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Physical simulation of an active pollutant dispersion in a trapezoidal channel

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ABSTRACT

Organic, thermal, and chemical pollutions that are injected either on purpose or accidentally in the river hydrosystems are transported under the effect of an average fluid motion by convection, and disseminated in the river hydrosystems by turbulent agitation. These two processes control the pollution in a natural watercourse. The goal of this paper is to study the evolution of an active pollutant dispersion, in this case phenol, in time and space, inside a trapezoidal channel. After presenting the experimental apparatus, designed and manufactured in our laboratory, several types of tests are carried out by injecting the selected pollutant inside the channel, with different concentrations of the phenol solutions. Treatments and analyses of the different tests were conducted, highlighting the evolution of the phenol concentration in time and space, with profiles in the lateral and longitudinal flow directions. A qualitative understanding of the specific phenomenal pollutant movement is described in detail, showing experimental results in agreement with general theories describing the phenomenal pollutants movement in prismatic experimental channels studied previously.

Keywords: Dispersion; Trapezoidal channel; Active pollutant; Phenol

1. Introduction

The pollution migration in streams is rather poorly known particularly in cases with complex shapes sections. The follow-up of pollutant trajectories is extremely complicated, as the stream hydrodynamics is strongly influenced by the section form. Hence, the cloud characteristics generated by the pollution is also strongly influenced on the stream section form. Current numerical models are only reproducing average migration of pollutants in the space and in time. The parameters that highlight accurately pollutant behavior must be experimentally specified, according to the passive or active nature of the pollutant introduced in the studied stream.

The study of the pollution circulating in water streams can be simulated using experimental models, by reconstructing the different mechanisms [1] present in the environment and then providing all the necessary information for an analysis and quantification of representative quantities within a laboratory scale [2–4]. Indeed, when any substance is injected into a flow, a high concentration cloud is formed. The substance trip within the flow will occupy a larger

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area and the concentration will then become weaker. The attenuation of a concentration is closely explained by several physical mechanisms such as a stream transport: diffusion (turbulent fluctuation and molecular diffusion) and advection which consists of bulk transport under the action of the velocity [5]. The longitudinal spread caused by the non-uniformity of the horizontal and vertical velocity fields characterizes dispersion [6,7]. In other words, dispersion is a combined effect of advection and diffusion [8]. The best way to reproduce the processes in quality and quantity of a natural watercourse is by implementing a physical model which would represent it better in the form of a prismatic trapezoidal channel [9]. In what follows, the experience monitoring, in time and space of an active pollutant dispersion, in this case phenol, along a trapezoidal channel will be studied.

2. Equipment and methods

2.1. Experimental facility

The experimental facility in which various tests were conducted is made of Plexiglass with steel supports. This installation was described in detail in [10]. Nevertheless, the prismatic shape of the channel section was re-designed in such a way that it can take a set of different forms, ranging from the rectangular form to a trapezoidal shape. This allows the researcher to model a channel with different inclines and therefore variable sections using the same basic device. The total channel length is 11 m, the width is 40 cm, and the slope angle is set at 60°. This provides the device with a trapezoidal shape across the flow generated by the installation. The bottom of the channel was filled with sand picked from a local river in order to reproduce the natural watercourse ruggedness (Fig. 1).

The pollutant injected apparatus used in this study is the same system described during previous experiments by Benziada et al. [1,10]. The apparatus consists of two small tanks, one feeding the other to maintain a constant injection flow of the pollutant at a fixed point on the test apparatus. The injection can be done once or maintained continuously. The system for testing water samples consists mainly of very slender stems located at every meter along the flow longitudinal direction.

2.2. Means of measurement

2.2.1. Flow measurement and water levels

The flows control and measurement are taken upstream by using a volumetric meter and adjusted with a triangular spillway calibrated and placed inside the channel at the downstream end. Water-level measurements are carried out by a point gage movable both longitudinally and transversely. The gage allows to draw the traffic's flow directly within the facility and the water flow measurement line. The hydraulic parameters are than perfectly determined by these types of measurements.

2.2.2. Concentrations measurement

The analyzed adopted method is intended to determine the concentrations of samples collected in function of their optical densities by spectrophotometry. The drawing of the phenol calibration curve is performed by matching the optical densities at various known concentrations (Fig. 2).

The concentration of each sample is drawn directly from the calibration curve, by using a simple transformation obtained from the optical density measured from the sample itself.

