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INDIRECT METHODS FOR ESTIMATING THE HYDRAULIC PROPERTIES OF UNSATURATED SOILS

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ANALYSIS OF PREDICTED HYDRAULIC CONDUCTIVITIES USING RETC

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The computer program RETC was used to analyze unsaturated hydraulic conductivity data of 36 soils obtained from the literature using the empirical relationship of van Genuchten [1980] to describe the soil water retention curve, and the predictive model of Mualem [1976a] to estimate the hydraulic conductivity. By comparing the measured and estimated conductivities for the group of data, the accuracy of the approach could be determined for various conditions. The analysis consisted of comparing measured and estimated conductivities using the predictive method (i.e., when the unsaturated hydraulic conductivity is assumed to be unknown), the simultaneous method (i.e., when both water retention and unsaturated hydraulic conductivity data are available), a matching point (at a point somewhat dryer than saturation) to scale the estimated value of the conductivity, and a methods involving the adjustment of Mualem's empirical factor, ℓ, to improve the fit between the measured and estimated conductivity. The results indicate that for this group of data, the best estimates of the unsaturated hydraulic conductivity are obtained using either the predictive approach with a matching point, or the simultaneous approach using a 6-parameter fit (i.e., including $\theta_r, \theta_s, \alpha, n, \ell$ and K_s *in the* fitting procedure). Surprisingly, the worst and most biased estimates were obtained using the simultaneous approach with a S-parameter fit (i.e., when K_s *was fixed).*

INTRODUCTION

There is an ever increasing need for more accurate numerical models to solve groundwater flow and contamination problems. To achieve this. better methods for characterizing the soil hydraulic properties are needed. Currently, our ability to create complex numerical models far exceeds our capacity to describe the physical system on which the models are based. The basic soil hydraulic properties, and in particular the unsaturated hydraulic conductivity, play an integral role in determining the accuracy of any numerical solution to flow, and therefore, transport problems. This inability to characterize the functional relationship between the unsaturated hydraulic conductivity and the water content (or pressure head) will result in an inaccurate representation of the simulated flow process. Incorporating an inaccurate flow representation into a contaminant transport model, in turn. will seriously affect the overall accuracy of the transport simulation.

The problem of determining the unsaturated hydraulic conductivity is confounded by the expense of experimentally obtaining this relationship, and the number of observations required due to field scale variability. This has led to the introduction of predictive techniques for obtaining the unsaturated hydraulic conductivity from soil water retention data which are much easier to obtain. The advantage of predictive methods is that more measurements can be obtained for a given investment, and hence, that a better characterization of the flow domain can be obtained given that the methods provide adequate predictions.

The purpose of this paper is to demonstrate the use of **RETC by** undertaking several analyses on a soil hydraulic data set consisting of a large number of different soil types. water retention data, and unsaturated hydraulic conductivities. By analyzing the group as a whole and comparing the measured and estimated unsaturated hydraulic conductivities, it is possible to make a qualitative judgment as to the accuracy of the predictive techniques, whether the estimated conductivities are systematically biased, and whether measured unsaturated hydraulic conductivity values are necessary to obtain an accurate representation of this soil property. A more detailed discussion of the results of this study is given by Yates et al. [1992].

METHODS

A data set consisting of 23 different soil types and 36 distributions for the moisture retention relationship and the unsaturated hydraulic conductivity were obtained from the literature and used in the following analysis. These data are reported in Table 1 and include the ***Mualem [1976b] soil*** index, the soil name, and values of four parameters in -the water retention function of van ***Genuchten [*** 1980]. The connectivity parameter ℓ [van Genuchten and ***Nielsen,*** 1985; ***Luckner et al.,*** 1989] was also used as a potential unknown. The program RETC, described in more detail by van Genuchten et al. [1991] and ***Leij et al.*** [1992]. was used to determine the vaiues for the soil hydraulic properties using a least squares parameter optimization method. The same set of initial parameters were used for each soil type considered, and were modified only if the minimization process failed to converge.

The analysis consisted of using RETC in several ways. The first method, termed the predicted method, determines the optimal soil hydraulic parameters (θ_r, θ_s, I, and n) using only the measured water retention data. These soil hydraulic parameters are subsequently used to predict the relative unsaturated hydraulic conductivity (assuming a saturated conductivity, K_s, of unity). Since the measured hydraulic conductivity data for each soil listed in Table 1 are known, and assuming that the data are free from error, a direct comparison can be made between the predicted and measured unsaturated hydraulic conductivity giving some indication of the quality of the predictor.

