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Doctoral School of Environmental Sciences

Conservative tracer transport and evapotranspiration study of the horizontal subsurface flow constructed wetland filled with coarse gravel

Thesis of the PhD Dissertation

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Gödöllő

2022

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1. Introduction

1.1. Background

Climate change is an important, if not the most important, problem of the 21st century. The last decade has been one of the warmest on Earth. We can mitigate this process primarily by protecting our environment and by reducing emissions. We need to prioritize technologies that reduce pollution in our environment, as unfortunately, significant amounts of pollutants are released into the air as well as into the soil and water. One such area is the protection of water purity. It is very important that the wastewater to be introduced is treated as much as possible. The most widespread wastewater treatment modality includes intensive technologies, such as activated sludge process. The other possibility is referred to in the Hungarian literature as extensive technologies, which are also called natural wastewater treatment systems. These wastewater treatment processes are still being researched as they are not yet fully developed technologies, mainly due to the fact that they were rediscovered only 40 years ago by KICKUTH (1981).

One of these extensive technologies is constructed wetland. Constructed wetland wastewater treatment technology is widespread in both the US and the EU, as well as in Australia.

In Hungary, there has been research of subsurface flow constructed wetlands (SF-CW-s) since the 1980s (FLEIT 1988). One of the most significant researchers working in this area is Ferenc Szilágyi (SZILÁGYI 1994, SZILÁGYI 1998, SZILÁGYI 2004). He has been researching the technological application problems and opportunities of development of SF-CW-s in Hungary for over 25 years.

SF-CW-s have not spread optimally in Hungary. The main reasons are the following (DITTRICH 2006a):

1. Limited experiences and inadequate design practices in Hungary.
2. Unfavourable operational experiences in Hungary.

The above problems are still present today, but fortunately more and more constructed wetlands are working well in Hungary as well. According to data from 2019, there are 1,054 settlements in Hungary without a public sewage system, the majority of which have a population size of less than 1,000 people. These settlements are mostly located in areas where the economical operation of the sewage system is not feasible. In Hungary, the use of wastewater treatment plants could be beneficial particularly in these settlements. Especially settlements with less than

600 population equivalents are the ones where it would be crucial to treat the generated wastewater with such systems.

One of the areas of the present research was the measurement of the exact water balance of these constructed wetlands under Hungarian climatic conditions. An important parameter of water balance is evapotranspiration, which results from the combination of the evaporation of the gravel and the transpiration of the plants. Without knowing these parameters, the water balance of the constructed wetland can only be estimated, which however, has a direct influence upon the quality of the effluent water. In Hungary, especially during the summer, evapotranspiration can significantly influence the water balance of the constructed wetland, including the quality of the effluent water. To the best of our knowledge, there has been any in –depth Hungarian publication discussing this problem. Publications in the international literature have investigated only daytime evapotranspiration (BEEBE et al. 2014, TUTTOLUMONDO et al. 2015).

There is a scarcity of international publications on the transport processes of constructed wetland wastewater treatment plants, and I have no knowledge of domestic publications other than those of my supervisors' (DITTRICH and KLINCSIK 2015a, DITTRICH and KLINCSIK 2015b). The main reasons for this is that the transport modelling of these systems is very difficult, as the weather characteristics that strongly influence the water balance of the constructed wetland system make the material flow processes of the flow system stochastic. In addition, the active pore system, which is interwoven with roots and saturated with biofilm and dynamically changes in space and time, makes it difficult to describe these processes accurately. Based on the above, it becomes clear why a high-precision transport model for constructed wetland systems has not been developed to date. This dissertation outlines a unique application of a novel transport modelling direction and presents useful scientific results.

1.2. Content and objectives of the dissertation

The thesis solely discusses is working only with SF-CW for wastewater treatment. In the first part of the dissertation, the effect of transpiration on the water management of the horizontal subsurface flow constructed wetland using laboratory measurements is investigated. In addition, a field monitoring system was used to investigate the effect of evapotranspiration on the water balance of horizontal subsurface flow constructed wetland.

Research in this direction had three aims:

1. To investigate the tufted sedge (*Carex elata*) transpiration, and the effect of the water balance of planted horizontal subsurface flow constructed wetland's in spring, summer and autumn under the Hungarian climatic conditions.
2. Based on the results of field measurements, to determine the daily evapotranspiration for domestic climatic conditions and its effect on the water balance of the horizontal subsurface flow constructed wetland in spring, summer, and autumn.
3. In the course of my research to determine the extent and effect of the morning and evening condensation on the water balance of the horizontal subsurface flow constructed wetland in Hungarian climatic conditions.

Using the statistical method developed by DITTRICH and KLINCSIK (2015a, 2015b), the transport processes of horizontal subsurface flow constructed wetland were investigated, from which conclusions were drawn facilitating the understanding of the process. **The novelty and uniqueness of the present research is given by the fact that the method developed for the whole system was used to the internal points of the constructed wetland, for which it was necessary to supplement the method.**

In connection with the above, further aims of the dissertation were:

4. To investigate whether the most widely used method (convective-dispersive transport equation) published to date is suitable for describing transport processes with sufficient accuracy in the interior points of this type of constructed wetland.
5. Searching for hitherto unused distribution functions at the inner points of constructed wetlands to describe transport processes in order to find a more accurate model
6. My further goal was to prove whether the transport modelling method developed by DITTRICH and KLINCSIK (2015b) could be applied to describe the transport processes of constructed wetlands.
7. To prove that the divided convective-dispersive transport model more accurately describes the reality than the traditionally used transport models.

