GEMSTRAC1 - An Induced Gradient Tracer Test in an Alluvial Sand and Gravel Aquifer

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Prepared for
IUGG XXI General Assembly: Geophysics and the Environment
Boulder, CO, July 2-14, 1995

Kansas Geological Survey
Open File Report 95-80

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ABSTRACT

A series of radially convergent tracer tests is being carried out in an alluvial sand and gravel aquifer underlying the Geohydrologic Experimental and Monitoring Site (GEMS) near Lawrence, KS. These tests are part of a research effort directed at the study of spatial variations in flow and transport properties in unconsolidated alluvial aquifers. The first test of this series (GEMSTRAC1) was performed in the fall of 1994 using a bromide tracer. The monitoring network for this test consisted of 23 multilevel samplers, each of which has 17 sampling ports spaced at either 0.30- or 0.61-meter intervals throughout the sand and gravel aquifer. Eight of the samplers are located along a 14.2-meter centerline between the injection well and discharge wells. Test results indicate a much larger vertical variation of horizontal flow velocity than was anticipated based on initial hydraulic testing. Very strong vertical concentration gradients were maintained throughout the test; concentration variations between vertically adjacent ports of hundreds of mg/l were seen at the multilevel samplers closest to the injection well. Our ability to detect these strong vertical contrasts is an indication of the success of the sampling scheme, which involved pumping all 17 ports simultaneously with multichannel peristaltic pumps. This procedure seems to have minimized the mixing of water from adjacent vertical levels by establishing flow divides between adjacent ports. Preliminary analysis of selected breakthrough curves based on a model for conservative transport in a radially convergent flow field indicates that strong vertical contrasts in flow and transport properties are required to produce the observed tracer movement.

I. SITE DESCRIPTION

The Geohydrologic Experimental and Monitoring Site (GEMS) is located in the Kansas River Valley northeast of Lawrence, KS (Figure 1). The alluvial sand and gravel aquifer at the site is 10-11 meters thick and is overlain by 10-11 meters of silt and clay (Figure 1). The stratigraphy of the sand and gravel is a complex system of stream-channel sand and overbank deposits. Permeameter measurements of core samples from the sand and gravel aquifer indicate hydraulic conductivity values ranging from about 0.002 to 300 m/day. These core permeameter results indicate that hydraulic conductivity can vary by up to three orders of magnitude over several centimeters of vertical distance.

The site is instrumented with several well nests and a network of 23 multilevel samplers. The network of multilevel samplers, along with the injection and discharge wells (IW and DW, both in blue) and an observation well (TMO-1) is shown in Figure 2. Results from TMC-7 and TMC-1 (in red) will be discussed in most detail. Most multilevel samplers have 17 sampling ports spaced at 0.61-meter intervals throughout the aquifer thickness. Four of the samplers along the network centerline (between IW and DW) have 17 ports at 0.30-meter intervals throughout the bottom half of the aquifer. Figure 3 shows the locations of the centerline sampling ports (•), along with the screen locations (--) of IW, DW, and TMO-1. The elevation datum corresponds very roughly with the bottom of the aquifer (the top of the underlying sandstone).

II. SAMPLER CONSTRUCTION/INSTALLATION

The multilevel samplers are similar to those described by Pickens et al. (1978), with the 17 ports being connected to the surface by 6-mm polyethylene tubing bundled inside 3.2-cm PVC casing. About 7.6 cm of each tube protrudes through a hole in the PVC. Stainless steel wire was used to attach a nylon screen to the end of the tube and then to tie both the screen and tubing down to the PVC, forming a sampling port. The samplers were installed inside thin-walled drive casing that had been driven into the aquifer using a jackhammer. During driving, the bottom of the drive casing was closed off with a plastic cap to block entry of the saturated sands. After the sampler was installed inside the drive casing the casing was carefully withdrawn, allowing the aquifer material to collapse back onto the sampler. Water was pumped down the drive casing during withdrawal to keep the saturated sands from heaving into the casing and locking the sampler inside. After development, the ports yielded 150 ml/min or more in response to pumping with multichannel peristaltic pumps. Only five of the 391 ports in the network failed to yield water.

III. TEST PROCEDURES

The tracer test began on October 7, 1994, with the introduction of 4.5 kg of potassium bromide (3.02 kg of bromide) into the injection well, IW, along with 7570 liters of water from the discharge well, resulting in a concentration of about 400 mg/l bromide in the injected water. The discharge well pumped continuously at about 261 liters/minute throughout the 32-day test. Sampling rounds occurred five times per day early in the test, with the frequency of sampling decreasing as the test progressed. The tracer network was enclosed in a large tent to allow sampling to continue during inclement weather. All 17 ports were pumped simultaneously using multichannel peristaltic pumps mounted on a sampling cart. The outlet tubes from the peristaltic pumps emptied into 50-ml sample vials which were held in a tray on the sampling cart. The samples were analyzed in the lab using five pairs of ion-specific electrodes mounted in a specially constructed rack. The electrodes were attached to a data logger which allowed immediate downloading of the data to a PC. Once lab procedures were streamlined, the 17 samples from a single sampler could be analyzed in about 10 minutes. Almost 6000 samples were collected and analyzed for bromide during the 32-day test.

