Journal of Urban and Environmental Engineering, v.17, n.1, p.51-57

ISSN 1982-3932
doi: 10.4090/juee.2023.v17n1.051057

Journal of Urban and Environmental Engineering

www.journal-uee.org

COMPUTER MODELING AND FORECASTING OF CLOGGING DYNAMICS IN THE BIO-PLATEAU FILTER BASED ON A FILTER PROFILE LAYOUT

Natalya Ivanchuk[1*], Petro Martyniuk[1*], Viktor Filipchuk[2*], Olga Michuta[1*], Sergiy Kunytskyi[3*], Sergiy Shatnyi[4*]

[1]Department of Computer Sciences and Applied Mathematics, National University of Water and Environmental Engineering, Ukraine

[2]Department of Labor Protection and Life Safety, National University of Water and Environmental Engineering, Ukraine

[3]Research and Development Department, National University of Water and Environmental Engineering, Ukraine

[4]Department of Computer Engineering, National University of Water and Environmental Engineering, Ukraine

Received 7 November 2022; received in revised form 16 February 2023; accepted 18 March 2023

Abstract: A mathematical model of the clogging of the porous backfill of the bio-plateau filter in the process of water purification was developed based on the profile filtration scheme, which takes into account the removal of part of the water from the bulk of the bio-plateau filter backfill. According to the assumption, the proposed technical improvement would help the stability of the bio-plateau filter during a longer period of operation. The assumption was validated by a numerical experiment. The authors took into account the degree of the clogging of the pore space of filter backfill and bottom drainage with mineralized sediment and the accumulation of silt in the bottom part of the bio-plateau filter. These processes reduce the supply of oxygen to the root system of plants which can lead to a decrease in the efficiency of the structures, peptization of sediment, and secondary water pollution. The numerical solution of the developed mathematical model in the form of a nonlinear boundary value problem was found using the finite element method. Based on the developed algorithms, a software package was created for forecasting by means of numerical experiments in the FreeFem++ freeware. Numerical experiments and their analysis were performed. Specifically, it was shown that with the presence of a system of perforated pipes for partial drainage of water from the middle part of the bio-plateau, the maximum relative difference in filtration rates reaches 5% after a year (while without such an additional pipe system, this difference is 25% in half a year). Proposing an internal system of perforated pipes, the predicted productivity of the bio-plateau should be increased. This allows us to assert that the adequacy of the improved mathematical model to the investigated physical processes is increased and thereby to reduce the negative impact of clogging on the filtration processes in the bio-plateau filter system.

Keywords: Bio-plateau filter. Clogging. Filtration. Finite element method. Water purification. FreeFem++.

INTRODUCTION

There is no doubt about the relevance of research and forecasting of water purification processes. One of the Sustainable Development Goals adopted by the United Nations is Clean Water and Sanitation. Currently, various methods and technologies of water treatment are developed, corresponding mathematical and computer models were built, both numerical and field experiments are performed, efficiency proposed solutions is tested (Liu *et al*., 2020; Martynov *et al*., 2018; Fylypchuk *et al*., 2017; Hassan *et al*., 2021; Orlov *et al*., 2016; Martynov *et al*., 2017; Bomba *et al*., 2018; Bomba & Safonyk, 2018). One of the water purification methods is the use of bio-plateau filters (Moshynskyi *et al*., 2018; Ji *et al*., 2022; Aguado *et al*., 2022; Gorgoglione & Torretta, 2018). This technology is characterized by low energy consumption and simplicity of operation.

Bio-plateau filters as facilities for wastewater treatment, both domestic and industrial and polluted surface runoff, have gained popularity in various countries in recent years (Bondar *et al*., 2017; Ilyas *et al*., 2021; Monsalves *et al*., 2022). The advantage of bio-plateaus is that they require virually no consumption of electricity and chemical reagents or significant operation maintenance and provide the necessary quality of water purification from a wide range of organic and mineral pollutants. Among the methods of research and forecasting of water purification processes in bio-plateau filters, machine learning methods (Yang *et al*., 2023; Nguyen *et al*., 2021) are being developed along with mathematical and computer modeling (Aguado *et al*., 2022; Yuan *et al*., 2020; Soares *et al*., 2022; Ramos *et al*., 2022; Bomba *et al*., 2018; Bomba & Safonyk, 2018). Bio-plateau filters which are used to purify water from organic pollution can also to be considered as repositories of organic carbon (humus) (Stepanchenko *et al*., 2021; Stepanchenko *et al*., 2023).

