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Mathematical Modelling and Parameter Estimation for the Design of Constructed Wetlands

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Original scientific paper

Efficiency of waste water treatment in a subsurface constructed wetland depends on influent water quality, quality water effluent demand, climate conditions, substrate type and plants used. Therefore, the efficiency of the constructed wetlands that are designed and constructed according to the literature design parameters can be different then expected.
The results of waste water treatment using a subsurface constructed wetland that is designed according to the literature data are presented. Experimental results and a mathematical model are described, and parameter estimation was conducted in order to determinate the reaction rate constant necessary for design of the constructed subsurface wetland that could be implemented in the continental area of Croatia. Achieved results indicate that a decrease of the constructed wetland area from 10 to 30% is possible.

Keywords
BOD_5
COD
Design
Parameter assessment method
Subsurface constructed wetland

Ključne riječi
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Dimenzioniranje
KPK
Metoda procjene parametara
Podpovršinski biljni uređaj

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Matematičko modeliranje i procjena parametara za dimenzioniranje biljnih uređaja

Izvornoznanstveni članak

Učinkovitost podpovršinskog biljnog uređaja za obradu otpadne vode ovisi o kvaliteti ulazne vode, zahtjevu za kvalitetom izlaznog efluenta, klimatskim uvjetima, vrsti substrata i biljkama koje se koriste. Stoga se učinkovitost podpovršinskih biljnih uređaja koji su projektirani i izvedeni prema literaturnim parametrima projektiranja može razlikovati od očekivane.
U ovom radu prikazani su rezultati rada podpovršinskog pilot biljnog uređaja na području kontinentalne Hrvatske, projektiranog i izgrađenog temeljem literaturnih podataka. Opisana je provedena analiza eksperimentalnih rezultata, matematički model i postupak procjene parametara kako bi se utvrdila konstanta brzine reakcije s ciljem preciznijeg projektiranja. Rezultati provedene analize ukazuju na mogućnost smanjenja površine od 10 - 30 % uređaja za vodu sličnih karakteristika, u klimatskim uvjetima koji odgovaraju području kontinentalne Hrvatske.

1. Introduction

Increased concern for environmental protection has forced the industry to find more effective and cheaper technology for waste water treatment systems. The present requirements for the treatment of waste water include low product costs, reliability and efficiency changing the device's conditions, (flow and composition of input water) and the ability to re-use waste water in industry or watering. As interesting and acceptable solution for these requirements are eco systems – constructed wetlands [1].

Natural microbial processes of decomposition of organic matter that occur in the sludge systems are the basis of the development and application of constructed wetland for the treatment of waste water [2].

The use of constructed wetlands is constantly increasing, finding new applications for them and developing the new technological possibilities that are modified considering the geographical and climatic specifics. But still there isn't any accord on the optimal design and operation of these systems [3].

Constructed wetlands can be classified into two basic types: surface constructed wetland (Free Water

Symbols/Oznake

A	- area, m^2 - površina	L	- length, m - duljina
BOD_5	- biochemical oxygen demand in 5 days, mg/L - biološka potrošnja kisika u 5 dana	$n_{i,j}$	- quantity of substance *i* within observed segment *j,* mol - množina tvari *i* unutar promatranog segmenta *j*
$c_{i,j}$	- input concentration, mg/L - koncentracija tvari na ulazu	q	- volume flow, m^3/s - protok
$c_{i,j,I}$	- output concentration, mg/L - koncentracija tvari na izlazu	q_V	- volume flow thru device, m^3/s - volumni protok kroz uređaj
H	- depth, m - dubina	V	- volume of the observed segment, m^3 - volumen promatranog segmenta
$\dot{n}_{i,j,U}$	- molar flux of substance *i* at *j*-th segment exit, mol/s - molarni tok tvari i na izlazu iz segmenta	V	- volume, m^3 - volumen
$\dot{n}_{i,j,I}$	- molar flux of substance *i* at *j*-th segment entrance, mol/s - molarni tok tvari *i* na ulazu u segment	V_r	- real volume, m^3 - realni volumen
$\dot{n}_{i,j,R}$	- molar flux of substance *i* that originate from chemical reaction in segment *j,* mol/s - tok tvari koja nestaje kemijskom reakcijom	W	- width, m - širina
j	- observed segment - promatrani segment	ε	- porosity, - poroznost
COD	- chemical oxygen demand, mg/L - kemijska potrošnja kisika	τ	- retention time, d - vrijeme zadržavanja
k_V	- reaction rate constant, 1/s - konstanta brzine reakcije		

