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On Inert Tracer Modeling in a Compound Open Channel

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Abstract

This study investigates the impact on the pollutant transport and mixing processes of strong lateral momentum transfer effects associated with severely compound flow fields. Consideration was limited to conservative, non-buoyant material represented by a (dye) tracer. The experiments include measurements of dye concentrations downstream from steady-injection point source(s). In general, it is not possible to obtain analytical solutions to the dispersion equation in natural waterways with arbitrary boundary conditions. However, a variety of simplified solutions exists for idealized situations, which can be useful in obtaining order-of-magnitude estimates. These solutions were applied to our experimental data. Also, the 2-D depth-averaged advection–diffusion equation was solved numerically and applied to the data sets. Comparison between measured and numerically predicted concentration curves indicates a reasonably good agreement in regards to general shape, peak concentrations and time to peak.

Introduction

When a substance is discharged into a body of water, it is often desirable to be able to predict the concentration of the materials downstream from the release point. A conservation equation for the discharged material can be used in this prediction. Applying such an equation requires that: (i) the general hydraulics of the stream; (ii) any physical, chemical, biological changes in the material; and (iii) the rates of mixing with respect to the velocity used in category (i) are known. In general, the results of channel-flow simulations are often used as the hydrodynamic basis for water quality analysis and/or modeling. It is worth noting at this point that the literature indicates that there are still very few research papers dealing with tracer experiments in compound channels, e.g. Arnold et. al[1]. In general, simplified versions of the equations of continuity and momentum are applied to obtain a solution, e.g. Cunge[2]. An example of such a simplification is dividing a compound channel into a series of stream tubes. Another example is determining the distribution of the eddy viscosity by a turbulence model, such as the depth-averaged k-ϵ model, and neglecting inertia terms.

Experimental Investigation

The experimental channel employed in this investigation was 29.25 m long x 0.79 m deep x 1.50 m wide on a bed slope of 0.0007. The channel had a simple rectangular cross-section, however, this was modified using aluminum sheeting to produce an asymmetrical compound shape. The main channel of the compound section is 0.79 m wide and the right-side flood plain is 0.71 m wide. The compound channel is shown in figure 1. The channel bottom is concrete and was painted with black asphalt to ensure uniform water tightness at the bottom or sides of the channel. The experiments involved measuring the concentration distribution downstream of instantaneous injection or a steady point source of tracer (Rhodamine WT) discharging into steady, uniform compound channel flows. However, due to space limitations, only steady-injections are reported. The function of the inlet multi-port diffuser pipe was to supply, with minimal disturbance, smooth entrance flow to the main channel and flood plain sections of the channel. Screens (mesh) and baffles were installed downstream of the diffuser to dissipate large-scale turbulence and secondary circulation in the entrance channel. The downstream end of the channel contained a transition section which conveyed the flow smoothly from the flood plain to the channel exit. While the discharge was varied in the various experiments, the depth (d) on the flood plain was maintained at values below 0.35 of the main channel depth (D) throughout. Throughout the experiments, depths were measured with a point gauge mounted on the channel's instrument carriage. Although depth measurements were accurate to 0.1 mm, the unevenness of the flume floor demanded some degree of subjective judgement. Due to the small slope in the channel bottom, any error in setting uniform flow could cause substantial errors in the measurements and the consequent calculations. It is noted that meeting the criterion used to determine the existence of uniform flow was not without its difficulties. It was also important to have the velocity contours at two sections within the test reach similar. The downstream variable-height weir was used to adjust the water surface profile in order to have equal depth measurements at one station just upstream and another just downstream of the test section. This process was lengthy and required considerable patience and preciseness on the experimenter's part. Once nearly uniform flow was established in the vicinity of the test section, the other parameters were then measured. Velocity measurements were performed at two stations, one 12.25 m and the other 22.75 m from the channel entrance using a propeller-type current meter. Discharge was calculated using *stream gaging* procedure, e.g. Ranga-Raju[3]. The ideal tracer would be nontoxic, usable in small quantities, cost-effective, invisible, easy to measure at low concentrations, specific, and stable during the course of the study. Since Rhodamine WT meets all the above requirements it was used as the tracer in this study. For the mixing tests, the Rhodamine WT tracer solution was released at different rates and locations as specified in each test case. Release points were varied across the transverse direction and the vertical dimension of the compound channel to check the effect of point of release on the mixing properties of the tracer. Tracer injections were done at a station 7.75 m from the channel entrance where the inflow effect was relatively considered negligible. Different flow conditions and injection points were considered. For continuous steady injections, the dye injection was performed at different points in the main channel, near the main channel/flood plain interface, over the flood plain, or a combination of injectors where more than one injector was used and the injection rates were measured in each. The Reynolds numbers over the main channel and the flood plain zone were always in the *fully-developed turbulent* range. Samples were collected by direct pumping and the upstream and downstream stations using 4 variable-speed pumps with 8 sampling ports. The intake velocity was adjusted, by trial and error, to a value approximately equal to the average local stream velocity. A Turner Designs Model 10-AU fluorometer, which had to be calibrated, was used in the study.

