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MODELS OF RAPID EVALUATION AND CHOICE OF SLUDGE AND WASTEWATER TREATMENT METHOD

The methods of rapid and comparative evaluation of wastewater and sludge treatment were developed. The methods were based on the three criteria (sanitary-ecological, technological-geographical and economic), on the classification of wastewater and sludge treatment technologies (type, subtype, category) and on the mathematical models developed. The models allow a quantitative assessment of the low-waste and non-waste ordinary and multiple technologies and a rapid approximate determination of the operating costs and capital costs of each technology application. The most familiar wastewater indexes (BOD, COD and TOC) participate in the technological and economical mathematical models proposed.

1. INTRODUCTION. CRITERIA AND DEFINITIONS

An evaluation and choice of the existing, developed or new technologies of wastewater or sludge treatment are based on three criteria, on a methods' classification and on mathematical models applicable to quantitative assessment.

To satisfy a sanitary-ecological criterion, the treatment should cause minimum or optimum effect upon the environment. If technological-geographical criterion is established, the feasibility of the technology proposed in a certain geographical region with a minimum or even without any additional treatment of the wastes should be taken into account. Finally, the economic criterion requires minimum expenses in the technology application and a minimum predictable future increment in the operating costs; possible trade products' recovery from the wastes as well as low energy, transport and labour expenses, which could increase in the future, are also considered from the viewpoint of the minimum cost requirements.

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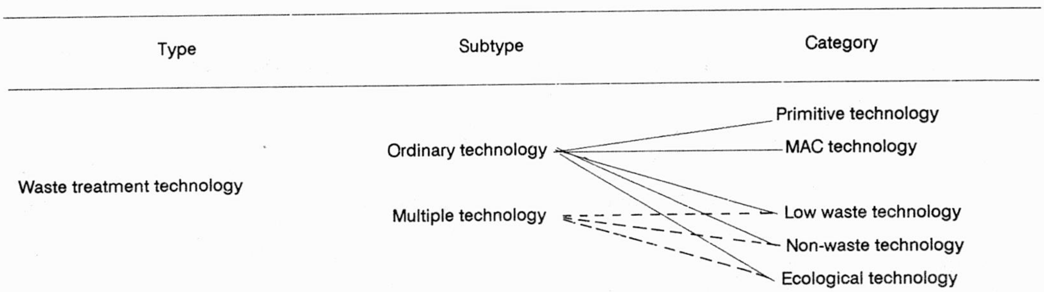
In principle, each of these three criteria should be considered in the choice of the treatment method and the technology, which proves to be the most efficient, should be preferred.

The classification of the technologies for wastewater and sludge treatment is directly associated with the sanitary-ecological criterion (table 1). The categories of the technology in table 1 as well as the definitions adopted correspond to a gradual improvement of the technology in respect of environment protection. Thus, technologies allowing discharging a waste of pollutant concentration higher than the maximum allowable concentration (MAC) are determined as "primitive technologies". "MAC technologies" are such technologies which guarantee the concentrations of effluents meeting the requirements of the MAC standards. There are two requirements concerning the low-waste technologies: 1. Total amount of wastes should be less than 10% of the total quantity of raw materials. 2. Pollutant concentration in each waste should be lower than the respective MAC standards measured in all controls. In non-waste technologies no waste should be produced or they should not pollute the surrounding environment during a predictable long period. Finally, the "ecological" technologies produce only such products (or products and wastes) which do not affect the environment.

Table 1

Sanitary and ecological classification of technologies of wastewater and sludge treatment



However, the quality of a certain technology, determinable by those definitions, is always a dynamic one, since our notions, knowledge and technical possibilities of treatment have been developing continuously. MAC standards of chemical substances, in the air, water and soil vary considerably, depending on the country. The development of our knowledge about toxicity of pollutants or the change of some requirements satisfying the demands for a given effluent receiver enacted by the authorites makes often the category of a working MAC technology lower than that characteristic of the primitive technologies. The wastes considered are solid, liquid or gaseous substances or their mixtures, which cannot be used effectively as raw materials in any production process at the contemporary technology. Therefore, the notion *waste* should be ascribed to a given material only temporarily; the use of wastes depends on the level of the technological development which is specific not only to each geographical region, but also to each country.

The difference between non-waste technologies and ecological technologies should be seen and explained. The ecological technologies correspond to our ecological strategy, which is anthropocentric, i.e. the devotees of such a strategy do not only try to preserve the environment unchanged, but they also try to cause the changes which seem to be the most favourable to us. In ecological technologies, some wastes can be even discharged, e.g. nitrates applicable to simultaneous irrigation and fertilization of tilth in some regions. On the other hand, the technologies developed for production of arms, narcotics or poisons cannot be considered ecological even if no wastes are discharged. Ecological technology is the last and the highest technology.