The known bio-plateau designs suffer from gradual clogging of the pore space of the filter backfill and lower drainage with mineralized sediment and accumulation of silt in the bottom part of the structures (Moshynskyi *et al*., 2018; Wang *et al*., 2021; Fang *et al*., 2022). These processes reduce the supply of oxygen to the root system of plants which can lead to a decrease in the efficiency of the structures, peptization of sediment, and secondary water pollution.

Restoration of the bio-plateau operation requires periodical maintenance related to washing and regeneration of filter backfill and drainage. To ensure the stability of the bio-plateau operation, continuous removal of part of the water from the layer of the filter backfill was proposed, followed by its cleaning and return to the entrance of the bio-plateau (Bondar *et al*., 2017). From the viewpoint of the physics of the above phenomenon, the process of migration of undissolved particles in porous media is investigated.

Some of the aforementioned reports propose mathematical models of filtration clogging processes.

The main attention is paid to the processes of nanoparticle transfer and the clogging kinetics. However, the clogging process is accompanied by dynamic change in the porosity of the medium, which in turn affects the filtration coefficient and, indirectly, the entire filtration process. These effects were considered, and the corresponding filtration equation was modified in (Moshynskyi *et al*., 2018). Using mathematical and computer modeling methods, the authors investigated the longitudinal profile section of a bio-plateau with perforated pipes on top for supplying contaminated water and perforated pipes on the bottom for removing purified water. However, no studies on a presence of a system of perforated pipes for partial drainage from the middle part of a bio-plateau were reported. Numerical predictive calculations for the proposed technical improvement is the objective of this work.

The following tasks were set to achieve this goal: (a) to develop a mathematical model of filtration taking into account clogging in the presence of a system of perforated pipes for partial removal of water from the middle part of the bio-plateau; (b) to find numerical finite element solutions of the corresponding nonlinear boundary value problem for the system of differential equations; and (c) to perform a series of numerical experiments and their analysis.

Statement of the problem and its mathematical model

Considering the filtration region similarly to (Moshynskyi *et al*., 2018), we encounter a number of computational difficulties due to the large proportion between the height and length of the region. Therefore, it is more convenient to consider the profile cross-section of a bio-plateau with a perforated pipe for partial drainage of water inside the region (border Γ_3 in **Fig. 1**). Borders Γ_6 and Γ_5 are symmetry boundaries passing in the middle between the perforated pipes (Γ_3 and Γ'_3 in **Fig. 1**).

According to (Moshynskyi *et al*., 2018), using approaches to modeling interrelated processes in (Herus *et al*., 2018), the mathematical model of filtration involving clogging contains the following equations:

$$\nabla \cdot (\rho_p(c)k_h(c,\sigma)\nabla h) = \sigma \frac{\partial \rho_p}{\partial c} \cdot \frac{\partial c}{\partial t} - \frac{\rho_p}{\rho_s}\frac{\partial s}{\partial t}, X \in \Omega, \quad (1)$$

$$\sigma\left(1-\frac{c}{\rho_p}\frac{\partial \rho_p}{\partial c}\right)\frac{\partial c}{\partial t} = \nabla \cdot (D_c \nabla c) - u\left(1-\frac{c}{\rho_p}\frac{\partial \rho_p}{\partial c}\right)\nabla c - \frac{\partial s}{\partial t}, X \in \Omega, \quad (2)$$

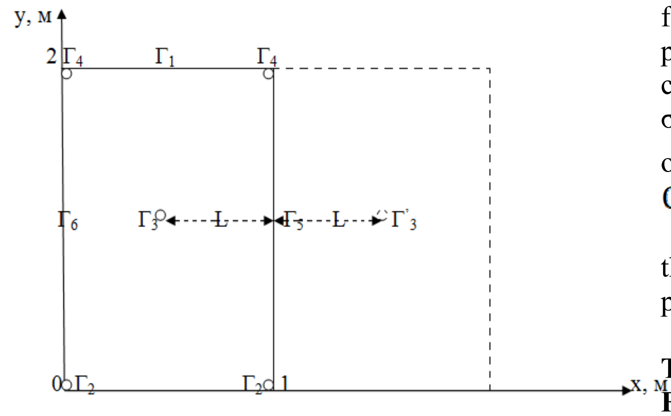

Fig. 1 Problem solution región.

$$\frac{\partial s}{\partial t} = \alpha \cdot c - \beta \cdot s, X \in \Omega, \quad (3)$$

$$u = -k_h(c, s, \sigma)\nabla h, X \in \Omega. \quad (4)$$

Let us supplement the bio-plateau filter system with an additional system of perforated pipes in the form of a medium drain (Γ_3 and Γ'_3 in **Fig. 1**) which is placed inside the filter backfill. The conditions for the partial removal of water are set on the additional system, but with lower consumption than the bottom drainage.

