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Modelling of a constructed wetland for pesticide mitigation

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Abstract

The Water Framework Directive and the Ecophyto 2018 plan provides for measures against water chemical pollution. In the agricultural context, pesticide are a real stress for surrounding environment. Measures have been taken to reduce this stress, namely the reduction of chemical application, and the implantation of buffer zones like artificial wetland at the outlet of the agricultural watershed. A PhD thesis has begun in November 2012 on the modelling of the wetland functioning for pesticide mitigation. This work takes place in the team TAPAHS in the unit Hydrosystem and Bioprocesses of the Institute Irstea. The motivation of this work takes birth in the preceding studies of the team on the removal efficiency of a wetland regarding several pesticides. Several tools are yet available to reach our objectives. An experimental site has been instrumented in the city of Rampillon (France) and a state of art is under construction. The bibliography's study focus on two subjects: the tracer experiments and the constructed wetlands models which have been developed. These tools lead to a methodology which we propose to follow for the next steps of the PhD thesis.

Keywords

Hydrodynamic modelling, transport modelling, shallow water, wetland, vegetation

INTRODUCTION

General context of the study

Water resources are subject to anthropological stress, via industrial, domestic and agricultural wastewater. Europe assumes its responsibility by taking measures to protect the resource. On 23 October 2000, the EU Water Framework Directive was adopted. In 2006, a groundwater Directive has been developed. Member States are required to take actions to meet the quality standards in the "Environmental Quality Standards Directives – EQSD" (Directive 2008/105/EC) by 2015.

In addition to this European legislation, France adopted in 2008 the plan "Ecophyto 2018", which aims to encourage the change in agricultural practices concerning the use of pesticide. However, the change in practices is unfortunately not enough to reach the objectives. Even if the pesticide applications are reduced, the water coming from crops still contains pollutants. The pollutant load can be then reduced by collecting this water before to release it in the natural environment. For this purpose, wetlands have shown a significant potential for pesticides mitigation.

The wetland system

Wetlands consist of cohabitation between water, plants and some kind of media (Kadlec and Wallace, 2009). It can be either natural or constructed. Our study deals with free-water surface wetland. This means that we do not consider either infiltration into the soil or underground flow.

A large part of natural wetlands are nowadays protected, because of the biodiversity which is sheltered by the system, namely insects, molluscs, fish, amphibians, reptiles, bird, and mammals. In addition with this ecological function, wetlands have a pollutant treatment potential. In fact, physical and chemical processes can appear in the wetland, such as sedimentation, sorption or photo-degradation. Those mitigation processes are facilitated by the large biodiversity and the vegetation. Constructed wetlands aim to reproduce these natural wetland functions.

The treatment function of a wetland has been well studied in the agricultural context for nutrient as nitrates and phosphorus (Kadlec and Wallace, 2009). Similar ideas have been explored more recently for pesticide. Namely, the team TAPAHS of the Institute Irstea studies this question for several years. So far, the performance of a constructed wetland for pesticide mitigation was studied in the PhD thesis of Passeport E. (Passeport, 2010). A constructed wetland which collects drained water of agricultural field has been instrumented in the middle west of France (Bray, 47) to collect experimental data. On average, the artificial wetland reduced pesticides loads by 73% (Passeport, 2010). Several other works come to the same conclusion. Braskerud and Haarstad (2003) found pesticide reduction between 0 to 67% according to a study realized on a constructed wetland in Norway and a complete removal (100%) of the pesticide atrazine has been recorded by Kao et al. (2001).

Performance and optimization of a constructed wetland

The previous results suggest a real potential of such ecological solution for pesticides mitigation. It is then possible to estimate the performance and the optimization of the wetland with the help of the three following parameters.

- The *removal efficiency* of a wetland is the parameter which provides its pollutant mitigation performance. It represents the ratio of the pollutant mass which enters the system to the mass of the same pollutant which leaves it. This parameter strongly depends on the time spent by the pollutant in the wetland. Degradation and physical processes may need long time. It is the reason why the flow pattern has to be optimize to maximise the retention time in the wetland.