2. Methods

2.1. Brief introduction of the constructed wetland

The study site was a subsurface flow constructed wetland treatment plant near Hódmezővásárhely (Hungary). This constructed wetland treats 1,0-1,5 m^3 of wastewater per day from a dairy farm. The technology consists of a septic tank, a pump system, vertical subsurface flow constructed wetland planted with common reed (*Pragmites australis*), horizontal subsurface flow constructed wetland planted with tufted sedge (*Carex elata),* a polishing pond and a trickling system planted with poplar trees. This study focuses exclusively on horizontal subsurface flow constructed wetland.

2.2. Methods and equipment used for evapotranspiration and transpiration measurements

2.2.1. Brief introduction of the gas analyzer used for transpiration measurements

A portable infrared gas exchange analyser (LCA-Pro+, ADC Ltd., UK) was used for the laboratory measurements of the transpiration rate of the individual model plants. This device measures and regulates the environment inside the leaf chamber and calculates the photosynthetic activity of the leaf. The main console delivers controllable CO_2 and H_2O air into the chamber with measurable values. The air flows around both sides of the leaf so that it can be examined, and CO_2 and H_2O content are simultaneously measured in the analyser.

2.2.2. Description of the measurement model used for laboratory measurements

During model constructed wetland measurements, the tufted sedge (*Carex elata*) (approx. 1m^2 area) was obtained from the constructed wetland wastewater treatment plant in Hódmezővásárhely.

The total surface area of the plants for system-level water loss estimation in the constructed wetland was determined by using a leaf area meter (AM-100-002, ADC Ltd., UK). Transpiration rate (**E**) was calculated approximately every 20 seconds by the analyser

Before starting the measurements, undamaged, matured (but not too young or old) leaves that are rich in photosynthetic pigments were selected and marked. Three types of gas exchange protocols were performed on the selected leaf-pairs by adequate parameters of light, temperature, and air humidity and constant CO_2. In general, three of the four abiotic variables were kept constant, the fourth was changed in ascending or descending order during the measurements.

2.2.3. Procedure for laboratory measurements

Light responses were recorded between 0 and 1566 μmol m^{-2} s^{-1}, under fixed levels of carbon-dioxide (370 ppm), temperature (20ºC, 25ºC, 30ºC), and air humidity (1 to 19 mBar equal to 3,6 to 62,5 % relative air humidity). Temperature responses were recorded between 17,5 and 39,0ºC, under fixed levels of irradiation (1218 μmol m^{-2} s^{-1}), carbon-dioxide (370 ppm), and air water vapour (1 to 19 mBar equal with 3,6 to 62,5 % relative air humidity). Humidity responses were recorded between 1 and 19 mBar, under fixed levels of light (1218 μmol m^{-2} s^{-1}), carbon-dioxide (370 ppm), and temperature (20ºC, 25ºC, 30ºC).

2.2.3. Calculation of transpiration water loss

The leaf area of the experimental unit was determined by a leaf area meter. The following equation was used to determine water loss:

$$\mathbf{V} = \frac{\mathbf{E*A*t*M_{H_2O}}}{\boldsymbol{\rho}} \quad (1)$$

where **V** is water loss due to transpiration [m^3], **E** is the transpiration rate of the given period's value [mol $m^{-2}s^{-1}$], **A**: leaf surface [m^2], is the duration of the transpiration of the given period's value [s], $\mathbf{M_{H2O}}$ is the molar mass of water [g mol^{-1}], and **ρ** is the density of water [g m^{-3}].

Measurements were made with minimum and maximum values. The goal was to establish intervals for the rate of seasonal plant transpiration in a constructed wetland.

2.2.4. Calculation of evapotranspiration from field measurement results

For the investigation of the daily fluctuation, days that were ideal for research had to meet the following criteria:

- No inflow and outflow
- No precipitation
- Significant decrease in daily water levels

Apparently, the change in water level on such days depends only on the extent of evapotranspiration. I found 16 days that met the requirements.

2.3. The software used for detailed investigation of distribution types

Maple 16, regular procedure was used to make the fittings. Maple 16 is a mathematical software, in which the calculation procedures can be easily and simply programmed, this software was thus chosen for performing fitting optimization. The program fits Fatigue Life, Lognormal, Fréchet, Pearson5, Inverse Gaussian distributions for different measurement series. Functions were selected by pre-screening by DITTRICH and KLINCSIK (2015a). Input distributions have three parameters (**a, b, c**), but the program examines the condition **c** = 0 as well. Parameter **c** expresses its x-axis delay for each distribution. The goal was to find the best fit R^2 value.

2.4. Description of the program used to fit the divided convective-dispersive model

During the research the divided convective-dispersive transport (D-CDT) model was also fitted (DITTRICH and KLINCSIK 2015b) to the measurement results. This model was assumed to be a more suitable method for fitting the measurement results of the inner points of the constructed wetland than the ones used in the literature so far. The model generates an Inverse Gaussian curve for the high-speed mainstream (herein after referred to as the 1st IG curve) and a completely independent Inverse Gaussian curve for the side stream flowing through the low-speed micropore system (herein after referred to as the 2nd IG curve). With the fitting method, only the main stream was assumed to play a significant role in the rapidly rising phase of the measured response function. The **s** parameter can be used to specify the ratio of the area under the 1st IG curve to the total area. At first, **s** was an arbitrarily added value, and the first IG curve was fitted to the fast growing part of the measured data series. Subsequently, the difference between the measured data and the 1st IG curve was calculated. The 2nd IG curve was fitted onto the difference curve. The value **s** was moved by 0.01, and the best fitting integrated D-CDT curve was searched. This model is a divided convective-dispersive transport (D-CDT) model that fixes the ratio of the main and side-streams. and with the help of the parameter (**s**), it also records the proportion of processes in the main and side streams.