Eqs. (1)–(4) must be supplemented with the initial

$c(x, y, 0) = C_0(X)$, $X \in \overline{\Omega}$,

$s(x, y, 0) = 0$, $X \in \overline{\Omega}$,

and boundary conditions

$h(X, t)\big|_{X \in \Gamma_1, \Gamma_4} = y$,

$c(X,t)\big|_{X \in \Gamma_1, \Gamma_4} = C_\Gamma(X, t), X \in \Gamma_1, \Gamma_4, t \geq 0$.

Γ_5, Γ_6 are symmetry boundaries.

Fluid flow is specified at the boundaries Γ_2 and Γ_3 which may depend on time t:

$q\big|_{X \in \Gamma_2} = Q(t)$,

$q\big|_{X \in \Gamma_3} = w \cdot q\big|_{X \in \Gamma_2}$,

where w (0<w<1) is a coefficient that specifies the share of water that is removed by the middle drainage.

Here σ(X,t) is soil porosity which is variable over time due to changes in the concentration of clogging particles; s (X,t) is the mass concentration of clogging particles ($[s]=kg/m^3$, the mass per unit volume of particles that are associated with the soil skeleton); c is the concentration of the suspension that is filtered ($[c]=kg/m^3$, the mass of suspension particles in a unit volume of pore liquid); ρ_s is the density of clogging particle material; $\rho_p=\rho_p(c)$ is the density of the pore fluid (suspension) which depends on the concentration of suspension particles c; $k_h=k_h(c,\sigma)$ is the filtration coefficient which depends on the suspension concentration and porosity; h is the pressure in the pore fluid; D_c is the dispersion coefficient of particles in porous suspension; a is the particle adhesion rate coefficient; β is the particle detachment rate coefficient; σ_s is the porosity of the porous medium which consists only of clogging particles; $X = (x, y)$; $C_0(X), Q(t), C_\Gamma(X, t)$ are known functions.

The finite element method (FEM) was used to find the approximate solution of the present boundary value problem.

THE RESULTS OF RESEARCH ON THE FILTRATION PROBLEM INVOLVING CLOGGING

Numerical solution of the formed mathematical model of filtration involving clogging

The weak formulation of the boundary value problem is as follows. Let us multiply **Eq. (1)** by the test function

$v1(X) \in H_0 = \{v1(X) : v1(X) \in W_2^1(\Omega)\}, v1(X)\big|_{\Gamma_1 \cup \Gamma_2} = 0$,

integrate over the domain Ω, apply the Gauss-Ostrogradsky formula and obtain

$$\iint_\Omega (k_h \rho_p \nabla h \nabla v1) d\Omega + \iint_\Omega (\sigma \frac{\partial \rho_p}{\partial c} \cdot \frac{\partial c}{\partial t} \cdot v1) d\Omega - \iint_\Omega (\frac{\rho_p}{\rho_s} \cdot \frac{\partial s}{\partial t} \cdot v1) d\Omega = 0,$$

Here $W_2^1(\Omega)$ is a Sobolev space.

Let us multiply **Eq. (2)** and the initial condition for the concentration of the suspension by the test function

$v2(X) \in H_0 = \{v2(X) : v2(X) \in W_2^1(\Omega)\}, v2(X)\big|_{\Gamma_1} = 0$,

integrate over the domain Ω, apply the Gauss-Ostrogradsky formula and obtain

$$\iint_\Omega (D_c \nabla c \nabla v2) d\Omega - \iint_\Omega (u(1 - \frac{c}{\rho_p} \frac{\partial \rho_p}{\partial c}) \cdot \nabla c \cdot v2) d\Omega + \iint_\Omega (\frac{\partial s}{\partial t} \cdot v2) d\Omega =$$

$$\iint_\Omega (\sigma(1 - \frac{c}{\rho_p} \frac{\partial \rho_p}{\partial c}) \cdot \frac{c^i - c^{i-1}}{dt} \cdot v2) d\Omega,$$

$$\iint_\Omega c(x, y, 0) \cdot v2(X) d\Omega = \iint_\Omega c_0 \cdot v2(X) d\Omega.$$

$$u = -k_h \nabla h.$$

$$s^i = (\alpha \cdot c^{i-1} - \beta \cdot s^{i-1}) \cdot dt + s^{i-1}.$$

Finding an approximate generalized solution of the obtained problem requires applying time discretization (for more detailed information, see (Moshynskyi *et al.*, 2018; Michuta *et al.*, 2020)).