2.3. Experimental procedure

The simulation pollution is materialized by two-point injection procedures: one instant and the other continuous. These injections at fixed rates of phenol solutions have concentrations ranging from 500 to 1,500 mg/l. For a fixed rate upstream from the installation, and the flow stabilizing along the channel, the water heights are measured at both longitudinal and transverse sections. Selected rates are 0.52, 0.79, 1.6, 1.75, and 1.95 l/s. For each fixed rate, a series of samples is conducted simultaneously for different injection scenarios (in terms of procedure and change in concentration). Samples are analyzed immediately in the laboratory by spectrophotometry. The experimental data obtained allow the tracking of the longitudinal dispersion over time, and phenol concentration at every 1 m section in the x-axis coordinate direction. The same also applies to the profiles of concentration in each cross section along the y-axis direction (Fig. 3).

3. Results

By implementing several trials, the following results were obtained for various types of injection.

3.1. Instant injection

3.1.1. Changes in phenol concentrations for different flow rates

Figs. 4 and 5 indicate that the temporal concentration profiles are asymmetrical. They are characterized firstly by a quasi-linear fast rise of concentrations and then by their slow decrease. The drop of the

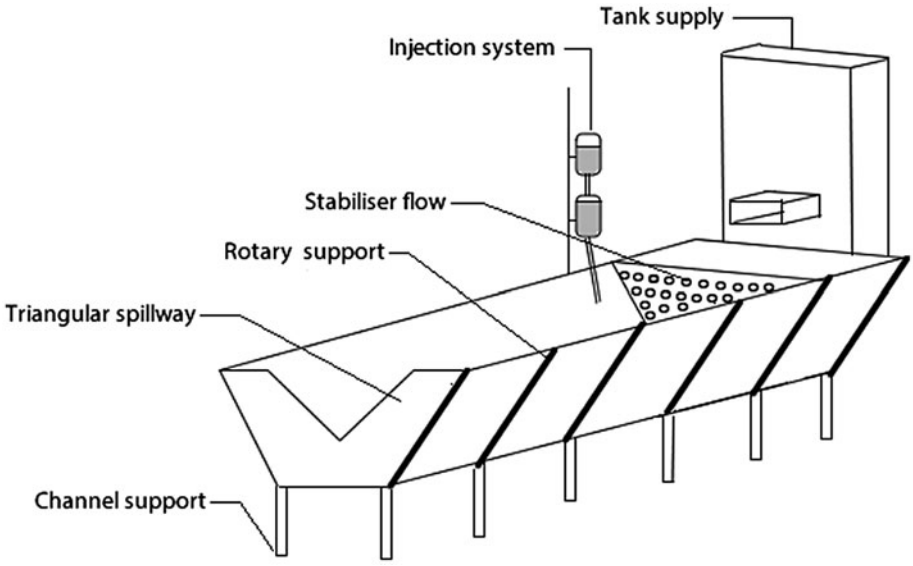

Fig. 1. Experimental apparatus.

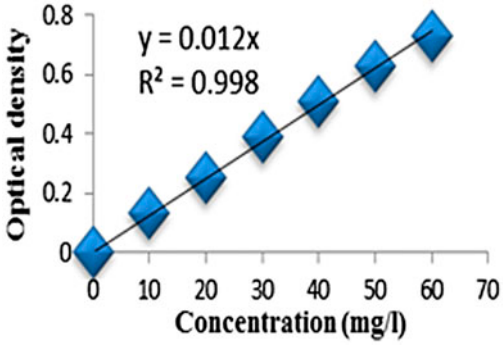

Fig. 2. The phenol calibration curve.

maximum concentrations compared to the injected initial concentrations is mainly the result of dilution phenomenon which occurs soon after the pollutant injection [11,12]. Tails that are observed for some concentration profiles (x = 4 m of Fig. 4) refer to creation of trapping zones of the pollutant.

3.1.2. Influence of flow at a constant initial concentration

Concentrations values as well as resting time of the pollutant (Figs. 6 and 7) are more important for low flows. These results have been noticed for any injected initial concentration C_0.

3.1.3. Monitoring of peak concentrations in function of the flow rate along the outflow

Recorded concentration peaks (Fig. 8) are weaker for important flows as a result of the dilution which increases with the growth of the flow rate [11,12].