Surface) and subsurface constructed wetland (Subsurface Flow System). Device, in which the surface of flowing water is exposed to the atmosphere, is known as surface constructed wetland. In subsurface constructed wetland, the water flows through gravel media, without direct contact with the atmosphere.

The process of decomposition mostly conducts in the biofilm on the border layer of liquid- granulate, in which the efficacy of these devices increase because of high active surface area [4, 5]. The main part of a constructed wetland consists of plants whose root penetrates through the granulated medium. Active zone reaction in plant devices is the root zone (rhizosphere) where they are conducted physical-chemical and biological processes that are stimulated with the interaction of plants, microorganisms, soil and waste materials [6]. Transport of oxygen throughout root system anticipates the growth and activity of micro organisms in the current zone.

In subsurface constructed wetland, oxygen is supplied using plants that can adapt to the anoxic conditions of the rhizosphere and may survive because of their ability to supplying their root systems with oxygen from the atmosphere which are microorganisms using in the biological processes of decomposition [7].

An efficient constructed wetland must include an adequate pre-treatment and provide large amounts of oxygen. Another important parameter for the effective operation of the devices is its area.

Experience and measurements showed that the plant devices can reduce the content of BOD_5 of 65 - 97 %, total nitrogen 22,6 – 48,5 %, total phosphorus 26 – – 60,6 % and faecal coliforms up to 99 %, and it is known that the efficiency is the function of removing of input concentration and the flow rate of waste water [8-10].

For the practical application of these devices is important that concentration of waste matter in the output is bellow legally prescribed limits. Designing devices that will allow the removal of waste matter in a sufficiently is complex task because of uncertainties that are associated with living organisms and their dependency on climate, meteorological and other conditions. The correct approach to designing constructed wetland includes evaluation of the work of the pilot constructed wetland, which then serve as the basis for the detailed design of real systems.

The process of biological decomposition of waste matter, which takes place in constructed wetland, is extremely complex and it is impossible to describe it mathematically. In fact, the basic parts of process space make overground parts of plants, roots, ruin parts of surface plants and roots, biofilms, soil, water and dissolved substances. The process of decomposition of organic substances is mostly conducted within the biofilm, which is created on the border layer of water-granulate and root-water [11]. It is very demanding to define the type and number of present microorganisms, and kinetic parameters of bioreaction that are ongoing in the process space. System's sensitivity to weather conditions, precipitation primarily, air temperature and solar radiation contribute to its complexity [12, 13].

The purpose of this work was to determinate the real value of reaction rate constant of decomposition (k_v) for BOD_5 using the method for evaluation parameters of supposed model, considering that the reaction rate constant of decomposition (k_v) is one of the crucial project parameters for sizing subsurface constructed wetland. During the implementation of the experiment COD values were measured, so using the same method reaction rate constant for COD was determined.

2. Materials and methods

2.1. Mathematical model for parameters estimation

Observed process is a process with distributed parameters, where the concentration of substances changes with the point in flow direction and with the depth of process space. Practice has shown that the model of a process can significantly simplify the process by replacing it with a set of serially connected fed batch reactors with the ideal stirring (Figure 1), or by dividing the process space into a series of imaginary segments in which is assumed that the processes is with lumped parameters [14].