The results of numerical experiments on the solution of the filtering problem taking into account occlusion

The distribution of pressures taking into account the effect of clogging in the presence of a system of perforated pipes for partial drainage of water from the middle part of the bio-plateau is shown in **Figs. 2−5**.

Numerical experiments show that the maximum relative difference in filtration rates with and without taking into account the effect of clogging is about 5% after one year of the bio-plateau operation.

DISCUSSION OF THE RESULTS OF NUMERICAL EXPERIMENTS

The research showed, if on the example of a model problem, that it is relevant at the design stage to study the clogging processes that occur in the bulk of the bio-plateau filter backfill during the filtration of polluted water. These processes significantly affect the efficiency of the bio-plateau filter. The used mathematical and computer modeling tools allow considering the non-linear interactions of the parameters of both the porous medium and of the processes themselves. This enables significant economy of resources and time for performing field experiments.

Numerical experiments show that the maximum relative difference in filtration rates in the presence of a system of perforated pipes for partial removal of water from the middle part of the bio-plateau reaches 5% after a year. Previous numerical experiments of the authors with a similar model problem but without a system of pipes (Moshynskyi *et al.*, 2018) showed that the maximum relative difference in the values of the filtration rates was about 25% in half a year. Taking into account the proposed internal system of perforated pipes should increase the predicted productivity of the bio-plateau. This allows us to assert that the adequacy of the mathematical model to the investigated physical processes has increased. The nonlinearity of the developed model disables analytical solutions of the corresponding boundary value problem. That is precisely why it is advisable to employ mathematical and computer modeling and thus evaluate the effect of the considered factors without performing field experiments.

CONCLUSIONS

1. An improved mathematical model of water treatment in the bio-plateau was formed based on a filtration profile scheme, which takes into account the removal of part of the water from the bulk of the bio-plateau filter backfill, which allows predicting the stability of its operation during a long period of operation.
2. Numerical solutions of the corresponding nonlinear boundary value problem were found using the finite element method realized in the FreeFem++ freeware. The use of FreeFem++ enables partial automation of the software implementation of algorithms for solving nonlinear boundary value problems for systems of partial differential equations. Specifically, one of the advantages of the used environment is the automatic covering of areas with a grid of triangular finite elements, as well as the automatic reduction of the problem in a weak formulation to a system of linear algebraic equations.
3. Computer modeling showed that the maximum relative difference in filtration rates is only 5% after a year with the system of perforated pipes for partial removal of water from the middle part of the bio-plateau. The mathematical model and the proposed engineering solutions increase the adequacy of the results to the investigated physical processes and thereby reduce the negative impact of clogging.

REFERENCES

Bondar A., Fylypchuk V., Kuryliuk M., Ayaya Aniyefiok. (2017). Deep Purification of waters in filtration-regeneration bioplateau of hydroponic type. Scientific and practical journal "Ecological sciences", 16–17, 39–45.

Liu J., Liu L., Huang Z., Fu Y., Huang Z. (2020). Contaminant Removal and Optimal Operation of Bio-Slow Sand Filtration Water Treatment Based on Nature-Based Solutions. Pol. J. Environ. Stud., 29(2), 1703–1713.

Martynov S., Fylypchuk V., Zoshchuk V. (2018). Technological model of water contact iron removal. J. Water Land Development, 39(X–XII), 93–99.

Moshynskyi V., Filipchuk V., Ivanchuk N., Martyniuk P. (2018). Computer modeling of water cleaning in wetland taking into account of suffosion and colmatation. Eastern European J. Enterprise Technologies, 1/10(91), 38–43.

Herus V. A., Ivanchuk N. V., Martyniuk P. M. (2018). A System Approach to Mathematical and Computer Modeling of Geomigration Processes Using Freefem ++ and Parallelization of Computations. Cybernetics and Systems Analysis, 54(2), 284–294.

Michuta O., Ivanchuk N., Martyniuk P., Ostapchuk O. (2020). A finite-element study of elastic filtration in soils with thin inclusions. Eastern European J. Enterprise Technologies, 5/5(107), 41–48.

Fylypchuk V., Induchny S., Pearce P., Fylypchuk L., Martynov S. (2017). Application of expanded polystyrene filter for tertiary treatment of domestic waste effluent in the UK. J. of Water and Land Development, 35(1), 41–47.

