Analysis of Time Domain Reflectometry Data From LTPP Seasonal Monitoring Program Test Sections—Final Report

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LTPP

FOREWORD

As a part of the Long Term Pavement Performance (LTPP) Seasonal Monitoring Program, Time Domain Reflectometry (TDR) technology has been used to monitor in situ moisture conditions at selected LTPP test sites. The raw TDR wave form data have been available in the LTPP database for some time. However, to be useful in engineering analyses, the raw data must be interpreted to derive estimates of the in situ moisture content. This report documents analysis conducted to develop and apply procedures for interpretation of the raw LTPP TDR data. The "computed parameters" - volumetric and gravimetric moisture contents and related parameters - derived through this analysis have been added to the LTPP database.

This report will be of interest to those who wish to use the LTPP seasonal monitoring data, and to other users (or potential users) of TDR technology for in situ moisture monitoring.

T. Paul Teng, P.E.
Director
Office of Infrastructure
Research and Development

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16. Abstract

Time domain reflectometry (TDR) has become one of the most reliable methods for measuring in-situ soil moisture content. TDR sensors developed by the Federal Highway Administration (FHWA) are being used in the Long-Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) to monitor the in-situ moisture content at selected LTPP sites. The main goal of the study reported here was to develop procedures to produce good estimates of in-situ gravimetric moisture content. All the TDR traces in the LTPP database were processed using the approach described in this report.

To estimate the in-situ gravimetric moisture content, methods were selected to interpret TDR traces. An algorithm and a computer program, Moister, were developed to implement these TDR interpretative methods. After that, the apparent length of the TDR trace and the dielectric constant of the unbound material were computed. Models were developed to relate dielectric constant with in-situ volumetric moisture content. Finally, gravimetric moisture content was computed using the volumetric moisture content value and dry density of the soil. A diagnostic study of the computed gravimetric moisture content was also conducted to evaluate the reasonableness of the computed moisture contents.

As part of the overall LTPP data analysis effort, it is expected that the information on the seasonal variation in the moisture content of the unbound base, subbase, and subgrade layers will be used to develop improved understanding of the seasonal variation in the load-carrying capacity of pavements and the subsequent effect on pavement performance.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1. INTRODUCTION AND BACKGROUND

It is well known that the moisture condition of pavement materials can significantly affect pavement performance. An increase in moisture in subgrade and unbound base materials can weaken these materials and affect the pavement's response to traffic loading, ultimately affecting pavement service life. Also, variation in moisture in the subgrade can change the volume of the swelling soil, which may result in detrimental deformation of the pavement structure.

To better understand the environmental factors and their effects on pavement performance, the Long-Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) was initiated during 1992. Sixty-four LTPP sections were identified to be included in the SMP. These sections are monitored frequently to acquire data on seasonal variation in pavement conditions. As part of this effort, time domain reflectometry (TDR) sensors are used to measure moisture content in unbound base and subgrade materials. TDR data are being collected using the three-prong TDR probes developed by the Federal Highway Administration (FHWA), as illustrated in figure 1 [1]. Ten TDR probes are used at each section, with the first 8 probes spaced at 152 mm and the last 2 probes spaced at 302 mm. Figure 2 shows a typical instrumentation layout at LTPP SMP sites [1].

Several calibration and function checks are performed during the installation of the TDR probes at the SMP sites. TDR probes are checked in air, distilled water, and shorted. The dielectric constant in air should be between 0.75 and 2.0, and the dielectric constant in distilled water should be between 76 and 84. When shorted, the resulting TDR trace should have a sharp single peak at the beginning of the probe trace. TDR traces and on-site moisture measurements (obtained using traditional methods) are also collected during the installation of each TDR probe. It is very important to understand the installation situation when conducting analysis on the TDR traces. For example, from the site installation report for LTPP section 271018 in Little Falls, Minnesota, it was noted that TDR probe placement and resulting data from probes 8, 9, and 10 could be questionable because these probes were placed in a slurry of sand and water.

The TDR procedure has been used to determine the in-situ moisture content in soils since the late 1970's, and it has become one of the most reliable methods for measuring in-situ soil moisture. In the TDR method, an electromagnetic wave is transmitted along a coaxial metallic cable that acts as a waveguide. The velocity of the pulse is influenced by the dielectric constant of the material (for example, as a result of moisture changes), which can create wave reflections (indicated by slope changes in the return wave pulse recorded by the TDR readout unit). TDR waveforms can be recorded using TDR sensors connected to a personal computer. A TDR trace normally consists of a peak followed by a valley, which is typically characterized by two inflection points. The apparent length of the trace can then be computed from the identified inflection points. The bulk soil dielectric can be computed from apparent length. The dielectric constant of air is 1 and the dielectric constant of water is approximately 80, whereas that of dry soil is between 3 and 8, depending on soil type and density. Several methods exist for computation of apparent length. The Method of Tangents and the Method of Peaks are widely used by researchers.

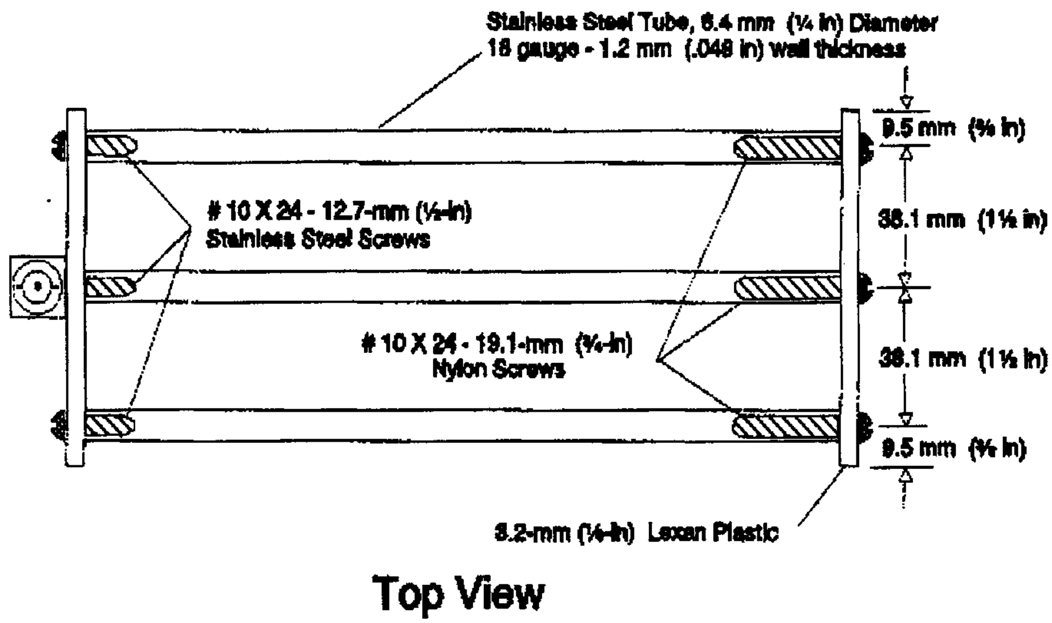


Figure 1. TDR probe installed in the LTPP SMP sites [1].

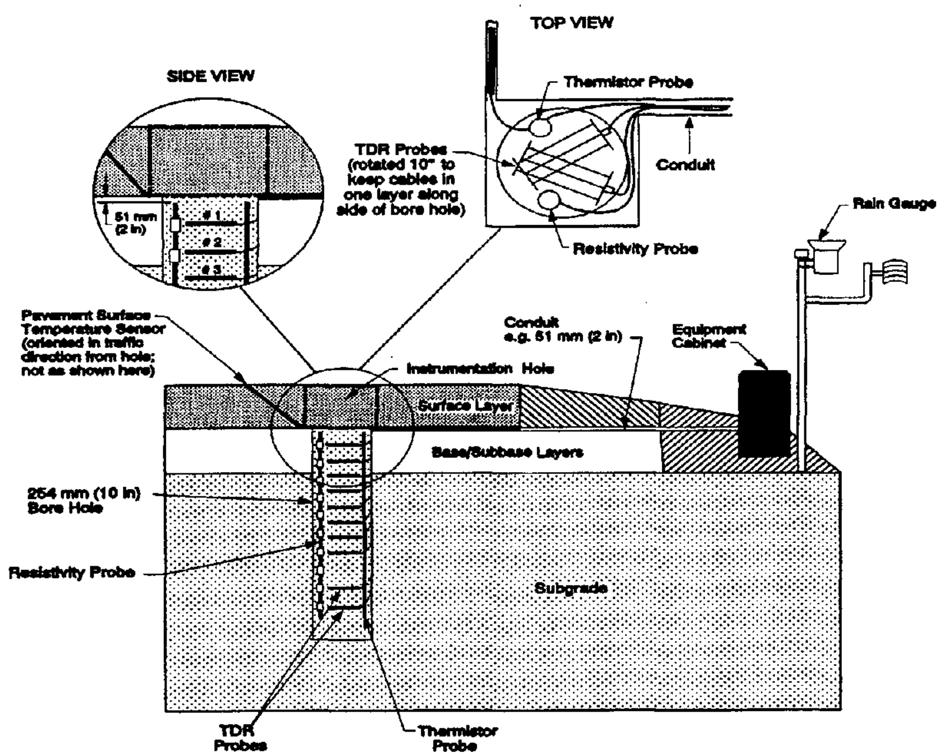


Figure 2. LTPP SMP instrumentation layout [1].

The volumetric moisture content is estimated from the measured dielectric constant using regression type equations such as Topp's equation [1] or semi-empirical soil mixing formulations such as Roth's model [2]. Topp's equation was previously proposed for use with the LTPP SMP data. The gravimetric moisture content is then determined using standard formulations that require knowledge of the dry density of the soil.

Objectives and Work Scope

The goal of the study reported here was to produce good estimates of in-situ gravimetric moisture contents and associated computation errors from interpretation of TDR measurements. All TDR traces in the LTPP information management system (IMS) table SMP_TDR_AUTO that were recorded at LTPP SMP test sections and available in the IMS as of Spring 1998 were processed using the approach developed in this study. Table 1 lists all SMP sites with TDR probes installed and trace data collected. The following list enumerates the tasks performed in this study:

- Interpretation of the TDR traces.
- Computation of the apparent length and dielectric constant.
- Precision and bias study of the computed apparent length.
- Diagnostic study of the computed soil dielectric constant.
- Development of the models to estimate volumetric moisture content.
- Determination of the gravimetric moisture content.
- Error estimate of the computed moisture contents.
- Diagnostic study of the computed moisture contents.
- Identification of the necessary material properties for the computation.
- Development of guidelines for uploading computed parameter tables relating to the interpretation of the TDR data and moisture contents.
- Development of procedures for routine analysis of the TDR traces.
- Processing and quality checking all the available TDR traces in the IMS database.

Report Organization

This report documents the research efforts and findings of the TDR data study. The report consists of six chapters and four appendixes. Chapter 1 discusses the background information, objectives, and the scope of work. The selection of the TDR trace interpretation method; computer program (Moister) for interpreting TDR traces; computation of the trace apparent length, dielectric constant, and the associated error estimates; and the diagnostic study of the computed dielectric constant are discussed in chapter 2. Chapter 3 describes the development of models to compute volumetric moisture contents using dielectric constants and material properties and the equation to compute the gravimetric moisture content. Error estimates of the computed volumetric and gravimetric moisture contents and diagnostic study of the moisture contents are also discussed in chapter 3. Identification of the needed material properties for all the computations are described in chapter 4. Chapter 5 describes procedures for routine processing of the TDR trace data. Finally, conclusions and recommendations for future activities are presented in chapter 6.

Table 1. All SMP sites with TDR probes installed and trace data collected.

Section ID	State Name	Experiment Type	Pavement Type	TDR Installation Date	Monitoring Period	Seasonal Round
40113	Arizona	SPS 1	ACP	8/15/95	08/95 - 08/96	A
40114	Arizona	SPS 1	ACP	8/16/95	10/95 - 08/96	B
40215	Arizona	SPS 2	PCCP	8/24/95	10/95 - 08/96	D
41024	Arizona	GPS 1	ACP	8/21/95	11/95 - 08/96	C
63042	California	GPS 3	JPCP	7/12/95	07/95 - 08/96	A
81053	Colorado	GPS 1	ACP	7/1/93	10/93 - 09/97	A
91803	Connecticut	GPS 1	ACP	8/19/93	08/93 - 10/97	A
133019	Georgia	GPS 3	JPCP	7/31/95	08/95 - 10/96	A
131031	Georgia	GPS 1	ACP	8/2/95	08/95 - 10/96	B
131005	Georgia	GPS 1	ACP	8/7/95	08/95 - 10/96	C
161010	Idaho	GPS 1	ACP	9/30/93	10/93 - 06/97	B
183002	Indiana	GPS 3	JPCP	9/7/95	09/95 - 08/96	A
204054	Kansas	GPS 4	JRCP	8/24/95	08/95 - 08/96	A
231026	Maine	GPS 1	ACP	9/15/93	09/93 - 06/95	A
831801	Manitoba	GPS 1	ACP	10/12/93	10/93 - 09/97	A
833802	Manitoba	GPS 3	JPCP	10/14/93	10/93 - 09/97	B
241634	Maryland	GPS 2	ACP	5/11/95	05/95 - 11/97	A
251002	Massachusetts	GPS 1	ACP	9/1/93	09/93 - 10/97	A
271018	Minnesota	GPS 1	ACP	8/24/93	08/93 - 06/95	A
271028	Minnesota	GPS 1	ACP	9/8/93	09/93 - 09/97	B
276251	Minnesota	GPS 1	ACP	9/14/93	09/93 - 09/97	C
274040	Minnesota	GPS 4	JRCP	9/21/93	09/93 - 09/97	D
281016	Mississippi	GPS 2	ACP	7/18/95	07/95 - 10/96	B
281802	Mississippi	GPS 2	ACP	7/20/95	07/95 - 10/96	A
308129	Montana	GPS 1	ACP	8/12/92	10/93 - 10/97	A
313018	Nebraska	GPS 3	JPCP	8/10/95	08/95 - 08/96	B
331001	New Hampshire	GPS 1	ACP	10/14/93	10/93 - 10/97	A
351112	New Mexico	GPS 1	ACP	4/5/94	04/94 - 08/97	A
364018	New York	GPS 4	JRCP	10/27/93	10/93 - 10/97	A
370205	North Carolina	SPS 2	PCCP	10/18/93	05/95 - 10/96	D
370208	North Carolina	SPS 2	PCCP	10/17/93	05/95 - 10/96	A
370212	North Carolina	SPS 2	PCCP	10/17/93	05/95 - 10/96	B
371028	North Carolina	GPS 1	ACP	5/17/95	05/95 - 09/96	E
404165	Oklahoma	GPS 2	ACP	4/29/94	03/94 - 09/97	A
871622	Ontario	GPS 1	ACP	9/22/93	09/93 - 10/97	A
421606	Pennsylvania	GPS 4	JRCP	8/9/95	08/95 - 10/97	A
893015	Quebec	GPS 3	JPCP	9/29/93	09/93 - 11/97	A
906405	Saskatchewan	GPS 1	ACP	10/6/93	10/93 - 09/97	A
460804	South Dakota	SPS 8	ACP	7/14/94	07/94 - 09/97	
469187	South Dakota	GPS 1	ACP	7/18/94	07/94 - 06/95	B
483739	Texas	GPS 1	ACP	12/6/93	01/94 - 09/94	G
484143	Texas	GPS 4	JRCP	11/17/93	11/93 - 09/97	D
481122	Texas	GPS 1	ACP	11/22/93	11/93 - 09/97	E
481060	Texas	GPS 1	ACP	11/30/93	12/93 - 09/97	F
481077	Texas	GPS 1	ACP	10/25/93	12/93 - 09/97	A
481068	Texas	GPS 1	ACP	11/1/93	12/93 - 08/97	B
484142	Texas	GPS 4	JRCP	11/8/93	12/93 - 09/97	C
493011	Utah	GPS 3	JPCP	8/3/93	11/93 - 09/97	A
491001	Utah	GPS 1	ACP	8/5/93	11/93 - 09/97	B
501002	Vermont	GPS 1	ACP	10/6/93	10/93 - 10/97	A
533813	Washington	GPS 3	JPCP	7/18/95	07/95 - 08/96	A
561007	Wyoming	GPS 1	ACP	8/10/93	08/97 - 09/97	A

Appendix A provides a list of the TDR traces from the IMS database that are abnormal and not interpretable. Traces that were selected for the precision and bias study for the computed apparent length are given in appendix B. Appendix C lists the material properties that were identified and used for computation of the gravimetric moisture contents. Appendix D provides charts showing seasonal variation in volumetric moisture content, gravimetric moisture content, and corresponding daily rainfall for each test section included in this study.

2. INTERPRETATION OF TDR TRACES

The first major step to determine in-situ soil moisture content using the TDR procedure is to determine the apparent length, La, of the TDR trace. The apparent length of the interpretable TDR traces is then used to compute the dielectric constant and the volumetric moisture content for the material surrounding the TDR gauge. The theory and approaches to determine the apparent length have been discussed in the literature [1-11].

The TDR probes used are three-prong TDR probes developed by FHWA, as shown in figure 1. An ideal trace of the propagation of a voltage pulse in a three-prong transmission line cable-handle-waveguide is given in figure 3. As shown, the rectangular wave above the interval OA is caused by the reflection from the cable-handle connection, travel along the handle, and reflection from the handle-waveguide connection. The rising signal beginning at B is caused by the reflection from the ends of the waveguides. After point B, the trace pattern is a result of multiple reflections from the handle and waveguides. The apparent length of the ideal trace is very easily identified as length AB.

For actual TDR probes embedded in soil, the recorded traces are rounded, as shown in figure 4, by wave dispersion due to the measurement delay of the instrument and non-ideal behavior of the soil (the dielectric medium), and the probe and cable. The degree of dispersion increases with longer cables and number of reflections [5]. Variations in soil water content along the rods may also contribute to dispersion. The differences between the shapes of the measured and ideal traces complicate the determination of the apparent length of the TDR trace, as shown in figure 4. A typical TDR waveform consists of a peak followed by a valley. The apparent length of a TDR trace is the difference between the two inflection points of the peak and the valley. In a few cases, the peak may not be followed by a valley. In these cases, the trailing or end portion of the waveform simply exhibits a flat trend. It may not be possible to interpret such traces.

Selection of the Trace Interpretation Method

Several methods exist for identifying inflection points of a TDR trace, but the Method of Tangents and the Method of Peaks are most widely used [6]. The Method of Tangents was found to be the most accurate method by comparing the TDR results and the laboratory-determined moisture content in a recent study by Klemunes using soil samples from 28 LTPP SMP test sites [7]. This conclusion was verified in this study using Klemunes' calibration database [6]. The Method of Tangents is illustrated in figure 5. The initial inflection point is determined by locating the intersection of the horizontal and negatively sloped tangents at the trace's local maximum value, and the final inflection point is located at the intersection of the horizontal and positively sloped tangents at the trace's local minimum value.

Although the Method of Tangents is applicable to most TDR traces, it does not apply to all soils, especially very dry or partially frozen soils. For these situations, the Method of Peaks (illustrated in figure 6) may be used. The initial inflection point is determined by locating the intersection of the tangents drawn on both sides of the first inflection point. The final inflection

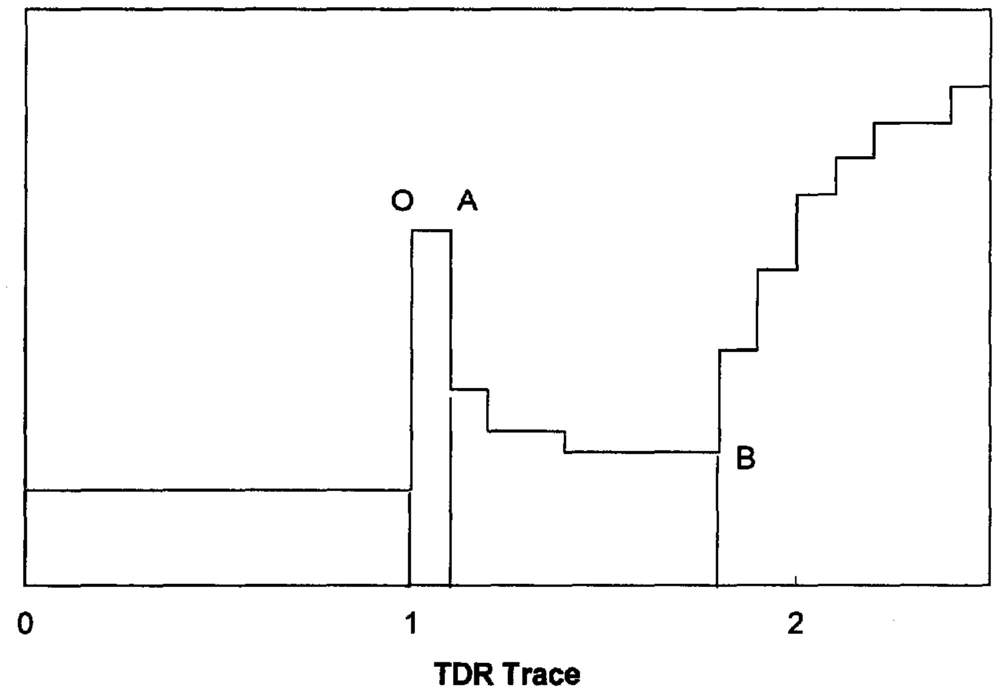


Figure 3. Illustration of an ideal TDR trace.

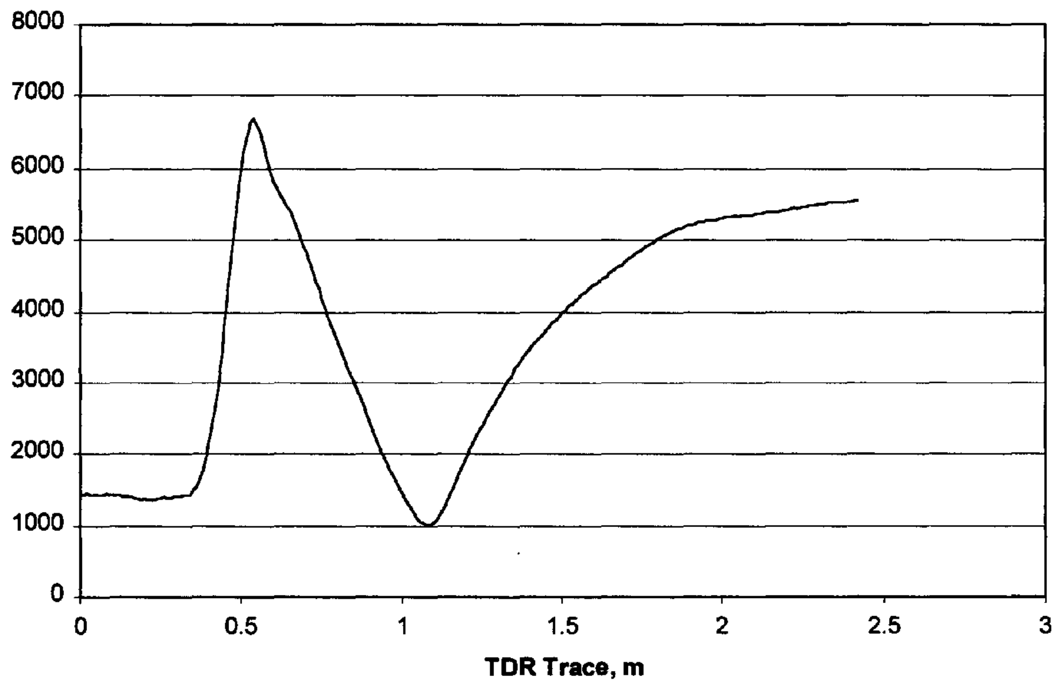


Figure 4. Example of an actual TDR trace.

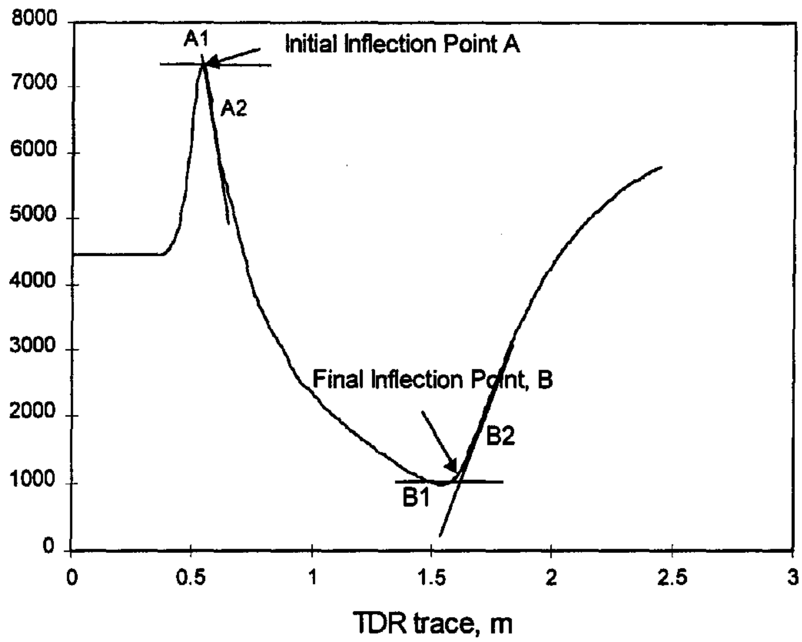


Figure 5. Illustration of the Method of Tangents (section 510113).

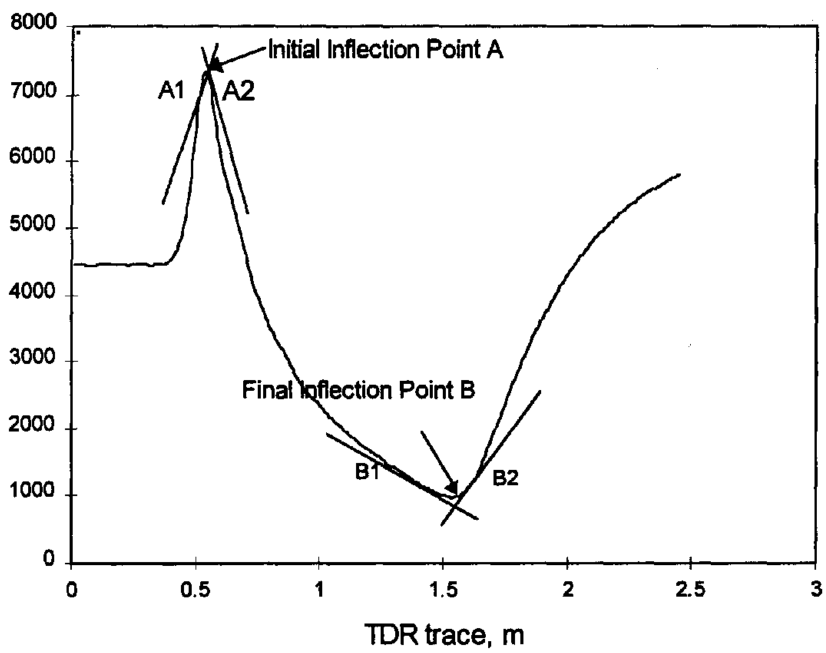


Figure 6. Illustration of the Method of Peaks (section 510113).

point is located at the intersection of the tangents drawn on both sides of the final inflection point.

On the basis of work performed under this study, the Method of Tangents was selected as the primary method to determine the apparent length for the LTPP data. For the TDR traces representing very dry or frozen soils, the Method of Peaks was selected for identifying the inflection points and estimating the apparent length. Figures 7 and 8 provide example TDR traces for data where the Method of Tangents applies, and figure 9 shows an example trace for which the Method of Peaks applies.

Factors influencing the accuracy and precision of the TDR interpretation method include extremes in soil mixture conductivity, salinity, and possibly temperature effects. Saline-like conditions in the soil can cause a short circuit in the TDR probes, which makes the final inflection point of the TDR trace difficult to locate. In the trace interpretation procedure, an error code is assigned to flag such conditions. In some cases, the initial inflection point is missing from the TDR trace. Error code "a1" is assigned to these traces, an example of which is shown in figure 10. For the traces where the final inflection point is either missing or not interpretable, an error code "b1" is assigned. Examples of such traces are given in figures 11 and 12. TDR traces showing other abnormalities are given the error code "OT," as shown in figure 13. Many abnormal traces tend to occur at the same TDR probe, which may indicate any of the following problems:

- Signal noise, mostly applicable to "OT" type abnormal traces.
- Equipment malfunction, mostly applicable to "OT" type abnormal traces.
- Operator errors, applicable to "a1" and "b1" type abnormal traces.
- Highly conductive materials, such as material with highly conductive mineral content or soils under saline conditions, applicable to "b1" type abnormal traces.

Typical TDR trace patterns and error codes used to classify TDR trace shapes are listed in table 2. Appendix A provides a complete listing of the problematic traces that cannot be used to determine apparent length of the trace. The number of traces where the apparent length could not be determined accurately was 1,519 out of a total of 19,663 TDR traces (or about 80 percent of the traces) available as of Spring 1998.

Development of the Computer Program Moister

As part of this study, a computer program called Moister was developed to view and process TDR traces. Figure 14 shows the main TDR trace viewing and interpretation window of Moister. As shown, the program uses the TDR trace data from a table containing TDR trace point data in an Access® database and plots the smoothed trace on the screen. The trace shown on the screen can then be processed automatically using the algorithm implemented in the program, and the identified inflection points and the corresponding tangent lines will show up on the same screen for user review. The program can process the TDR traces in the following two ways:

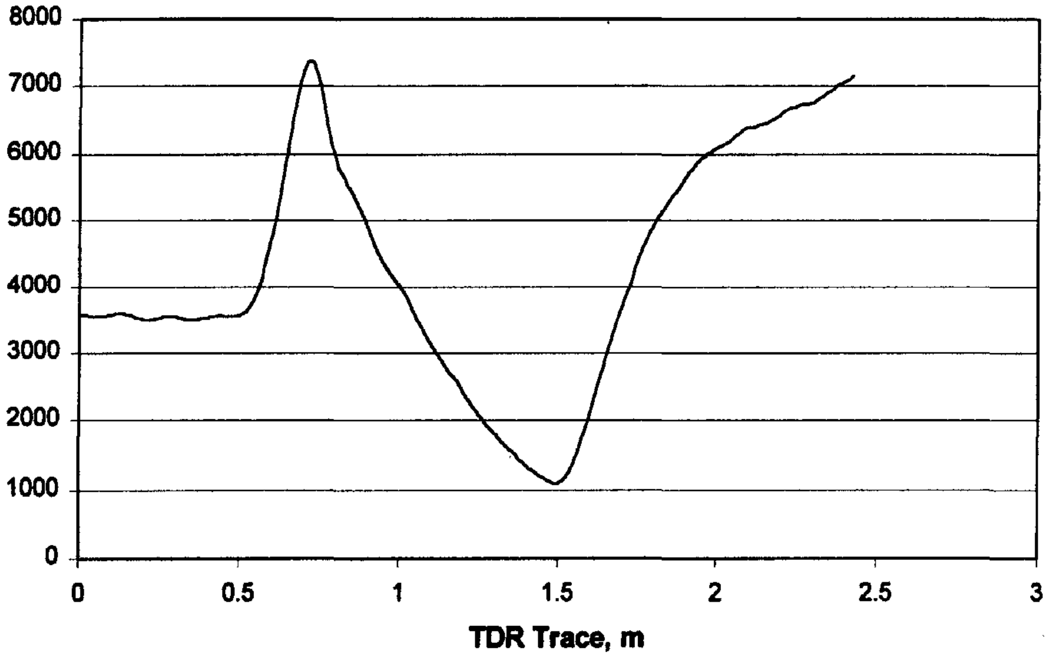


Figure 7. Example TDR trace for which Method of Tangents applies (section 331001).

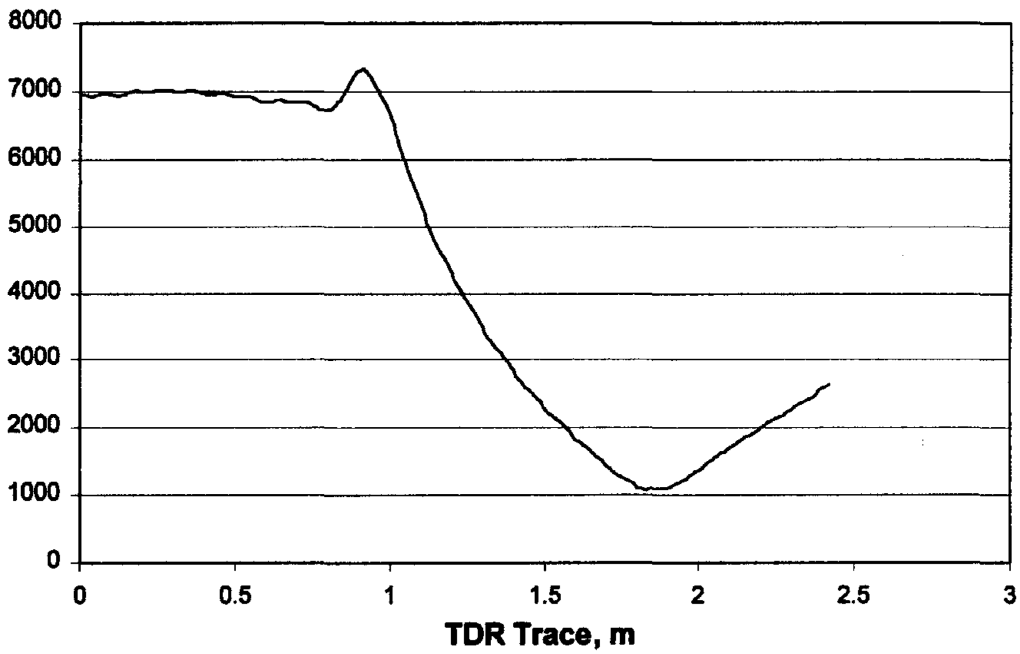


Figure 8. Example TDR trace for which Method of Tangents applies (section 281016).

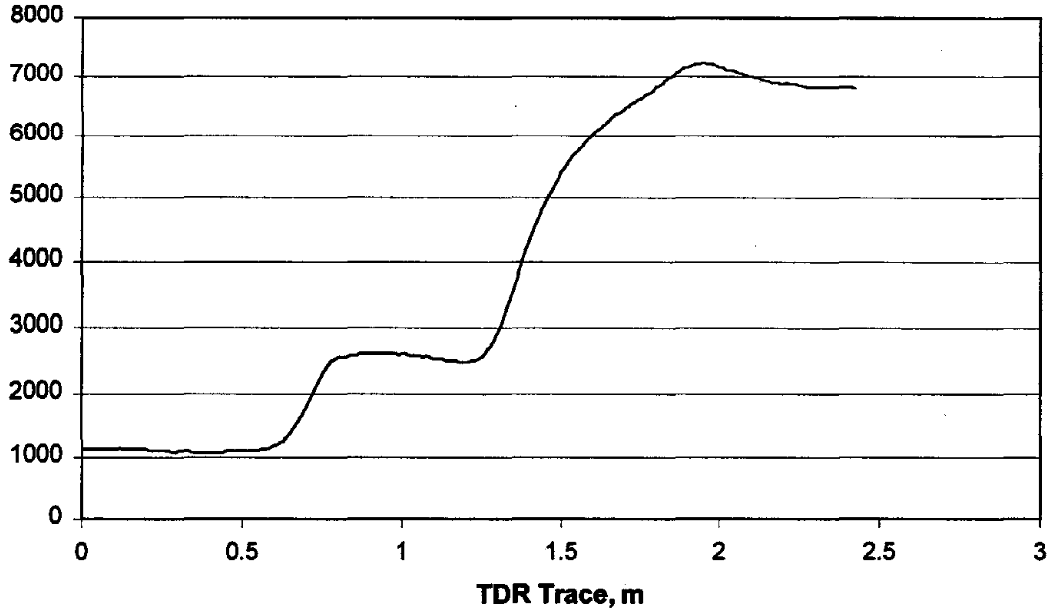


Figure 9. Example TDR trace for which Method of Peaks applies (section 251002).

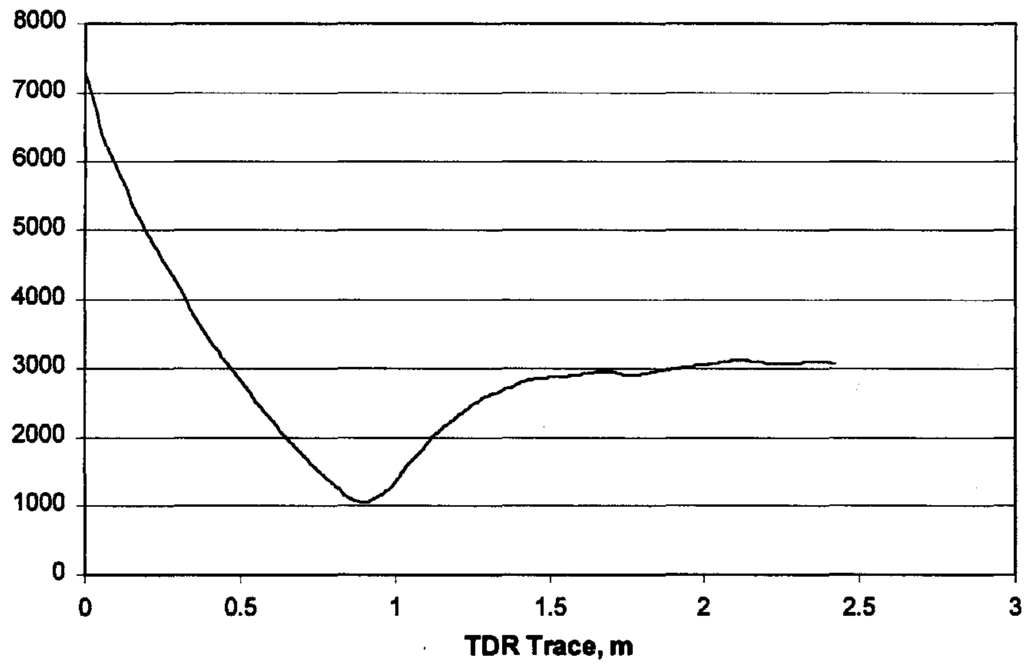


Figure 10. Example TDR trace for which error code "a1" applies (section 271018).

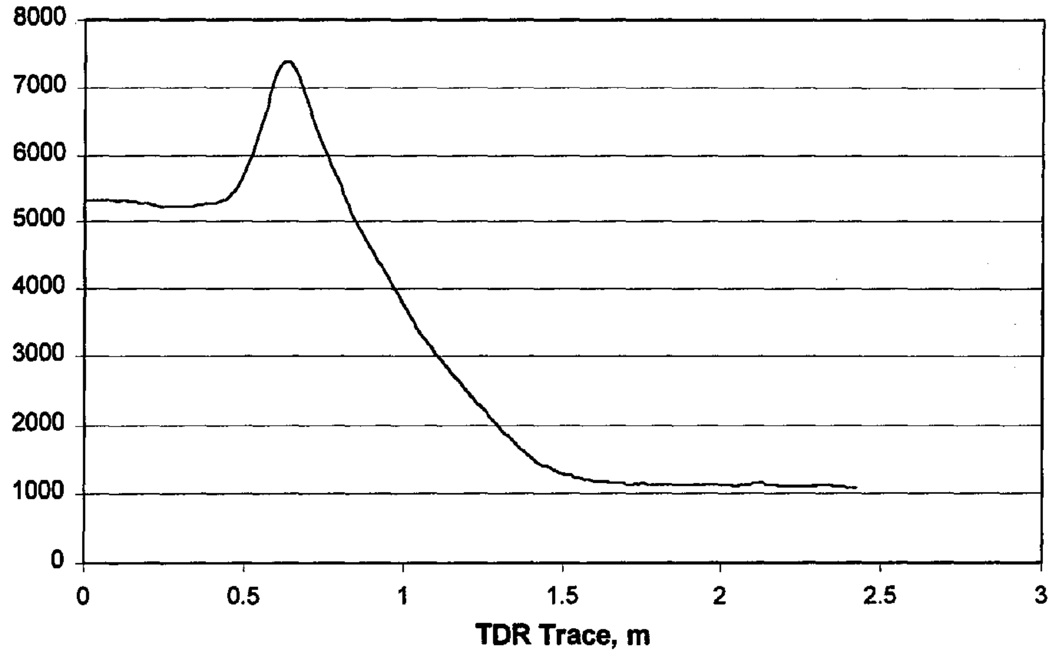


Figure 11. Example TDR trace for which error code "b1" applies (section 331001).