- Secondly, the *hydraulic efficiency* (λ) represents the ratio of the mean real time spent by the water in the wetland to the nominal time:

  $$\lambda = \frac{\tau}{t_n}$$

  with τ the mean value of the residence time and t_n the nominal time (ratio of the wetland's volume to the flow ; $t_n = \frac{V}{Q}$) . This parameter gives a good idea of the optimization degree of the wetland.

- The *volume efficiency* (e_v) represents the volume mobilized for the flow divided by the entire volume of the wetland. If a significant part of the wetland volume is never used for the flow, the active volume will be considerably diminished. The water flows faster and short-circuiting occurs. The retention time is therefore reduced.

We have seen above that the performance of the system depends on its flow pattern and the time spent in the wetland. It is then important to determine the hydraulic response of the system prior to including the chemical and biological behaviour. To better understand the mechanisms which influence the hydraulic characteristics, several models have been developed. The numerical approach enables to simulate different scenarios and investigate larger possibilities than field experiment. However, it is important to notice that the modelling task is constrained by the complexity of the system. So far, Su et al. (2009), studied the influence of the aspect ratio (the length (L) divided by the width (W) of a CW) on the hydraulic efficiency for a non-vegetated pond. The result of the hydrodynamic simulations suggests to recommend an aspect ratio higher than 1.88 to reach a hydraulic efficiency of 0.7. Others studies explore the interior plan of the wetland (bathymetry, island, baffles) and their influence on the flow pattern (Persson, 2005; Wörman and Kronnas, 2005; Lightbody et al., 2009). The fundamental transport processes, as advection and diffusion, have been also studied. Some works examine the influence of the vegetation on this transport processes (Burke and Wadzuk, 2009; Kadlec, 1990; Nepf et al., 1997).

Concerning the chemical degradation of pesticide, light, temperature, pH, oxygen and the presence of micro-organisms in the wetland are also important factors which can influence the removal efficiency.

These scientific considerations have allowed to establish several rules for wetland design (e.g. the practical guide of Economopoulou and Tsihrintzis (2004)). It is important to notice that the available place, the land ownership and other related economics factors have also to be accounted.

The objectives of the PhD thesis

The aim of my PhD work is to contribute to the understanding and modelling of the realistic wetland. We will investigate several approaches which could be adopted for numerical modelling. Namely, we suggest to emphasize the following scientific questions:

Wetland representation:
- Which scale has to be used for the numerical modelling of the constructed wetland?
- Which processes (advection, diffusion, coupled phenomena) have to be accounted?
- How the vegetation blocks/zones have to be presented in the model (roughness, porous media ...)?

Modelling consideration:
- How to couple efficiently a design optimization tool and a physical model?
- Finally, how to validate the model?

This present paper aims to present the material already available to reach the objectives. As a result, we propose a methodology that we could follow.

MATERIAL

We firstly describe the experimental site of Rampillon, and then we present the preliminary state of art on hydraulic characterization of constructed wetland.

Site description

Rampillon's wetland

The experimental wetland is located in the city of Rampillon (70 km south-east of Paris, France) in a 500 ha watershed. The surrounding area is mostly tile-drained agricultural field (Tournebize et al., 2012). The wetland collects the drained water of around 80 ha of drained parcels. A pipe of 500 mm is placed at the inlet of the basin as at the outlet. Then, the water flows in a deep region, excavated in order to lower the velocity and to enhance sedimentation. The configuration of the wetland, the dykes and the vegetation cover are shown on the Figure 1. The principal characteristics of the constructed wetland are presented in the Table 1.

Table 1: Characteristics of the wetland

	Rampillon wetland values
Basin max length (m)	114,5
Basin max width (m)	61,2
Deep zone depth (m)	0,95
Shallow zone depth (m)	0.3 – 0.6
Q_{in} (l/s)	0 - 110
Q_{out} (l/s)	0 - 120
Sparse vegetation cover (%)	30
Dense vegetation cover (%)	15
Volume (m^3)	2000 - 4000