The subtype of technology is also important. In evaluation of the multiple technologies, the consumption wastes from the trade products are balanced by the production wastes, i.e. in the multiple technologies the consumption wastes should be recycled.

2. MODELS OF SANITARY-ECOLOGICAL ASSESSMENT

The models basing on analysis and measurements are developed for a quantitative assessment; thus, the data quoted or the data available through sanitary observations can be used in the evaluation. In the quantitative evaluation, index OB of the ordinary low-waste technologies is expressed in the following model:

$$OB = OB_1/OB_2, \tag{1}$$

$$OB_1 = \frac{On}{Ct+Bt+Mt}, \tag{2}$$

where:

- On – total amount of all wastes produced and discharged [t/y],
- Ct – amount of primary raw materials used [t/y],
- Bt – amount of recycled production wastes [t/y],
- Mt – amount of other materials used [t/y].

According to the above definition, the technology is a low-waste one if OB_1 is less than 0.1. This relative value of 10% content of wastes produced has been accepted [1] even as a criterion for the non-waste technologies, but such an acceptance cannot be backed up. If $OB_1 = 0$, i.e. $On = 0$, the technology becomes a non-waste one and OB_2 should not be calculated. The OB_2 index expresses to what extent the technology surpasses the requirements of the MAC standards.

$$OB_2 = \sum_{a=1}^{P} \sum_{k=1}^{p} v_a(\mathrm{MAC}_k - g_{a,k}) + \sum_{b=1}^{R} \sum_{e=1}^{w} 1000\ m_b(\mathrm{MAC}_e - q_{b,e}) + \sum_{c=1}^{Q} \sum_{r=1}^{z} s_c(\mathrm{MAC}_r - f_{c,r})\ [\mathrm{mg/y}] \quad (3)$$

at the obligatory conditions:

$$\mathrm{MAC}_k - g_{a,k} > 0; \quad \mathrm{MAC}_e - q_{b,e} > 0; \quad \mathrm{MAC}_r - f_{c,r} > 0,$$

where:

P – total number of gaseous waste streams,
p – total number of pollutants in the gaseous streams,
v_a – volume of a stream gaseous waste [m^3/y],
MAC_k – standard of k pollutant [mg/m^3],
R – total number of liquid waste streams,
w – total number of pollutants in the liquid streams,
m_b – volume of b stream liquid waste [m^3/y],
$q_{b,e}$ – concentration of e pollutant in b stream [mg/dm^3],
$g_{a,k}$ – concentration of k pollutant in a stream [mg/m^3],
MAC_e – standard for e pollutant [mg/dm^3],
Q – total number of solid waste streams,
z – total number of pollutants in the solid streams,
s_c – amount of c stream solid waste [t/y],
$f_{c,r}$ – concentration of r pollutant in c stream [mg/t],
MAC_r – standard for r pollutant [mg/t].

OB_2 corresponds to those quantities of pollutant which have not been discharged yearly as a result of the low-waste technology application. The same model is applicable to multiple low-waste technologies, but the quantity of the consumption wastes should be included in the *On* values. *OB* is an universal index; it decreases with the increase in the efficiency of low-waste technology. The dimension of *OB* is not interpretable.

The values of the quantitative assessment indexes *KO* and *KM* of the respective ordinary and multiple non-waste technologies are dimensionless and are calculated as parts of unity:

$$KO = Tp/(Tp + N + D), \quad (4)$$

$$KM = Tp/(Tp + N + D + U), \quad (5)$$

where:

Tp – total weight of trade products [t/y],

N – total weight of products whose composition is the same as that of some harmless natural substances, e.g. pure steam [t/y],

D – total weight of products disposed without contact with the environment [t/y],

U – total weight of consumption wastes of unchanged composition, but below the trade standard [t/y].

Obviously, the values of KO and KM increase with the improvement of non-waste technologies.

3. MODELS OF TECHNOLOGICAL AND GEOGRAPHICAL ASSESSMENT

A technological and geographical evaluation of the technologies is qualitative and specific; it depends almost entirely on the project site. Thus, e.g. in the assessment there are considered the following factors: suitable receivers for the waste stream, the disposal possibilities in region, the possibility of dilution of wastewaters with fresh or with less polluted water, etc.

The quantitative assessment of fresh-water diluting possibility can be calculated according to the equation:

$$C_w = \sum_{b=1}^{R} m_b(q_{b,e}/\mathrm{MAC}_e - 1) \ [\mathrm{m}^3/\mathrm{h}] \tag{6}$$

where C_w denotes fresh water volume required and the other symbols are the same as in eq. (3).