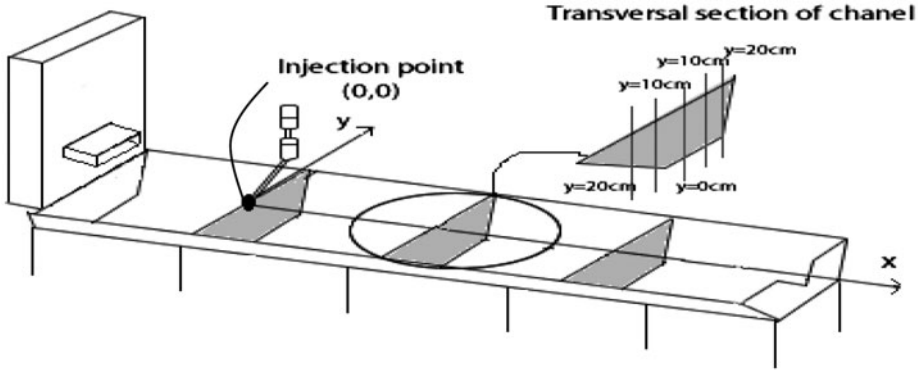

Fig. 3. Sampling sections in longitudinal and transversal directions.

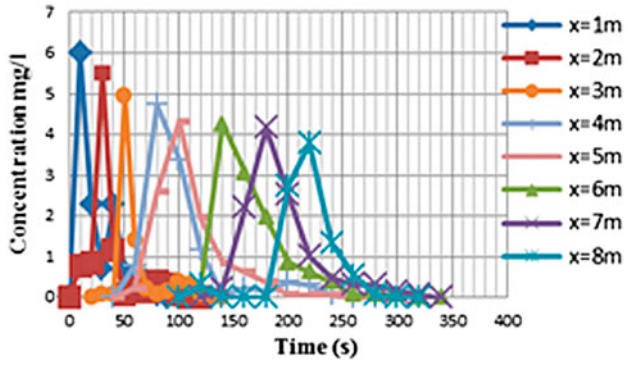

Fig. 4. Change in phenol concentration for $Q = 0.52$ l/s and $C_0 = 500$ mg/l-instant injection.

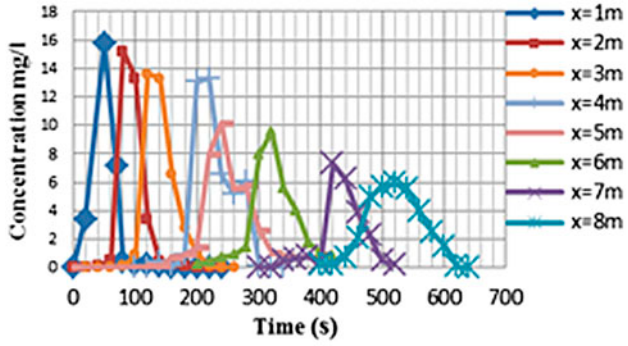

Fig. 5. Change in phenol concentration for $Q = 1.95$ l/s and $C_0 = 500$ mg/l-instant injection.

Rates of concentration drops (Fig. 9) increase with the decrease of the flow rates. In fact, the more important resting time for low flow rates gives more time for dispersion to occur.

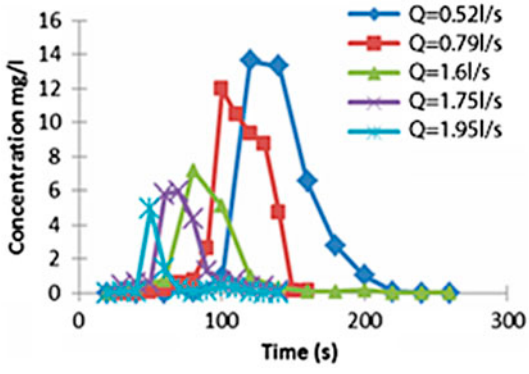

Fig. 6. Changes in phenol concentration in time at $x = 3$ m and $C_0 = 500$ mg/l and for various flows.