If the unsaturated hydraulic conductivity is known at only one moisture content or pressure head, but not at saturation, it is possible to scale the estimated hydraulic conductivity using the method proposed by ***Luckner er al. [1989].*** When combined with the predictive method described above, this approach is termed the scaled-predictive method.

Using RETC it is also possible to include known values of the unsaturated hydraulic conductivity in the parameter optimization process to simultaneously fit the water retention and unsaturated hydraulic conductivity functions. In this case, two additional parameters (i.e., ℓ and K,) may be adjusted during the fitting procedure. For our analysis, a 5-parameter fit indicates that (was adjusted, while a 6-parameter fit indicates that both ℓ and K_s were adjusted during the optimization. The scaling technique proposed by Luckner et al. [1989] was also used in conjunction with the simultaneous fitting procedure.

The final analysis, termed the predictive mode with adjustable I. indicates the use of fitted soil hydraulic parameters resulting from the predictive method (i.e., when the measured unsaturated hydraulic conductivity is not used), fixing these values. and subsequently using RETC to find the best value for the parameter ℓ. In this manner, only the parameter ℓ is adjusted and the sensitivity of the method to the parameter ℓ ***can be*** obtained.

Table 1. Basic Soil Hydraulic Data Set and Parameter Estimation Results using the Predictive Method

soil Index	Soil Name	θ_r	θ_s	α (1/cm)	n
3310	Silt Loam GE 3	0.139	0.394	0.00414	2.15
----	Yolo Light Clay K(WC)	0.205	0.499	0.02793	1.71
—	Yolo Light Clay K(H)	0.205	0.499	0.02793	1.71
4130	Hygiene Sandstone	0.000	0.256	0.00562	3.27
1003	Lambcrg Clay	0.000	0.502	0.140	1.93
1006	Beit Netofa Clay Soil	0.000	0.447	0.00156	1.17
1101	Shiohot Silty Clay	0.000	0.456	183	1.17
2001	silt Columbia	0.146	0397	0.0145	1.85
2002	Silt Mont Cenis	0.000	0.425	0.0103	134
2004	Slate Dust	0.000	0.498	0.00981	6.75
3001	Weld Silty Clay Loam	0.159	0.496	0.0136	5.45
3101a	Rideau Clay Loam, Wetting	0.279	0.419	0.0661	1.89
3101b	Rideau Clay Loam, Drying	0.290	0.419	0.0177	3.18
3301a	Caribou Silt Loam, Drying	0.000	0.451	0.00845	1.29
3301b	Caribou Silt Loam, Wetting	0.000	0.450	0.140	1.09
3302a	Grenville Silt Loam, Wetting	0.013	0523	0.0630	1.24
3302c	Grenville Silt Loam, Drying	0.000	0.488	0.0112	1.23
3304	Touchet Silt Loam	0.183	0.498	0.0104	5.78
3402a	Gilat Loam	0.000	0.454	0.0291	1.47
3403	Pachapa Loam	0.000	0.472	0.00829	1.62
3404	Adelanto Loam	0.000	0.444	0.00710	1.26
3405a	Indio Loam	0.000	0.507	0.00847	1.60
3407a	Guclph Loam	0.000	0.563	0.0275	1.27
3407b	Guclph Loam	0.236	0.435	0.0271	262
3501a	Rubicon Sandy Loam	0.000	0393	0.00972	2.18
350lb	Rubicon Sandy Loam	0.000	0.433	0.147	1.28
3503a	Pachapa Fme Sandy Clay	0.000	0.340	0.0194	1.45
3504	Gilat Sandy Loam	0.000	0.432	0.0103	1.48
4101a	Plainfield Sand (210-250 μm)	0.000	0351	0.0236	1230
4101b	Plainfield Sand (210-250 μm)	0.000	0312	0.0387	4.48
4102a	Plainfield Sand (177-210 μm)	0.000	0361	0.0207	10.m
4102b	Plainfield Sand (177-210 μm)	0.022	0309	0.0328	6.23
4103a	Plainfield Sand (149-177 μm)	0.000	0387	0.0173	7.80
4103b	Plainfield Sand (149-177 μm)	0.025	0321	0.0272	6.69
4104a	Plainfield Sand (l25-149 μm)	0.000	0377	0.0145	10.60
4104b	Plainfield Sand (125-149 μm)	0.000	0.342	0.0230	5.18

