Method for Measuring High Tracer Concentrations in River Mixing Studies

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A b s t r a c t

Tracer experiments are a well-established technique for investigating mixing processes in rivers. A critical aspect of these experiments is ensuring the use of an appropriate amount of fluorescent tracer so that its concentration can be accurately measured with the available equipment. However, determining the optimal amount of tracer beforehand is often challenging. Furthermore, tracer concentrations can vary significantly during mixing processes, making accurate measurements at cross-sections near the injection point, as well as at more distant river cross-sections, particularly difficult. To overcome these challenges, a method was developed to retrieve valuable data when tracer concentrations exceed the measurement capabilities of the equipment. This approach utilizes the optical properties of the tracer solution in the presence of scattering particles within the fluid. By combining turbidity and fluorescence intensity readings, the method enables calibration of the turbidity–concentration relationship. This allows for the determination of tracer concentrations even when the fluorescence intensity–concentration relationship exceeds the linear regime.

1. INTRODUCTION

Fluorometers excite the tracer molecules with short wavelength light. During subsequent relaxation, longer wavelength fluorescence light is emitted. For low tracer concentrations, fluorescence light intensity is proportional to the tracer concentration. However, for high tracer concentrations proportionality fails (Wilson et al. 1986). It is caused mainly by absorption of fluorescence by tracer and self-quenching (excited tracer molecules relax without fluorescence emission due to interactions with each other). Those effects make fluorescence unsuited for measurements of high tracer concentrations. But for high tracer concentration absorption can be used to determine its value.

2. RESULTS

The Submersible Fluorometer from Turner Designs (SCUFA), enables simultaneous measurement of turbidity and fluorescence of tracer. This device utilises the same light beam for fluorescence excitation and for measuring light scattered by suspended particles in water – in order to estimate turbidity. Assuming constant amount of scattering particles in a solution, turbidity readings are mainly influenced by the absorption – determined by the tracer concentration. This enables calibration of turbidity–concentration relation.

A series of rhodamine WT water solution samples with a constant amount of suspended particles (kaolin powder) was prepared to test our approach. Tracer concentrations and turbidities readings were recorded for series of samples. The result of this experiment is presented in Fig. 1. As expected for very high tracer concentrations, the concentration readings recorded by SCUFA is dropping. At the same time turbidity readings decrease.
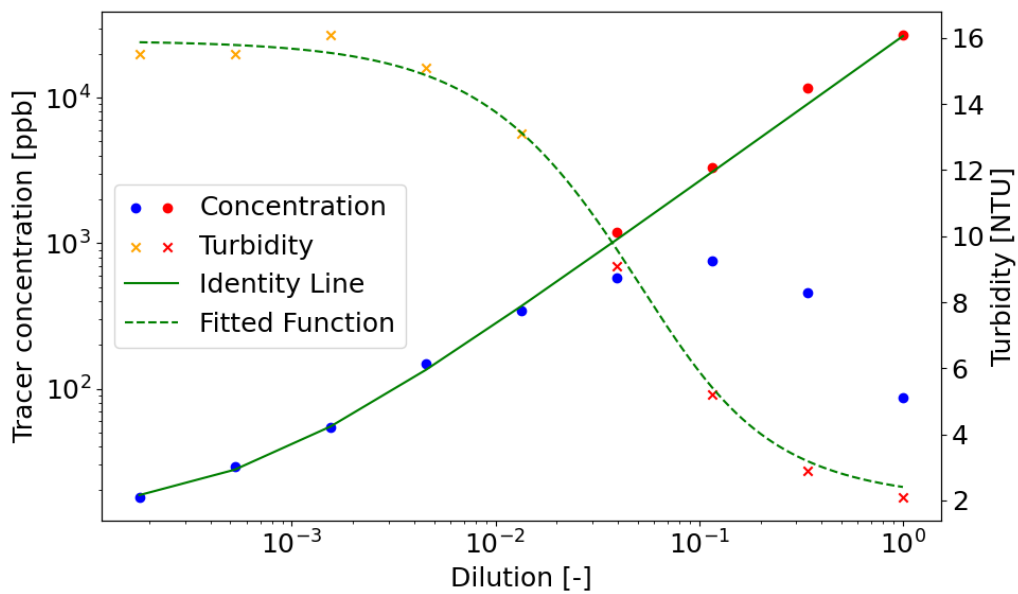

Fig. 1. Recorded tracer concentration and turbidity for dilution series of rhodamine WT. Blue dots represent direct fluorometer readings, while red dots indicate tracer concentrations recovered from turbidity data. Crosses denote turbidity readings. The dashed line represents the fitted turbidity–concentration relation. Only data represented as yellow crosses was used to perform the fit. Turbidity readings marked as red crosses were used to recover tracer concentration data (red dots) and were skipped. Identity line is a linear relation fitted to the five lowest tracer concentration points. Tracer concentration was treated as dependent variable and dilution as independent variable. Apparent curvature is due to log-log scale.

The relation between turbidity read and tracer concentration read was fitted. In the fitting procedure, only five lowest tracer concentration data points were used. This decision was motivated by the fact that this way we simulate a real-world scenario in which true tracer concentration outside linear region remains unknown.

To determine the proper form of the fitted function, a simple physical model was introduced. We assume that the amount of scattered lights reaching the detector per unit volume, denoted as ρ, is constant within a given space. Thus, the detector optical power I can be expressed as:

$$I = \int_V \rho dV. \tag{1}$$

Considering that scattered light is absorbed by the tracer and assuming that the path length of a scattered light ray is proportional to its distance from the detector window, we modify this equation using the Beer–Lambert law:

$$I = \int_V \rho e^{-\mu xc} dV,\qquad(2)$$

where x is distance to the detector window, c is tracer concentration, and μ is a constant that encapsulates information about the extinction coefficient and the relationship between x and the actual path length along the ray. This integral can be computed for a specific scattering region geometry. For simplicity, we assume the scattering region to be a cuboid with dimensions $L_x \times L_y \times L_z$. Under this assumption the integral simplifies to:

$$I = \frac{L_y L_z \rho}{\mu c}(e^{-\mu L_x c} - 1).\qquad(3)$$

This equation can be reparametrized to form:

$$I(c) = \frac{P_1}{c}(e^{-P_2 c} - 1) + P_3,\qquad(4)$$

where P_1 and P_2 account for constants in Eq. 3 and P_3 was introduced to account for residual signal. During fit we assumed a priori knowledge of P_3 parameter. Taking into account that the turbidity reading is proportional to the optical power detected (Davies-Colley and Smith 2001), a function of this form can be fitted to the turbidity–concentration relationship.

Equation 4 was numerically inverted to retrieve tracer concentration data. Recovered points align very well in line with directly measured tracer concentration (see Fig. 1), which confirms that concentration was successfully recovered.

3. CONCLUSIONS

This study presents a method for estimating high tracer concentrations using turbidity measurements, addressing the challenges of measuring high concentrations when dilution or other alternative methods are not feasible. The approach was experimentally validated, showing good agreement between recovered and directly measured concentrations.

A key limitation is that the instrument must rely on light wavelength absorbed by the tracer. Initial tests in natural river environments have been conducted and preliminarily confirm the validity of the approach. However, further research is planned to drive final conclusions.

R e f e r e n c e s

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