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Development of statistical methods to support the design and modelling of subsurface flow constructed wetlands.

PhD thesis

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1. Introduction

Increase of environmental problems showed for humanity, that without changing to sustainable social life, our development cannot easy to imagine. This process has got higher speed since 2004. That time the European Union has officially declared that global climate change as a fact accepted. In that becoming increasingly environmental friendly society, one of the most important aim is the maximized reduction of anthropogenic emissions. Wastewater treatment has the largest technical history in this area. The management of wastewater point pollution sources is one of the important issues of environmental protection. There are many technologies available to meet the water quality standards. However, the selection among these technologies is still a challenge and requires a detailed analysis of the local situation. There is especially difficult to find the golden mean between the environmental aims and the economic opportunities. One problem is that the development level of the technological alternatives, and the design methods are different. Generally, can be said that the intensive technologies with higher history (f.e. activated sludge systems) have scientifically supported model based design methods. On the other hand, the extensive (natural) wastewater treatment technologies design methods are under fast stage of development.

Natural wastewater treatment technologies have different construction mode and loading rates than the intensive ones. Because of the most complex processes in the system and more significant weather impacts, scientists need to use other research technics and measurement methods than we have got to use at activated sludge systems or trickling systems.

Kichkuth published the very famous „root zone method" at 1981 (**Kichkuth 1981**). This scientific result caused that the natural wastewater treatment technologies were placed into the centre of attention again. The development of subsurface-flow constructed wetlands (SF-CW-s) started based on that results too. SFCW-s as wastewater treatment systems are very popular in West-Europe, USA and Australia and are getting popular worldwide. In the 80s the operational SF-CW-s were rather an experimental nature (**Brix 1994a**). Based on experiences of 80s the first design guidelines were published in the USA, Germany, Great-Brittan, and EU (**USEPA 1988, USEPA 1993,** ATV A 262, Good Building Guide 42, **EC Guide 2002 etc.).** At the beginning of the 21st century the second generation design guidelines were published in some countries **(**f.e. Great-Brittan, Denmark) (**Weedon 2003, Brix 2005**), and first professional dynamic models were published (**Langergraber 2003**). This development process is being nowadays, that is supported by high amount of operational experiences and large number of deep scientific publications.

The SF-CW-s as natural wastewater treatment technology is most popular than in Hungary. For example, 130 experimental horizontal flow SF-CW were in Denmark in the 80s (**Schierup et al. 1990)** and **Vymazal (1999**) showed 130 experimental plants in Checz Republic. **Bergier (2005)** explained about 150 SF-CW-s in Poland. In spite of this only 18 SF-CW was in Hungary until 2008 **(Dittrich 2008).**

The research of SF-CW-s is being since the years of 80s (**Fleit 1988**). One of the most significant researcher working class associated with Ferenc Szilágyi (**Szilágyi 1994, Szilágyi 1998, Szilágyi et al. 2001, Szilágyi 2004**). He is researching the technological application problems and opportunities of development of SF-CW-s in Hungray for over 15 years. Jobbágy Sándor and Horváth László had outstanding role at the starting of local application of this technology (**Jobbágy 1995**). Bácskai Zsolt **(Bácskai 1996)** made a summary about the Hungarian experiences, and after that BME-VKKT continued and expanded it (**BME-VKKT 2002**). This summary supported my research too. The first Hungarian design guideline (**MASZESZ MI-I-1:2003**) for vertical flow SF-CW-s was made by Hungarian Wastewater Technology Asiciation (MASZESZ). That was due to leading work of Dulovics Dezső, and that guidelines filled a large need in this area. Gampel Tamás has some publication about Hungarian soil based horizontal flow SF-CW-s (**Gampel 2000, Gampel 2003)**. Important to write about Kisgyörgy Rozália who worked a lot to make more popular natural wastewater treatment technologies in Hungary (**KvVM 2005**).

SF-CW-s didn't spread well in Hungary. The main reasons are **(Dittrich 2006a)**:

- The Emission Limit Values are more rigorous in Hungary than the 271/91 EC Directive
- The Hungarian competitions didn't supported this technology until a few years ago
- Hunarian experiences are limited and the Hungarian design practice is not edaquate
- The bad operational experiences in Hungary

I tried to support the better Hungarian practice with my practice oriented publications in last few years **(Dittrich 2006b, 2008a, 2008b, 2009, 2012)**. This dissertation contains research results those can help to make more precise design of Hungarian SF-CW-s.

