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Vegetation Effect on The Pollutant Transport- Laboratory channel Experiments and Simulations

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Abstract: Over the past decades, the Medjerda river, like most rivers, has seen its quality deteriorate. This water resources degradation is due to the development of urbanization, industrial and agricultural activities throughout the basin. In fact, natural watercourses generally receive domestic, industrial and agricultural waste; in some cases, accidental discharges are found in rivers and irrigation networks, such as the Medjerda Cap Bon channel. These discharges are generally punctual, and can cause various problems, for water quality, infrastructure, river morphology and they can also lead to hydraulic and road structures damage, which become more pronounced with the vegetation presence. This deterioration in water quality is particularly associated to several pollutants input. It is therefore important to know the rivers capacity to mix and transport these pollutants and to determine the pollutant dispersion rate in solution, as well as the particulate pollutant behavior. In this context was leaded this experimental analysis work concerning the pollution propagation in free surface flows, at a laboratory channel over a vegetated or smooth bottom. Two experimental scenarios were considered; the first one was leaded with a discontinuous pollution source (case of an accidental release), and the second one with a continuous pollution source (case of a permanent release). Then preliminary numerical simulations of these results were carried out. The aim is to show the vegetation effect on the pollutant propagation.

Nomenclature

A	Absorption (-)	n	Manning roughness coefficient (s/m$^{1/3}$)
A_x	Flow cross section (m²)	$\overline{P}$	Thermodynamic pressure (Pa)
D_L	longitudinal dispersion coefficient (m²/s)	Q	Flow rate (m^3/s)
F_x, F_z	Mass force resultant (-)	S	Section (m²)
K	Dispersion constant (-)	$\overline{U}, \overline{W}$	Mean flow velocity (m/s)
k	Proportionality coefficient (L.mol^{-1})	X, Z	Flow direction (-)
h	Water surface (m)	λ	Wavelength (-)
l	Length of the solution crossed by the light (-)	ε	Molar absorption coefficient (-)
M	Mass added (mg/l/s)	ν, ν_t	Kinematic viscosity (Molecular, turbulent) (m^2 s^{-1})

1. Introduction

Water pollution in free surface flows is a topic of a great interest to scientists. As a result, more and more researches are being done on water quality. They respond to a demand expressed by environmental protection specialists. (Yang *et al.,* 2016, Yvetta *et al.,* 2014). Remember that the natural environment can fight against pollution that remains in small proportions, this is what is called "self-purification". This biological process allows rivers and lakes to eliminate this pollution thanks to bacteria and algae. But, today and in front of all pollution types, nature's self-purification capacities are now insufficient (Khaldi, 2016). It all starts with the precipitation that feeds waterways and groundwater. Thus, each year and throughout their journey, some 70 billion m^3 of water become loaded with pollutants, urban, agricultural and industrial, before running off into waterways and contaminating them (Hermann *et al.,* 2014; Lagoun and Benziada, 2016).

Often the water quality is more important than the quantity. The water quality affects how we use it, but the reverse is also true. When we use water, we alter its quality. This vicious circle indicates that our long-standing habit of dumping untreated sewage and chemical wastes directly into rivers, lakes and seas for possible assimilation into the environment is no longer acceptable, whether from a technical or moral view point. (Ulrich, 2004; Ulrich *et al.,* 1990; Li *et al.,* 2019). Population explosion, industrial activity and the rate at which new chemicals and products are developed and used pose a threat to the global environment. The natural decomposition processes in water bodies are no longer sufficient to overcome these pollutants inputs. Technology can be used in many cases to reduce or eliminate substances that can harm the environment. (Benmamar *et al.,* 2008). But what happens when the contaminants are not removed, even by the most modern water treatment methods? They may be present in only minimal quantities; however, as they are persistent, they can accumulate to form very harmful concentrations (Romdhane *et al.,* 2020). In this case, there is only one way to protect future generations and the entire ecosystem, is to keep chemicals out of the river system. (Jabbour, 2006; Hart *et al.,* 2020). So, it has already been recognized that the excessive plant growth in streams is of great importance, as it can significantly affect flow patterns. Indeed, the vegetation can create a favorable condition to the deposition of fine sediment and pollutant, which later infiltrate in terrain and accumulate in the culture and then treat the human health (Alaqarbeh *et al.,* 2020). In fact, the vegetation presence represents wall roughness for flow, so it significantly changes the velocity profile, and modifies the transfer and transport of momentum, sediments, and pollutants. (Romdhane *et al.,* 2018, 2019a, 2019b).