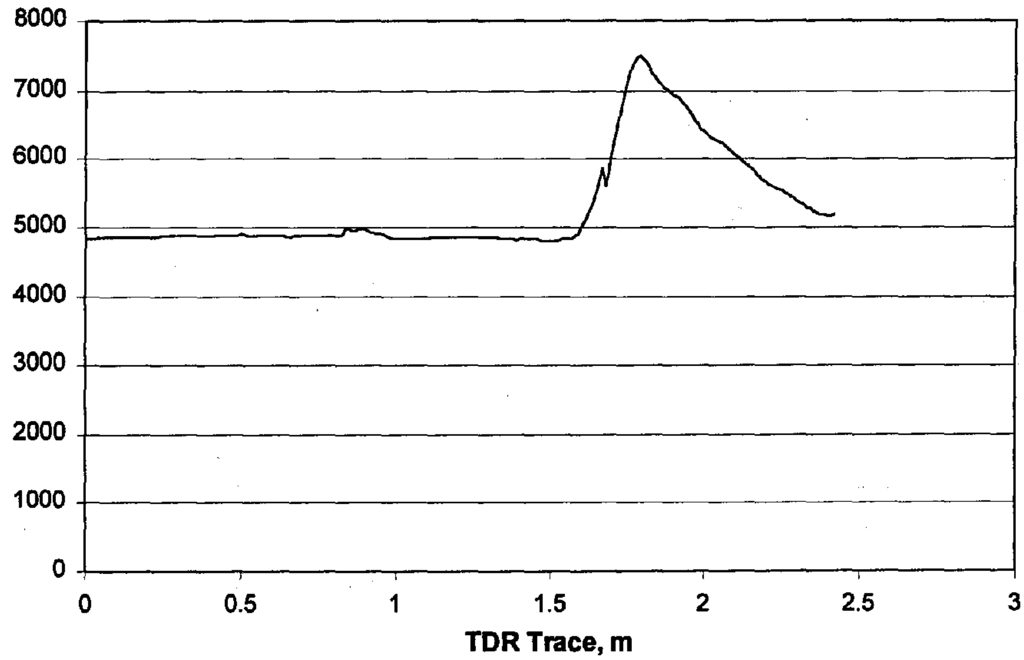


Figure 12. Example TDR trace for which error code "b1" applies (section 131031).

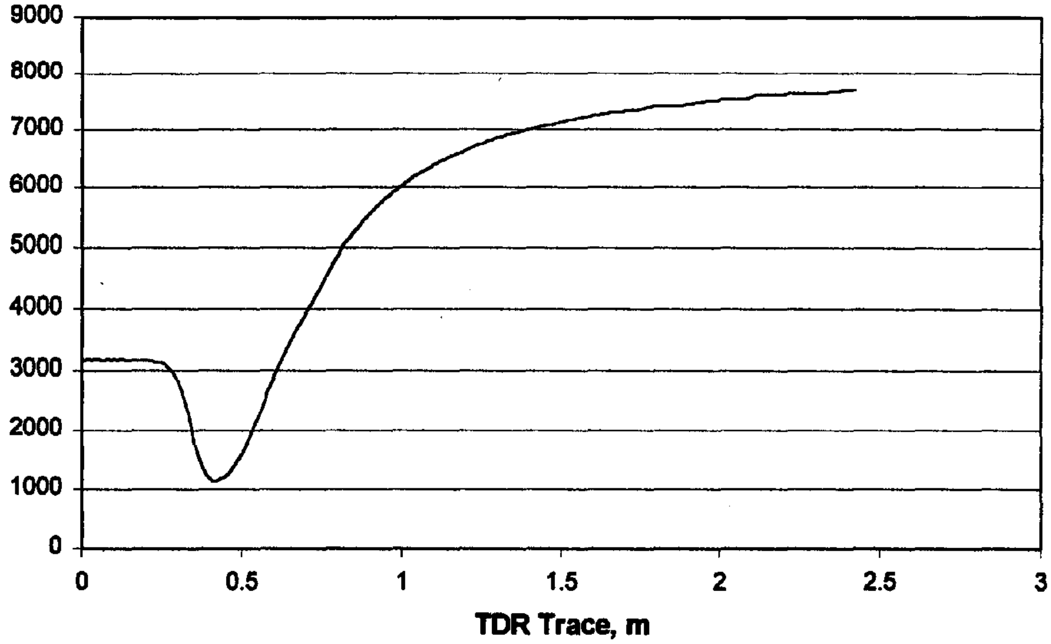


Figure 13. Example TDR trace for which error code "OT" applies (section 271018).

Table 2. Typical TDR trace pattern or error codes.

Pattern or Error Code	Description
TG	Automatically processed using Method of Tangents
PK	Automatically processed using Method of Peaks
MT	Manually identified using Method of Tangents
MP	Manually identified using Method of Peaks
a1	Error associated with the first inflection point
b1	Error associated with the second inflection point
OT	Other abnormal traces

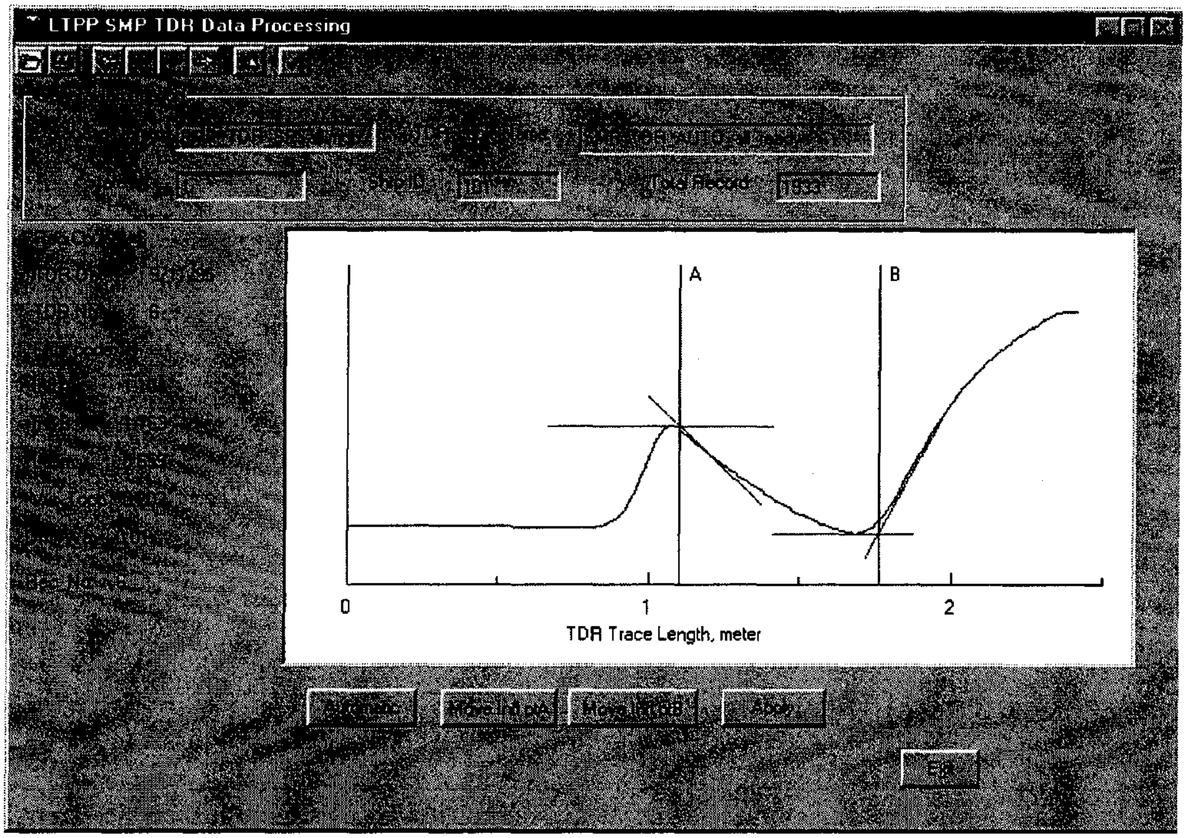


Figure 14. Program Moister's main trace viewing and processing screen.

1. Moister can automatically process all the TDR traces collectively and show the identified inflection points on the screen for user review.

2. Alternatively, Moister can locate the inflection points one trace at a time interactively with the user (semi-automatic procedure). This can be done by using the algorithm implemented by the program or by moving the inflection points on the program screen 0.01 m at a time. Once the user is satisfied with the location of the inflection points, the inflection points are recorded by using the "Apply" button and selecting an appropriate TDR trace pattern or error code.

The location of the inflection points A and B and the corresponding trace pattern or error code are stored in the same table as the original TDR trace points for later review. Moister provides a user-friendly interface to easily view and interpret TDR traces. Tool buttons are available for easy navigation within the TDR trace table, namely "Next Record," "Previous Record," "Last Record," "First Record," and "Go To". Moister also serves as a very efficient tool for quality control of the computed quantities.

Moister Algorithm

An algorithm was developed for Moister to interpret the first and second inflection points of the TDR traces using both the Method of Tangents and the Method of Peaks. Before identifying the inflection points, the raw TDR traces are smoothed out using a seven-point moving average approach. The first inflection point occurs at the crest of the peak, and the second inflection point occurs at the bottom of the valley. The distance between the two inflection points is referred to as the apparent length of the TDR gauge, as shown in figures 5 and 6. The following is a brief description of the algorithm implemented by Moister.

Method of Tangents

As shown in figure 5, the implementation of the Method of Tangents involves the following steps:

Determine the first inflection point, A

1. Identify the first waveform maximum, point A1, and draw a horizontal line at A1.
2. Identify the waveform minimum point, B1.
3. Identify the sharpest negative slope point between point A1 and (A1+ (B1-A1)/2), point A2.
4. Draw the tangent line at point A2.
5. The intersection point of these straight lines is the first inflection point, A.

Determine the second inflection point, B

1. Draw a horizontal line at minimum point, B1, as identified above.
2. Identify the sharpest positive slope point between B1 and B1+60 (or B1(m) +0.6 m), which gives point B2.
3. Draw the tangent line at point B2.
4. The intersection point of these two straight lines is the second inflection point, B.

Method of Peaks

Figure 6 illustrates the implementation of the Method of Peaks, which involves the following steps:

Determine the first inflection point, A

1. Identify the first maximum rise point (sharpest positive slope point), A1.
2. Identify the minimum slope point between point A1 and the global minimum. This gives point A2.
3. Draw the tangent line at point A1 and the tangent line at point A2.
4. The intersection point of these straight lines is the first inflection point, A.

Determine the second inflection point, B

1. Identify the smallest or flattest slope point between a point halfway between the first maximum point and the global minimum. This gives point B1.
2. Identify the sharpest positive slope point between B1 and B1+60 (or B1(m) +0.6 m), which gives B2.
3. Draw the tangent line at point B1 and the tangent line at point B2.
4. The intersection point of these two straight lines is the second inflection point, B.

Computation of Apparent Length and Soil Dielectric Constant

Once the TDR trace inflection points are determined, the apparent length and the dielectric constant of the soil can be calculated using the following standard equation [7]:

$$Ka = \left(\frac{La}{(L * Vp)} \right)^2 \tag{1}$$

where: *La*	=	Apparent length of the TDR trace, m.
	=	Inflection_B - Inflection_A.
Inflection_A	=	First inflection point.
Inflection_B	=	Second inflection point.
Ka	=	Dielectric constant of the soil.
L	=	Actual length of the TDR probe, m (typically 0.203 m for LTPP data).
Vp	=	Propagation velocity of the TDR wave, typically 0.99.

Precision and Bias of the Computed Apparent Length and Dielectric Constant

Since TDR waveforms come in different shapes and have different radii at the inflection points, any interpretation method and algorithm will introduce some degree of error or uncertainty. It is, therefore, important to quantify the quality of the measurements and computations, specifically, the precision and bias of the computed apparent lengths and the computed dielectric constants. The following two sections discuss the error estimates of the computed apparent length and dielectric constant, respectively.

Error Estimate of the Computed Apparent Length

According to ASTM standard E 177-90a [12], precision is a generic concept related to the closeness of agreement between test results obtained under prescribed like conditions from the measurement process being evaluated. A statement on precision is not intended to contain values that can be exactly duplicated in every user's laboratory. Therefore, in the cases that the apparent length can be determined using the computer program Moister automatically, a precision statement does not apply since there is always a unique value for each trace. When the apparent lengths need to be identified manually or semi-automatically, a precision statement needs to be developed. The two-standard deviation limit was selected as the index of precision of the TDR trace interpretation process.

According to ASTM standard E 177-90a [12], the bias of a measurement process is a generic concept related to a consistent or systematic difference between a set of test results from the process and an accepted reference value of the property being measured. In determining the bias, the effect of the imprecision is averaged out by taking the average of the very large set of test results. This average minus the accepted reference value is an estimate of the bias of the process.

According to ASTM standard E-456-96 [13], an accepted reference value is a value that serves as an agreed-upon reference for comparison and may be:

1. A theoretical or established value, based on scientific principles.
2. An assigned or certified value, based on experimental work of some national or international organization.
3. A consensus or certified value, based on collaborative experimental work under the auspices of a scientific or engineering group.

Method 3 was selected to establish the accepted reference value for apparent length in this study.

Four engineers were recruited to perform the precision and bias study for the computed apparent length using TDR traces. A total of 25 TDR traces representing typical TDR trace patterns recorded from the SMP sites were selected for the precision and bias study. The TDR traces selected for the precision and bias study are given in appendix B.

A short training session on the principles of the TDR trace analysis was conducted first for the four engineers involved. After that, the selected engineers did the trace interpretation manually, using ruler and pencil. The average manual trace reduction time for individual traces was about 2 to 3 minutes. The results of the manual trace reduction are provided in table 3. Assuming that the variance is same for all the TDR trace interpretations, then the pooled sample standard deviation can be computed using the following equation:

$$S_p^2 = \frac{\sum (n_i - 1)\, S_i^2}{\sum (n_i - 1)} \tag{2}$$

where: S_p = Pooled sample standard deviation.
S_i = Sample standard deviation for i^th^ population group.
n_i = Number of samples for i^th^ population group.
i = i^th^ population group.

The pooled sample standard deviation for the 25 TDR traces was determined to be 0.011 m.

After the manual trace reduction exercise was completed, the same four engineers performed the TDR trace analysis using the semi-automated method. The computer program Moister was used to view and identify the initial and the final inflection points of the traces in the semi-automated trace interpretation method. The program assists the analyst by drawing the logical tangent line and horizontal line using the inflection points picked up by the analyst and the information embedded in the trace itself. This makes trace reduction easier and more accurate. The engineers' average trace reduction time was about 20 to 40 s per trace using the semi-automated method. Table 4 gives the apparent length results obtained by the semi-automated method. The pooled sample standard deviation for the 25 TDR traces was determined to be 0.010 m.

Table 3. Apparent length results using manual trace interpretation method.

Section ID	TDR No.	Test Date	Test Time	Record No.	La (m) by Operator				Avg. La, m	Std. Dev., m
					1	2	3	4		
331001	1	10/14/93	11:13	1	0.473	0.466	0.475	0.455	0.470	0.010
331001	5	10/14/93	11:16	5	0.698	0.706	0.685	0.700	0.700	0.011
331001	9	10/14/93	11:18	9	0.650	0.643	0.650	0.640	0.640	0.005
331001	7	10/14/93	11:29	17	0.840	0.883	0.865	0.850	0.870	0.017
331001	2	03/21/94	10:07	21	0.737	0.731	0.740	0.730	0.730	0.006
331001	6	11/17/94	12:56	157	0.648	0.625	0.630	0.600	0.620	0.016
331001	7	03/30/95	08:41	228	0.805	0.799	0.805	0.790	0.800	0.008
331001	10	04/27/95	07:56	241	1.085	1.071	1.080	1.078	1.080	0.005
491001	4	01/14/94	08:46	315	0.560	0.562	0.580	0.555	0.570	0.013
491001	10	02/11/94	09:14	334	0.450	0.440	0.455	0.455	0.450	0.009
491001	1	03/25/94	16:17	387	0.500	0.494	0.505	0.502	0.500	0.006
491001	8	04/28/94	11:28	424	0.520	0.519	0.550	0.520	0.530	0.018
491001	8	01/13/95	08:48	594	0.463	0.451	0.440	0.430	0.440	0.011
251002	10	09/28/94	09:10	890	0.508	0.497	0.490	0.495	0.490	0.004
251002	10	11/29/94	12:39	928	0.491	0.489	0.485	0.493	0.490	0.004
501002	5	08/17/94	08:15	1219	0.855	0.849	0.845	0.850	0.850	0.003
501002	4	06/28/95	09:19	1397	0.837	0.869	0.845	0.830	0.850	0.020
131005	1	03/25/96	11:31	1587	0.780	0.771	0.775	0.800	0.780	0.016
161010	9	05/22/95	12:27	2258	0.859	0.849	0.845	0.853	0.850	0.004
281016	10	03/21/96	07:15	2406	0.950	0.959	0.950	0.968	0.960	0.009
281016	8	07/22/96	07:23	2524	0.827	0.819	0.840	0.830	0.830	0.011
281016	8	09/30/96	08:33	2544	0.843	0.847	0.845	0.830	0.840	0.009
371028	9	11/16/95	09:18	3640	0.678	0.689	0.680	0.710	0.690	0.015
281802	3	05/10/96	15:25	7677	0.543	0.526	0.535	0.540	0.530	0.007
281802	8	07/23/96	15:44	7742	0.748	0.744	0.710	0.721	0.730	0.017
Pooled Standard Deviation, m										0.011

Table 4. Apparent length results using semi-automated trace interpretation method.

Section ID	TDR No.	Test Date	Test Time	Record No.	La (m) by Operator				Avg. La, m	Std. Dev. m
					1	2	3	4		
331001	1	10/14/93	11:13	1	0.455	0.431	0.466	0.466	0.450	0.016
331001	5	10/14/93	11:16	5	0.748	0.748	0.741	0.752	0.750	0.004
331001	9	10/14/93	11:18	9	0.628	0.629	0.635	0.625	0.630	0.004
331001	7	10/14/93	11:29	17	0.868	0.842	0.861	0.868	0.860	0.012
331001	2	03/21/94	10:07	21	0.750	0.742	0.730	0.725	0.740	0.011
331001	6	11/17/94	12:56	157	0.623	0.625	0.629	0.619	0.620	0.005
331001	7	03/30/95	08:41	228	0.791	0.795	0.799	0.799	0.800	0.004
331001	10	04/27/95	07:56	241	1.076	1.062	1.059	1.069	1.070	0.008
491001	4	01/14/94	08:46	315	0.542	0.535	0.566	0.545	0.550	0.013
491001	10	02/11/94	09:14	334	0.398	0.402	0.429	0.402	0.410	0.014
491001	1	03/25/94	16:17	387	0.429	0.429	0.434	0.439	0.430	0.005
491001	8	04/28/94	11:28	424	0.476	0.483	0.486	0.482	0.480	0.003
491001	8	01/13/95	08:48	594	0.430	0.435	0.450	0.434	0.440	0.009
251002	10	09/28/94	09:10	890	0.476	0.471	0.466	0.466	0.470	0.005
251002	10	11/29/94	12:39	928	0.466	0.466	0.471	0.466	0.470	0.003
501002	5	08/17/94	08:15	1219	0.850	0.845	0.852	0.847	0.850	0.003
501002	4	06/28/95	09:19	1397	0.860	0.855	0.884	0.900	0.870	0.021
131005	1	03/25/96	11:31	1587	0.783	0.774	0.778	0.810	0.790	0.016
161010	9	05/22/95	12:27	2258	0.777	0.777	0.767	0.767	0.770	0.002
281016	10	03/21/96	07:15	2406	0.945	0.937	0.942	0.947	0.940	0.005
281016	8	07/22/96	07:23	2524	0.848	0.836	0.857	0.831	0.840	0.012
281016	8	09/30/96	08:33	2544	0.847	0.843	0.826	0.868	0.850	0.017
371028	9	11/16/95	09:18	3640	0.705	0.699	0.709	0.704	0.700	0.004
281802	3	05/10/96	15:25	7677	0.488	0.467	0.460	0.476	0.470	0.012
281802	8	07/23/96	15:44	7742	0.639	0.636	0.641	0.635	0.730	0.001
Pooled Standard Deviation, m										0.010

Because of the reduction time and the number of TDR traces involved, manual trace reduction was considered too time consuming and not feasible for production purposes. For example, for the currently available 20,000 TDR traces collected from the SMP sites, approximately 800 to 1100 hours of processing time would be required using the manual trace interpretation method without gaining much on accuracy.

Moister was developed to address the automated and semi-automated TDR trace reduction needs. Most TDR traces can be processed automatically using the algorithm implemented in the program. For traces that require use of the semi-automated method, the precision is defined by the two-standard deviation limit, as recommended by the ASTM standard E 177-90a. In this case, the following equation applies because the average standard deviation of this method was determined to be 0.010 m.

$$\textit{Precision of semi-automated TDR trace interpretation} = 2 * 0.01\ m = 0.02\ m \qquad (3)$$

To estimate the bias of the TDR trace analysis algorithm implemented by Moister, consensus values were established among the participating engineers for the selected 25 traces. The consensus values were used as the reference values for the automated TDR trace interpretation method. Table 5 provides the apparent length results obtained both by Moister and by consensus, as well as the differences between the two sets of values. The average difference between the apparent length obtained from Moister and the reference value was 0.002 m. This is the estimated bias for the TDR interpretation method used by Moister. Since the bias is smaller than the resolution of the TDR waveform (0.01 m), the bias of the method implemented by Moister can be considered insignificant.

Error Estimate of the Computed Dielectric Constant

Dielectric constant was calculated using the following formula:

$$Ka = \left(\frac{La}{(L * Vp)} \right)^2 \qquad (4)$$

where: Ka = Dielectric constant of the soil mix.
La = Apparent length of the TDR trace, m.
L = Actual length of the TDR probe (typically 0.203 m for this work).
Vp = Propagation velocity of the TDR wave, typically 0.99.

Since the actual length of the TDR probe is a controlled design dimension and the propagation velocity is a controlled equipment setting, they both can be assumed to be accurate; the error of the computed dielectric constant, Ka, depends solely on the error introduced by the apparent length. By error propagation law, the error in Ka can be calculated using the following equation:

$$\triangle Ka = \frac{\partial Ka}{\partial La} \triangle La \qquad (5)$$

Table 5. Comparison of La results from Moister and consensus values.

Section ID	TDR No.	Test Date	Test Time	Record No.	La, m		La Difference, m
					By Program	By Consensus	
331001	1	10/14/93	11:13	1	0.436	0.448	-0.012
331001	5	10/14/93	11:16	5	0.761	0.753	0.008
331001	9	10/14/93	11:18	9	0.629	0.632	-0.003
331001	7	10/14/93	11:29	17	0.879	0.860	0.019
331001	2	03/21/94	10:07	21	0.727	0.735	-0.008
331001	6	11/17/94	12:56	157	0.629	0.631	-0.002
331001	7	03/30/95	08:41	228	0.800	0.805	-0.005
331001	10	04/27/95	07:56	241	1.068	1.073	-0.005
491001	4	01/14/94	08:46	315	0.537	0.530	0.007
491001	10	02/11/94	09:14	334	0.397	0.392	0.005
491001	1	03/25/94	16:17	387	0.428	0.435	-0.007
491001	8	04/28/94	11:28	424	0.485	0.478	0.007
491001	8	01/13/95	08:48	594	0.421	0.425	0.004
251002	10	09/28/94	09:10	890	0.466	0.461	0.005
251002	10	11/29/94	12:39	928	0.463	0.456	0.007
501002	5	08/17/94	08:15	1219	0.836	0.843	-0.007
501002	4	06/28/95	09:19	1397	0.879	0.873	0.006
131005	1	03/25/96	11:31	1587	0.779	0.766	0.013
161010	9	05/22/95	12:27	2258	0.770	0.762	0.008
281016	10	03/21/96	07:15	2406	0.944	0.940	0.004
281016	8	07/22/96	07:23	2524	0.840	0.842	-0.002
281016	8	09/30/96	08:33	2544	0.839	0.841	-0.002
371028	9	11/16/95	09:18	3640	0.707	0.704	0.003
281802	3	05/10/96	15:25	7677	0.479	0.476	0.003
281802	8	07/23/96	15:44	7742	0.637	0.634	0.003
Mean Difference, m							0.002
Standard deviation of the Difference, m							0.007

Applying the partial differentiate:

$$\Delta Ka = 2 * (La/(L * Vp)^2) * \Delta La \tag{6}$$

Substitute the following values:

Vp	=	0.99
L	=	0.203 m (LTPP data)
ΔLa	=	0.01 m (as determined in the previous section)

then

$$\Delta Ka = 0.5\ La \tag{7}$$

The above equation gives the estimated error of the computed dielectric constant. For example, at an La of 1.2 m, the estimated error associated with the computed dielectric constant value of 35.64 is about 0.6.

Diagnostic Study of the Computed Dielectric Constant

The dielectric constant of a material is defined as the ratio of the capacitance of that material to the capacitance in air. Unbound materials in pavement base, subbase, and subgrade contain basically solids, water, and air. The dielectric constant of air is 1.0, and for water it is typically around 80. For soil solids, the dielectric constant is typically between 3 and 8.

For a completely dry soil that contains only soil solids and air, the composite dielectric constant should be slightly less than that of the soil solids. As moisture is added to the soil, the composite dielectric constant will increase because of the large dielectric constant of the water. Therefore, theoretically, the dielectric constant of the soil mixture can be between 1 and 80; a typical range is between about 2 and 50.

Figures 15 and 16 show the frequency distribution of the dielectric constant values of coarse- and fine-grained soils as determined for the 19,663 traces from the LTPP SMP sites. As shown, dielectric constant values for coarse-grained soils are between 1.6 and 25, and for fine-grained soils they are between 1.8 and 58, with about 99 percent of values between 3 and 50. This difference in dielectric constant distribution between the coarse and fine soils is expected, since the fine-grained soils tend to retain more moisture. The computed dielectric constant values from the LTPP SMP sites are within a reasonable range.

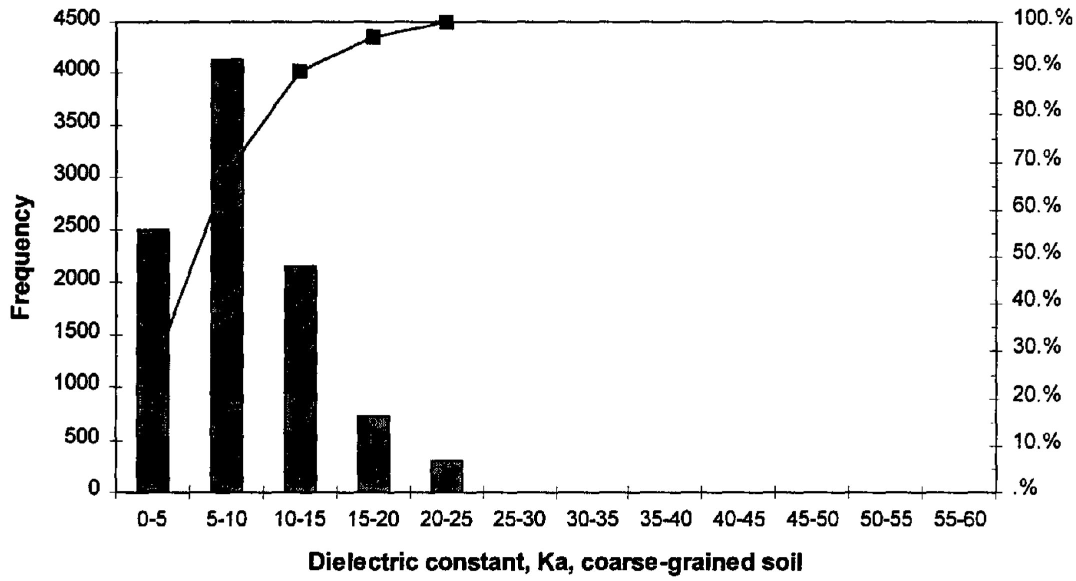


Figure 15. Frequency distribution of the dielectric constants for the LTPP SMP coarse-grained soils.

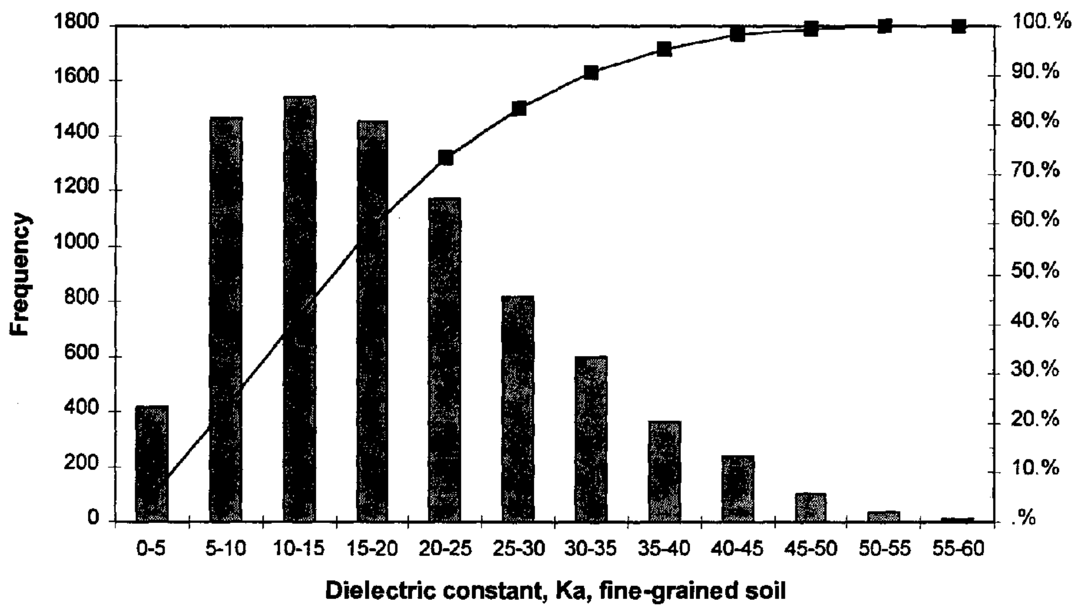


Figure 16. Frequency distribution of the dielectric constants for the LTPP SMP fine-grained soils.

3. DETERMINATION OF VOLUMETRIC AND GRAVIMETRIC MOISTURE CONTENTS

As previously discussed, in-situ moisture contents of the unbound materials and subgrade soil are important material properties that can affect pavement performance. This section of the report documents the research effort to develop models to compute the volumetric moisture content and the gravimetric moisture content of the base, subbase, and subgrade materials at the LTPP SMP sites.

Determination of In-Situ Volumetric Moisture Content

Two common approaches are used to relate the apparent dielectric constant to soil volumetric moisture content (Vw%): the empirical approach and the theoretical approach.

In the empirical approach, the apparent dielectric constant, Ka, is related to the volumetric moisture content directly using empirical regression functions. No physical justification of the model form is considered in this approach. The functional form most frequently used is the third-order polynomial. Topp was one of the first researchers who obtained the third-order polynomial empirical model relating Ka to Vw% [2], and his equation is the most widely used to determine volumetric moisture content directly from the apparent dielectric constant in the agricultural field. Topp's equation applies to all types of soils; however, because it is a generic model applicable to all soils, it is not very accurate in all cases. Topp's model is given below:

$$Vw\% = -5.3 + 2.92 * Ka - 0.055 * Ka^2 + 0.00043 * Ka^3 \tag{8}$$

where: $Vw\%$ = Volumetric moisture content, %.
Ka = Dielectric constant.

The advantage of the empirical model is its ease of use. When calibrated to a specific soil type, this approach can give accurate results.

The theoretical approach involves derivation of a fundamental equation from the soil dielectric mixing models. The soil mixing models relate the composite dielectric number of a multi-phase mixture to the dielectric number and volume fractions of its constituents—soil, water, and air. The following three mixing models are the most widely used:

- Three-phase model [3], which includes soil, water, and air.
- Four-phase model [4], which includes soil, free water, bound water, and air.
- Maxwell-De Loor model [5], which also includes four phases.

Compared with the empirical models, the mixing models are theoretically more sound and have the potential to describe the relationship between the apparent dielectric constant and the volumetric moisture content because they account for the influence of the individual soil constituents. These more theoretically oriented approaches were not adopted for the following reasons:

- The semi-theoretical models require more material property inputs (e.g., dry density and specific gravity) for the material around the TDR probes. These material properties are not available in the IMS database at the present time.
- The models developed using the more theoretical approach sometimes yield physically meaningless estimates of some parameters (e.g., negative soil dielectric constant).

Klemunes recently performed a comprehensive study to develop calibrated mixing models for specific soil samples [7]. Twenty-eight soil samples were obtained from 28 LTPP SMP sites. For each soil sample, TDR traces were obtained and soil testing for dry density and gravimetric moisture content was conducted at several moisture levels and up to six compaction levels. A total of 415 data points was obtained, with measurements including specific gravity, dry density, gradation parameters, plastic limit, liquid limit, gravimetric moisture content, volumetric percentage of the soil mixture, and the corresponding TDR traces. Some traces exhibited shorted trace characteristics and could not be interpreted accurately. They were therefore viewed as outliers. After eliminating the outliers, 397 data points remained in the database. This provided a good database for calibrating the models relating Ka with Vw%.

Klemunes' database also provided a good opportunity to evaluate the different methodologies used to compute the volumetric moisture content using the apparent dielectric constant of the mixture. In the study reported here, empirical models, three-phase models, and four-phase mixing models were evaluated using Klemunes' data base. It was found that the four-phase mixing model yielded slightly higher R^2 than the three-phase mixing model, but it often gave physically meaningless parameter estimates. Therefore, four-phase models were not considered in this study. The three-phase mixing models and empirical models yielded comparable accuracy. The three-phase mixing models require the knowledge of the dry density and specific gravity of the soil and sometimes give physically meaningless parameter estimates.

As a result, only empirical models were considered and proposed for use in this study. Four empirical models were developed in this study. They are discussed in detail in the following sections.

Third-Order Polynomial Ka Models

Figure 17 shows the computed dielectric constants versus laboratory determined volumetric moisture contents used in the model development database. As shown, values for coarse-grained soil show different characteristics compared with those of the fine-grained soil. Furthermore, they both follow approximately a third-order polynomial functional form within the inference range of the dielectric constant. As a result, data for coarse-grained soil and fine-grained soil were modeled separately in order to provide a more accurate model. The third-order polynomial function form was selected for both material types. Data for all soil types were also modeled together for the use of dielectric constant values that fell out of the inference range of the individual models.

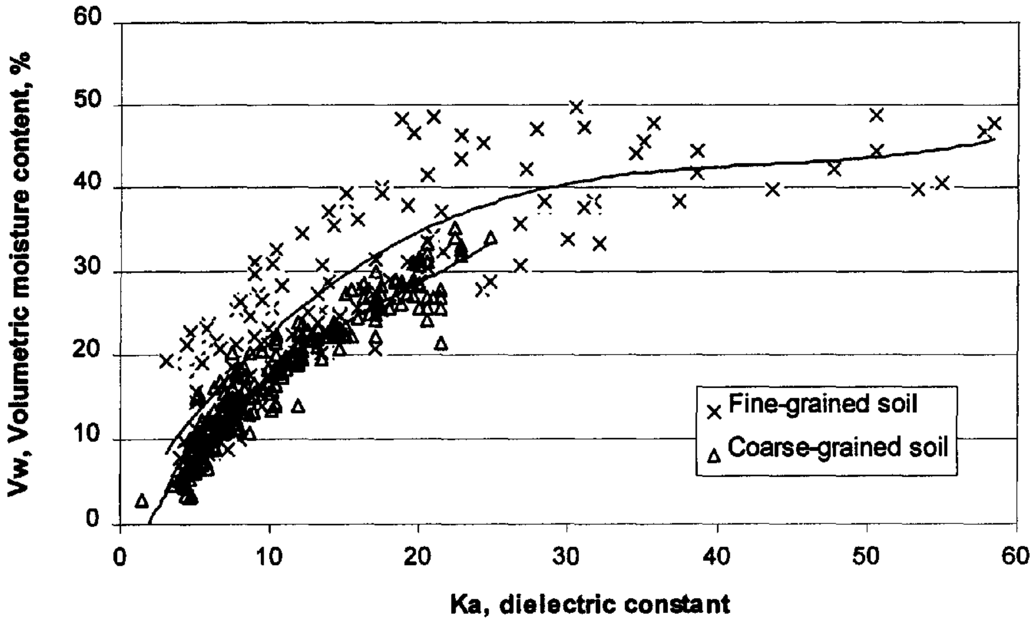


Figure 17. Volumetric moisture content versus dielectric constant data used in the model development.

It is important to recognize that the models presented here reflect only the dielectric constant range or the inference space that was used to develop the model. They are valid only for these conditions (as given in table 6) because there is no evidence that the models are appropriate outside the range of the existing data. Care must be exercised in extending these models beyond the conditions for which they were developed.

The empirical regression equations developed using only dielectric constant as independent variable in this study are given below:

$$Vw\% = a_0 + a_1 Ka + a_2 Ka^2 + a_3 Ka^3 \qquad (9)$$

where: a_0, a_1, a_2, a_3 = Regression coefficients as given in table 6.
Ka = Bulk dielectric constant.

Table 6. Volumetric moisture model parameter estimates and standard errors.

Model Type	a0	a1	a2	a3
Coarse-grained soil, N = 237, R^2 = 91%, Adjusted R^2 = 91%, Standard error of estimate (SEE) = 2.3, 1.5<Ka<24.8				
Coarse-Ka model	-5.7875	3.41763	-.13117	0.00231
Standard Error	1.5968	0.4588	0.03912	0.001011
Fine-grained soil, N=160, R^2=75%, Adjusted R^2 = 75%, SEE = 6.0, 3<Ka<58.4				
Fine-Ka model	0.4756	2.75634	-0.061667	0.000476
Standard Error	2.1725	0.3575	0.00476	0.000175
All soil, N=397, R^2=80%, Adjusted R^2 = 79%, SEE = 4.8, 1.5<Ka<58.4				
AllSoil-Ka model	-0.8120	2.38682	-0.04427	0.000292
Standard Error	1.1107	0.19875	0.009292	0.000114

Figures 18 through 20 compare the actual volumetric moisture contents with the predicted volumetric moisture contents for the third-order polynomial models developed for the coarse-grained soil, the fine-grained soil, and all soils combined. As shown, the fine-grained soil data exhibit more scatter than the coarse-grained soil data. The fine-grained model has a lower R^2. Figures 21 through 23 plot the raw residual distribution for all three models. Again, the fine-grained model residuals deviate most from the normal distribution. Figure 24 shows all three polynomial models together with Topp's model. Within their inference range, the models are reasonably close to each other.

