table 1 and the weights assigned to those criteria by the authors. The sequences were written using the symbol "→", while the symbol "↔" denotes equivalent technologies. The first column in the Table presents the weights of the criteria

Table 1. Decision matrix for selecting technology for domestic WWTP for Q=1 $m^3 \cdot d^{-1}$ and RLM=8

Criteria of technology assessment	Evaluated technology of household WWTP					
	1	**2**	**3**	**4**	**5**	**6**
Simplicity and ease of use	10	10	7	8	7	10
Stability of technology	7	8	6	8	9	10
Technical reliability	8	8	6	7	7	8
Investment costs (in thousand zloty)	10	15	20	20	20	20
Operating costs (zloty)	250	250	800	600	800	250
Impact on the environment	0	8	8	8	9	9
Space required (m^2/RLM)	20	7	0.3	0.3	0.2	12
Aesthetics	9	9	8	8	8	10

Explanation: **1** – a drainage system, **2** – a sand filter, **3** – an activated sludge, **4** – a trickling filter, **5** – a hybrid system (activated sludge + trickling filter), **6** – a hybrid constructed wetland system, VFCW-HFCW type.

Table 2. Decision-making task solution – ranking of technological solutions for household WWTP, depending on the weight of the individual evaluation criteria

Weights attached to the criteria	Ranking of strategy		
	α = 1	α = 2	α = ∞
1:1:1:1:1:1:1:1	**2→6→1→ 4→5→3**	**2→6→4→ 1→5→3**	**2→6↔4→ 1↔5↔3**
2:1:1:1:1:1:1:1	**2→6→1→ 4→5→3**	**2→6→4→ 1→5→3**	**2→6↔4→ 1↔5↔3**
10:1:1:1:1:1:1:1	**2→6→1→ 4→5→3**	**2→6→1→ 4→5→3**	**2→6↔4→ 1↔5↔3**
1:2:1:1:1:1:1:1	**2→6→1→ 4→5→3**	**2→6→4→ 5→1→3**	**2→6↔4→ 1↔5↔3**
1:10:1:1:1:1:1:1	**6→2→5 → 4→1→3**	**6→5→ 2→ 4→1→3**	**2→6↔4→ 1↔5↔3**
1::1:2:1:1:1:1	**2→6→1→4→5→3**	**2→6→4→ 1→5→3**	**2→6↔4→ 1↔5↔3**
1:1:10:1:1:1:1:1	**2→6→1→ 4→5→3**	**2→6→1→ 4→5→3**	**2→6↔4→ 1↔5↔3**
1:1:1:2:1:1:1:1	**2→1→6→4→5→3**	**2→1→6→ 4→5→3**	**2→1**
1:1:1:10:1:1:1:1	**1→2→6→ 4→5→3**	**1→2→6→ 4→5→3**	**2→1**
1:1:1:1:2:1:1:1	**2→6→1→ 4→5→3**	**2→6→1→ 4→5→3**	**2→4↔6→ 1**
1:1:1:1:10:1:1:1	**2→6→1→ 4→5→3**	**2→6→1→ 4→5→3**	**2→4↔6→ 1**
1:1:1:1:1:2:1:1	**2→6→4→ 5→1→3**	**2→6→4→ 5→3→1**	**2→6↔4→ 5↔3**
1:1:1:1:1:10:1:1	**6→2→ 5→4→3→1**	**6→5→2→ 4→3→1**	**2→6↔4→5↔3**
1:1:1:1:1:1:2:1	**2→6→4→5→3→1**	**2→4→5→ 3→6→3**	**2→6↔4→ 5↔3**
1:1:1:1:1:1:10:1	**4→5→3→ 2→6→1**	**4→5→3→ 2→6→1**	**2→6↔4→ 5↔3**
1:1:1:1:1:1:1:2	**2→6→1→ 4→5→3**	**2→6→4→1→5→3**	**2→6↔4→ 1↔5↔3**
1:1:1:1:1:1:1:10	**6→2→1→4→5→3**	**6→2→1→ 4→5→3**	**2→6↔4→ 1↔5↔3**
1:1:1:2:2:1:1:1	**2→1→6→ 4→5→3**	**2→1→6→ 4→5→3**	**2→1**
1:1:1:10:10:1:1:1	**1→2→6→ 4→5→3**	**1→2→6→ 4→5→3**	**2→1**

adopted by the authors for the calculations. For example, in the first line the technologies are arranged assuming that all the criteria have the same weights of 1, while in the final two lines higher weights were assigned to the economic criteria, thus testing the change in the sequences of the technologies under analysis.