IV. RESULTS

The bromide breakthrough curves revealed striking contrasts in transport behavior in the vertical. The breakthrough curves for TMC-7, 3.3 meters from the injection well, and TMC-1, 12.4 meters from the injection well, are shown in Figures 4 and 5. Both of these samplers have ports at 0.61-meter intervals throughout the aquifer thickness. Ports are numbered from the bottom of the sampler up. These plots show a zone of very rapid transport centered at about port 3 for both samplers, 2.0 meters above datum at TMC-7 and 1.6 meters above datum at TMC-1. There is another zone of rapid transport indicated at port 8 of TMC-7 (5.0 meters above datum) and ports 6 and 7 of TMC-1 (3.4 and 4.0 meters above datum). In these zones the tracer moved much more rapidly than we had anticipated based on previous hydraulic tests, resulting in our missing the peak concentrations at several downgradient ports. Nevertheless, many aspects of the test were quite successful. The very high contrasts in concentration observed between vertically adjacent ports indicates that the sampling procedure produces negligible mixing in the vertical. For example, one day into the test port 3 of TMC-7 yielded a concentration exceeding 300 mg/l while port 4 yielded a near-zero concentration. We hypothesize that the simultaneous pumping of all sampling ports creates flow divides between the ports, minimizing mixing.

V. TRANSPORT MODEL

In order to estimate transport parameters, an analytical solution for conservative transport in radially convergent flow fields (Moench, 1989, 1991) was fitted to the observed breakthrough curves. Moench developed his solution to describe breakthrough at the discharge well, which represents a concentration that is averaged both in the vertical and angular directions. We have modified this solution to apply to arbitrary observation points by assuming that transport is perfectly stratified and that the tracer is distributed uniformly across a narrow wedge whose angular width is determined by the initial transverse width of the injected pulse, Δy. The three parameters for this model are the reference concentration,

$$C_i = \frac{2\pi r_L}{\Delta y} \frac{M}{\pi h \phi \left(r_L^2 - r_w^2\right)},$$

the discharge rate per unit thickness,

$$q_0 = \frac{Q}{\phi h},$$

and the longitudinal dispersivity, α. In these equations, r_L is the distance between the injection and discharge wells, r_w is the radius of the discharge well, M is tracer mass, h and ϕ are thickness and porosity, and Q is discharge rate. In Moench's original formulation, the latter four quantities apply over the entire aquifer thickness. However, assuming perfectly stratified horizontal flow, we take them to apply over limited vertical zones. The distribution of q_0 in the vertical and the initial distribution of tracer mass in the vertical (described by the factor $M/\Delta y h \phi$) will be determined primarily by the vertical distribution of hydraulic conductivity.

VI. DATA ANALYSIS

Breakthrough curves at most ports along the centerline were analyzed using the Moench transport model. Data from TMC-3 and TMC-2 were not analyzed because most ports at these samplers showed negligible breakthrough. Those ports that did show significant breakthrough peaked prior to sampling. Since the fitted parameters are highly non-unique when only the falling limb of the breakthrough curve is available, these data were not analyzed. The reason that most ports at TMC-3 and TMC-2 showed negligible concentrations is not yet understood. Figures 6 and 7 show the fitted breakthrough curves for all ports at TMC-7 and TMC-1. **Note that concentration scales vary significantly from one plot to the next.**

Some ports show systematic lack of fit between the data and the fitted model. The two most common forms of deviation observed were excessive tailing, with later samples showing consistently higher concentrations than those predicted by the model (see for example port 7 of TMC-7 and port 4 of TMC-1), and double-peaked behavior (port 6 of TMC-7). As described by Li et al. (1994), such systematic deviation could result from the mixing of concentrations from adjacent zones with different advective velocities.

VII. ESTIMATED PARAMETERS

Figures 8, 9, and 10 show the fitted values of C_i, q_0, and α along the network centerline. The previously mentioned high-permeability zones are apparent in the distribution of estimated C_i and q_0. These zones, especially the one between 1 and 2.5 meters above datum, took much of the tracer mass and moved it rapidly downgradient, leading to a high correlation between C_i and q_0. In addition, there appears to be a tendency for the estimated dispersivity to increase slightly with travel distance. However, these results should not be taken as conclusive evidence of an actual increase of dispersivity with distance; they could at least in part be due to violations of model assumptions, such as the stratified transport assumption and the assumption of negligible transverse dispersion.

VIII. CONCLUSIONS

Despite some systematic deviations between the observed and fitted breakthrough data, the estimated values for q_0 can probably be taken as a reliable indicator of the vertical distribution of the relative horizontal hydraulic conductivity. These results indicate much sharper contrasts in conductivity than were indicated by earlier well tests at the site, including a set of multilevel slug tests employing packers to isolate discrete vertical intervals (McElwee and Butler, 1995). Figures 8 and 9 together indicate that a high conductivity zone roughly between 1 and 2.5 meters above datum served as a preferential flow path, moving large amounts of tracer downgradient much more rapidly than we had anticipated. This result emphasizes the need to identify such site-specific features of the conductivity distribution in order to reliably predict contaminant transport. We are continuing research on the development of accessible and accurate methodologies for identifying such features.