Gradation Models

It was suggested by the LTPP Data Analysis Expert Task Group that gradation parameters, plastic limit, and liquid limit be included as independent variables for the regression models. These variables were selected because they are intrinsic material properties that significantly affect the soil behavior, especially for fine-grained soil. This was an attempt to refine the regression model and to increase the R^2 of the model. The following gradation parameters and Atterberg limits were considered in developing the gradation moisture content models:

G11_2	Percent passing 1½-in sieve
G1	Percent passing 1-in sieve
G3_4	Percent passing ¾-in sieve
G1_2	Percent passing ½-in sieve
G3_8	Percent passing ⅜-in sieve
No4	Percent passing No. 4 sieve
No10	Percent passing No. 10 sieve

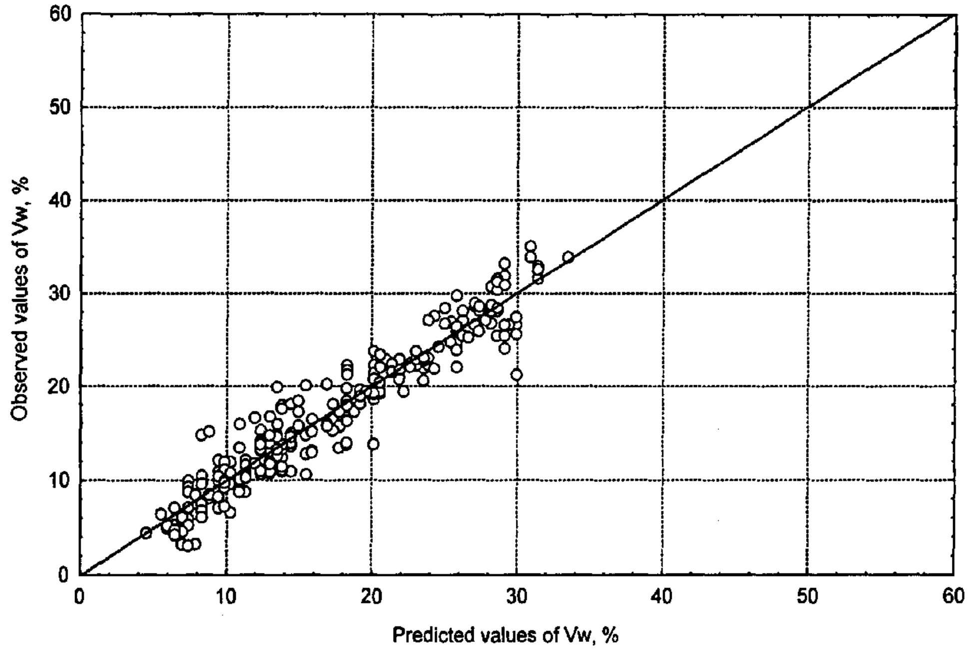


Figure 18. Predicted versus observed volumetric moisture content for coarse-grained soil Ka model.

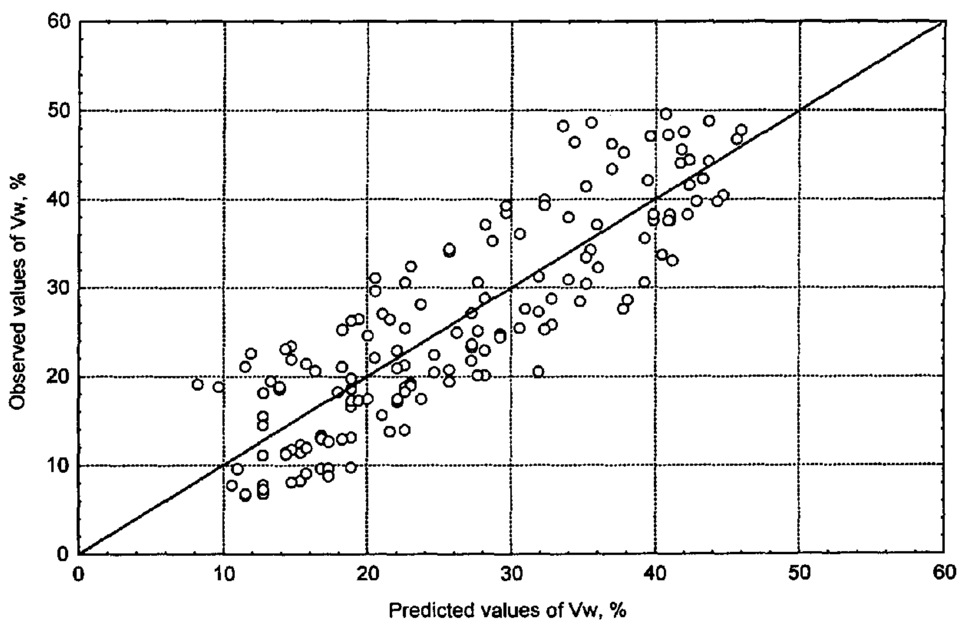


Figure 19. Predicted versus observed volumetric moisture content for fine-grained soil Ka model.

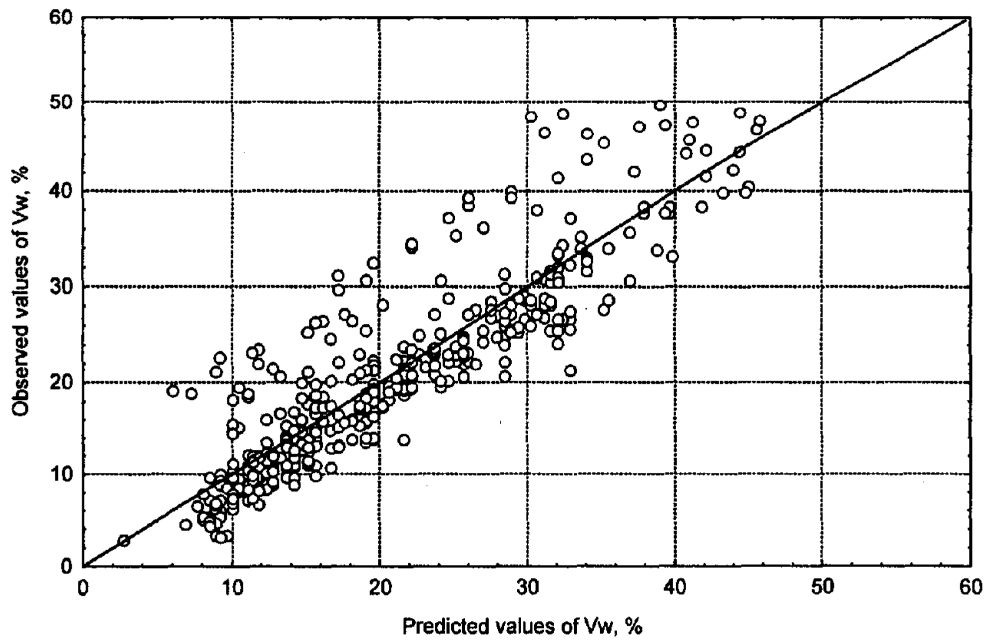


Figure 20. Predicted versus observed volumetric moisture content for AllSoil-Ka model.

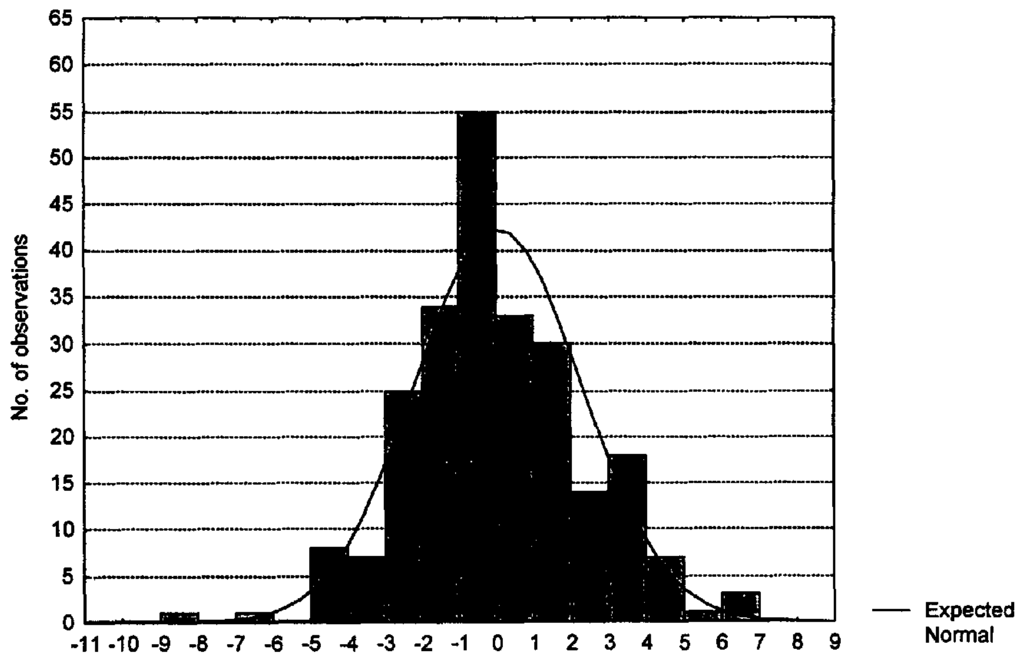


Figure 21. Raw residual distribution for Coarse-Ka model.

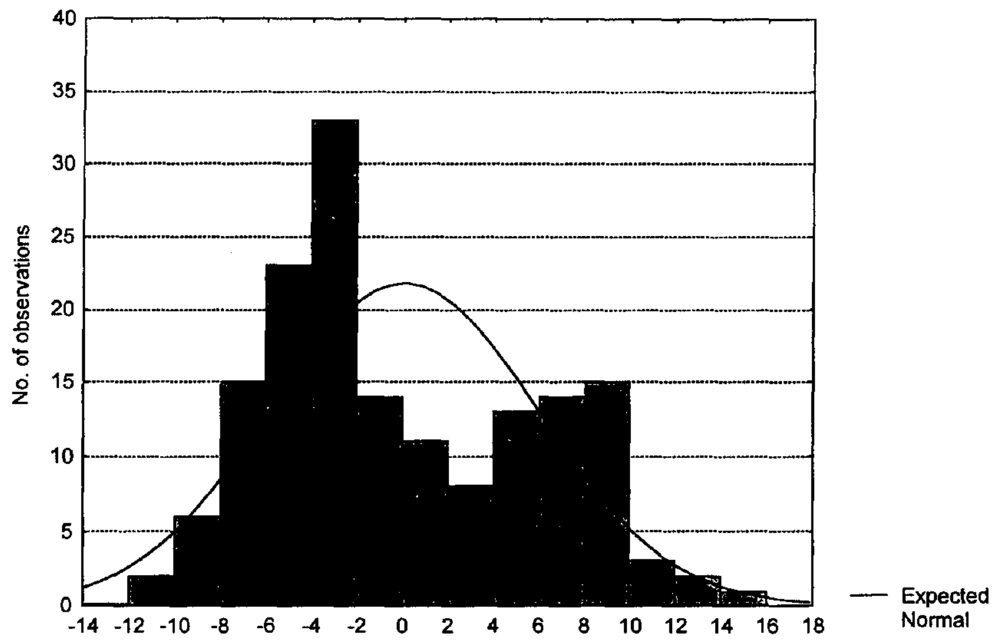


Figure 22. Residual distribution for Fine-Ka model.

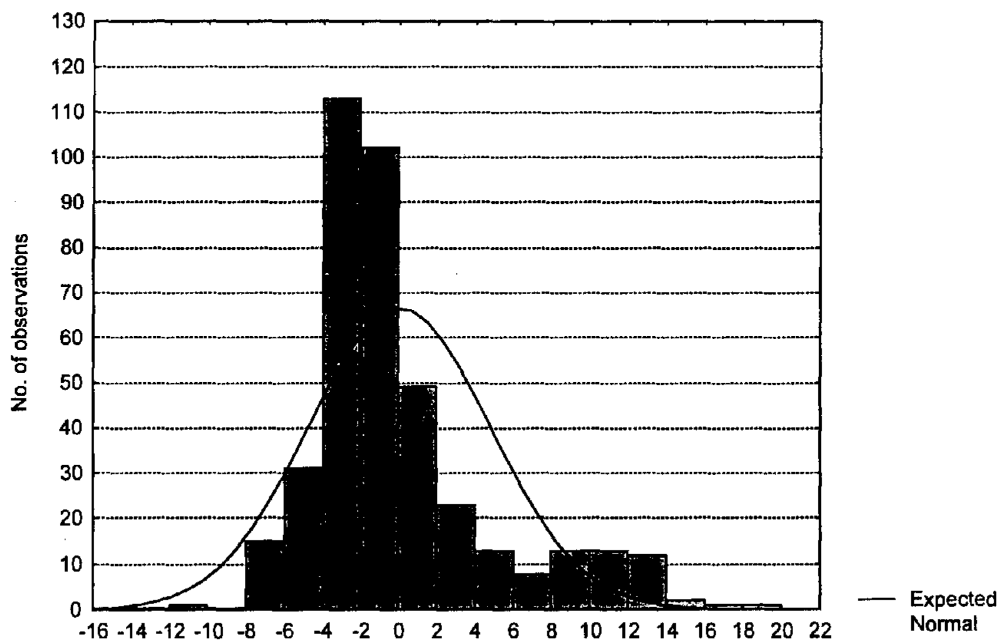


Figure 23. Residual distribution of the AllSoil-Ka model.

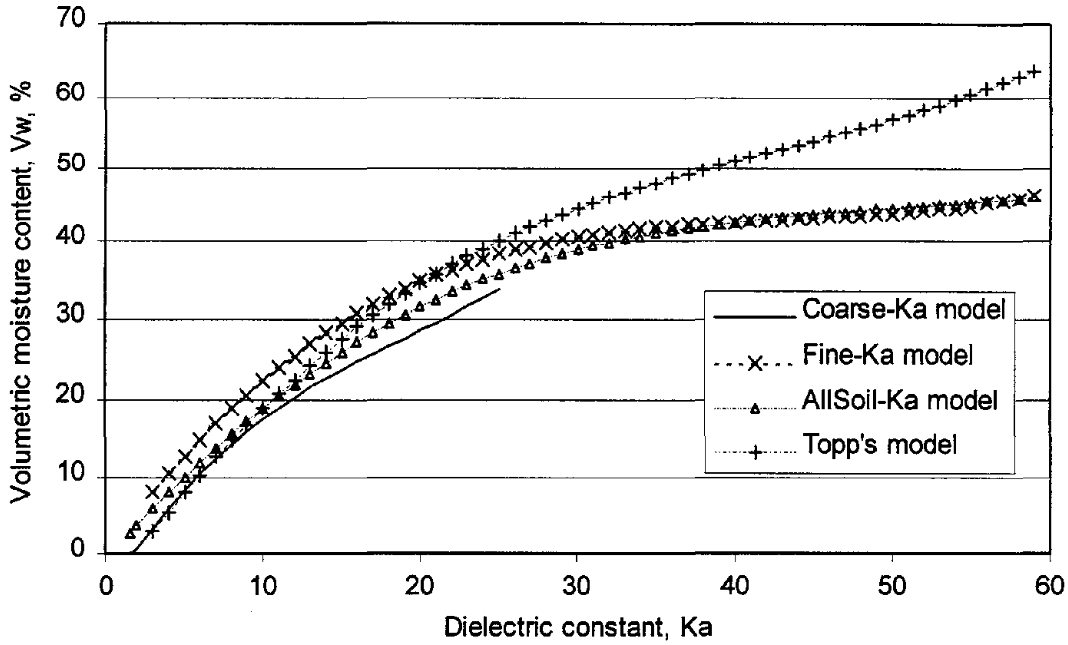


Figure 24. Comparison of various volumetric moisture content models.

No40	Percent passing No. 200 sieve
No80	Percent passing No. 200 sieve
No200	Percent passing No. 200 sieve
PL	Plastic limit
LL	Liquid limit

For this large number of independent variables, many potential models could be developed that are based on linear combinations of independent variables and an infinite number of nonlinear combinations. Step-wise regression is a procedure to search quickly through a number of these potential models to give a statistically most significant model. This procedure employs a series of t-tests to check the significance of explanatory variables entered into, or deleted from, the model. The forward step-wise procedure adds one variable at a time without trying to delete variables. At each regression analysis step, a variable is added and the absolute value of the variable's t-ratio is computed. To enter the model, the t-ratio of the variable must exceed a prespecified t-value (e.g., 2.0). The forward step-wise method was used to pick the significant variables and the final functional form. The Software package Statistica® was used to perform the modeling [14].

Comparison of the R-squares and standard error estimates for the "gradation" based models and those of the dielectric constant only models are provided in table 7.

Table 7. Comparison of the R^2 and SEE of the gradation and Ka volumetric moisture content models.

Soil Type	Model Type	No. of Independent Variables	R-Square, %	Standard Error of Estimate (SEE), %
Coarse-grained	Ka only	1	91	2.3
	Gradation	6	94	1.9
Fine-grained	Ka only	1	75	6.0
	Gradation	8	92	3.5
All soil	Ka only	1	79	4.8
	Gradation	9	86	4.0

As shown in table 7, the improvements in R^2 for the coarse-grained material, fine-grained material, and all types of soil were 3 percent, 7 percent, and 16 percent, respectively. Only the R^2 of the fine-grain model with gradation parameters increased significantly. Note that each additional independent variable introduced brings measurement error of that variable into the model. Furthermore, the inference space of the model is reduced by the inference range brought in by each additional variable. For these reasons, the gradation models for coarse-grained material and all soils were not adopted for this study.

The following is the volumetric moisture content model for fine-grained soil with gradation parameters, developed using Klemunes' data base:

$$Vw = a0 + a1Ka + a2Ka^2 + a3\,Ka^3 + a4G11\_2 + a5G1\_2 + a6\,No4 + a7No10 + a8\,No200 + a9\,PL + a10\,LL \qquad (10)$$

R^2	=	92%
Adjusted R^2	=	92%
SEE	=	3.45
N	=	160

where: *a0, a1, ..., a10* = Regression coefficients, as defined in table 8.
Ka = Bulk dielectric constant.

The description and values of the independent variables, as well as the inference ranges of all the variables, are given in table 8. It should be noted again that this empirical model applies only within the inference region of all the variables.

The R^2 for the model was greatly improved by introducing gradation parameters, plastic limit, and liquid limit (from 75 percent to 92 percent). Figure 25 shows the predicted versus actual volumetric moisture contents used to develop the model. The raw residual distribution is given in figure 26. As shown, compared with the fine-grain Ka model, the fine-grain gradation model has less scatter distribution of the predicted versus actual volumetric moisture content plot, and the raw residual distribution is closer to a normal distribution. This model was used for computing the volumetric moisture content for the fine-grained soils where gradation and other parameters were available and were within the inference region of the model.

Table 8. Coefficient estimates and standard errors for the fine-grained model with gradation and other parameters (Fine-Gradation model).

Variables	Description	Coef.	Value	Std. Error	Inference Range
Intercept		a0	1761.78	201.83	
Ka	Dielectric constant	a1	2.9145	0.2168	3-58.4
Ka^2		a2	-0.07674	0.00921	
Ka^3		a3	0.000722	0.000108	
G11_2	Percent passing 1½-in sieve	a4	-19.6649	2.1168	99-100
G1_2	Percent passing ½-in sieve	a5	4.3667	0.5994	97-100
No4	Percent passing No. 4 sieve	a6	5.1516	0.4638	90-100
No10	Percent passing No. 10 sieve	a7	2.7737	0.3182	84-100
No200	Percent passing No. 200 sieve	a8	0.06057	0.02445	12.6-94.6
PL	Plastic limit	a9	-0.2057	0.05371	0-45
LL	Liquid limit	a10	0.10231	0.03743	0-69

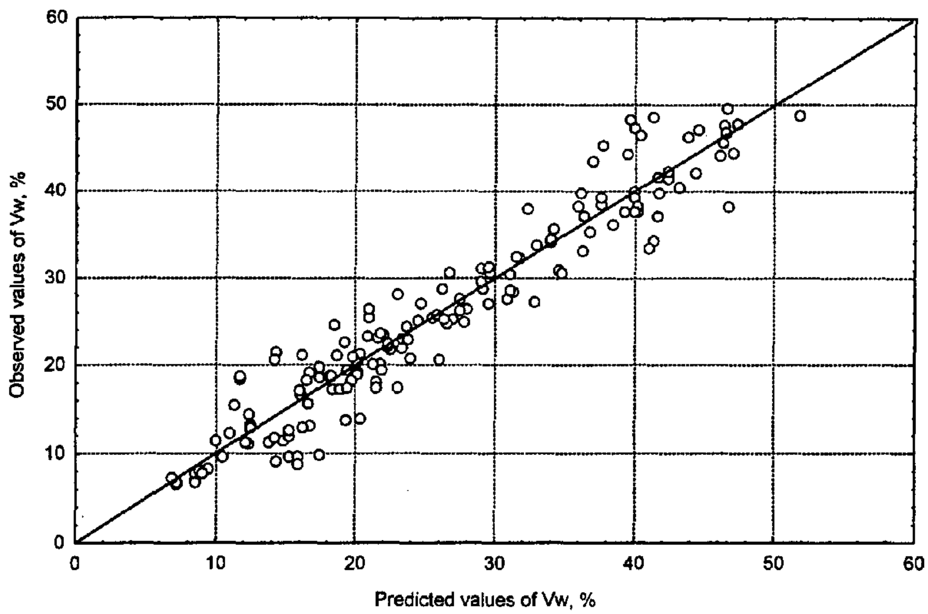


Figure 25. Predicted versus observed volumetric moisture content for fine-grained soil gradation model.

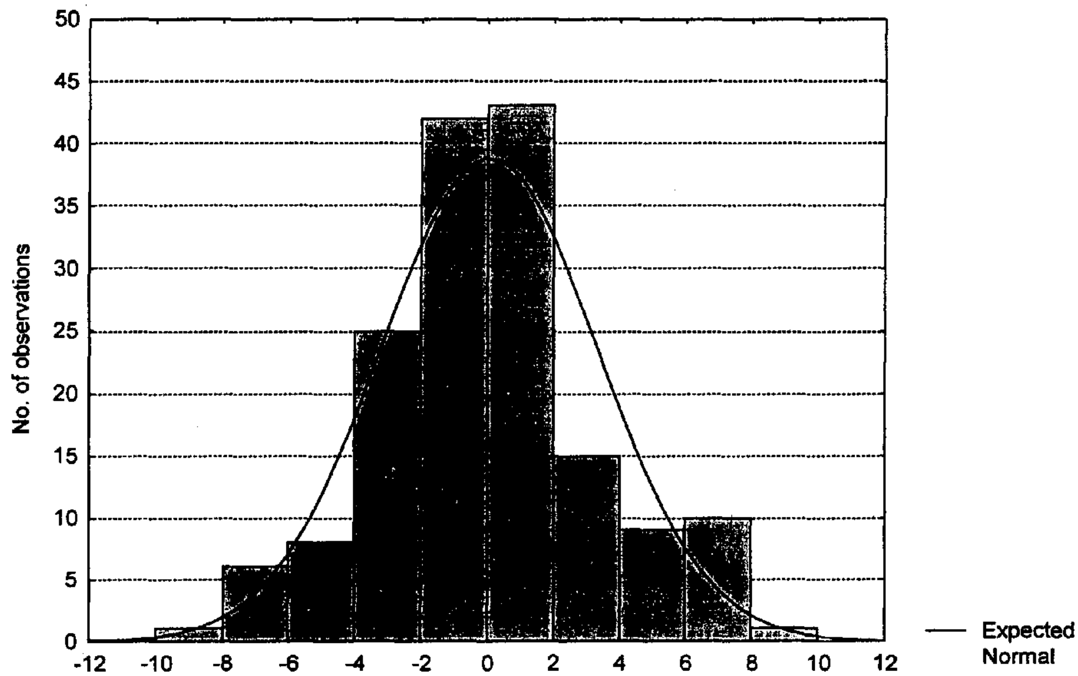


Figure 26. Raw residual distribution of the Fine-Gradation model.

A complete list of the soil properties for the soil samples used in the model development is given in appendix C. Frequency distributions of all the independent variables used in the model are provided in figures 27 through 35.

Vw Model Selection Scheme

The following scheme was used for calculation of the volumetric moisture content.

1. If Ka < 1.5 or Ka > 58.4, check the original TDR waveform and make sure the results are reasonable. These outlier values should exist very rarely, if at all. If these values exist, the data are flagged and reviewed.

2. For coarse-grained soils
   - If 1.5 < Ka < 24.8, then use the coarse-grained soil volumetric moisture content empirical model with only Ka as the independent variable (coarse-grain Ka model).
   - If Ka > 24.8, use the all-soil volumetric moisture content model with only Ka as the independent variable (AllSoil-Ka model).

3. For fine-grained soils
   - For observations with 3 < Ka < 58.4 and gradation, plastic limit, and liquid limit values within the inference ranges of those used in the model development (fine-grain gradation model), use this model to calculate the volumetric moisture content.
   - For sections with 3 < Ka < 58.4 and not satisfying the above criteria, use the fine-grained soil volumetric moisture model using only Ka as the independent variable (fine-grain Ka model).
   - For sections with Ka < 3, use the all-soil volumetric moisture content model with only Ka as the independent variable (AllSoil-Ka model). This should occur very rarely.

Figure 36 illustrates the model selection scheme. There are slight jumps among the models. The jumps are considerably less than the error limits, and hence are considered acceptable.

Computation of the Gravimetric Moisture Content

Once the volumetric moisture content is determined, the gravimetric moisture content can be calculated using the following equation:

$$GVw = \gamma_w/\gamma_d * Vw\% \quad (11)$$

where: γ_w = 9.81 KN/m^3, unit weight of water.
γ_d = Dry unit weight of the soil.

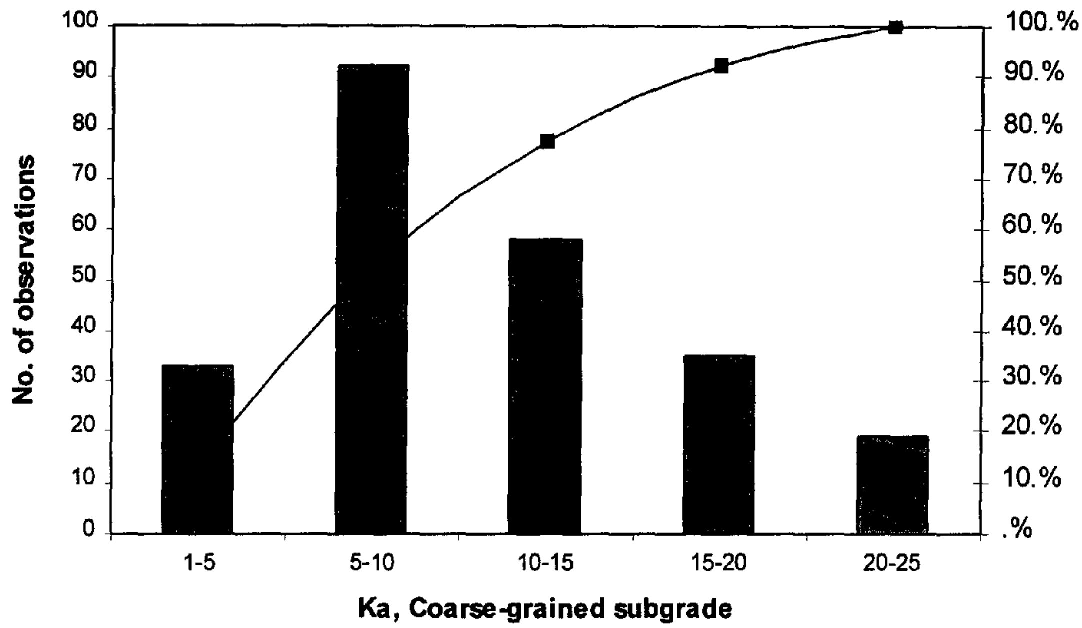


Figure 27. Frequency distribution of the dielectric constant for coarse-grained soils used in the model development.

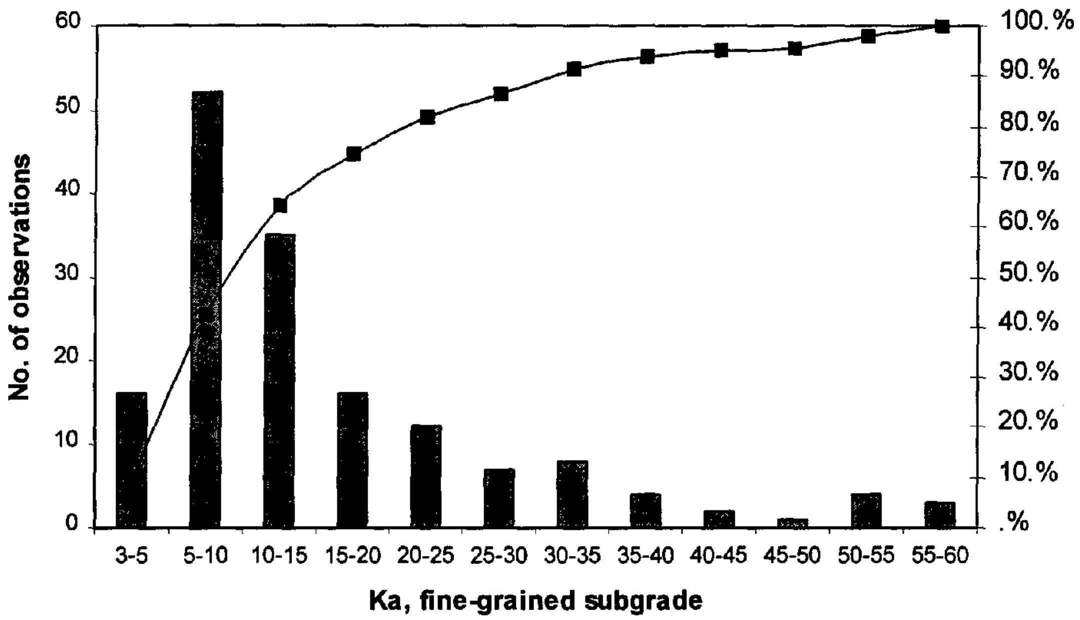


Figure 28. Frequency distribution of the dielectric constant for fine-grained soils used in the model development.

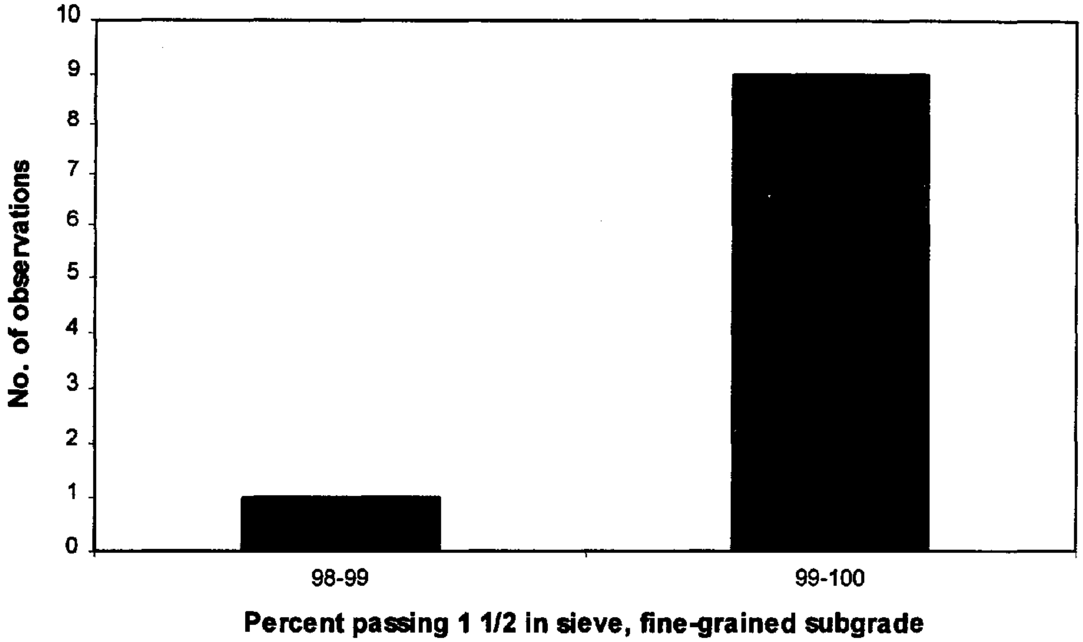


Figure 29. Frequency distribution of percent passing the 1½-in sieve for the fine-grained soils used in the model development.

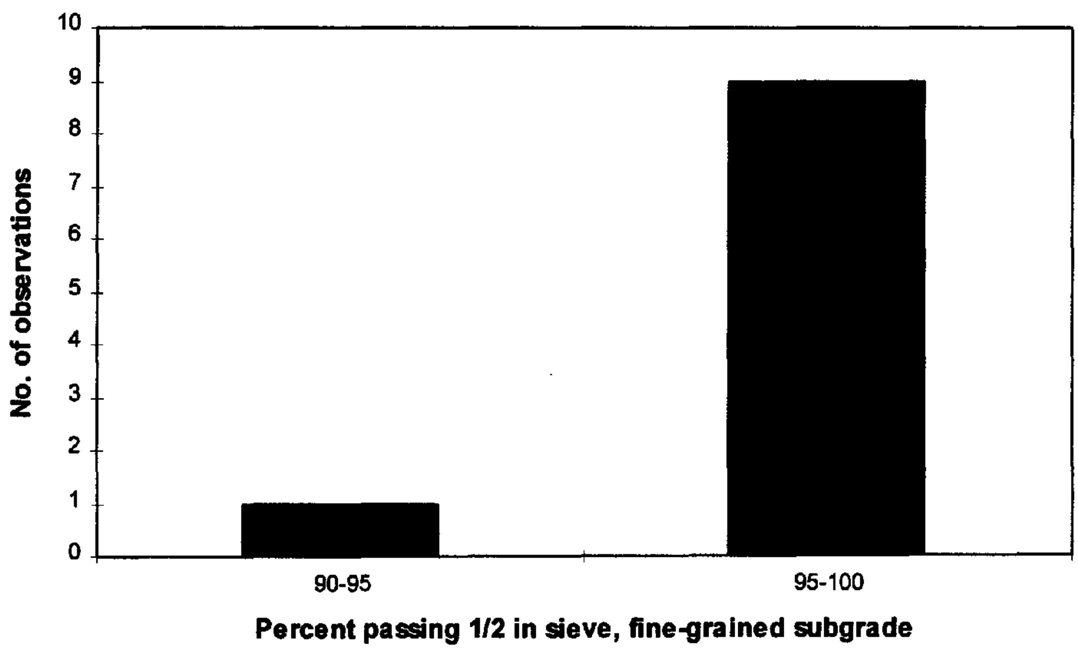


Figure 30. Frequency distribution of percent passing the ½-in sieve for the fine-grained soils used in the model development.

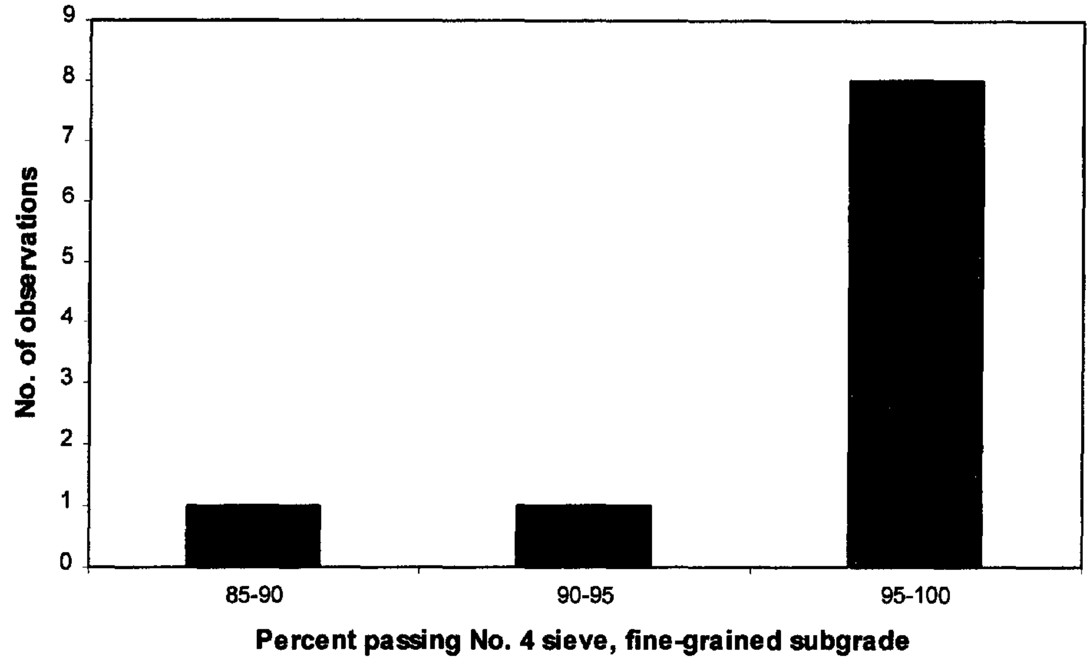


Figure 31. Frequency distribution of percent passing the No. 4 sieve for the fine-grained soils used in the model development.

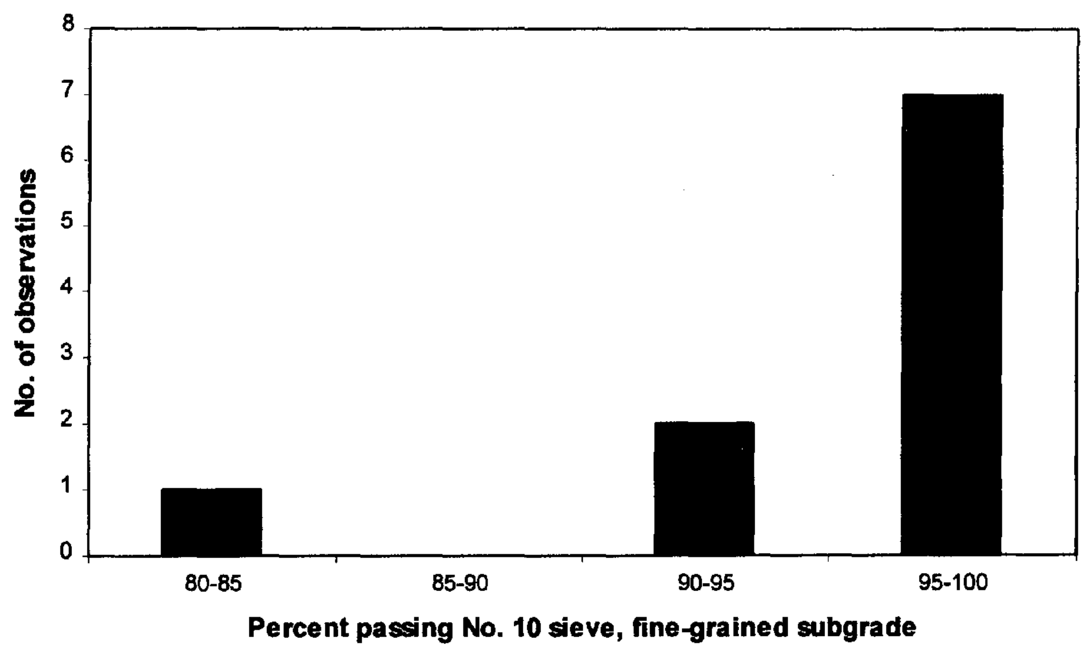


Figure 32. Frequency distribution of percent passing the No. 10 sieve for the fine-grained soils used in the model development.

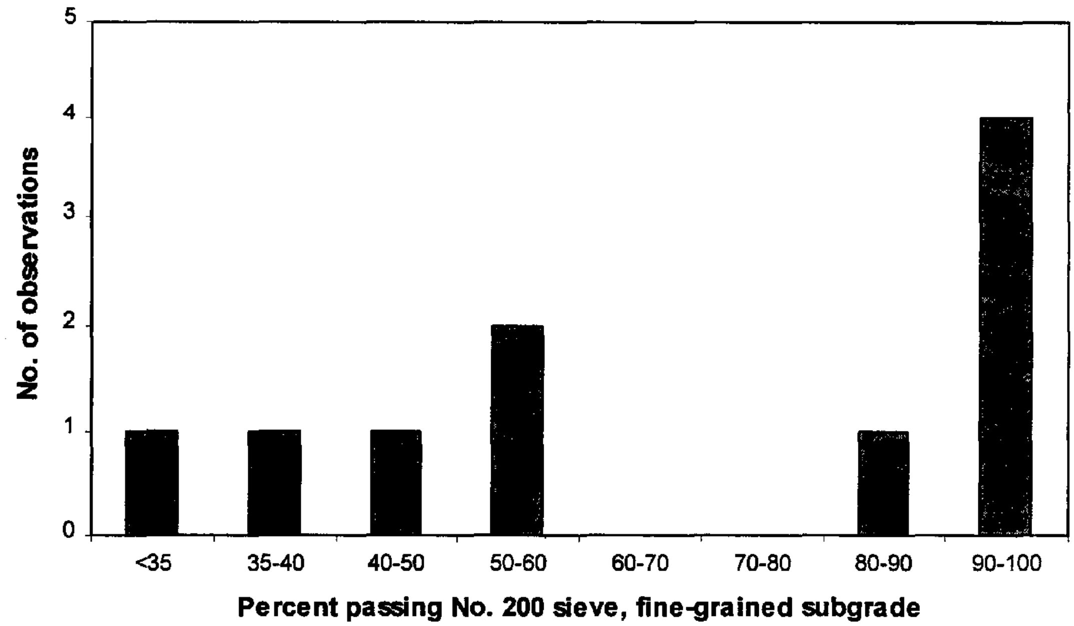


Figure 33. Frequency distribution of percent passing the No. 200 sieve for the fine-grained soils used in the model development.