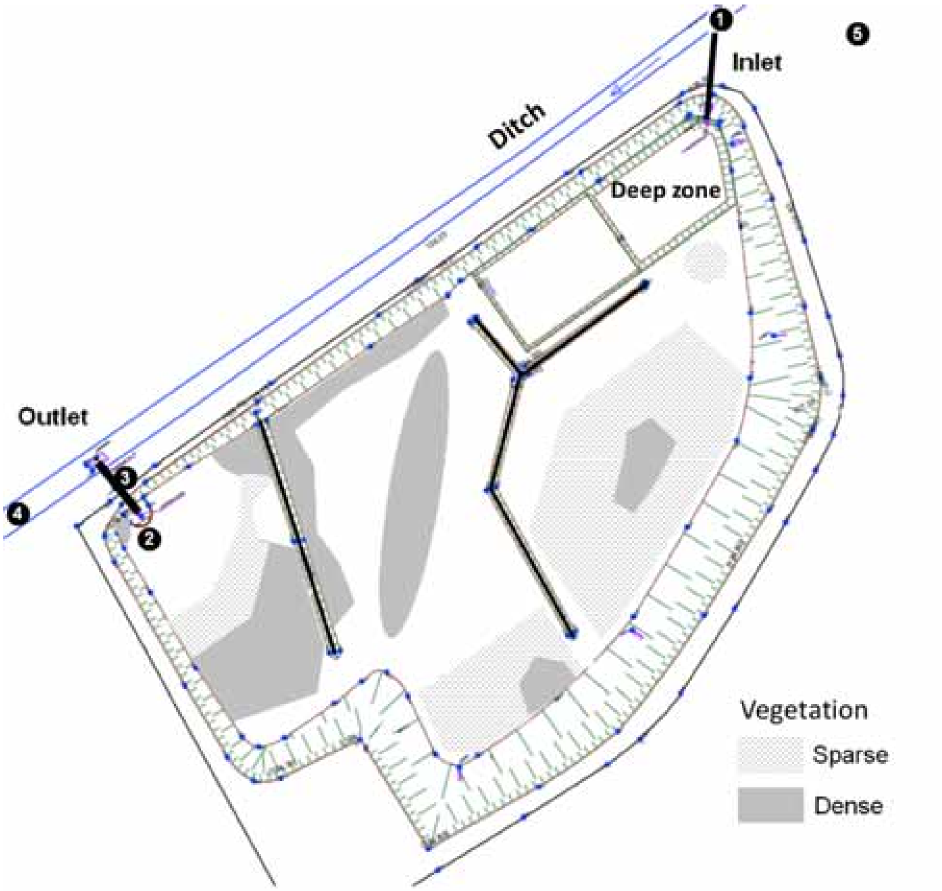

Figure 1: Rampillon's wetland. The numbers show locations of experimental equipment.

Equipment

To evaluate the performance of the wetland, equipment has been installed at the five locations shown on the Figure 1. The record of the data has begun in 2006 in the ditch (location 4), downstream the outlet of the wetland, and sometimes later for other locations as indicated in the Table 2.

Table 2: Beginning of the data collection on the experimental site

		T(°c)	h (m)	v (m/s)	C(µS/cm)	Water Samples	Rain gauge (mm)
1	Inlet	Oct 2012	Dec 2011	Dec 2011	Oct 2012	Dec 2011	-
2	Inside	Sept 2011	Sept 2011	-	-	-	-
3	Outlet	Oct 2012	Dec 2011	Dec 2011	Oct 2012	Dec 2011	-
4	Ditch	-	2006	2006	-	Oct 2012	-
5	Outside	-	-	-	-	-	Dec 2011

At the inlet and outlet of the CW, all measurements are performed on the bottom of the pipes. The water sampler is automatic and the sampling is set up at a constant flow weight volume. The composite sample is then got back each two weeks. The rain gauge is located next to the inlet. The temperature and depth measurement in the wetland (location 2) are carried out just before the outlet. The measurements in the ditch are fulfilled about 5 metres downstream the outlet pipe.

All the measurements are nowadays stored but not yet explored. The water samples are frozen for future analysis of about 70 pesticides molecules with the help of an external chemical laboratory. This data will be used for the calibration and the validation of our model.

State of art

Tracer experiment

Our main objective is to analyse the hydraulic characteristics of the wetland. The most popular field experiment to obtain such properties is the tracer test. It is nowadays well known this method is a convenient method to assess retention times, the degree of mixing and water velocities.