Water resources have a paramount importance for humans, aquatic life and agriculture. However, the increasingly frequent presence of point pollution in rivers encourages the numerical simulation tools development to exactly determine the propagation rate of these pollutants and their concentrations as functions of space and time (Khaldi, 2016). These tools make it easy to provide more complete information and the results sought in a shorter time and at a relatively reduced cost. The pollutant evolution depends mainly on the flow characteristics that carry it. A precise presentation of all the hydrodynamic phenomena present in the receiving environment, including also turbulence, is therefore necessary (Benmamar and Arrar, 2004; Hermann *et al.,* 2013, 2019).

The objective of this research work is therefore to experimentally analyze the propagation of such pollution in free surface flows.

2. Methodology

2.1 Spectrophotometry principle

Spectrophotometry is the field that studies the energy measurement carried by electromagnetic radiation in the visible light field. It is a quantitative and qualitative analytical method that measures the absorbance or optical density of a given chemical, usually in solution. The more concentrated the sample, the lighter it absorbs within the limits of proportionality set out by the Beer-Lambert law. (Hart *et al.,* 2020; Yang *et al.,* 2016). The samples optical density is determined by a spectrometer previously calibrated on the absorption wavelength of the studied substance. The absorbance A at the solution wavelength λ depends on the solution concentration (C) and the solution length (l) crossed by the light (**Eqn. 1**):

$$A = k \times C \qquad \textbf{Eqn. 1}$$

with A: Absorption (without unit); C: Molar concentration (mol. L^{-1}) and K= $\varepsilon * l$ ($L.mol^{-1}$): called Proportionality coefficient and is constant for a given chemical species and wavelength.

The pollutant chosen for this study is the potassium permanganate ($KMnO_4$) (0.1 N) having an initial concentration $C_0 = 0.02$ mol/l, which is a purple-colored, water-soluble chemical compound. It can be seen that potassium permanganate has an absorption maximum for a wavelength λ = 530 nm and has a second non-negligible absorption peak for λ = 550 nm. After measuring the absorption of the 5 diluted solutions by the spectrophotometer, the calibration curve A (C) was plotted **(Figure 1).**

