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HYDRAULIC TRACERS: A NEW TOOL FOR CHARACTERIZING SUBSURFACE VARIATIONS IN HYDRAULIC CONDUCTIVITY

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ABSTRACT

Tracer tests performed in networks of multilevel sampling wells (MLSs) are a commonly used research tool for assessing the impact of spatial variations in hydraulic conductivity (K) on solute movement. This approach, however, tends to be quite labor and cost intensive. Information about K variations similar to what can be obtained with a nonreactive chemical tracer can also be obtained from pumping tests performed in MLS networks. In this case, the propagation of the pumping-induced pressure disturbance (i.e. a hydraulic tracer) is the focus of interest. Measurement of head changes in the small-diameter (< 5 mm ID) MLS tubing can be obtained using miniature downhole pressure transducers or by monitoring air pressure changes in sealed tubing. An extensive series of experiments in a heavily instrumented field site in the Kansas River alluvium has demonstrated the potential of the approach. As with many types of hydraulic tests, success is critically dependent on the thoroughness of well development. In this case, the particular design used for the MLS ports will largely determine the effectiveness of development activities and, therefore, the ultimate success of the approach. The very detailed information about vertical and lateral variations in pumping-induced head changes obtained with this method can potentially lead to significant improvements in the characterization of interwell variations in hydraulic conductivity.

INTRODUCTION

The identification of hydraulic conductivity (K) variations on a scale of relevance for contaminant transport investigations has proven to be a difficult task. Although a wide variety of experimental methods have been reported in the literature, most are of rather limited use for characterizing variations in K between wells. Tracer tests performed in networks of multilevel sampling wells (MLSs) are currently the best source of information about interwell variations in K. Such tests, however, are very expensive in terms of time, money, and effort, and are thus best classified as research tools. Other techniques are needed if information about K variations is to be incorporated into models of contaminant transport on a routine basis.

At the Kansas Geological Survey (KGS), we are in the process of developing a new field method for the estimation of interwell variations in hydraulic conductivity. This approach is a combination of a method for hydraulic tomography (Bohling, 1993), multilevel sampling wells (Pickens et al., 1978; Boggs et al., 1988), and a sensing device for measuring drawdown in the small-diameter tubing of a multilevel sampling well (Butler et al., 1997). The emphasis of the approach is on monitoring the propagation of a pumping-induced pressure disturbance through the MLS network. This presentation describes our preliminary field testing of the proposed methodology.

FIELD SITE

The field testing was carried out at the Geohydrologic Experimental and Monitoring Site (GEMS), a KGS research area in the Kansas River valley just north of Lawrence, Kansas (Fig. 1). The shallow subsurface at GEMS consists of an alluvial facies assemblage of approximately 21.3 m in thickness. The upper half is primarily clay and silt, while the lower half, the focus of this work, is composed of coarse sand and gravel (Fig. 2). Analyses of sampled cores (McElwee et al., 1991) and a multiwell tracer test (Bohling et al., 1995) in the lower half of the alluvium indicate that a considerable degree of lateral and vertical heterogeneity in hydraulic conductivity exists in this sequence. The multiwell tracer test was performed in an extensive network of MLSs, an areal view of which is presented in Fig. 3. The field experiments described in this presentation were performed in this same MLS network. In all the cases reported here, the well labelled DW (discharge well) was pumped at a constant rate of approximately 70 gpm (4.4 l/s) and pressure responses were monitored in several MLSs and observation well TMO-1.

MEASUREMENT OF DRAWDOWN IN MLS TUBING

The pressure transducers commonly employed in hydrogeologic investigations are too large for use in the small diameter tubing (often < 5 mm ID) of multilevel sampling wells. Butler et al. (1997) describe two approaches for measurement of drawdown in MLS tubing. One approach uses miniature fiber-optic pressure sensors that can be readily positioned within the water column in the tubing. A second approach uses air-pressure transducers to monitor pumping-induced changes in air pressure in sealed MLS tubing. A number of tests were performed to evaluate the viability of these sensors under field conditions. One series of tests involved measuring drawdown in the 0.05 m ID well (TMO-1) at the center of the MLS network. In this assessment, two sets of MLS tubing were placed in TMO-1 and drawdown was measured using a standard submersible pressure transducer inside the well (Fig. 4A), a fiber-optic sensor inside a MLS tube, an air-pressure transducer monitoring pressure changes in an airtight MLS tube (Fig. 4B), and an electric tape. Each set of sensor measurements was normalized by the maximum drawdown measured by that sensor immediately prior to cutting off the pump (approx. 0.24 m) to remove the influence of calibration parameters. Fig. 5 shows the close agreement that was found between all measurement methods. The maximum deviation between the air- and water-pressure transducers is, in absolute terms, less than 7 mm. Such field experiments demonstrate that accurate transient drawdown measurements can be obtained in MLS tubing.

IMPORTANCE OF WELL DEVELOPMENT

One of the goals of well development is to remove fine material from the near well portions of the formation (e.g., Wendling et al., 1997). The standard port design for multilevel sampling wells (e.g., Boggs et al., 1988; LeBlanc et al., 1991) involves placing a fine nylon mesh over the tubing end (Fig. 6). The purpose of this mesh is to prevent particulate matter from being pumped during water sampling. The problem with this design for drawdown measurements is that the mesh filters out the fine particulate matter, which forms a low-K cake around the port. Fig. 7 is a record of drawdown obtained with air-pressure transducers in TMC-3. In this case, the cake on the mesh was so thick that there was virtually no response in the tubing to the cessation of pumpage. Note that dependence of response data on flow direction, which was found repeatedly in the MLS tubing at GEMS, has also been found in conventional hydraulic tests (e.g., Butler and Healey, 1998). Unfortunately, standard overpumping or backflushing development methods had no effect on this fine cake. The MLS ports could only be successfully developed by threading a small diameter steel cable through the tubing and punching through the mesh at the tubing end. After breaching the mesh, pumping with a peristaltic pump removed the fines in the vicinity of the port and drawdown records such as that of Fig. 8 could be obtained. Given the difficulties involved in development of MLS ports of the standard design, alternate port designs are recommended when drawdown measurements are to be collected.

