Received: 21 May 2021 | Revised: 7 October 2021 | Accepted: 13 October 2021
DOI: 10.1002/rra.3890

SHORT COMMUNICATION

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A simple low-cost approach for transport parameter determination in mountain rivers

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Funding information
Fondo de Financiamiento de Centros de Investigación en Áreas Prioritarias, Grant/Award Number: 15130015; Fondo Nacional de Desarrollo Científico y Tecnológico, Grant/Award Number: 1180153

Abstract

A simplified low-cost approach to experimentally determine transport parameters in mountain rivers is described, with an emphasis on the longitudinal dispersion coefficient (D_L). The approach is based on a slug injection of table salt (NaCl) as a tracer and specific conductance readings at different locations downstream of the injection spot. Observed specific conductance readings are fit using the advection-dispersion equation with OTIS-P, yielding estimates of cross-sectional area and longitudinal dispersion coefficient for various stream reaches. Estimates of the D_L are used to assess the accuracy of several empirical equations reported in the literature. This allowed the determination of complementary transport parameters related to transient storage zones. The empirical equations yielded rather high D_L values, with some reaching up an order of magnitude higher to those obtained from tracer additions and OTIS-P. Overall, the proposed approach seems reliable and pertinent for river reaches of ca. 150 m in length.

KEYWORDS
hydraulic properties, longitudinal dispersion coefficient, OTIS/OTIS-P, tracer addition

1 | INTRODUCTION

The longitudinal dispersion coefficient (D_L) is a key parameter for modeling transport of pollutants in river systems (Azamathulla & Ghani, 2011; Camacho-Suárez et al., 2019; Disley et al., 2014; Haghiabi, 2016; Sahin, 2014). One approach to estimate D_L is the use of empirical equations parameterized on the basis of morphological features of a given river (e.g., Haghiabi, 2016; Tenebe et al., 2016).

However, this empirical approach requires field validation, given that setting differences between site conditions where they were developed and where they are applied normally results in large uncertainties (e.g., Azamathulla & Ghani, 2011; Haghiabi, 2016). A second approach to determine D_L is to use tracer additions, which provide fairly accurate estimates of flow velocity, while offering further characterization of the mixing processes and the role of transient storage zones (Bencala et al., 1990; Kelleher et al., 2013; Szeftel et al., 2011). The effects of transient storage are normally not explicitly considered in the empirical equations (Fischer, Fischer et al., 1979). Thus, parameters such as D_L and others can be estimated by modeling the tracer transport. The OTIS solute transport model (One-dimensional Transport with Inflow and Storage; Runkel, 1998), for example, allows for such determination. Moreover, it considers a transient storage component, improving the fit for systems that might show an elongated tail in the breakthrough curve due to the effect of transient storage (Bencala et al., 1983; Runkel, 1998). This is important as such process, if not addressed, could cause unrealistic D_L estimations (McQuivey & Keefer, 1974).

In acid waters, widely used organic tracers, such as rhodamine, become nonconservative and unstable (Bencala et al., 1983; Runkel, 2015). The potential toxicity of fluorescent tracers has also been recently noted (e.g., Benischke, 2021). The use of inorganic salts such as LiCl, LiBr, NaBr, and KBr is therefore an attractive alternative. However, the application of salts may result in some operational difficulties, such as the adsorption of Li in circumneutral or basic river waters (Bencala et al., 1990; Runkel et al., 2007), and the cost of applying these salts in large systems where high tracer dosage is needed (Haghiabi, 2016; Tenebe et al., 2016). Thus, considering costs and potentially nonconservative behavior for some cations (e.g., Li), table salt (NaCl) emerges as a convenient option.

Although NaCl slug injections have been utilized at low flow (<30 L/s; Szeftel et al., 2011; Kelleher et al., 2013), it remains unclear its suitability for determining D_L and assessing the importance of transient storage under larger flow rates (e.g., over 800 L/s) and more complex settings, that is, high stream water velocities (e.g., over 0.8 m/s), river systems with both acid and neutral *pH* waters, high background salinity (over 2.0 mS/cm), and high stream sinuosity. These conditions can be easily found in mountain river systems affected by acid drainage (e.g., Zegers et al., 2021). Therefore, the possibility to have a simple and low cost approach becomes of great practical importance for the study and modeling of contaminant transport and fate in mountain headwater river systems. Thus, this contribution aims to assess this research gap by (i) assessing a low-cost approach that could be useful in other systems affected by acid drainage, where an estimation of transport parameters (such as D_L and travel-time) is needed to assess pollutant transport and (ii) compare D_L results to empirical equations and illustrate how this approach can be extended to cases where transient storage is important.