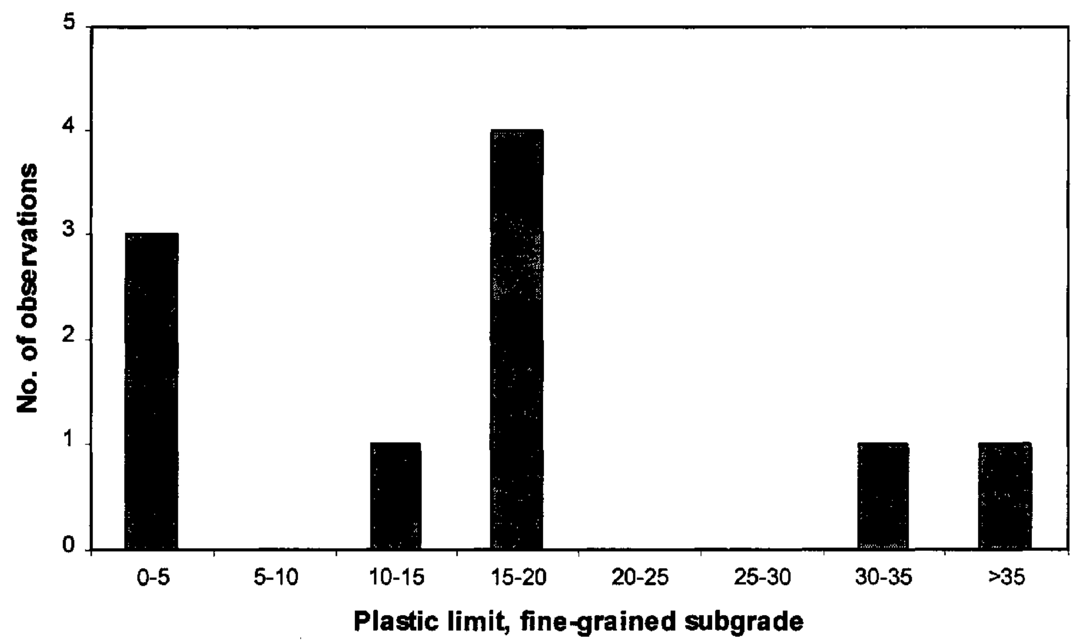


Figure 34. Frequency distribution of plastic limit for the fine-grained soils used in the model development.

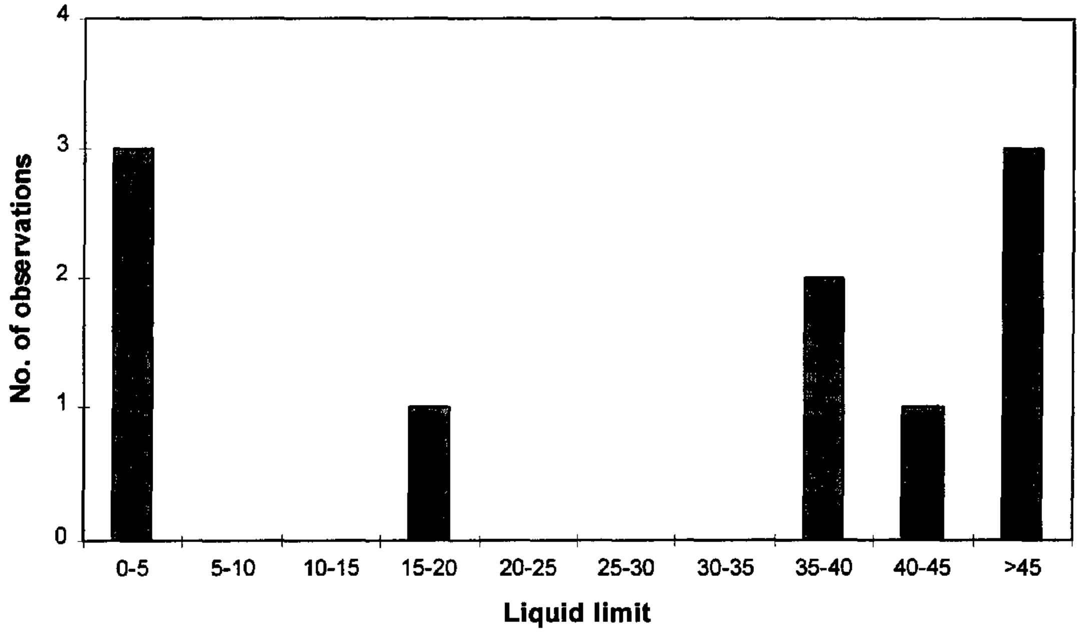


Figure 35. Frequency distribution of liquid limit for the fine-grained soils used in the model development.

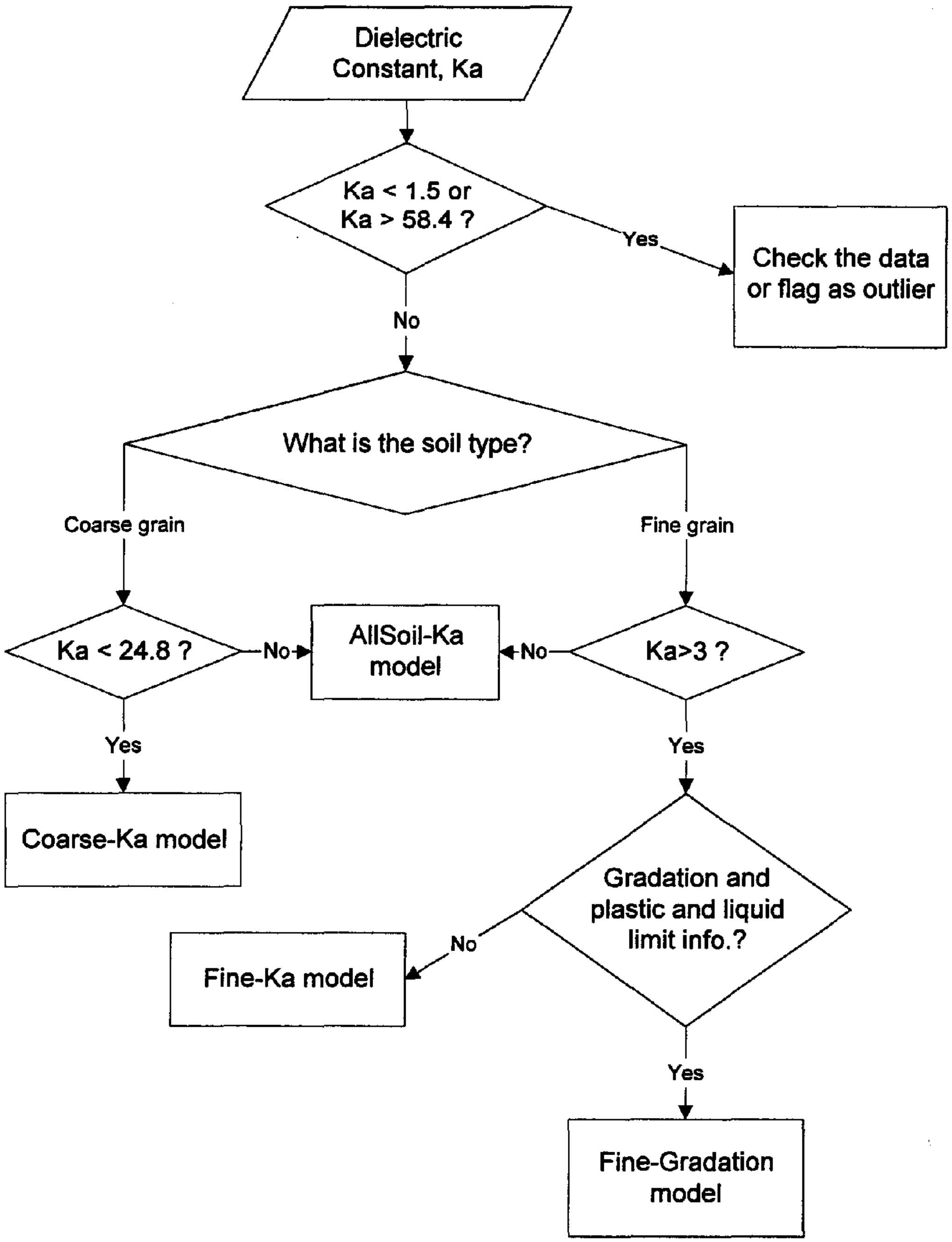


Figure 36. Flow chart for selecting appropriate model for computing volumetric moisture content.

Error Estimate of the Computed Volumetric Moisture Content

As presented previously, four models were developed to compute the volumetric moisture contents: Coarse-Ka, Fine-Ka, AllSoil-Ka, and Fine-Gradation. The first three models are third-order polynomial models with only dielectric constant as an independent variable. The Fine-Gradation model has gradation parameters as additional independent variables. The following sections discuss the error estimate of the computed volumetric moisture content.

Third-Order Polynomial Ka Models

The third-order polynomial Ka models are given in the following general equation:

$$Vw = a0 + a1 * Ka + a2 * Ka^2 + a3 * Ka^3 \quad (12)$$

where: a_0, a_1, a_2, a_3 = Regression coefficients, as given in table 6.
Ka = Bulk dielectric constant.

For prediction or estimate of Vw* for a given Ka*:

$$Vw^* = a0 + a1 * Ka^* + a2 * Ka^{*2} + a3 * Ka^{*3} \quad (13)$$

The prediction interval of Vw is then given as [15]:

$$Vw^* \pm (t\text{-}value)\ se(pred) \quad (14)$$

where: *t-value* = t-value at a given confidence level, typically 95 percent, for degrees of freedom of n-(k+1), where k is the number of the independent variables.
se(pred) = Standard error of the prediction, as defined below.

For most degrees of freedom of the model and independent variables, the t-value for 95 percent confidence is approximately 2.0. Therefore, a t-value of 2.0 is used as the approximate t-value of the prediction interval at a 95 percent confidence level.

It can be shown that for a linear regression model [15]:

$$se(pred) = s(1+x^{*\prime}(X'X)^{-1}x^*)^{1/2} \quad (15)$$

where: $x^{*\prime} = (1, x^*_1, x^*_2, ..., x^*_k)$

$$\begin{bmatrix} 1 & x_{11} & x_{12} & . & . & . & x_{1k} \\ 1 & x_{21} & x_{22} & . & . & . & x_{2k} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ 1 & x_{n-1,1} & x_{n-1,2} & . & . & . & x_{n-1,k} \\ 1 & x_{n1} & x_{n2} & . & . & . & x_{nk} \end{bmatrix}$$

For third-order polynomial models using Ka as an independent variable, then

k	=	3
x^*_1	=	Ka^*, $x^*_2 = Ka^{*2}$, $x^*_3 = Ka^{*3}$
x_{i1}	=	Ka_i, ith observation of Ka used in the model development
x_{i2}	=	Ka_i^2
x_{i3}	=	Ka_i^3
n	=	Total number of observations used in the model development

Assuming that the errors from the regression model and the dielectric constant are independent, the following equation then applies to the computation of the estimated error of the computed volumetric moisture content [16]:

$$\Delta Vw = \sqrt{[Error\ from\ regression\ model]^2 + \left[Error\ from\ independent\ variable\ \left(\frac{\partial Vw}{\partial Ka}\ \Delta Ka\right)\right]^2} \quad (16)$$

Substituting the prediction error term and performing the partial derivative:

$$\Delta Vw = \sqrt{[2 * se(pred)]^2 + [(a1 + 2*a2*Ka + 3*a3*Ka^2\ \Delta Ka)]^2} \quad (17)$$

Table 9 provides an example of computed volumetric moisture contents and estimated error limits for the dielectric constants within the inference range of all three empirical models discussed above.

Fine-Gradation Model

The Fine-Gradation model takes the following functional form:

$$Vw = a0 + a1Ka + a2Ka^2 + a3\ Ka^3 + a4G11\_2 + a5G1\_2 + a6\ No4 + a7No10 + a8\ No200 + a9\ PL + a10\ LL \quad (18)$$

Table 9. Computed volumetric moisture contents and estimated error limits for empirical Ka models.

Ka	Coarse-Ka model		Fine-Ka model		AllSoil-Ka model	
	Vw, %	Est. Error, %	Vw, %	Est. Error, %	Vw, %	Est. Error, %
1.5	0.0	5.1			2.7	9.8
2	0.5	4.9			3.8	9.7
3	3.3	4.8	8.2	12.2	6.0	9.7
4	5.9	4.7	10.5	12.1	8.0	9.7
5	8.3	4.7	12.8	12.1	10.1	9.7
6	10.5	4.7	14.9	12.0	12.0	9.6
7	12.5	4.7	16.9	12.0	13.8	9.6
8	14.3	4.7	18.8	12.0	15.6	9.6
9	16.0	4.7	20.6	12.0	17.3	9.6
10	17.6	4.7	22.3	12.0	18.9	9.6
11	19.0	4.7	24.0	12.0	20.5	9.6
12	20.3	4.7	25.5	12.0	22.0	9.6
13	21.5	4.7	26.9	12.0	23.4	9.7
14	22.7	4.7	28.3	12.0	24.7	9.7
15	23.8	4.7	29.6	12.0	26.0	9.7
16	24.8	4.7	30.7	12.0	27.2	9.7
17	25.8	4.7	31.9	12.0	28.4	9.7
18	26.7	4.7	32.9	12.0	29.5	9.7
19	27.6	4.7	33.8	12.0	30.6	9.7
20	28.6	4.7	34.7	12.0	31.6	9.7
21	29.5	4.7	35.6	12.0	32.5	9.7
22	30.5	4.8	36.3	12.0	33.4	9.7
23	31.5	4.9	37.0	12.0	34.2	9.7
24	32.6	5.1	37.7	12.0	35.0	9.7
25	33.8	5.4	38.3	12.0	35.8	9.7
26			38.8	12.1	36.5	9.7
27			39.3	12.1	37.1	9.7
28			39.8	12.1	37.7	9.7
29			40.2	12.1	38.3	9.7
30			40.5	12.1	38.8	9.7
32			41.1	12.1	39.3	9.8
34			41.6	12.2	39.8	9.8
36			42.0	12.2	40.2	9.8
38			42.3	12.3	40.6	9.8
40			42.5	12.3	41.0	9.8
42			42.7	12.3	41.4	9.8
44			42.9	12.3	41.7	9.8
46			43.1	12.4	42.0	9.9
48			43.3	12.4	42.3	9.9
50			43.6	12.4	42.5	9.9
52			44.0	12.4	42.8	9.9
54			44.4	12.5	43.0	9.9
56			45.0	12.8	43.2	9.9
58			45.8	13.2	43.4	9.9
59			46.2	13.5	43.4	9.9

where: $a0, a1, ..., a10$ = Regression coefficients, as defined in table 7.
Ka = Bulk dielectric constant.

Following the same logic as in the third-order polynomial models, the following equation applies for the estimate of the associated error of the volumetric moisture content:

$$\Delta Vw = \sqrt{[Error\ from\ regression\ model]^2 + [Error\ from\ independent\ variables]^2} \tag{19}$$

that is,

$$\Delta Vw = 2 * se(pred) + \frac{\partial Vw}{\partial Ka}\Delta Ka + \frac{\partial Vw}{\partial G11_2} + \frac{\partial Vw}{\partial G1_2}\Delta G1_2 + \frac{\partial Vw}{\partial No4}\Delta No4 + \frac{\partial Vw}{\partial No10}\Delta No10 + \frac{\partial Vw}{\partial No200}\Delta No200 + \frac{\partial Vw}{\partial PL}\Delta PL + \frac{\partial Vw}{\partial LL}\Delta LL \tag{20}$$

The measurement errors for the gradation parameters are omitted for several reasons. First, the precision and bias are not defined for the percent passing each sieve in the ASTM standard D 422 [19]. Second, many of the gradation values used for SMP subgrade soil are the average of two or even three measurements. Substituting ΔKa = 0.5 La, as shown previously in chapter 2, and performing partial derivatives:

$$\Delta Vw = \sqrt{[2 * se(pred)]^2 + [(a1 + 2*a2*Ka + 3*a3*Ka^2\ \Delta Ka)]^2} \tag{21}$$

where: $se(pred) = s(1+x^{*\prime}(X'X)^{-1}x^*)^{1/2}$

and $x^{*\prime} = (1, x^*_1, x^*_2, ..., x^*_k)$

$$\begin{vmatrix} 1 & x_{11} & x_{12} & . & . & . & x_{1k} \\ 1 & x_{21} & x_{22} & . & . & . & x_{2k} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ 1 & x_{n-1,1} & x_{n-1,2} & . & . & . & x_{n-1,k} \\ 1 & x_{n1} & x_{n2} & . & . & . & x_{nk} \end{vmatrix}$$

For the fine-grain gradation model:

k = 10
x^*_1 = Ka^*
x^*_2 = Ka^{*2}
x^*_3 = Ka^{*3}

x^*_3 = Ka^{*3}
x^*_4 = G11_2*
x^*_5 = G1_2*
x^*_6 = No4*
x^*_7 = No10*
x^*_8 = No200*
x^*_9 = PL*
x^*_{10} = LL*
x_{i1} = Ka_i, ith observation of Ka used in the model development
x_{i2} = Ka_i^2
x_{i3} = Ka_i^3
x_{i4} = $G11\_2_i$
x_{i5} = $G1\_2_i$
x_{i6} = $No4_i$
x_{i7} = $No10_i$
x_{i8} = $No200_i$
x_{i9} = PL_i
x_{i10} = LL_i
n = Total number of observations used in the model development

It was considered impractical to vary all eight independent variables within their inference ranges and provide a comprehensive list of estimated errors for all the possible values of predicted volumetric moisture contents. Therefore, only the sensitivity analysis of the error estimates as a function of the key variable, dielectric constant over its whole inference range, is provided. The estimated error limits are provided in tables 10, 11, and 12, in which the gradation parameters and plastic and liquid limits were set to their minimum values, their mean values, and their maximum values, for which the fine-grain model was developed, respectively. It is seen that the error estimates are not significantly affected by the ranges in values used for the gradation parameters and the plastic and liquid limits.

Error Estimate for Computed Gravimetric Moisture Content

As shown before, gravimetric moisture content, Gw, is determined by the following equation:

$$Gw = \frac{\gamma_w}{\gamma_d} Vw \qquad (22)$$

where: γ_w = 9.81 N/cm^3, unit weight of water.
γ_d = Dry unit weight of the soil, = 9.81 ρ_d.
Where ρ_d is the dry density of the soil, g/cm^3.

Substituting the above values into the equation, we have

$$Gw = \frac{Vw}{\rho_d} \qquad (23)$$

Table 10. Computed volumetric moisture contents and estimated error limits for Fine-Gradation model with gradation parameters set at their minimum model values.

Ka	G11_2	G1_2	NO4	NO10	NO200	PL	LL	Vw%	Est. Error, %
3	99	97	90	84	12.6	0	0	16.7	7.2
4	99	97	90	84	12.6	0	0	19.1	7.2
5	99	97	90	84	12.6	0	0	21.4	7.1
6	99	97	90	84	12.6	0	0	23.5	7.1
7	99	97	90	84	12.6	0	0	25.5	7.1
8	99	97	90	84	12.6	0	0	27.4	7.1
9	99	97	90	84	12.6	0	0	29.2	7.1
10	99	97	90	84	12.6	0	0	30.8	7.1
11	99	97	90	84	12.6	0	0	32.4	7.1
12	99	97	90	84	12.6	0	0	33.8	7.1
13	99	97	90	84	12.6	0	0	35.1	7.1
14	99	97	90	84	12.6	0	0	36.4	7.1
15	99	97	90	84	12.6	0	0	37.5	7.1
16	99	97	90	84	12.6	0	0	38.6	7.1
17	99	97	90	84	12.6	0	0	39.6	7.1
18	99	97	90	84	12.6	0	0	40.4	7.1
19	99	97	90	84	12.6	0	0	41.3	7.1
20	99	97	90	84	12.6	0	0	42.0	7.1
21	99	97	90	84	12.6	0	0	42.7	7.1
22	99	97	90	84	12.6	0	0	43.3	7.1
23	99	97	90	84	12.6	0	0	43.9	7.1
24	99	97	90	84	12.6	0	0	44.4	7.1
25	99	97	90	84	12.6	0	0	44.8	7.1
26	99	97	90	84	12.6	0	0	45.2	7.1
27	99	97	90	84	12.6	0	0	45.6	7.1
28	99	97	90	84	12.6	0	0	45.9	7.1
29	99	97	90	84	12.6	0	0	46.2	7.1
30	99	97	90	84	12.6	0	0	46.5	7.2
32	99	97	90	84	12.6	0	0	47.0	7.2
34	99	97	90	84	12.6	0	0	47.4	7.2
36	99	97	90	84	12.6	0	0	47.8	7.3
38	99	97	90	84	12.6	0	0	48.2	7.3
40	99	97	90	84	12.6	0	0	48.6	7.3
42	99	97	90	84	12.6	0	0	49.2	7.3
44	99	97	90	84	12.6	0	0	49.8	7.4
46	99	97	90	84	12.6	0	0	50.6	7.4
48	99	97	90	84	12.6	0	0	51.6	7.4
50	99	97	90	84	12.6	0	0	52.8	7.4
52	99	97	90	84	12.6	0	0	54.2	7.4
54	99	97	90	84	12.6	0	0	55.9	7.5
56	99	97	90	84	12.6	0	0	58.0	7.7
58	99	97	90	84	12.6	0	0	60.4	8.0
59	99	97	90	84	12.6	0	0	61.7	8.2

Table 11. Computed volumetric moisture contents and estimated error limits for Fine-Gradation model with gradation parameters set at their average model values.

Ka	G11_2	G1_2	NO4	NO10	NO200	PL	LL	Vw%	Est. Error, %
3	99.84	99.25	96.78	94.98	65.85	16.71	32.56	8.7	7.1
4	99.84	99.25	96.78	94.98	65.85	16.71	32.56	11.1	7.0
5	99.84	99.25	96.78	94.98	65.85	16.71	32.56	13.3	7.0
6	99.84	99.25	96.78	94.98	65.85	16.71	32.56	15.5	7.0
7	99.84	99.25	96.78	94.98	65.85	16.71	32.56	17.5	7.0
8	99.84	99.25	96.78	94.98	65.85	16.71	32.56	19.4	7.0
9	99.84	99.25	96.78	94.98	65.85	16.71	32.56	21.1	7.0
10	99.84	99.25	96.78	94.98	65.85	16.71	32.56	22.8	7.0
11	99.84	99.25	96.78	94.98	65.85	16.71	32.56	24.3	7.0
12	99.84	99.25	96.78	94.98	65.85	16.71	32.56	25.8	7.0
13	99.84	99.25	96.78	94.98	65.85	16.71	32.56	27.1	7.0
14	99.84	99.25	96.78	94.98	65.85	16.71	32.56	28.3	7.0
15	99.84	99.25	96.78	94.98	65.85	16.71	32.56	29.5	7.0
16	99.84	99.25	96.78	94.98	65.85	16.71	32.56	30.5	7.0
17	99.84	99.25	96.78	94.98	65.85	16.71	32.56	31.5	7.0
18	99.84	99.25	96.78	94.98	65.85	16.71	32.56	32.4	7.0
19	99.84	99.25	96.78	94.98	65.85	16.71	32.56	33.2	7.0
20	99.84	99.25	96.78	94.98	65.85	16.71	32.56	34.0	7.0
21	99.84	99.25	96.78	94.98	65.85	16.71	32.56	34.6	7.0
22	99.84	99.25	96.78	94.98	65.85	16.71	32.56	35.3	7.0
23	99.84	99.25	96.78	94.98	65.85	16.71	32.56	35.8	7.0
24	99.84	99.25	96.78	94.98	65.85	16.71	32.56	36.3	7.0
25	99.84	99.25	96.78	94.98	65.85	16.71	32.56	36.8	7.0
26	99.84	99.25	96.78	94.98	65.85	16.71	32.56	37.2	7.0
27	99.84	99.25	96.78	94.98	65.85	16.71	32.56	37.5	7.0
28	99.84	99.25	96.78	94.98	65.85	16.71	32.56	37.9	7.0
29	99.84	99.25	96.78	94.98	65.85	16.71	32.56	38.2	7.0
30	99.84	99.25	96.78	94.98	65.85	16.71	32.56	38.5	7.0
32	99.84	99.25	96.78	94.98	65.85	16.71	32.56	38.9	7.1
34	99.84	99.25	96.78	94.98	65.85	16.71	32.56	39.3	7.1
36	99.84	99.25	96.78	94.98	65.85	16.71	32.56	39.7	7.1
38	99.84	99.25	96.78	94.98	65.85	16.71	32.56	40.1	7.1
40	99.84	99.25	96.78	94.98	65.85	16.71	32.56	40.6	7.2
42	99.84	99.25	96.78	94.98	65.85	16.71	32.56	41.1	7.2
44	99.84	99.25	96.78	94.98	65.85	16.71	32.56	41.8	7.2
46	99.84	99.25	96.78	94.98	65.85	16.71	32.56	42.6	7.2
48	99.84	99.25	96.78	94.98	65.85	16.71	32.56	43.5	7.2
50	99.84	99.25	96.78	94.98	65.85	16.71	32.56	44.7	7.2
52	99.84	99.25	96.78	94.98	65.85	16.71	32.56	46.2	7.3
54	99.84	99.25	96.78	94.98	65.85	16.71	32.56	47.9	7.4
56	99.84	99.25	96.78	94.98	65.85	16.71	32.56	49.9	7.5
58	99.84	99.25	96.78	94.98	65.85	16.71	32.56	52.3	7.9
59	99.84	99.25	96.78	94.98	65.85	16.71	32.56	53.7	8.1

Table 12. Computed volumetric moisture contents and estimated error limits for Fine-Gradation model with gradation parameters set at their maximum model values.

Ka	G11_2	G1_2	NO4	NO10	NO200	PL	LL	Vw%	Est. Error, %
3	100	100	100	100	94.6	45	69	5.8	7.3
4	100	100	100	100	94.6	45	69	8.2	7.2
5	100	100	100	100	94.6	45	69	10.4	7.2
6	100	100	100	100	94.6	45	69	12.6	7.2
7	100	100	100	100	94.6	45	69	14.6	7.2
8	100	100	100	100	94.6	45	69	16.5	7.2
9	100	100	100	100	94.6	45	69	18.2	7.2
10	100	100	100	100	94.6	45	69	19.9	7.2
11	100	100	100	100	94.6	45	69	21.4	7.2
12	100	100	100	100	94.6	45	69	22.9	7.2
13	100	100	100	100	94.6	45	69	24.2	7.2
14	100	100	100	100	94.6	45	69	25.4	7.2
15	100	100	100	100	94.6	45	69	26.6	7.2
16	100	100	100	100	94.6	45	69	27.6	7.2
17	100	100	100	100	94.6	45	69	28.6	7.2
18	100	100	100	100	94.6	45	69	29.5	7.2
19	100	100	100	100	94.6	45	69	30.3	7.2
20	100	100	100	100	94.6	45	69	31.1	7.2
21	100	100	100	100	94.6	45	69	31.8	7.2
22	100	100	100	100	94.6	45	69	32.4	7.2
23	100	100	100	100	94.6	45	69	32.9	7.2
24	100	100	100	100	94.6	45	69	33.4	7.2
25	100	100	100	100	94.6	45	69	33.9	7.3
26	100	100	100	100	94.6	45	69	34.3	7.3
27	100	100	100	100	94.6	45	69	34.7	7.3
28	100	100	100	100	94.6	45	69	35.0	7.3
29	100	100	100	100	94.6	45	69	35.3	7.3
30	100	100	100	100	94.6	45	69	35.6	7.3
32	100	100	100	100	94.6	45	69	36.0	7.3
34	100	100	100	100	94.6	45	69	36.5	7.4
36	100	100	100	100	94.6	45	69	36.9	7.4
38	100	100	100	100	94.6	45	69	37.3	7.4
40	100	100	100	100	94.6	45	69	37.7	7.5
42	100	100	100	100	94.6	45	69	38.2	7.5
44	100	100	100	100	94.6	45	69	38.9	7.5
46	100	100	100	100	94.6	45	69	39.7	7.5
48	100	100	100	100	94.6	45	69	40.6	7.5
50	100	100	100	100	94.6	45	69	41.8	7.5
52	100	100	100	100	94.6	45	69	43.3	7.5
54	100	100	100	100	94.6	45	69	45.0	7.6
56	100	100	100	100	94.6	45	69	47.1	7.8
58	100	100	100	100	94.6	45	69	49.5	8.1
59	100	100	100	100	94.6	45	69	50.8	8.3

The error in Gw, ΔGw, is given as follows:

$$\Delta Gw = \sqrt{\left(\frac{\partial Gw}{\partial Vw}\,\Delta Vw\right)^2 + \left(\frac{\partial Gw}{\partial \rho_d}\,\Delta \rho_d\right)^2} \tag{24}$$

that is,

$$\Delta Gw = \sqrt{\left(\frac{1}{\rho_d}\,\Delta Vw\right)^2 + \left(\frac{Vw}{\rho_d^2}\,\Delta \rho_d\right)^2} \tag{25}$$

where: ΔVw = Error estimate of the computed volumetric moisture content.
$\Delta \rho_d$ = Error estimate of the assigned dry density value.

Only one dry density measurement is available at each SMP section for the subgrade soils at the SMP sites. Many factors can affect the accuracy of the assigned in-situ dry density at each TDR sensor depth. These factors include material variability with depth, laboratory measurement error of the dry densities, and dry density changes with temperature and moisture. Lack of information makes it impossible to identify the precision and bias of the in-situ dry density at each TDR depth. In this report, 10 percent of the assumed dry density was assigned as the error estimate of the in-situ dry density values.

For illustration purposes, a dry density of 1.90 g/cm^3 is used as an example to compute the error estimate of the computed gravimetric moisture content. This value is the global average of all the dry densities assigned to the TDR sensors at all SMP sections. Using 10 percent of the selected dry density value as the estimated error, then

$$\Delta Gw = \sqrt{\left(\frac{1}{1.9}\,\Delta Vw\right)^2 + \left(\frac{Vw}{1.9^2}\,0.19\right)^2} \tag{26}$$

or

$$\Delta Gw = \sqrt{\left(\frac{\Delta Vw}{1.9}\right)^2 + \left(\frac{Vw}{19}\right)^2} \tag{27}$$

Table 13 lists the computed values and estimated error limits for the computed gravimetric moisture contents for the Ka only models. Again for the Fine-Gradation model, it was considered impractical to vary all eight independent variables within their inference ranges and provide a comprehensive list of estimated errors for all the possible values of the estimated gravimetric moisture contents. Therefore, only the sensitivity analysis of the error estimates as a function of the key variable, dielectric constant over its whole inference range, is provided. The estimated error limits are provided in tables 14, 15, and 16, in which the gradation parameters and plastic and liquid limits were set to their minimum values, their mean values, and their

Table 13. Computed gravimetric moisture contents and estimated error limits for empirical Ka models.

	Coarse-Ka model		Fine-Ka model		AllSoil-Ka model	
Ka	**Vw, %**	**Est. Error, %**	**Vw, %**	**Est. Error, %**	**Vw, %**	**Est. Error, %**
1.5	0.0	2.7			1.4	5.1
2	0.3	2.6			2.0	5.1
3	1.8	2.5	4.3	6.4	3.1	5.1
4	3.1	2.5	5.5	6.4	4.2	5.1
5	4.4	2.5	6.7	6.4	5.3	5.1
6	5.5	2.5	7.8	6.4	6.3	5.1
7	6.6	2.5	8.9	6.4	7.3	5.1
8	7.5	2.6	9.9	6.4	8.2	5.1
9	8.4	2.6	10.9	6.4	9.1	5.2
10	9.3	2.6	11.8	6.4	10.0	5.2
11	10.0	2.7	12.6	6.4	10.8	5.2
12	10.7	2.7	13.4	6.5	11.6	5.2
13	11.3	2.7	14.2	6.5	12.3	5.2
14	11.9	2.7	14.9	6.5	13.0	5.2
15	12.5	2.8	15.6	6.5	13.7	5.3
16	13.0	2.8	16.2	6.5	14.3	5.3
17	13.6	2.8	16.8	6.5	14.9	5.3
18	14.1	2.8	17.3	6.6	15.5	5.3
19	14.5	2.9	17.8	6.6	16.1	5.3
20	15.0	2.9	18.3	6.6	16.6	5.3
21	15.5	2.9	18.7	6.6	17.1	5.4
22	16.1	3.0	19.1	6.6	17.6	5.4
23	16.6	3.1	19.5	6.6	18.0	5.4
24	17.2	3.2	19.8	6.6	18.4	5.4
25	17.8	3.3	20.1	6.7	18.8	5.4
26			20.4	6.7	19.2	5.4
27			20.7	6.7	19.5	5.5
28			20.9	6.7	19.9	5.5
29			21.1	6.7	20.2	5.5
30			21.3	6.7	20.4	5.5
32			21.6	6.7	20.7	5.5
34			21.9	6.8	20.9	5.6
36			22.1	6.8	21.2	5.6
38			22.3	6.8	21.4	5.6
40			22.4	6.9	21.6	5.6
42			22.5	6.9	21.8	5.6
44			22.6	6.9	21.9	5.6
46			22.7	6.9	22.1	5.6
48			22.8	6.9	22.2	5.6
50			23.0	6.9	22.4	5.7
52			23.2	6.9	22.5	5.7
54			23.4	7.0	22.6	5.7
56			23.7	7.1	22.7	5.7
58			24.1	7.3	22.8	5.7
59			24.3	7.5	22.9	5.7

Table 14. Computed gravimetric moisture contents and estimated error limits for Fine-Gradation model with gradation parameters set at their minimum model values.

Ka	G11_2	G1_2	NO4	NO10	NO200	PL	LL	Vw%	Est. Error, %
3	99	97	90	84	12.6	0	0	8.8	3.9
4	99	97	90	84	12.6	0	0	10.1	3.9
5	99	97	90	84	12.6	0	0	11.3	3.9
6	99	97	90	84	12.6	0	0	12.4	3.9
7	99	97	90	84	12.6	0	0	13.4	4.0
8	99	97	90	84	12.6	0	0	14.4	4.0
9	99	97	90	84	12.6	0	0	15.4	4.0
10	99	97	90	84	12.6	0	0	16.2	4.1
11	99	97	90	84	12.6	0	0	17.0	4.1
12	99	97	90	84	12.6	0	0	17.8	4.1
13	99	97	90	84	12.6	0	0	18.5	4.2
14	99	97	90	84	12.6	0	0	19.1	4.2
15	99	97	90	84	12.6	0	0	19.7	4.2
16	99	97	90	84	12.6	0	0	20.3	4.2
17	99	97	90	84	12.6	0	0	20.8	4.3
18	99	97	90	84	12.6	0	0	21.3	4.3
19	99	97	90	84	12.6	0	0	21.7	4.3
20	99	97	90	84	12.6	0	0	22.1	4.3
21	99	97	90	84	12.6	0	0	22.5	4.4
22	99	97	90	84	12.6	0	0	22.8	4.4
23	99	97	90	84	12.6	0	0	23.1	4.4
24	99	97	90	84	12.6	0	0	23.3	4.4
25	99	97	90	84	12.6	0	0	23.6	4.4
26	99	97	90	84	12.6	0	0	23.8	4.4
27	99	97	90	84	12.6	0	0	24.0	4.5
28	99	97	90	84	12.6	0	0	24.2	4.5
29	99	97	90	84	12.6	0	0	24.3	4.5
30	99	97	90	84	12.6	0	0	24.5	4.5
32	99	97	90	84	12.6	0	0	24.7	4.5
34	99	97	90	84	12.6	0	0	24.9	4.6
36	99	97	90	84	12.6	0	0	25.2	4.6
38	99	97	90	84	12.6	0	0	25.4	4.6
40	99	97	90	84	12.6	0	0	25.6	4.6
42	99	97	90	84	12.6	0	0	25.9	4.7
44	99	97	90	84	12.6	0	0	26.2	4.7
46	99	97	90	84	12.6	0	0	26.6	4.7
48	99	97	90	84	12.6	0	0	27.1	4.7
50	99	97	90	84	12.6	0	0	27.8	4.8
52	99	97	90	84	12.6	0	0	28.5	4.8
54	99	97	90	84	12.6	0	0	29.4	4.9
56	99	97	90	84	12.6	0	0	30.5	5.1
58	99	97	90	84	12.6	0	0	31.8	5.3
59	99	97	90	84	12.6	0	0	32.5	5.4

Table 15. Computed gravimetric moisture contents and estimated error limits for Fine-Gradation model with gradation parameters set at their average model values.

Ka	G11_2	G1_2	NO4	NO10	NO200	PL	LL	Vw%	Est. Error, %
3	99.84	99.25	96.78	94.98	65.85	16.71	32.56	4.6	3.8
4	99.84	99.25	96.78	94.98	65.85	16.71	32.56	5.8	3.8
5	99.84	99.25	96.78	94.98	65.85	16.71	32.56	7.0	3.8
6	99.84	99.25	96.78	94.98	65.85	16.71	32.56	8.1	3.8
7	99.84	99.25	96.78	94.98	65.85	16.71	32.56	9.2	3.8
8	99.84	99.25	96.78	94.98	65.85	16.71	32.56	10.2	3.8
9	99.84	99.25	96.78	94.98	65.85	16.71	32.56	11.1	3.8
10	99.84	99.25	96.78	94.98	65.85	16.71	32.56	12.0	3.8
11	99.84	99.25	96.78	94.98	65.85	16.71	32.56	12.8	3.9
12	99.84	99.25	96.78	94.98	65.85	16.71	32.56	13.6	3.9
13	99.84	99.25	96.78	94.98	65.85	16.71	32.56	14.3	3.9
14	99.84	99.25	96.78	94.98	65.85	16.71	32.56	14.9	4.0
15	99.84	99.25	96.78	94.98	65.85	16.71	32.56	15.5	4.0
16	99.84	99.25	96.78	94.98	65.85	16.71	32.56	16.1	4.0
17	99.84	99.25	96.78	94.98	65.85	16.71	32.56	16.6	4.0
18	99.84	99.25	96.78	94.98	65.85	16.71	32.56	17.1	4.0
19	99.84	99.25	96.78	94.98	65.85	16.71	32.56	17.5	4.1
20	99.84	99.25	96.78	94.98	65.85	16.71	32.56	17.9	4.1
21	99.84	99.25	96.78	94.98	65.85	16.71	32.56	18.2	4.1
22	99.84	99.25	96.78	94.98	65.85	16.71	32.56	18.6	4.1
23	99.84	99.25	96.78	94.98	65.85	16.71	32.56	18.8	4.1
24	99.84	99.25	96.78	94.98	65.85	16.71	32.56	19.1	4.1
25	99.84	99.25	96.78	94.98	65.85	16.71	32.56	19.4	4.2
26	99.84	99.25	96.78	94.98	65.85	16.71	32.56	19.6	4.2
27	99.84	99.25	96.78	94.98	65.85	16.71	32.56	19.8	4.2
28	99.84	99.25	96.78	94.98	65.85	16.71	32.56	19.9	4.2
29	99.84	99.25	96.78	94.98	65.85	16.71	32.56	20.1	4.2
30	99.84	99.25	96.78	94.98	65.85	16.71	32.56	20.2	4.2
32	99.84	99.25	96.78	94.98	65.85	16.71	32.56	20.5	4.2
34	99.84	99.25	96.78	94.98	65.85	16.71	32.56	20.7	4.3
36	99.84	99.25	96.78	94.98	65.85	16.71	32.56	20.9	4.3
38	99.84	99.25	96.78	94.98	65.85	16.71	32.56	21.1	4.3
40	99.84	99.25	96.78	94.98	65.85	16.71	32.56	21.4	4.3
42	99.84	99.25	96.78	94.98	65.85	16.71	32.56	21.6	4.4
44	99.84	99.25	96.78	94.98	65.85	16.71	32.56	22.0	4.4
46	99.84	99.25	96.78	94.98	65.85	16.71	32.56	22.4	4.4
48	99.84	99.25	96.78	94.98	65.85	16.71	32.56	22.9	4.4
50	99.84	99.25	96.78	94.98	65.85	16.71	32.56	23.5	4.5
52	99.84	99.25	96.78	94.98	65.85	16.71	32.56	24.3	4.5
54	99.84	99.25	96.78	94.98	65.85	16.71	32.56	25.2	4.6
56	99.84	99.25	96.78	94.98	65.85	16.71	32.56	26.3	4.8
58	99.84	99.25	96.78	94.98	65.85	16.71	32.56	27.6	5.0
59	99.84	99.25	96.78	94.98	65.85	16.71	32.56	28.3	5.1

Table 16. Computed gravimetric moisture contents and estimated error limits for Fine-Gradation model with gradation parameters set at their maximum model values.