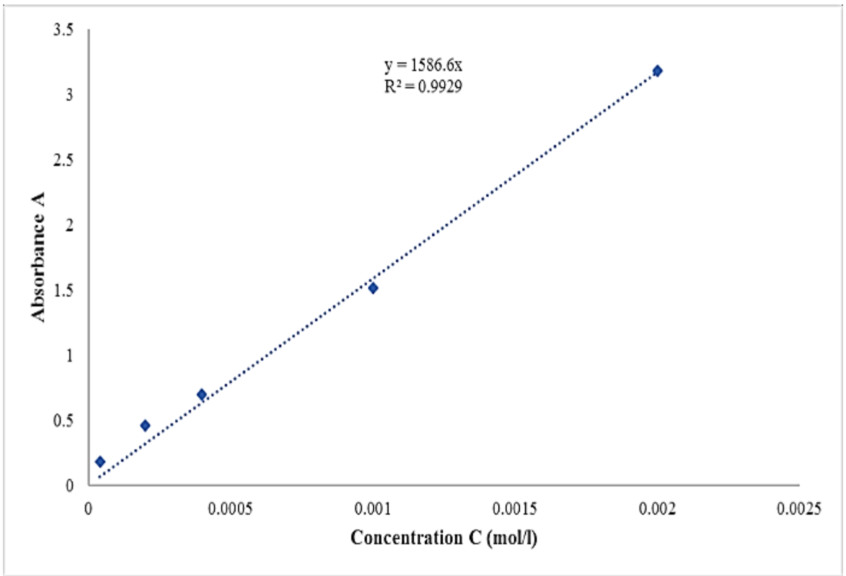

Figure 1. Calibration Curve of a Potassium Permanganate solution

According to the Beer-Lambert law, A is a linear function of C so the curve A (C) is a line passing through the origin. This curve is the calibration curve which makes it possible to determine the concentrations of various samples taken from the channel, it has a determination coefficient close to the unity ($R^2 = 0.9929$) and a coefficient K = 1586.6 for this case. It is therefore sufficient to measure the absorbance of each sample by the spectrophotometer and then project on the curve and read its abscissa which represents the concentration. (Benmamar *et al.,* 2004, 2008).

2.2 Experiments

Experiments were carried out in a rectangular channel at the National Institute of Agronomy of Tunisia in the laboratory of water science and technology **(Figure 2).** These experiments concern the analyses of a solution pollutants transport phenomenon in two cases, over smooth bed and over a vegetated bed. To do this, a concentrated solution of a tracer (potassium permanganate) was injected upstream at the channel, then water sampling was taken as functions of time at the channel center and for the different scenarios. This is in order to measure the dye concentrations, using a laboratory spectrophotometer. The objective was to analyze the dye propagation phenomena, and to understand the dispersion rate of this pollutant in the water, and the effect of the bottom vegetation presence on this phenomenon. (Romdhane *et al.,* 2018, 2019a, 2019b).

Figure 2. Experimental Setup at the INAT laboratory (Length: 10m; width: 0.8m; Hight: 0.6m)

The injection and withdrawal operations were carried out through a set of syringes.

Two experimental scenarios were carried out: a discontinuous pollution source case (model of an accidental release case), where the pollutant injection was carried out upstream the channel for 20 seconds and then it was stopped; and a continuous pollution source case (model of a permanent release case), where the pollutant injection into the channel upstream was done permanently. These two scenarios were carried out over the smooth bed and then over the vegetated bed.

These experiments were carried out initially with several flow rates and a dye fixed concentration. Secondly, this concentration was varied and the flow rate was kept constant. We will therefore analyze the increasing flow rate effect on the mixing rate, and also the varying concentrations effect. Sampling were taken in the middle of the channel after 2 m from the injection point.

3. Results and discussions

During the different scenarios carried out, we observe that the pollution dispersion occurs according to two mechanisms which are convection and turbulent diffusion. In fact, first the pollutant moves longitudinally (cloudy movement of the pollutant in the flow direction, X) according to the flow velocity effect, it is the advection process; and afterwards it gains the whole width of the channel and so decreases in concentrations within the cloud, it is the dispersion phenomenon. (Benmamar et al., 2004, 2008; Lagoun and Benziada, 2016). So, when a quantity of polluted material is released into a river, whether it is an accident or an intentional release, a stain forms and begins to expand. The pollutants concentrations reduction in the task is carried out by several mechanisms:

a. The vertical turbulent diffusion which tends to mix the polluting material over the entire depth;

b. The horizontal turbulent diffusion which tends to mix the polluting material over the entire width of the river;
c. The longitudinal differential convection which moves one part of the spot away from another, owing to the non-uniformity of speeds in the section;
d. The decrease in concentration by internal processes, either chemical, biological or biochemical;
e. Exchanges with the atmosphere and/or the bottom of the river (deposition, evaporation).