Zehua Ji, Wenzhong Tang, Yuansheng Pei (2022). Constructed wetland substrates: A review on development, function mechanisms, and application in contaminants removal. Chemosphere, 286(1), 131564.

Huma Ilyas, Ilyas Masih, Eric D. van Hullebusch (2021). Prediction of the removal efficiency of emerging organic contaminants in constructed wetlands based on their physicochemical properties. J. Environmental Management, 294, 112916.

Hanxi Wang, Lianxi Sheng, Jianling Xu (2021). Clogging mechanisms of constructed wetlands: A critical review. J. Cleaner Production, 295, 126455.

Yuxin Fang, Lingwei Kong, Pei Zhang, Lu Zhang, Huawen Zhao, Xiaoqin Xiang, Shuiping Cheng, Hangjun Zhang, Feng Ju, Ling Li (2022). Fifteen-year analysis of constructed wetland clogging: A critical review. J. Cleaner Production, 365, 132755.

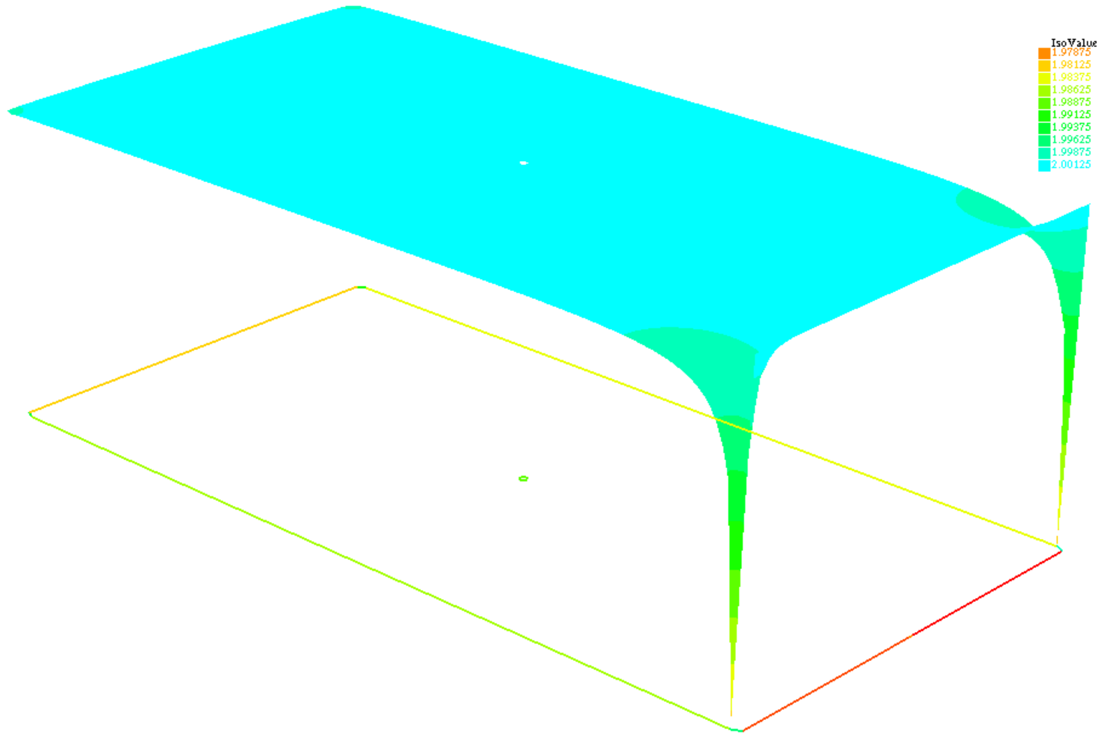

Fig. 2 Distribution of pressures in the bio-plateau backfill after 360 days.