3. Results

3.1. Results of laboratory transpiration measurements

Using the method presented in chapters 2.1.1.-2.1.3., measurements were performed on the tufted sedge obtained from the constructed wetland in Hódmezővásárhely under laboratory conditions. The transpiration of the tufted sedge was investigated using three environmental parameters (temperature, humidity and irradiation). For measurement of the plant transpiration characteristics of the environmental response curves of model plant individuals were described based on three parameters examined (Figure 1.). Considering light responses, as expected, saturation curves were more or less progressively increasing in all seasons.

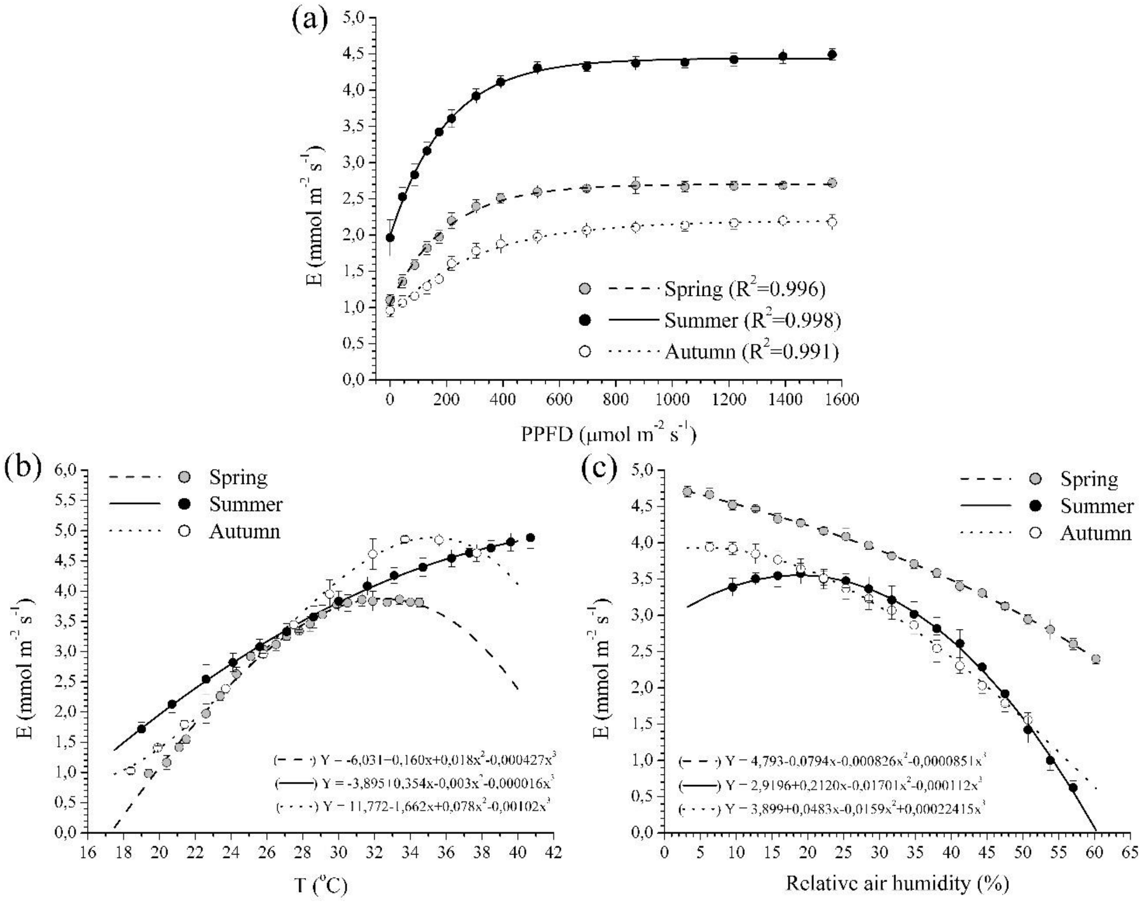

Figure 1. Transpiration rates (E) of Tufted-sedge (Carex elata) to (a) light (PPFD: Photosynthetic Photon Flux Density); (b) leaf temperature (T), and (c) relative air humidity (RH). Light responses refer to mean temperatures in the seasons (Spring: 20±2,5 °C; Summer: 30±2,5 °C; Autumn: 25±2,5 °C); first order exponential curves are constructed in a wide range of irradiation (0 to 1566 µmol m^{-2} s^{-1}). Third order polynomials are calculated for standardized temperature (17,5 to 42,0 °C) and humidity (3,2 to 60,2 %) ranges corresponding with the representative levels of environmental parameters of the seasons

Transpiration was the lowest in spring and increased over time. During spring and summer, the maximum rate of transpiration was reached at a relatively low level of irradiation (198,5 and 197,7 μmol m^{-2} s^{-1}, respectively). During autumn, maximum water loss (302,5 μmol m^{-2} s^{-1}) required a more intense irradiation. There was no close correlation with transpiration and the mean temperature increase of the seasons.

Temperature responses steadily increased throughout the seasons, and third-order polynomial curves fitted best to the changes of transpiration. The most dynamic transpiration increase was observed during summer, at temperatures above 40°C. During autumn and spring, water loss was highest at lower temperatures (35.5 and 32.5°C, respectively). This phenomenon shows that the water loss process in the model plant can be controlled by temperature conditions during spring and autumn, which means a seasonal abiotic constraint.

