Chemical Engineering Journal 321 (2017) 86–96

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Seasonal and ageing effects on SFTW hydrodynamics study by full-scale tracer experiments and dynamic time warping algorithms

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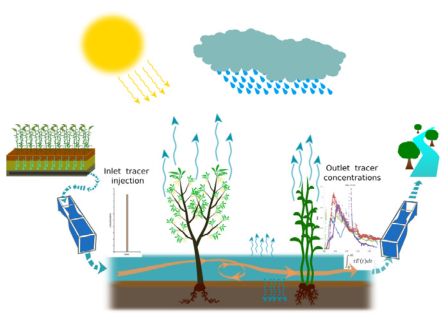
HIGHLIGHTS

- Seasonal characterization of SFTW hydraulic behavior in full-scale system.
- Evidence of ageing effect on surface flow treatment wetland.
- Breakthrough curves comparison by dynamic time warping method.
- Highest short-cutting index and strongest advective flow regime occurred in winter.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 4 March 2017
Accepted 6 March 2017
Available online 16 March 2017

Keywords:
Surface flow constructed wetland
Residence time distribution
Dynamic time warping
Fluorescent tracers
Hydraulic behavior

ABSTRACT

Surface flow treatment wetlands (SFTW) are considered as ecological engineering treatment wetlands used for wastewater and stormwater treatment. In France SFTW are commonly located between the wastewater treatment plant (WWTP) and the receiving aquatic environment. Furthermore, they are not considered as a regulatory treatment step but as a complementary element to WWTP. In this regard, there is currently no established design and sizing rule since (i) they are built on the remaining space after WWTP construction, (ii) it is a nature-based system, subject to high variability and complex interactions and (iii) feedback on ageing effects is lacking. This study permitted to qualify and to quantify seasonal and ageing effects on the SFTW hydraulic behavior which is a pond. The combination of fluorescent dye tracer application in a real system and data analysis by dynamic time warping (DTW) allowed to perform efficiency comparisons between all campaigns. Similar behaviors of dimensionless retention time distributions were observed for all campaigns. They were eventually linked with the SFTW shape. The analysis of these curves highlighted that the measured mean residence time was always lower than the nominal hydraulic residence time, due to preferential flow and dead-zones. A statistical approach suggested that the winter hydraulic behavior was characterized by the highest short-cutting index and strongest convective flow regime in comparison to others campaigns. A lower vegetation density, especially subaquatic plants, and presence of important preferential flow could explain this observation. DTW processing on RTD curves shed light on the ageing effect that has a much bigger impact than seasonal effect. This is mainly due to sediments accumulation, sludge and vegetation development.

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http://dx.doi.org/10.1016/j.cej.2017.03.013
1385-8947/

Nomenclature

σ_c^2	RTD variance
θ	dimensionless time
τ	theoretical residence time
AFBDTW	adaptative feature based DTW
ATR	tracer retention by area
C	tracer concentration
C_{max}	maximal tracer concentration
$C(t)$	tracer concentration at time t
CD	cumulative distances
CD_X	minimal cumulative distance calculated thanks to the algorithm X.
DDTW	derivative DTW
DTW	dynamic time warping
E(t)	residence time distribution (RTD)
FBDTW	feature based DTW
GC	global warp cost
GC_X	global warp cost calculates thanks to the algorithm X
M_{out}	total mass of recovered tracer
Pe	Peclet number
P.E.	people-equivalent
R	tracer recovery
RTD	residence time Distribution
$S_{Aut.}$	autumn fluorometer signal
SFTW	surface flow treatment wetlands
SPA	specific peak attenuation
SRB	sulforhodamine B
SS	suspended solids
$S_{Spri.}$	spring fluorometer signal
$S_{Sum.}$	summer fluorometer signal
STR	specific tracer retention
STR	specific tracer retention
S_{Win}	winter fluorometer signal
T	nominal hydraulic residence time
t	mean residence time
TSS	total Suspended Solids
TW	treatment Wetlands
V_{sys}	mean water volume of the wetland system during the tracer study
WWTP	wastewater treatment plant

1. Introduction

1.1. SFTW in French context

Surface flow treatment wetlands (SFTW) are considered as ecological engineering treatment wetlands used for wastewater and stormwater treatment. SFTWs have water flowing above the surface of a permanently saturated soil in a horizontal direction, flowing through macrophytic vegetation [7]. In France, since 2009, there is an increase of SFTW commonly known as “Planted Discharge Areas” [22] built between the wastewater treatment plant (WWTP) and the receiving aquatic environment. They are considered as a complementary treatment to WWTP but there is no regulatory removal efficiencies envisioned. Considering international references, this study approaches the case of a pond as an aquatic system. Nevertheless, to be consistent with French context and previous studies [12,21], SFTW acronym is used in this study.

The main expected ecosystem services are [17] (i) particulate matter retention: Total Suspended Solids (TSS) from WWTP by-pass (overflow during rain events for combined sewer systems) or due to secondary clarifier failure, (ii) limitation of hydraulic and pollutants loads to surface waters through infiltration, evapotranspiration or evaporation [3], (iii) hydraulic peak attenuation in order to protect surface water bodies from erosion and washout, (iv) complementary pollutant mitigation: in this case, the wetland acts as a polishing step usually focusing on nutrients, pathogens and micro-pollutants removal [29]. The main mechanisms likely to be involved are [27]:

- Infiltration;
- Evapotranspiration;
- Biological degradation;
- Nutrients uptake by plants;
- Photo-degradation or transformation;
- Settling.

Most of these processes follow kinetics with orders different than 0. As such, their efficiency depends on the residence time of contaminants inside the system. However, there is no established design and sizing rule for this kind of treatment wetland at present since (i) they are built on remaining space after WWTP construction, (ii) it is a nature-based system, subject to high variability and complex interactions (iii) feedback on ageing effects is lacking and (iv) in France they are not considered as regulatory treatment step. Resulting surfaces and shapes may not be optimal and lead to strong non-idealities of the flow: preferential pathways, mixed zones, dead-zones as well as internal recirculation could occur and affect the wetland mitigation capacity [26]. Our previous study [12] highlighted that the various size and shapes of tertiary treatment SFTW strongly influence their hydrodynamic properties and in turn their contaminant mitigation capacities. Systemic models deriving from the concepts of chemical reaction engineering [14] were successfully developed to simulate the hydrodynamic behavior of three different SFTWs. However, residence time distribution and hydraulic parameters are expected to change due to seasonal and ageing effects. These effects include WWTP inflow variations due to the variability of water discharges, water drainage from raining events, sediment accumulation, climatic conditions and seasonal vegetation evolution.

1.2. SFTW ageing

Ageing is mainly caused by Suspended Solids (SS) accumulation that occurs over years in the system. The SFTW receives water from the upstream WWTP but also from the hydraulic by-pass resulting from long-lasting rain events or any WWTP malfunction. Thus, in this context, the SFTW is the last step before sewage is discharged into the receiving water body. Furthermore, according to seasonal cycles, plants generate significant head-losses and/or further SS accumulation, hence a reduction of the flow volume and a strong impact on hydraulic behavior [9].

In this study, four dye tracer experiments involving a fluorescent dye were carried out on a full-scale tertiary SFTW at different times of the year. Breakthrough curves analysis following the statistical moments method as well as interpretation thanks to dynamic time warping algorithms allowed the observation of ageing or seasonal effect on hydrodynamics.

2. Materials and method

2.1. Study site description

The studied SFTW is located in Lutter (Alsace, France). The upstream WWTP consists of a two stages vertical flow constructed