The interaction between the mechanisms of turbulent diffusion and differential convection is expressed by the term "dispersion"; dispersion is therefore the essential hydrodynamic phenomenon concerning the pollutants mixing in a river. For this, we can define three domains, or physical fields, of dispersion:

- The near field, where it is generally the quantity of movement of the release and its possible buoyancy which governs the initial mixture. This is the area generally close to the release in which mixing takes place over the entire height.
- The average field, where there is no more "memory" of the local conditions of the release, and in which the dispersion has a two-dimensional character. This is the area between the near field and the downstream point where the spot occupies the entire flow section. This point is generally quite far from the discharge place, even hundreds of kilometers downstream for large rivers;
- The far field, where the dispersion has a one-dimensional character, the spot occupying the entire section. In this zone, we are no longer interested in the details of the dispersion, but in the overall decrease in the average concentration as a function of time and distance downstream.

3.1 Continuous injection

In these experiments, the pollutant was injected into the channel permanently for two cases, with a vegetated bottom, and without vegetation. The figures below show the pollutant concentration evolution for the different injected volume and for different flow rates for the two cases, in presence and absence of vegetation.

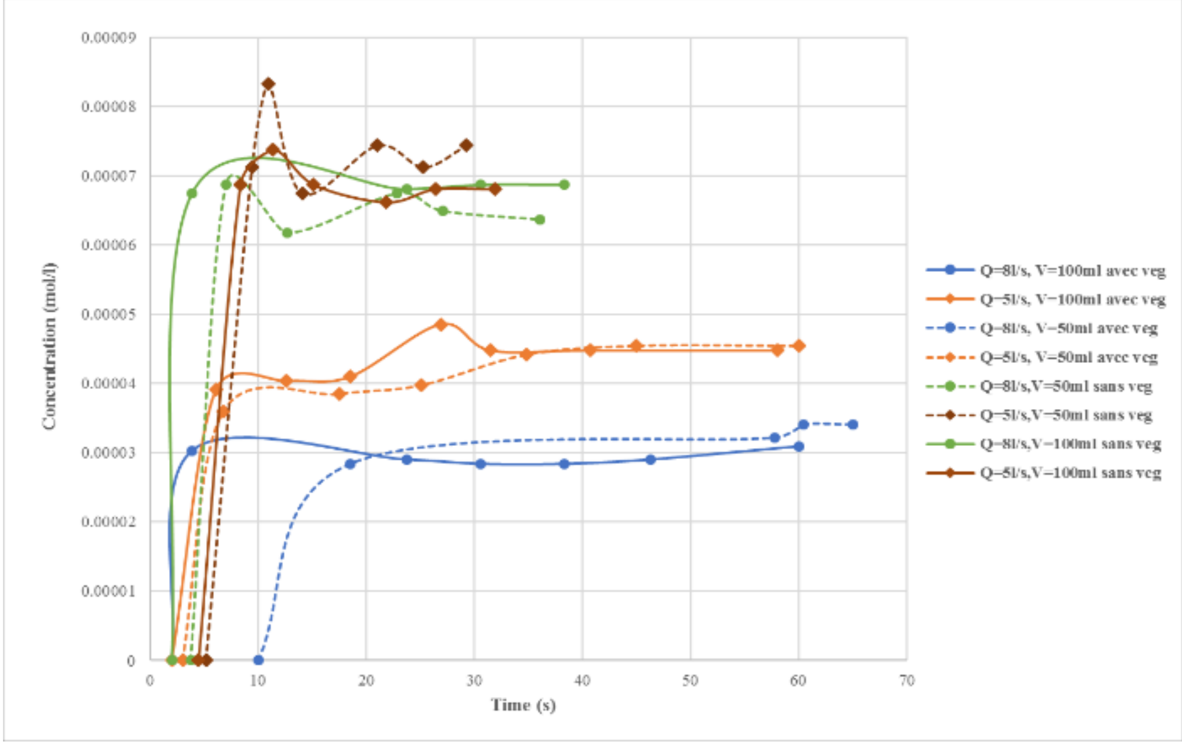

Figure 3. Concentration profiles for the different continuous injected pollutant volumes of 100 ml and 50 ml and for Q= 8 l/s and Q= 5 l/s, over a vegetated and a smooth bed

From this curve we noticed that for the different cases, the concentration variation was as follows: First a very rapid rise was observed, this is the convective period. The last phase was characterized by a very slow rise, which over time becomes almost constant, this is the diffusive period. On the other hand, the increased flow rate generates an increase of the pollutant concentration presence in water. This is due to the fact that more the velocity flow increases, more the injected quantity diffuses quickly downstream where the mixture will be completed and a stability state was reached.