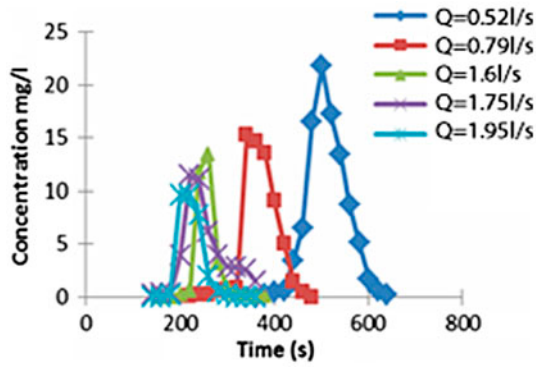

Fig. 7. Changes in phenol concentration in time at $x = 8$ m and $C_0 = 500$ mg/l and for various flows.

3.1.4. Influence of initial concentration of injected pollutant C_0

Note that an increase in the initial injected concentration cause an increase in the peaks, but does not affect their time of arrival and stay (Figs. 10 and 11).

3.1.5. Monitoring of transversal mixture

The profiles in time of the concentration in phenol for the flows $Q = 0.52$ and 1.95 l/s at different lateral distances for an instantaneous phenol injection with an initial concentration of $C_0 = 500$ mg/l are shown in Figs. 12 and 13.

The concentration profiles are more important at the channel center of ($y = 0$) than at its two other sides. These profiles follow closely the velocity change according to the longitudinal direction (X). Concentration peak levels decrease when the flow rates increase.

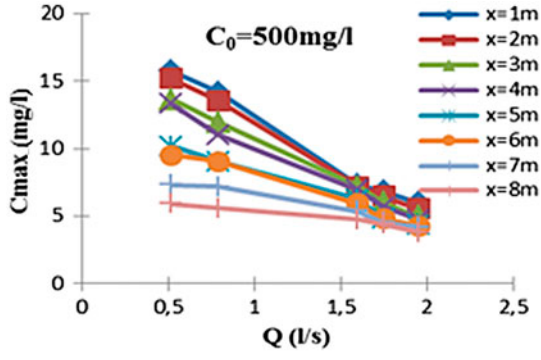

Fig. 8. Peaks of phenol concentration in function of the flow for $C_0 = 500$ mg/l at various (x_i) sections.

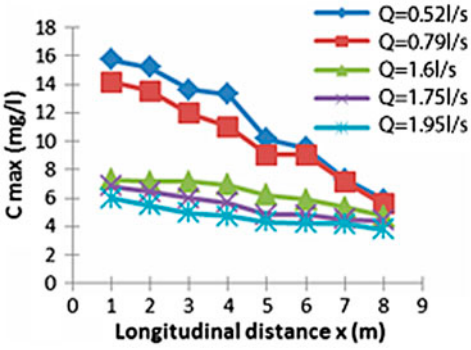

Fig. 9. Evolution of maximum phenol concentrations in function of the downstream distance of the discharge for various flows and for C_0 = 500 mg/l.

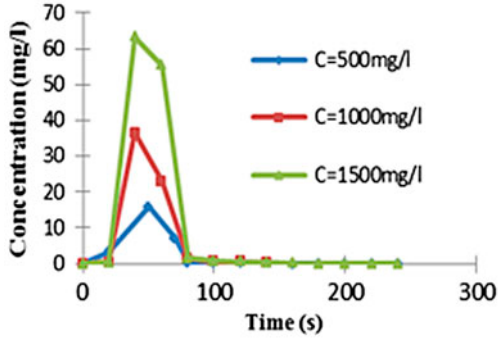

Fig. 10. Change in phenol concentration in function of time at x = 1 m and Q = 0.52 l/s and for various concentrations initial injection.

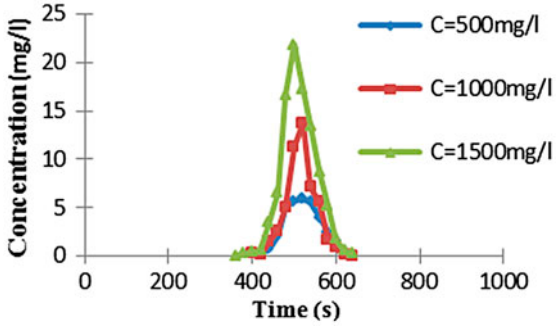

Fig. 11. Changes in phenol concentration in function of time at x = 6 m and Q = 0.521 l/s and for various concentrations initial injection.

3.1.6. Comparison between the iso-concentrations Q = 1.95 and 0.52 l/s

Fig. 14 shows a quantitative comparison of trajectories over time of clouds observed after injection of phenol at an initial concentration of C_0 = 500 mg/l for two flows, Q = 0.52 and 1.95 l/s.