Dynamic balance equations are set for each segment (1) and describing the variation of concentration of substances over time, whereby the output values in each segment (concentrations of substances) are input values in the process which takes place in the next (downstream) segment. Microbiological degradation can be approximated with the first order chemical reaction, which further simplifies making a model of the process. Concentration distribution through the length of the device can be obtained, which is really important, but only for assessing the effectiveness of the device.

$$\frac{dn_{\mathrm{i,j}}}{dt} = \dot{n}_{\mathrm{i,j,U}} - \dot{n}_{\mathrm{i,j,I}} - \dot{n}_{\mathrm{i,j,R}} \,. \qquad (1)$$

Balance equation can be set for each substance (chemical compound), which is dissolved or suspended in waste water or for biological and chemical oxygen demand and total content of a particular element or molecule (such as for the total carbon or dissolved nitrate). If we assume that the process of decomposition of organic matter is first order reaction, the equation (1) is:

$$V\frac{dc_{\mathrm{i,j}}}{dt} = q_V \cdot c_{\mathrm{i,j,V}} - q_{\mathrm{V}} \cdot c_{\mathrm{i,j,I}} - V \cdot k_{\mathrm{V}} \cdot c_{\mathrm{i,j}} \,. \qquad (2)$$

Further simplification comes from the assumption of lumped parameters in the observed segment, so the concentration on the exit from the segment is equal to the concentration within the segment $c_{i,j} = c_{i,j,I}$, and with readjustment of equation (2):

$$\frac{V}{q_{\mathrm{V}} + V \cdot k_{\mathrm{V}}} \cdot \frac{dc_{\mathrm{i,j}}}{dt} + c_{\mathrm{i,j}} = \frac{q_{\mathrm{V}}}{q_{\mathrm{V}} + V \cdot k_{\mathrm{V}}} \cdot c_{\mathrm{i,j,U}} \,. \qquad (3)$$

Equation (3) represents the mathematical description of the first order process, where $V/(q_V+V*k_V)$ is time constant, and $q_V/(q_V+V*k_V i)$ static sensitivity. Equaling the expression that describes the variation of concentration over time gives a static model of the process:

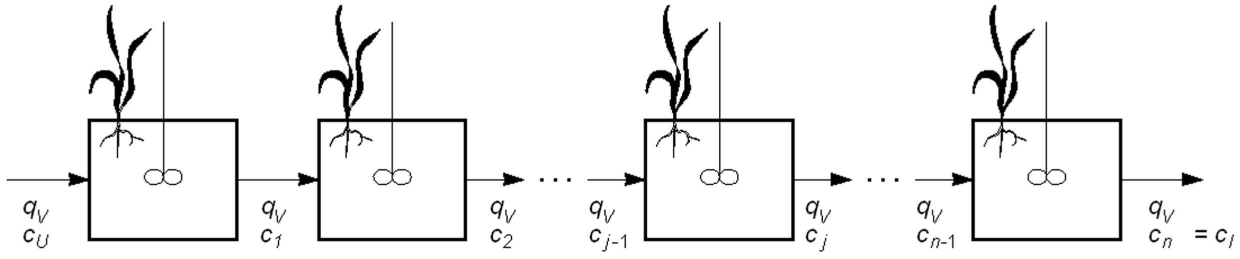


Figure 1. Set of serially connected fed batch reactors with the ideal stirring

Slika 1. Serijski povezani protočni kotlasti reaktori s idealnim miješanjem

$$c_{\mathrm{i,j}} = \frac{q_{\mathrm{V}}}{q_{\mathrm{V}} + V \cdot k_{\mathrm{V}}} \cdot c_{\mathrm{i,j,U}} \,. \quad (4)$$

2.2. Constructed wetland device

The constructed wetland device for waste water treatment which is designed according to the literature data of reaction rate constant (k_v), average value of BOD_5 (118.83 mg O_2/L) for waste water from main drainage canal (GOK) city of Zagreb (Table 1.). The request for outgoing BOD_5 value is 25 mg O_2/L, which corresponds to the permitted value of concentration for the released waste water in a natural aquifer II category [15].