The increased flow rate lengthens the convective period and therefore accelerates the pollution transport, but in return generates a larger concentrations peak. This can be explained by the turbulence rate which increases with the flow, in fact, the turbulent diffusion will be important and this will increase the mixing rate and in return decreases the necessary time to reach the stability state.

It can also be seen that the vegetation presence on the channel bottom causes a decrease in the pollutant concentration in water, this is due to the fact that the vegetation presence increases the bed shear stress and subsequently will delay the solution propagation in water. Indeed, vegetation plays a retarding role of these pollutants' types dispersion.

3.2 Discontinuous injection

For these experiments, the pollutant injection into the channel was done during 20 seconds, but the sampling processes were continued even after the injection had been stopped. The figures below showed the pollutant concentration evolution for the different injected volumes and for different flow rates in the two cases, with the presence and the absence of bottom vegetation. For the different cases we first observe a rise to reach a peak before descending. On the other hand, we notice an increase in concentration with increasing flow. This is quite correct because more the flow increases, more the velocity increases, which also leads to an increase in the advection and diffusion phenomena which play a preponderant role in the transport process.

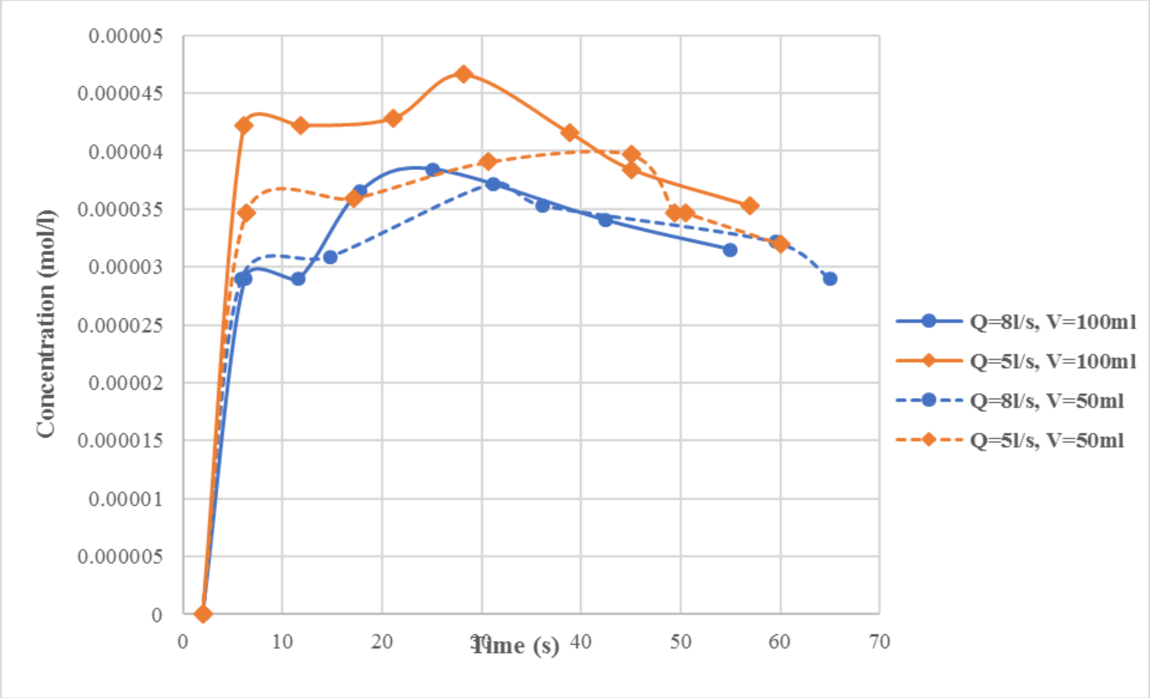

Figure 4. Concentration profiles for the different discontinuous injected pollutant volumes of 100 ml and 50 ml and for Q= 8 l/s and Q= 5 l/s, over a vegetated bed