The flow rate increase induces a growing of the dilution rate: that means that weaker concentrations correspond to great flow rates. Hence, the increase of stream speeds conducts the pollution cloud to leave quickly the field involving reduction of pollutant resting time, and thus a minimal dispersion. Therefore, the growing of Reynolds number will induce the rate of transversal mixture generated by the diffusion to increase as a result of turbulence. The pollution cloud is then stretched in the lateral direction.

3.2. Continuous injection

3.2.1. Sampling for different longitudinal sections

The concentration profiles at different longitudinal distances for Q = 0.52 l/s for a continuous injection of phenol with a 500 mg/l concentration is presented in Fig. 15.

In all (x_i) sections, the concentration increases quickly and then stabilizes at an average level. The rapid rise in concentration corresponds to the convective period, while the stabilization phase indicates that the pollutant has been completely diluted and mixed. The stabilization period is dominated by the pollutant longitudinal dispersion.

3.2.2. Sampling for different lateral distances

Figs. 16–19 represent the evolutions of the profiles of phenol concentrations over time for different (y_i) lateral distances at x = 6 and 7 m from the injection point, for different flow rates, and with a 500 mg/l continuously injected phenol concentration.

For a given longitudinal distance (x_i), the concentration profiles are similar for each transversal

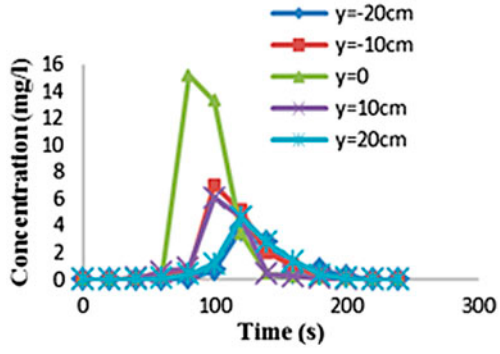

Fig. 12. Concentration profiles for various lateral y distances, for Q = 0.52 l/s at x = 2 m and C_0 = 500 mg/l.

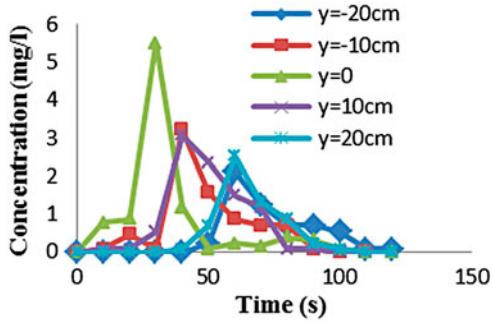

Fig. 13. Concentration profiles for various lateral y distances, for Q = 1.95 l/s at x = 2 m and C_0 = 500 mg.

distance, which indicates that the pollutant is mixed transversely, and that the concentration distribution is uniform and homogeneous across the transversal and homogeneous across the transversal direction.

4. Discussion and conclusion

In instantaneous injection, the changes analyzed in space and time of phenol concentrations helped confirm the distinction of two areas:

(1) An area known as advection; near the injection where obtained profiles are sharp, and for which the transport is convective.
(2) A diffusive area, in the far field, where the level of the concentration profiles is more important, and which the transport than becomes more and more diffusive.

The results analyzed allows the visualization of non-uniformity role within the transverse profile on the cloud stretching and then dissociating the mechanisms which constitute the transport by advection and carries all of the polluting cloud in the flow direction.