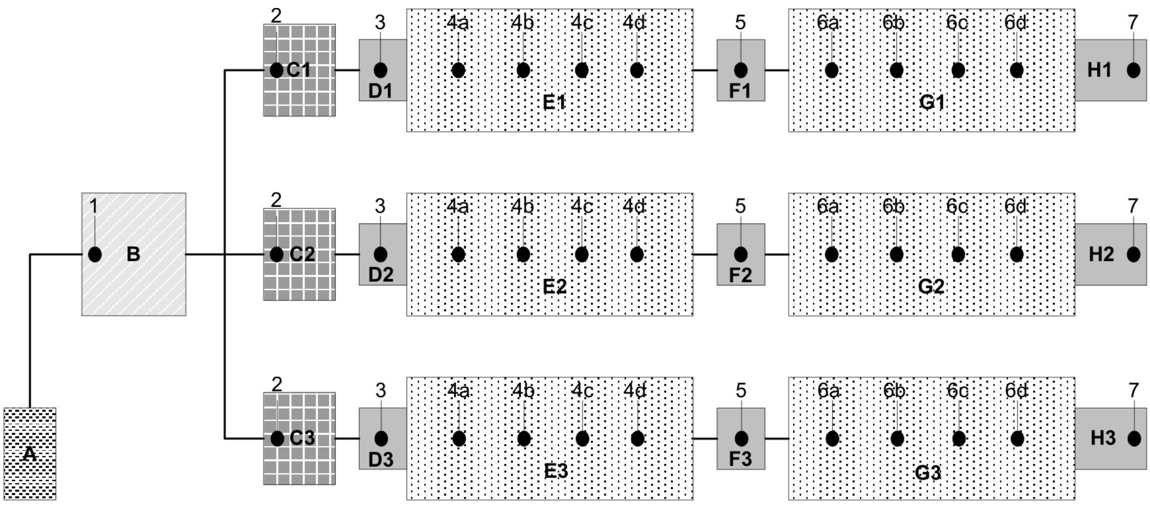
Each single line is designed for flow of 1,0 m^3/s. The constructed wetland device is designed according to the equation (4) and length and width ratio of the pool.

Table 1. Design parameters for the constructed wetland device

Tablica 1. Projektni parametri za biljni pilot uređaj

Input parameters/ Ulazni parametri	**Value/Vrijednost**	**Designed parameters/ Projektirani parametri**	**Value/Vrijednost**
C_u – input value of BOD_5	118,83 mg/L	number of pools	2
C_i – output value BOD_5	25 mg/L	L – length (one pool)	5 m
Q - flow	1 m^3/s	W – width (one pool)	2 m
ε- porosity	0,35	V_r – real volume	3,5 m^3
the length (L) and width ratio (W)	5:1	A – surface of the device	20 m^2
k_v - reaction rate constant	0,5 d^{-1}	τ – residence time	3,5 ds
h – plant depth	0,5 m		

The scheme of subsurface constructed wetland device is shown in Figure 2.



A - pump / pumpa
B - primary sedimentation basin /primarni taložnik
C - trickling filter / prokapnik
D - retention reservoar / prihvatni spremnik
E - subsurface constructed wetland 1/ podpovršinski biljni uređaj 1
F - retention reservoar / prihvatni spremnik
G - subsurface constructed wetland 1/ podpovršinski biljni uređaj 1
H - reservoar for treated wastewater / spremnik za obrađenu vodu
1 - control subsurface constructed wetland / kontrolni podpovršinski biljni uređaj
2 - subsurface constructed wetland / podpovršinski biljni uređaj
3 - subsurface constructed wetland / podpovršinski biljni uređaj

Figure 2. The scheme of the subsurface constructed wetland device

Slika 2. Shema podpovršinskog pilot biljnog uređaja

The constructed wetland is designed with subsurface flow and it consists of 3 parallel lines with common primary settlement tank (B). Each line consists of a trickling filter (C) filed with gravel granulation φ=1,6 and two separated pools (E and G). Effluent flows from the primary settlement tank (B) through the gravity aerator into the perforated pipe situated at the entrance to the first pool, which provides uniform distribution of the flow of waste water per width device. Water from the first pool (E) goes to the retention reservoir (F), and then to the second pool (G), and finally in the tank for the treated water (H).

