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Comparative Analysis of Analytical and Empirical Methods for Estimating the Longitudinal Dispersion Coefficient in Open-Channel Flows

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Abstract: The accurate estimation of the longitudinal dispersion coefficient is crucial for predicting solute transport in natural water bodies. In this study, an analytical (integral) method based on first principles is compared with Fischer's widely used empirical approach, which is implemented in hydraulic modeling software such as the Hydrologic Engineering Center-River Analysis System (HEC-RAS). The primary objective is to evaluate the accuracy, applicability, and limitations of both methods under varying hydraulic conditions. A key advantage of the analytical approach is its ability to estimate the dispersion coefficient using velocity data alone, eliminating the need for high-cost tracer experiments that rely on solute concentration measurements. The determination index suggests an acceptable level of agreement between the two methods; however, the empirical approach systematically overestimates dispersion coefficients. Furthermore, a clear inverse relationship is observed between the slope of the channel and the magnitude of the dispersion coefficient, which is attributed to the increasing influence of shear velocity on the diffusion process. As slope values increase, solute separation time decreases, and concentration gradients become steeper. Conversely, at lower slopes, solute dispersion occurs over a broader time frame, resulting in lower concentration peaks. These findings indicate that while Fischer's method provides a robust empirical framework, it should be supplemented with field measurements to improve reliability. In contrast, the analytical method offers a more theoretically grounded alternative that may enhance predictive accuracy in solute transport modeling. The implications of these results extend to water quality management, contaminant transport studies, and hydraulic engineering applications, where the selection of an appropriate dispersion estimation method significantly influences predictive outcomes.

Keywords: Longitudinal dispersion coefficient; Empirical estimation; Hydrologic Engineering Center-River Analysis System (HEC-RAS); Analytical method; Solute transport; Shear velocity; Open-channel flow

1 Introduction

The study of solute transport in open channels is critical for understanding the behavior of pollutants and nutrients in natural and engineered water systems [1]. Due to the inherent coupling of hydrodynamic and ecological equations, water quality models are typically defined by significant complexity and challenging mathematical issues [2]. A one dimensional (1D) advection dispersion equation is widely used in water quality modelling in rivers [3]. The concentration change can be succinctly expressed in one dimension, according to the principle of conservation of mass. One key parameter in this context is the longitudinal dispersion coefficient (D), which quantifies the spreading of a solute along the direction of flow due to the combined effects of advection and diffusion. Over the years, various empirical and theoretical approaches have been developed to estimate this coefficient, reflecting the complex interplay of factors such as channel geometry, flow velocity, and turbulence. These methods range from empirical approaches like Fischer's method, widely adopted in hydraulic modeling tools such as HEC-RAS, to more theoretically grounded analytical methods that involve integral calculus. Each method offers unique advantages and limitations, depending on the specific conditions of the flow and the channel geometry.

Field tracer investigations may be costly and labor-intensive, particularly for long rivers [2], and the estimated dispersion coefficient is applicable just to the specific stream segment analyzed and the hydraulic conditions present