In spite of international development in more than three decades, the well-known design methods got failure. It seems from the unfavourable experiences of operational Hungarian plants (**Dittrich 2006a**). So there is a need to develop better design methods that can be adapted to local conditions. First part fo the dissertation tries to help in that direction with the adaptation of wetland-model, and with given a modification of wetland-model fitted to Hungarian demands.

In last ten years have appeared increasing number of complex dynamic models to simulate SF-CW-s (**Wang ez al 2011**). There is not model type till that time, that could get worldwide reputation. The favourable operation of these models is more difficult, because some of factors affecting the operation have stochastic nature (**Kadlec 1997**). So the deterministic models can describe a short part of operation in time only. Further problem that some parts of process aren't enough well described scientifically. So important to develop these „model-parts" too. This kind of important area is the transport processes in SF-CW-s.

Józsa János and Krámer Tamás has professional significant research activity at hydrodynamic and transport processes modelling (**Józsa et al. 1994, Józsa and Kármer 2008, Józsa and Krámer 2000a**). They researched hydrodynamic modelling of free surface water CW-s too (**Józsa et al. 2000b**). Koncsos László and Somlyody László has highly recognized working in water quality modeling sector (**Koncsos et al. 2003, Koncsos et al. 1998a, Koncsos et al. 1998b, Koncsos et al. 1998c, Somlyódy 1980, Somlyódy 1982**), but mainly for free surface water bodies. Kovács Balázs have given comprehensive book about hydrodynamic modelling and transport processes in porous medias, but he focused mainly the higher scaled seepage problems. Small scaled transport processes in porous media was researched by Simonffy Zoltán **(Simonffy 1998).**

The number of publications about SF-CW-s are not too much in the international literature, and I don't know any Hungarian publications without my results. The weather features have strong impact to water balance equation of SF-CW-s, that causes stochastic nature for transport processes in time. The real hydraulic behaviour is more difficult because of biofilm activity, rhizome system development, and clogging processes in the porous media. These difficult problems cause that there isn't adequate precise transport model system until that time. This dissertation gives new development direction in that scientific area, and show new scientific results too.

2. Aims and area of research

The thesis is working only with SF-CW for wastewater treatment. There are high number of complex processes in the SF-CW-s, those have impacts on treating wastewater. From the viewpoint of effluent wastewater quality, the most important processes are showed (Figure 1):