To realize this experiment, the tracer has to respect several properties:

(i) highly soluble in water,
(ii) does not react with constituents within the wetland
(iii) easy and inexpensive to analyse
(iv)low toxicity
(v) does not influence the flow pathway.

Bromide is used as conservative tracer (Keefe et al, 2004; Keefe et al., 2010; Min and Wise, 2009). Fluorescent tracers as Uranine, Rhodamine WT or Sulforhodamine can be used as a reactive tracer, because of their sensitive properties to photolysis and sorption (Keefe et al., 2004; Lange et al, 2011; Holland et al., 2004). Furthermore, they are considered as environmentally harmless and can be detected at very low concentration. Tritiated water has been used for its non-reactive property (Kjellin et al, 2006). More information about strengths and weaknesses of tracers used for wetland studies can be found in the practical guide by Headley and Kadlec (2007).

The experiment consists of introducing an impulse of an inert substance at the inlet of the wetland. After introducing the tracer, concentration measurements are recorded at the outlet. A breakthrough curve (tracer concentration = f(t)) is then formed. It usually has a bell-shape form.

This tracer response curve can be interpreted as a probability density function E(t) (h^{-1}) for residence times in the wetland referred to as hydraulic residence time distribution (RTD) (Kadlec, 1994) :

$$E(t) = \frac{C(t) * Q(t)}{\int_0^{\infty} C(t) * Q(t) dt}$$

The first moment of this distribution represents the mean residence time τ of the wetland.

$$\tau = \int_0^{\infty} t * E(t) dt$$

The second moment σ^2 is the variance of the distribution. It represents the spread of the breakthrough curve about the mean detention time.

$$\sigma^2 = \int_0^{\infty} (t - \tau)^2 * E(t) dt$$

The variance is used to characterize the degree of mixing and heterogeneity in the wetland (Lange et al, 2011; Holland et al 2004).

Finally, to be considered acceptable, the experiment has to present a recovery rate (*R*) of the tracer higher than 80% (Headley and Kadlec, 2007) :

$$R = \frac{\int_0^{\infty} C(t) * Q(t) dt}{M} * 100$$

with *C(t)* the outlet concentration of the tracer (mg/m^3), *Q(t)* the outlet flow (m^3/s) and *M* the masse injected at the inlet of the CW.

Wetland modelling

Two approaches have been developed to simulate the functioning of a wetland: the physically-based modelling and the conceptual modelling.

Physically based modelling

The physically-based modelling solves the Navier-Stokes equations to describe velocity and pressure distribution. The advection-diffusion equation is then used to describe the transport phenomena. The hydrodynamic and advection-diffusion simulations can be coupled to predict solute behaviour under various conditions.

Numerous studies simplify the system and replace 3D approach by a shallow water model (2D) (German et al, 2005; Su et al, 2009). This suggests that the variations in the vertical direction can be omitted because the vertical stratification is not dominant. To take into account the variation in the bathymetry, the depth-averaged Navier-Stokes equations are computed (Persson, 2004; Koskiaho, 2003; Kjellin et al, 2006; Min and Wise, 2009). Three-dimensional models have been used for non-vegetated pond (Shilton, 2000). Todays, this approach seems to be too much computationally expensive because of the complexity and the size of the system.

However, depending on the model, the vegetation is represented in different ways. It is mainly taken into account via the roughness coefficient or Manning coefficient (Min and Wise, 2009; Persson, 2005 ; Koskiaho, 2003). In recent work, the vegetation is also represented as a porous media (Mattis et al., 2012).

Conceptual modelling

Next, the conceptual modelling considers the wetland as a black-box and does not represent what happens physically inside. This approach is based on two opposite ideal reactors model: the plug flow reactor (PFR) model and the continuous stirred tank reactor (CSTR) model (Kadlec and Wallace, 2009). The PFR considers that each parcel of water which enters in the wetland has the same velocity, and no mixing occurs. The velocity of the fluid is assumed to be constant in each cross section perpendicular to the flow axis. The breakthrough curve at the outlet of the system in response of a pulse tracer experiment will be a pulse as well (Figure 2). The CSTR model considers that the water is continuously and uniformly mixed in the wetland. The concentration is instantly homogeneous. The breakthrough curve of such reactor is a decreasing exponential (Figure 2).