2 | STUDY AREA

The proposed approach was tested in the upper Elqui River, Coquimbo Region, Northern Chile (Figure 1). The low *pH* and high specific conductance (*SC*) Toro River drains an area with well-known acid rock drainage (ARD) generation of natural and anthropogenic origin (Oyarzún et al., 2018). This river mixes with more alkaline and lower *SC* rivers (i.e., La Laguna, Incaguaz, and Claro Rivers), contributing to the dilution and attenuation of the original ARD heavy metal load (Flores et al., 2017; Rossi et al., 2021).

3 | METHODS

3.1 | Field work

Slug injection tests were performed using table salt (NaCl) as a tracer in six reaches (Figure 1) selected to cover different morphological, hydraulic, and hydrochemical conditions, during August 28, August 30, and September 4, 2019. Each reach extended for ~120–150 m and was divided into 3–4 segments (~30–40 m in length). Reach characteristics are presented in Table 1, and an overview of one site is presented in Figure 2.

The slug injections consisted of 12 kg of common table salt dissolved in 30 L of river water and poured instantly. Specific conductance measurements were taken every 5 s, simultaneously in each segment end, with Hanna conductivity meters (Model HI 99301) probes. Measurements started 2 min before the slug injection and continued past the peak until *SC* returned to background levels; thus, each test lasted approximately 10 min.

The flow velocity in the easternmost reach (Toro River, TO-LL) was determined with a Hydro-Bios (HB-445510) current meter and from the travel time of a floating object (i.e., a bottle cork or shrub branches) through a distance of 15–20 m (10 repetitions). For the rest of the reaches, due to safety and accessibility considerations, only the second method was used, and flow velocities were corrected by a factor of 0.65 to obtain a more representative value of the water column profile. The corrector factor is based on research using both a current meter and the float method in other rivers in the Coquimbo region (Oyarzún et al., 2016) and elsewhere (Hundt & Blasch, 2019). Stream widths were manually measured at regular intervals (i.e., every 10–20 m) with a measuring tape, and the water column depths were measured with a graded pole, when possible. The reach slope and the sinuosity index were determined using elevation and distance measurements obtained from Google Earth images.

3.2 | D_L calculations

3.2.1 | OTIS and OTIS-P

The OTIS solute transport model is based on the Advection-Dispersion (AD) equation and considers transient storage, lateral inflow, and dispersion (Equation 1 and 2), among other processes (Runkel, 1998). OTIS-P, a complementary version, uses nonlinear regression to provide an optimized parameter set (Runkel, 1998). The parameters that are determined are the longitudinal dispersion

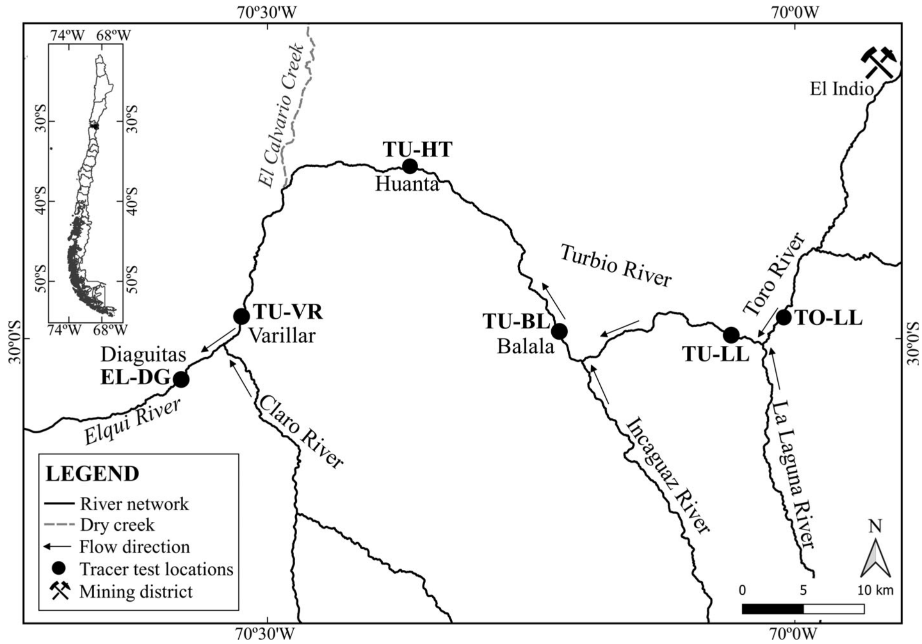


FIGURE 1 Study area and tracer addition sites: TO-LL, Toro River before La Laguna River; TU-LL, Turbio River after La Laguna River; TU-BL, Turbio River at Balala; TU-HT, Turbio River at Huanta; TU-VR, Turbio River at Varillar; EL-DG, Elqui River at Diaguitas

