

EXPERIENCES ON HYDRAULIC PERFORMANCE OF SUB–SURFACE FLOW CONSTRUCTED WETLANDS

Erno DITTRICH

Department of Environmental Engineering, Pollack Mihály Faculty of Engineering,
University of Pécs, Boszorkány u. 2, H–7624 Pécs, Hungary, e–mail: dittrich@witch.pmmf.hu

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Abstract: In this article new result of international researches focused on the hydraulic behavior of the subsurface–flow constructed wetlands (SF–CW–s) for wastewater treatment are shown. The results presented below are focused on the tracer experiments to simulate transport processes, the effect of Total Suspended Solids (TSS) and organic substances loads, and the effect of macrophytes, meteorological conditions. The Hungarian experiences of constructed wetlands are compared to that of international ones and the main differences are discussed. The main considerations of comparison are: specific load of organic substances, specific load of TSS, specific hydraulic load, the type of soil, the pre–treatment systems, etc. The conclusion of this comparison is the main directions of development of the subsurface–flow constructed wetlands in Hungary.

Keywords: Subsurface–flow constructed wetlands, Hydraulic transport and mixing, Clogging, TSS load, Load of organic substances, Macrophytes

1. Introduction

Designing, constructing and operating of wastewater treatment plants is one of the important parts of civil engineering practice and significant part of environmental protection, too. So, lot of engineers and scientists are interested in development and research of wastewater systems. Today, a range of different wastewater treatment systems is available. These can be classified as follows:

- a) Intensive technologies such as activated sludge systems, trickling filters, Sequencing Batch Reactors (SBR), etc;

- b) Extensive technologies such as ponds, constructed wetlands (CW-s), irrigation systems, etc.

Simple construction, large buffering capacity, little excess sludge production, simple operation and maintenance, low operational and maintenance costs are the main advantages of extensive systems [1].

CW-s are used as wastewater treatment systems from the 70's, when Kickuth (1977) published his root-zone method. CW-s as wastewater treatment systems are very popular in West-Europe, USA and Australia and are getting popular worldwide. Two main different type, can be designed within CW-s:

- a) Free-surface flow systems (FS-CW-s);
- b) Sub-surface flow systems (SF-CW-s).

In FS-CW the wastewater flows through the system with free surface. In the SF-CW-s – usually pre-treated – the wastewater flows through the filter media is planted with macrophytes (f.e. *Phragmites australis*).

The first Hungarian SF-CW was constructed in Tóalmás in 1991 [2]. Now there are 16 SF-CW-s in Hungary. There are 10 domestic wastewater treatment plants (Boldog, Kacorlak, Kám, Salgótarján, Sióagárd, Szépalmapusztá, Szügy, Tóalmás, Fertőrákos, Komlódtótfalu) and 3 septic-tank disposal treatment plants (Aparhant, Magyarbóly, Bakonyszombathely) and 2 industrial wastewater treatment plants (Kerecsend, Demjén). There is an agricultural wastewater treatment plant in Hódmezővásárhely. The Hungarian experiences of operational SF-CW-s are more unfavorable than the West-European ones. This is one of the reasons why SF-CW as wastewater treatment technology type is not too popular. This article will show that is mainly owing to inadequacies of the Hungarian designing practice.

The aim of this article to show the new results of international researches focused on the hydraulic behavior and on the problems of numerical hydraulic modeling of the subsurface-flow constructed wetlands (SF-CW-s) for wastewater treatment. This article will make a comparison between the Hungarian and the international experiences. The conclusion will be the main directions of development of the subsurface-flow constructed wetlands in Hungary.

2. Main construction types

There are two main construction types of SF-CW-s:

- a) Vertical flow systems (*Fig. 1*);
- b) Horizontal flow systems (*Fig. 2*).

The main differences between these two types are the main flow direction, the contact time, the mode of oxygen transport, and the saturation in the volume of substrate.