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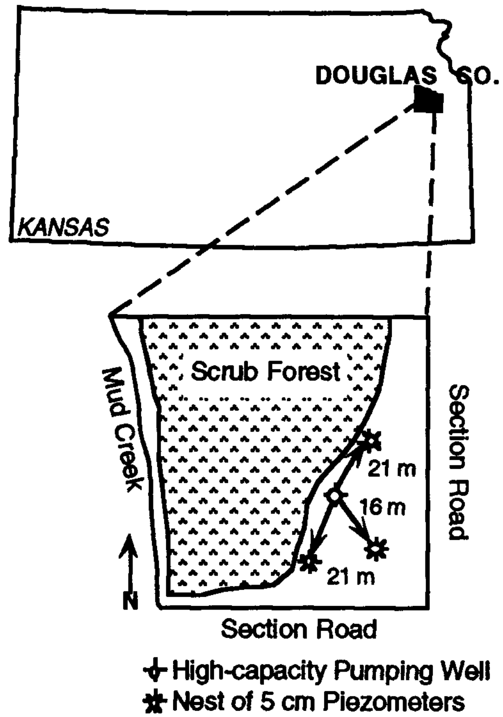
Figure 1. Site Locator Map and Typical Well Nest



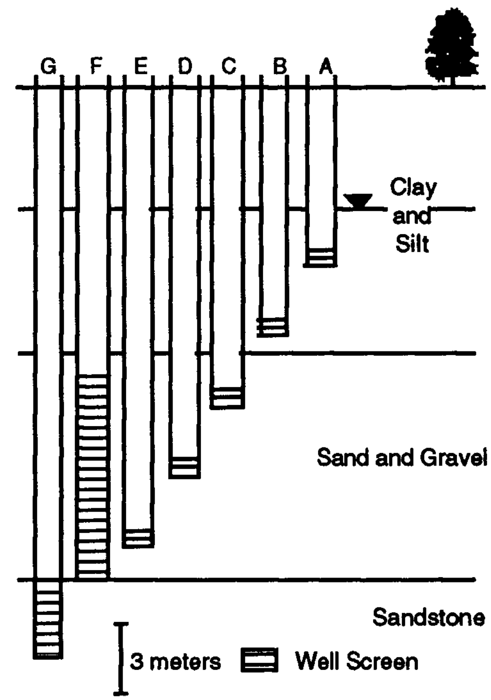


Figure 2: Areal View of Sampling Network

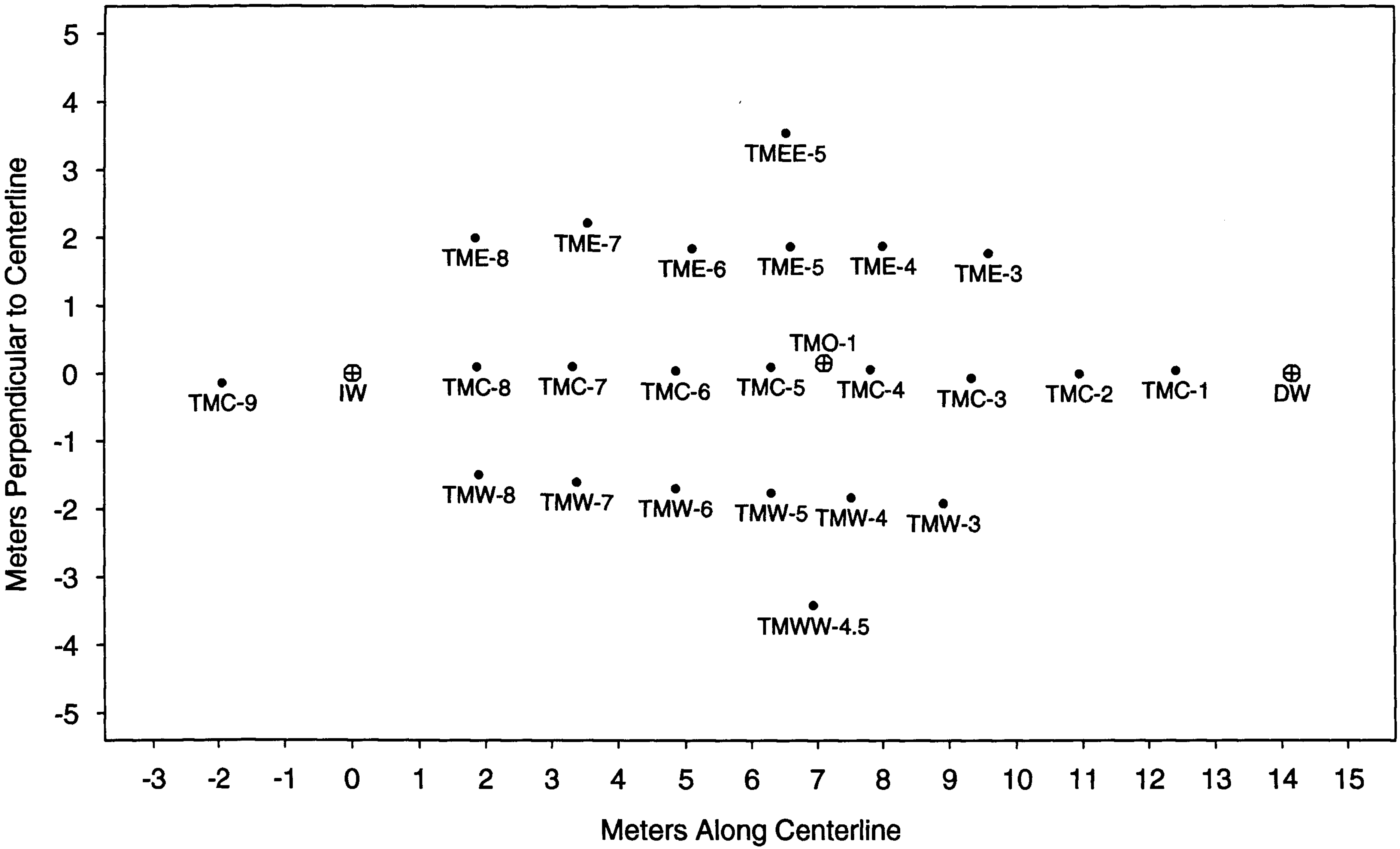


Figure 3: Locations of Centerline Sampling Ports