TABLE 1 Reach characteristics

Reach	*L* (m)	Segments	*w* (m)	*d* (m)	*A* (m^2)	*U* (m/s)	*Q* (m^3/s)	SC_B (μS/cm)	*pH*	Turbidity (NTU)	*S* (m/m)	*SI*
TO-LL	150	40^a–80–150^a	2.73	0.21	0.57	0.95	0.54	2,400	4.5	93.5	0.05	1.21
TU-LL	120	40–80^a–120^a	8.71	0.38	3.31	0.72	2.38	1,200	7.6	54.8	0.07	1.03
TU-BL	120	38–75^a–120^a	9.67	0.44	4.25	0.97	4.12	950	8.1	49.5	0.02	1.02
TU-HT	120	40^a–120^a	7.01	0.51	3.58	1.02	3.65	940	8.0	47.2	0.02	1.04
TU-VR	120	40^a–120^a	5.47	0.48	2.63	0.83	2.18	860	7.9	47.3	0.03	1.06
EL-DG	119	40–80^a–119^a	8.29	0.50	4.15	0.91	3.78	700	8.2	27.9	0.01	1.01

Note: *L*, length of the reach; *w*, average width; d, average water column depth; *A*, cross-sectional area; S, reach slope; *SI*, sinuosity index; *U*, average water velocity; *Q*, average flow rate; SC_B, background specific conductance. Turbidity and *pH* values are averages from field campaigns (September 2018 and January 2019). "a" reaches considered for simulation (outside the mixed zone).

coefficient, D_L (m^2/s); the main channel cross-sectional area, A (m^2); the transient storage zone cross-sectional area, A_S (m^2); and the exchange coefficient between A and A_S, α (s^{-1}), based on the following transport equations.

$$\frac{\partial C}{\partial t} = \underbrace{-\frac{Q\partial C}{A\partial x}}_{\text{Advection}} + \underbrace{\frac{1\partial}{A\partial x}\left(AD_L\frac{\partial C}{\partial x}\right)}_{\text{Dispersion}} + \underbrace{\frac{Q_{Lat}}{A}(C_{Lat}-C)}_{\text{Lateral inflow}} + \underbrace{\alpha(C_s-C)}_{\text{Transient storage zone}} \quad (1)$$

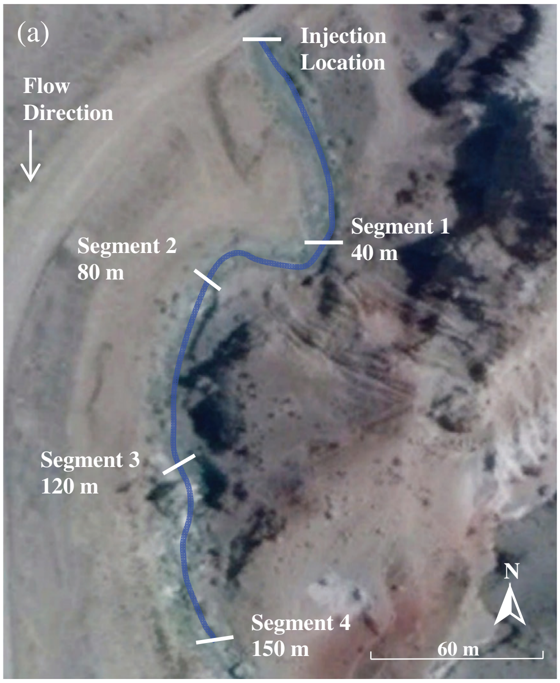
$$\frac{\partial C_S}{\partial t} = \alpha\frac{A}{A_S}(C-C_S) \quad (2)$$

where C is the solute concentration (mg/L); Q is the volumetric flow rate (m^3/s); t is the time (s); x is the distance (m); C_s is the transient storage zone concentration (mg/L); C_{Lat} is the lateral inflow solute concentration (mg/L); and Q_{Lat} is the lateral inflow rate (m^3/s-m).