3. Ideal flow distribution in SF-CW-s

3.1. Ideal flow distribution in horizontal flow systems

Let us suppose that the filter media has the same condition in time and in its volume, and the flow-system is permanent saturated flow. The most simple equation expressing the flow regime in horizontal flow systems is Darcys' law [3]:

$$v = \text{grad}(-k \cdot h), \quad (1)$$

where v is the pore-water velocity [m/d], k is the hydraulic conductivity of media [m/d], h is the level of pressure potential [m].

If it is supposed that the flow-regime is one-dimensional and the bottom slope is constant, we can get the simple form of Darcy's law:

$$v = k \cdot S, \text{ or } Q = A_c \cdot k \cdot S, \quad (2)$$

where S is the bottom slope [m/m], Q is the hydraulic loading rate [m³/d], A_c is the cross sectional area [m²].

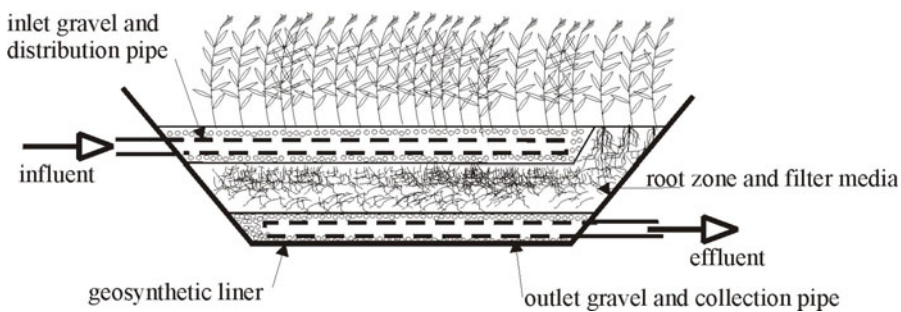


Fig.1. Cross section of vertical flow system

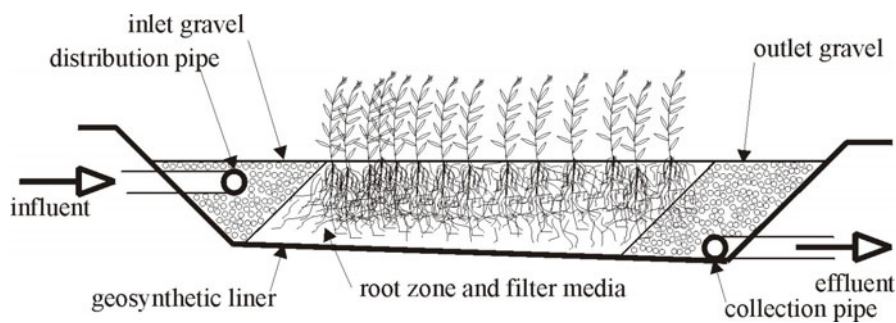


Fig.2. Horizontal flow system

The flow regime can be described 2 or 3 dimensionally with Boussinesq's equation. This is the 2D-form of Boussinesq's equation below [4]

$$\frac{\partial h(t,x) \cdot \frac{\partial z(t,x)}{\partial x}}{\partial x} = \frac{n}{k} \cdot \frac{\partial h(t,x)}{\partial t}, \quad (3)$$

where n is the porosity of the media [–], z is the distance between the water level and the fixed relative level [m], x is the horizontal coordinate [m], t is the time [d]. It has to be supposed that the distribution of flow is uniform along the distribution pipe at 2D describing mode. The hydraulic processes can be modeled more precise with this equation as non-permanent, saturated flow. The main problem is that a huge amount of data is needed to calibrate the hydraulic-model. If data enough are available it could be solved to take changes of porosity and hydraulic conductivity in consideration in the hydraulic model.