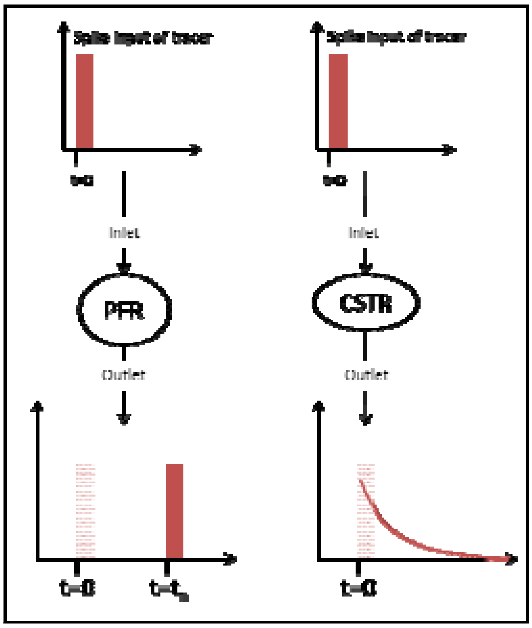

Figure 2: Comparison of tracer output of ideal reactors

However, the flow patterns through treatment wetland system are non-ideal and do not conform to either the PF or CSTR ideals. In fact, in free-water surface wetland environment, there are mixing processes on a number of different distance scales. The degree of mixing and heterogeneity in the wetland has to be considered. The following models include more complexity.

The “plug-flow with dispersion” model is a one-dimensional conceptual model which assumes that the flow pattern can be represented with dispersion process superimposed on a plug-flow model. The mixing processes follow a diffusion equation (Kadlec, 1994). The diffusive boundary conditions for wetlands are closed-closed conditions. This means that, at the inlet no tracer can diffuse back outside the wetland, and at the outlet no tracer can diffuse back up in the wetland (Folger, 1992). This model is characterized by a dimensionless dispersion parameter, the Peclet number which is proportional to the inverse of the wetland diffusion coefficient (Kadlec and Wallace, 2009).

The “Tank-in-series” model (TIS) represents the wetland by a number of equal-sized CSTRs in series. The flow enters the first CSTR, is instantly mixed, and flows into the next CSTR. Two parameters characterized this representation, the detention time (τ), and the number of CSTRs (N).
The "zones of diminished mixing" model represents the wetland as a plug flow connected with a very large number of CSTR (Werner and Kadlec, 2000; German et al. 2005). The lateral CSTRs represent zones of diminished mixing.
Finally, a combined one-dimensional model has been developed, the "OTIS" model. It combines a plug flow with dispersion, and adjacent storage zones. It aims to represent the dead zones an recirculation eddies (Martinez et al. 2003; Keefe et al., 2010).

RESULTS AND DISCUSSION

As a result of this preliminary bibliography study, a plan for the thesis is proposed.

I- Experimental results
II- Physically-based modelling
    i. Transport
    ii. Flow
b. Coupling
III- Simplified approach and optimization
IV- Validation and application

The first part concerns the field experiments results. Nowadays, no tracer test has been realized on the wetland of Rampillon. It is expected to prepare it in the following months. Also we are planning to develop an experiment inspired by Burke and al. (2012) to investigate the diffusion processes in the different parts of the wetland.

The second part deals with the modelling of the wetland. We may imagine to first consider modelling of transport phenomena in this heterogeneous system with a constant flow. Wetland could be considered as a porous media. Then a physically-based hydrodynamic simulation will allow to investigate the flow pattern (constant and transient). In this approach we will take into account the variable vegetation distribution. The next step will consist to find a methodology to couple these two signals (flow and transport). This physically-based approach will serve as a reference for simplified representation. The conceptual ideas shortly presented above have still to be discussed.

The third and fourth parts consider the optimization of the wetland design and the validation and application of the model. The work is nowadays not enough advanced to allow a description.

CONCLUSIONS

The work reported in this paper presents the first reflexions made concerning the PhD thesis. The ideas described in the results are nowadays just under construction and discussion. A more accurate bibliography report is also being written. The modelling work will begin as soon as possible. The first result collected will allow to feed the discussion about the further step to follow.

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