RESULTS

Shown in Figure 1 is a scatter diagram of the measured versus estimated values for the unsaturated hydraulic conductivity using the predictive method. The solid line is a 1:l line and denotes the location on the graph where the measured and calculated conductivities are equal. It is apparent from this figure that the hydraulic conductivity shows considerable variation around the 1:l line. Except for a few outliers, most of the values fall within one to three orders of magnitude from the 1:l line in the wet region, and within three to five orders of magnitude in the dry range.

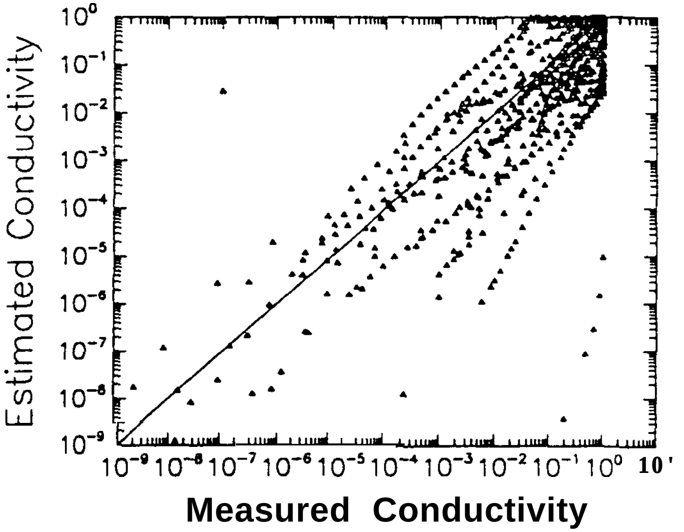

Fig. 1. Scatter diagram of measured versus estimated values for the unsaturated hydraulic conductivity using the predictive method.

Shown in Figure 2 is a scatter diagram when the water retention and unsaturated hydraulic conductivity curves are fitted simultaneously. The K_s parameter for this example was fixed. It is apparent from this figure and the mean sum-of-deviations given in Tables 2 and 3 that the calculated unsaturated hydraulic conductivity consistently underestimates the measured values, and hence, that the estimated values are biased.

Shown in Figure 3 are measured versus estimated hydraulic conductivities using a simultaneous tit assuming 6 parameters. This figure indicates that there is considerable improvement in the correspondence between the measured and estimated values for most of the soils.

Figure 4 shows the results when the predictive method is used but with the estimated values scaled according to the method described by Luckner er al. [1989]. This method uses one value of the unsaturated hydraulic conductivity measured at a point near (but not at) saturation as a matching point. This technique improves the correspondence between the measured and estimated values. Comparing Figures 1 and 4 demonstrate a considerable improvement in the estimated value, especially in the near-saturated region. and illustrates the difficulty of obtaining accurate values for the soil hydraulic properties at water contents very close to saturation. In the dryer regions, the scaling technique Seems to lead to conductivity values which slightly overestimate the measured values.

Figure 5 demonstrates how the scaling technique can be used to remove the bias that occurs from using a simultaneous fitting procedure with 5 parameters (see Figure 2). For the data set used in this study, use of a matching point to scale the unsaturated conductivity removes the bias and improves the estimates near saturation; however, the matching factor also seems to increase the Scatter in the dry region.