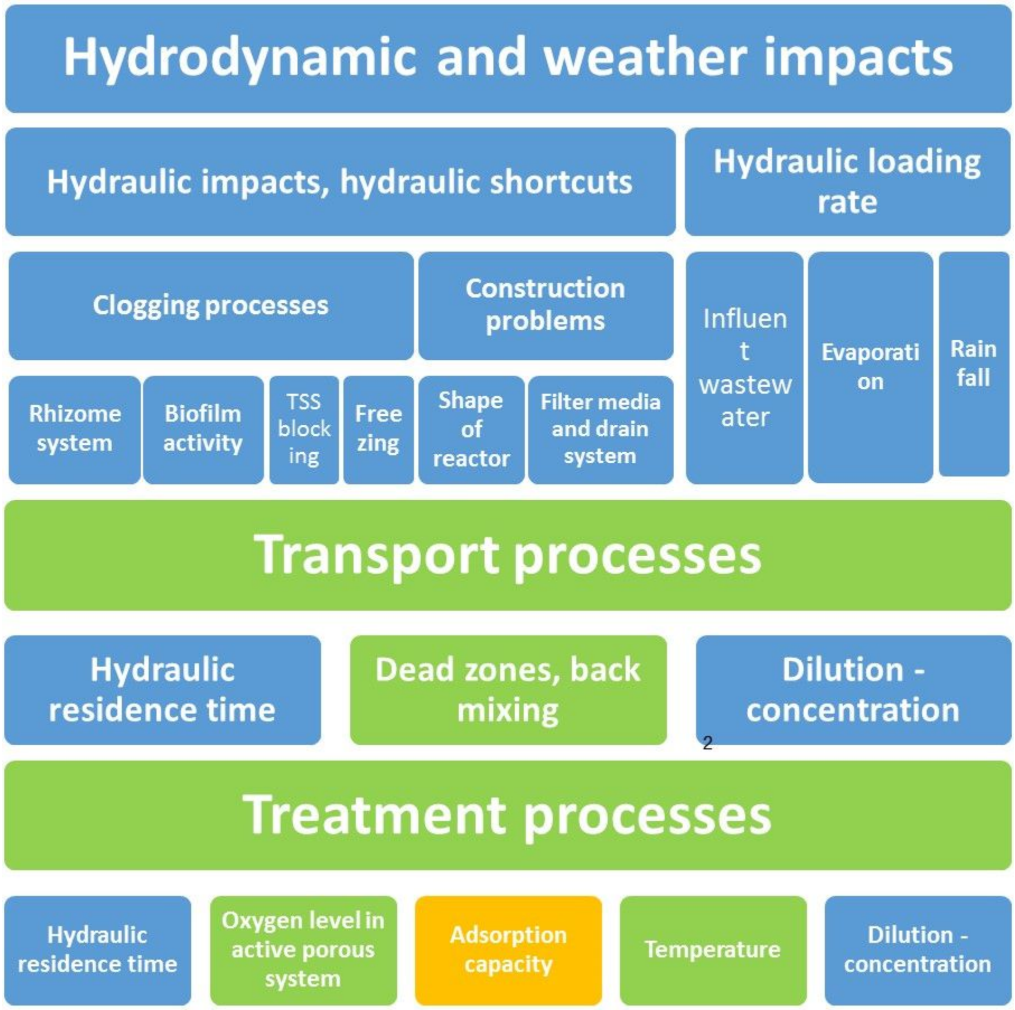


Figure 1: More important factors and processes affecting the wastewater treatment effluent quality

Figure 1 shows so difficult the scientific describe of SF-CW-s. The topics of this research is limited and shows methods those help the more precise design and modelling development. Because of stochastic nature of these systems, the dissertation is supported mainly statistical and probability mathematical methods. Inside of this, the thesis can be divided two basic part:

I. The first part of thesis makes detailed analysis about the adaptation of wetland model into Hungarian conditions. The main aims of that part of my research are:
   a. Very important to specify the parameters of wetland modell for Hungarian wastewater quality and local environmental conditions.
   b. Built in the unfavourable adaptation results of wetland modell, my aim is to convert the deterministic wetland-model to a semi-stochastic model that can decrease the disadvantages of model for Hungarian adaptation.

II. The second part of thesis analyses the transport processes of horizontal flow SF-CW-s (HF SF-CW). The main aims of that part of my research are:

c. To make a statistic method that is successful in decreasing the error of measurement results and in the precise calculation of the moments of corrected tracer functions. It needs to be proved that with this process the measured tracer results of horizontal subsurface flow constructed wetlands filled with coarse gravel (HF-CW-C) can be fitted more accurately than with the conventionally used distribution functions (Gaussian, Lognormal, Fick (Inverse Gaussian), Gamma).

d. My other aim is to analise that the conventionally used concektives-dispersive (CDT) and completely stirred tank reactor (CSTR) models are applicable or not to describe well the transport processes of HF-CW-C-s.

e. Further aim of my research is to develop a new modelling method, that can describe better the transport prosesses in HF-CW-C-s, than the conventional methods.

f. Last aim of my research to make a detailed analysis about the real residence time in that kind of systems.

The Chapter 1 and 2 show detailed summary about the international and Hungarian literature about SF-CW, deeper focused on wetland-model and transport proceses of SF-CW-s. These chapters shows the main describing methods of conservative transport processes, and tha statistic and stochastic functions for support the analysis of subsequent chapters.

Chapter 3 shows the analyzed database, the own measurement results and the methods of analysis.

Chapter 4.1. shows the detailed adaptation of wetland-model, and Chapter 4.2. describe the semi-stochastic development of wetland model. Chapters 4.3. – 4.8 shows the detailed analysis of conservative transport processes of HF-SF-CW-s.