Computations

In general, it is not possible to obtain analytical solutions to the dispersion equation in natural waterways with arbitrary boundary conditions. However, a variety of simplified solutions exists for idealized situations, which can be useful in obtaining order-of-magnitude estimates. Dye concentrations were predicted using simplified analytical solutions of the corresponding partial differential equations. These equations are usually applied for limited situations where many simplifying assumptions are involved, e.g. Ranga-Raju[3]. Also, a 2-D finite-difference mathematical model has been developed for simulating pollutant transport in compound open-channels, e.g. Chatila and Townsend[4]. The model, which couples depth-averaged (depth-integrated) versions of the classical 3-D Navier-Stokes equations with a similar form of the advection-diffusion equation, also incorporates the constant eddy-viscosity model in its formulation. Calibration of the model was performed by adapting the model to our laboratory compound channel configuration and identifying the various coefficient values by applying the model to a representative data set. Validation studies were then performed by comparing the model output to *experimental* data of pollutant transport simulated through various dye-tracer studies performed in the channel described in this paper.

Results

With regards to the experimental data, figure 2 shows sample cross-stream distributions of the depth-averaged longitudinal velocity (U) in our compound channel, for small $d/D = 0.15$ and large $d/D = 0.43$, which are within and outside the accepted range for generating the typical compound channel characteristic of strong lateral momentum transfer LMT effects (i.e. $0 \leq d/D \leq 0.35$). Referring to $d/D = 0.15$, the large cross-stream gradient in U (i.e.$\partial U/\partial y$) in the vicinity of the channel junction is an indicator of the strong LMT associated with this region of high shear flow. On the other hand, when mean flow velocity in the flood plain approaches that in the main channel ($d/D = 0.43$), $\partial U/\partial y$ (and hence LMT-effects) in the junction region is much smaller. The same phenomenon was also observed by Bhowmik and Demissie[5].

Upon inspection of the horizontal variation in dye concentration with time, it can be concluded that proper mixing is not occurring in the transverse direction, (figure 3). Provided that injection of the dye was restricted to the main channel, high concentrations of dye were observed at the first and second sampling stations (in the main channel) and rather low concentrations were observed at the other two sampling stations. Changing the location of the injection point significantly affected both longitudinal and transverse diffusion of dye in the channel.

In applying the simplified solutions to the data, the predicted values of concentrations are far from the measured and the model simulated values. Figures 4 and 5 compare predicted and measured concentrations. Clearly, concentrations are over-estimated in the main channel and considerably under-predicted over the flood plain zone using the simplified solutions.

Comparison between the measured and model-predicted dye concentration curves shows reasonable agreement in the general shapes of the curves, in the peak concentrations and times to peak, (figures 4 and 5). Inspection of the simulated dye concentrations indicates that the model slightly over-estimates observed values and especially the peak values. However, there is no indication of time delay or phase shift between the observed and simulated peak values. The observed and simulated flow depths and dye concentrations have similar times to peak.