To develop initial estimates of D_L and A, several OTIS simulations were performed using the AD equations until simulated and observed data converged. Next, an optimized and final estimate was obtained with OTIS-P. In addition, to identify the storage zone effect on the parameter set, OTIS-P was applied under two conditions:

1. Advection-Dispersion model (AD). The D_L and A parameters were estimated by an iterative process, using the initial value resulting from the OTIS simulation (or a previous run in OTIS-P) and setting $\alpha = 0$ (i.e., not considering transient storage, so Equation (1) becomes the basic advection-dispersion equation). This process was repeated until convergence and stability are achieved. The results were verified by positive confidence interval ranges, stability in the estimated value/SD ratios, and residuals sum of squares; a higher ratio and lower error were also considered as improvement indicators (Runkel, 1998).
2. Advection-Dispersion-Storage model (ADS). The storage parameters, A_S and α, were considered to obtain a new optimized set that combines these four parameters (D_L, A, A_S, and α).

The continuous breakthrough curve (time vs. *SC*) from the upstream location of the tracer tests was used to set the upstream boundary



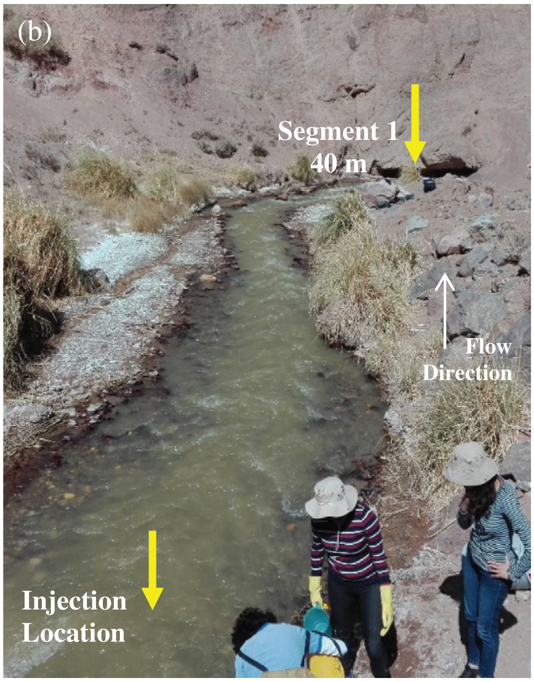


FIGURE 2 (a) Reach of Toro River and segments of *SC* measurements; (b) Injection location and Segment 1 for Toro River [Color figure can be viewed at wileyonlinelibrary.com]

condition (type 3 boundary condition). The downstream boundary condition was considered as a dispersive *SC* flow of zero gradient, for which, a fictitious section, of at least 50 m long, was added downstream. Finally, the model routes all this information farther downstream as the simulation is compared with a second breakthrough curve to estimate the parameters (Runkel, 1998).

In addition, using the parameters from OTIS-P ADS model and Equation 3, the fraction of median travel time due to transient storage standardized by a segment of 200 m of longitude ($F_{med}{}^{200}$) was estimated. This metric provides a quantitative and integrated assessment of the relative importance of the transient storage zones (surface and hyporheic), which is a key feature in the context of whole-stream mass transport (Runkel, 2002).

$$F_{med}^{200} \cong \left(1 - e^{-200(\propto/U)}\right)\frac{A_S}{A + A_S} \tag{3}$$

where U is the average velocity (m/s).

3.2.2 | Empirical equations

The empirical expressions considered in this research were

- McQuivey and Keefer (1974)

$$D_L\left(\mathrm{m}^2/\mathrm{s}\right) = 0.058\frac{Q}{Sw} \tag{4}$$

where Q is the flow rate (m^3/s), w is the width of the river (m), and S is the stream slope (m/m).

- Fischer et al. (1979)

$$D_L\left(\mathrm{m}^2/\mathrm{s}\right) = 0.011\frac{U^2 w^2}{dU*} \tag{5}$$

$$U^*\left(\mathrm{m/s}\right) = \sqrt{gdS} \tag{6}$$

where d is the depth (m); U^* (m/s) is the shear velocity; and g is the acceleration of gravity (m/s^2).