Each pool is 5 meters long, 2 meters width and 0,5 meters deep with heeling of 1 %. Effective used area is about 20 m^2 per line. Each pool is covered with PVC foil and then loaded with gravel granulation φ=1.6 - 3.2 cm, and lateral sites are constructed under the angle of 45 °. Exits and entrances to the pool are filled with gravel granulation φ =3,2 - 6,4 cm to prevent plugging. Line 1 was planted with sedge (*Typhim latifolia*) and wood club rush (*Scirpus sylvaticus*) in both pools, line 2 is planted in the first pool with sedge (*Carex sp.*) and in the second pool common reed (*Phragmites australis*) with the 5 plants per m^2. Mentioned species are taken from the natural location in the nearby of the constructed wetland. Line 3 is not planted.

2.3. Measurements

During the research the following parameters are measured: pH, temperature, flow, BOD_5 and COD at the entrance to the primary settlement tank (B), retention reservoir (D) and (F) and the exit from plant devices (H).

For examination of the efficiency of the constructed wetland device measurements were carried out in the field of flow from 0,5 to 2,8 m^3/s. The study lasted 3 years continuously, and samples were taken every 2 weeks.

There are two key parameters which indicate the quality and the degree of pollution of wastewater: biochemical oxygen demand (BOD) and chemical oxygen demand (COD).

BOD_5 [mg/L] is measure of oxygen consumption by micro organisms for oxidation of organic substances. In implementing these experiments BOD_5 is determinate with incubation of diluted sample of water at 20 °C during the 5 days. Concentration of dissolved oxygen was measured with oxymeter WTW Oxi 330i. The value of the COD is determinate by Reactor Digestion method on the device HACH 8000

3. Results

3.1. The results of measurements

Figure 3 and Figure 4 are showing the value of BOD_5 and COD for a set of measurement data in the line 1 at the flow of waste water of 1 m^3/d. Figure 5 and 6 are showing the value of BOD_5 and COD for a set of measurement data for all three lines, at the flow of waste water of 1 m^3/d

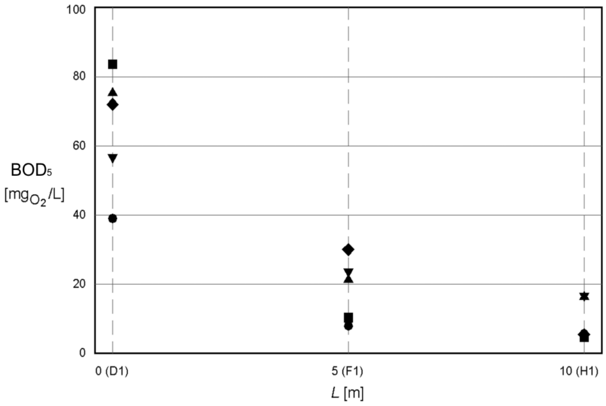


Figure 3. Measured values BOD_5 in line 1 at the flow rate of waste water 1 m^3/s.

Slika 3. Izmjerene vrijednosti BPK_5 u liniji 1 pri protoku otpadne vode od 1 m^3/ s.