3.2. Ideal flow distribution in vertical flow systems

There is unsaturated non-permanent flow in these types of systems with vertical flow direction. Let us suppose that the filter media has the same condition in time and in volume, and the flow-distribution is uniform along the distribution pipe-system. So the flow-regime can be described 2 or 3 dimensionally with Richard's equation [5, 6]

$$c(\psi) \cdot \frac{\partial \psi}{\partial t} = \frac{d\Theta}{dt} = -\frac{\partial}{\partial x} \cdot \left(k(\psi) \cdot \frac{\partial \psi}{\partial x} \right) - \frac{\partial}{\partial z} \cdot \left(k(\psi) \cdot \frac{\partial \psi + z}{\partial z} \right), \quad (4)$$

where Θ is the volumetric water content of the media [–], ψ is the matrix potential [m]. The main problems are that a huge amount of data is needed to calibrate the hydraulic-model, and dynamical changes of the water content in the pore-system.

3.3. Ideal transport processes in SF-CW-s

By injecting a tracer into the system, an assessment of the hydraulic regime can be obtained. After the injection the residence time distribution (RTD) can be measured at the outflow. The real average hydraulic retention time (HRT) can be calculated from RTD-function. The difference between the real HRT distribution and the theoretical HRT shows the degree of hydraulic irregularities.

The simplest method to design the hydraulics of SF-CW-s is the supposition of plug-flow in the construction. Than the theoretical HRT can be calculated as

$$HRT = \frac{n \cdot V}{Q}, \quad (5)$$

where V is the effective volume of substrate [m³].

The plug-flow design assumption does not describe adequately the water flow through the SF-CW [7]. The transport process of conservative tracer is composed of

advection and dispersion. The 1D transport equation to conservative tracer in porous media is [8]

$$\frac{\partial C}{\partial t} = \frac{\alpha_L \cdot v_x}{R} \cdot \frac{\partial^2 C}{\partial x^2} - \frac{v_x}{R} \frac{\partial C}{\partial x}, \quad (6)$$

$$\alpha_T \cdot v_x = D_x, \quad (7)$$

where D_x is the dispersion constant [m^2/d], $v_x = Q/A_c$ is the average pore-water velocity [m/d], α_L is the dispersion coefficient [m], R is the retardation coefficient [–], C is the tracer concentration [g/m^3], x is the longitudinal coordinate [m], t is the time [d]. From this viewpoint the application of R is different from the conventional interpretation. In this solution R is applied to describe the dead-zones of flow regime. So in this case $R > 1$, and it can be calculated from the rate of dead-zones in the construction

$$R = \frac{V}{V - V_h}. \quad (8)$$

The momentum of conservative tracer injection can be described with the Dirac-delta function at $x=0$ and $t=0$

$$C_\delta(x,0) = \frac{M}{n \cdot m \cdot w \cdot R} \cdot \delta(x), \quad (9)$$

where M is the mass of tracer [kg], m is the average depth of water level [m], w is the infinitesimally small width of the flow-system [m]. If $C(\pm\infty, t)=0$, the analytical solution of the 1D transport equation (6) is [8]

$$C(x,t) = \frac{M}{2 \cdot w \cdot m \cdot n_0 \cdot R \cdot \sqrt{\frac{\pi \cdot \alpha_L \cdot v_x \cdot t}{R}}} \exp \left[-\frac{\left(x - \frac{v_x \cdot t}{R} \right)^2}{\frac{4 \alpha_L \cdot v_x \cdot t}{R}} \right]. \quad (10)$$

This solution is the Gauss-distribution curve. This curve flows with v_x/R average velocity, and the function of spreading is

$$\sigma = \sqrt{2 \alpha_L \cdot v_x \cdot t / R}. \quad (11)$$

It is easy to describe the transport of conservative tracer with these equations, if the significant parameters are known. The solution is illustrated in *Fig. 3*. The RTD-curve can be calculated from Eq. (10) at the measurement point, if $x=L$ [m] the distance from the injection point is known. The form of RTD-curve by way of ideal transport processes (dispersion and advection) is illustrated in *Fig. 4*.