EXAMPLE APPLICATION

After development of a number of ports, a series of pumping tests were performed in the MLS network. Fig. 9 displays drawdown at two sets of ports at distances of 4.6 m (TMC-3) and 10.7 m (TMC-7) from the pumping well. The parallel drawdown plots at late times are what would be expected from a pumping test in a heterogeneous formation (e.g., Butler and Liu, 1993; Schad and Teutsch, 1994). The slope of the line fit to the latter portions of the drawdown in port 3 of TMC-3 is within 2.5% of lines fit to the other drawdown records shown in Fig. 9, and within 3.6% of the slope of a drawdown plot from TMO-1 recorded with a conventional submersible pressure transducer in a 5/14/97 pumping test performed in the same configuration. The consistency of late-time changes in drawdown from ports at different positions within the network, as well as from a conventional observation well, is a demonstration of the quality of the drawdown data that can be obtained from MLS tubing. The head differences seen at the same MLS ($\Delta h_{TMC\text{-}3}$ and $\Delta h_{TMC\text{-}7}$) are a result of heterogeneity. Numerical experiments performed with a cylindrical-coordinate, finite-difference model (Butler et al., 1994) revealed that such head differences could only be found in conditions of significant media heterogeneity. These numerical experiments also demonstrated that the S-shaped pattern in the early-time data is primarily a product of well-bore storage in the pumping well. Although the data displayed in Fig. 9 are only from the initial round of field testing, they do reveal the considerable potential of this new approach.

CONCLUSIONS

The identification of variations in hydraulic conductivity on a scale of relevance for transport investigations has proven to be a considerable challenge. Recently, a new field method for the estimation of interwell variations in K has been proposed. This method involves use of drawdown data from the small diameter tubing of multilevel sampling wells. In this presentation, preliminary field testing of the methodology is described. Field experiments demonstrate that transient drawdown data can be obtained in MLS tubing either directly using miniature fiber-optic sensors or indirectly using air-pressure transducers. As with any type of hydraulic test, well development is a critical issue. Standard port designs used in MLS networks constructed for large-scale tracer tests are prone to clogging, so alternate designs are necessary when drawdown measurements are needed. Field experiments have shown that very detailed information about vertical and lateral variations in pumping-induced drawdown can be obtained using sensors in MLS tubing. Thus, the proposed methodology appears to have considerable potential for providing valuable information about spatial variations in hydraulic properties.

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Figure 1. Location map for the Geohydrologic Experimental and Monitoring Site (GEMS).