Summary

A laboratory data was generated through dye-tracer studies performed in a large compound-shaped channel of the Hydraulics Laboratory, University of Ottawa. The experiments included measurements of dye concentrations at various stations downstream of continuous injection point sources. A developed numerical model was used as a useful tool for predicting concentration of injections of inert pollutants. Comparison between measured and predicted concentration curves indicated a reasonable level of agreement in the general shapes of the concentration curves, the peak concentrations, and the times to peak.

References

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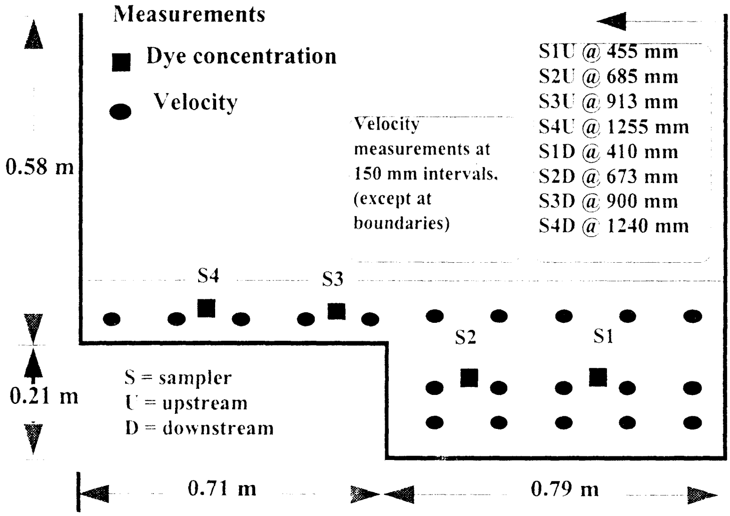

Figure 1 Cross-section of the experimental channel.

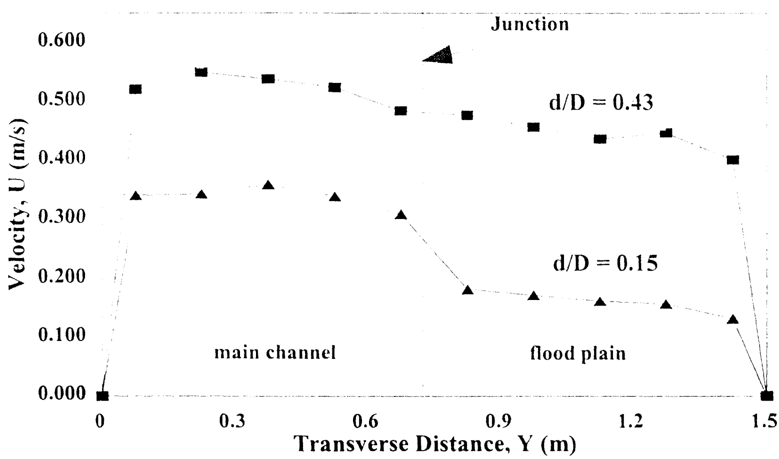

Figure 2 Cross-stream variation of longitudinal velocity.