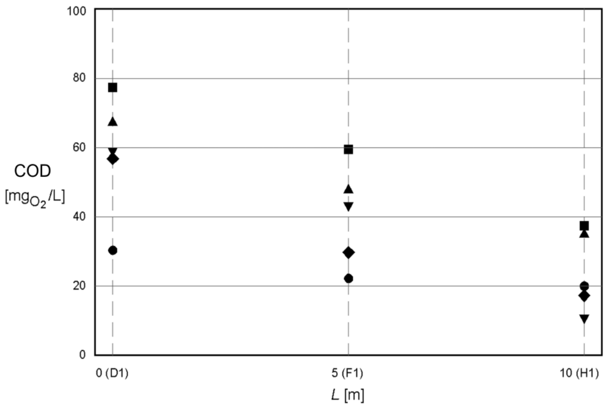


Figure 4. Measured values COD in the line 1 at the flow rate of waste water 1 m^3/s.

Slika 4. Izmjerene vrijednosti KPK u liniji 1 pri protoku otpadne vode od 1 m^3/s.

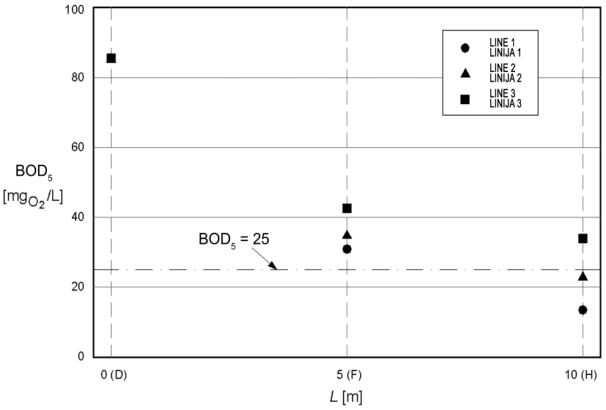


Figure 5. Average BOD_5 measured values of on measuring spots D, F and H in the line 1, 2 and 3 at the flow rate of waste water 1 m^3/s

Slika 5. Srednje izmjerene vrijednosti BPK_5 na mjernim mjestima D, F i H u liniji 1, 2 i 3 pri protoku 1 m^3/s.

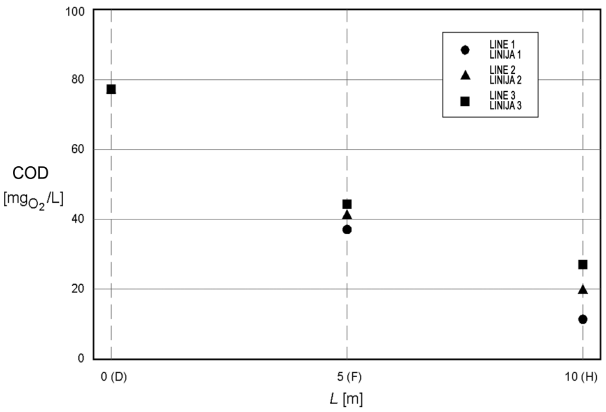


Figure 6. Average COD measured values on measuring spots D, F and H in the line 1, 2 and 3 at the flow rate of waste water 1 m^3/s

Slika 6. Srednje izmjerene vrijednosti KPK na mjernim mjestima D, F i H u liniji 1, 2 i 3 pri protoku 1 m^3/s.

3.2. The results of estimated parameters

The task of designing a pilot constructed wetland for waste water treatment is to find dimensions of the devices that will provide necessary time to keep the waste water that ensures that concentration of waste substances is under the values prescribed by law. Along with the flow rate of waste water and the depth of the device, the task is to define the width and length for devices.

Statistic model of the process is used as basis estimation (4), where the precise design must know the right reaction rate constant k_v. On the basis of equation (4) and a set of experimental data parameter k_v was evaluated, minimising square deviation of experimental data and data obtained from the model of the process. Measurement of the distance $J_j(k_v)$ response of model output and measurements for a particular set of measurement data (for a particular flow), or output of the actual system in terms of square deviation is defined for the system in the following manner:

$$J_{\mathrm{j}}(k_{\mathrm{v}}) = \sum_{i=1}^{3} (c_{\mathrm{exp}} - c_{\mathrm{mod}})^2, \tag{5}$$

where the concentration deviations values are recapitulated at the beginning (i=1), middle (i=2) and end (i=3) of devices, i.e., the positions where are taken the samples for measurement.