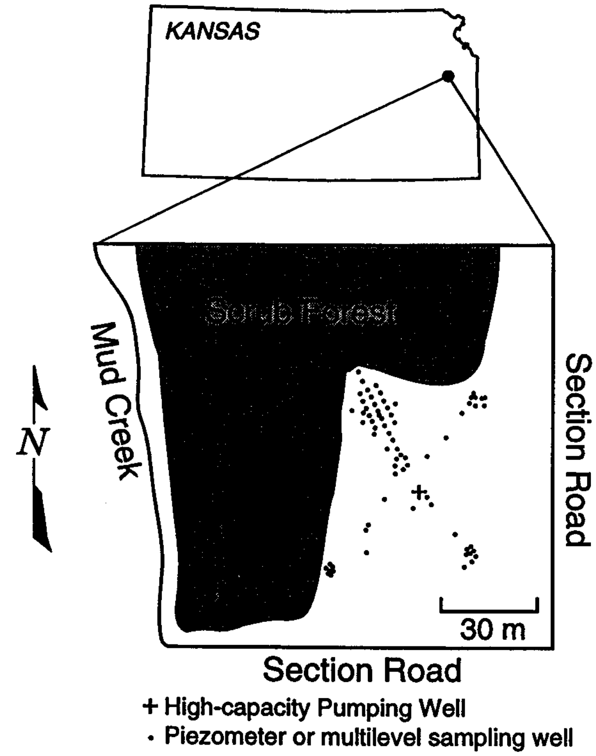


Figure 2. GEMS Stratigraphy and Natural Gamma Logs