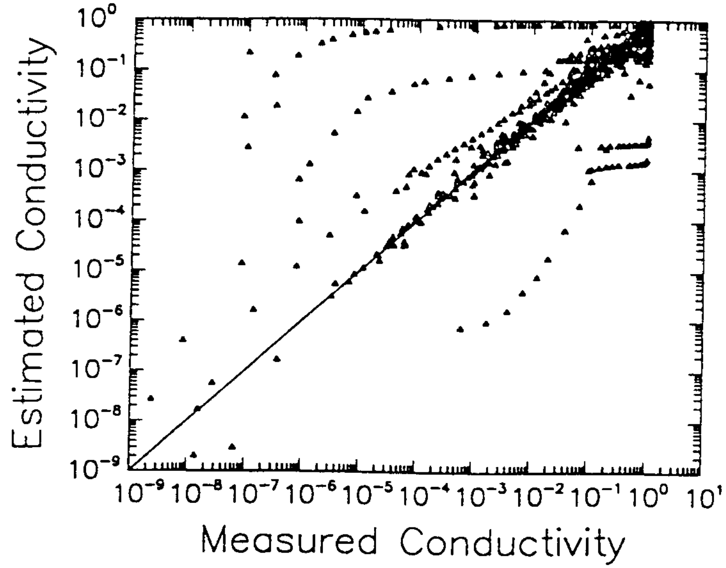

Figure 2. Scatter diagram of measured versus estimated values of the hydraulic conductivity using a simultaneous fit of the retention and conductivity data (K_s = 1.0).

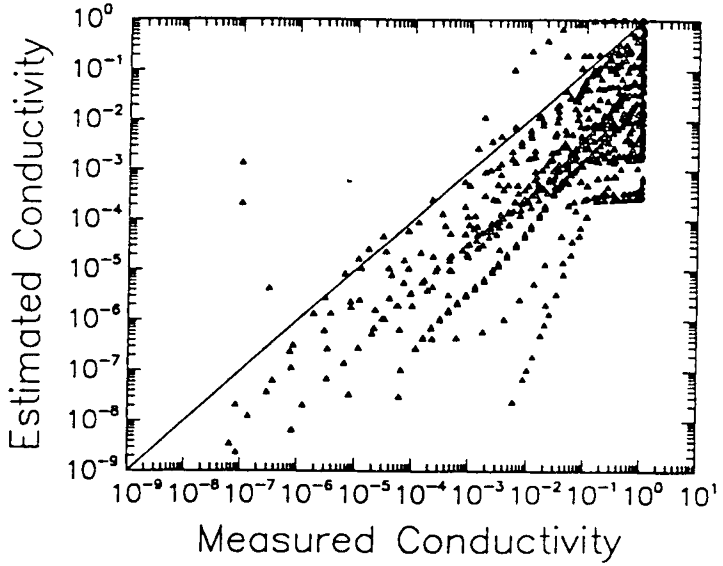

Figure 3. Measured versus estimated hydraulic conductivities using a simultaneous fit with 6 unknown parameters (K_s variable).

TABLE 2. Statistics Comparing Measured and Estimated Hydraulic Conductivities Using RETC

	Mean Sum of Deviation (Regr., 1:1)	Mean Sum of Squares (Regr., 1:1)	Sum of Squares (Regression)	Sum of Squares (Residual)	Linear Regression Line	r^2
Predictive Method	0.060	0.118	26.06	58.28	$0.075+0.538\ K_m$	0.309
Simultaneous Fit, 5 Parameters	0.226	0.166	4.20	23.04	$0.006+0.216\ K_m$	0.154
Simultaneous Fit, 6 Parameters	0.048	0.340	49.66	99.95	$0.038+0.759\ K_m$	0.332
Scaled Predictive Method	-0.043	0.038	38.66	17.15	$0.059+0.930\ K_m$	0.693
Scaled Simultaneous Fit, 5 Parameters	-0.068	0.046	42.97	23.56	$0.083+0.932\ K_m$	0.646
Scaled Simultaneous Fit, 6 Parameter	-0.066	0.050	31.28	20.20	$0.025+0.682\ K_m$	0.608
Predictive Method with Fitted ℓ	0.115	0.115	16.90	40.73	$0.049+0.446\ K_m$	0.293

TABLE 3. Statistics Comparing Measured and Estimated Hydraulic Conductivities Using RETC (Log_{10} Transformed Hydraulic Conductivity)