4. Real flow distribution in SF–CW–s, international experiences

4.1. Main differences between ideal and real flow distribution

There are significant differences between ideal and real flow distribution. The main reasons of these differences are:

- a) the impacts of the weather: rainfall, evapotranspiration, freezing, snow melting;
- b) deficiencies of the construction: differences of hydraulic conductivity and porosity of the filter media, deficiencies of distribution pipe–system;
- c) clogging processes: deposition of organic and inorganic particles, microbial biomass (bio–film activity), root–growing in the filter–media, mechanical compaction of the media, chemical precipitation and deposition in media, entrapped gas blocking the pores.

The measures of these effects to the real flow distribution, have been collected in *Table I* from the international specified literature. A goal of recent research is to develop a numerical hydraulic model, that can able to simulate the real flow distribution. This model is based on the equations have been presented in Paragraph 2. The CW is modelised as a few Completely Stirred Tank Reactors (CSTR) in series. The number of these reactors depend on the measure of the effects are shown in *Table I*. In this hydraulic model it does not need to take in consideration the insignificant factors from the inelement effects (*Table I*). In spite of the fact the number of remainder factors are numerous, so the model calibration should be done step by step. The effects of factors should be separated at the data collection step because of the complex effects in the examined construction. This separation form a very interesting group of problem. The number of seasonally significant factors (group of weather factors) can be reduced by chosen of good weather period (f.e. chosen of dry and warm periods). The group of construction factors has to be measured before the clogging processes had started in the construction. The factors of clogging group are depending on the temperature, seasonality, hydraulic loading rate, TSS loading rate, organic–substances loading rate, etc. So, it needs to make a precise and komplex monitoring to separate the effects of these factors. The best method to separate these effects to measure tracer response curves step by step in the agequate “moments” in the lifetime of examined CW–s.

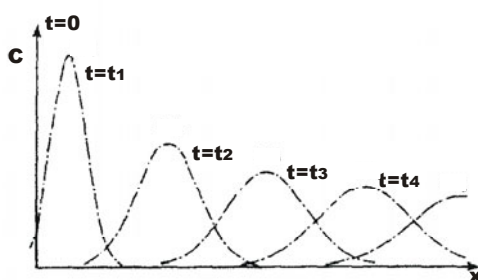


Fig.3. The transport of conservative tracer in porous media suggested plug flow with dispersion of [7]

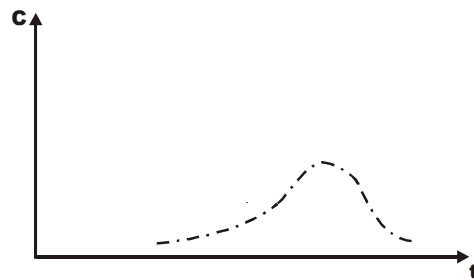


Fig. 4. The calculated RTD curve from the 1D transport equation

Table I

The measure of the effects to the flow distribution

Group of factors	Factors	Vertical flow system		Horizontal flow system	
		Measure of effect	Ref.	Measure of effect	Ref.
weather	rainfall	seasonally sign.	[7, 18]	seasonally sign.	[7, 15, 18]
	evapotraspiration	seasonally sign.	[7, 18]	seasonally sign.	[7, 9, 18]
	dissolution of snow	seasonally significant	–	seasonally sign.	–
	freezing	insignificant	–	insignificant	–
construction	diff. of hydr. cond. and porosity	significant	–	significant	[10]
	deficiencies of distr. pipe system	significant	–	significant	[19]
	shape of media volume	significant	[14]	significant	[14]
clogging	depositioning of particles	significant	[12, 14]	significant	
	microbial biomass	significant	[6, 12]	significant	
	root density	insignificant	[12]	significant	
	mechanical compction	insignificant	[12, 13]	insignificant	
	chemical precipitation	insignificant	[12, 13]	insignificant	
	gas blocking	insignificant	[12, 13]	insignificant	

As a result of these factors (*Table I*) there are inclement effects to the opeation of the constructions:

- a) inclement effects to the hydraulic behaviour: chanelling [9, 10], short-circuiting [9, 10], surface-flows [11], ponding [12, 13];
- b) inclement effects to the transport processes: irregular mixing processes [14], lower detention time than the theoretical value [9, 15, 16];

- c) inclement effects to the removal efficiencies: lower removal efficiencies [17], higher concentration–fluctuation in the effluent [17].