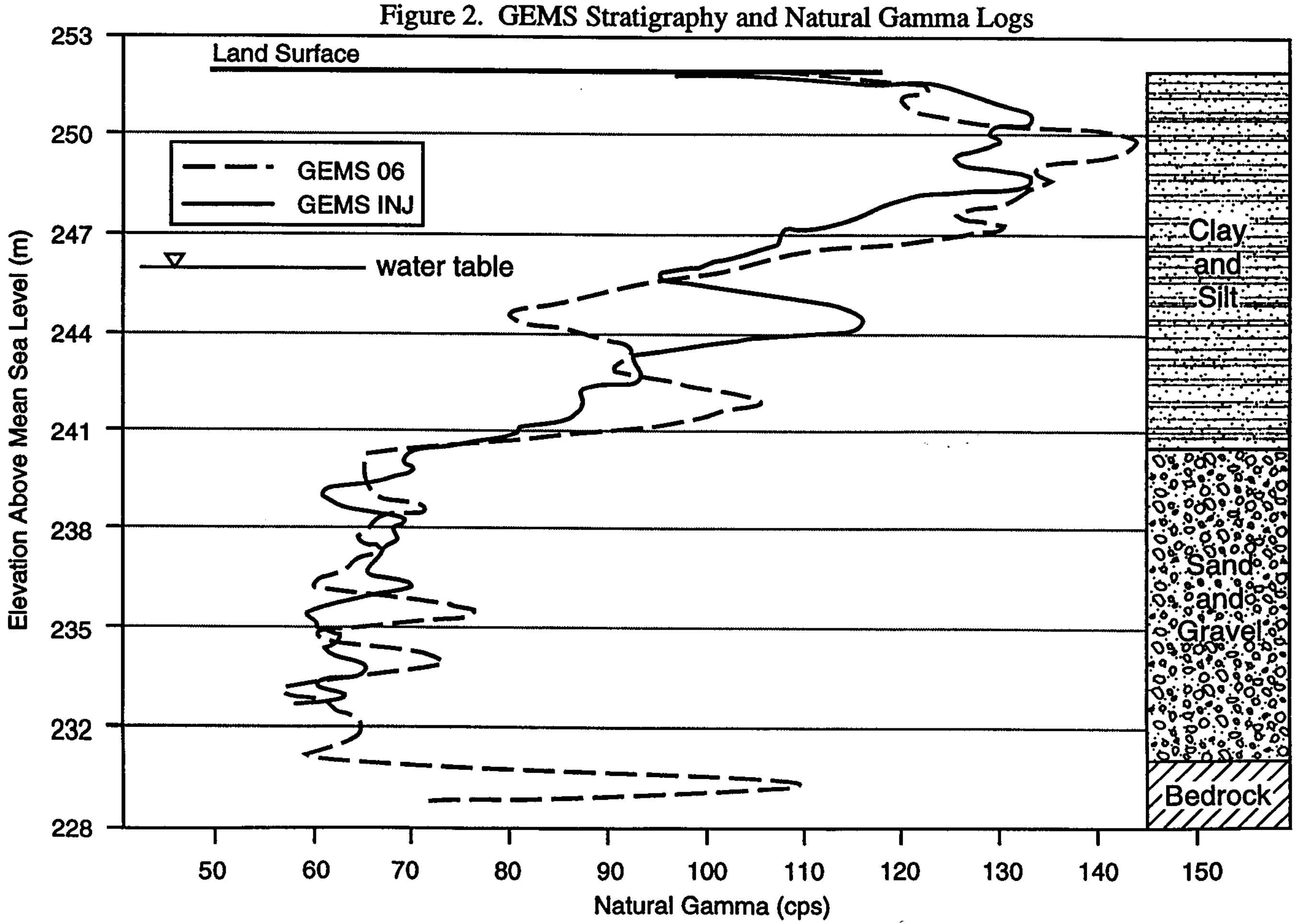
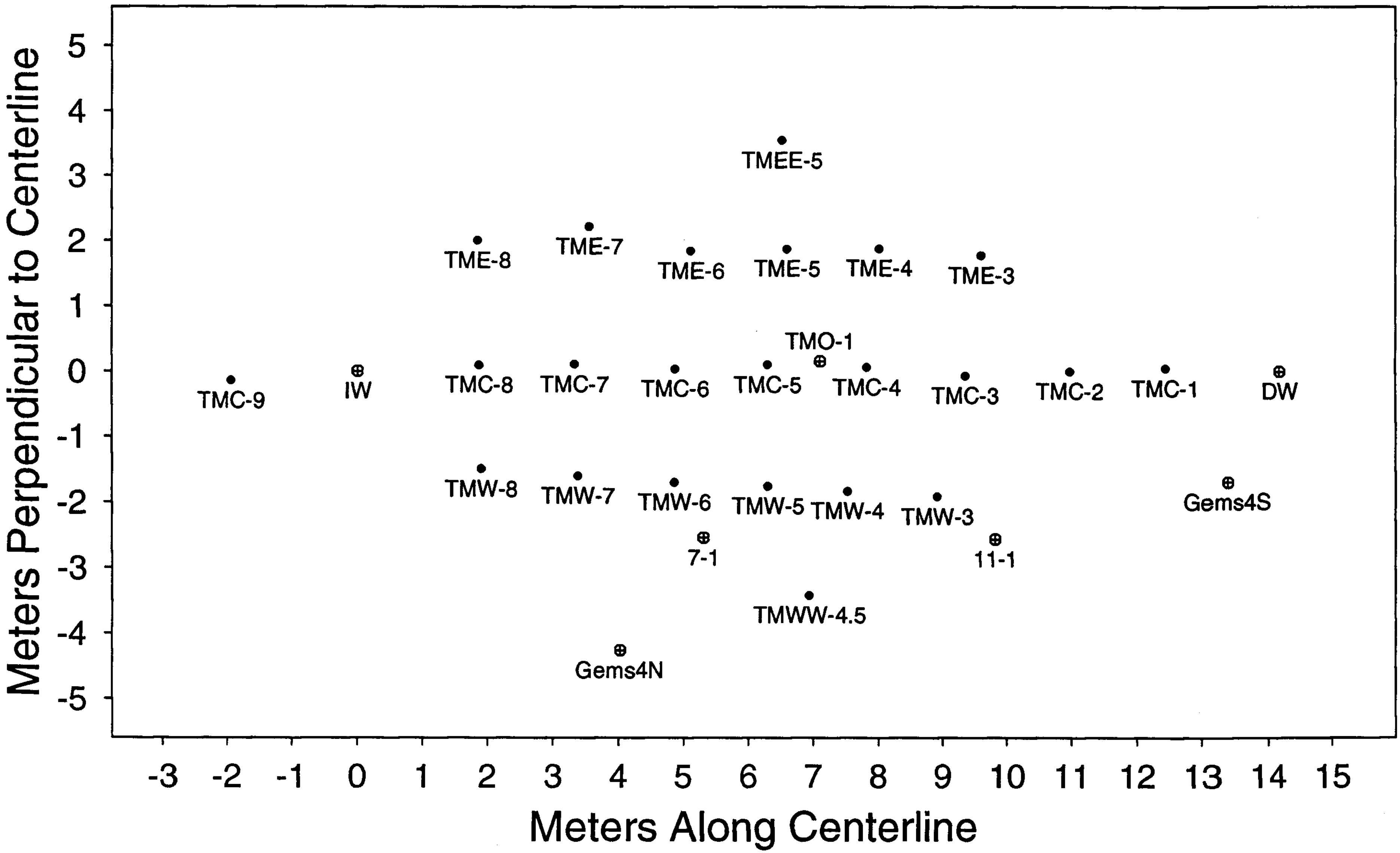