	Mean Sum of Deviation (Regr., 1:1)	Mean Sum of Squares (Regr., 1:1)	Sum of Squares (Regression)	Sum of Squares (Residual)	Linear Regression Line	r^2
Predictive Method	0.661	6.353	1875	3986	$-0.62+1.038\ K_m$	0.320
Simultaneous Fit, 5 Parameters	1.414	3.115	1548	752	$-1.51+0.943\ K_m$	0.673
Simultaneous Fit, 6 Parameters	-0.031	1.150	742	562	$-0.48+0.657\ K_m$	0.569
Scaled Predictive Method	0.097	4.285	1490	2924	$-0.14+1.036\ K_m$	0.337
Scaled Simultaneous Fit, 5 Parameters	-0.205	1.129	728	490	$-0.29+0.702\ K_m$	0.598
Scaled Simultaneous Fit, 6 Parameters	-0.324	1.232	553	435	$-0.32+0.606\ K_m$	0.560
Predictive Method with Fitted ℓ	0.698	4.823	1710	2831	$-0.67+1.017\ K_m$	0.377

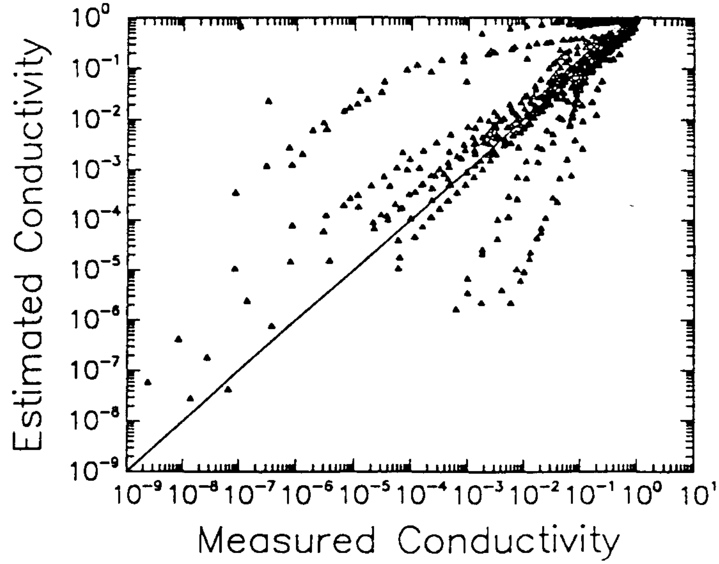

Figure 4. Measured versus estimated hydraulic conductivities using the predictive method and a matching point near saturation.

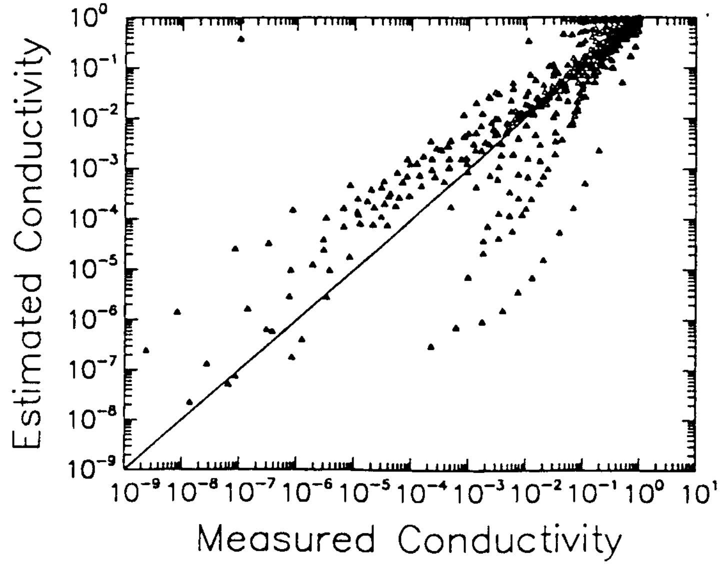

Figure 5. Measured and estimated conductivities using a simultaneous fit with 5 parameters and a matching point near saturation (fixed K_s).