Chapter 5 collect the new scientific results into 5 piece of thesis.

At the end of the dissertation, Annexes support the calculations and help to get deeper understanding of main Chapters.

3. Materials and methods

To support the analysis of thesis 1, I collected a data about the operational Hungarian SF-CW-s. This database was analized with wetland-model, to calculate the design parameters for Hungarian conditions.

At thesis 2, I developed a mathematical method to develop wetland-model to semi-stochastic model. This method assumes the neglected parameters in wetland-model as one uniform distributed probability parameter. The applicability of model was controlled with the database of Hungarian operational SF-CW-s.

Thesis 3 – 5 used own conservative transport measurement result at HF-SFCW-C in Hódmezővásárhely. That plant was built as part of a Belgian-Hungarian research cooperation. Many mathematical procedures were developed in MAPLE environment to make model testing and deep analysis. I used two published international conservative measurement results too, to get objective control about my results.

4. Novelty and practical applicability of scientific results

The results of analysis of wetland-model gives volumetric rate constant (K [m/d]) values of Hungarian operational experiences. Because of mainly different operational mechanisms, the Hungarian SF-CW-s were divided into 3 different group:

I. plant type: vertical flow SF-CW-s
II. plant type: horizontal flow soil based SF-CW-s
III. plant type: Multi-stage systems

The K parameter values of I plant type for BOD and COD can written into thesis 1, because of the main reasons before:

- Some of international scientists can not accept to use wetland-model to other parameters.
- I can not get statistically enough good fitting properties at analysis of type II and III.

In spite of this the determined K values can be helpful and interesting from the viewpoint of practical applicability. These values are collected in Table 1.

K [m/d]	BOD	COD	TSS	NH_4-N	TP
I. plant type	0,1	0,1	0,007	0,05	*
II. plant type	0,023	0,017	0,009	0,014	0,009
III. plant type	0,12	0,12	*	0,08	0,022

*Can not be determined from database

Table 1: The volumetric rate constant values of wetland-model for Hungarian SF-CW-s and commercial wastewater

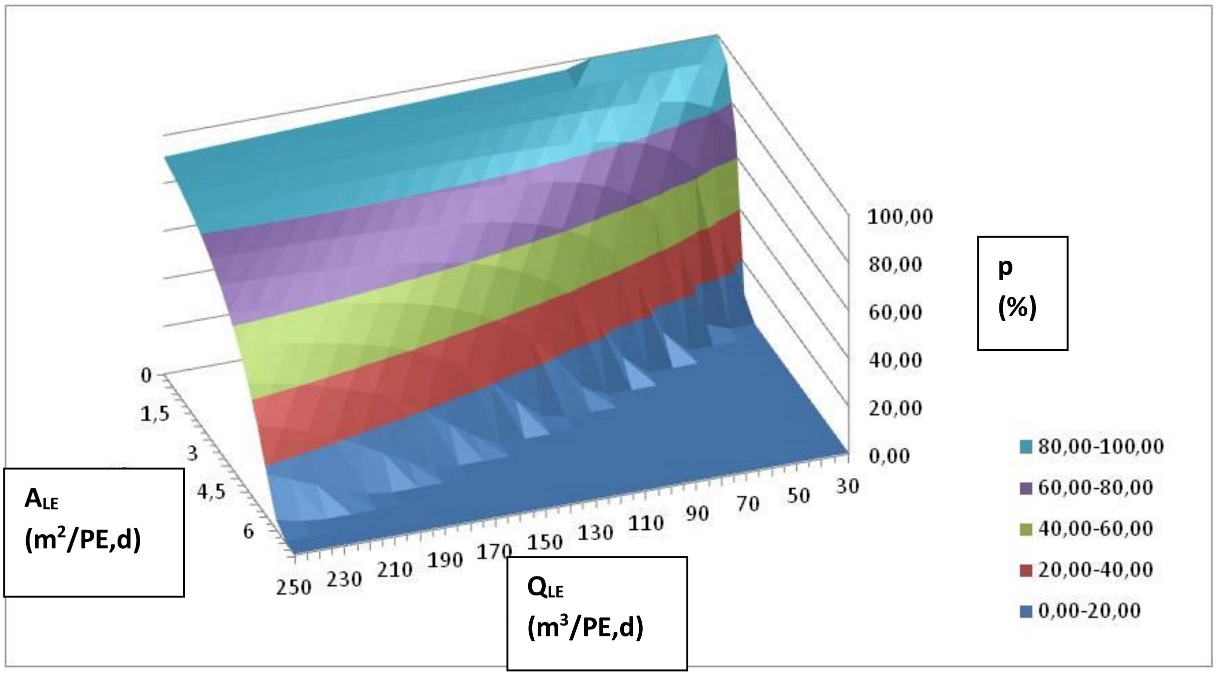
As a part of analysis area demand values were calculated too for Hungarian emission limit values too. From the results some interesting conclusion can be summarized for Hungarian practitioners:

- In spite of 271/91 EC Directive, in Hungary we have emission limit values for small settlements (under 2000 PE) for TN, NH_4-N and TP too. The analysis shows, that the area demand can be calculated from TN, TN, NH_4-N and TP parameters, not from BOD or COD.
- The commercial wastewater quality at Hungarian settlements is more concentrated than in the West-European countries. This is one of the main reason why SW-CW-s doesn't work well in Hungary, with other countries suggested specific area demand.
- K-values for BOD, COD, and NH_4-N parameters of plant type I shows same values than it is published in international literature. So the average treatment capacity is same in Hungary than in other countries.
- At the analyzed Hungarian I type plants, the main reasons of unfavourable emission values were the low specific area, and the highly developed clogging processes
- The soil based (type II) HF-SFCW-s treatment capacity more lower than the published experiences of international literature. One of the main reason is the unfavourable construction of basins, and the high ratio of free surface flow wastewater (hydraulic shortcuts) in the system.
- Type III shows the best specified parameter results, so this can be the basic developed technological alternative to Hungarian wastewater treatment problems.

At thesis 2 a special mathematical method was developed, that is applicable for decrease the uncertainties of wetland-model. This method can be used to design any other wastewater treatment technologies those meet the following criteria:

- The set of measured Co-Ci function points reach minimally 0,5 correlation rate with linear regression.
- Between the processes those have impact for the quality of effluent wastewater have stochastic nature.
- That can be assióumed: the measured values have uniform probaility inside the defined probability area

One result of the method is shown below (Figure 2).



**The figure is true only commercial wastewater.*

*** The figure is true only to Hungarian climatic conditions*

**** The figure is adapted for BOD and 50 mg/l emission limit value*

Figure 2: Emission limit values exceedance probability (p) dependent from specific area (A_{LE}) and specific wastewater loading rate (Q_{LE}) for Hungarian I type SF-CW-s

The practical applicability of this method is that this kind of figure can be made for all of plant type and all at design component, differentiated for all of emission limit values. So the group of these figures can give a good design solution for practicing designers. If under the figures, there are a dynamic database than increased imported data give more safe design opportunities. With this method, other natural wastewater treatment technologies can be analized.

Result of thesis 3 uses Frechet-distribution, that is a new distribution function type in conservative transport processes simulation practice. This distribution type can give great fitting properties with measured data. That can see in Figure 3.

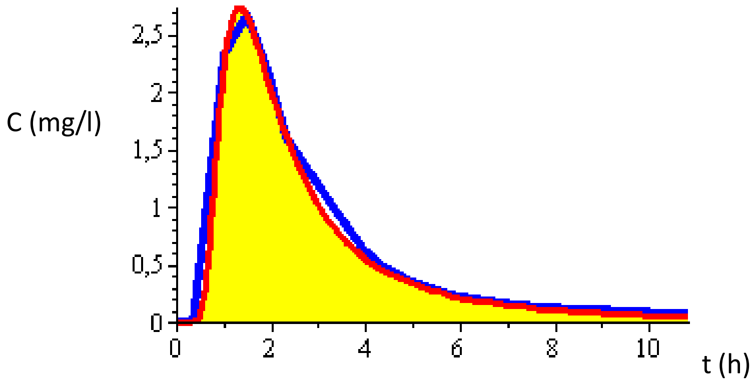


Figure 3: Fitted Frechet-distribution onto the measurement results of conservative tracer test of horizontal flow SF-CW in Hódmezővásárhely, Hungary (blue line: measured data, red line: Frechet-distribution function)