Figure 3 - Areal View of MLS Network



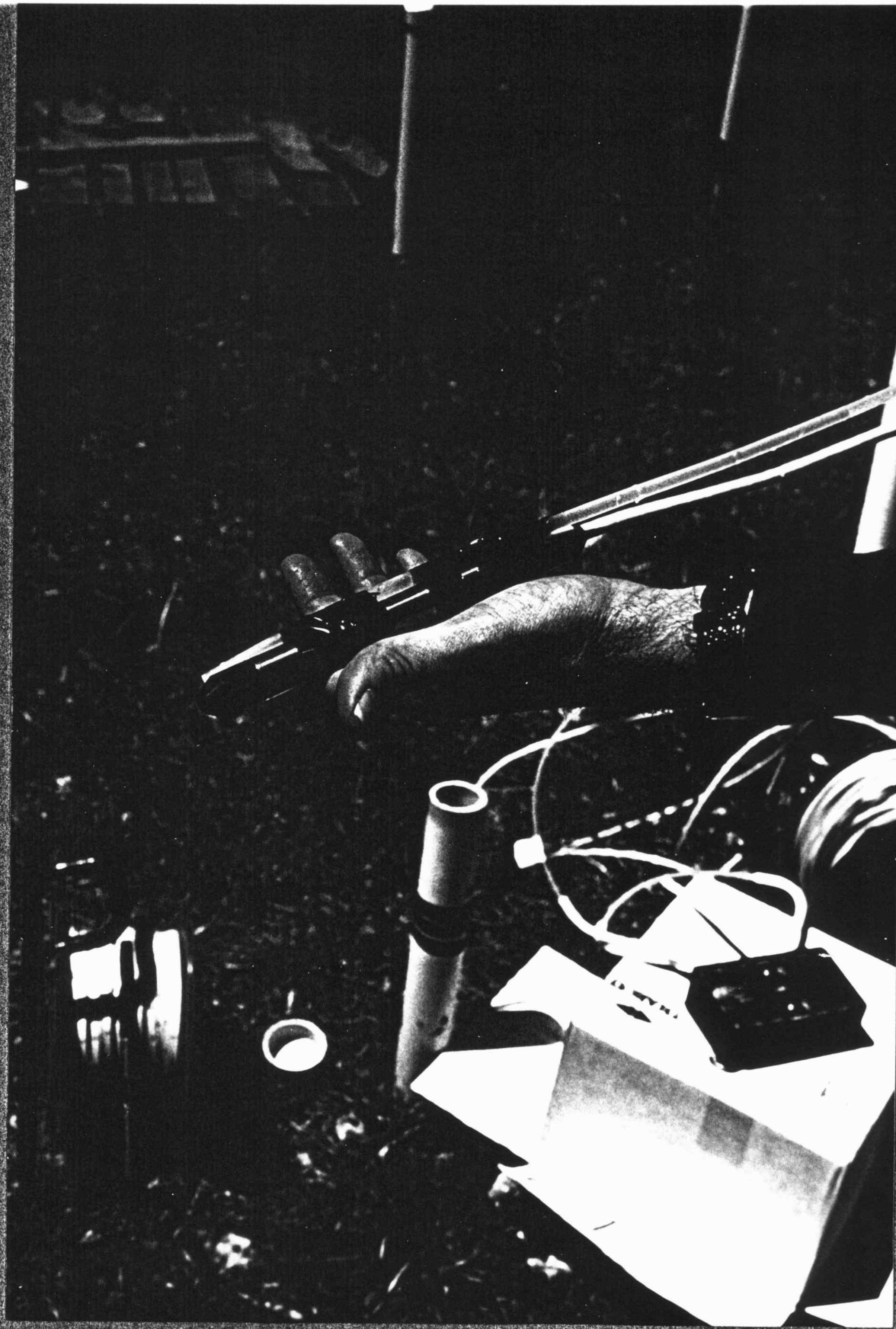


Figure 4A

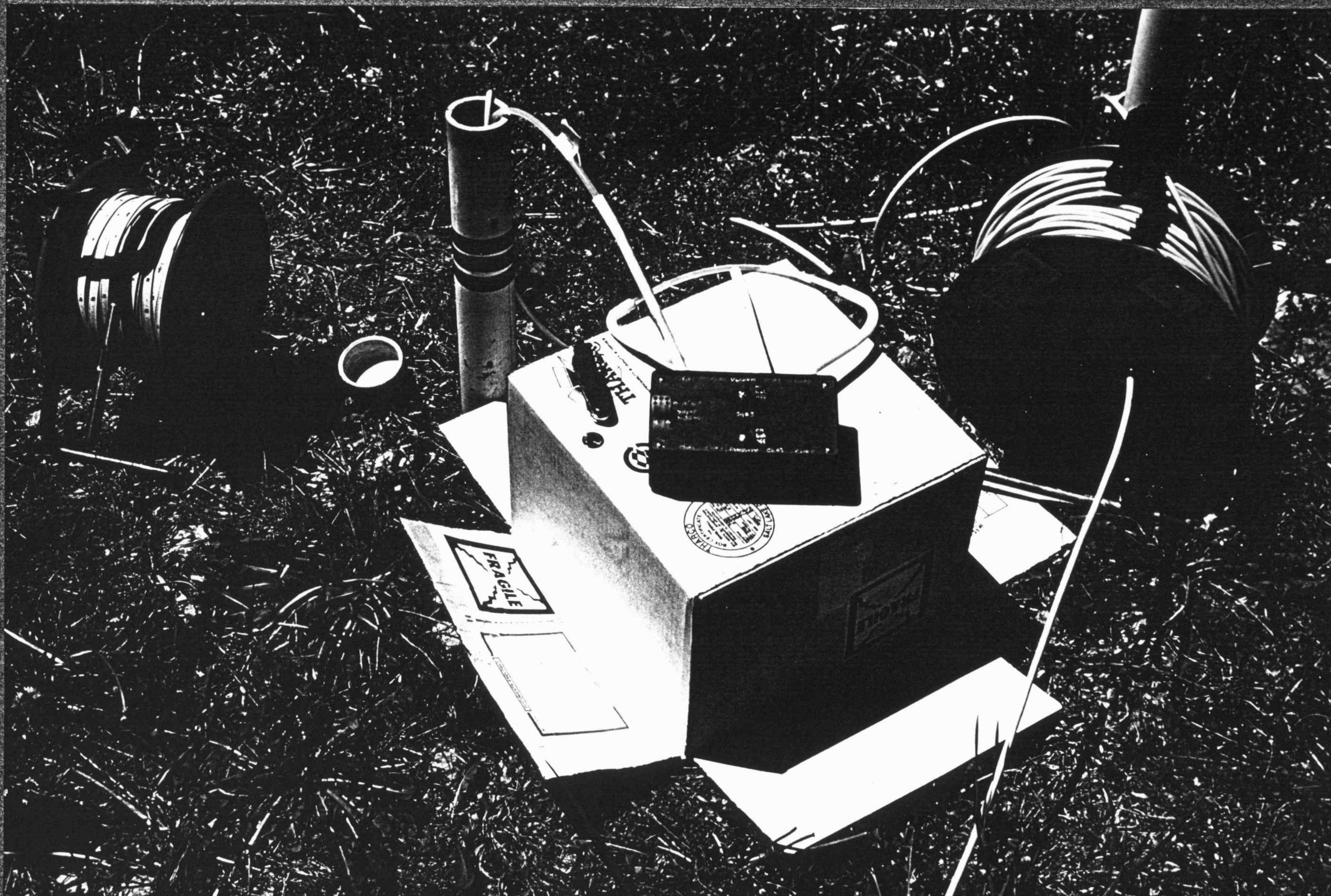


Figure 4B

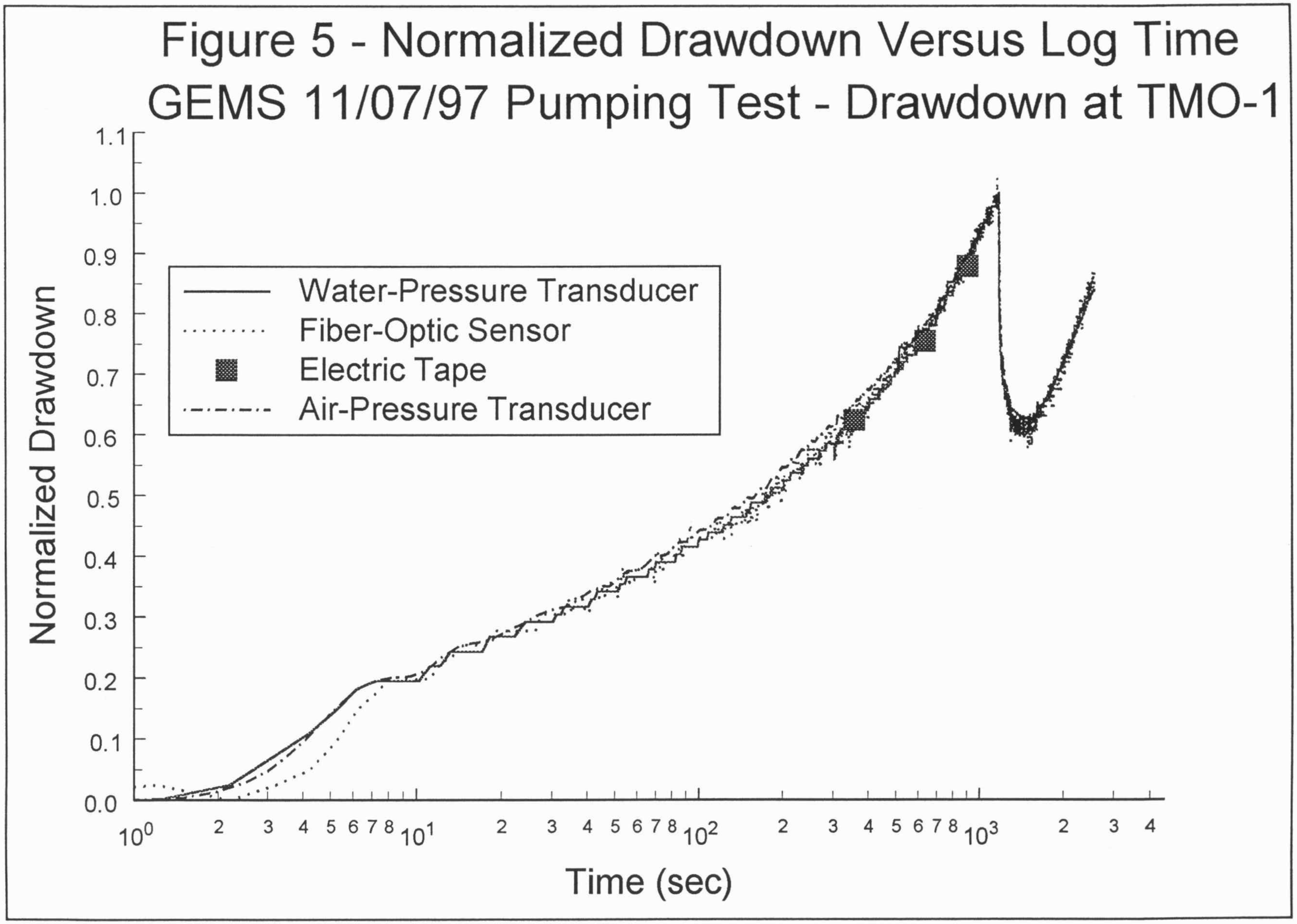