The final environmental response studied was humidity. Increasing water content of the air caused a monotonous decrease in transpiration. In general, there is increased water loss at a lower level of humidity which can dramatically decrease with increasing air humidity. During summer, extreme low humidity can decrease transpiration, which means that at elevated temperatures transpiration can be controlled by water conditions. Accordingly, low atmospheric humidity coupled with high temperatures may be an environmental barrier to reaching maximum transpiration.

The most significant part of plants' water release is through the stomas, which account for nearly 90% of all water loss. An important factor in this is the water vapour concentration gradient between the leaf and the surrounding airspace. There are an average 100 stomas per square millimetre on the leaf surface, but there can be up to ten times more. The stoma millings are quite small, even in an open state, they account for a maximum of 1-2% of the total leaf area. Stoma openings also ensure water release and carbon sequestration. Plants have different ways to ensure that enough carbon dioxide enters the leaf for photosynthesis, but the concomitant release of water is kept to a minimum. From among external environmental factors, stoma movement is mostly regulated by carbon dioxide concentration, light, temperature, and air humidity. Higher concentrations of carbon dioxide in the intercellular passages of leaves lead to stoma closure, while lower concentrations lead to stoma opening. However, at higher temperatures, respiration increases more strongly than photosynthesis, leading to even higher concentrations of carbon dioxide in the leaf and ultimately leading to stoma closure. As air humidity decreases, transpiration through open stomas increases.

3.1.2. Water losses due to seasonal transpiration of the constructed wetland

Based on the calculation method presented in Chapter 2.1.4., seasonal intervals were determined for the amount of water loss caused by transpiration in the constructed wetland. Results presented in chapter 3.1.1. were used for the calculation.

The total leaf area of the four sampling units was 2,65 m^2. The leaf area of the CW was estimated based on this value. The surface of the constructed wetland was 25,2 m^2 yielding an estimated leaf surface of 267 m^2.

During spring, daytime water losses via transpiration were between 0,46–0,83 m^3 and under typical climatic conditions water loss was 0,50 m^3. The daily influent wastewater was around 1 m^3, which means that in spring this value is half the amount of daily influent wastewater. During summer, daytime water losses via transpiration were between 0,52–1,08 m^3 and under typical climatic conditions water loss was 0,97 m^3. This value suggests that the water loss can account for almost 100% of the daily hydraulic load. The excess water above 100 % comes from the constructed wetland. During autumn, the daytime water loss via transpiration was 0,17–0,48 m^3 and under typical climatic conditions water loss was 0,31 m^3, which is lower than the spring values.

In summary, under extreme daytime weather conditions the water loss caused by transpiration can exceed the rate of hydraulic loading. This conclusion is very important for effluent concentration and emission limit values.

In the laboratory measurements, the effect of wind was not taken into account, which can nevertheless, influence the temperature and humidity in the constructed wetland even during the day, and consequently can have a considerable effect on transpiration. In addition, the effect of clouds was not taken into account either, which can also influence irradiation and temperature during the day.

3.2. Measurement results of the daily evapotranspiration

From the database, the daily evapotranspiration was investigated for 16 days, and based on these 16 days I also determined the seasonal evapotranspiration. My studies also focused on how the maximum hydraulic load and evapotranspiration were related to each other.

Daily evapotranspiration values and the degree of condensation were compared to the maximum hydraulic load. In horizontal subsurface flow constructed wetlands this value is 40 mm/day (MASZESZ MI-I-1:2003). Daytime and nighttime evapotranspiration were separated. I drew the following conclusion from the results:

- On the days under investigation, 71,7-93,1% of the total daily amount evaporated during the daytime hours, it means that the concentration processes caused by evapotranspiration were 4-10 times more potent during daytime than nighttime in this constructed wetland.
- The evapotranspiration at night is significant, as there were some days when the nighttime water loss via evapotranspiration was 21,9-28,3 % of the total daily water loss,
- There were days when the condensation values were high, therefore, the daytime and nighttime ratio could not be divided

  During the spring, the evapotranspiration varied between 18,0-42,6 mm/day, which was 45,0 -106,0 % of the maximum hydraulic load.
- During the summer, the evapotranspiration varied between 12,3-42,3 mm/day, which was 30,8-105,8 % of the maximum hydraulic load.
- During autumn the evapotranspiration ranged between 13,6-22,7 mm/day, which was 34,0-56,8 % of the maximum hydraulic load.
- Days when there was measurable condensation in the constructed wetland, the value varied between 1,8 to 10,0 % of the daily maximum hydraulic load, especially, after sunrise the condensation may decrease the concentration in the CW.

The peak spring hourly evapotranspiration was around 16,3 % of the daily evapotranspiration, this value was around 15,8 % in summer and 16,2 % in autumn. The maximum spring hourly evapotranspiration was 42,6 mm/day, this value was 6,9 mm/h, which was 415 % of the average hourly hydraulic load (1,7 mm/h) of this constructed wetland. In summer and autumn these values are 229 % and 150 % of the average hourly hydraulic load of the constructed wetland.

This means that the concentration processes occurring during the spring and summer can be extremely significant.

3.3. Fitting results of the distributions used to describe transport processes

In the course of my research, I fitted the following 5 density functions to the results of conservative tracer measurements at the inner points of constructed wetland in Hódmezővásrhely: Fatigue Life, Fréchet, Inverse Gaussian, LogNormal, and Pearson5. A customized program in Maple software was used for the fittings. For the S/1 measurement, the sampling data refer to the two-day CW. (The installation took place on 01.09.2007.) Generally, points I-III. gave good results. These points were characterized by fast-rising, peaked curves. The second segment (IV-VI.) had wider, flatter curves, caused by leakage rate deceleration and mixing processes. In the case of point VII-IX., the measurement results were no longer included in the run of the function, so the fitting results significantly deteriorated.