The irregularities of hydraulic behaviour can be described well with measured tracer response (RTD) curves (Fig. 5). This RTD–curves of Fig. 5 shows the significant deviation from plug flow by the difference between the measured HRT and the theoretical value. The different function–forms (Fig. 4 and Fig. 5) describe the impacts of the inclement factors well (Table I).

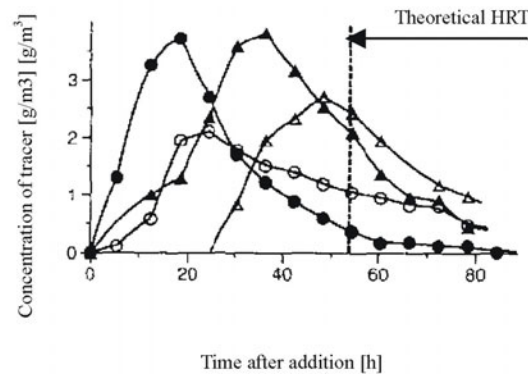


Fig. 5. Measured RTD curves of a few SF–CW according to [9]

4.2. Methods to reduction the irregularities of real flow distribution

The main goal at the design stage is to reduce these inclement effects in SF–CW–s. There are some methods collected from the international specific literature to reduce these impacts:

- 1) Application of sufficiently porous media and large enough contact–surface [14]:
The Germanian designing guideline suggests as minimal specific area to horizontal flow systems $5 \text{ m}^2/\text{pe}$ and $2.5 \text{ m}^2/\text{pe}$ to vertical flow systems. At horizontal flow systems the application of Darcy's law is not enough to calculate the width of SF–CW. The designed width should be higher because of clogging processes. According to Kickuth–theory (1981) when rhizomes die and decay, they may leave behind tubular pores and channels. This macro–pore system, increase and stabilize the hydraulic conductivity of the soil. So, after a 3–year–period the hydraulic conductivity of any soil will be developed to 10^{-3} m/s . According to the international experiences this statement does not work [17]. A significant part of wastewater flows through the SF–CW on the surface with minimal HRT, and because of this the removal efficiencies are lower than the designed values. In the international guidelines and articles the suggested filter media is only gravel with 3–5 mm minimal diameter in horizontal flow systems [20]. The high pore–volume is needed because of the inclement clogging processes.

- 2) In the vertical flow systems gravel should not be used as filter media because of the too short HRT. So the researchers usually suggest sand or sandy-gravel layer with 60 cm depth as filter media with gravel size of 0.06–4 mm. More criterias to filter media are $d_{10} > 0.2$ mm and $U = d_{60}/d_{10} < 5$ [21, 22].
- 3) Application pretreatment systems with high TSS removal efficient: The TSS-loading is one of the main reasons of clogging processes, so it has to be limited. The suggested maximum values are different in the literature: 5 g/m²,d [13], 7 g/m²,d [20].
- 4) Limitation of the organic substances loading: The organic substances loading is the other main reason of clogging processes, so it has to be limited too. The suggested maximum values from the literature are different: 20 gCOD/m²,d [13], 25 gCOD/m²,d [23], (COD: Chemical Oxygen Demand).
- 5) Resting beds periodically: The clogging process is partly reversible. In order to prevent the system from long term clogging, it is useful to have at least 2 or more beds in parallel, and operation periodically [12, 13].
- 6) Accurate placement of media and distribution-pipe system to get uniform media porosity and flow distribution [10].
- 7) Placement the surface of media with minimal back-slope: It is needed to reduce the decrease of HRT caused by surface flows.
- 8) Limitation of hydraulic loading rate (HLR). The maximum value of HLR should not exceed 40 mm/d at horizontal flow systems, and 60 mm/d at vertical flow systems [22, 24].