Figure 5 - Normalized Drawdown Versus Log Time
GEMS 11/07/97 Pumping Test - Drawdown at TMO-1
Normalized Drawdown
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Water-Pressure Transducer
Fiber-Optic Sensor
Electric Tape
Air-Pressure Transducer
10^0
2 3 4 5 6 7 8
10^1
2 3 4 5 6 7 8
10^2
2 3 4 5 6 7 8
10^3
2 3 4
Time (sec)

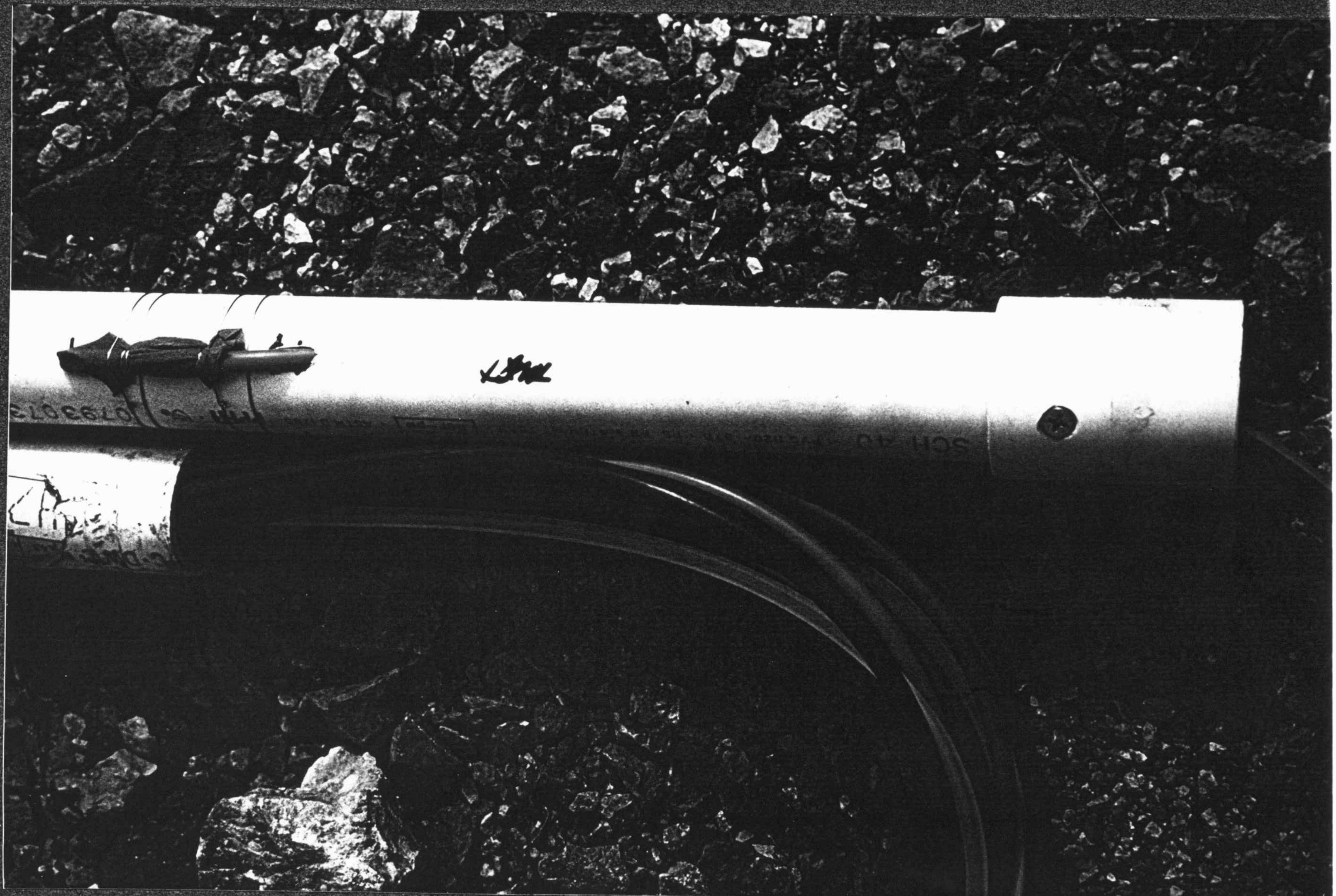
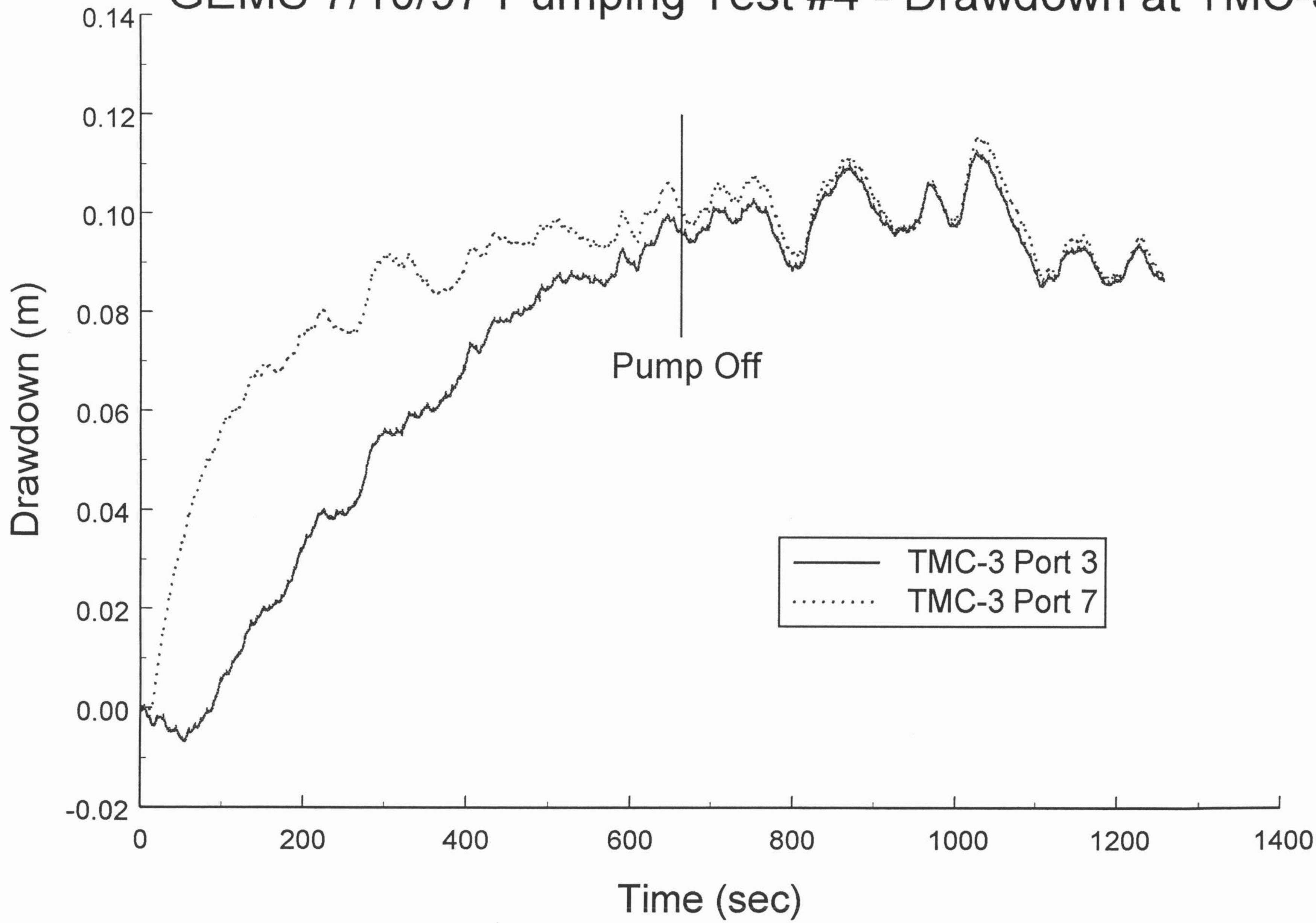