The results of the S/2 measurement present the transport processes of the constructed wetland at age 1 month. The first segment produced similarly favourable fittings. However, in the case of the second segment, only point IV. showed flatter functions. For points V-VI., similarly good fittings were found than at the first section. This is possible due to the inhomogeneous flow distribution in this cross section (IV-VI.). At point IV., the root growth and the biofilm activity caused a slower flow. At points V. and VI., the flow was faster as the there were less roots and the biofilm activity was lower.

The measurement of the S/3 was perhaps the most difficult to fit the functions to. For the first two sections (points I. to VI.), the picture of all functions showed that the area under the specified function was too small, only for the third section was it identical to the area drawn by the measurement points. The reason for this observation was that the wastewater was misaligned without pre-treatment in the vertical flow constructed wetland and this led to significant clogging in the horizontal subsurface flow constructed wetland.

The other reason is that the roots of the tufted sedge have developed during the first five months in the constructed wetland, resulting in further flow distortions. Due to the development of dead spaces, there is intense biofilm activity and clogging processes, and secondary stream is becoming more significant. This is clearly visible on the following figure (figure 2.). The red arrows show the second peaks (side stream). The black line shows the Fréchet, the black dotted line the Pearson 5, the blue dashed line the Fatigue Life, the green dashed line the Inverse

Gaussian, and the yellow dashed line represents the 1-dimensional convective-dispersive transport model (Inverse-Gaussian distribution).

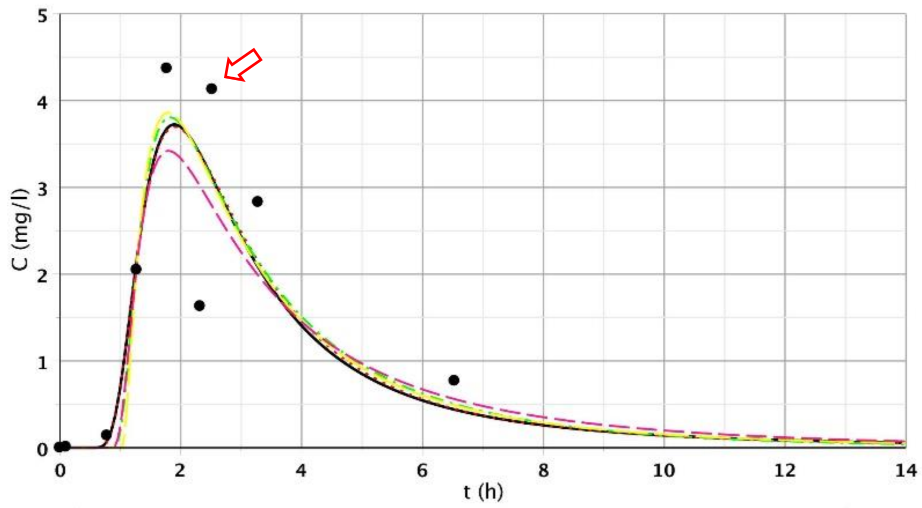

Figure 2.: Fitting results of the 5 distribution functions and the CDT model on the S/3 VI. bottom point

The results of the last measurement were better, as a result of to the changed filter media of the constructed wetland. The results were completely different from the S/3 results; nevertheless, the results obtained were as expected. There is a functional problem for this S/4 measurement that has to be mentioned. As there was a two-peak curve which revealed worse fittings, the use of the divided convective-dispersive model was needed. This model could not only fit the first but the second peak as well, and it gave much better fitting results than for example the CDT model.

Fitting results of the top and bottom measuring points R^2 values were examined. In the case of the top points, only Fréchet and Pearson5 gave a better fit than the bottom points; the others were weaker, and when applying the Inverse Gaussian, the average R^2 of the top points gave very bad fittings. When setting the functions' fitting order, Fréchet and Pearson5 ranked first and second and the Inverse Gaussian ranked last. The top layer, with slower flow and denser roots, is characterised by more dead zones and more intense biofilm activity. The functions are difficult to adapt to these conditions. This means that the main flow is at the bottom.

I compared inner points results with the effluent results (DITTRICH and KLINCSIK 2015a). The order was similar to that found in the previous measurements. The two best-fit functions were Fréchet and Pearson5, the worst was the Inverse Gaussian.

It is important to note that for internal points, the standard deviation of the R^2 average was higher, and that the internal points yielded worse fitting results than the effluent points. The average of R^2 for any function did not reach 0,95, so none of these fit measurement points well.

This is due to the fact that the tracer carried by the liquid fibers coming from different directions is integrated in the outflow section. Therefore, some of the flow distortions compensate for each other. This is why, the measurement results in the outflow section give a "smoother" curve than in the internal points. The uniqueness and value of my research is that these analyses were performed in a more diverse system. Taking these into account, it came as a great surprise and scientific finding that the same distribution function gave the best fit for the more extreme processes measured at the internal points. The Fréchet distribution is used to estimate extreme events, mainly because of its flexibility, so it is possible that this distribution also gave the best fit at the internal points. To the best of my knowledge, the Fréchet distribution for fitting the interior points of a constructed wetland has not yet been analyzed by any other study to date.

3.4. Use of a 1-dimensional convective-dispersive transport model and a 1-dimensional divided convective-dispersive model for horizontal subsurface flow constructed wetland

3.4.1. Fitting results of the 1-dimensional convective-dispersive model and the 1-dimensional divided convective-dispersive model

The model presented in Chapter 2.4. was fitted to the measurement results of the tracer taken at the interior points of the constructed wetland. Both top and bottom samplings were performed at the inner points, primarily, to examine the differences in flow processes in the top and bottom layers. The aim was to prove that the divided convective-dispersive transport model can be applied to the interior points as well. Publications to date have applied this model exclusively to the entire constructed wetland (DITTRICH and KLINCSIK 2015b). The results help to better understand the complexity and variability of transport processes within the system.