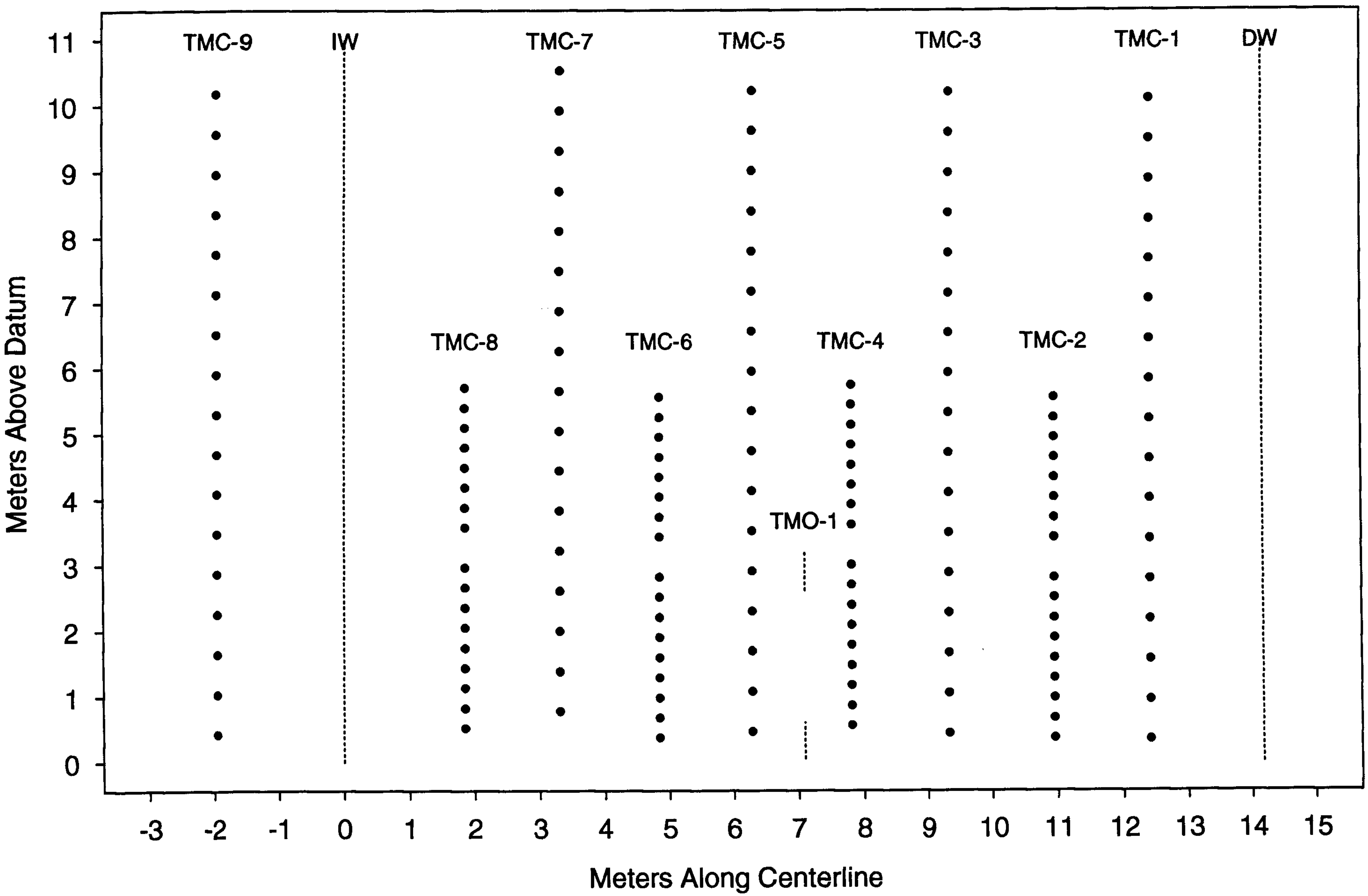


Figure 4: Breakthrough Curves at TMC-7

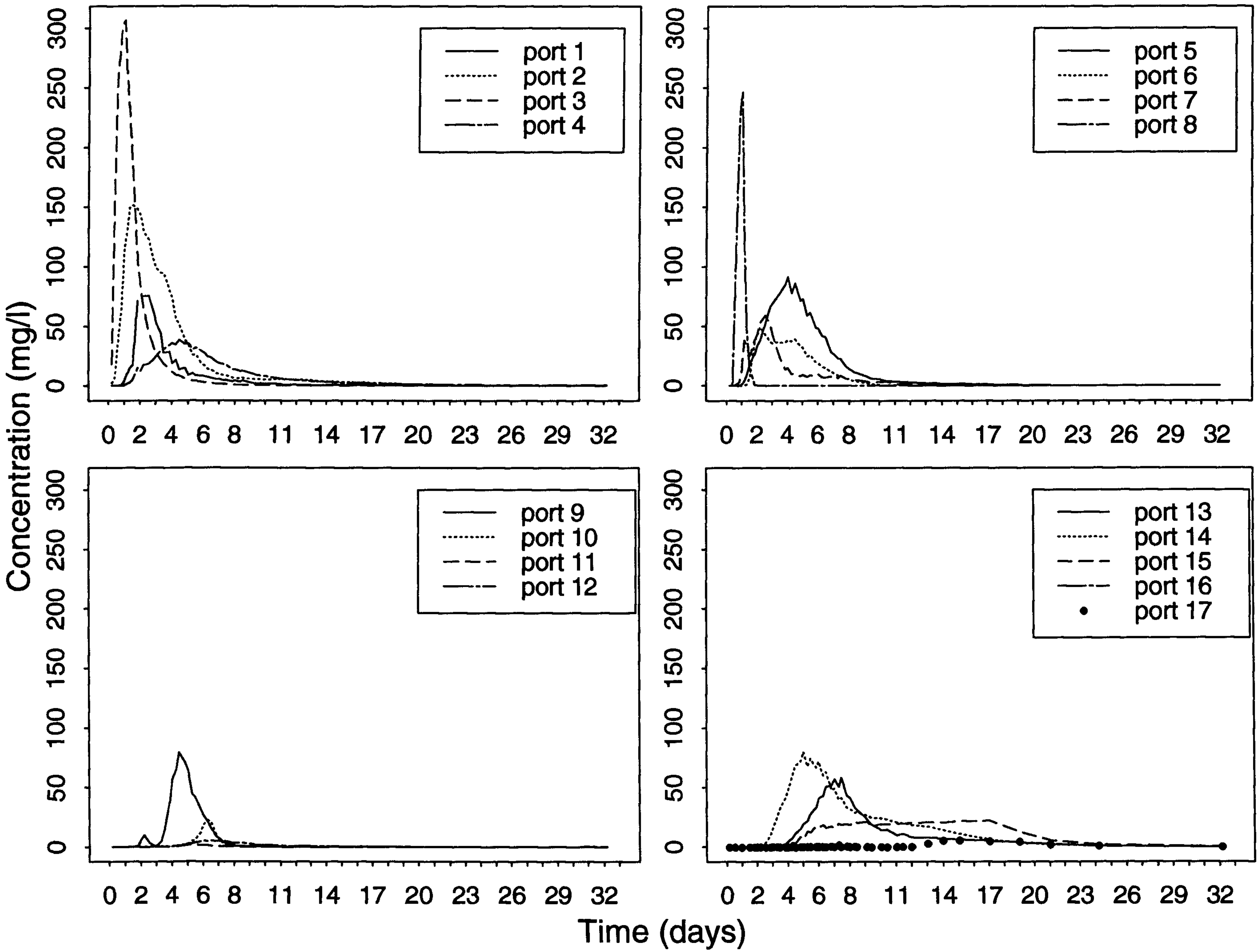