- Liu (1977)

$$D_L\left(\mathrm{m}^2/\mathrm{s}\right) = \mu\frac{U^2 w^2}{dU*} \tag{7}$$

$$\mu = 0.18\left(\frac{U^*}{U}\right)^{1.5} \tag{8}$$

- Kashefipour and Falconer (2002)

$$D_L\left(\mathrm{m}^2/\mathrm{s}\right) = \left[7.428 + 1.775\left(\frac{w}{d}\right)^{0.620}\left(\frac{U^*}{U}\right)^{0.572}\right] dU\left(\frac{U}{U^*}\right) \tag{9}$$

With all the variables already defined.

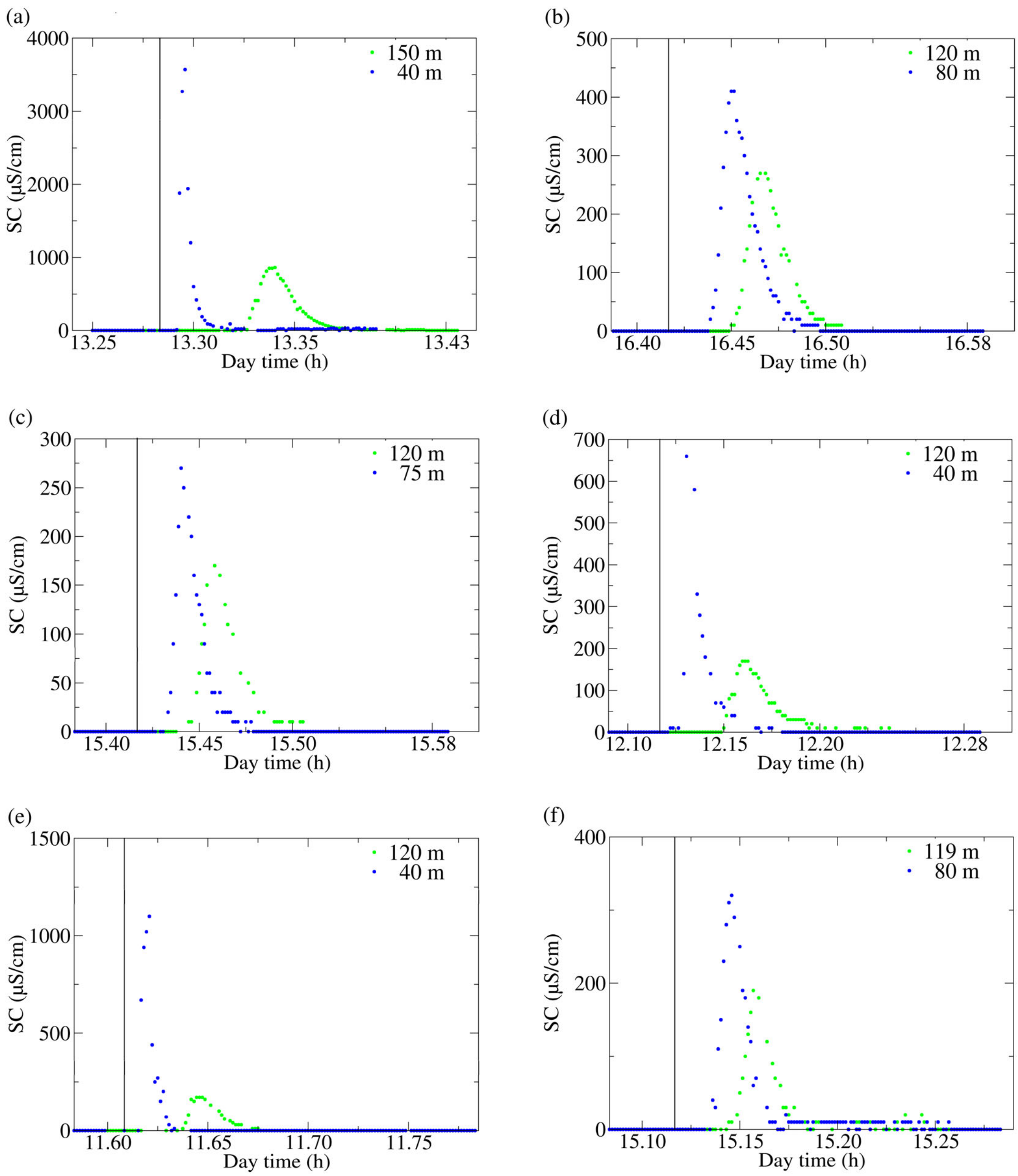


FIGURE 3 Tracer breakthrough curves for the different reaches. (a) TO-LL, Toro River before La Laguna River; (b) TU-LL, Turbio River after La Laguna River; (c) TU-BL, Turbio River at Balala; (d) TU-HT, Turbio at Huanta; (e) TU-VR, Turbio River at Varillar; (f) EL-DG, Elqui River at Diaguitas. The vertical line represents the time of tracer injection [Color figure can be viewed at wileyonlinelibrary.com]