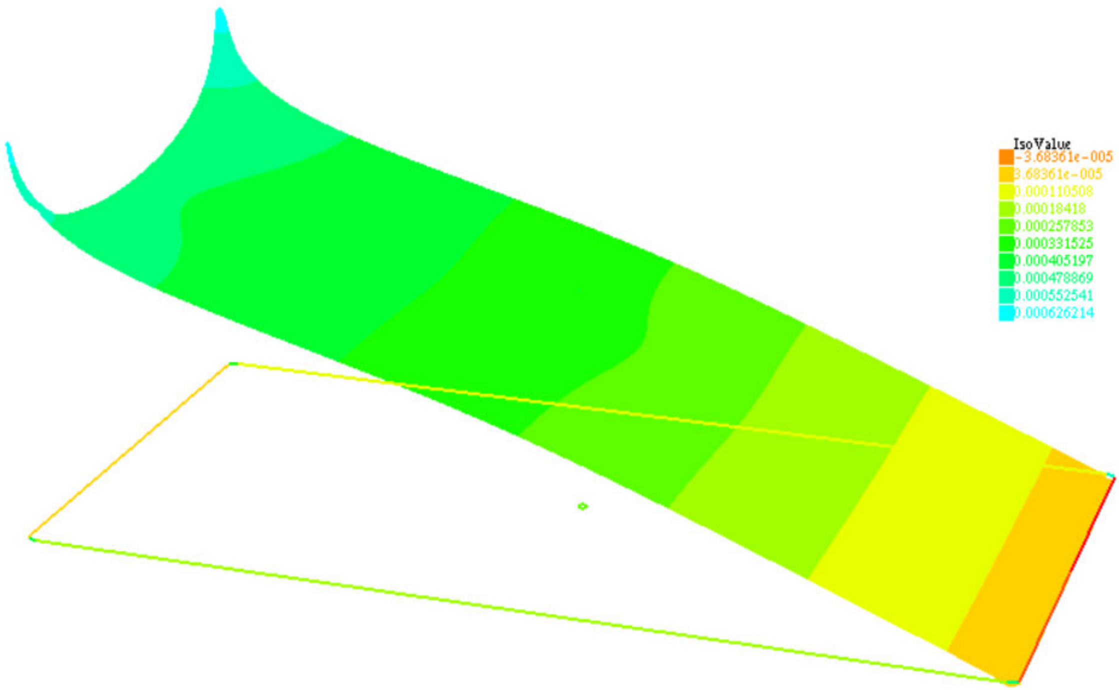

Fig. 3 Difference of the pressure distribution with and without taking into account the effect of clogging in the presence of a system of perforated pipes for the partial drainage of water from the middle part of the bio-plateau after 360 days.