Index C_{wj} should be calculated using eq. (7) when less polluted water is available:

$$C_{wj} = \sum_{b=1}^{R} \frac{m_b(q_{b,e} - \mathrm{MAC}_e)}{\mathrm{MAC}_e - j_e} \ [\mathrm{m}^3/\mathrm{h}] \tag{7}$$

where:

C_{wj} — less polluted water volume required [m^3/h],

j_e -- concentration of e pollutant in the diluting water [$\mathrm{mg}/\mathrm{dm}^3$],

C_w and C_{wj} should be calculated for e pollutant of the highest concentration and the lowest MAC standard.

To choose the highest value of C_w *or* C_{wj}, several calculations should be made for several pollutants of similar concentrations and/or MAC standards.

4. MODELS OF ECONOMIC ASSESSMENT

The wastewaters and sludges, depending on their contents of organic, toxic and combustible substances, can be divided into two classes, namely: 1. Wastes for technological treatment. 2. Wastes for burning.

4.1. MODELS OF ECONOMIC ASSESSMENT OF TECHNOLOGIES

Mathematical models for economic assessment of technologies of wastewater and sludge removal should fulfil the following requirements:

1. Most of the treatment expenses cover the removal of soluble pollutants; therefore a theoretical, basic minimum cost of such a removal should be determined.

2. The amount of money spent on the wastewater treatment should be included within the production costs of the trade products.

3. The assessment should be also made basing on the well known index data such as BOD, COD and TOC.

Since the sludges can be always treated as water systems of high content of unsoluble phases (organic and inorganic substances), some expressions referring also to the sludges are specified below. Starting from the minimum quantity of energy (labour), A_{min} required for a full separation of the solvent (water) and the dissolved substances in a given solution and using the known expression of Clausius–Clapeyron, we obtain:

$$A_{min} = (WT\Delta T)/T_0^2 \quad [\text{kJ/mol}] \tag{8}$$

where:

T – temperature of the solution, usually ca. 288 K,
W – heat of the water evaporation, 40.68 kJ/mol,
T_0 – boiling point of the pure water, 373 K,
ΔT – increment in the value of solution boiling point [K],

$$\Delta T = \frac{0.516\,G}{M(1000\,d - 0.001\,G)}, \tag{9}$$

G – total concentration of soluble substances [mg/dm^3],
M – mean molecular mass of dissolved substances [daltons],
d – density of the solution [kg/dm^3].

Introducing ΔT and numerical values of T, W and T_0 into eq. (8) and transforming the dimension of A_{min} into kWh/m^3, we get:

$$A_{min} = \frac{0.66244\,G}{M(1000\,d - 0.001\,G)} \quad [\text{kWh/m}^3].$$

Since the mean costs of the electric power, heat, operation and maintenance represent about 50% of the wastewater treatment expenses [2], theoretical minimum costs (TC) of the soluble pollutant removal can be determined approximately, provided that a price is established as 0.08 \$/kWh [3], as follows:

$$TC = \frac{0.106\,G}{M(1000\,d - 0.001\,G)} \quad [\$/\text{m}^3]. \tag{11}$$

TC can be calculated basing on eq. (11) when G, M and d are known. For wastewaters of unknown composition, but of known BOD, COD or TOC, a molecular mass M_m of some "mean" compound, i.e. $C_\alpha H_\beta N_\gamma O_\delta P_\varepsilon S_\zeta Cl_\eta Br_\theta J_\kappa$, has been determined. The value of M_m(117.34 D) was calculated in such a manner that 138 organic compounds most often present in industrial wastewaters were taken into consideration. That numerical value corresponds to the following formula of "mean" compound: $C_{5.89}H_{8.36}N_{0.25}O_{1.38}P_{0.07}S_{0.035}Cl_{0.14}Br_{0.007}J_{0.03}$.