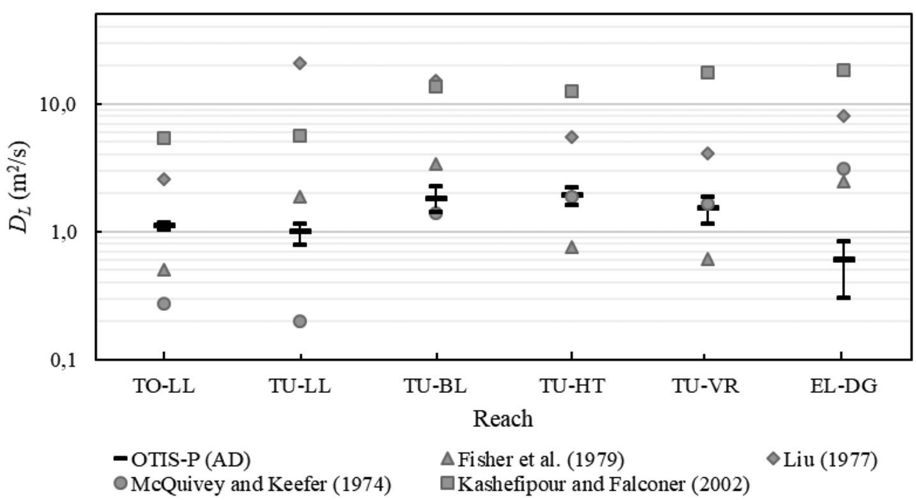


FIGURE 4 Comparison of D_L with 95% confidence intervals for OTIS-P (AD) model and empirical equations. TO-LL, Toro River before La Laguna River; TU-LL, Turbio River after La Laguna River; TU-BL, Turbio River at Balala; TU-HT, Turbio at Huanta; TU-VR, Turbio River at Varillar; EL-DG, Elqui River at Diaguitas

TABLE 2 D_L values from empirical equations

Location	Fischer et al. (1979)	McQuivey and Keefer (1974)	Liu (1977)	Kashefipour and Falconer (2002)
TO-LL	0.5	0.3	2.6	5.4
TU-LL	1.9	0.2	21.0	5.6
TU-BL	3.4	1.4	15.0	13.5
TU-HT	0.8	1.9	5.5	12.6
TU-VR	0.6	1.7	4.1	17.5
EL-DG	2.5	3.1	8.0	18.3