5. Analysis of Hungarian SF-CW-s

5.1. Data sources, and mode of analyses

The Department of Sanitary and Environmental Eng. at Budapest University of Technology and Economics made a surveying 2 about Hungarian SF-CW-s in 2002. The data from that study are including the investigation. Additional data are used from other Hungarian works and surveying [25, 26, 27, 28] and my own experiences. This database was not detailed enough to do deep analysis. Eventually main design parameters of seven Hungarian SF-CW-s were analyzed. All of them were constructed at the biological stage in the wastewater treatment technology. The operation of these plants started before 2002, so I have enough data and experiences about these plants.

A new research has been started to get more detailed data about Hungarian SF-CW-s. The main mode of the data collection is measurements focused on the missing data to deeper analysis.

Surface-flows, ponding, low removal efficiencies, and high concentration-fluctuation in the effluent show that there are hydraulical problems at the examined SF-CW-s. The main reasons of these operation problems are being showed below.

5.2. Raw wastewater quality and the pre-treatment systems

The concentration of wastewater is higher in Hungarian small communities than in the West-European countries (*Table II*). This is mainly because of the significantly lower water consumption, and the animal keeping at the households. In spite of the fact the pre-treatment systems applied at Hungarian wastewater treatment plants are the same as the West-European practice (*Table III*). There are attempts with chemical pre-treatment in Szügy. These attempts show that the TP removal efficiency can increase. So it needs to apply pre-treatment systems with higher removal efficiencies than the conventional ones. The limitation of TSS, and COD at the pre-treatment stage is especially important because of inclement clogging processes.

Table II

Raw wastewater quality in small communities

	West-European countries	Hungary
BOD [mg/l]	150–250	250–450
COD [mg/l]	300–450	550–1100
TSS [mg/l]	250–300	250–350
NH ₄ -N [mg/l]	15–50	15–200

(* BOD: Biochemical Oxygen Demand, ** NH₄-N: Ammonium–Nitrogen)

5.3. Specific area and HLR of SF–CW–s

The specific areas ranging from 6.2 to 7.9 m²/pe have been found at horizontal flow systems, and ranging from 0.8 to 2.2 m²/pe have been found at vertical flow systems (*Table IV*). The values of horizontal flow systems have been found to be appropriate, but the values of vertical flow systems are lower than the suggested values in German designing guidelines (min. 2.5 m²/pe). It has to be listened about the high influent concentrations so it needs to apply higher specific areas than the suggested minimum values.

Table III

Pre-treatment systems at examined treatment plants

Treatment plant	Pre-treatment system
Kacorlak	septic-tank
Kám	septic-tank
Salgótarján	sedimentation tank
Sióagárd	sedimentation tank
Szépalmapuszta	sedimentation tank
Tóalmás	sedimentation tank
Szügy	sedimentation tank + chemical pre-treatment

The values of HLR are from 10 to 30 mm/d at horizontal flow systems, and from 73 to 100 mm/d at vertical flow systems (*Table IV*). The calculated values of HLR are lower than the suggested maximum values (40 mm/d) at horizontal flow systems. The calculated range of HLR is higher than the suggested maximum values (60 mm/d). So it needs to reduce the HLR at Hungarian vertical flow SF-CW-s. That shows too, it needs to grow up the specific area of vertical flow systems in Hungary.