Ka	G11_2	G1_2	NO4	NO10	NO200	PL	LL	Vw%	Est. Error, %
3	100	100	100	100	94.6	45	69	3.0	3.8
4	100	100	100	100	94.6	45	69	4.3	3.8
5	100	100	100	100	94.6	45	69	5.5	3.8
6	100	100	100	100	94.6	45	69	6.6	3.8
7	100	100	100	100	94.6	45	69	7.7	3.9
8	100	100	100	100	94.6	45	69	8.7	3.9
9	100	100	100	100	94.6	45	69	9.6	3.9
10	100	100	100	100	94.6	45	69	10.5	3.9
11	100	100	100	100	94.6	45	69	11.3	3.9
12	100	100	100	100	94.6	45	69	12.0	4.0
13	100	100	100	100	94.6	45	69	12.7	4.0
14	100	100	100	100	94.6	45	69	13.4	4.0
15	100	100	100	100	94.6	45	69	14.0	4.0
16	100	100	100	100	94.6	45	69	14.6	4.1
17	100	100	100	100	94.6	45	69	15.1	4.1
18	100	100	100	100	94.6	45	69	15.5	4.1
19	100	100	100	100	94.6	45	69	16.0	4.1
20	100	100	100	100	94.6	45	69	16.4	4.1
21	100	100	100	100	94.6	45	69	16.7	4.2
22	100	100	100	100	94.6	45	69	17.0	4.2
23	100	100	100	100	94.6	45	69	17.3	4.2
24	100	100	100	100	94.6	45	69	17.6	4.2
25	100	100	100	100	94.6	45	69	17.8	4.2
26	100	100	100	100	94.6	45	69	18.1	4.2
27	100	100	100	100	94.6	45	69	18.2	4.2
28	100	100	100	100	94.6	45	69	18.4	4.3
29	100	100	100	100	94.6	45	69	18.6	4.3
30	100	100	100	100	94.6	45	69	18.7	4.3
32	100	100	100	100	94.6	45	69	19.0	4.3
34	100	100	100	100	94.6	45	69	19.2	4.3
36	100	100	100	100	94.6	45	69	19.4	4.4
38	100	100	100	100	94.6	45	69	19.6	4.4
40	100	100	100	100	94.6	45	69	19.8	4.4
42	100	100	100	100	94.6	45	69	20.1	4.4
44	100	100	100	100	94.6	45	69	20.5	4.4
46	100	100	100	100	94.6	45	69	20.9	4.5
48	100	100	100	100	94.6	45	69	21.4	4.5
50	100	100	100	100	94.6	45	69	22.0	4.5
52	100	100	100	100	94.6	45	69	22.8	4.6
54	100	100	100	100	94.6	45	69	23.7	4.7
56	100	100	100	100	94.6	45	69	24.8	4.8
58	100	100	100	100	94.6	45	69	26.0	5.0
59	100	100	100	100	94.6	45	69	26.7	5.1

maximum values, for which the model was developed, respectively. It is seen that the error estimates are not significantly affected by the ranges in values used for the gradation parameters and the plastic and liquid limits. Figures 37 through 40 show the computed and estimated error limits of the computed gravimetric moisture content for each of the four models.

Diagnostic Study of the Computed Gravimetric Moisture Content

Using the procedures discussed in this report, volumetric and gravimetric moisture contents were calculated for the valid TDR traces. To test the reasonableness of the computed moisture content, several types of diagnostic graphs were generated. Figures 41 through 44 provide the frequency distribution of both the computed volumetric and gravimetric moisture contents for coarse-grained and fine-grained soil. As shown in these figures, moisture contents of the coarse-grained soils are generally smaller than those of the fine-grained soils. This is expected, since fine soils can generally be expected to retain more moisture.

Seasonal variation graphs of the volumetric and gravimetric moisture contents for each SMP section were generated and are presented in appendix D. In addition, daily rainfall values were also generated and are given in appendix B for comparison purposes.

Figure 45 shows an example time history plot for LTPP section 831801 in Manitoba. It should be noted that the TDR method can only be used to estimate the liquid moisture content. As shown, the soil moisture content at section 831801 does vary significantly throughout the year. During the winter, the volumetric moisture content dropped to a very low level, which may indicate a frozen soil condition since this section is in a deep freeze zone. Furthermore, the soil volumetric moisture contents also vary considerably by depth. This may be because of many factors, such as precipitation, soil permeability, and groundwater level. Figure 46 shows another example of time history plot for LTPP section 040114 in Arizona. It is clear that the seasonal variation of the computed moisture content of this section is much less than that of the Manitoba section. Moreover, there is no sharp drop in moisture content during the winter for this section since it is in a nonfreeze zone.

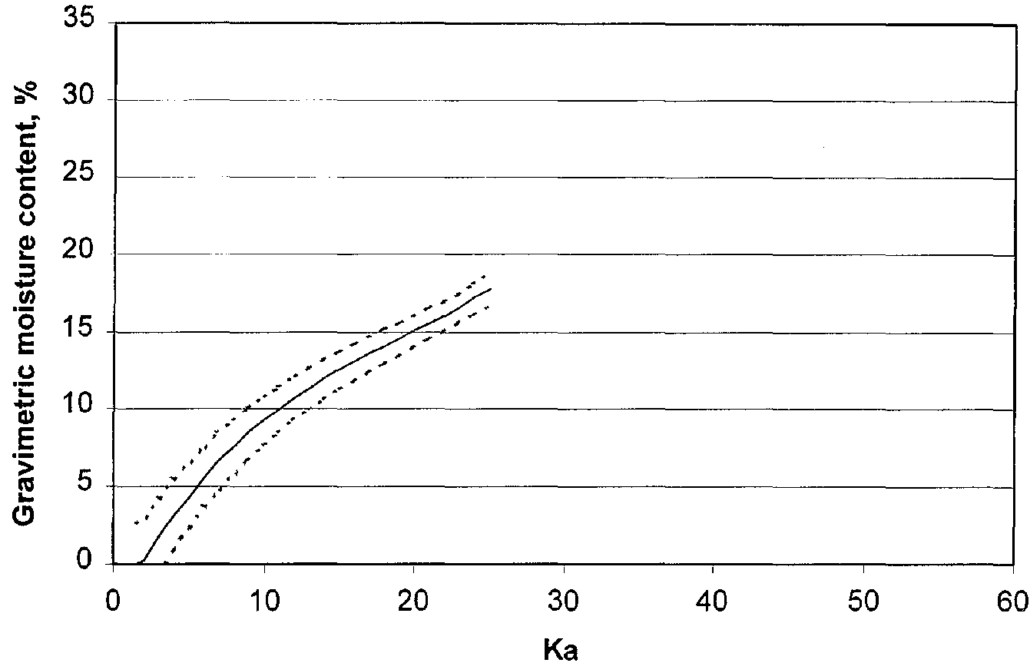


Figure 37. Computed gravimetric moisture contents and estimated error limits for the Coarse-Ka model.

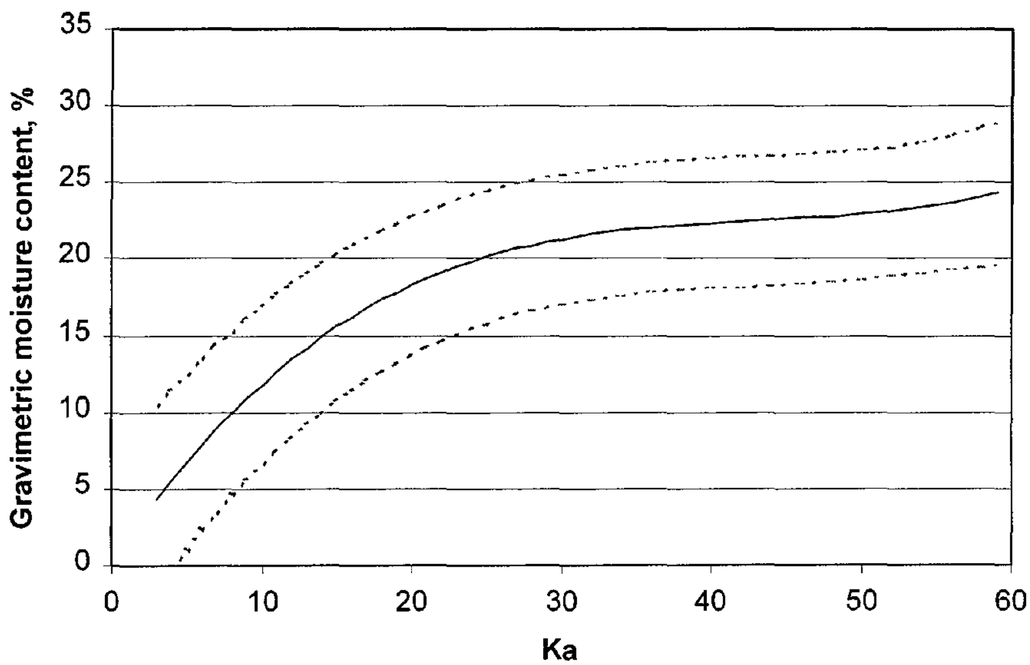


Figure 38. Computed gravimetric moisture contents and estimated error limits for the Fine-Ka model.

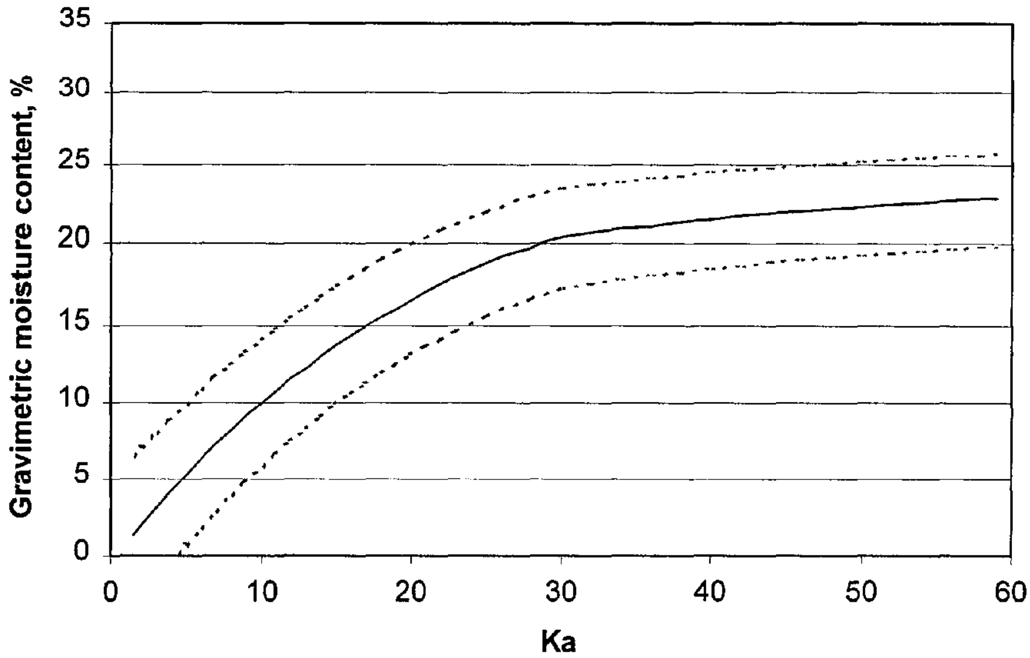


Figure 39. Computed gravimetric moisture contents and estimated error limits for the AllSoil-Ka model.

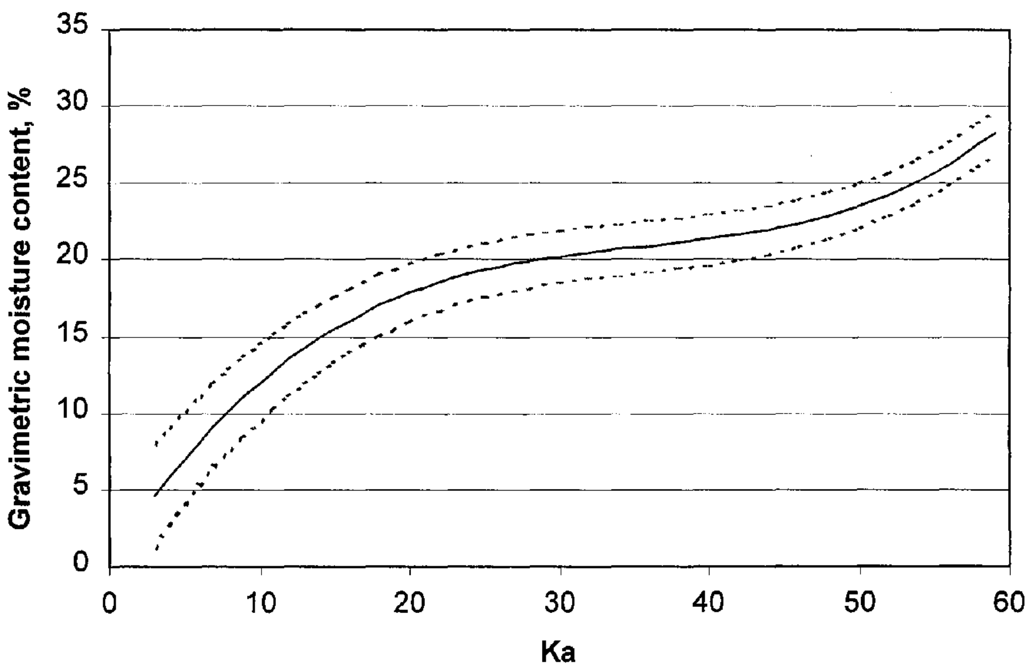


Figure 40. Computed gravimetric moisture contents and estimated error limits for the Fine-Gradation model.

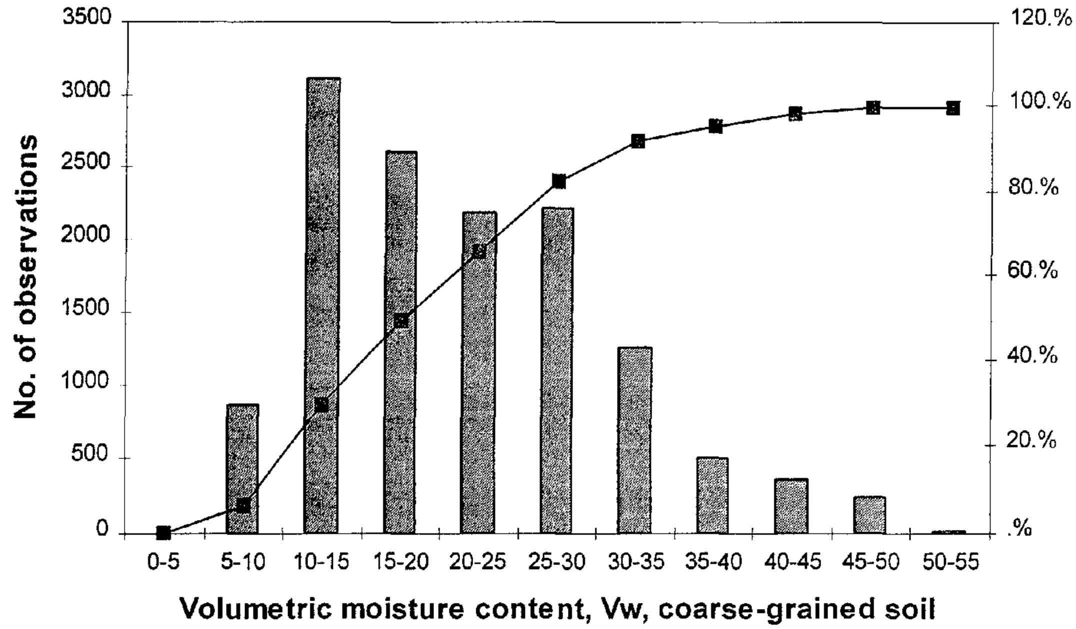


Figure 41. Frequency distribution of the computed volumetric moisture contents using the TDR traces collected at SMP sites, coarse-grained material.

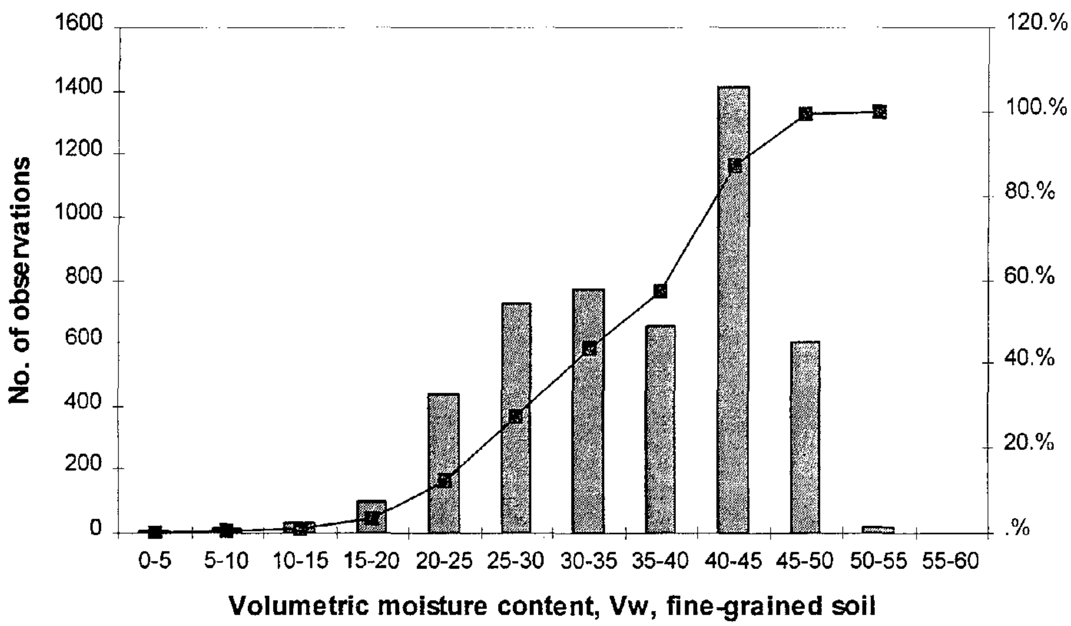


Figure 42. Frequency distribution of the computed volumetric moisture contents using the TDR traces collected at SMP sites, fine-grained material.

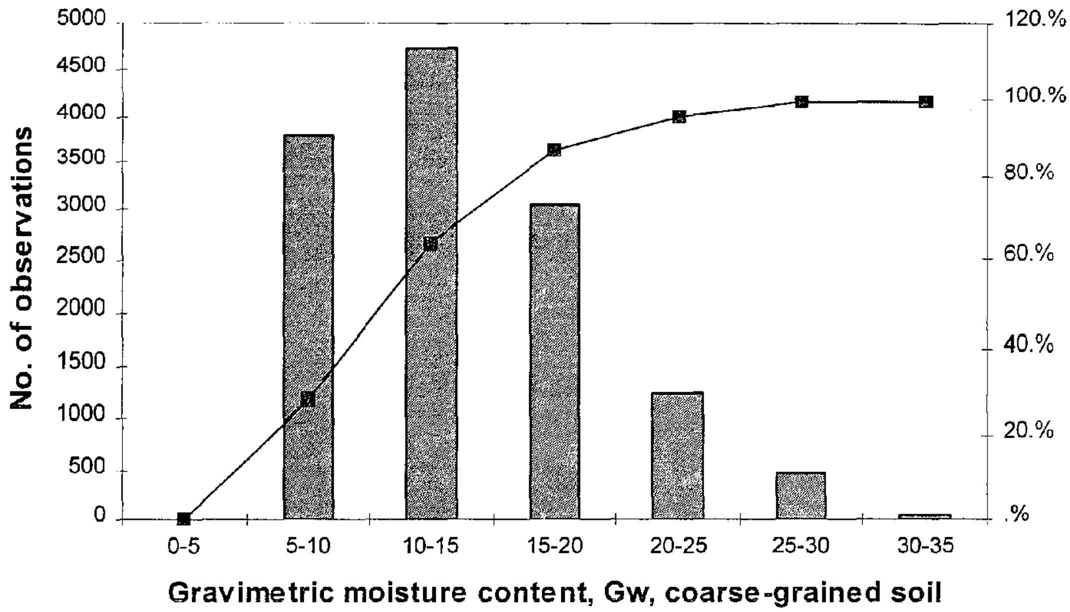


Figure 43. Frequency distribution of the computed gravimetric moisture contents using the TDR traces collected at SMP sites, coarse-grained material.

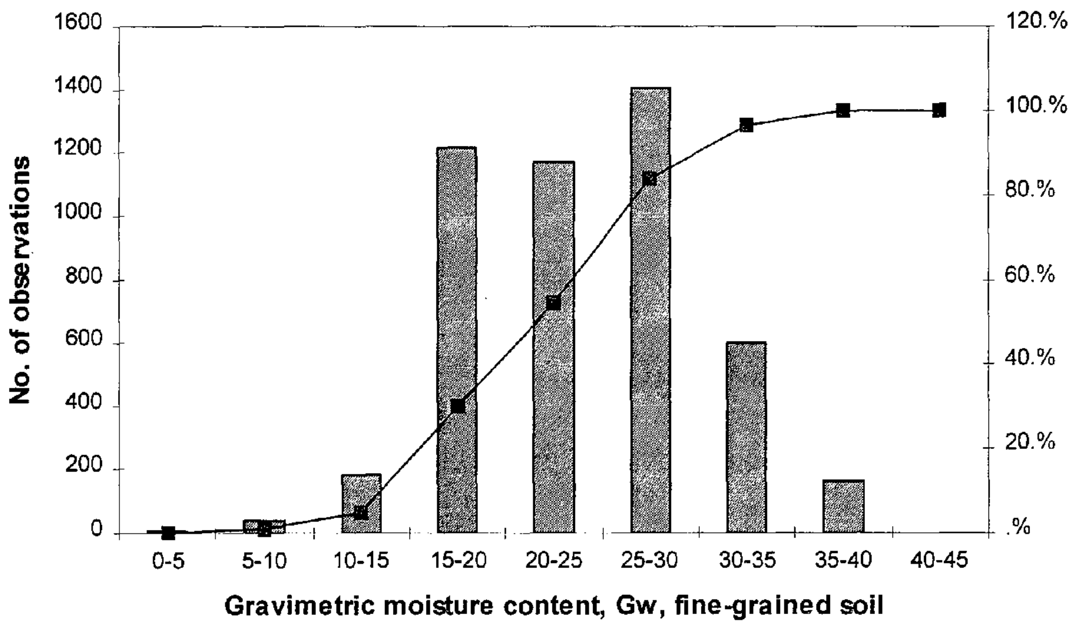


Figure 44. Frequency distribution of the computed gravimetric moisture contents using the TDR traces collected at SMP sites, fine-grained material.

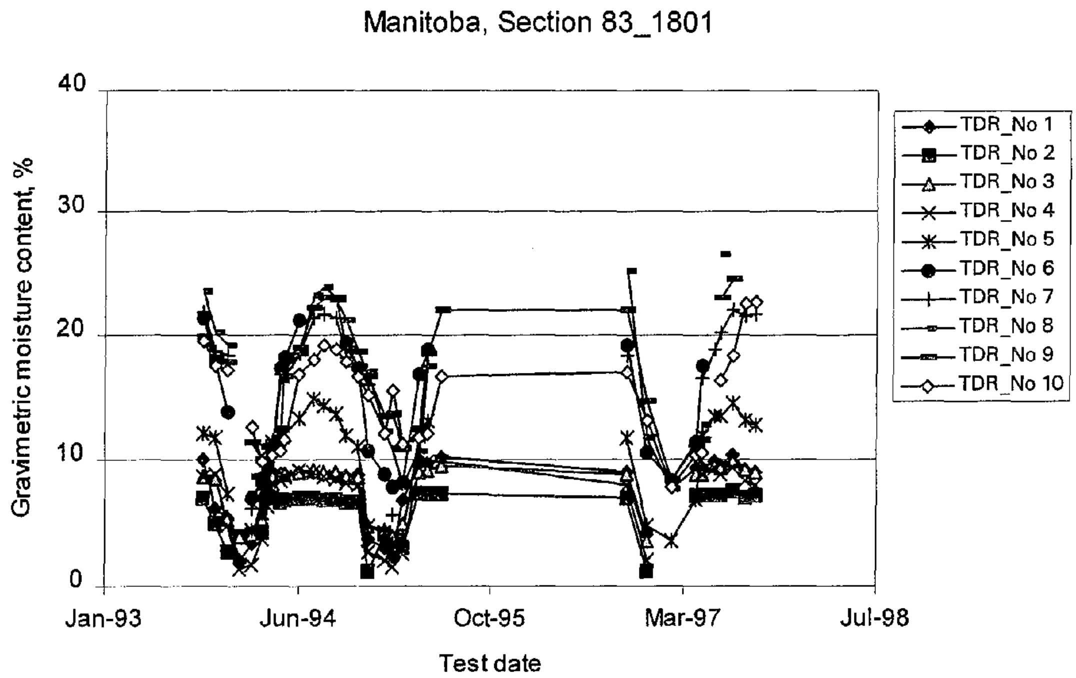


Figure 45. Example of seasonal variation in gravimetric moisture content for section 831801 in Manitoba.

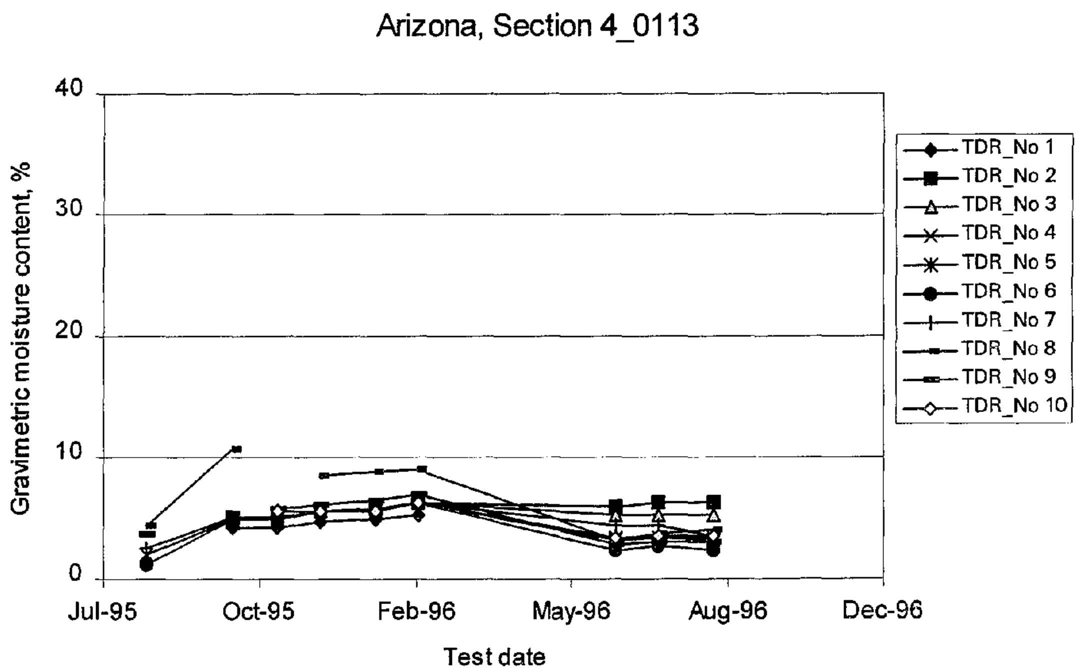


Figure 46. Example of seasonal variation in gravimetric moisture content for section 040113 in Arizona.

4. IDENTIFICATION OF THE NEEDED MATERIAL PROPERTIES

To compute the volumetric moisture content using various models and to compute the gravimetric moisture content, the following soil properties are needed for each SMP section at each TDR sensor location:

- Dry density of the unbound material.
- Soil type.
- Gradation parameters for fine-grained soils at the TDR sensor location.
- Plastic limit and liquid limit.

This section describes the procedures used to identify the above soil properties for the SMP base and subgrade materials. A complete list of the needed soil properties is given in appendix C.

Dry Density

To compute the gravimetric moisture content, the in-situ dry density needs to be known for all the SMP sites at each TDR depth. However, such dry density information with depth is not available in the LTPP IMS. As such, only a single value of dry density was used for base and subgrade for each test section.

The SMP installation report and several LTPP IMS database tables were reviewed to identify soil dry density data. The following are the sources that were used to determine the dry densities at each TDR probe location:

- SMP Installation Report (priority 1).
- SMP_DRY_DENSITY (file extension .S04) (priority 2).
- TST_ISD_MOIST (file extension .T20) (priority 3).
- TST_UG05_SS05 (file extension .T16) (priority 4).
- INV_SUBGRADE (file extension .I23) (priority 5).

Where more than one dry density measurement was available, the dry density value of the higher priority source was used. At least one dry density value was available for the subgrade at each SMP site. For most sites, a value was found for the aggregate base, subbase, or treated subgrade soil. The following scheme was used to determine the needed dry density values.

- Use was made of the available subgrade dry density values for all the subgrade TDR probe depths.
- For the sections for which the dry densities for the aggregate base or subbase were not available, use was made of the global average dry density for the aggregate base or subbase.
- For the sections for which the dry densities for the lime-treated subgrade were not available, the average subgrade dry density of the section was used.

It should be noted that the above extrapolation scheme does not consider the vertical variation of the dry densities. The sources of the dry density values are listed in table 17. Frequency distributions of the dry density for base and subgrade are given in figures 47 and 48, respectively.

Soil Classification

In the proposed volumetric moisture content models, soil classifications of "coarse-grained" and "fine-grained" are used. In the ASTM Standard D3282 [17], coarse-grained subgrade soil (granular material) is defined as soil with 35 percent or less passing the No. 200 sieve, and fine-grained subgrade soil (silt-clay material) is defined as soil with 36 percent or more passing the No. 200 sieve. Therefore, coarse-grained soils correspond to American Association of State Highway and Transportation Officials (AASHTO) soil classes A-1, A-2, A-3, and all subgroups. Fine-grained soils include A-4, A-5, A-6, A-7, and all subgroups. Note that the Unified Soil Classification System [18] uses 50 percent passing the No. 200 sieve as the threshold value for the classification of coarse-grained and fine-grained soil.

LTPP IMS table TST_L05B and SMP installation reports were used to determine if the subgrade soil at an SMP site was fine or coarse.

Gradation Parameters

LTPP IMS table TST_SS01_UG02 was used to search for the gradation parameters for the sections with fine-grained soil subgrade. Not all of the SMP sections currently have the gradation values available in the LTPP database. Frequency distributions of the gradation parameters that are needed in the fine-grained soil volumetric moisture content model are given in figures 49 through 53.

Plastic Limit and Liquid Limit

Plastic limit and liquid limit of the sections with fine-grained subgrade were obtained from LTPP IMS table TST_UG04_SS03. The test method of these parameters are defined in ASTM standard D422 [19]. Again, not all of the SMP sections currently have the needed plastic limit and liquid limit data in the LTPP database. Frequency distributions of the plastic limit and liquid limit of the fine-grained subgrade SMP sites are given in figures 54 and 55.

Table 17. Sources of the dry density values.

	Source
1	SMP installation report
2	SMP installation report - I07 form
3	SMP installation report - S04 form
4	SMP installation report - I05 form
5	IMS table SMP_DRY_DENSITY
6	IMS table TST_ISD_MOIST
7	Calculated, 95% lab max dry density from IMS table TST_UG05_SS05
8	IMS table INV_SUBGRADE
9	Base dry density from the same section
10	Subgrade dry density value from the same section
11	Global average of all available aggregate base dry densities from all the SMP sites

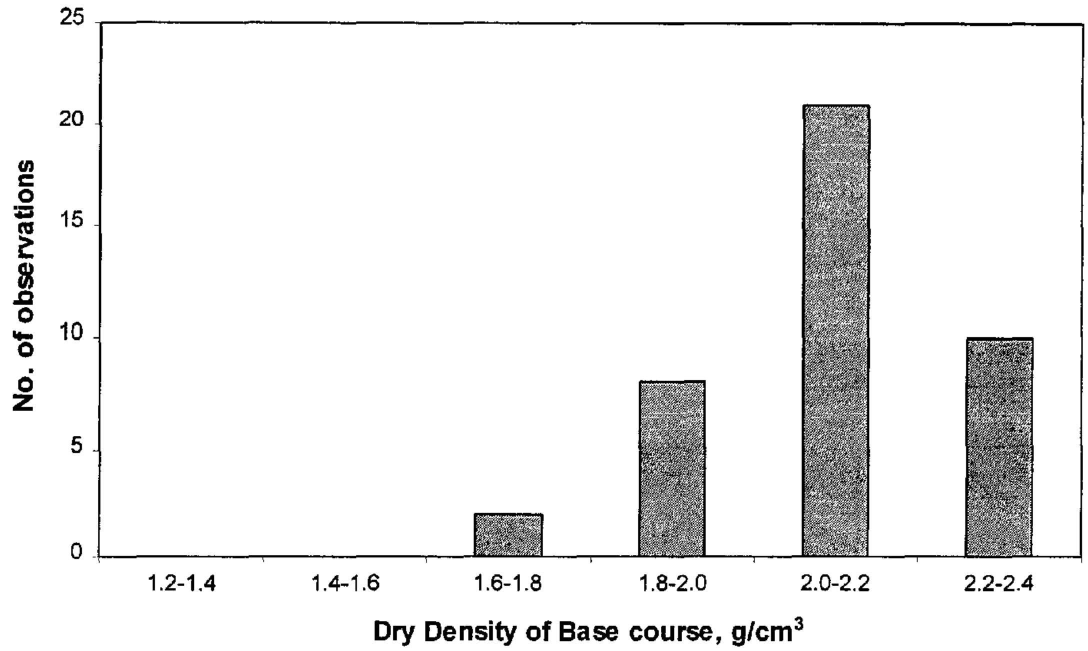


Figure 47. Frequency distribution of base course dry density for the SMP sites.

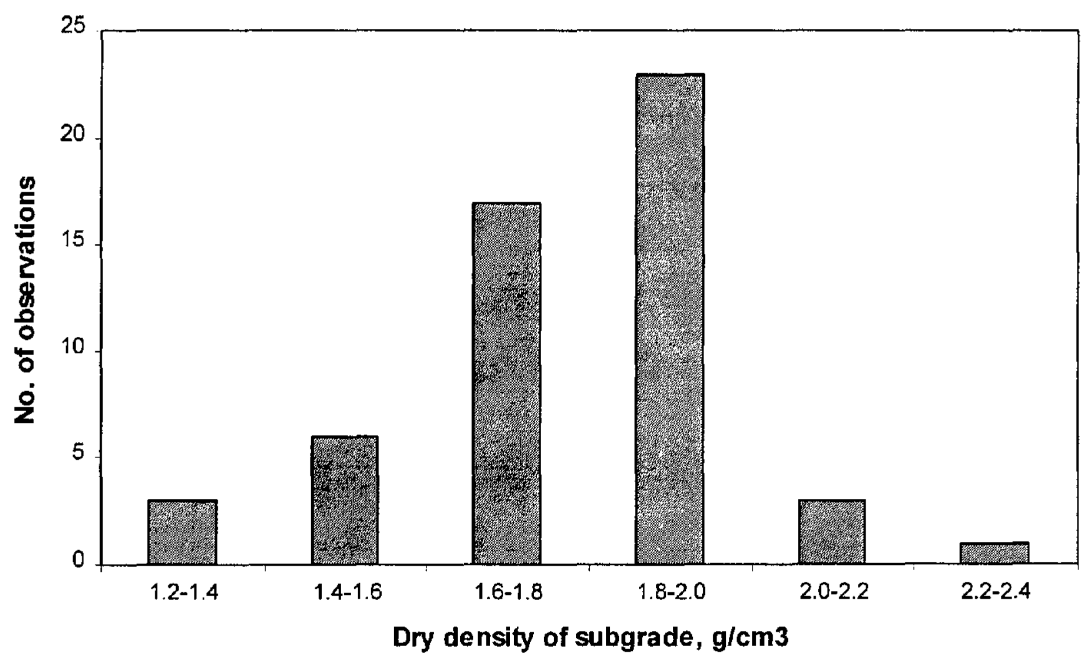


Figure 48. Frequency distribution of subgrade dry density for the SMP sites.

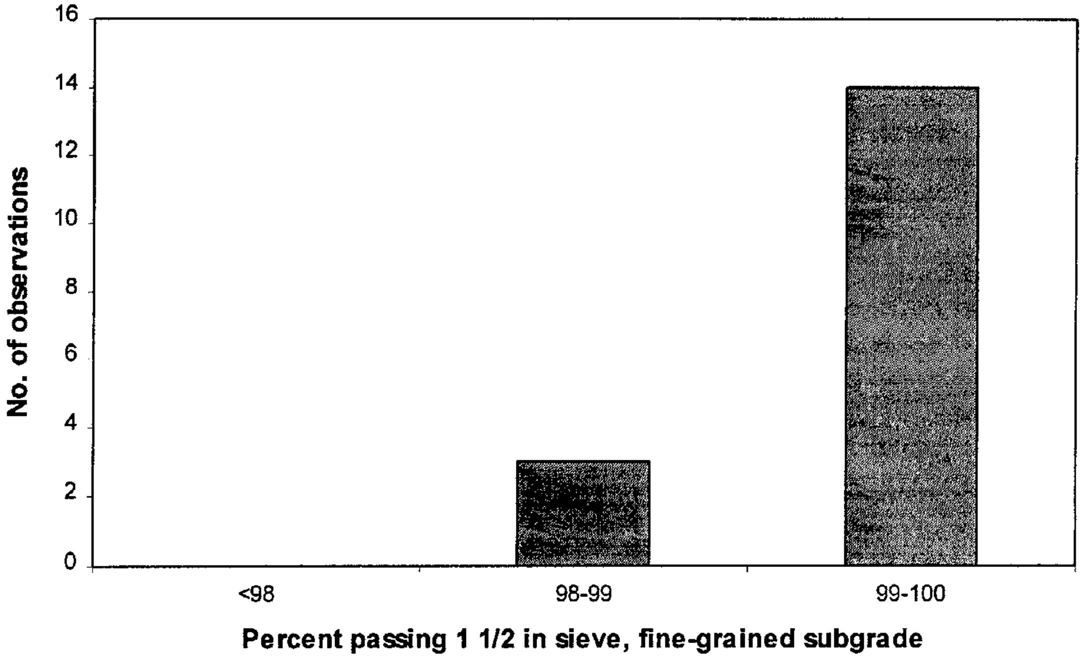


Figure 49. Frequency distribution of percent passing the 1½-in sieve for SMP sites, fine-grained soils.