BOD of such a substance can be determined as follows:

$$\text{BOD} = [(\alpha + 0.25\beta - 0.75\gamma - 0.5\delta + 2(\varepsilon + \zeta) + 1.5(\eta + \theta + \kappa)] \; 32, \tag{12}$$

BOD = 242.512 mg/dm^3, therefore:

$$G = 0.483 \; \text{BOD} \, [\text{mg/dm}^3], \quad \text{BOD} \approx 2.07\, G \; [\text{mg/dm}^3]. \tag{13}$$

For the same "mean" compound:

$$\text{TOC} = 0.292 \; \text{BOD} \approx 0.3 \; \text{BOD} \; [\text{mg/dm}^3], \tag{14}$$

$$\text{TOC} \approx 0.13 \; \text{COD} \; [\text{mg/dm}^3], \tag{15}$$

since the mean relation (16) can be experimentally obtained:

$$\text{COD} \approx 2.25 \; \text{BOD} \; [\text{mg/dm}^3]. \tag{16}$$

Introducing BOD from eq. (13) and $M_m = 117.34$ into eq. (11), we obtain:

$$\text{TC} \approx \frac{0.00044 \; \text{BOD}}{1000\, d - 0.000 \; \text{BOD}} \quad [\$/\text{m}^3]. \tag{17}$$

Denoting the real costs of the soluble pollutant removal by *RC*, we can write:

$$RC = Y \cdot TC \; [\$/\text{m}^3] \tag{18}$$

where Y is a dimensionless coefficient of the technology effectiveness. According to relation (19), Y depends on the annual wastewater flow K:

$$Y_2 = Y_1 (K_1/K_2)^{0.5} \; [\text{m}^3/\text{y}], \; (K_2 > K_1) \tag{19}$$

where Y and K are indexed by two different annual flows. Approximate values of Y for various treatment methods applicable to wastewaters from chemical plants are given in table 2; they have been based on the recent data [4].

The approximate value of TC for wastewater containing organic pollutants calculated by eq. (17) (at, e.g. BOD = 10,000 mg/dm^3, and $d = 1.003$ kg/dm^3) is equal to 0.004 \$/m^3. Using eqs. (18) and (19) we can approximately estimate the economic effectiveness of a given technology.

Models of the maximum permissible treatment costs and capital costs have been developed. It should be stressed that those costs are always comprised in the production costs and capital costs. The maximum permissible treatment costs C are expressed by the inequality:

$$C \leqslant 0.1875 \, \frac{E \cdot Kp}{K} \, (S - Cp) \; [\$/\text{m}^3] \tag{20}$$

where:

E – number of years for the facility amortization [y],
Kp – plant production capacity [t/y],
K – wastewater flow [m^3/y],
S – trade product price [\$/t],
Cp – production costs [\$/t].

In ineq. (20), a 10 year amortization and also an 8% amortization are taken into account [3].

Table 2

Values of coefficient Y for various treatment methods (wastewater flow: 4000 m^3/day)

Treatment process	Y
Activated sludge treatment	40
Physical and chemical treatment	62
Rotating biological contactor with solid handling	84
Activated sludge treatment with solid handling	89
Adsorption on powdered activated carbon with solid handling and carbon regeneration	95
Activated sludge treatment with solid handling and two-stage nitrogen removal	100
Physical and chemical treatment and adsorption on granular activated carbon	127

For the maximum capital costs F_w of the treatment facility, ineq. (21) has been derived:

$$F_w \leqslant 0.15\ E \cdot Kp(S - Cp)\ [\$] \tag{21}$$

(see ineq. (20) for explanations). If there are n trade products of the respective production costs Cp_i [\$/t] and capacities Kp_i [t/y], the Cp value in ineqs. (20) and (21) should be substituted for a mean value Cp_{mean} calculated as follows:

$$Cp_{\text{mean}} = \sum_{i=1}^{n} Cp_i \cdot Kp_i / \sum_{i=1}^{n} Kp_i\ [\$/\text{t}]. \tag{22}$$

Capital costs $F_{w(19..)}$ to be paid in a future year 19.. can be calculated according to the formula:

$$F_{w(19..)} = F_{w(1987)}[1 + 0.105(19.. - 1987)]\ [\$] \tag{23}$$

where:

$F_{w(19..)}$ – capital costs in 19..,
$F_{w(1987)}$ – capital costs in 1987.

4.2. MODELS OF ECONOMIC ASSESSMENT OF WASTEWATER AND SLUDGE COMBUSTION

In view of economic efficiency, liquid wastes, i.e. waters and sludges, should be combusted only if they contain a sufficient amounts of combustible organic pollutants. Most often such wastes are the sludges in the petrochemical plants. Burning of other liquid wastes can be justified if they contain very toxic or inflammable substances. Theoretically, wastewaters and sludges may be burnt without additional heat supply if they have a calorific value of at least 8400 kJ/kg [5]. Therefore, the first assessment regarding the combustion economics in the case of liquid waste can be made by the model:

$$H = \frac{\sum_{b=1}^{R} m_b (9240 - Q_b)}{Q_h - 9240} \quad [\text{kg/h}] \tag{24}$$

where:

H – amount of additional fuel required [kg/h],
Q_h – calorific value of additional fuel [kJ/kg],
m_b – amount of b stream liquid waste [kg/h],
Q_b – calorific value of b stream liquid waste [kJ/kg],
R – total number of liquid waste streams,
$9240 = 8400 + 10\%$ excess [kJ/kg].