Table IV

Specific area and HLR of examined SF-CW-s

Construction type	SF-CW systems	Specific area [m ² /pe]	HLR [cm/day]
Horizontal flow system	Kacorlak (H.F.)	7.9	3
	Kám (H.F.)	6.2	1
Vertical flow system	Salgótarján (V.F.)	1	10
	Sióagárd (V.F.)	0.8	9.8
	Szépalmapuszta (V.F.)	1.35	7.4
	Tóalmás (V.F.)	1	10
	Szügy (V.F.)	2.2	7.3

5.4. TSS-loading rate and COD-loading rate of Hungarian SF-CW-s

The specific TSS-loading rates ranging from 0.44 g/m²,d to 0.45 g/m²,d were found at examined horizontal flow systems, and from 0.44 g/m²,d to 17.4–0.44 g/m²,d at vertical flow systems (*Table V*). 5–7 g/m²,d is suggested as maximum value by the international literature. So the calculated TSS-loading rate is too high at Szügy and Sióagárd. The specific COD-loading values are from 3.3 to 5.1 gCOD/m²,d at horizontal flow systems, and from 5.1 to 43.3 gCOD/m²,d at vertical flow systems (*Table V*). The values of horizontal flow systems are appropriate but the values of vertical flow systems are higher than the suggested maximum values in international specific articles (20–25 g/m²,d). There are especially high COD-loading rates in Sióagárd and Szépalmapuszta.

5.5. Filter media at Hungarian SF-CW-s

The applied filter media is soil in the examined horizontal flow systems. These systems were built supported to Kickuth-theory. The Hungarian experiences are the same as the international ones. A big part of wastewater flows through the SF-CW-s with surface-flow [2, 28]. This is because of the low hydraulic conductivity of soil based filter media.

At the vertical flow systems the applied filter media is sand 2 usually with fractions of natural grain-distribution. The filter media is clogged at the examined vertical flow

systems. So it seems to be not a good practice because the level of fine fraction is usually too high in natural sand. It is important to limit fine fraction in the filter media (f.e.: $d_{10} > 0.2$ mm and $U < 5$) to reduce the risk of clogging.

Table V

TSS- and COD-loading rates of examined SF-CW-s

Construction type	SF-CW systems	Specific TSS-loading rate [$\text{g}/\text{m}^2, \text{d}$]	Specific COD-loading rate [$\text{gCOD}/\text{m}^2, \text{d}$]
Horizontal flow system	Kacorlak (H.F.)	0.45	5.1
	Kám (H.F.)	0.44	3.3
Vertical flow system	Salgótarján (V.F.)	6.6	8.8
	Sióagárd (V.F.)	9.8	43.3
	Szépalmapuszta (V.F.)	4	35.5
	Tóalmás (V.F.)	2.8	5.1
	Szűgy (V.F.)	17.4	23.7

6. Conclusions

A new research with rigorous monitoring has been started to get more detailed data about real hydraulic distribution and real mixing processes in SF-CW-s. This needs more detailed data to do deeper analysis and calibrate hydraulic and transport models. The calibrated transport model could help us to work out more precise design methods. Further research is needed to get measured data and theoretical results closer to each other.

Conclusions as regards the construction and operation of SF-CW-s, based on the evaluation of Hungarian data and international experiences are as follows:

- The horizontal flow systems based on Kichkuth-theory does not work. So soil should not be used as filter media.
- At the design stage it needs to apply sufficiently porous media (grain with $d_{\min}=3-5$ mm) and large enough contact surfaces at the Hungarian horizontal flow systems. Darcy's law does not work to calculate the cross sectional area because of the clogging processes.
- It needs to apply pre-treatment systems with higher TSS and COD removal efficiencies than the conventional pre-treatment systems (septic tank or sedimentation tank) in Hungary, because of the high raw wastewater concentration in Hungarian small communities.
- It is very important to use higher specific area and limitation of the hydraulic loading rate at the design stage especially at the vertical flow systems.
- It is important to limit fine fraction in the filter media (f.e.: $d_{10} > 0.2$ and $U < 5$) to reduce the risk of clogging at Hungarian vertical flow systems.

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