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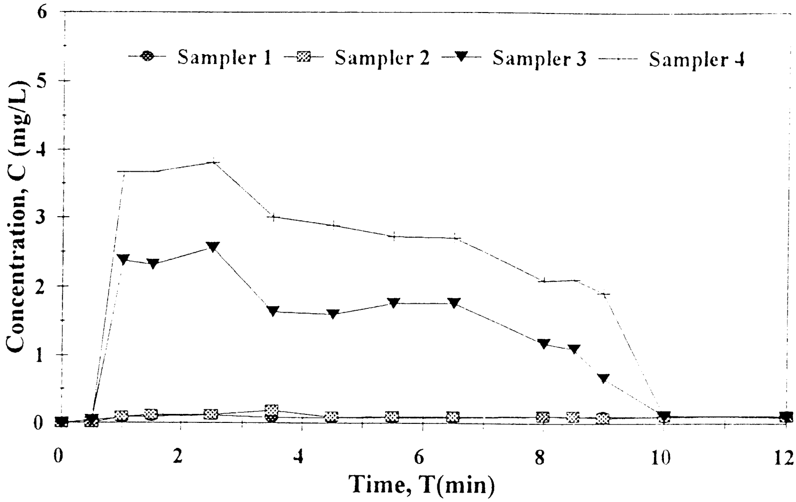
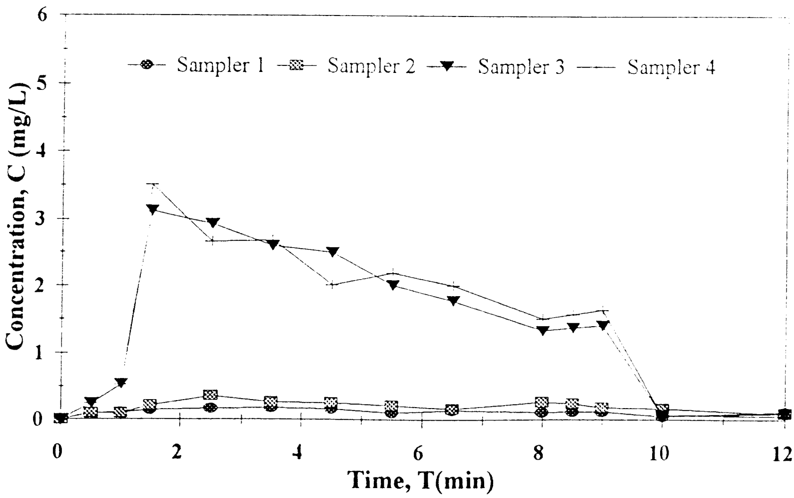


(a) Upstream



(b) Downstream

Figure 3 **Cross-stream variation of dye concentration with time at: (a) upstream sampling station, (b) downstream sampling station, (for d/D = 0.29).**

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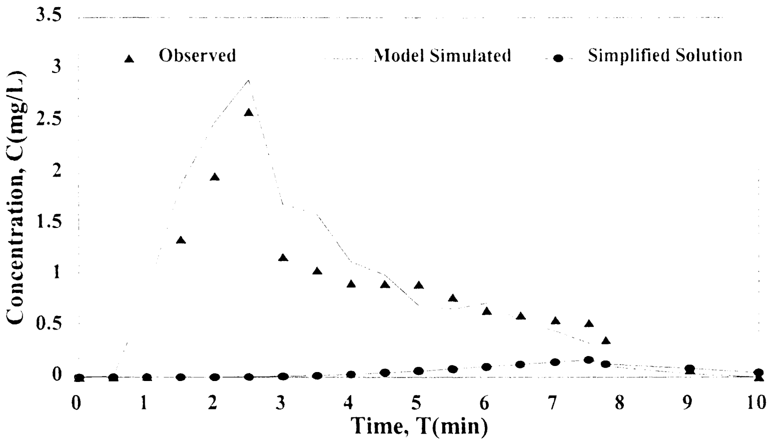

Figure 4 Observed vs. simulated dye concentrations at Sampler 3 of the downstream sampling station, (d/D = 0.18).

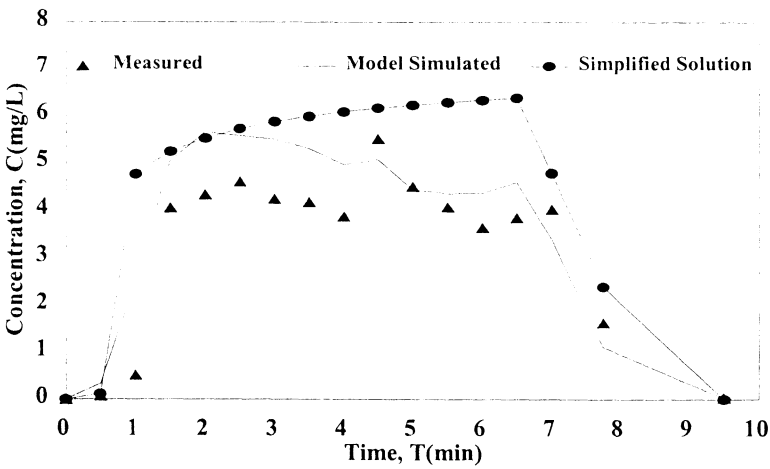

Figure 5 Observed vs. simulated dye concentrations at Sampler 1 of the downstream sampling station, (d/D = 0.30).