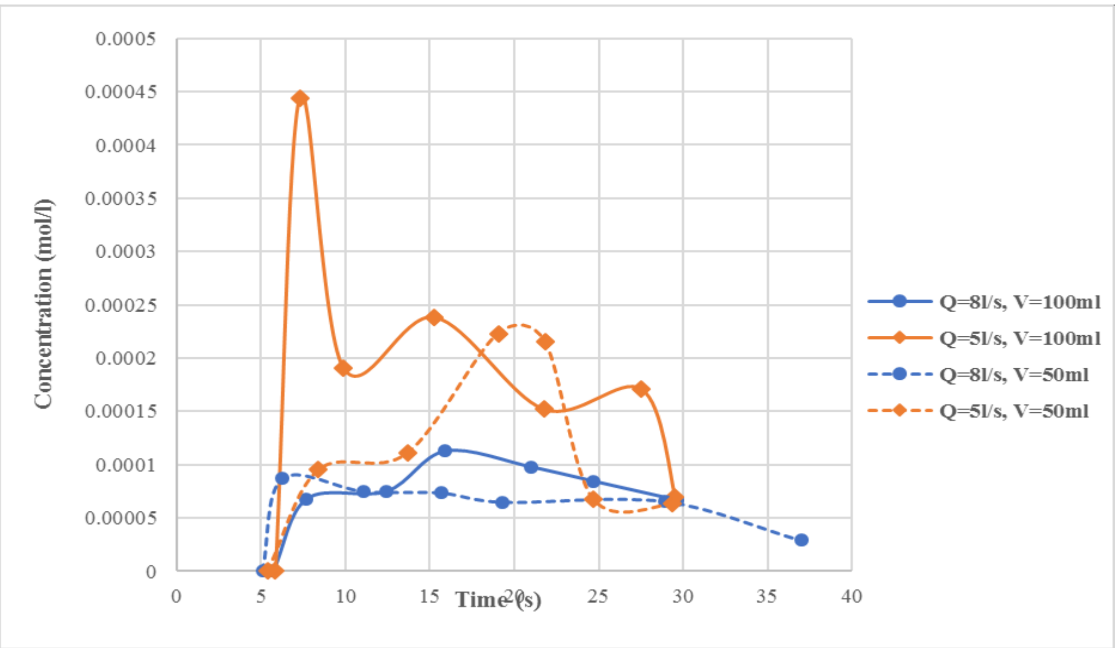

Figure 5. Concentration profiles for the different discontinuous injected pollutant volumes of 100 ml and 50 ml and for Q= 8 l/s and Q= 5 l/s, over smooth bed

Note that more the flow rate increases for the same volume injected, the greater the reduction in concentration in the downstream section. This can be explained by the turbulence rate which increases with the flow, the turbulent diffusion will be important which will increase the mixing rate and in return decreases the pollutant propagation time. Also, For the same flow rate, we see that the greater the upstream injected pollutant quantity, the greater the concentration peaks were observed during the convective period. It can also be seen that the vegetation presence on the channel bottom causes a decrease in the water pollutant concentration, also for the case of discontinuous injection.

4. Water quality modeling and simulations

4.1 Water quality modeling

The water quality degradation and the competing uses of this resource are accelerating, particularly in the Mediterranean region. Some countries already suffering from the scarcity of their water resources. Tunisia is one of the most vulnerable countries in the Mediterranean region.