Minimising the parameter $J_j(k_v)$ is given reaction rate constant for a particular flow rate for which the discrepancy model and the actual process at least. The procedure can be expanded by taking the full set of measurement data into account:

$$J_{\mathrm{j}}(k_{\mathrm{v}}) = \sum_{i=1}^{3} (c_{\mathrm{exp}} - c_{\mathrm{mod}})^2, \tag{6}$$

where *n* is the dimension of the set of measurement data. Dependence of the $J(k_v)$ parameter on the reaction rate constant k_v, obtained on equation (6) is displayed on the Figure 7.

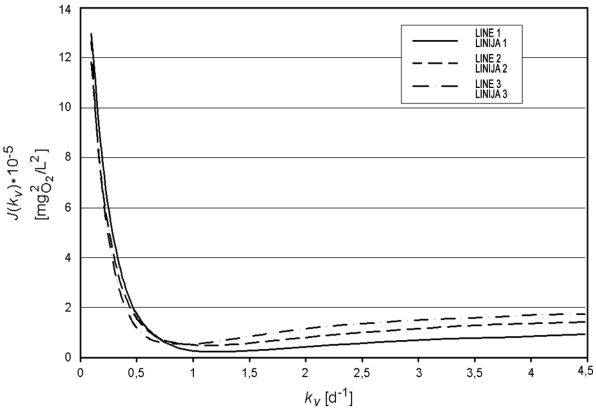


Figure 7. Dependence $J(k_v)$ parameter on the reaction rate constant k_v, for the measured parameter BOD $_5$

Slika 7. Zavisnost parametra $J(k_v)$ o konstanti brzine reakcije k_v, za mjereni parametar BPK_5

Esimated minimums of the curve in Figure 7 are:

Line 1: k_v (BOD_5) = 0,884 d^{-1}

Line 2: k_v (BOD_5) = 0,788 d^{-1}

Line 3: k_v (BOD_5) = 0,631 d^{-1}

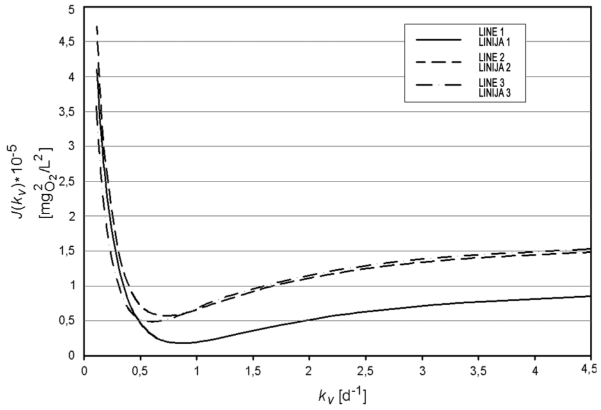


Figure 8. Dependence parameter $J(k_v)$ on the reaction rate constants k_v, for the measured parameter COD.

Slika 8. Zavisnost parametra $J(k_v)$ o konstanti brzine reakcije k_v, za mjereni parametar KPK.

Estimated minimums of the curve in Figure 8 are:

Line 1: k_v (COD) = 0,613 d^{-1}

Line 2: k_v (COD) = 0,509 d^{-1}

Line 3: k_v (COD) = 0,425 d^{-1}

4. Discussion

The results of measurements which are used during system analysis and parameter estimation are collected at the pilot constructed wetland in Ivanja Reka where input waste water is taken from the GOK. Inlet concentrations of waste water, or the value of COD and BOD_5 change in the course of time (from 40 to 90 mg O_2/L for BOD_5, from 45 to 165 mg/L for COD), and for the estimation is taken a small set of measurement data, when the input values of COD and BOD_5 were approximately constant. However, a constant value of these sizes does not guarantee constant concentration of different chemical compounds in waste water. Storage of larger amounts of waste water also does not guarantee the achievement of a fixed concentration of waste matter in the course of entrance because of their chemical and microbiological disintegration over time. For accurate analysis of the function of the system should be used water with the well known and time independent entrance concentrations of waste substances should be used.