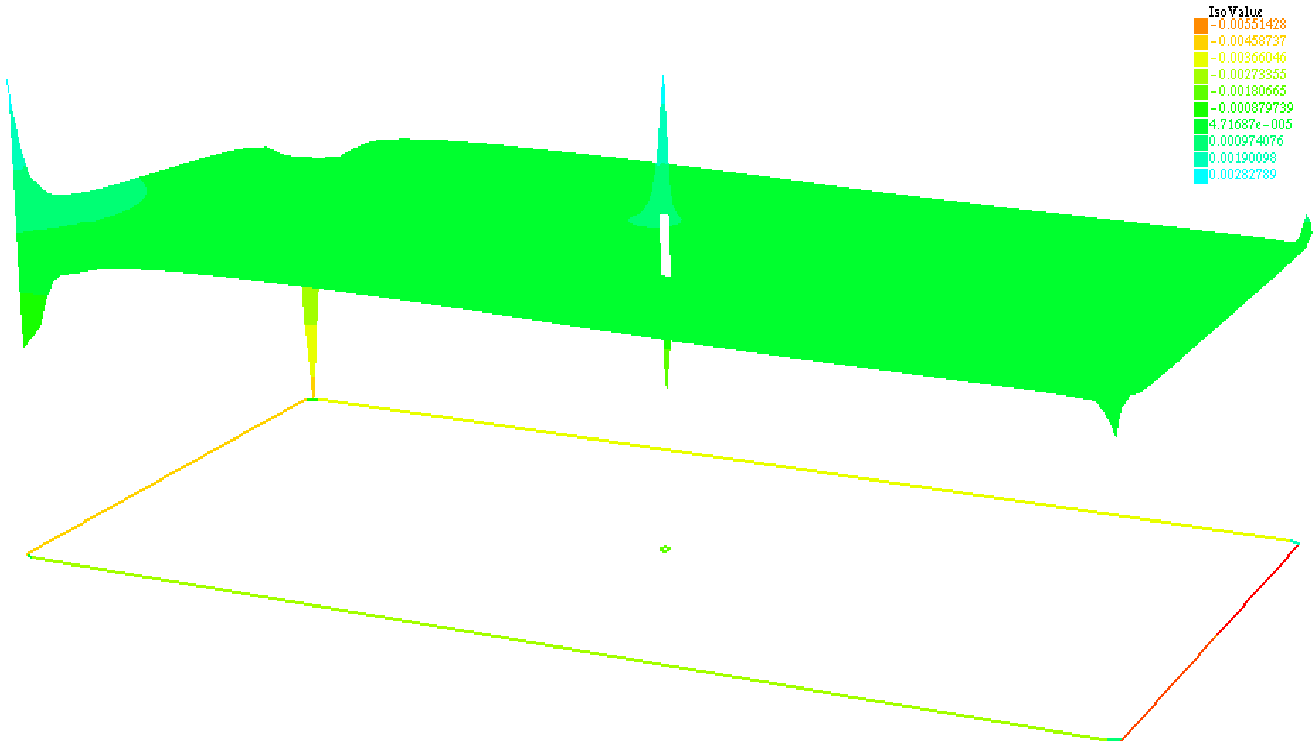

Fig. 4 Distribution of the difference in filtration rates with and without taking into account the effect of clogging in the presence of a system of perforated pipes for partial drainage of water from the middle part of the bio-plateau after 360 days.

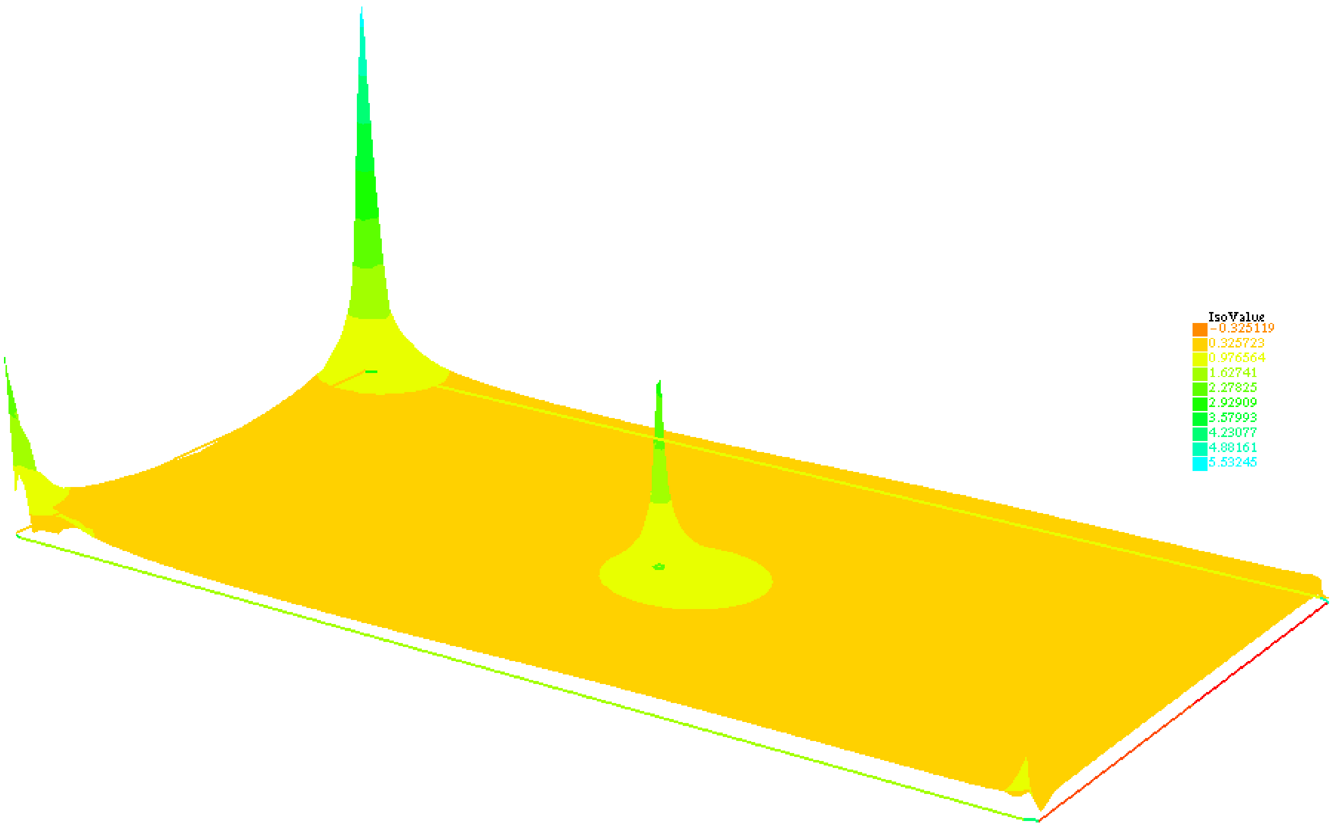

Fig. 5 Distribution of the relative difference in filtration rates with and without taking into account the effect of clogging in the presence of a system of perforated pipes for partial drainage of water from the middle part of the bio-plateau after 360 days.