Figure 6

FIGURE 7 - Drawdown Versus Time (Pre-development)
GEMS 7/10/97 Pumping Test #4 - Drawdown at TMC-3



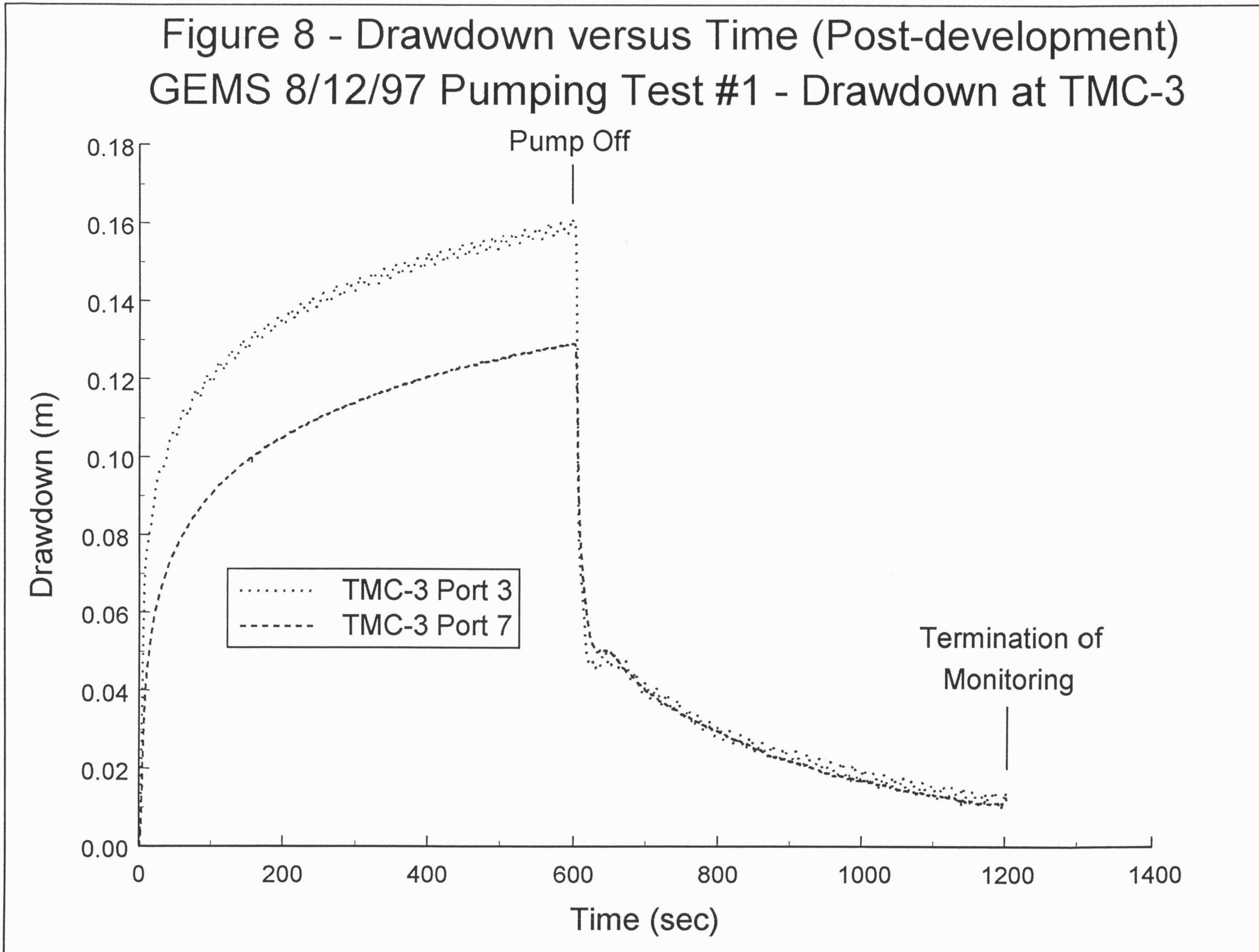


Figure 8 - Drawdown versus Time (Post-development)
GEMS 8/12/97 Pumping Test #1 - Drawdown at TMC-3
Pump Off
Termination of Monitoring
TMC-3 Port 3
TMC-3 Port 7
Drawdown (m)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
Time (sec)
0
200
400
600
800
1000
1200
1400

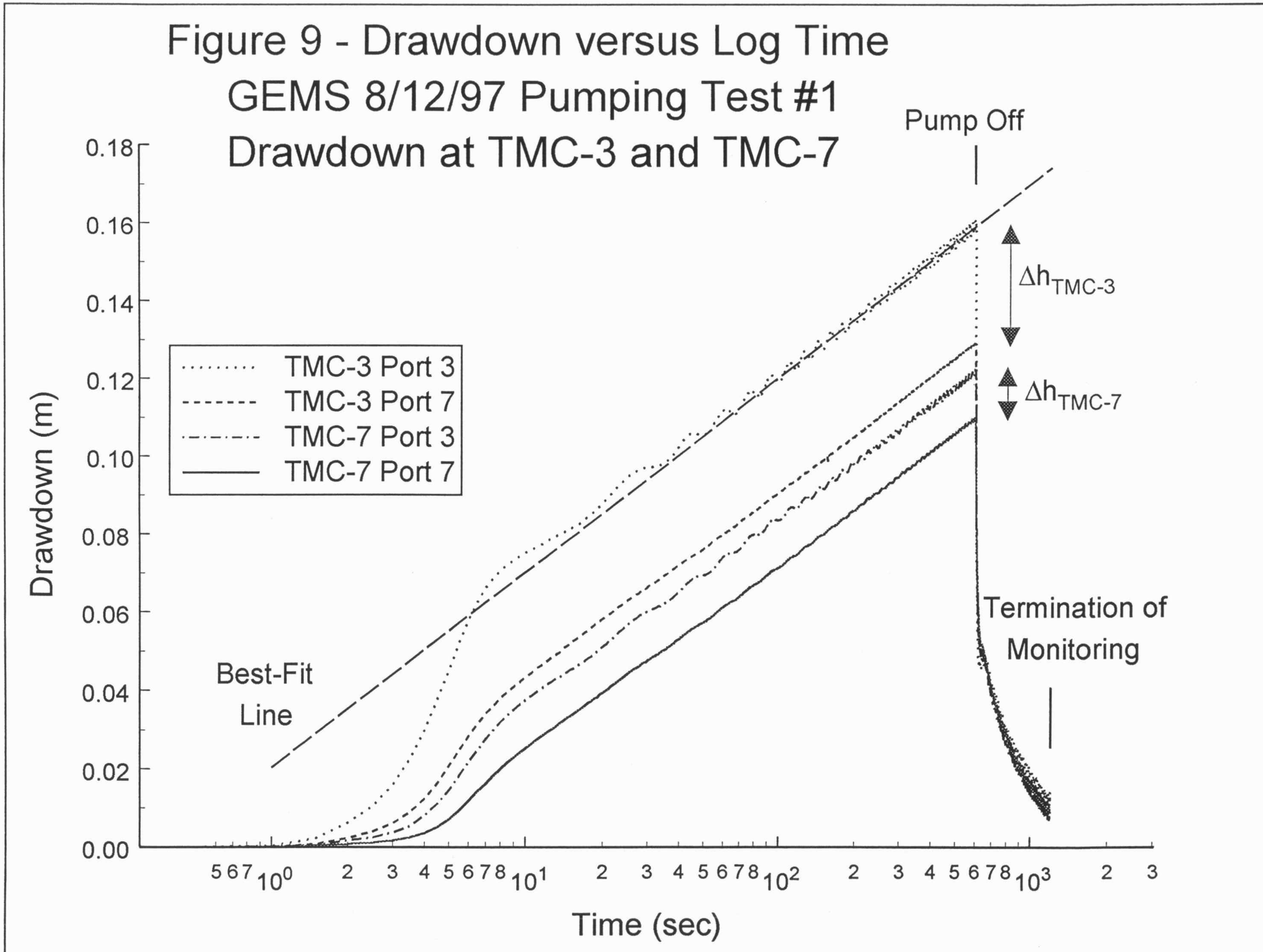


Figure 9 - Drawdown versus Log Time
GEMS 8/12/97 Pumping Test #1
Drawdown at TMC-3 and TMC-7
Pump Off
Δh TMC-3
Δh TMC-7
TMC-3 Port 3
TMC-3 Port 7
TMC-7 Port 3
TMC-7 Port 7
Termination of Monitoring
Best-Fit Line
Drawdown (m)
Time (sec)
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
5 6 7 10^0 2 3 4 5 6 7 8 10^1 2 3 4 5 6 7 8 10^2 2 3 4 5 6 7 8 10^3 2 3