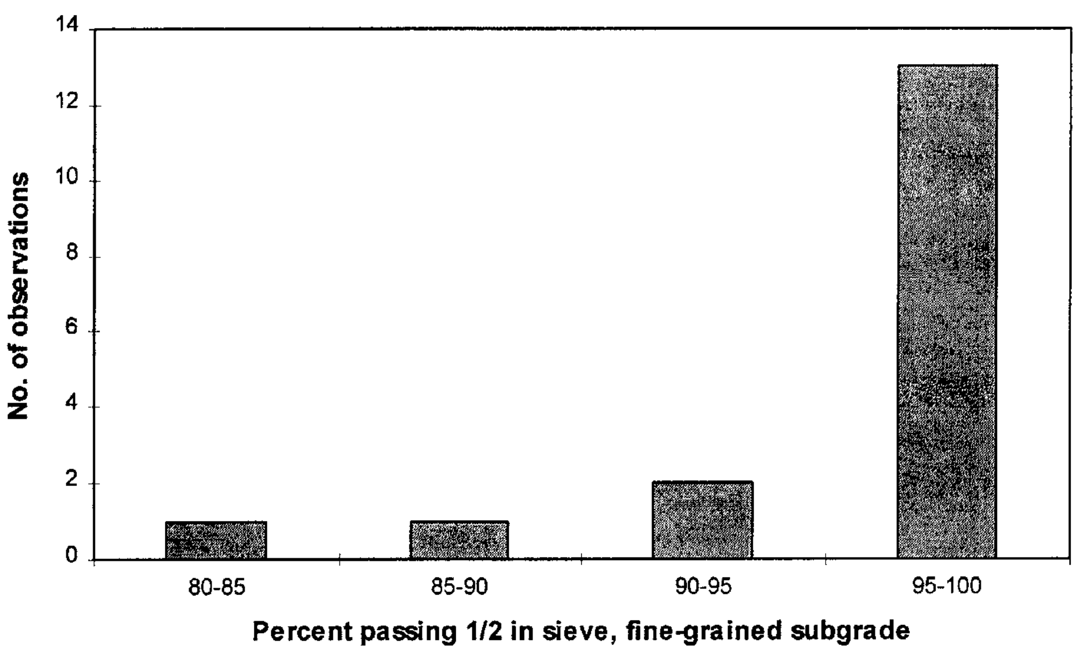


Figure 50. Frequency distribution of percent passing the ½-in sieve for SMP sites, fine-grained soils.

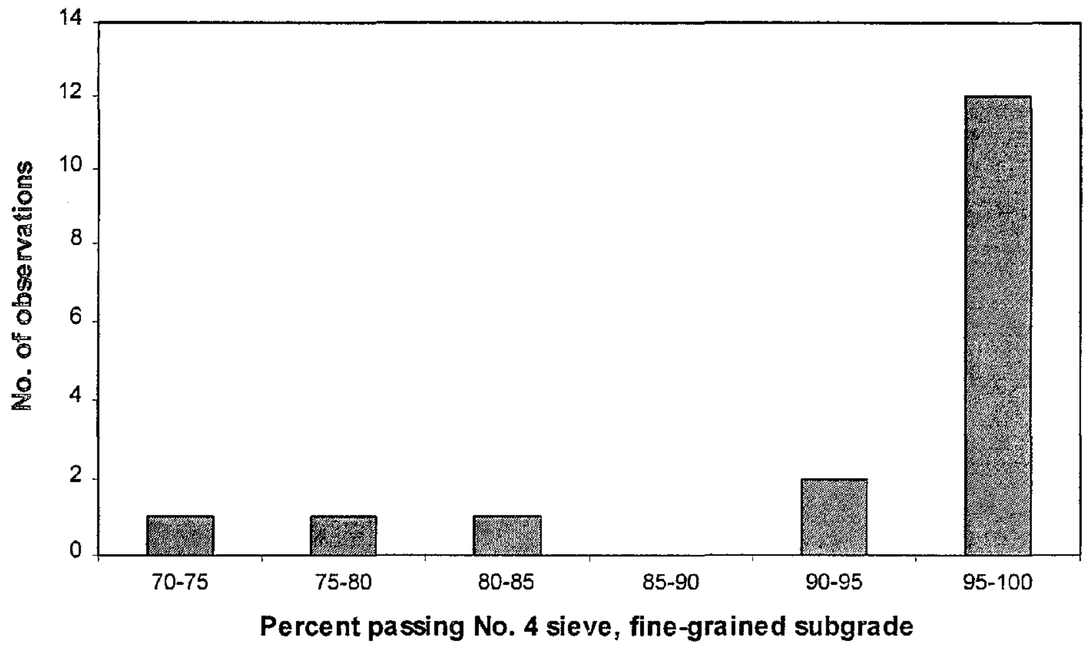


Figure 51. Frequency distribution of percent passing the No. 4 sieve for SMP sites, fine-grained soils.

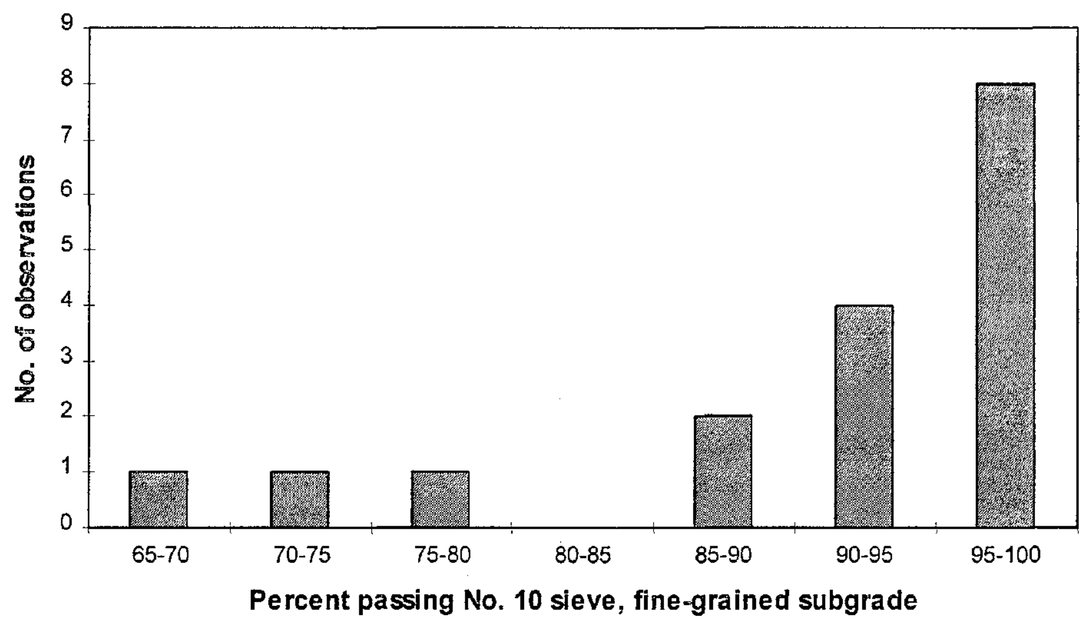


Figure 52. Frequency distribution of percent passing the No. 10 sieve for SMP sites, fine-grained soils.

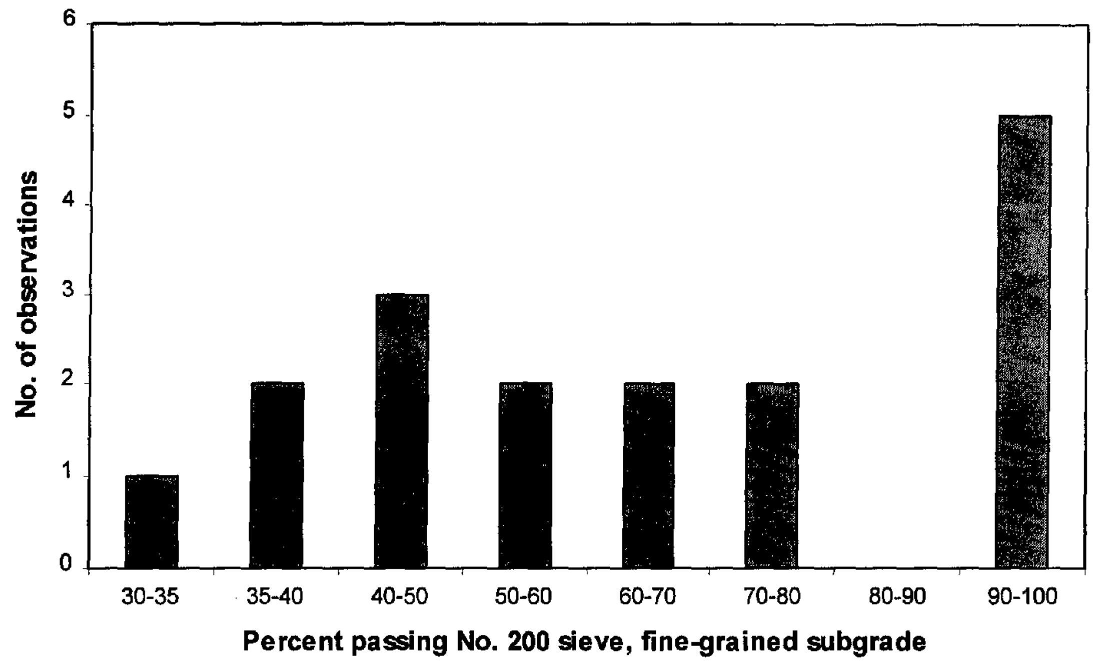


Figure 53. Frequency distribution of percent passing the No. 200 sieve for SMP sites, fine-grained soils.

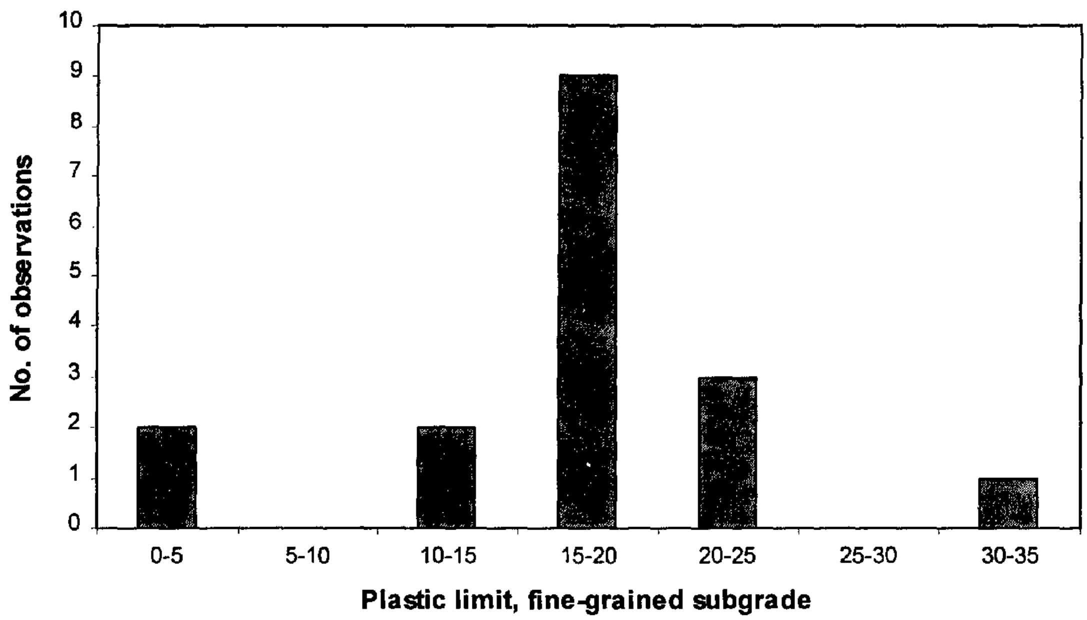


Figure 54. Frequency distribution of plastic limit for SMP sites, fine-grained soils.

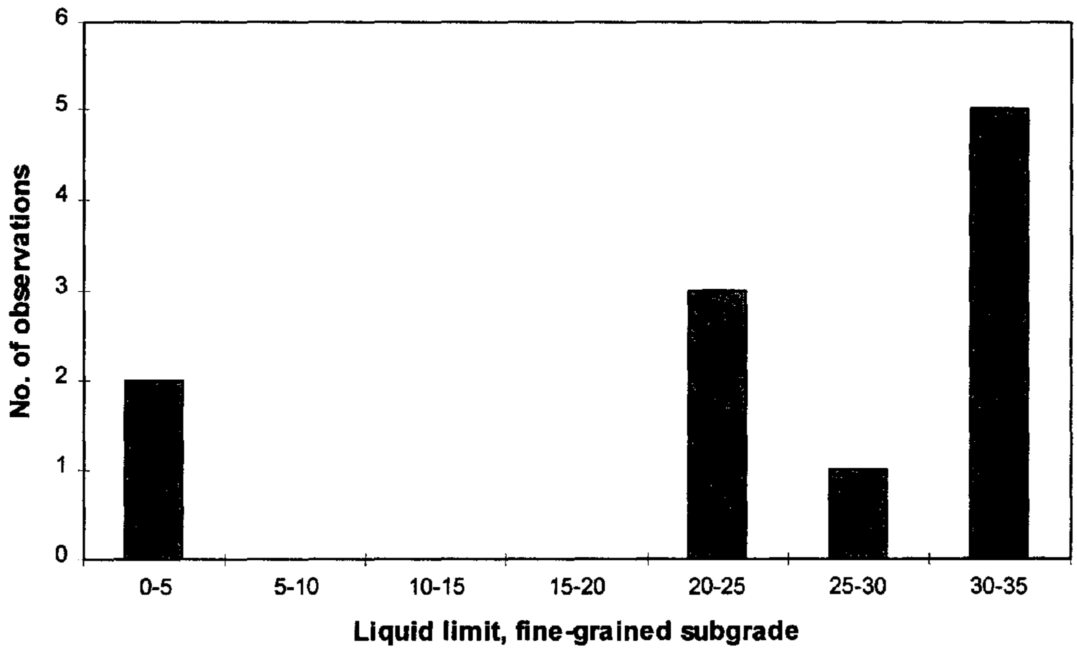


Figure 55. Frequency distribution of liquid limit for SMP sites, fine-grained soils.

5. ROUTINE DATA PROCESSING OF TDR DATA

An objective of this study was to develop routine procedures to process future TDR data. As a result, the following step-by-step procedures were developed for the routine interpretation of TDR measurements and computation of the moisture contents:

1. Obtain raw TDR trace data from IMS database.
2. Pre-process the raw TDR trace data.
3. Conduct TDR trace interpretation.
4. Quality check the interpretation results.
5. Compute dielectric constants.
6. Compute volumetric moisture contents.
7. Compute gravimetric moisture contents.
8. Upload the computed parameters into IMS database.

Each of the above steps is discussed briefly in this chapter.

Obtain Raw TDR Trace Data from IMS Database

Raw TDR trace data can be obtained from table SMP_TDR_AUTO in the IMS database. This table needs to be imported into Access® database format for processing. The structure or the schema of the table remains the same as in the IMS database.

Pre-Process the Raw TDR Trace Data

Interpreting the TDR data and updating the corresponding computed parameter tables will be a continuous effort. Part of the raw TDR table may have been processed at the time of previous data processing. Therefore, pre-processing of the raw TDR traces is necessary to exclude the traces that were previously processed. This can be done by comparing the current TDR trace data with the IMS table SMP_TDR_MOISTURE_AUTO. The trace records that have common key fields should be excluded from the processing of the new TDR data.

Conduct TDR Trace Interpretation

A Windows®-based program, Moister, was developed under this project to view and process all the TDR traces stored in an Access® database table. The program opens a designated table with a name starting with SMP_TDR_AUTO_*, processes the TDR traces, and records the inflection points and the corresponding trace pattern in the same table. The format of this table is very similar to that of IMS table SMP_TDR_AUTO, except that the first 242 trace points are kept instead of 245. Further, four more fields are added in the table to describe the interpretation results. The elimination of three trace points is necessary to accommodate the addition of the above-mentioned fields because Access® database tables are limited to 255 fields.

The following steps are needed to conduct the TDR trace interpretation:

1. Eliminate the following three fields from the IMS table SMP_TDR_AUTO: WAVP_243, WAVP_244, and WAVP_245. Rename the table SMP_TDR_AUTO_* if necessary.
2. Run Moister using the table created in step 1 above.

Quality Check of the Interpretation Results

Because of the noise in the collected TDR traces, it is not practical to process them all automatically with 100 percent reliability using Moister. Therefore, it is necessary to have qualified personnel perform a quality check of the interpretation results. Moister can be used interactively to view the interpretation results to make sure that the results are correct or to adjust the inflection points if necessary. On average, a qualified person can review 1000 to 2000 TDR traces per hour, depending on the actual number of traces that need to be corrected.

Compute Soil Dielectric Constants

After the inflection points are identified, several spreadsheet manipulations and computations are needed to calculate the moisture contents. The following equations are used to compute the apparent length and the dielectric constant:

$$La = (Inf.B - Inf.\ A) \tag{28}$$

$$Ka = \left(\frac{La}{(L * Vp)} \right)^2 \tag{29}$$

where: *Inf. B* = Inflection point B, m.
Inf. A = Inflection point A, m.
La = Apparent length of the TDR trace, m.
Ka = Dielectric constant of the soil mix.
L = Actual length of the TDR probe, typically 0.203 m.
Vp = Propagation velocity of the TDR wave, typically 0.99.

Compute Volumetric Moisture Contents

Four models were developed for the computation of the volumetric moisture content. The first three models take the following third-order polynomial form:

$$Vw\% = a_0 + a_1 Ka + a_2 Ka^2 + a_3 Ka^3 \tag{30}$$

where: a_0, a_1, a_2, a_3 = Regression coefficients, as given in table 18.
Ka = Bulk dielectric constant.

Table 18. Volumetric moisture model parameter estimates.

Model Name	a0	a1	a2	a3
Coarse-Ka model	-5.7875	3.41763	-.13117	0.00231
Fine-Ka model	0.4756	2.75634	-0.061667	0.000476
AllSoil-Ka model	-0.8120	2.38682	-0.04427	0.000292

The fourth model takes the following form:

$$Vw = a0 + a1Ka + a2Ka^2 + a3\,Ka^3 + a4\,ONE\_AND\_HALF\_PASSING + a5\,ONE\_HALF\_PASSING + a6\,NO\_4\_PASSING + a7\,NO\_10\_PASSING + a8\,NO\_200\_PASSING + a9\,PLASTIC\_LIMIT + a10\,LIQUID\_LIMIT \quad (31)$$

where: *a0, a1, ..., a10* = Regression coefficients, as defined in table 19.
Ka = Bulk dielectric constant.

Table 19. Variables and coefficient estimates for the Fine-Gradation model.

Variables	Coef.	Value	Std. Error	Inference Range
Intercept	a0	1761.78	201.83	
Ka	a1	2.9145	0.2168	3-58.4
Ka^2	a2	-0.07674	0.00921	
Ka^3	a3	0.000722	0.000108	
ONE_AND_HALF_PASSING	a4	-19.6649	2.1168	99-100
ONE_HALF_PASSING	a5	4.3667	0.5994	97-100
NO_4_PASSING	a6	5.1516	0.4638	90-100
NO_10_PASSING	a7	2.7737	0.3182	84-100
NO_200_PASSING	a8	0.06057	0.02445	12.6-94.6
PLASTIC_LIMIT	a9	-0.2057	0.05371	0-45
LIQUID_LIMIT	a10	0.10231	0.03743	0-69

The following scheme is used for calculation of the volumetric moisture content:

1. If Ka < 1.5 or Ka > 58.4, check the original TDR waveform and make sure the results are reasonable. These values should exist very rarely, if at all. If these

values exist, flag the data. Ka < 1.5 would indicate a very dry soil and Ka > 58.4 would indicate a very wet soil.

2. For coarse-grained soils
    - If 1.5 < Ka < 24.8, use the coarse-grained soil volumetric moisture content empirical model with only Ka as the independent variable (Coarse-Ka model).
    - If Ka > 24.8, use the all-soil volumetric moisture content model with only Ka as the independent variable (AllSoil-Ka model).

3. For fine-grained soils
    - For sections with 3 < Ka < 58.4 and gradation, plastic limit, and liquid limit values within the inference ranges of those used in the model development (Fine-Gradation model), use this model to calculate the volumetric moisture content.
    - For sections with 3 < Ka < 58.4 and not satisfying the above criteria, use the fine-grained soil volumetric moisture model using only Ka as the independent variable (Fine-Ka model).
    - For sections with Ka < 3, use the all-soil volumetric moisture content model with only Ka as the independent variable (AllSoil-Ka model). This should occur very rarely.

A flow chart of the model selection scheme is shown in figure 36.

Compute Gravimetric Moisture Contents

Gravimetric moisture content can be calculated using the following equation:

$$GVw = \gamma_w/\gamma_d * Vw\% \qquad (32)$$

where: γ_w = 9.81 N/cm^3, unit weight of water.
γ_d = Dry unit weight of the soil, N/cm^3.
$Vw\%$ = Volumetric moisture content, %.

6. SUMMARY AND RECOMMENDATIONS

This chapter summarizes the research effort and findings of this study. Products from this research that can be implemented are also discussed. Recommendations for future research in the determination of moisture contents using TDR measurements are also provided.

The overall objective of this study was to develop procedures to estimate the in-situ gravimetric moisture content and associated errors and to process the available TDR traces in the IMS database. This project accomplished the following:

- Selected the methods for interpreting TDR traces, namely, Method of Tangents and Method of Peaks.
- Developed an algorithm to implement the selected TDR interpretation methods.
- Developed a user-friendly interactive computer program, Moister, to interpret the TDR traces.
- Conducted a precision and bias study for the computed apparent length from the interpretation of the TDR traces.
- Developed empirical models to estimate in-situ volumetric moisture content using the TDR measurements, namely Coarse-Ka model, Fine-Ka model, AllSoil-Ka model, and Fine-Gradation model.
- Identified and estimated necessary material properties for all the computations.
- Performed error estimates of the computed dielectric constant, volumetric moisture content, and gravimetric moisture content.
- Developed guidelines for creating and uploading the TDR trace interpretation results and corresponding moisture contents.
- Developed step-by-step procedures for routine interpretation of the TDR traces.
- Interpreted 19,663 TDR traces that are available in the IMS database.

Products for Implementation

Based on the accomplishments of this study, the following is a list of the products for implementation:

- Software to interpret the TDR traces (Program Moister).
- Models for computation of volumetric moisture content
- Computed parameter tables to be included in the IMS database.
- Routine procedure for processing TDR data and uploading the computed parameters into the IMS database.
- A series of feedback reports to clarify and/or correct TDR trace data and related data.

Recommendations for Future Research

The following recommendations are made to improve the reliability of the computed moisture content data:

- Investigate possible changes in the TDR probe length design, to allow the probes to be used effectively for a wide range of soil conditions.
- Measure in-situ subgrade density at various depths in the subgrade at each SMP section.
- Investigate the interpretation of bulk conductivity of the soils from TDR measurements.
- Conduct laboratory tests to calibrate and/or validate the volumetric moisture computation models.
- Evaluate the relationship of the computed in-situ moisture contents to the backcalculated moduli of the base and subgrade materials to determine the sensitivity of the moisture content to the stiffness of the paving materials.
- Evaluate the relationship between the TDR waveforms and the presence of frost.
- Evaluate the relationship between precipitation and subsurface moisture changes.