All fitted curves had better fitting properties than the very well fitting Fréchet distribution and CDT model. All measurements average R^2 values were above 0,96. In the S/2 measurement, results showed the biggest differences between the D-CDT model (0,97) and the CDT model (0,88) R^2 values.

Fitting figure below shows the considerable differences in the three functions.

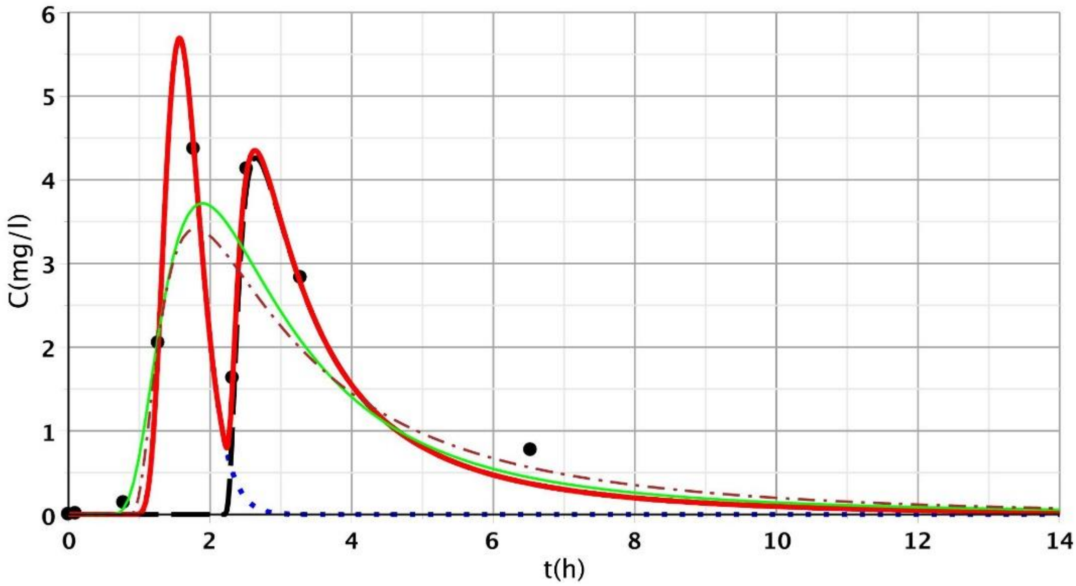

Figure 3.: Fitting results of the three models (D-CDT, Fréchet, CDT) on the S/3 VI. top point

In Figure 3. the black dots show measurement results, the blue line shows the first Inverse Gaussian curve, the black dashed line shows the second Inverse Gaussian curve, the green line represents the Fréchet distribution, the red dashed line the one dimensional convected-dispersive transport model, and the red line shows the D-CDT model. Figure 3. demonstrates that at the second peak only the D-CDT model fitted well.

3.4.2. Porous velocity, dispersion coefficient calculated from the divided convective-dispersive model and comparison with the currently used method

Transport parameters (porous velocity and dispersion coefficient) obtainable from the CDT and D-CDT models were compared. At all top and bottom points of the first measurement it was the D-CDT model that provided higher porous velocity and lower dispersion coefficient values compared to the CDT model. However, in some cases there were big differences. The velocities were higher by 5,91-71,99 % and dispersion coefficients were lower by 0,00-352,06%.

Results of the second measurements showed that the D-CDT model provided (except the VI. top point) higher porous velocity and lower dispersion coefficient values than the CDT model in most cases. The velocities were higher by 0,40-82,52 % and dispersion coefficients were lower by 11,46-394,66 %.

Results gained at the third measurements it was the D-CDT model that provided the best fitting result in most cases (except for bottom point IV.). Therefore, the model needs to be further improved. It showed higher porous velocity and lower dispersion coefficient values than the CDT model. The velocities were higher by 7,76-81,14 % and dispersion coefficients were lower by 2,53-343,13 %.

Results of the last measurement with the D-CDT model provided higher porous velocity and lower dispersion coefficient values at all top and bottom points compared to the CDT model. The velocities were higher by 11,84-97,18 % and dispersion coefficients were lower by 11,11-390,66 %.

4. Conclusions, suggestions

4.1. Conclusions

The first part of the dissertation discusses the water loss of constructed wetland by transpiration in spring, summer, and autumn. First, I measured the transpiration of the sedge, which planted on the constructed wetland under laboratory conditions, then I determined the amount of sedge in the constructed wetland, finally calculated the water loss due to seasonal transpiration. The results showed that in the spring, water loss by daily transpiration was 46-83% of the hydraulic load. In the spring, there may be days when the water balance is significantly affected by the transpiration of plants. In summer, this value ranged from 52 to 108% water loss by transpiration. It can be seen from the values that even the total amount of wastewater discharged per day can be evaporated by the vegetation, therefore, the water supply of the horizontal subsurface flow constructed wetland is significantly reduced. As a result, the concentration in the constructed wetland may increase, which may also increase the effluent concentration. In the autumn, water loss by daily transpiration ranged from 17 to 48%. Overall, compared to the hydraulic load, the vegetation had a significant effect on the water balance of the constructed wetland, including the efficiency of treatment.