In the case of biologically degradable organic pollutants, Q_b can be calculated approximately, using the calorific values of "mean" organic substance:

$$Q_b \approx 0.00588\,\text{BOD} \approx 0.026\,\text{COD} \quad [\text{kJ/kg}]. \tag{25}$$

The mean operating cost of high temperature combustion at 1233 K of industrial wastewaters of Q_b lower than 1250 kJ/kg is given in table 3. The combustion cost (OC) can be determined approximately as follows:

$$OC = (H\, h_y\, P_h) / 547\, K \quad [\$/\text{m}^3] \tag{26}$$

where:

H – amount of the additional fuel calculable by eq. (24), [kg/h],
h_y – working hours per year [h/y],
P_h – fuel price [\$/t],
K – flow of wastewaters [m^3/y].

Furthermore, there are equations for permissible capital costs, $F_{w(1987)}$ and $F_{w(19..)}$ (data in table 3):

$$F_{w(1987)} = 4.28\, OC\, K \quad [\$], \tag{27}$$

$$F_{w(19..)} = 4.28\, OC\, K\, [1 + 0105(19.. - 1987) \quad [\$] \tag{28}$$

where definitions of the symbols correspond to those in eqs. (23) and (26).

Burning of the waste product, which proceeds with or without additional fuel, is usually connected with steam production, and the capital costs can be compensated in EM years:

$$EM = \frac{F_w(1+0.105(19..-1987)]}{A_6 - \frac{A_1+A_2+A_3+A_4+A_5}{0.97} - A_7} \text{ [y]} \tag{29}$$

where:

F_w – capital costs in 1987 [$],
A_6 – value of steam produced [$],
A_1 – fuel costs [$],
A_2 – amortization costs [$],
A_3 – labour costs [$/y],
A_4 – power costs [$/y],
A_5 – costs of water for steam production [$/y],
A_7 – costs of wastewater or sludge transport [$/y],
$A_1 - A_7$ values can be calculated according to appropriate equations.

Table 3

Mean operating cost of high temperature combustion of industrial wastewaters of calorific value lower than 1250 kJ/kg

Expenses	Percent
Fuel	54.7
Amortization	34.3
Steam	5.0
Labour	4.6
Electric power	0.8
Others	0.6
Total:	100.0

All basic models can be improved and adapted to each specific case. The programmes developed allow an easy and convenient application of the models as well as the choice of an optimum technological alternative to solving each problem of liquid waste.

The models programmed have been fruitfully used for comparing and selecting the alternatives of wastewater and sludge treatment methods.

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METODY SZYBKIEJ OCENY I WYBORU TECHNOLOGII PRZERÓBKI OSADÓW I OCZYSZCZANIA ŚCIEKÓW

Opracowano metody szybkiej oceny porównawczej technologii przeróbki osadów i oczyszczania ścieków. Przedstawione metody oparto na kryteriach sanitarno-ekologicznych, technologiczno-geograficznych i ekonomicznych, klasyfikacji (typ, podtyp, kategoria) technologii oczyszczania oraz na opracowanych modelach matematycznych. Modele umożliwiają ilościową ocenę niskoodpadowych i bezodpadowych jedno- i wielostopniowych technologii oraz przybliżone oszacowanie eksploatacyjnych i całkowitych kosztów zastosowania każdej technologii. W zaproponowanych technologiczno-ekonomicznych modelach matematycznych wykorzystano powszechnie stosowane wskaźniki zanieczyszczeń (BZT, ChZT, OWO).

МЕТОДЫ БЫСТРОЙ ОЦЕНКИ И ВЫБОРА ТЕХНОЛОГИИ ПЕРЕРАБОТКИ ОТЛОЖЕНИЙ И ОЧИСТКИ СТОЧНЫХ ВОД

Разработаны методы быстрой сравнительной оценки технологии переработки отложений и очистки сточных вод. Представленные методы базируют на санитарно-экологических, технолого-географических и экономических критериях, проведенной классификации (тип, подтип, категория) технологии очистки, а также на разработанных математических моделях. Модели способствуют количественной оценке низкоотбросных и безотбросных одно- и многостепенных технологий, а также приблизительной оценке эксплуатационных и полных затрат применения каждой технологии. В предложенных технолого-экономических математических моделях применены общеприменяемые показатели загрязнений (BZT, ChZT, OWO).