Solving the decision problem described above a total of 57 calculation cases were performed, adopting various weights for the particular criteria and each time evaluating all the technologies, using the same evaluation criteria. The result of the calculations were sequences of the technologies for household wastewater treatment plants, from the most to the least advantageous (Tab. 2).

The analyses indicate that among the household wastewater treatment plant systems under evaluation the sand filter system was selected 45 times as the most advantageous technology (Tab. 2). It can be said, therefore, that with the large number of calculation cases and the notable divergences in the adopted weights of the criteria that solution is decidedly the most advantageous. The hybrid, type VFCW – HFCW, constructed wetland technology was selected six times as the most advantageous solution. This system appeared 36 times as second most advantageous in the sequence of the technologies. Therefore, this is a technology that can be treated as equally advantageous to the sand filter solution.

It appears to be interesting that with a notable predominance of economic criteria it is the system with screening drainage that is indicated as the most advantageous solution (this solution is presented in the bottom line of Table 2).

On the basis of the multi-criteria analysis the most disadvantageous (most frequently selected) was the technology involving the use of activated sludge. The analysis demonstrated that the application of that technology is not compliant with the principles of sustainable development.

Discussion of the results

The results of the multi-criteria analysis revealed that the most advantageous technologies for WWTPs, conforming with the principles of sustainable development, are the systems with sand filter and hybrid VFCW – HFCW. As to the overriding (ecological) criterion of selection of household WWTPs, i.e. the effectiveness of wastewater treatment, also the results of earlier research (Chmielowski 2009, 2013, Gajewska and Obarska-Pempkowiak 2009, Jóźwiakowski 2012a, Pawęska and Kuczewski 2013, Tuszyńska et al. 2004, Tuszyńska and Obarska-Pempkowiak 2008) confirm that the systems selected meet that criterion. The studies by the referenced authors indicate that the average effectiveness of pollution removal in systems with sand filters and in hybrid VFCW – HFCW is above 75% in the case of total suspended solids, and in the case of BOD_5 and COD removal it considerably exceeds 80%, and sometimes even attains 95%. In addition, it should be mentioned that hybrid VFCW – HFCW is characterised by over 99% operation reliability, confirmed by multi-year research results (Jóźwiakowski 2012a).

A different situation was observed in the case of the reliability of operation and environmental effects of systems with drainage. Research shows (Jóźwiakowski 2003; Orlik and Jóźwiakowski 2003) that in such systems the effectiveness of wastewater treatment does not exceed 40% in the case of removal of suspended solids, and the maximum levels of BOD_5 and COD removal reach up to 38%. Although according to the economic criterion those systems are indicated as the most advantageous technology, taking into account the overriding (ecological) criterion the possibility of their application on a larger scale should excluded for the purpose of compliance with the principles of sustainable development.

For years now there has been an ongoing discussion in Poland as to whether screening drainage systems ensure wastewater treatment or whether they are just a means of disposal of untreated wastewater to the soil (Błażejewski 1995; Jucherski and Walczowski 2001; Paluch and Pulikowski 2004).

According to Obarska-Pempkowiak (2005) septic tanks, combined with soil treatment, provide only mechanical treatment of sewage that is next discharged directly to the receivers. Since rural areas in Poland have small water resources that cannot accommodate such pollutant loads, such technology cannot be accepted as a long term solution.

In 2002 also in Germany it was concluded that household WWTPs based on the application of drainage preceded only by a septic tank "*do not conform with current state of technology*" (Błażejewski 2005).

In spite of all the discussions, systems with drainage are the most common household WWTPs in Poland. According to Błażejewski (2005), those systems constitute about 63% of all household wastewater treatment plants in the country, while a poll conducted in 2011 in 70 communes of the Lublin Province showed that among the household WWTPs constructed by that time systems with drainage constituted 71% (Jóźwiakowski et al. 2012). Without doubt this situation is partially due to the fact that the main criterion used in the selection of a technology for household WWTPs in communes is the cost of investment. A WWTP with drainage for a single household can be built for even several thousand PLN (Jóźwiakowski 2012b). The lack of control of the operation of effluent WWTPs, as well as of monitoring of the quality of underground waters in communes where such systems are used on a large scale, can lead, within a short time, to considerable degradation of water quality. Poland may find itself in the same situation as France, where more than a decade ago due to an extensive use of soil treatment a significant deterioration in the groundwater quality was observed.

In France objects of this type were eliminated and a ban was imposed on the construction of new ones (Malarski 1999). Of course we cannot totally exclude the use of drainage systems, as they can be employed as the final element of biological WWTPs that will ensure the disposal of biologically purified wastewaters to the ground.