Figure 5: Breakthrough Curves at TMC-1

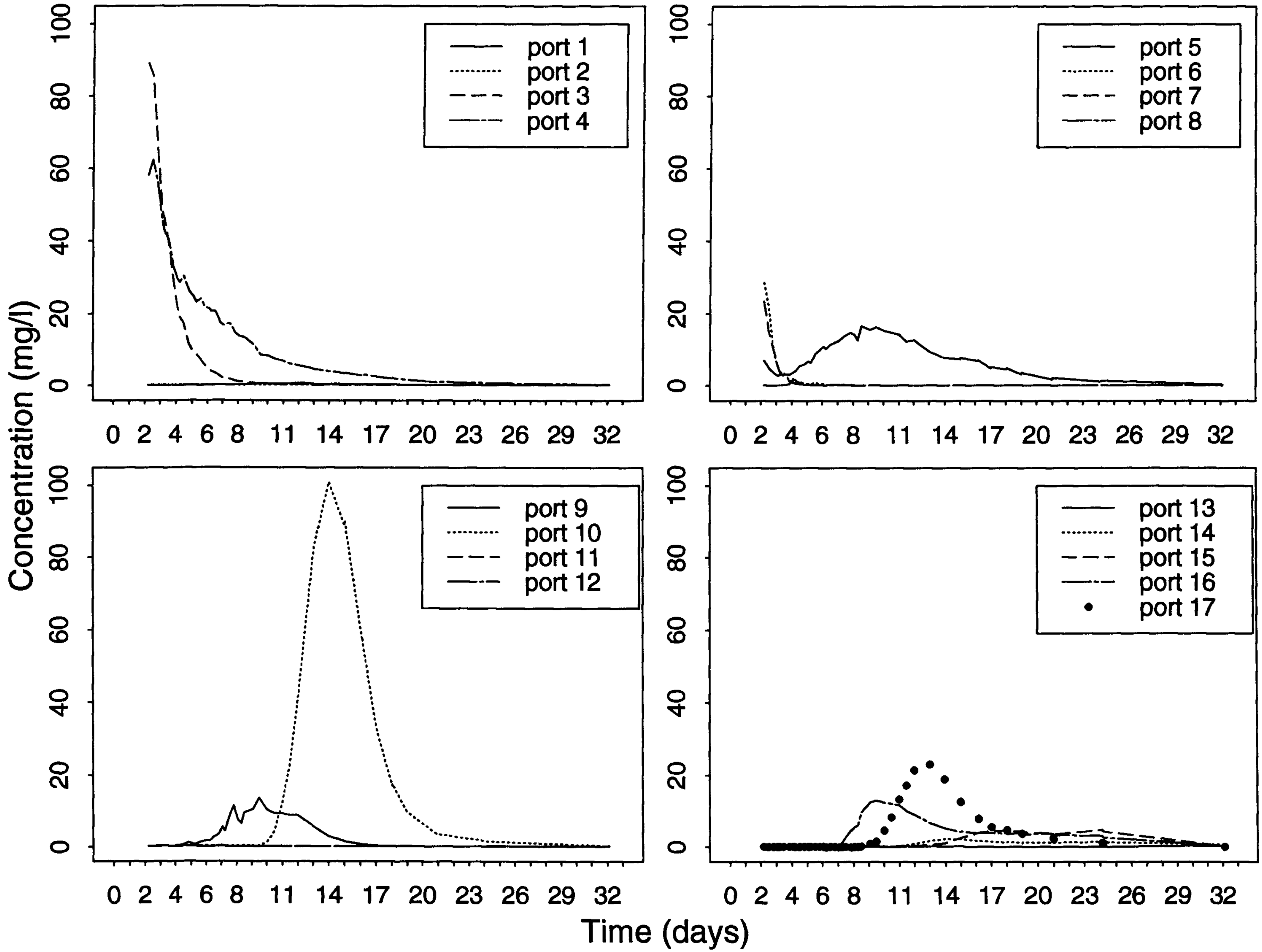


Figure 6: Fitted Breakthrough Curves for TMC-7

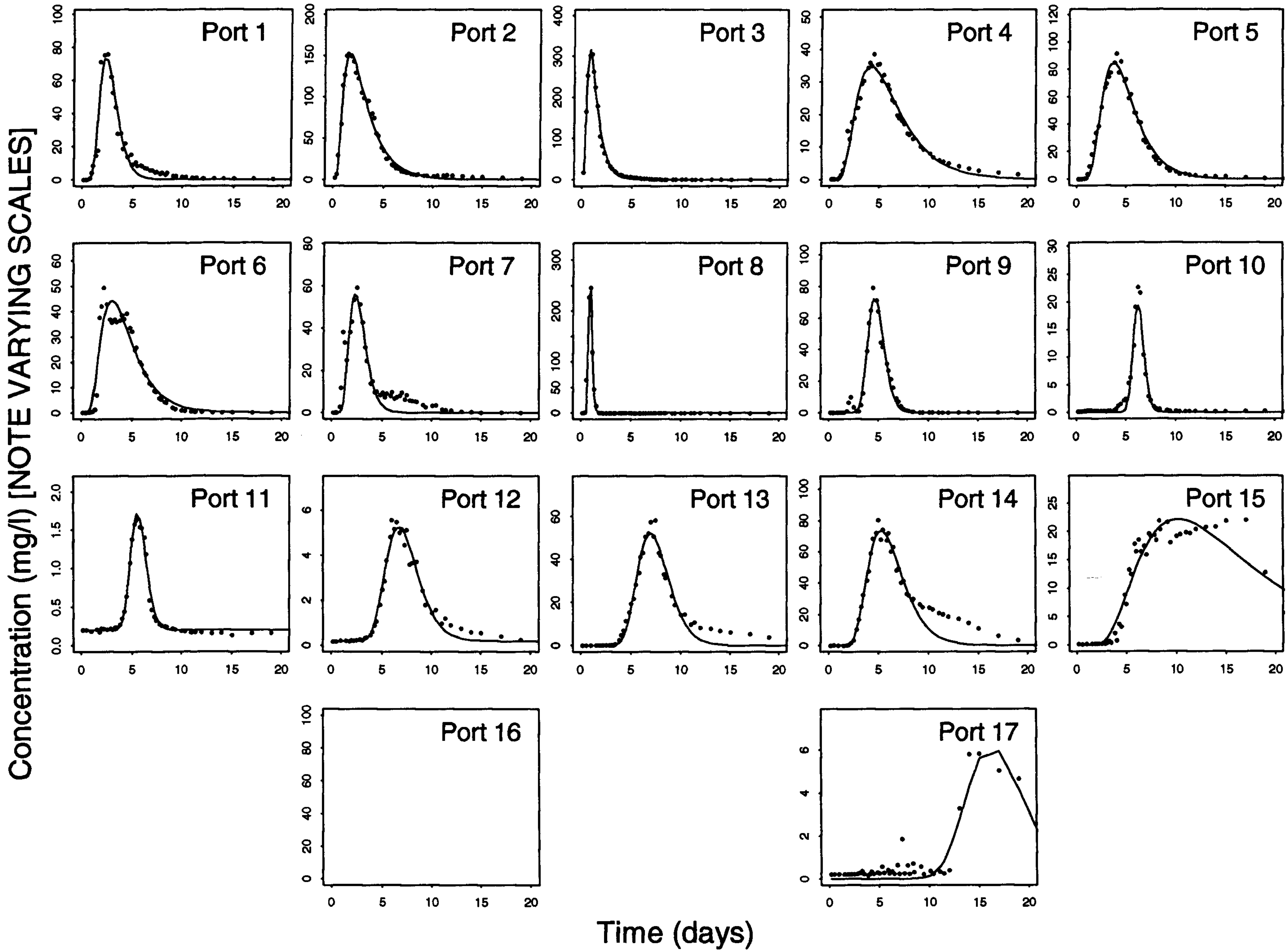