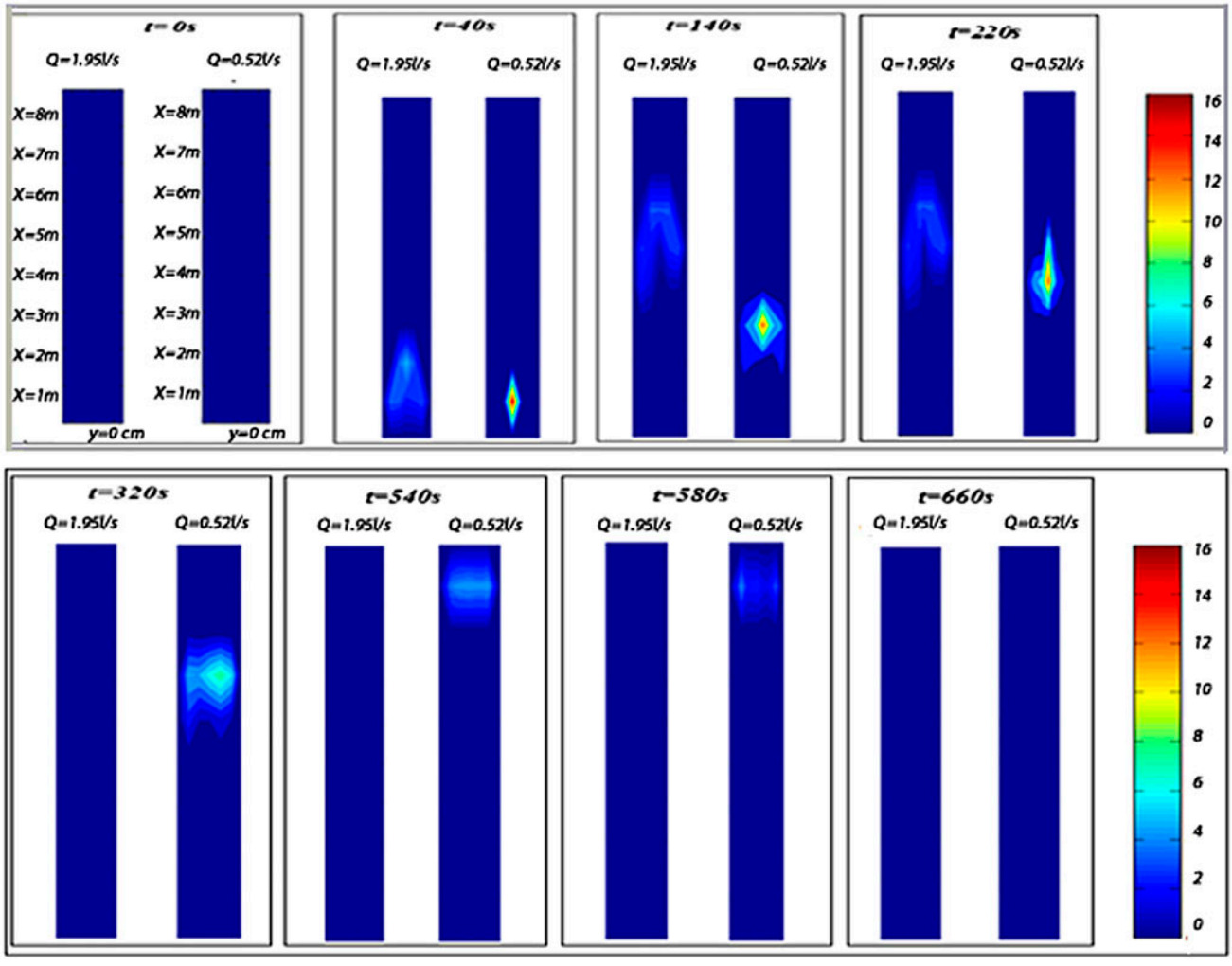

Fig. 14. Iso-concentrations at various times for C_0 = 500 mg/l.

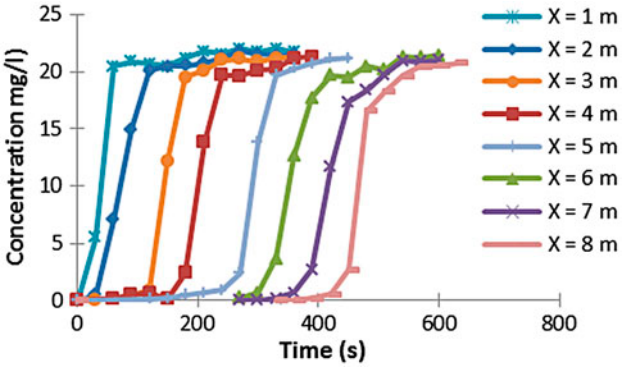

Fig. 15. Changes in phenol concentration in function of time for $Q = 0.52$ l/s and $C_0 = 500$ mg/l-continuous injection.