The multi-criteria analysis revealed that the application of the activated sludge technology for household WWTPs is against the principles of sustainable development. That result was determined by the points awarded for technological stability and technical reliability (Tab. 1). A study on household WWTPs with activated sludge, conducted in Polish conditions, showed that such systems guarantee the removal of organic contaminants (BOD_5 and COD) within the range of 71–87% and of total suspended solids in the range of 72–85% (Bugajski and Ślizowski 2003). However, another study (Bugajski and Wałęga 2010) indicated that the activated sludge technology is characterised by only 66% effectiveness in eliminating total suspended solids, and 72 and 93%, respectively, in the case of BOD_5 and COD removal. Even though household WWTPs with activated sludge are characterised by usually sufficient effectiveness of removal of pollutants, their high sensitivity to fluctuations in wastewater inflow and its composition is a significant shortcoming. Also, objects of this type are not resistant to periodic breaks in power supply (interruptions in the operation of the pump and the aeration system). Besides, the process of wastewater treatment with the method of activated sludge is highly demanding in use and requires permanent supervision by an experienced specialist (Jóźwiakowski 2012b).

Household WWTPs cannot be the primary method of treatment of wastewater in rural areas and replace collective WWTPs in which there is a possibility of controlling the process of wastewater purification. However, in areas with scattered housing, where collective sewerage systems and WWTPs cannot be built, they still provide a better solution than keeping wastewater in closed tanks (cesspools). An unquestionable advantage of household WWTPs is the possibility of wastewater purification at the location where the wastewater is generated. If such systems are properly operated and maintained, it is possible to output to the environment treated wastewaters that may contribute to the local resources of water. Nevertheless, it is necessary to conduct educational activities that should make the potential users aware of which technologies of household WWTPs are recommended and how a given system should be operated and maintained to ensure sustainable development of rural areas and effective protection and conservation of the current status of the environment for future generations.

Conclusions

1. On the basis of multi-criteria analysis it was found that the most advantageous technologies among those used in household WWTPs are systems with sand filters and hybrid constructed wetlands of the type VFCW and HFCW.
2. With a notable predominance of economic criteria it is the system with drainage that was indicated as the most advantageous solution, but taking into account the overriding criterion (ecological), the possibility of application of that technology on any larger scale should be excluded.
3. It was found that the most disadvantageous was the technology involving the use of activated sludge. The analysis demonstrated that the application of that technology is not compliant with the principles of sustainable development, due to its insufficient technological stability and low reliability of operation.

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Zastosowanie analizy wielokryterialnej do wyboru rozwiązania technologicznego przydomowej oczyszczalni ścieków zgodnego z ideą zrównoważonego rozwoju

Streszczenie: W pracy przedstawiono sposób wykorzystania analizy wielokryterialnej jako narzędzia pomocniczego do wyboru właściwego rozwiązania technologicznego przydomowej oczyszczalni ścieków. Przy wyborze uwzględniano kryteria zgodne z zasadami zrównoważonego rozwoju. Do porównawczej analizy wielokryterialnej wybrano 5 wariantów przydomowych, mechaniczno-biologicznych oczyszczalni ścieków. Porównywano systemy z filtrem piaskowym, z osadem czynnym, ze złożem biologicznym zraszanym, system hybrydowy – osad czynny ze złożem biologicznym oraz hybrydowy system hydrofitowy typu VF-HF (z pionowym i poziomym przepływem ścieków). Analizowano rozwiązania o przepustowości 1 $m^3 \cdot d^{-1}$ (Równoważna Liczba Mieszkańców – RLM = 8), spełniające wymagania przepisów ochrony środowiska. Dodatkowo także rozwiązanie z zastosowaniem drenażu rozsączającego. Na podstawie analizy wielokryterialnej stwierdzono, że najbardziej korzystnymi rozwiązaniami technologicznymi, zgodnymi z zasadami zrównoważonego rozwoju, są systemy z filtrem piaskowym i hybrydowe systemy hydrofitowe typu VF-HF. Przy znacznej przewadze kryteriów ekonomicznych, jako najbardziej korzystne rozwiązanie wybrany został system z drenażem rozsączający, jednak biorąc pod uwagę kryterium nadrzędne (ekologiczne), aby zachować zasadę zrównoważonego rozwoju, należałoby wykluczyć możliwość stosowania tych rozwiązań na większą skalę. Stwierdzono, że najbardziej niekorzystnym jest rozwiązanie technologiczne z wykorzystaniem osadu czynnego. Wykonana analiza wykazała, że stosowanie tej technologii jest niezgodne z ideą zrównoważonego rozwoju. Jest to spowodowane brakiem odpowiedniej stabilności technologicznej i niewielką niezawodnością działania.