Figure 7: Fitted Breakthrough Curves for TMC-1

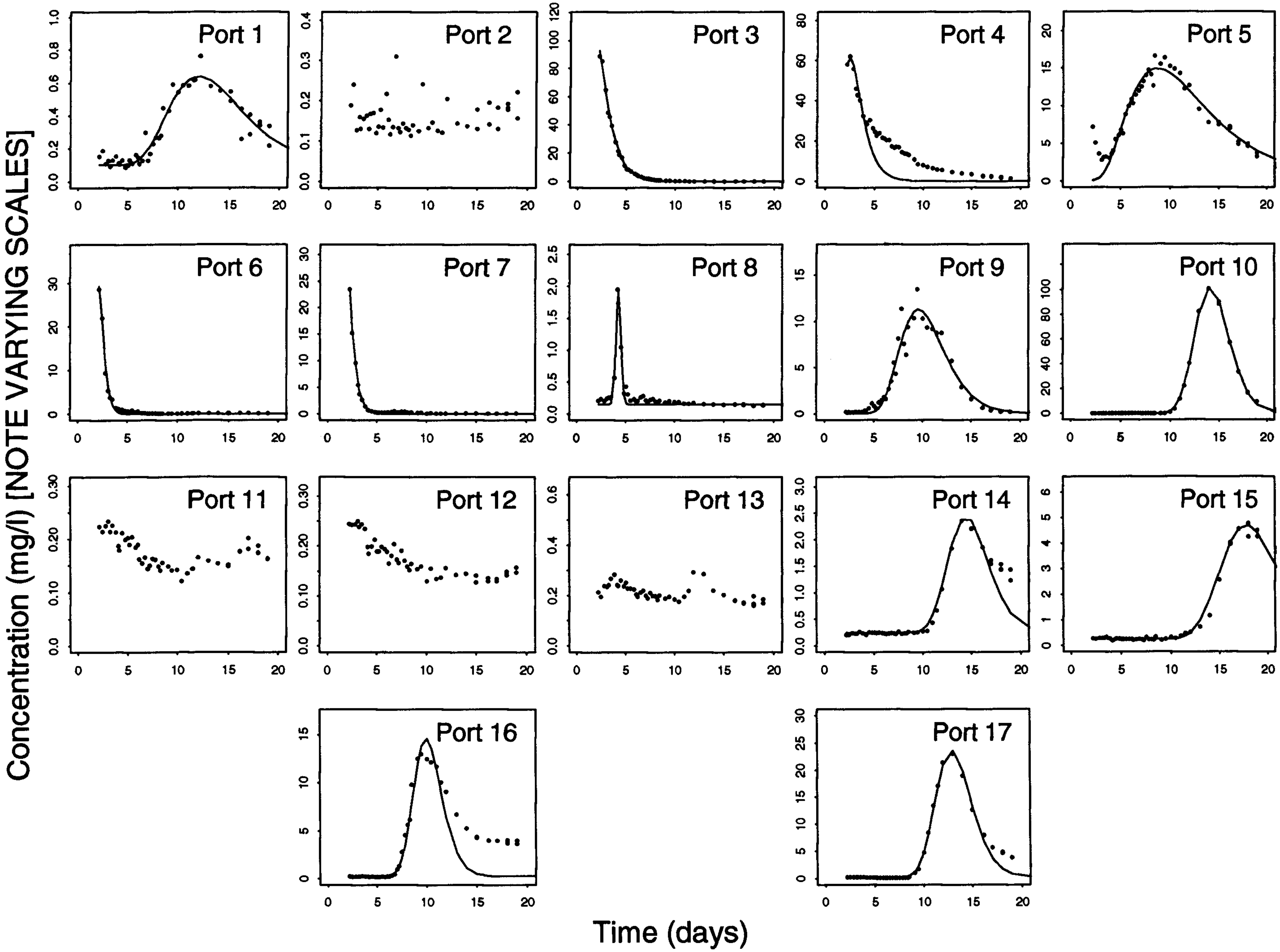


Figure 8: Fitted Reference Concentrations