Roberto Aguado, Onintze Parra, Leire García, Mikel Manso, Leire Urquijo, Federico Mijangos (2022). Modeling and simulation of subsurface horizontal flow constructed wetlands. J. Water Process Engineering, 47, 102676.

Bowen Yang, Zijie Xiao, Qingjie Meng, Yuan Yuan, Wenqian Wang, Haoyu Wang, Yongmei Wang, Xiaochi Feng (2023). Deep learning-based prediction of effluent quality of a constructed wetland. Environmental Science and Ecotechnology, 13, 100207.

Naomi Monsalves, Ana María Leiva, Gloria Gómez, Gladys Vidal (2022). Antibiotic-Resistant Gene Behavior in Constructed Wetlands Treating Sewage: A Critical Review. Sustainability, 14, 8524.

Xuan Cuong Nguyen, Quang Viet Ly, Wanxi Peng, Van-Huy Nguyen, Dinh Duc Nguyen, Quoc Ba Tran, Thi Thanh Huyen Nguyen, Christian Sonne, Su Shiung Lam, Huu Hao Ngo, Peter Goethals, Quyet Van Le (2021). Vertical flow constructed wetlands using expanded clay and biochar for wastewater remediation: A comparative study and prediction of effluents using machine learning. J. Hazardous Materials, 413, 125426.

Ikrema Hassan, Saidur R. Chowdhury, Perdana K. Prihartato, Shaikh A. Razzak (2021). Wastewater Treatment Using Constructed Wetland: Current Trends and Future Potential. Processes, 9, 1917.

Angela Gorgoglione, Vincenzo Torretta (2018). Sustainable Management and Successful Application of Constructed Wetlands: A Critical Review. Sustainability, 10, 3910.

Chunbo Yuan, Ting Huang, Xiaohong Zhao, Yaqian Zhao (2020). Numerical Models of Subsurface Flow Constructed Wetlands: Review and Future Development. Sustainability, 12, 3498.

Bárbara Santos Soares, Alisson Carraro Borges, Antonio Teixeira de Matos, Rubens Barrichello Gomes Barbosa, Fabyano Fonseca de Silva (2022). Exploring the Removal of Organic Matter in Constructed Wetlands Using First Order Kinetic Models. Water, 14, 472.

Nilton de Freitas Souza Ramos, Alisson Carraro Borges, Eder Carlos Lopes Coimbra, Gustavo Castro Gonçalves, Ana Paula Ferreira Colares, Antonio Teixeira de Matos (2022). Swine Wastewater Treatment in Constructed Wetland Systems: Hydraulic and Kinetic Modeling. Water, 14, 681.

Stepanchenko O., Shostak L., Kozhushko O., Moshynskyi V., Martyniuk P. (2021). Modelling soil organic carbon turnover with assimilation of satellite soil moisture data. Modeling, Control and Information Technologies: Proceedings of International Scientific and Practical Conference, 5, 97–99.

Stepanchenko O., Shostak L., Moshynskyi V., Kozhushko O., Martyniuk P. (2023). Simulating Soil Organic Carbon Turnover with a Layered Model and Improved Moisture and Temperature Impacts. In: Babichev S., Lytvynenko V. (eds.) Lecture Notes in Data Engineering, Computational Intelligence, and Decision Making. ISDMCI 2022. Lecture Notes on Data Engineering and Communications Technologies, 149, 74–91. Springer, Cham.

Orlov V., Martynov S., Kunytskiy S. (2016). Energy saving in water treatment technologies with polystyrene foam filters. J. Water Land Development, 31(1), 119–122.

Martynov S., Kunytskyi S., Orlova A. (2017). A simulation study of surface water purifying through a polystyrene foam filter. Eastern-European J. Enterprise Technologies, 5(10-89), 19–26.

Bomba A., Safonyk A., Voloshchuk V. (2018). Spatial modeling of multicomponent pollution removal for liquid treatment under identification of mass transfer coefficient. Mathematical modeling and computing, 5(2), 108–118.

Bomba A., Safonyk A. (2018). Mathematical Simulation of the Process of Aerobic Treatment of Wastewater under Conditions of Diffusion and Mass Transfer Perturbations. J. Engineering Physics and Thermophysics, 91, 318–323.