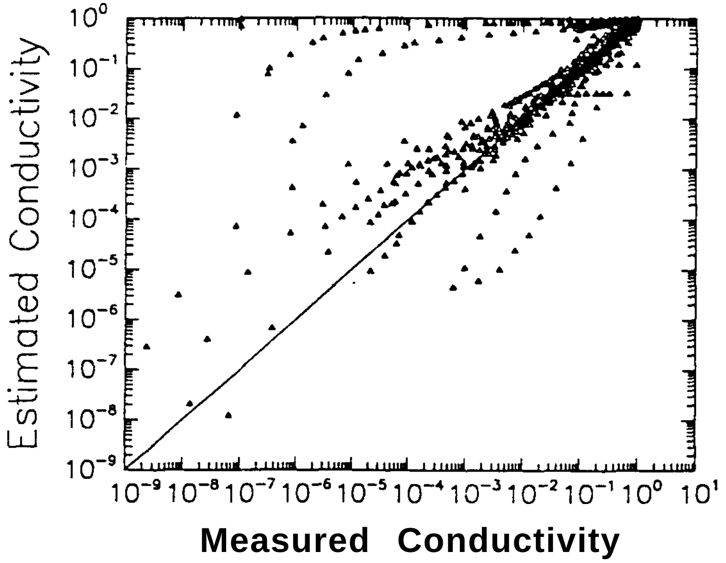

Fig. 6. Measured and estimated conductivitics using a matching point near saturation (K_s variable).

Figure 6 shows that there is little improvement from using a matching point to scale the unsaturated conductivity if the saturated hydraulic conductivity is one of the parameters used in the fitting procedure. For these circumstances, the parameter K_s acts in a similar manner as the matching point and provides a means to linearly translate the estimated values to more closely correspond to the measured values.

Figure 7 demonstrates the effect of using the parameter, ℓ (i.e., the exponent in the tortuosity factor), as the only fitting parameter and with the parameters θ_r, θ_s, α, and n fiied at values which resulted from the predictive method (see Figure 1). For this data set, it appears that the estimated values of the conductivity are somewhat insensitive to the value of the connectivity parameter ℓ. Hence, adjusting this parameter offers only slight improvement in the correspondence between the measured and estimated values of the conductivity as compared to the predictive method.

Tables 2 and 3 give several statistics comparing the degree of correspondence between the measured and estimated conductivity for each of the methods. Tables 2 and 3 report, respectively, the results for the hydraulic conductivity and the log,, transformed conductivity. The two tables also give an indication of the accuracy of the estimator in the near saturated region and the dryer region for each of the methods described in this paper. The mean sum-of-deviation and mean sum-of-squares provides information on how close the estimates fall to the 1:l line. The other statistics in Tables 2 and 3 give information about the best possible linear regression line through the estimates.

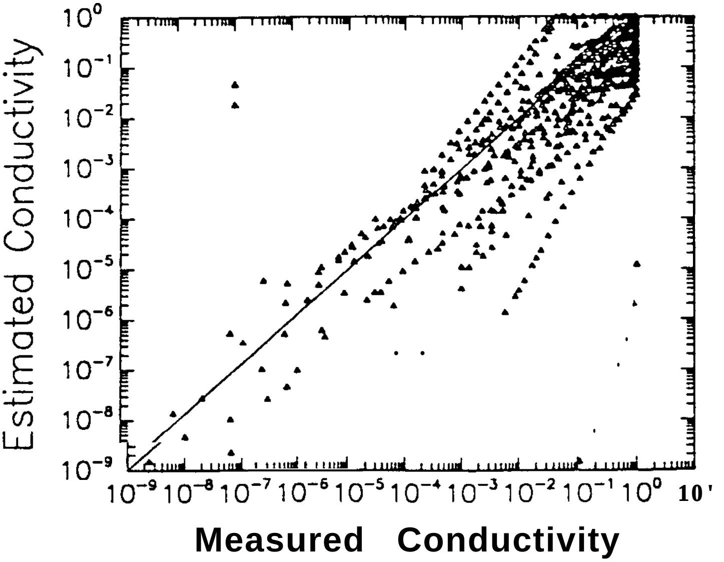

Fig. 7. Measured and calculated conductivities using the predictive method, but with adjustment of the connectivity parameter, *ℓ*.

CONCLUSIONS

RETC has been successfully used to analyze 36 water retention curves from 23 different soils. The nonlinear least-squares optimization technique employed by RETC offers an attractive and efficient method for predicting the unsaturated hydraulic conductivity from water retention data when measured conductivities are not available. For the data set of this study, the use of a matching point improved the correspondence between measured and calculated conductivity. When used in combination with RETC's predictive capabilities offers the most accuracy with the minimum cost since only one value for the unsaturated hydraulic conductivity need be known. Trying to tit measured and calculated values using only the parameter *ℓ* as a fitting parameter did not improve the results significantly. For the data set used here, the results seem to be insensitive to this parameter.

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