Using mathematical solutions in the MAPLE environment it is possible to determine what can decrease measurement errors of tracer tests and accurately calculate the moments of fitted function. With this method we demonstrated that the planted HSFCW-Cs conservative tracer response curves have a Frechet distribution. This result and correlation provides some important conclusions:

- The analytical solution of the CDT model is an Inverse Gaussian distribution function. So the normal CDT model cannot accurately generate a correctly fitting correlation. The error increases with the age of the CW.
- The analytical solution of the CSTR model gives a Gamma distribution function. This distribution function is not applicable for gaining a suitably accurate solution.
- The Frechet-distribution as an optimal distribution type that can give a very good fitting solution to the measured data, minimizing the measuring errors and providing more precise real HRT values.

Result of thesis 4 gives a new model to simulate conservative transport processes in HFSFCW-s. The significance of this new model is that it can simulate more accurately the transport processes in this kind of system than the conventionally used convective-dispersive transport (CDT) model. The calculated velocity and dispersion coefficients with the D-CDT model gave differences of 24-54% (of velocity) and 22-308% (of dispersion coeff.) from the conventional CDT model, more closely approximating the real hydraulic behaviour. Figure 4 shows the precize fitting properties of the model.

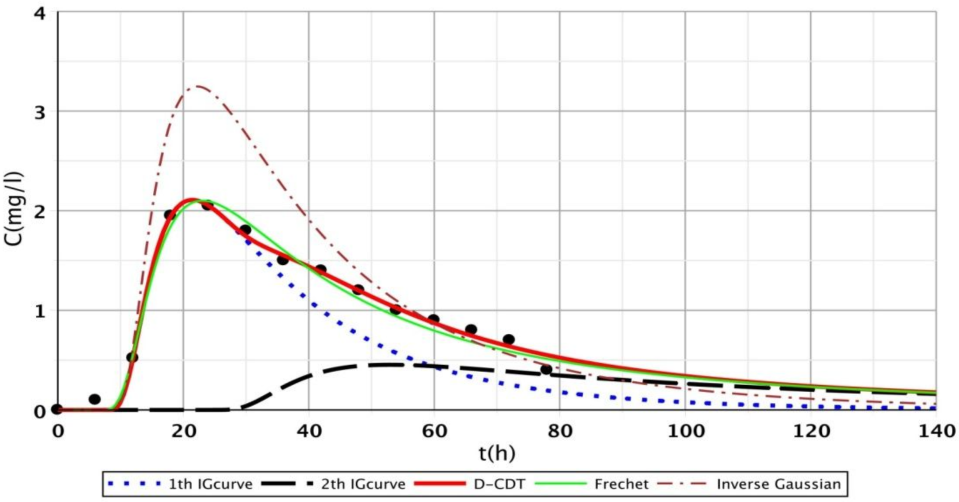


Figure 4: Divided-convective-dispersive transport model fitting results compared with Frechet-distribution and conventional CDT model

Result of thesis 5 shows important practical applicability results. It was shown that the real HRT is higher than theoretical HRT in contrast to most of existing literature. That conclusion remains true as long as a high rate of hydraulic shortcuts don't exist. This analysis also showed that the CDT model is inaccurate, and the calculated dispersion coefficient and real HRT from the CDT model contain errors. The dominant impacts of the growth of the micro-porous systems are microbial activity and clogging of filter media. Root growth is less important with these processes. These conclusions are valid only in the absence of significant hydraulic shortcuts or free surface flow in the system. Why the real HRT is higher than we thought from the conventional literature, it affects the decaying models too, because that can causes lower degradation coefficients in models.

5. Summary of theses

Thesis 1:

The volumetric rate constant (K [m/d]) values of wetland-model was determined for Hungarian vertical flow SF-CW-s. The values for BOD and COD are 0,1 m/d. This result proves that the Hungarian vertical flow SF-CW-s average specific organic matter treatment capacity is same than the West-European ones.