To cope with this degradation, investments have been made in many water quality simulation programs. In most models, there are always two calculation options, by considering a constant water flow, or by considering a variable flow at each time step. The other parameters are adjusted to obtain concentrations that approach the observed values in the field or in the laboratory. The scalar variable transport depends on both the value and the direction of the local velocity field. We will consider in this work, the evolution of a liquid pollution in a hydro system (**Eqn. 5**) which depends closely on the flow characteristics, and which is governed by the following equations system (**Eqn. 2, 3, 4**):

Continuity equation:

$$\frac{\partial \overline{U}}{\partial x} + \frac{\partial \overline{W}}{\partial z} = 0 \qquad \textbf{Eqn. 2}$$

Momentum equations:

$$\left(\frac{\partial \overline{U}}{\partial t} + \overline{U}\frac{\partial \overline{U}}{\partial x} + \overline{W}\frac{\partial \overline{U}}{\partial z}\right) = F_x - \frac{1}{\rho}\frac{\partial \overline{P}}{\partial t} + (\nu + 2\nu_t)\frac{\partial^2 \overline{U}}{\partial x^2} + (\nu + \nu_t)\frac{\partial^2 \overline{U}}{\partial z^2} + \nu_t\frac{\partial^2 \overline{W}}{\partial zx} - \frac{2}{3}\frac{\partial \overline{K}}{\partial x} \qquad \textbf{Eqn. 3}$$

$$\left(\frac{\partial \overline{W}}{\partial t} + \overline{U}\frac{\partial \overline{W}}{\partial x} + \overline{W}\frac{\partial \overline{W}}{\partial z}\right) = F_z - \frac{1}{\rho}\frac{\partial \overline{P}}{\partial t} + (\nu + 2\nu_t)\frac{\partial^2 \overline{W}}{\partial z^2} + (\nu + \nu_t)\frac{\partial^2 \overline{W}}{\partial x^2} + \nu_t\frac{\partial^2 \overline{U}}{\partial zx} - \frac{2}{3}\frac{\partial \overline{K}}{\partial x} \qquad \textbf{Eqn. 4}$$

Concentration equation:

$$\frac{\partial C}{\partial t} = \frac{1}{A_x}\frac{\partial\left(A_x D_L \frac{\partial C}{\partial X}\right)}{\partial x} - \frac{1}{A_x}\frac{\partial(A_x \overline{u} C)}{\partial x} - \frac{C}{A_x}\frac{\partial A_x}{\partial t} + \frac{dC}{dt} + S \qquad \textbf{Eqn. 5}$$

Note that the longitudinal dispersion coefficient D_L is calculated by the following equation (**Eqn. 6**):

$$D_L = K\, n\, \overline{U}\, h^{5/6} \qquad \textbf{Eqn. 6}$$

When the punctual discharges evolve slowly, then the longitudinal dispersion coefficient has little impacts on the simulation results. Whereas if the discharges evolve significantly, the concentrations change rapidly, and this will considerably influence the simulations.

4.2 Water quality simulations

Simulations were carried out using the HEC-RAS water quality module, to validate the experimental results. For this, initial conditions must be specified, such that the pollutant initial concentration corresponding to the concentration found in the channel before the injection (0.005 mg/l). Also, the pollutant discharged masses (158 g) into the channel as well as the discharge moment must be indicated in the software, as well as the simulation time corresponding to the period for which the monitoring is carried out (60 s). At the location where the injection occurs, the pollutant concentration (0.02 mol/l) as well as the injection duration (60 s) must also be indicated for the model. In the following, we presented a comparison of the simulated and measured concentration profiles for the continuous injected pollutant volume of 50 ml and for Q= 5 l/s, in the case over a vegetated bed.