APPENDIX A – PROCESSED TDR TRACES WITH AN ERROR CODE

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
4	0113	8/31/95	1503	5	b1
6	3042	5/16/95	1335	1	OT
8	1053	6/24/97	1244	10	b1
8	1053	8/12/94	0759	10	b1
8	1053	10/24/96	1051	10	b1
8	1053	6/27/95	1324	9	b1
8	1053	6/27/95	1324	10	b1
8	1053	6/27/95	1429	7	b1
8	1053	6/27/95	1429	8	b1
8	1053	6/27/95	1429	9	b1
8	1053	6/27/95	1429	10	b1
8	1053	10/24/96	0827	4	b1
8	1053	10/24/96	0829	8	b1
8	1053	10/24/96	0830	9	b1
8	1053	10/24/96	1051	9	b1
8	1053	6/27/95	0921	10	b1
8	1053	10/24/96	1454	9	b1
8	1053	10/24/96	1454	10	b1
8	1053	6/24/97	0840	9	b1
8	1053	6/24/97	1244	9	b1
8	1053	7/22/97	0803	8	b1
8	1053	7/22/97	0803	9	b1
8	1053	7/22/97	0803	10	b1
8	1053	7/22/97	1207	8	b1
8	1053	7/22/97	1207	9	b1
8	1053	10/24/96	0830	10	b1
8	1053	9/27/94	1220	8	b1
8	1053	7/15/94	0812	8	b1
8	1053	7/15/94	0812	9	b1
8	1053	7/15/94	1215	8	b1
8	1053	7/15/94	1215	9	b1
8	1053	8/12/94	0759	7	b1
8	1053	8/12/94	0759	8	b1
8	1053	8/12/94	0759	9	b1
8	1053	8/12/94	1202	9	b1
8	1053	9/27/94	0817	8	b1
8	1053	6/27/95	1324	8	b1
8	1053	9/27/94	0817	10	b1
8	1053	6/27/95	1324	7	b1
8	1053	9/27/94	1220	9	b1
8	1053	9/27/94	1220	10	b1
8	1053	10/25/94	0934	9	b1
8	1053	10/25/94	0934	10	b1
8	1053	10/25/94	1204	9	b1
8	1053	10/25/94	1204	10	b1
8	1053	6/27/95	0921	7	b1
8	1053	6/27/95	0921	8	b1
8	1053	6/27/95	0921	9	b1
8	1053	8/24/97	0945	9	b1
8	1053	9/27/94	0817	9	b1
8	1053	7/22/97	1207	10	b1
8	1053	8/24/97	0945	10	b1
8	1053	9/22/97	1304	8	b1
8	1053	9/22/97	1304	9	b1
8	1053	9/22/97	1304	10	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
8	1053	8/24/97	0945	8	b1
8	1053	2/11/97	1258	10	OT
8	1053	2/11/97	0855	10	OT
8	1053	8/5/94	1328	8	b1
8	1053	9/9/94	1021	5	b1
8	1053	9/9/94	1021	6	b1
8	1053	9/9/94	1022	7	b1
8	1053	9/9/94	1108	5	b1
8	1053	9/9/94	1108	6	b1
8	1053	9/9/94	1109	7	b1
8	1053	9/9/94	1512	5	b1
8	1053	9/9/94	1512	6	b1
8	1053	9/9/94	1513	8	b1
8	1053	9/9/94	1512	7	b1
8	1053	8/5/94	1327	5	b1
8	1053	8/5/94	1327	7	b1
8	1053	7/15/94	1239	7	b1
8	1053	6/17/94	0839	7	b1
8	1053	6/17/94	1242	5	b1
8	1053	6/17/94	1242	6	b1
8	1053	6/17/94	1242	7	b1
8	1053	7/15/94	0835	5	b1
8	1053	7/15/94	0835	6	b1
8	1053	7/15/94	0836	7	b1
8	1053	7/15/94	0836	8	b1
8	1053	6/17/94	0838	5	b1
8	1053	7/15/94	1239	6	b1
8	1053	10/22/97	1241	10	b1
8	1053	7/15/94	1240	8	b1
8	1053	7/15/94	1642	5	b1
8	1053	7/15/94	1642	6	b1
8	1053	7/15/94	1642	7	b1
8	1053	7/15/94	1643	8	b1
8	1053	8/5/94	0923	5	b1
8	1053	8/5/94	0923	6	b1
8	1053	8/5/94	0924	7	b1
8	1053	8/5/94	0924	8	b1
8	1053	7/15/94	1239	5	b1
8	1053	11/17/94	0854	10	b1
8	1053	8/5/94	1327	6	b1
8	1053	10/14/93	1117	8	b1
8	1053	10/14/93	1130	8	b1
8	1053	9/22/94	0752	10	b1
8	1053	9/22/94	1155	10	b1
8	1053	6/17/94	0838	6	b1
8	1053	10/20/94	1253	10	b1
8	1053	11/17/94	1257	10	b1
8	1053	10/10/96	1405	8	b1
8	1053	10/10/96	1405	10	b1
8	1053	11/13/96	0925	10	b1
8	1053	11/13/96	1329	10	b1
8	1053	3/26/97	0924	3	b1
8	1053	3/26/97	0925	4	b1
8	1053	9/17/97	0835	10	b1
8	1053	9/17/97	1239	10	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
8	1053	10/22/97	0836	10	b1
8	1053	10/20/94	0850	10	b1
8	1053	3/6/97	0855	10	a1
8	1053	11/14/96	1138	10	b1
8	1053	9/16/97	0928	10	b1
8	1053	8/14/97	0920	8	b1
8	1053	7/17/97	1343	10	b1
8	1053	7/17/97	1005	10	b1
8	1053	4/2/97	1224	10	b1
8	1053	3/5/97	0815	8	b1
8	1053	3/5/97	0816	9	b1
8	1053	3/5/97	0816	10	b1
8	1053	3/5/97	1220	8	b1
8	1053	3/5/97	1220	9	b1
8	1053	3/5/97	1221	10	b1
8	1053	4/2/97	0819	8	b1
8	1053	4/2/97	0820	9	b1
8	1053	4/2/97	0820	10	b1
8	1053	5/7/97	1300	9	b1
8	1053	4/2/97	1224	9	b1
8	1053	2/5/97	0855	7	b1
9	1803	4/16/97	0832	8	b1
9	1803	4/16/97	0833	9	b1
13	1031	4/16/97	1236	7	b1
13	1031	4/16/97	1237	8	b1
13	1031	4/16/97	1238	9	b1
13	1031	4/16/97	1239	10	b1
13	1031	5/7/97	0855	8	b1
13	1031	5/7/97	0856	9	b1
13	1031	4/2/97	1224	8	b1
13	1031	3/9/94	0820	8	b1
13	1031	2/5/97	0856	9	b1
13	1031	2/5/97	0855	8	b1
13	1031	3/9/94	1223	8	b1
13	1031	3/1/95	0805	3	b1
13	1031	3/1/95	0808	8	b1
13	1031	3/1/95	1210	3	b1
13	1031	1/8/97	0807	3	b1
13	1031	1/8/97	1213	3	b1
13	1031	2/5/97	0853	4	b1
13	1031	2/5/97	0854	5	b1
13	1031	2/5/97	0854	6	b1
13	1031	7/20/94	1309	7	b1
13	1031	5/7/97	1300	8	b1
13	3019	8/14/97	0921	10	b1
13	3019	7/20/94	1310	10	b1
13	3019	8/17/94	0817	10	b1
13	3019	8/17/94	1220	10	b1
13	3019	9/21/94	0832	10	b1
13	3019	9/21/94	1235	10	b1
13	3019	10/17/96	1335	10	b1
13	3019	7/17/97	1004	7	b1
13	3019	7/17/97	1004	8	b1
16	1010	7/17/97	1341	7	b1
16	1010	8/14/97	0920	7	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
18	3002	9/16/97	0927	7	b1
20	4054	9/16/97	1331	7	b1
20	4054	9/16/97	1332	8	b1
20	4054	9/16/97	1332	10	b1
20	4054	7/17/97	1341	8	b1
20	4054	12/19/96	1306	8	OT
20	4054	12/19/96	0902	8	OT
20	4054	10/19/96	1219	2	b1
20	4054	5/9/96	1526	4	b1
20	4054	4/10/96	0708	3	b1
20	4054	4/10/96	0709	4	b1
20	4054	4/10/96	1113	2	b1
20	4054	4/10/96	1114	4	b1
20	4054	4/10/96	1517	2	b1
20	4054	4/10/96	1518	4	b1
20	4054	5/9/96	0717	2	b1
23	1026	5/9/96	0718	4	b1
23	1026	5/9/96	1122	2	b1
23	1026	5/9/96	1525	2	b1
23	1026	3/21/96	1520	2	b1
23	1026	6/3/96	0710	2	b1
23	1026	6/3/96	0711	4	b1
23	1026	6/3/96	1115	2	b1
23	1026	6/3/96	1518	2	b1
23	1026	7/22/96	0719	2	b1
23	1026	8/26/96	0846	2	b1
23	1026	9/30/96	0830	2	b1
23	1026	9/30/96	1235	2	b1
23	1026	5/9/96	1123	4	b1
23	1026	4/10/96	0708	2	b1
24	1634	3/21/96	1521	4	b1
24	1634	3/21/96	0711	2	b1
24	1634	3/21/96	0711	3	b1
24	1634	3/21/96	0712	4	b1
24	1634	3/21/96	1116	2	b1
24	1634	3/21/96	1117	4	b1
24	1634	10/19/96	0814	2	b1
25	1002	6/3/96	0713	8	a1
25	1002	11/7/94	0911	8	OT
25	1002	1/9/95	0859	8	OT
25	1002	4/17/95	0822	8	OT
25	1002	4/17/95	1226	8	OT
25	1002	3/31/95	0753	2	b1
25	1002	3/31/95	1200	2	b1
25	1002	8/24/93	1405	8	a1
25	1002	8/24/93	1342	8	a1
25	1002	7/11/94	1108	5	a1
25	1002	7/11/94	0704	5	a1
25	1002	8/24/93	1353	8	a1
25	1002	8/24/93	1329	8	a1
25	1002	8/15/94	1029	9	b1
25	1002	3/24/94	0736	4	b1
25	1002	3/24/94	0736	5	b1
25	1002	3/24/94	0737	6	b1
25	1002	3/24/94	0738	7	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
25	1002	3/24/94	1141	4	b1
25	1002	3/24/94	1141	5	b1
25	1002	3/24/94	1141	6	b1
25	1002	3/24/94	1141	7	b1
25	1002	6/20/94	1138	8	b1
25	1002	8/15/94	1432	9	b1
25	1002	6/20/94	0734	8	b1
25	1002	4/3/95	1120	9	a1
25	1002	6/26/95	0907	9	a1
25	1002	7/18/96	0904	10	b1
25	1002	8/15/96	0833	10	b1
25	1002	9/26/96	0931	10	b1
25	1002	4/18/96	0841	10	a1
25	1002	5/14/96	0839	10	a1
25	1002	10/17/96	1631	7	b1
25	1002	8/21/96	0827	7	b1
25	1002	8/21/96	0827	8	b1
27	1018	8/21/96	1231	7	b1
27	1018	8/21/96	1231	8	b1
27	1018	9/26/96	0813	7	b1
27	1018	9/26/96	0813	8	b1
27	1018	9/26/96	1217	7	b1
27	1018	9/26/96	1217	8	b1
27	1018	10/17/96	0824	8	b1
27	1018	10/17/96	1228	8	b1
27	1018	4/25/96	1121	8	b1
27	1018	10/17/96	1632	8	b1
27	1018	10/17/96	1228	7	b1
27	1018	4/25/96	1524	8	b1
27	4040	4/25/96	1523	7	b1
27	4040	4/25/96	0659	7	b1
27	4040	4/25/96	0659	8	b1
27	4040	4/25/96	0715	7	b1
27	4040	4/25/96	0716	8	b1
27	4040	4/25/96	1120	7	b1
27	4040	3/14/94	1238	3	OT
27	4040	3/14/94	1641	3	OT
27	4040	3/14/94	0833	3	OT
27	4040	12/11/96	0845	10	b1
27	4040	4/21/95	0853	9	b1
27	4040	4/21/95	0853	10	b1
27	4040	5/8/95	0833	9	b1
27	4040	5/8/95	0833	10	b1
27	4040	11/14/96	0839	9	b1
27	4040	11/14/96	0840	10	b1
27	4040	11/14/96	0857	9	b1
27	4040	11/14/96	0857	10	b1
27	4040	11/14/96	1300	9	b1
27	4040	2/13/97	1252	10	b1
27	4040	12/11/96	0845	9	b1
27	4040	3/17/95	0854	10	b1
27	4040	12/11/96	1248	9	b1
27	4040	12/11/96	1249	10	b1
27	4040	1/16/97	0856	9	b1
27	4040	1/16/97	0856	10	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
27	4040	1/16/97	1300	9	b1
27	4040	1/16/97	1300	10	b1
27	4040	2/13/97	0849	9	b1
27	4040	2/13/97	0849	10	b1
27	4040	11/14/96	1300	10	b1
27	4040	11/10/94	0854	10	b1
27	4040	9/12/94	1428	7	b1
27	4040	9/12/94	1429	8	b1
27	4040	9/12/94	1429	9	b1
27	4040	9/12/94	1429	10	b1
27	4040	10/21/94	0842	9	b1
27	4040	10/21/94	0842	10	b1
27	4040	10/21/94	1245	9	b1
27	4040	10/21/94	1245	10	b1
27	4040	10/21/94	1648	9	b1
27	4040	4/5/95	1058	10	b1
27	4040	11/10/94	0854	9	b1
27	4040	4/5/95	1058	9	b1
27	4040	1/17/95	0936	9	b1
27	4040	1/17/95	0936	10	b1
27	4040	2/13/95	0902	9	b1
27	4040	2/13/95	0902	10	b1
27	4040	3/2/95	0902	9	b1
27	4040	3/2/95	0902	10	b1
27	4040	3/2/95	1305	9	b1
27	4040	3/2/95	1306	10	b1
27	4040	3/17/95	0852	6	b1
27	4040	3/7/97	0902	9	b1
27	4040	10/21/94	1648	10	b1
27	4040	2/13/97	1252	9	b1
27	4040	6/13/97	1227	9	b1
27	4040	3/7/97	0902	10	b1
27	4040	3/20/97	0836	9	b1
27	4040	3/20/97	0836	10	b1
27	4040	4/8/97	0829	9	b1
27	4040	4/8/97	0829	10	b1
27	4040	4/23/97	0828	9	b1
27	4040	4/23/97	0828	10	b1
27	4040	4/23/97	1259	9	b1
27	4040	4/23/97	1259	10	b1
27	4040	6/13/97	0822	10	b1
27	4040	6/13/97	1227	10	b1
27	4040	8/5/97	0835	9	b1
27	4040	8/5/97	0836	10	b1
27	4040	8/5/97	1156	9	b1
28	1016	8/5/97	1156	10	b1
28	1016	9/26/97	0827	6	b1
28	1016	9/26/97	0829	10	b1
28	1016	9/26/97	1232	6	b1
28	1016	9/26/97	1233	10	b1
28	1016	9/12/94	1025	8	b1
28	1016	6/13/97	0822	9	b1
28	1016	9/12/94	1026	10	b1
28	1016	10/15/93	1345	6	b1
28	1016	10/15/93	1345	7	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
28	1016	10/15/93	1345	9	b1
28	1016	10/15/93	1346	10	b1
28	1016	11/9/93	0933	9	b1
28	1016	11/9/93	0933	10	b1
28	1016	11/9/93	1336	9	b1
28	1016	11/9/93	1336	10	b1
28	1016	12/6/93	1349	9	b1
28	1016	7/13/94	1330	10	b1
28	1016	12/6/93	0946	9	b1
28	1016	6/15/94	0950	8	b1
28	1016	6/15/94	0951	9	b1
28	1016	6/15/94	0951	10	b1
28	1016	6/16/94	1315	7	b1
28	1016	6/16/94	1315	8	b1
28	1016	6/16/94	1316	9	b1
28	1016	6/16/94	1316	10	b1
28	1016	7/13/94	1329	7	b1
28	1016	4/11/94	1307	10	b1
28	1016	7/13/94	1330	9	b1
28	1016	4/11/94	1307	9	b1
28	1016	8/7/94	1551	7	b1
28	1802	8/7/94	1551	8	b1
28	1802	8/7/94	1552	9	b1
30	8129	8/7/94	1553	10	b1
30	8129	8/8/94	0929	7	b1
30	8129	8/8/94	0929	8	b1
30	8129	8/8/94	0930	9	b1
30	8129	8/8/94	0930	10	b1
30	8129	9/12/94	1025	7	b1
30	8129	7/13/94	1329	8	b1
30	8129	2/14/94	1629	9	b1
30	8129	9/12/94	1026	9	b1
30	8129	12/6/93	1349	10	b1
30	8129	1/18/94	0942	9	b1
30	8129	1/18/94	0942	10	b1
30	8129	1/18/94	1345	9	b1
30	8129	1/18/94	1345	10	b1
30	8129	2/14/94	0952	9	b1
30	8129	2/14/94	0952	10	b1
30	8129	2/14/94	1355	9	b1
30	8129	6/15/94	0950	7	b1
30	8129	2/14/94	1628	8	b1
30	8129	12/6/93	0946	10	b1
30	8129	3/14/94	0837	9	b1
30	8129	3/14/94	0837	10	b1
30	8129	3/14/94	1240	9	b1
30	8129	3/14/94	1240	10	b1
30	8129	3/14/94	1643	9	b1
30	8129	3/14/94	1643	10	b1
30	8129	3/28/94	0853	9	b1
30	8129	3/28/94	0853	10	b1
30	8129	3/28/94	1256	10	b1
30	8129	4/11/94	0904	10	b1
30	8129	2/14/94	1355	10	b1
30	8129	7/9/97	0822	4	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
30	8129	7/9/97	0821	3	b1
30	8129	8/18/97	0929	8	OT
30	8129	3/26/97	1301	7	OT
30	8129	12/18/96	0927	9	b1
30	8129	11/20/96	1345	4	b1
30	8129	11/20/96	1346	5	b1
30	8129	11/20/96	1346	6	b1
33	1001	11/20/96	1405	4	b1
33	1001	11/20/96	1406	5	b1
33	1001	11/20/96	1406	6	b1
33	1001	12/18/96	0923	2	b1
33	1001	12/18/96	0925	6	b1
33	1001	11/20/96	0839	5	b1
33	1001	1/28/97	1101	1	b1
33	1001	1/28/97	1102	2	b1
33	1001	1/28/97	1105	8	b1
33	1001	1/28/97	1106	9	b1
33	1001	1/29/97	0847	1	b1
33	1001	2/19/97	0949	1	b1
33	1001	3/26/97	0853	1	b1
33	1001	3/26/97	1259	1	b1
33	1001	12/18/96	0925	5	b1
33	1001	3/2/95	1043	2	b1
33	1001	11/1/94	0603	3	b1
33	1001	11/1/94	1007	3	b1
35	1112	12/6/94	0629	3	b1
35	1112	12/6/94	1034	3	b1
35	1112	1/4/95	0632	2	b1
35	1112	1/4/95	1037	2	b1
35	1112	1/4/95	1441	2	b1
35	1112	2/7/95	0637	2	b1
35	1112	11/20/96	1344	2	b1
35	1112	2/7/95	1445	2	b1
35	1112	11/20/96	0839	6	b1
35	1112	5/2/95	0615	3	b1
35	1112	5/2/95	1020	3	b1
35	1112	5/2/95	1423	3	b1
35	1112	6/14/95	1010	3	b1
35	1112	11/20/96	0837	2	b1
35	1112	11/20/96	0837	3	b1
35	1112	11/20/96	0838	4	b1
35	1112	4/24/97	1253	9	b1
35	1112	2/7/95	1042	2	b1
35	1112	4/24/97	0831	9	b1
35	1112	6/28/97	1728	4	b1
35	1112	4/28/97	0916	1	b1
35	1112	4/28/97	1323	1	b1
35	1112	5/18/97	1448	2	b1
35	1112	5/18/97	1452	10	b1
35	1112	5/19/97	0856	5	b1
35	1112	5/19/97	0856	6	b1
35	1112	5/19/97	1301	5	b1
35	1112	6/28/97	1715	6	b1
35	1112	4/24/97	0831	10	b1
35	1112	6/28/97	1729	5	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
35	1112	7/9/97	0820	1	b1
35	1112	7/9/97	1113	2	b1
35	1112	7/10/97	0837	4	b1
35	1112	9/30/97	1039	1	b1
35	1112	5/19/97	1302	6	b1
35	1112	10/11/94	1504	3	b1
35	1112	3/10/94	0655	10	b1
35	1112	6/7/94	0609	3	b1
36	4018	6/7/94	1013	3	b1
36	4018	12/1/93	1137	6	b1
36	4018	1/20/94	1116	10	b1
36	4018	2/24/94	0615	2	b1
36	4018	2/24/94	0616	4	b1
36	4018	2/24/94	1020	2	b1
36	4018	2/24/94	1021	4	b1
36	4018	2/24/94	1423	4	b1
36	4018	2/24/94	1425	10	b1
36	4018	12/1/93	0733	5	b1
36	4018	6/7/94	1415	3	b1
36	4018	7/6/94	0612	3	b1
36	4018	7/6/94	1016	3	b1
36	4018	7/6/94	1418	3	b1
36	4018	7/6/94	1820	3	b1
36	4018	8/2/94	0608	3	b1
36	4018	8/2/94	1012	3	b1
36	4018	8/2/94	1414	3	b1
36	4018	8/2/94	1816	3	b1
36	4018	3/10/94	1501	4	b1
36	4018	12/1/93	1137	5	b1
36	4018	12/1/93	0734	6	b1
36	4018	9/7/94	1710	3	b1
36	4018	8/21/97	1335	1	OT
36	4018	12/29/94	0649	4	b1
36	4018	12/29/94	0648	2	b1
36	4018	11/10/94	1002	2	b1
37	0212	11/10/94	1405	2	b1
37	1028	4/13/95	1015	2	b1
37	1028	9/17/97	1257	1	b1
37	1028	9/17/97	0849	1	b1
37	1028	6/8/95	0957	2	b1
37	1028	6/8/95	0552	2	b1
40	4165	5/12/95	1011	2	b1
40	4165	5/12/95	0606	2	b1
40	4165	3/9/95	0605	4	b1
40	4165	2/24/95	1031	2	b1
40	4165	12/29/94	1054	4	b1
40	4165	1/27/95	0649	2	b1
40	4165	1/27/95	0650	4	b1
40	4165	1/27/95	1054	2	b1
40	4165	1/27/95	1055	4	b1
40	4165	4/13/95	1418	2	b1
40	4165	2/24/95	0627	4	b1
42	1606	4/13/95	1016	4	b1
42	1606	2/24/95	1032	4	b1
42	1606	3/9/95	0604	2	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
46	0804	3/9/95	1009	2	b1
46	0804	3/9/95	1010	4	b1
46	0804	4/13/95	0610	2	b1
46	0804	12/29/94	1053	2	b1
46	0804	2/24/95	0626	2	b1
46	0804	8/15/94	0550	2	b1
46	0804	7/14/94	1400	2	b1
46	0804	2/11/94	1143	4	b1
46	0804	4/13/94	1054	10	b1
46	0804	6/27/94	0658	2	b1
46	0804	6/27/94	1102	2	b1
46	0804	6/27/94	1505	2	b1
46	0804	6/27/94	1907	2	b1
46	0804	7/14/94	0553	2	b1
46	0804	2/11/94	0739	4	b1
46	0804	2/11/94	0738	2	b1
46	0804	8/15/94	0954	2	b1
46	0804	8/15/94	1356	2	b1
46	0804	8/15/94	1758	2	b1
46	0804	9/15/94	0551	2	b1
46	0804	9/15/94	0955	2	b1
46	0804	9/15/94	1357	2	b1
46	0804	10/20/94	0715	2	b1
46	0804	10/20/94	1119	2	b1
46	0804	7/14/94	0958	2	b1
46	0804	11/10/94	0558	2	b1
46	0804	2/11/94	0742	10	b1
46	0804	12/16/93	0659	4	b1
46	0804	12/16/93	1104	4	b1
46	0804	12/16/93	1507	4	b1
46	0804	8/21/97	0929	4	a1
46	0804	8/21/97	1337	4	a1
46	0804	6/10/97	0840	2	OT
46	0804	6/10/97	1246	2	OT
46	0804	6/10/97	0839	1	OT
46	0804	3/20/97	0853	1	b1
46	0804	2/15/97	1227	1	b1
46	0804	2/15/97	0821	1	b1
46	0804	1/23/97	0753	1	b1
46	0804	12/11/96	1240	2	b1
46	0804	12/11/96	0835	2	b1
46	0804	11/13/96	0741	1	b1
46	0804	4/21/97	0819	1	b1
46	0804	5/16/97	0836	5	b1
46	0804	3/20/97	1259	1	b1
46	0804	6/24/97	0940	3	OT
46	0804	5/30/97	1258	4	OT
46	0804	5/30/97	1257	3	OT
46	0804	5/30/97	0852	4	OT
46	0804	5/30/97	0851	3	OT
46	0804	8/25/97	0938	4	OT
46	0804	5/30/97	0851	2	OT
46	0804	6/24/97	0941	4	OT
46	0804	3/28/95	1505	9	b1
46	9187	3/28/95	0658	9	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
46	9187	2/4/97	0844	9	b1
46	9187	2/4/97	1247	9	b1
46	9187	3/11/97	0855	9	b1
46	9187	3/11/97	1258	9	b1
46	9187	4/15/97	0839	10	b1
46	9187	4/15/97	1244	10	b1
46	9187	7/29/97	0933	2	b1
46	9187	11/25/96	0945	9	b1
46	9187	1/18/95	1514	9	b1
46	9187	7/20/94	0630	8	b1
46	9187	8/23/94	0653	8	b1
46	9187	8/23/94	1056	8	b1
46	9187	8/23/94	1458	8	b1
46	9187	12/20/94	0707	9	b1
46	9187	12/20/94	1111	9	b1
46	9187	12/4/96	0838	9	b1
46	9187	1/18/95	1110	9	b1
46	9187	11/25/96	0945	10	b1
46	9187	2/27/95	0636	9	b1
46	9187	2/27/95	1039	9	b1
46	9187	3/28/95	1101	9	b1
46	9187	4/25/95	0613	9	b1
46	9187	4/25/95	1016	9	b1
46	9187	4/25/95	1419	9	b1
46	9187	1/18/95	0707	9	b1
46	9187	5/28/97	1540	7	a1
46	9187	5/28/97	1539	5	a1
46	9187	7/29/97	0934	4	a1
46	9187	11/21/96	1415	1	b1
46	9187	11/21/96	1217	1	b1
46	9187	11/21/96	1236	1	b1
46	9187	11/21/96	1221	8	b1
46	9187	8/8/96	1300	10	a1
46	9187	5/2/96	1318	2	a1
46	9187	6/6/96	0844	2	a1
46	9187	9/25/97	1336	10	OT
46	9187	9/11/96	1057	9	b1
46	9187	9/11/96	1057	10	b1
46	9187	9/11/96	1434	9	b1
46	9187	9/11/96	1434	10	b1
46	9187	6/19/97	0841	6	b1
46	9187	6/19/97	1246	5	b1
46	9187	6/19/97	1246	6	b1
46	9187	7/24/97	1440	6	b1
46	9187	8/21/97	0929	10	b1
46	9187	8/21/97	0927	6	b1
46	9187	9/25/97	0932	10	b1
46	9187	9/25/97	1336	9	b1
46	9187	10/30/97	0958	10	b1
46	9187	10/30/97	1410	10	b1
46	9187	8/21/97	0929	9	b1
46	9187	11/12/97	0836	9	OT
46	9187	11/12/97	1240	9	OT
46	9187	1/17/96	0848	1	b1
46	9187	2/28/96	1249	4	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
46	9187	3/13/96	1310	4	b1
46	9187	5/8/96	0842	4	b1
46	9187	4/17/96	0835	4	b1
46	9187	7/16/97	1055	8	b1
46	9187	4/17/97	0833	7	OT
46	9187	2/11/97	0830	7	OT
46	9187	12/11/96	0908	7	OT
46	9187	4/17/97	0831	4	OT
46	9187	9/16/97	1327	6	b1
46	9187	9/16/97	1327	9	b1
46	9187	6/18/97	0908	6	b1
46	9187	6/21/95	0837	8	b1
46	9187	6/21/95	1241	5	b1
46	9187	6/21/95	1241	6	b1
46	9187	6/21/95	1241	7	b1
46	9187	6/21/95	1241	8	b1
46	9187	10/16/96	0831	8	b1
46	9187	6/2/97	0842	6	b1
46	9187	6/21/95	0836	6	b1
46	9187	6/18/97	0845	6	b1
46	9187	6/21/95	0836	5	b1
46	9187	6/18/97	1312	6	b1
46	9187	7/16/97	1055	6	b1
46	9187	8/19/97	0853	6	b1
46	9187	8/19/97	0853	8	b1
46	9187	8/19/97	0853	9	b1
46	9187	9/16/97	0923	6	b1
46	9187	9/16/97	0923	8	b1
46	9187	9/16/97	0923	9	b1
46	9187	6/2/97	1249	6	b1
46	9187	6/17/94	0708	6	b1
46	9187	9/16/97	1327	8	b1
46	9187	6/21/95	0837	7	b1
46	9187	7/25/94	0655	6	b1
46	9187	7/25/94	1059	6	b1
46	9187	8/18/94	0741	6	b1
46	9187	8/18/94	1144	6	b1
46	9187	9/21/94	0812	6	b1
46	9187	9/21/94	1216	6	b1
46	9187	6/21/95	0807	5	b1
46	9187	6/21/95	0807	6	b1
46	9187	6/21/95	0807	7	b1
46	9187	10/16/96	0931	4	a1
46	9187	3/18/96	0704	2	b1
46	9187	3/18/96	0705	4	b1
46	9187	11/7/96	0947	8	OT
46	9187	11/7/96	1352	8	OT
46	9187	9/8/95	0833	5	b1
46	9187	3/5/97	0851	8	b1
46	9187	1/10/97	1215	8	b1
46	9187	4/21/97	0827	8	b1
46	9187	4/21/97	1307	8	b1
46	9187	4/21/97	1307	10	OT
46	9187	4/21/97	0827	10	OT
46	9187	4/26/94	1205	10	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
46	9187	3/23/94	1210	2	b1
46	9187	3/23/94	1210	3	b1
46	9187	3/23/94	1212	9	b1
46	9187	3/23/94	1212	10	b1
46	9187	3/23/94	1613	2	b1
46	9187	3/23/94	1613	3	b1
46	9187	3/23/94	1615	9	b1
46	9187	3/23/94	1615	10	b1
46	9187	7/11/94	1440	2	b1
46	9187	4/26/94	1205	9	b1
46	9187	3/23/94	0805	3	b1
46	9187	4/26/94	1608	8	b1
46	9187	4/26/94	1608	9	b1
46	9187	4/26/94	1608	10	b1
46	9187	6/20/94	0913	2	b1
46	9187	6/20/94	0917	10	b1
46	9187	6/20/94	1318	2	b1
46	9187	7/11/94	1035	2	b1
48	1060	4/26/94	1204	8	b1
48	1060	3/9/94	1228	8	b1
48	1060	3/9/94	0822	2	b1
48	1060	3/9/94	0822	3	b1
48	1060	3/9/94	0825	8	b1
48	1060	3/9/94	0826	9	b1
48	1060	3/9/94	0826	10	b1
48	1060	3/23/94	0809	10	b1
48	1060	3/9/94	1227	3	b1
48	1060	3/23/94	0809	9	b1
48	1060	3/9/94	1229	9	b1
48	1060	3/9/94	1229	10	b1
48	1060	3/9/94	1630	2	b1
48	1060	3/9/94	1630	3	b1
48	1060	3/9/94	1631	8	b1
48	1060	3/9/94	1632	9	b1
48	1060	3/9/94	1632	10	b1
48	1060	3/23/94	0805	2	b1
48	1060	8/2/94	0834	2	b1
48	1060	3/9/94	1227	2	b1
48	1060	3/29/95	1333	2	b1
48	1060	2/23/95	1253	2	b1
48	1060	2/23/95	1253	3	b1
48	1060	2/23/95	1656	2	b1
48	1060	2/23/95	1656	3	b1
48	1060	3/13/95	0824	2	b1
48	1060	3/13/95	1229	2	b1
48	1060	3/13/95	1632	2	b1
48	1060	3/29/95	0927	2	b1
48	1060	7/11/94	1035	3	b1
48	1060	3/29/95	0932	10	b1
48	1060	2/10/95	1351	3	b1
48	1060	3/29/95	1336	9	b1
48	1060	3/29/95	1336	10	b1
48	1060	4/18/95	1118	2	b1
48	1060	4/18/95	1122	9	b1
48	1060	4/18/95	1122	10	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
48	1060	5/24/95	0818	10	b1
48	1060	2/7/97	0848	8	b1
48	1060	2/7/97	0848	10	b1
48	1060	3/29/95	0931	9	b1
48	1060	11/4/94	1302	10	b1
48	1060	8/2/94	0834	3	b1
48	1060	8/2/94	1239	2	b1
48	1060	8/2/94	1239	3	b1
48	1060	8/2/94	1642	2	b1
48	1060	8/2/94	1642	3	b1
48	1060	9/7/94	0936	2	b1
48	1060	9/7/94	1341	2	b1
48	1060	9/7/94	1744	2	b1
48	1060	2/23/95	0848	3	b1
48	1060	11/4/94	0858	10	b1
48	1060	2/23/95	0848	2	b1
48	1060	11/29/94	0903	2	b1
48	1060	11/29/94	1505	2	b1
48	1060	1/12/95	0940	2	b1
48	1060	1/12/95	0940	3	b1
48	1060	1/12/95	1345	2	b1
48	1060	1/12/95	1345	3	b1
48	1060	2/10/95	0948	2	b1
48	1060	2/10/95	1351	2	b1
48	1060	9/7/94	1848	2	b1
48	1060	6/10/97	1231	7	b1
48	1060	2/7/97	1251	8	b1
48	1060	2/7/97	1251	10	b1
48	1060	5/16/97	0846	10	b1
48	1060	3/5/97	0851	10	b1
48	1060	3/17/97	0850	10	b1
48	1060	3/17/97	0902	2	b1
48	1060	3/17/97	0902	8	b1
48	1060	4/3/97	0844	8	b1
48	1060	4/21/97	0827	2	b1
48	1060	4/21/97	1307	2	b1
48	1060	5/16/97	0846	2	b1
48	1060	5/16/97	0846	7	b1
48	1060	5/16/97	0846	9	b1
48	1060	6/10/97	0827	8	b1
48	1060	6/10/97	0827	10	b1
48	1060	6/10/97	1231	2	b1
48	1060	6/10/97	1231	8	b1
48	1060	6/10/97	1231	10	b1
48	1060	5/16/97	0846	8	b1
48	1060	6/10/97	1231	4	a1
48	1060	3/23/94	0806	5	a1
48	1060	3/23/94	1211	5	a1
48	1060	6/16/94	1159	9	OT
48	1060	4/18/95	0822	8	b1
48	1068	4/18/95	1225	8	b1
48	1068	4/4/95	0811	6	b1
48	1068	4/4/95	0811	8	b1
48	1068	1/22/96	0736	8	OT
48	1068	3/26/96	1035	10	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
48	1068	8/20/96	0823	5	b1
48	1068	8/20/96	1227	5	b1
48	1068	9/25/96	0814	5	b1
48	1068	9/25/96	1218	5	b1
48	1068	9/25/96	1622	5	b1
48	1068	10/16/96	0812	5	b1
48	1068	3/26/96	1035	9	b1
48	1068	8/26/96	0810	6	b1
48	1068	4/25/94	1103	1	b1
48	1068	4/25/94	0657	1	b1
48	1068	4/25/94	1506	1	b1
48	1068	3/9/94	1622	1	b1
48	1068	6/20/97	1230	8	b1
48	1068	6/20/97	1230	9	b1
48	1068	8/18/97	0858	3	b1
48	1068	6/20/97	1230	3	b1
48	1068	9/15/97	1006	3	b1
48	1068	9/15/97	1410	3	b1
48	1068	6/20/97	0826	3	b1
48	1068	7/17/97	0824	3	b1
48	1068	5/31/97	1221	4	b1
48	1068	5/31/97	1221	7	b1
48	1068	6/20/97	0826	9	b1
48	1068	12/10/96	0910	6	OT
48	1068	12/10/96	0910	5	OT
48	1068	5/31/97	1221	6	MT
48	1068	9/20/94	1205	5	b1
48	1068	9/20/94	0802	3	b1
48	1068	9/20/94	0802	4	b1
48	1068	9/20/94	0802	5	b1
48	1068	9/20/94	0802	6	b1
48	1068	9/20/94	0802	7	b1
48	1068	9/20/94	0802	8	b1
48	1068	9/20/94	0802	9	b1
48	1068	9/20/94	0802	10	b1
48	1068	10/18/94	0800	8	b1
48	1068	9/20/94	1205	4	b1
48	1068	8/22/94	1546	8	b1
48	1068	9/20/94	1205	6	b1
48	1068	9/20/94	1205	7	b1
48	1068	9/20/94	1205	8	b1
48	1068	9/20/94	1205	9	b1
48	1068	9/20/94	1205	10	b1
48	1068	10/18/94	0800	4	b1
48	1068	10/18/94	0800	5	b1
48	1068	10/18/94	0800	6	b1
48	1068	10/15/96	1036	6	b1
48	1068	9/20/94	1205	3	b1
48	1068	8/22/94	1143	7	b1
48	1068	8/22/94	0740	4	b1
48	1068	8/22/94	0740	5	b1
48	1077	8/22/94	0740	6	b1
48	1077	8/22/94	0740	7	b1
48	1077	8/22/94	0740	8	b1
48	1077	8/22/94	0740	9	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
48	1077	8/22/94	0740	10	b1
48	1077	8/22/94	1143	3	b1
48	1077	8/22/94	1143	4	b1
48	1077	8/22/94	1546	10	b1
48	1077	8/22/94	1143	6	b1
48	1077	8/22/94	1546	9	b1
48	1077	8/22/94	1143	8	b1
48	1077	8/22/94	1143	9	b1
48	1077	8/22/94	1143	10	b1
48	1122	8/22/94	1546	3	b1
48	1122	8/22/94	1546	4	b1
48	1122	8/22/94	1546	5	b1
48	1122	8/22/94	1546	6	b1
48	3739	8/22/94	1546	7	b1
48	3739	10/18/94	0800	9	b1
48	3739	8/22/94	1143	5	b1
48	3739	12/13/94	1535	6	b1
48	4142	12/13/94	1536	7	b1
48	4142	12/13/94	1536	8	b1
48	4142	12/13/94	1537	9	b1
48	4142	12/13/94	1537	10	b1
48	4142	12/13/94	1548	6	b1
48	4142	12/13/94	1549	7	b1
48	4142	12/13/94	1549	8	b1
48	4142	10/18/94	0800	7	b1
48	4142	12/13/94	1550	10	b1
48	4142	11/15/94	1152	9	b1
48	4142	3/15/95	0833	10	b1
48	4142	5/16/95	0950	6	b1
48	4142	5/16/95	0951	7	b1
48	4142	5/16/95	1354	4	b1
48	4142	5/16/95	1354	6	b1
48	4142	5/16/95	1354	7	b1
48	4142	10/15/96	1036	4	b1
48	4142	10/15/96	1036	5	b1
48	4142	12/13/94	1550	9	b1
48	4142	11/15/94	0747	6	b1
48	4142	10/18/94	0800	10	b1
48	4142	10/18/94	1202	4	b1
48	4142	10/18/94	1202	5	b1
48	4142	10/18/94	1202	6	b1
48	4142	10/18/94	1202	7	b1
48	4142	10/18/94	1203	8	b1
48	4142	10/18/94	1203	9	b1
48	4142	10/18/94	1203	10	b1
48	4142	11/15/94	0745	3	b1
48	4142	12/13/94	1535	5	b1
48	4142	11/15/94	0747	5	b1
48	4142	11/15/94	1152	10	b1
48	4142	11/15/94	0748	7	b1
48	4142	11/15/94	0748	8	b1
48	4142	11/15/94	0749	9	b1
48	4142	11/15/94	0749	10	b1
48	4142	11/15/94	1151	4	b1
48	4142	11/15/94	1151	6	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
48	4142	11/15/94	1151	7	b1
48	4142	11/15/94	1152	8	b1
48	4142	7/26/94	1100	9	b1
48	4142	11/15/94	0746	4	b1
48	4142	8/22/94	0740	3	b1
48	4142	10/15/93	0834	8	b1
48	4142	10/15/93	0835	9	b1
48	4142	10/15/93	0835	10	b1
48	4142	10/15/93	1231	8	b1
48	4142	10/15/93	1232	9	b1
48	4142	10/15/93	1232	10	b1
48	4142	11/15/93	1333	4	b1
48	4142	11/15/93	1333	5	b1
48	4142	11/15/93	1335	8	b1
48	4142	7/26/94	0710	8	b1
48	4142	11/15/93	1334	6	b1
48	4142	6/20/94	1103	5	b1
48	4142	6/20/94	1103	6	b1
48	4142	6/20/94	1103	7	b1
48	4142	6/20/94	1103	8	b1
48	4142	6/20/94	1103	9	b1
48	4142	7/26/94	0707	3	b1
48	4142	7/26/94	0708	4	b1
48	4142	7/26/94	0709	5	b1
48	4142	6/20/94	0700	9	b1
48	4142	7/26/94	0710	7	b1
48	4142	6/20/94	0700	8	b1
48	4142	7/26/94	0711	9	b1
48	4142	7/26/94	0711	10	b1
48	4142	7/26/94	1100	3	b1
48	4142	7/26/94	1100	4	b1
48	4142	7/26/94	1100	5	b1
48	4142	7/26/94	1100	6	b1
48	4142	7/26/94	1100	7	b1
48	4142	7/26/94	1100	8	b1
48	4142	5/16/95	0949	4	b1
48	4142	7/26/94	0709	6	b1
48	4142	12/14/93	1200	10	b1
48	4142	7/26/94	1100	10	b1
48	4142	11/15/93	1336	9	b1
48	4142	11/15/93	1336	10	b1
48	4142	12/14/93	0755	6	b1
48	4142	12/14/93	0756	7	b1
48	4142	12/14/93	0756	8	b1
48	4142	12/14/93	0757	9	b1
48	4142	12/14/93	0757	10	b1
48	4142	12/14/93	1159	5	b1
48	4142	6/20/94	1103	4	b1
48	4142	12/14/93	1200	9	b1
48	4142	11/15/93	1335	7	b1
48	4142	1/18/94	1356	9	b1
48	4142	1/18/94	1356	10	b1
48	4142	5/16/94	0735	6	b1
48	4142	5/16/94	1140	6	b1
48	4142	6/20/94	0700	3	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
48	4142	6/20/94	0700	4	b1
48	4142	6/20/94	0700	5	b1
48	4142	6/20/94	0700	6	b1
48	4142	6/20/94	0700	7	b1
48	4142	12/14/93	1159	6	b1
48	4142	1/26/95	1026	8	b1
48	4142	7/17/97	0824	8	b1
48	4142	8/18/97	0858	5	b1
48	4142	7/17/97	0824	4	b1
48	4142	10/15/96	1439	5	b1
48	4142	10/15/96	1439	4	b1
48	4142	7/17/97	0824	5	b1
48	4142	7/17/97	0824	6	b1
48	4142	10/15/96	1439	6	b1
48	4142	7/17/97	0824	7	b1
48	4142	10/15/96	1036	9	b1
48	4142	7/17/97	0824	9	b1
48	4142	7/17/97	0824	10	b1
48	4142	10/15/96	1036	8	b1
48	4142	6/20/97	1230	7	b1
48	4142	8/18/97	0858	4	b1
48	4142	10/15/96	1036	10	b1
48	4142	6/20/97	0826	7	b1
48	4142	6/20/97	0826	5	b1
48	4142	6/20/97	0826	4	b1
48	4142	12/10/96	0912	10	b1
48	4142	12/10/96	0912	9	b1
48	4142	6/20/97	0826	6	b1
48	4142	12/10/96	0911	8	b1
48	4142	10/15/96	1439	9	b1
48	4142	10/15/96	1036	7	b1
48	4142	6/20/97	0826	8	b1
48	4142	6/20/97	1230	4	b1
48	4142	6/20/97	1230	5	b1
48	4142	10/15/96	1439	8	b1
48	4142	10/15/96	1439	7	b1
48	4142	6/20/97	1230	6	b1
48	4142	10/15/96	1439	10	b1
48	4142	9/15/97	1410	6	b1
48	4142	9/15/97	1410	7	b1
48	4142	9/15/97	1410	9	b1
48	4142	9/15/97	1410	10	b1
48	4142	9/15/97	1410	5	b1
48	4142	9/15/97	1410	8	b1
48	4142	9/15/97	1006	6	b1
48	4142	8/18/97	0858	9	b1
48	4142	8/18/97	0858	10	b1
48	4142	8/18/97	0858	8	b1
48	4142	8/18/97	0858	7	b1
48	4142	9/15/97	1410	4	b1
48	4142	9/15/97	1006	4	b1
48	4142	9/15/97	1006	5	b1
48	4142	9/15/97	1006	7	b1
48	4142	8/18/97	0858	6	b1
48	4142	9/15/97	1006	8	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
48	4142	9/15/97	1006	9	b1
48	4142	9/15/97	1006	10	b1
48	4142	2/21/96	0929	9	OT
48	4142	7/8/97	0908	3	b1
48	4142	2/15/94	0739	1	OT
48	4142	2/15/94	0739	2	OT
48	4142	7/8/97	1314	1	OT
48	4142	2/15/94	0739	3	OT
48	4142	6/3/97	1242	1	OT
48	4142	6/3/97	0835	1	OT
48	4142	7/8/97	0907	1	OT
48	4142	2/15/94	1142	1	OT
48	4142	2/15/94	1142	3	OT
48	4142	2/15/94	1142	2	OT
48	4142	2/15/94	1142	6	OT
48	4142	2/15/94	1142	5	OT
48	4142	2/15/94	1142	4	OT
48	4142	2/28/95	0854	6	OT
48	4142	10/14/97	1323	3	b1
48	4142	10/14/97	0917	3	b1
48	4142	12/3/96	0916	3	b1
48	4142	7/29/94	1349	10	b1
48	4142	9/19/96	1619	3	b1
48	4142	12/3/96	1322	3	b1
48	4142	1/7/97	1256	3	b1
48	4142	4/15/97	0829	1	b1
48	4142	4/15/97	1236	1	b1
48	4142	9/9/97	0924	3	b1
48	4142	9/9/97	1330	3	b1
48	4142	9/19/96	1348	3	b1
48	4142	9/9/97	0852	9	b1
48	4142	10/9/96	1323	8	b1
48	4142	10/9/96	1323	10	b1
48	4142	6/10/97	1320	8	OT
48	4142	7/11/97	0831	3	OT
48	4142	7/11/97	0831	8	OT
48	4142	8/13/97	0837	3	OT
48	4143	8/13/97	0837	8	OT
48	4143	9/9/97	0852	3	OT
48	4143	6/10/97	0917	3	OT
48	4143	9/9/97	0852	8	OT
48	4143	2/5/97	1243	8	OT
48	4143	6/10/97	1320	3	OT
48	4143	6/10/97	0917	8	OT
48	4143	4/8/97	1445	3	OT
48	4143	4/22/97	0840	2	OT
48	4143	5/6/97	1046	3	OT
48	4143	5/6/97	1450	3	OT
48	4143	5/28/97	0848	3	OT
48	4143	5/28/97	0848	8	OT
48	4143	5/28/97	1252	3	OT
48	4143	5/28/97	1252	8	OT
48	4143	3/31/95	1200	3	b1
48	4143	10/13/94	0741	2	b1
48	4143	10/13/94	0744	7	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
48	4143	10/13/94	1148	2	b1
48	4143	10/13/94	1148	3	b1
48	4143	10/13/94	1148	7	b1
48	4143	11/10/94	0716	2	b1
48	4143	11/10/94	0719	7	b1
48	4143	11/10/94	1121	2	b1
48	4143	12/8/94	0754	8	b1
48	4143	3/31/95	0753	3	b1
48	4143	9/30/94	1200	2	b1
48	4143	4/14/95	0800	2	b1
48	4143	4/14/95	1216	3	b1
48	4143	4/28/95	0829	2	b1
48	4143	4/28/95	1234	3	b1
48	4143	5/11/95	0802	2	b1
48	4143	5/11/95	1205	2	b1
48	4143	5/11/95	1413	2	b1
48	4143	6/16/95	0842	6	b1
48	4143	6/16/95	0952	8	b1
48	4143	10/9/96	0834	6	b1
48	4143	3/31/95	0753	2	b1
48	4143	7/28/94	0709	3	b1
48	4143	5/4/94	0011	3	b1
48	4143	5/4/94	0433	3	b1
48	4143	5/18/94	0728	3	b1
48	4143	5/18/94	1131	3	b1
48	4143	6/23/94	0722	2	b1
48	4143	6/23/94	0722	3	b1
48	4143	6/23/94	0725	8	b1
48	4143	6/23/94	1049	2	b1
48	4143	6/23/94	1049	3	b1
48	4143	9/30/94	1201	7	b1
49	1001	7/28/94	0709	2	b1
49	1001	9/30/94	1200	3	b1
49	1001	7/28/94	0709	7	b1
49	1001	7/28/94	1112	2	b1
49	1001	7/28/94	1112	3	b1
49	1001	7/28/94	1112	7	b1
49	1001	8/25/94	0749	3	b1
49	1001	8/25/94	0749	7	b1
49	1001	8/25/94	1152	7	b1
49	1001	9/30/94	0759	2	b1
49	1001	9/30/94	0759	7	b1
49	1001	6/23/94	1049	8	b1
49	1001	8/13/97	0837	7	b1
49	1001	11/16/93	1322	3	b1
49	1001	5/4/94	0030	3	b1
49	1001	8/25/95	0748	2	b1
49	1001	8/5/96	1211	1	b1
49	1001	8/25/95	0858	1	b1
49	1001	8/25/95	0858	2	b1
49	1001	9/21/95	0833	2	b1
49	1001	9/21/95	1031	2	b1
49	1001	10/18/95	0753	2	b1
49	1001	10/18/95	1154	2	b1
49	1001	4/25/96	0802	2	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
49	1001	4/25/96	0837	2	b1
49	1001	4/25/96	1240	2	b1
49	1001	8/5/96	0806	2	b1
49	1001	8/25/95	0747	1	b1
49	1001	8/5/96	1211	2	b1
49	1001	8/5/96	0805	1	b1
49	1001	6/24/97	1318	4	OT
49	1001	12/12/96	0809	8	b1
49	1001	6/26/97	1254	8	b1
49	1001	5/10/95	1406	5	b1
49	1001	5/10/95	1406	6	b1
49	1001	6/6/95	0558	4	b1
49	1001	6/6/95	0559	5	b1
49	1001	6/6/95	0559	6	b1
49	1001	6/6/95	1003	4	b1
49	3011	6/6/95	1003	5	b1
49	3011	5/10/95	1003	6	b1
49	3011	12/12/96	0806	2	b1
49	3011	5/10/95	1003	5	b1
49	3011	12/12/96	1211	2	b1
49	3011	12/12/96	1213	8	b1
49	3011	2/17/97	0755	1	b1
49	3011	2/17/97	1201	1	b1
49	3011	2/17/97	1605	1	b1
49	3011	3/21/97	0846	3	b1
49	3011	6/24/97	1320	8	b1
49	3011	6/26/97	0849	8	b1
49	3011	2/14/95	1424	5	b1
49	3011	6/6/95	1003	6	b1
49	3011	4/11/95	1012	4	b1
49	3011	4/18/94	1451	2	b1
49	3011	3/7/95	0859	4	b1
49	3011	3/7/95	0900	5	b1
49	3011	3/7/95	0900	6	b1
49	3011	3/7/95	1304	4	b1
49	3011	3/7/95	1304	5	b1
49	3011	3/7/95	1304	6	b1
49	3011	4/11/95	0607	4	b1
49	3011	5/10/95	1406	4	b1
49	3011	4/11/95	0608	6	b1
49	3011	6/26/97	1254	9	b1
49	3011	4/11/95	1012	5	b1
49	3011	4/11/95	1012	6	b1
49	3011	4/11/95	1416	4	b1
49	3011	4/11/95	1416	5	b1
49	3011	4/11/95	1416	6	b1
49	3011	5/10/95	0558	4	b1
49	3011	5/10/95	0559	5	b1
49	3011	5/10/95	0559	6	b1
49	3011	5/10/95	1003	4	b1
49	3011	4/11/95	0608	5	b1
49	3011	6/26/97	0850	9	b1
49	3011	7/8/97	0808	8	b1
49	3011	7/8/97	0809	9	b1
49	3011	7/8/97	1213	8	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
49	3011	7/8/97	1213	9	b1
49	3011	8/19/97	1055	2	b1
49	3011	8/20/97	0811	8	b1
49	3011	8/20/97	0812	9	b1
49	3011	8/20/97	1220	8	b1
49	3011	2/14/95	1424	4	b1
49	3011	8/20/97	1220	9	b1
49	3011	7/12/94	0955	5	b1
49	3011	8/10/94	1001	2	b1
49	3011	6/1/94	1411	4	b1
49	3011	6/1/94	1411	5	b1
49	3011	6/1/94	1411	6	b1
49	3011	7/12/94	0550	2	b1
49	3011	7/12/94	0551	4	b1
49	3011	7/12/94	0552	5	b1
49	3011	7/12/94	0552	6	b1
49	3011	6/1/94	1009	6	b1
49	3011	7/12/94	0955	4	b1
49	3011	6/1/94	1009	5	b1
49	3011	7/12/94	0955	6	b1
49	3011	7/12/94	1357	2	b1
49	3011	7/12/94	1358	4	b1
49	3011	7/12/94	1358	5	b1
49	3011	7/12/94	1358	6	b1
49	3011	8/10/94	0557	2	b1
49	3011	8/10/94	0558	4	b1
49	3011	8/10/94	0559	5	b1
49	3011	2/14/95	1424	6	b1
49	3011	7/12/94	0954	2	b1
49	3011	5/18/94	1018	6	b1
49	3011	4/18/94	1451	4	b1
49	3011	4/18/94	1452	5	b1
49	3011	4/18/94	1452	6	b1
49	3011	5/18/94	0613	2	b1
49	3011	5/18/94	0614	4	b1
49	3011	5/18/94	0615	5	b1
49	3011	5/18/94	0615	6	b1
49	3011	5/18/94	1017	2	b1
49	3011	6/1/94	1410	2	b1
49	3011	5/18/94	1018	5	b1
49	3011	8/10/94	1002	4	b1
49	3011	5/18/94	1419	2	b1
49	3011	5/18/94	1420	4	b1
49	3011	5/18/94	1420	6	b1
49	3011	6/1/94	0605	4	b1
49	3011	6/1/94	0606	5	b1
49	3011	6/1/94	0606	6	b1
49	3011	6/1/94	1008	2	b1
49	3011	6/1/94	1009	4	b1
49	3011	5/18/94	1018	4	b1
49	3011	1/11/95	1038	6	b1
49	3011	8/10/94	0559	6	b1
49	3011	11/7/94	1640	4	b1
49	3011	11/7/94	1640	6	b1
49	3011	11/7/94	2042	4	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
49	3011	11/7/94	2042	6	b1
49	3011	1/11/95	0633	4	b1
49	3011	1/11/95	0634	5	b1
49	3011	1/11/95	0634	6	b1
49	3011	11/7/94	1236	4	b1
49	3011	1/11/95	1038	5	b1
49	3011	10/18/94	1135	6	b1
49	3011	1/11/95	1441	4	b1
49	3011	1/11/95	1441	5	b1
49	3011	1/11/95	1441	6	b1
49	3011	2/14/95	0616	4	b1
49	3011	2/14/95	0617	5	b1
49	3011	2/14/95	0617	6	b1
49	3011	2/14/95	1021	4	b1
49	3011	2/14/95	1021	5	b1
50	1002	2/14/95	1021	6	b1
50	1002	1/11/95	1038	4	b1
50	1002	9/13/94	0939	5	b1
50	1002	8/10/94	1002	6	b1
50	1002	8/10/94	1403	2	b1
50	1002	8/10/94	1404	4	b1
50	1002	8/10/94	1404	6	b1
50	1002	9/13/94	0534	2	b1
50	1002	9/13/94	0535	4	b1
50	1002	9/13/94	0536	5	b1
50	1002	9/13/94	0536	6	b1
50	1002	11/7/94	1237	6	b1
50	1002	9/13/94	0939	4	b1
50	1002	9/13/94	0939	6	b1
50	1002	9/13/94	1340	2	b1
50	1002	9/13/94	1341	4	b1
50	1002	9/13/94	1341	6	b1
50	1002	10/18/94	0731	4	b1
50	1002	10/18/94	0732	5	b1
50	1002	10/18/94	0732	6	b1
50	1002	10/18/94	1135	4	b1
50	1002	10/18/94	1135	5	b1
53	3813	9/13/94	0938	2	b1
83	1801	5/18/94	1420	5	b1
83	1801	6/1/94	0604	2	b1
83	1801	4/18/94	1049	6	b1
83	1801	3/21/94	0645	6	b1
83	1801	1/17/94	1216	1	b1
83	1801	1/17/94	1216	2	b1
83	1801	1/17/94	1216	4	b1
83	1801	1/17/94	1217	6	b1
83	1801	1/17/94	1619	1	b1
83	1801	1/17/94	1619	2	b1
83	1801	1/17/94	1619	4	b1
83	1801	1/17/94	1620	6	b1
83	1801	3/21/94	0642	1	b1
83	1801	1/17/94	0812	4	b1
83	1801	3/21/94	0644	4	b1
83	1801	1/17/94	0811	2	b1
83	1801	3/21/94	1048	1	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
83	1801	3/21/94	1048	4	b1
83	1801	3/21/94	1049	6	b1
83	1801	4/18/94	0643	2	b1
83	1801	4/18/94	0644	4	b1
83	1801	4/18/94	0644	5	b1
83	1801	4/18/94	0645	6	b1
83	1801	4/18/94	1048	2	b1
83	1801	4/18/94	1048	4	b1
83	1801	4/18/94	1049	5	b1
83	1801	3/21/94	0643	2	b1
83	1801	1/17/94	0813	6	b1
83	1801	12/21/93	1518	1	b1
83	1801	12/21/93	1519	2	b1
83	1801	12/21/93	1520	4	b1
83	1801	12/21/93	1521	6	b1
83	1801	1/17/94	0755	1	b1
83	1801	1/17/94	0756	2	b1
83	1801	1/17/94	0757	4	b1
83	1801	1/17/94	0758	6	b1
83	1801	1/17/94	0810	1	b1
83	1801	6/26/97	0849	7	a1
83	1801	6/26/97	1253	7	a1
83	1801	7/8/97	0808	7	a1
83	3802	7/8/97	1212	7	a1
83	3802	8/20/97	1219	7	a1
83	3802	8/20/97	0811	7	a1
83	3802	7/9/97	0821	3	b1
83	3802	7/9/97	0822	4	b1
83	3802	8/18/97	1235	8	OT
83	3802	2/18/97	0847	9	b1
83	3802	1/28/97	1101	1	b1
83	3802	1/28/97	1102	2	b1
83	3802	1/28/97	1105	8	b1
83	3802	1/28/97	1106	9	b1
83	3802	2/18/97	0830	5	b1
83	3802	2/18/97	0831	8	b1
83	3802	2/18/97	0832	9	b1
83	3802	12/17/96	0831	3	b1
83	3802	2/18/97	0846	8	b1
83	3802	11/19/96	0915	6	b1
83	3802	3/25/97	0846	5	b1
83	3802	3/25/97	0847	8	b1
83	3802	3/25/97	0848	9	b1
83	3802	3/25/97	1250	5	b1
83	3802	3/25/97	1251	8	b1
83	3802	3/25/97	1251	9	b1
83	3802	4/24/97	0831	9	b1
83	3802	4/24/97	0831	10	b1
83	3802	4/24/97	1251	5	b1
83	3802	2/18/97	0845	5	b1
83	3802	1/18/94	0700	1	b1
83	3802	12/17/96	0831	4	b1
83	3802	11/18/93	1156	1	b1
83	3802	1/18/94	1106	1	b1
83	3802	1/18/94	1509	1	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
83	3802	5/9/95	0549	3	b1
83	3802	5/9/95	0608	3	b1
83	3802	5/9/95	0611	7	b1
83	3802	5/9/95	1013	3	b1
83	3802	5/9/95	1418	3	b1
83	3802	6/5/95	1021	3	b1
83	3802	11/18/96	1534	6	b1
83	3802	5/18/97	0905	9	b1
83	3802	4/24/97	1253	9	b1
83	3802	5/18/97	1308	5	b1
83	3802	5/18/97	1309	9	b1
83	3802	6/27/97	0942	2	b1
83	3802	6/27/97	1348	2	b1
83	3802	7/9/97	0820	1	b1
83	3802	9/25/97	0823	9	b1
83	3802	9/25/97	0823	10	b1
83	3802	9/25/97	1227	10	b1
83	3802	9/25/97	1227	9	b1
83	3802	5/18/97	0903	5	b1
83	3802	12/17/96	0833	7	a1
83	3802	12/6/96	0850	6	OT
83	3802	12/6/96	1254	6	OT
83	3802	7/31/97	0923	5	a1
83	3802	7/31/97	0924	7	a1
83	3802	7/31/97	1333	7	a1
83	3802	8/26/97	1150	3	a1
83	3802	9/11/97	1002	5	a1
83	3802	9/11/97	1003	7	a1
83	3802	9/11/97	1408	7	a1
83	3802	7/31/97	1331	5	a1
83	3802	9/11/97	1407	5	a1
83	3802	5/28/97	0846	8	b1
83	3802	9/23/94	0916	8	b1
83	3802	7/22/94	1305	9	b1
83	3802	7/22/94	1305	10	b1
83	3802	7/22/94	1708	7	b1
83	3802	7/22/94	1708	8	b1
83	3802	7/22/94	1708	9	b1
83	3802	7/22/94	1708	10	b1
83	3802	8/22/94	1650	8	b1
83	3802	7/22/94	1305	7	b1
83	3802	8/22/94	1650	10	b1
83	3802	7/22/94	0901	8	b1
83	3802	9/23/94	0916	9	b1
83	3802	9/23/94	1319	8	b1
83	3802	9/23/94	1722	8	b1
83	3802	9/23/94	1722	10	b1
83	3802	11/21/96	1232	7	b1
83	3802	5/28/97	1250	9	b1
83	3802	6/18/97	1115	10	b1
83	3802	6/18/97	1519	8	b1
83	3802	6/18/97	1519	10	b1
83	3802	8/22/94	1650	9	b1
83	3802	6/6/94	0849	8	b1
83	3802	7/22/94	1305	8	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
83	3802	8/11/97	1337	7	b1
83	3802	6/6/94	0850	9	b1
83	3802	6/6/94	0850	10	b1
83	3802	6/6/94	1253	8	b1
83	3802	6/6/94	1253	9	b1
83	3802	6/6/94	1254	10	b1
83	3802	6/6/94	1713	8	b1
83	3802	6/6/94	1714	9	b1
83	3802	6/6/94	1714	10	b1
83	3802	7/22/94	0901	7	b1
83	3802	8/11/97	0933	7	b1
83	3802	8/11/97	1339	10	b1
83	3802	10/1/97	0827	10	b1
83	3802	8/11/97	0934	10	b1
83	3802	1/23/97	1339	9	a1
83	3802	2/20/95	0947	5	b1
83	3802	4/21/95	0748	4	b1
83	3802	12/19/94	0746	5	b1
83	3802	12/19/94	0746	6	b1
83	3802	12/19/94	1150	4	b1
83	3802	12/19/94	1150	5	b1
83	3802	12/19/94	1150	6	b1
83	3802	1/20/95	0851	5	b1
83	3802	1/20/95	0851	6	b1
83	3802	11/21/94	0819	7	b1
83	3802	2/20/95	0840	6	b1
83	3802	11/21/94	0818	6	b1
83	3802	3/10/95	0810	5	b1
83	3802	3/10/95	1215	5	b1
83	3802	3/10/95	1215	6	b1
83	3802	3/24/95	0833	4	b1
83	3802	3/24/95	0834	5	b1
83	3802	3/24/95	0834	6	b1
83	3802	3/24/95	1045	4	b1
83	3802	3/24/95	1046	5	b1
83	3802	2/20/95	0840	5	b1
83	3802	10/24/94	1217	6	b1
83	3802	10/24/94	0810	3	b1
83	3802	10/24/94	0811	4	b1
83	3802	10/24/94	0812	5	b1
83	3802	10/24/94	0812	6	b1
83	3802	10/24/94	0813	7	b1
83	3802	10/24/94	0813	8	b1
83	3802	10/24/94	0814	9	b1
83	3802	10/24/94	1217	3	b1
83	3802	12/19/94	0745	4	b1
83	3802	10/24/94	1217	5	b1
83	3802	4/21/95	0749	5	b1
83	3802	10/24/94	1217	7	b1
83	3802	10/24/94	1217	8	b1
83	3802	10/24/94	1217	9	b1
83	3802	11/21/94	0743	4	b1
83	3802	11/21/94	0744	5	b1
83	3802	11/21/94	0744	6	b1
83	3802	11/21/94	0745	7	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
83	3802	11/21/94	0817	4	b1
83	3802	11/21/94	0818	5	b1
83	3802	10/24/94	1217	4	b1
83	3802	6/26/95	1156	6	b1
83	3802	3/24/95	1046	6	b1
83	3802	6/26/95	0753	4	b1
83	3802	6/26/95	0753	5	b1
83	3802	6/26/95	0753	6	b1
83	3802	6/26/95	0753	7	b1
83	3802	6/26/95	0753	8	b1
83	3802	6/26/95	0753	9	b1
83	3802	6/26/95	1156	3	b1
83	3802	5/22/95	1405	8	b1
83	3802	6/26/95	1156	5	b1
83	3802	5/22/95	1405	7	b1
83	3802	6/26/95	1156	7	b1
83	3802	6/26/95	1156	8	b1
83	3802	6/26/95	1156	9	b1
83	3802	6/26/95	1453	3	b1
83	3802	6/26/95	1453	4	b1
83	3802	6/26/95	1453	5	b1
83	3802	6/26/95	1453	6	b1
83	3802	6/26/95	1453	7	b1
83	3802	6/26/95	1453	8	b1
83	3802	6/26/95	1156	4	b1
83	3802	5/22/95	1038	3	b1
83	3802	4/21/95	0749	6	b1
83	3802	4/21/95	1154	4	b1
83	3802	4/21/95	1154	5	b1
83	3802	4/21/95	1154	6	b1
83	3802	5/22/95	0836	3	b1
83	3802	5/22/95	0836	4	b1
83	3802	5/22/95	0836	5	b1
83	3802	5/22/95	0836	6	b1
83	3802	6/26/95	0753	3	b1
83	3802	5/22/95	0836	8	b1
83	3802	9/26/94	1152	7	b1
83	3802	5/22/95	1038	4	b1
83	3802	5/22/95	1038	5	b1
83	3802	5/22/95	1038	6	b1
83	3802	5/22/95	1038	7	b1
83	3802	5/22/95	1038	8	b1
83	3802	5/22/95	1405	3	b1
83	3802	5/22/95	1405	4	b1
83	3802	5/22/95	1405	5	b1
83	3802	5/22/95	1405	6	b1
83	3802	5/22/95	0836	7	b1
83	3802	9/26/94	1152	9	b1
83	3802	9/26/94	0747	5	b1
83	3802	8/11/94	0750	9	b1
83	3802	8/11/94	1153	3	b1
83	3802	8/11/94	1153	4	b1
83	3802	8/11/94	1153	5	b1
83	3802	8/11/94	1153	6	b1
83	3802	8/11/94	1153	7	b1