Publications: [4], [5], [7]

Thesis 2:

A new mathematical procedure was developed to decrease the disadvantages of wetland-model. This method develop further wetland-model to semi-stochastic model. The model use the difference between the regression line and the measured value pairs as a uniform distribution probability parameter. The model gives Emission limit values exceedance probability (p) dependent from specific area (A_{LE}) and specific wastewater loading rate (Q_{LE}). The method can take into account the concentration of pre-treated wastewater too. The advantage of this solution is that the model can be used any other climatic condition if there are enough measurement data. If the method use more data, than gives more safe to designer.

Publication: [6]

3.tézis:

Using mathematical solutions in the MAPLE environment it is possible to determine what can decrease measurement errors of tracer tests and accurately calculate the moments of fitted function. The method can fit a continuous function onti measures conservative measured data with 100% tracer response. With this method we demonstrated that the planted HSFCW-Cs conservative tracer response curves have a Frechet distribution. This result and correlation provides some important conclusions:

- The analytical solution of the CDT model is an Inverse Gaussian distribution function. So the normal CDT model cannot accurately generate a correctly fitting correlation. The error increases with the age of the CW.
- The analytical solution of the CSTR model gives a Gamma distribution function. This distribution function is not applicable for gaining a suitably accurate solution.
- The Frechet-distribution as an optimal distribution type that can give a very good fitting solution to the measured data, minimizing the measuring errors and providing more precise real HRT values.

Publication: [1]

Thesis 4:

We have created a divided convective-dispersive transport (D-CDT) model that is able to simulate accurately the conservative transport processes in planted horizontal subsurface flow constructed wetlands filled with coarse gravel (HSFCW-C). This model makes fitted response curves from the sum of two independent CDT curves, while optimizing the ratio between the main and the side streams.

The analytical solutions of both CDT curves are Inverse Gaussian distribution functions. We used Fréchet distribution for a rapid optimisation of the mathematical procedure. As a result of our detailed analysis, we hypothesised that the most important role in the fast upward part of the tracer response curve is the main stream, with high porous velocity and dispersion. This gives the first Inverse Gaussian distribution function of the model. The side stream shows the slower transport processes in the micro-porous system, and this shows the impact of back-mixing and dead zones too. The significance of this new model is that it can simulate more accurately the transport processes in this kind of system than the conventionally used convective-dispersive transport (CDT) model.

Publications: [2, 3]

Thesis 5

It was shown that the real HRT is higher than theoretical HRT in contrast to most of existing literature. That conclusion remains true as long as a high rate of hydraulic shortcuts don't exist. This analysis also showed that the CDT model is inaccurate, and the calculated dispersion coefficient and real HRT from the CDT model contain errors. The ratio of real and theoretical HRT grows from about 1 month after starting operation. This is primarily due to the development of micro-porous systems in the filter media. The dominant impacts of the growth of the micro-porous systems are microbial activity and clogging of filter media. Root growth is less important with these processes. These conclusions are valid only in the absence of significant hydraulic shortcuts or free surface flow in the system. Why the real HRT is higher than we thought from the conventional literature, it affects the decaying models too, because that can causes lower degradation coefficients in models.

Publications: [1,2]

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6. Publications connected with dissertation

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[1] **Dittrich E. – Klincsik M. (2015a):** *Analysis of conservative tracer measurement results using the Frechet distribution at planted horizontal subsurface flow constructed wetlands filled with coarse gravel and showing the effect of clogging processes.* Environmental Science and Pollution Research SSN: 0944-1344 ***(Impact Factor 2.828)***

[2] **Dittrich E. – Klincsik M. (2015b)**: *Application of divided convective-dispersive transport model to simulate conservative transport processes in planted horizontal sub-surface flow constructed wetlandss.* Environmental Science and Pollution Research SSN: 0944-1344. ***(Impact Factor 2.828)***

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[3] **Dittrich, E. (2006)**: *Experiences on hydraulic performance of sub-surface flow constructed wetlands*. Pollack Periodica Vol. 1. No. 1. pp. 53-66. Akadémia kiadó, Budapest, 2006. http://www.akademiai.com/content/r634420523j5n382/?p=192abbeede67440484876d0b9703a338&pi=2

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