The next part of my dissertation, provides daily evapotranspiration data determined for spring, summer, and autumn based on field measurement data sets. On the studied days, 71,7-93,1% of the total water loss evaporated during the daytime, which means that the concentration processes caused by evapotranspiration were 4-10 times more potent during daytime than nighttime in this constructed wetland. Nighttime evapotranspiration was significant. There were days when 20,9-28,3% of the total water loss was caused by nighttime evapotranspiration, which is an important scientific result as the literature considers nighttime evapotranspiration to be 0 (GALVAÓ et al. 2010). On the studied spring days, the evapotranspiration ranged from 18,0 to 42,6 mm / day, which was 45,0 to 106,5% of the maximum hydraulic load. In summer, these values ranged from 12,3 to 42,3 mm / day. which was 30,8-105,8% of the maximum hydraulic load. In the autumn, the evapotranspiration was between 13,6 and 22,7 mm / day, which was 34,0-56,8% of the hydraulic load.

I also investigated the effect of morning and evening condensation on the water balance of the constructed wetland. Condensation raises the water level in the constructed wetland and results in 100% humidity, so there was no transpiration by plants at the time. There was a spring day when hourly evapotranspiration accounted for 16% of daily evapotranspiration, which means that this value was 415% of the average hourly hydraulic load. In summer, this value was 229%, while in autumn it was 150%. Concentration in spring and summer has a particularly significant effect on effluent water quality.

In the next chapter of my dissertation, I investigated density functions that may fit the measurement results of the conservative tracer better than those currently in use. Measurements proved that the Inverse Gaussian function gave the worst fit from among the investigated distribution function types, despite the fact that it is the most commonly used type of distribution in the literature. The analytical solution of the currently used CDT model is the Inverse Gaussian distribution, so it can be stated that the currently used CDT model is not suitable for accurate modelling, as the R^2 value did not reach the 0,95 fit value either. The error increases with the age of the constructed wetland. The Fréchet density function was found to follow the response curves best, so it can be said that the response curves obtained from the conservative tracer measurements taken at the inner points of the horizontal subsurface flow constructed wetland filled with coarse gravel had a Fréchet distribution. Where the response curve had two peaks, none of the investigated distribution types was suitable for accurately describing the response function.

The last part of my dissertation discusses results obtained by fitting the divided convective-dispersive model to the measurement results of the conservative tracer taken at the interior points of the constructed wetland. This model actually fits two independent Inverse Gaussian curves on the main stream and the side stream and makes a curve out of them that, as the results have shown, fits better than the CDT model. There were fittings where there was a big difference between the two models. The results also show that the main stream in the 9-month-old structure was in the bottom layer and dead spaces and hydraulic short circuits formed in the top layers. These appeared mainly due to the presence of roots and biofilm formation. With regard to the calculated porous velocity and dispersion coefficient, the D-CDT model showed a difference of 0,40-97,18% and 0,00-394,66% compared to the results obtained using the CDT model. Accordingly, the D-CDT model was closer to real hydraulic conditions. Based on the results, it can be stated that the developed D-CDT model can be applied to the internal points of the structure in order to get a more accurate and understandable picture of the hydraulic behaviour of the horizontal subsurface flow constructed wetland and the transport processes taking place in it

4.2. Thesis-like summary of results

Thesis 1.: Estimation of the transpiration in spring, summer, and autumn using laboratory measurements in a horizontal subsurface flow constructed wetland filled with coarse gravel planted with tufted sedge.

During laboratory measurements, I determined the minimum and maximum water loss caused by transpiration in spring, summer, and autumn in horizontal subsurface flow constructed wetland filled with coarse gravel and planted with tufted sedge under local climatic conditions. During the spring, water loss values caused by transpiration account for 46-83% of the daily hydraulic loading rate, while during the summer this value can be as high as 52-108%, which means that there may be days or weeks in summer when concentrations of wastewater may occur due to water loss. This value accounts for 17-48% of the monthly wastewater discharged in the autumn. Measurements revealed that out of light, temperature and humidity it is the latter that has the most significant impact upon the extent of transpiration.
Published in: Dittrich, E., Salamon-Albert É., Somfai D., Dolgos-Kovács A., Kiss T. (2019): Transpiration effect of Tufted sedge for a horizontal subsurface flow constructed wetland. Water Science and Technology 79(10) 1905-1911 p.

Thesis 2.: Determination of the evolution of daily evapotranspiration in horizontal subsurface flow constructed wetland filled with coarse gravel planted with tufted sedge under local climatic conditions in spring, summer and autumn

Based on the analysis of the measurement results, the value of the daytime evapotranspiration in the spring, summer and autumn period is 71,7–93,1% of the daily evapotranspiration. Consequently, it can be stated that the concentration processes caused by evapotranspiration were 4–10 times more intense during daytime than nighttime in planted horizontal subsurface flow constructed wetland filled with coarse gravel. Nighttime evapotranspiration was significant, there were days when nighttime evapotranspiration accounted for 21,0–28,3% of total water loss. The spring daily evapotranspiration was determined to be 18-42,6 mm / day, which is 45-106,5% of the daily hydraulic loading rate. The summer daily evapotranspiration was 12,3-42,3 mm / day, which was 30-105,8% of the daily hydraulic loading rate. The autumn

values varied between 13,6-22,7 mm / day, which was 34-56% of the daily hydraulic loading rate.
Published in: Dittrich, E., Somfai, D., Dolgos-Kovacs A., Salamon-Albert É. (2020): Estimated seasonal daily evapotranspiration rates for a horizontal subsurface flow constructed wetland. Review of Faculty of Engineering Analecta Technica Szegedinensia, 14(2) 1-12 p.

Thesis 3.: The effect of morning and evening condensation on the water management of horizontal subsurface flow constructed wetland filled with coarse gravel planted with tufted sedge under local climatic conditions.