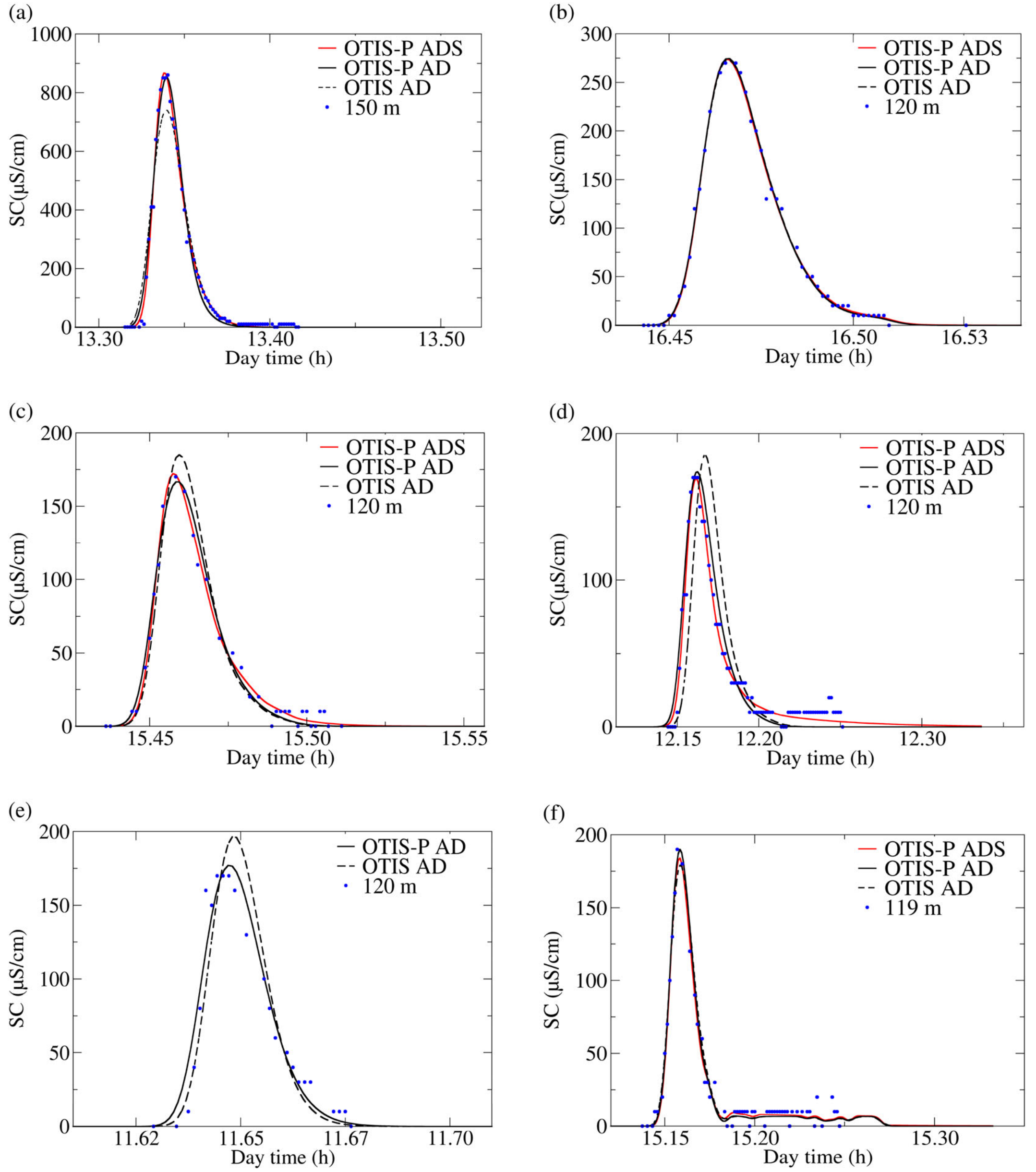


FIGURE 5 Observed *SC* and OTIS/OTIS-P simulation (AD and ADS). (a) TO-LL, Toro River before La Laguna River; (b) TU-LL, Tubio River after La Laguna River; (c) TU-BL, Turbio River at Balala; (d) TU-HT, Turbio at Huanta; (e) TU-VR, Turbio River at Varillar; (f) EL-DG, Elqui River at Diaguitas [Color figure can be viewed at wileyonlinelibrary.com]

4 | RESULTS AND DISCUSSION

4.1 | Tracer breakthrough curves

The tracer breakthrough curves for all reaches are presented in Figure 3. It shows that the tracer moves rapidly through the first segment (e.g., first 40 m) of each reach. This makes it somewhat difficult to accurately measure the rising and descending limbs of the curves given the measurement time of the *SC* probes and the inherent short-term variability under turbulent water flow conditions observed in mountain streams. Also, it was observed that the tracer cloud by the third segment (120 or 150 m downstream the injection spot) was still possible to clearly detect. Thus, for future tests or setting conditions similar to ours, it seems reasonable to extend the most downstream site farther to even at 180 or 200 m from the injection point, which would allow for an increase in spatial extent.

4.2 | Comparison of D_L values

The D_L values determined from tracer additions and OTIS-P application (AD) were considered to be more accurate than those derived from the empirical equations for the streams considered in this research. This is because the OTIS-P D_L values were derived using site-specific data and a rigorous model of advective-dispersive transport, in contrast to the empirical equations that were developed using data from other sites. Thus, the D_L values obtained from empirical equations were compared to those derived from OTIS-P (AD) (Figure 4).