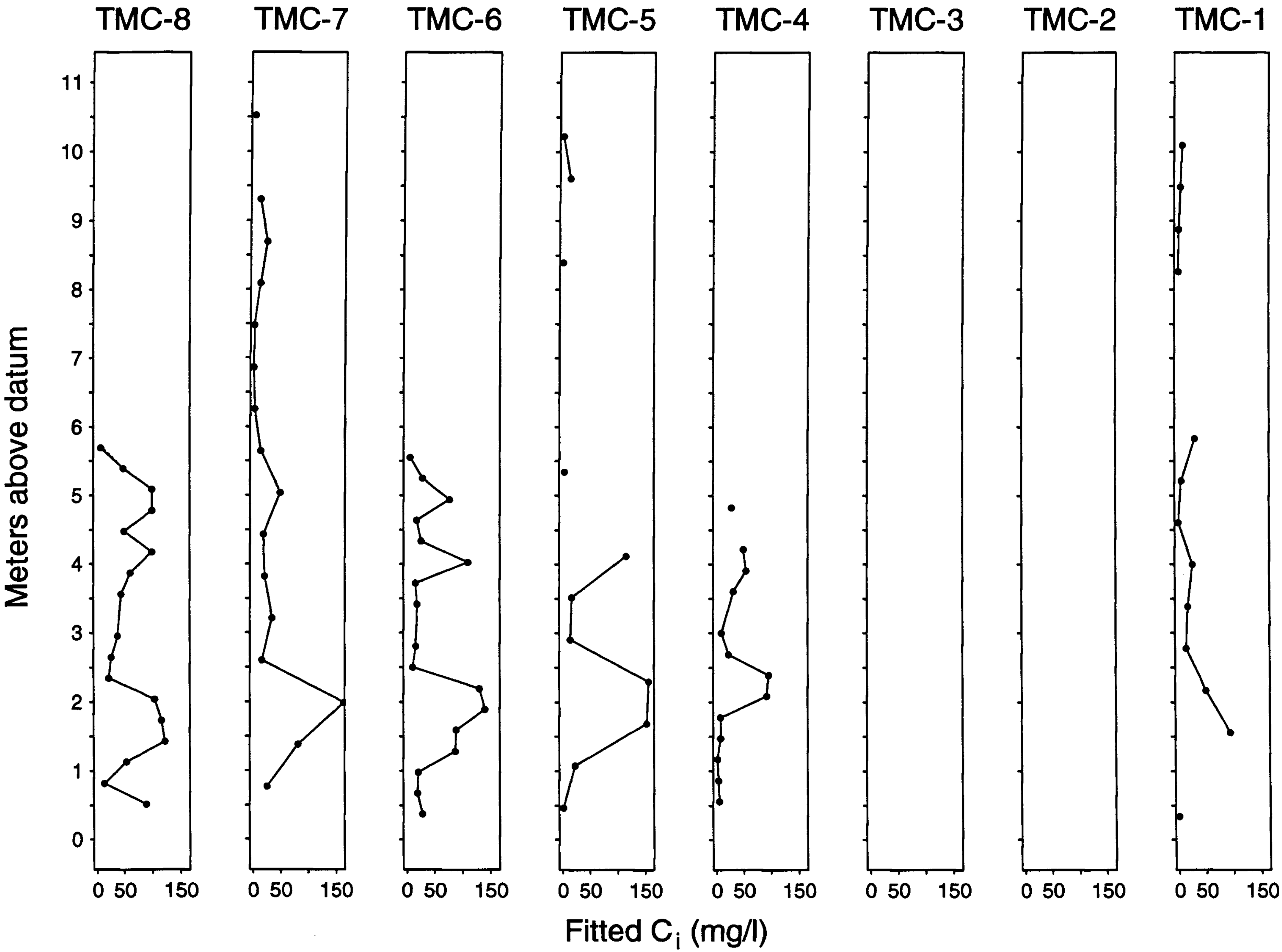


Figure 9: Fitted Pumping Rates Per Unit Thickness

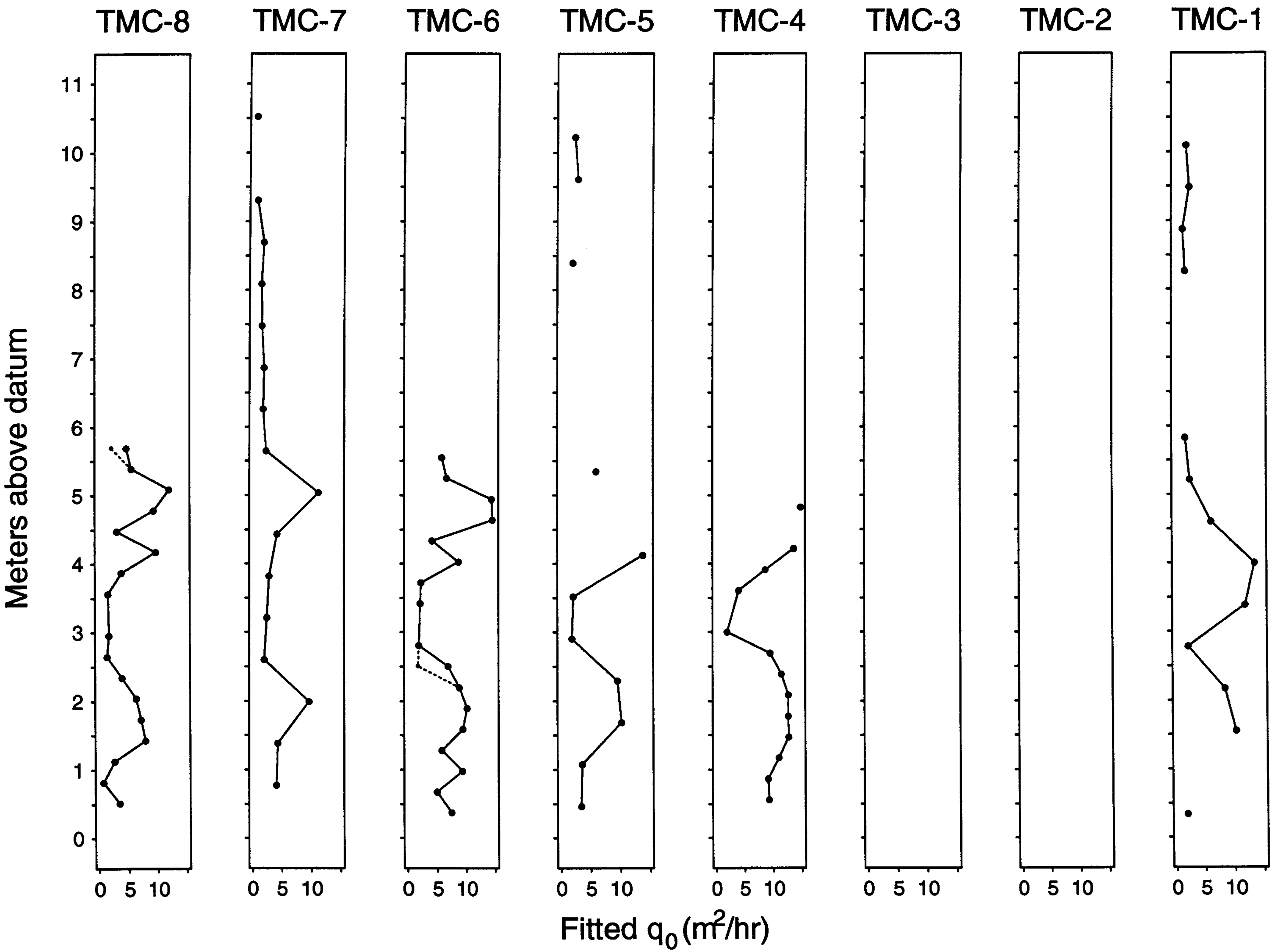


Figure 10: Fitted Dispersivities