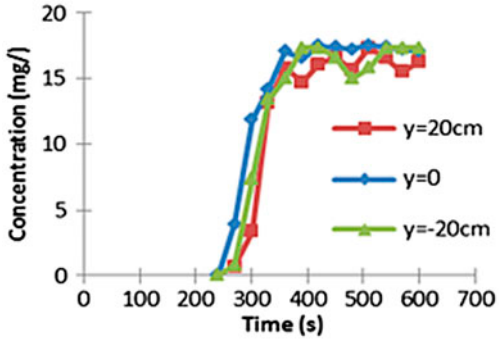

Fig. 16. Phenol concentration in function of time at $x = 6$ m for $Q = 0.52$ l/s and $C_0 = 500$ mg/l.

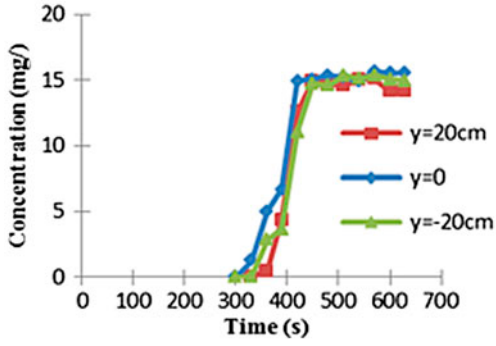

Fig. 17. Phenol concentration in function of time at $x = 7$ m for $Q = 0.52$ l/s and $C_0 = 500$ mg/l.

The dissemination and the non-uniformity of transversal profile of speeds are responsible for the expansion of the polluting cloud in the transverse direction (transverse mixing); but also in the

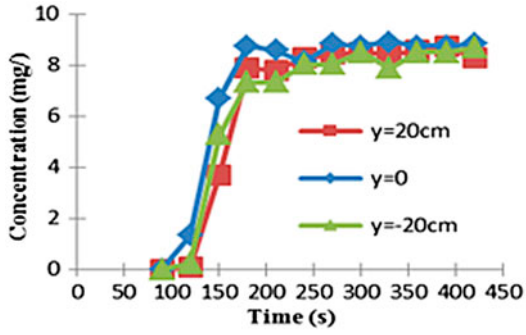

Fig. 18. Phenol concentration in function of time at $x = 6$ m for $Q = 1.95$ l/s and $C_0 = 500$ mg/l.

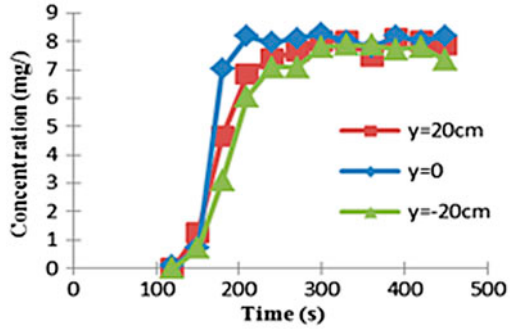

Fig. 19. Phenol concentration in function of time at $x = 7$ m for $Q = 1.95$ l/s and $C_0 = 500$ mg/l.

longitudinal direction with decreasing concentration (longitudinal dispersion). Different injection scenarios helped determining the flow's influence of and rejected quantities on the phenomenal transport. The latter is related to the flow variation hydrodynamics in terms of speed varied variation and the Reynolds number, which becomes significant at high speed levels. What accentuates the phenomenal turbulence; and ultimately the dissemination will be more important. What increases significantly the mixing rate. With higher speeds, the advection process accelerates, and transport becomes more convective. Finally, the staying time is longer for lower flow rates, and therefore the crashing rate of phenol concentration by longitudinal dispersion becomes more significant. An increase in dilution rate indicates a lower phenol concentration, which corresponds to greater flow levels. The results obtained show the initial concentration influence on peak concentrations that vary in the same direction as initial concentration variation of the injection, but "staying" time in any case remains constant.

In the case of a continuous injection, two periods have been observed:

(1) A period of rapid growth of the concentration which corresponds to a convective period.
(2) A second period which materializes a lateral homogeneity in concentration and a phenomenal preponderance of the pollutant longitudinal dispersion.

The experimental results are encouraging and should be refined by taking into account the influence of other parameters such as: the slope angle, the channel roughness at the bottom, and the channel's slope longitudinal variation.

The analysis consists to investigate spatial and temporal migration of pollution and its effects on hydrosystems to propose multiple measures to protect the pipeline from the accidental rupture, collector of purification, and rejections in the main streams. In fact, knowledge of the pollution migration laws will help to suggest management measures that will protect water quality in streams.

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