Exceptionally high D_L values were obtained, especially with Liu (1977) and Kashefipour and Falconer (2002) equations, which, in some cases, exceed the OTIS-P results by an order of magnitude. While Fisher (Fischer et al., 1979) and McQuivey and Keefer (1974) equations tend to be closer to the OTIS-P (AD) values (95% confidence interval limit), a difference as high as fivefold was recorded in some cases (Figure 4 and Table 2). Certainly, empirical equations, as they are dependent from the local conditions, show high variability, adding uncertainty regarding their use (Azamathulla & Ghani, 2011; Haghiabi, 2016; Sahin, 2014). This is especially relevant to mountain river settings, which tend to present high spatial variability in its geometrical-hydraulic parameters (i.e., width, depth, flow patterns, and bed roughness).

4.3 | Transient storage effect

An additional advantage of using OTIS/OTIS-P is the estimation of transport parameters such as *A* and A_S. The results of the tracer transport simulation with OTIS-P (AD and ADS) are presented in Figure 5 and Table 3. The results highlight the good adjustment obtained for the tracer breakthrough curves, verifying the convergence and stability of the parameter values. Regarding parameter estimation, the effect of transient storage (OTIS-P ADS) causes the reduction of the D_L to half its value, whereas *A* remains within the same ranges obtained with OTIS-P AD. Furthermore, the D_L values obtained from OTIS-P were of the same order of magnitude as those of Heron (2015) for rivers with features comparable to those of the upper Elqui River.

Finally, the F_{med}^{200} estimates are presented in Table 3. The three reaches with the higher sinuosity index (Table 1), that is, Toro (TO-LL), Turbio at Balala (TU-BL), and Turbio at Huanta (TU-HT) were also those with the highest F_{med}^{200}. Thus, a preliminary relationship between transient storage and the morphologic features of the reaches can be inferred.

5 | CONCLUSION

The simple low-cost approach proposed (multiple slug tests using NaCl as a tracer) is viable for a D_L determination, in reaches of 150–180 m, with flow rates of hundreds to thousands of L/s and a heterogeneous mountain river system with acidic and slightly alkaline *pH*. The use of OTIS/OTIS-P allowed the characterization of the relative importance of transient storage in some of the studied reaches, adding value to the results derived from the tracer breakthrough curves. As a consequence, by estimating a more representative set of study area parameters, the approach would help to avoid misinterpretations in future modeling of contaminant transport in surface waters. Conversely, the use of empirical equations for the determination of D_L in the studied area results in high and very variable values which confirms that their widespread use and transfer between sites is

TABLE 3 OTIS-P (AD and ADS) results

	OTIS-P (AD)		OTIS-P (ADS)				
Location	D_L (m^2/s)	*A* (m^2)	D_L (m^2/s)	*A* (m^2)	A_S (m^2)	α (s^{-1})	F_{med}^{200} (%)
TO-LL	1.1	0.8	0.5	0.7	0.1	0.013	14.3
TU-LL	1.0	3.3	0.8	3.2	0.1	0.001	0.6
TU-BL	1.8	5.7	0.7	5.0	1.1	0.007	14.4
TU-HT	1.9	6.2	1.2	5.9	2.2	0.003	13.1
TU-VR	1.5	5.0	[a]	[a]	[a]	[a]	[a]
EL-DG	0.6	5.8	0.4	5.6	1.4	0.002	6.1

[a]No convergence was attained for OTIS-P ADS, which explains the lack of A_S and α values.

difficult, so if possible, local tracers studies such as the one herein described should be favored.

ACKNOWLEDGMENTS

We thank T. Ceballos, D. Ocaranza, R. Cortés, P. Urrea, J. Oyarzún, E. González, L. Galleguillos, M. Aguirre, V. Hernández, M. Lincoqueo, C. Rojas, C. Sandoval, J. Olivares, N. Diaz, V. Núñez, S. Leiva, G. Navarro and D. Rivera for their logistic support and assistance in the field (tracer additions). This research was funded by ANID/FONDECYT/1180153 and ANID/FONDAP/15130015. Additional support was provided by the U.S. Geological Survey's Toxic Substances Hydrology Program and in particular Dr. Blaine McCleskey. The paper greatly benefited from the comments of an anonymous reviewer and the Editor in Chief. Model applications were the sole responsibility of the first author and were not performed by the U.S. Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

CONFLICT OF INTEREST

The authors do not declare any conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Castillo, D., Runkel, R. L., Duhalde, D., Pastén, P., Arumí, J. L., Oyarzún, J., Núñez, J., Maturana, H., & Oyarzún, R. (2021). A simple low-cost approach for transport parameter determination in mountain rivers. *River Research and Applications*, 1–9. https://doi.org/10.1002/rra.3890