The results of measurements and their analysis suggests that in all three lines of the pilot constructed wetland, which is designed according to the literature data, reached the calculated output value of BOD_5. During the passageway analyzed waste water through the constructed wetland in all three lines the effectiveness of removing BOD_5 ranged from 57 % (Line 2) to 97 % (line 1 %) and in all lines was realized the default criteria for outgoing BOD_5 values, which confirms the possibility of using literature data in the design of plant device. The efficiency of removing the COD in the researched period ranged for line 1 from 78,5 to 98,9 %, for line 2 from 74,0 to 98,7 %, and for line 3 of from 41,5 to 95,1 %.

The static mathematical model used to estimate parameters constants apparent chemical reactions significantly simplifies consideration of complex biochemical process that takes place in the constructed wetland device. According to the model line, the concentration of a particular segment, except on the concentration at the entrance, depends on the flow, and a constant rate of reaction and volume. How it is a "live" device, over time, porosity of the pool is reduced because of growth of root of the plants. Virtual balance, however, is realized after a while, where the growth rate root plant is equal to the ruin rate and rot rate of old roots. According to the literature data for porosity value, which amounted 0,35, is used for the budget. The values of constants apparent chemical reaction were in directly inversely proportion related with porosity by equation (4), and for their determination would determine the true value of porosity, but still represent a good basis for projecting future real plant device, provided they are built in the same way as the constructed wetland device.

Line 1, planted in each pool with plants from the nearby, rush (*Typhim latifolia*) and wood club rush (*Scirpus sylvaticus*) showed the best results in reducing the BOD_5 value. The results show that the activity of microorganisms in the area of the root systems of that line is greater than in the other two. Line 3 also shows a certain activity, or the existence of biological decomposition without the presence of plants, with efficiency less than 30% compared to the line 1 and 20 % compared to the line 2. It is believed that the reduced efficiency is a consequence of the lack of root system within the line, the relative reduction of active surface microbial biofilms and a lack of oxygen through the root of plants. Line 2 has 10% less efficacy than line 1.

Value results for the reaction rate constant of BOD_5 from the estimated parameters for all three test lines were significantly higher compared to literature data used in designing a constructed wetland device (Line 1: k_v = 0,884 d^{-1}, line 2: k_v = 0,788 d^{-1}, Line 3: k_v = 0,631 d^{-1}).

Based on the results of the budget criteria and sizing devices (the average BOD_5 concentration in the input and allowed concentration of BOD_5 in output), the required dimensions of the device (for two pools) amounted to: 5,7 m x 2 m (Line 1), 6,4 m x 2 m (Line 2) and 8,1 m x 2 m (Line 3), which is less than the dimensions obtained on the basis of use literature value for the constant rate of decomposition for reactions BOD_5 (10 m x 2 m).

5. Conclusion

A mathematical model of the process was developed in the constructed wetland for treating waste water, where the process is displayed with distributed parameters as a set of serially connected processes with the lumped parameters. The dimensions of the constructed wetland were calculated on the basis of literature data on the reaction rate of BOD_5 from the static model of the process. Based on the experimental results the assessment of parameters was obtained - reaction rate of BOD_5 amounts 0,884 d^{-1} for line 1, 0,788 d^{-1} for line 2 and 0,631 d^{-1} for line 3, and for the COD reaction rate amounts 0, 613 d^{-1} for line 1, 0,509 d^{-1} for line 2 and 0,425 the d^{-1} for the line 3. The results of research indicate that during the designing the device intended for processing waste water approximately the same properties, with the selected plant species can decrease the surface area of 43 % for line 1, 36 % for line 2 and 19 % for the line 3.

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