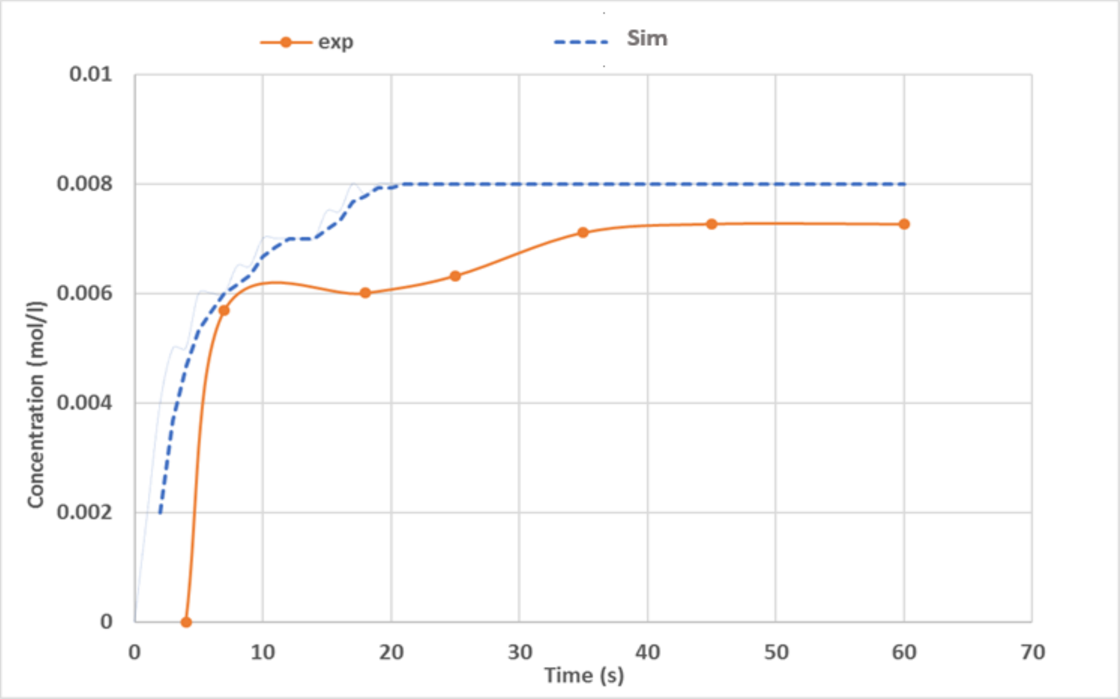

Figure 6. Comparison of the simulated and measured concentration profiles for the continuous injected pollutant volume of 50 ml and for Q= 5 l/s, over a vegetated bed

We note during the passage of the pollutant, the concentrations given by the numerical model are higher than those resulting from the experiments. At this level, we can say that for a continuous source, our model overestimates the concentration values.

The dispersion coefficient D_L has a determining role in the substances transport. In fact, it indicates the rate at which the substance decreases over time. To illustrate its influence on the pollutant transport, we carried out several scenarios by varying it. And finally, it was calibrated to a value of 0.01 m^2/s which makes it possible to bring the experimental results closer to the simulations.

In the simulations, we noticed that a small decrease or increase in D_L leads to a large variation in the concentration, with the same flow conditions.

Conclusion

This study concerns laboratory channel experiments and simulations with the objective of analyzing the bottom vegetation effect on the liquid pollutant propagation rate (the potassium permanganate), and to understand its dispersion rate.

Based on these experiments, there was a concentration increase in time along the channel with increasing flow rates for the both continuous and discontinuous injection types. This explains why the turbulence rate increases with the flow, whereby advection and diffusion phenomena increase, playing a major role in the transport process.

By comparing the two injection types, it was noticed that the discontinuous injection best promotes the pollutant mixing in the solution when compared to the continuous injection, where such a pollutant remains in the medium with greater concentration.

It can also be seen that the vegetation presence on the channel bottom causes a decrease in the pollutant concentration in water, this is due to the fact that the vegetation presence increases the bed shear stress and subsequently will delay a solution propagation in water. Indeed, vegetation plays a retarding role of these pollutants' types dispersion.

Disclosure statement

Conflict of Interest: The authors declare that there are no conflicts of interest.

Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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