Condensation can be observed around sunrise and sunset if temperature and humidity values are ideal. This works in two ways. On the one hand, the condensed vapour increases the water supply of the constructed wetland, on the other hand, the transpiration decreases for a short time due to the near 100% humidity. On the days studied, I determined the degree of condensation at night and at morning under local climatic conditions. The combined amount of nighttime and morning condensation was 1.8 and 10% of the maximum hydraulic load, which mostly reduces the concentration in the constructed wetland in the post-sunrise period and completely or partially inhibits plant transpiration.
Published in: Dittrich, E., Somfai, D., Dolgos-Kovacs A., Salamon-Albert É. (2020): Estimated seasonal daily evapotranspiration rates for a horizontal subsurface flow constructed wetland. Review of Faculty of Engineering Analecta Technica Szegedinensia, 14(2) 1-12 p.

Thesis 4.: Innovative application of custom software in horizontal subsurface flow constructed wetland filled with coarse gravel planted with tufted sedge to reduce measurement errors of conservative tracer-test on the interior points using Fréchet distribution.

A mathematical method developed in MAPLE environment was used, which can be used to reduce the measurement errors of conservative tracer transport studies at the internal points of a constructed wetland. The method fits a continuous function to the conservative tracer transport measurement results, which takes into account the boundary conditions and constraints imposed by the physical processes. This allows for continuous curves to be obtained from discrete measurements with 100% material recovery, which can enable precise transport process analyses. With the help of the software, it has been proved that the transport processes of planted horizontal subsurface flow constructed wetland filled with coarse gravel can be approximated with the highest accuracy by the Fréchet distribution in the case where the response function has one peak. Further research is needed for determining response function with two peaks. Furthermore, it has been indirectly, mathematically proved that the analytical solution of the 1-dimensional convective-dispersive transport equation at a fixed location, on a quarter of the concentration-time plane, fits inaccurately with the investigated measurement results.Published in: Dittrich, E., Klincsik, M., Somfai, D., Dolgos-Kovacs A., Kiss T., Szekeres A. (2021): Analysis of conservative tracer measurement results inside a planted horizontal subsurface flow constructed wetland filled with coarse gravel using Fréchet distribution**.** Environmental Science and Pollution Research 28(5) 5180-5204 p. (Impact Factor: 3,056)

Thesis 5.: Innovative use of divided convective-dispersive model in a planted horizontal subsurface flow constructed wetland filled with coarse gravel for modelling internal transport processes through conservative tracer-test.

A 1-dimensional divided convective-dispersive transport model was applied to more accurately model the internal transport processes in a planted horizontal subsurface flow constructed wetland filled with coarse gravel than other models published so far. Compared to the results of the currently most commonly used convective-dispersive model, our model gave a result, which was closer to reality, by 0,40-97,66% in terms of flow rate and 0,00-394,66% in terms of dispersion coefficient. Based on the results of my function fitting studies, I hypothesized that only the main stream plays a significant role in the rapidly rising phase of the measured response function. The generated model is in fact a divided convective-dispersive model that generates the flow process from the sum of two independent convective-dispersive Inverse Gaussian curves while recording the ratio of the processes in the main stream and the side stream, assuming the parallel course of the two processes. The results also confirmed that the most popular convective-dispersive transport model in the international literature is more inaccurate in describing the processes occurring in the interior points of planted horizontal subsurface flow constructed wetland filled with coarse gravel. The main internal flow path was also determined using the same model.

Published in: Dittrich, E., Klincsik, M., Somfai, D., Dolgos-Kovacs A., Kiss, T., Szekeres, A. (2021): Application of divided convective-dispersive transport model to simulate variability of conservative transport processes inside a planted horizontal subsurface flow constructed wetland. Environmental Science and Pollution Research, 28 15966–15994 p. (Impact Factor: 3,056)

Related publications

1. Peer-reviewed research articles

1.1. With impact factor (according to WEB OF SCIENCE), in English

1.1.1. Hungarian publisher

1.1.2. International publisher

E. Dittrich, É. Salamon-Albert, **D. Somfai**, A. Dolgos-Kovács, and T. Kiss, “Transpiration effect of Tufted sedge for a horizontal subsurface flow constructed wetland,” Water Science and Technology, 79 1905–1911 p. IF: 1,624 (2019)

E. Dittrich, M. Klincsik, **D. Somfai**, A. Dolgos-Kovács, T. Kiss, A. Szekeres (2020): Analysis of conservative tracer measurement results inside a planted horizontal sub-surface flow constructed wetland filled with coarse gravel using Fréchet distribution. Environmental Science and Pollution Research, 28, pp. 5180–5204, IF:3,056 (2021)

E. Dittrich, M. Klincsik, **D. Somfai**, A. Dolgos-Kovács, T. Kiss, A. Szekeres (2020): Application of divided convective-dispersive transport model to simulate variability of conservative transport processes inside a planted horizontal sub-surface flow constructed wetland. Environmental Science and Pollution Research, 28 15966–15994 p. 3,056 (2021)

1.2. In foreign language, non impact factor

1.2.1. Hungarian publisher

D. Somfai ,E. Dittrich, É. Salamon- Albert, A. Dolgos-Kovács (2020): Estimated seasonal daily evapotranspiration rates for a horizontal subsurface flow constructed wetland. *Analecta Technica Szegedinesia* Vol. 14., II.

1.2.2. International publisher

1.3.In Hungarian, non impact factor

Somfai D., Dittrich E., Dolgosné Kovács A. (2020): Innovatív szennyvíztisztító kutatótelep Pécsen. *Dunakavics* VIII. évfolyam, X. szám

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