STATE_CODE	SHRP_ID	SMP_DATE	TDR_TIME	TDR_NO	Trace Error Type
83	3802	8/11/94	1153	8	b1
83	3802	8/11/94	1153	9	b1
83	3802	9/26/94	0746	4	b1
83	3802	8/11/94	0750	6	b1
83	3802	9/26/94	0747	6	b1
83	3802	9/26/94	0748	7	b1
83	3802	9/26/94	0748	8	b1
83	3802	9/26/94	0749	9	b1
83	3802	9/26/94	1152	3	b1
83	3802	9/26/94	1152	4	b1
83	3802	9/26/94	1152	5	b1
83	3802	9/26/94	1152	6	b1
83	3802	9/26/94	0745	3	b1
87	1622	7/19/94	0917	4	b1
87	1622	9/26/94	1152	8	b1
87	1622	7/19/94	0721	3	b1
87	1622	7/19/94	0721	4	b1
87	1622	7/19/94	0721	5	b1
87	1622	7/19/94	0721	6	b1
87	1622	7/19/94	0721	7	b1
87	1622	7/19/94	0721	8	b1
87	1622	8/11/94	0750	8	b1
87	1622	7/19/94	0916	3	b1
87	1622	8/11/94	0750	7	b1
87	1622	7/19/94	0918	5	b1
87	1622	7/19/94	0918	6	b1
87	1622	7/19/94	0919	7	b1
87	1622	7/19/94	0919	8	b1
87	1622	7/19/94	0920	9	b1
89	3015	8/11/94	0750	3	b1
89	3015	8/11/94	0750	4	b1
89	3015	8/11/94	0750	5	b1
89	3015	7/19/94	0721	9	b1
89	3015	6/26/95	1453	9	b1

APPENDIX B – SELECTED TDR TRACES FOR PRECISION AND BIAS STUDY OF THE COMPUTED APPARENT LENGTH

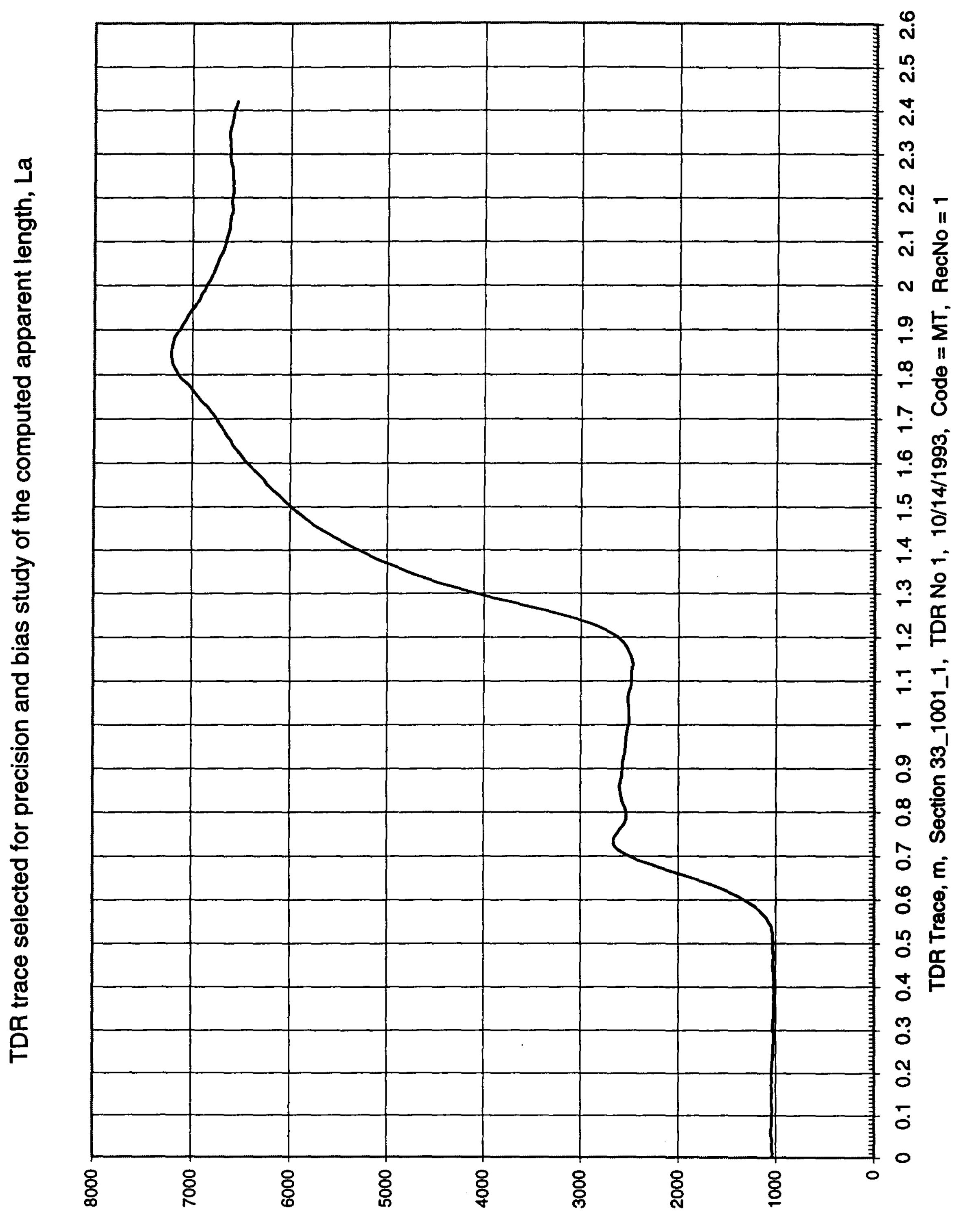


Figure 56. TDR trace 01 for precision and bias study.

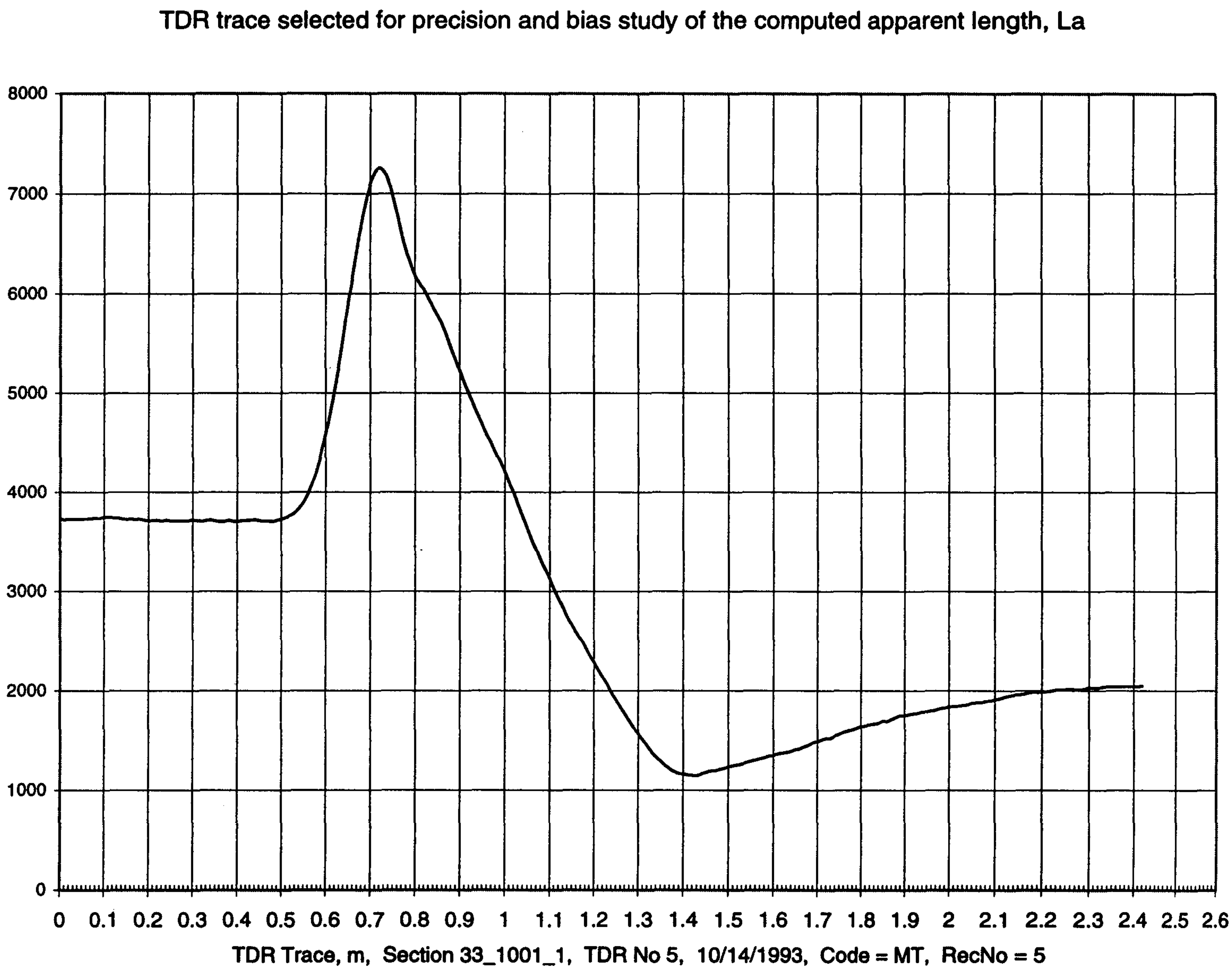


Figure 57. TDR trace 02 for precision and bias study.

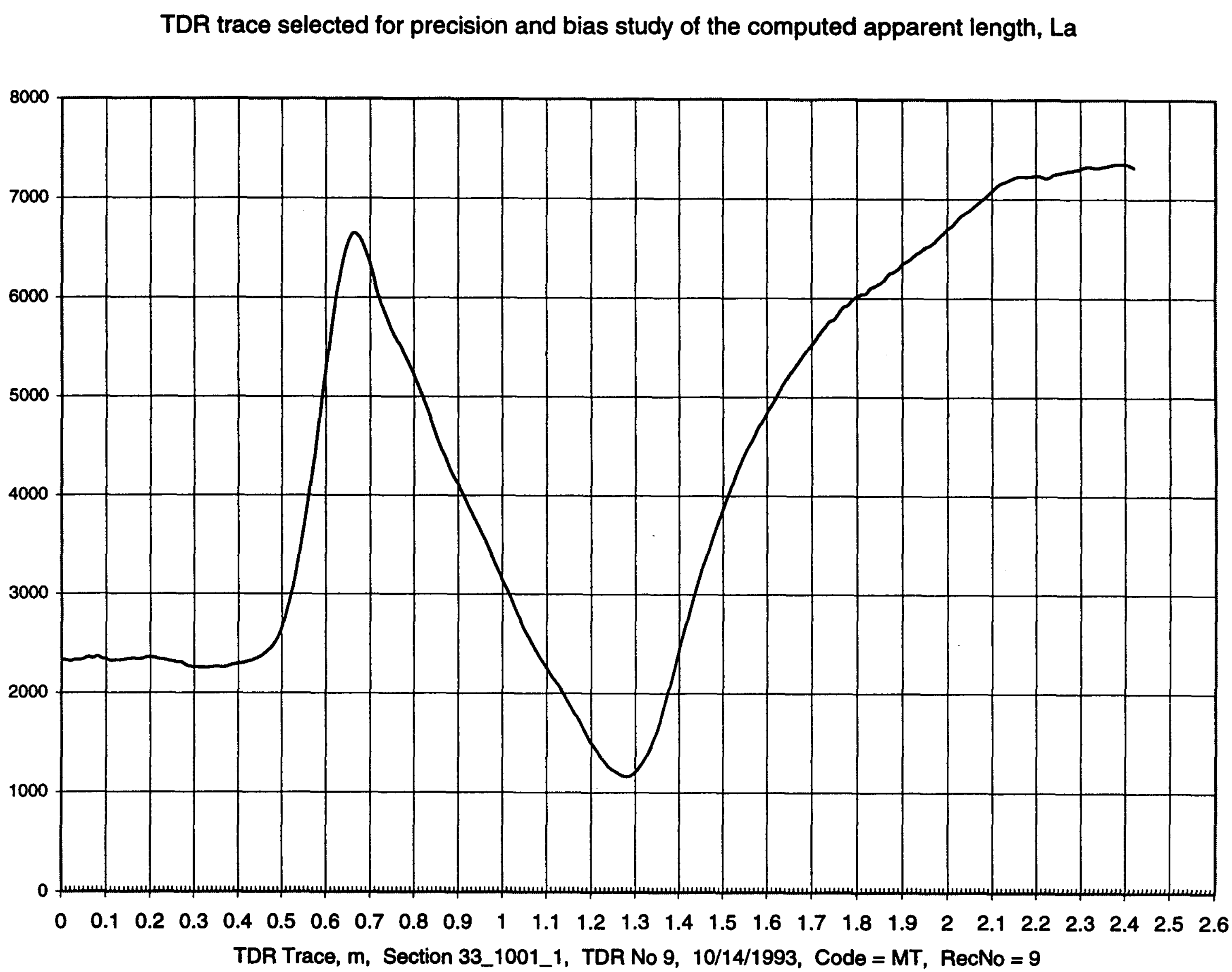


Figure 58. TDR trace 03 for precision and bias study.

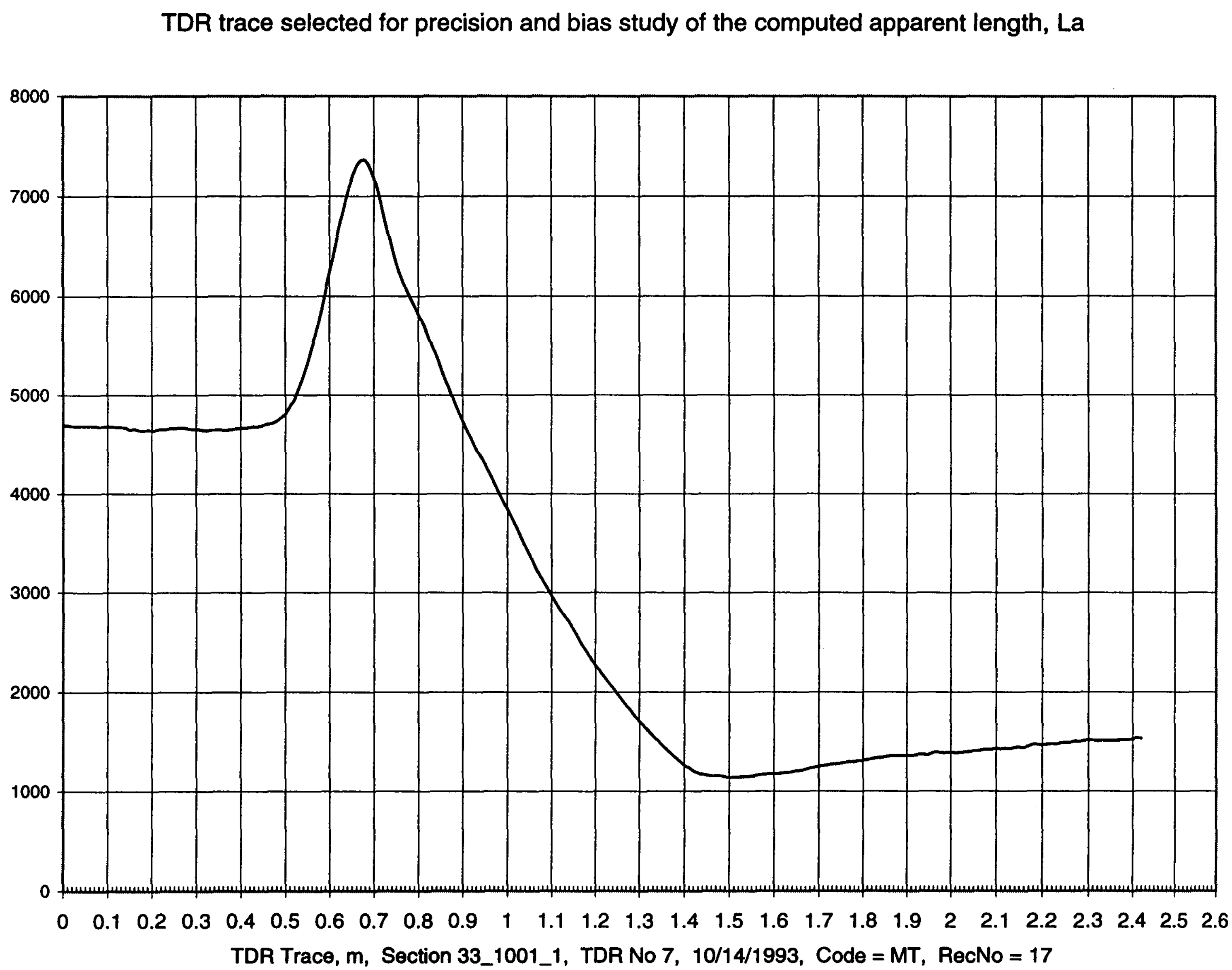


Figure 59. TDR trace 04 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

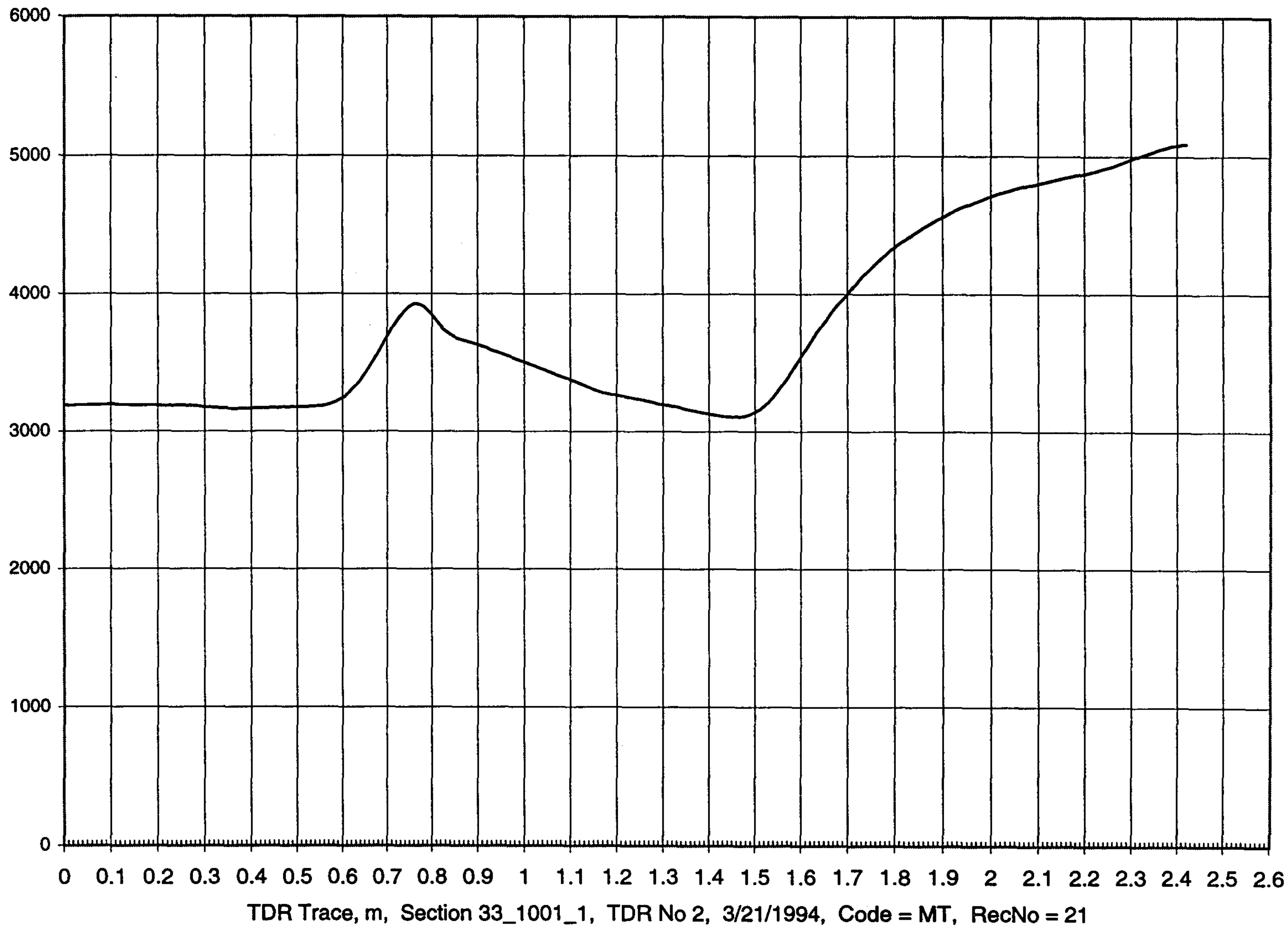


Figure 60. TDR trace 05 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

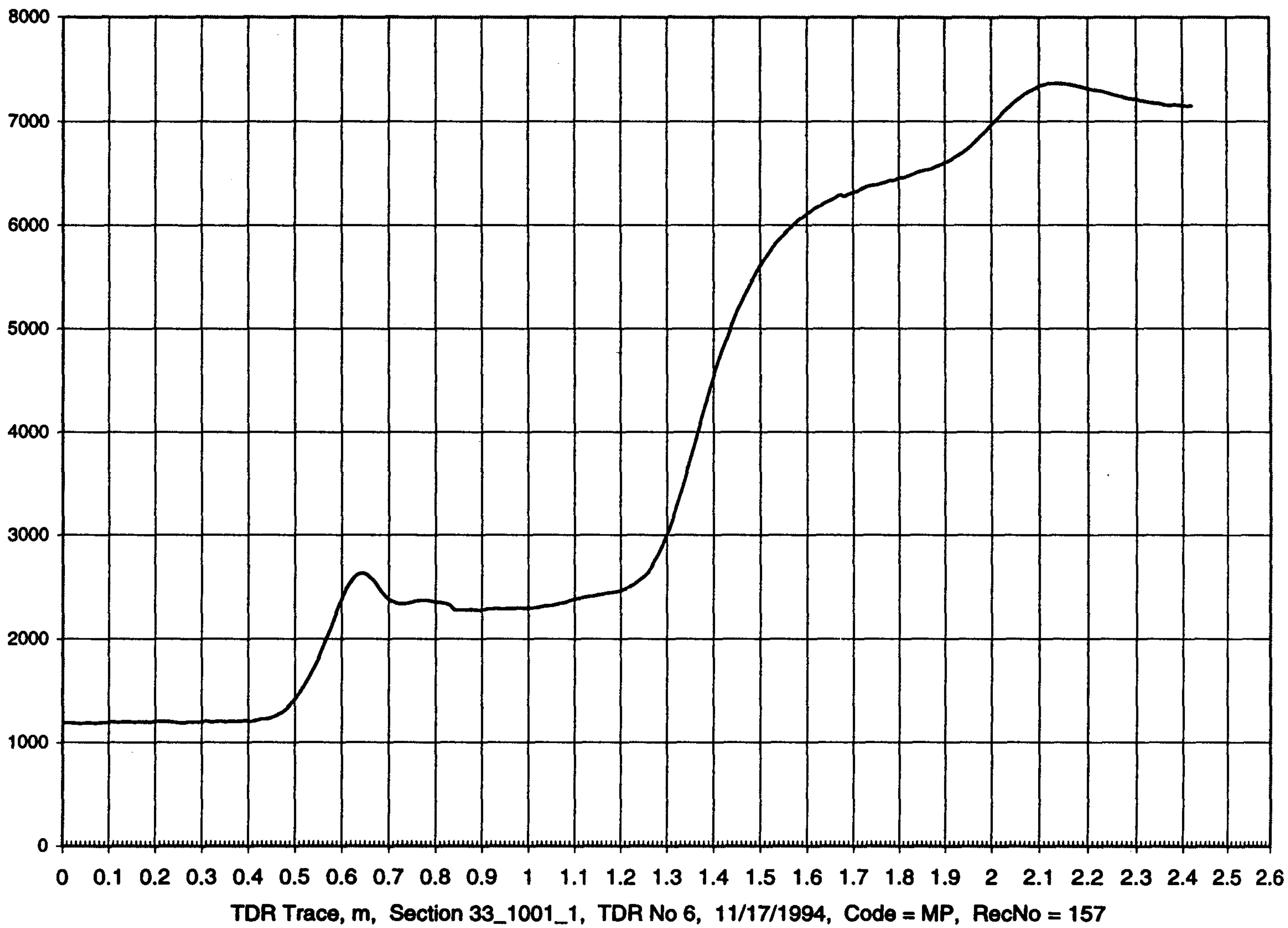


Figure 61. TDR trace 06 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

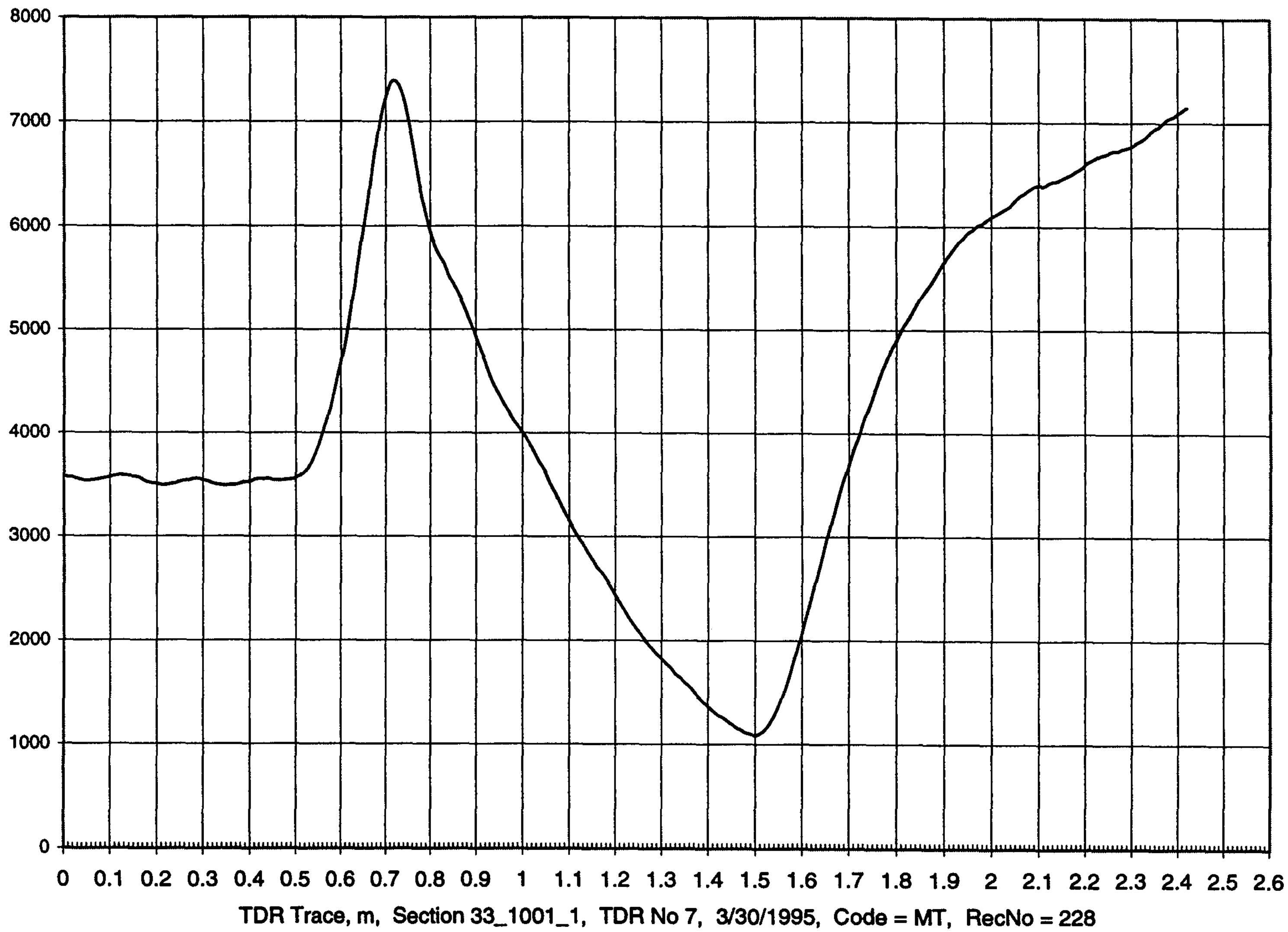


Figure 62. TDR trace 07 for precision and bias study.

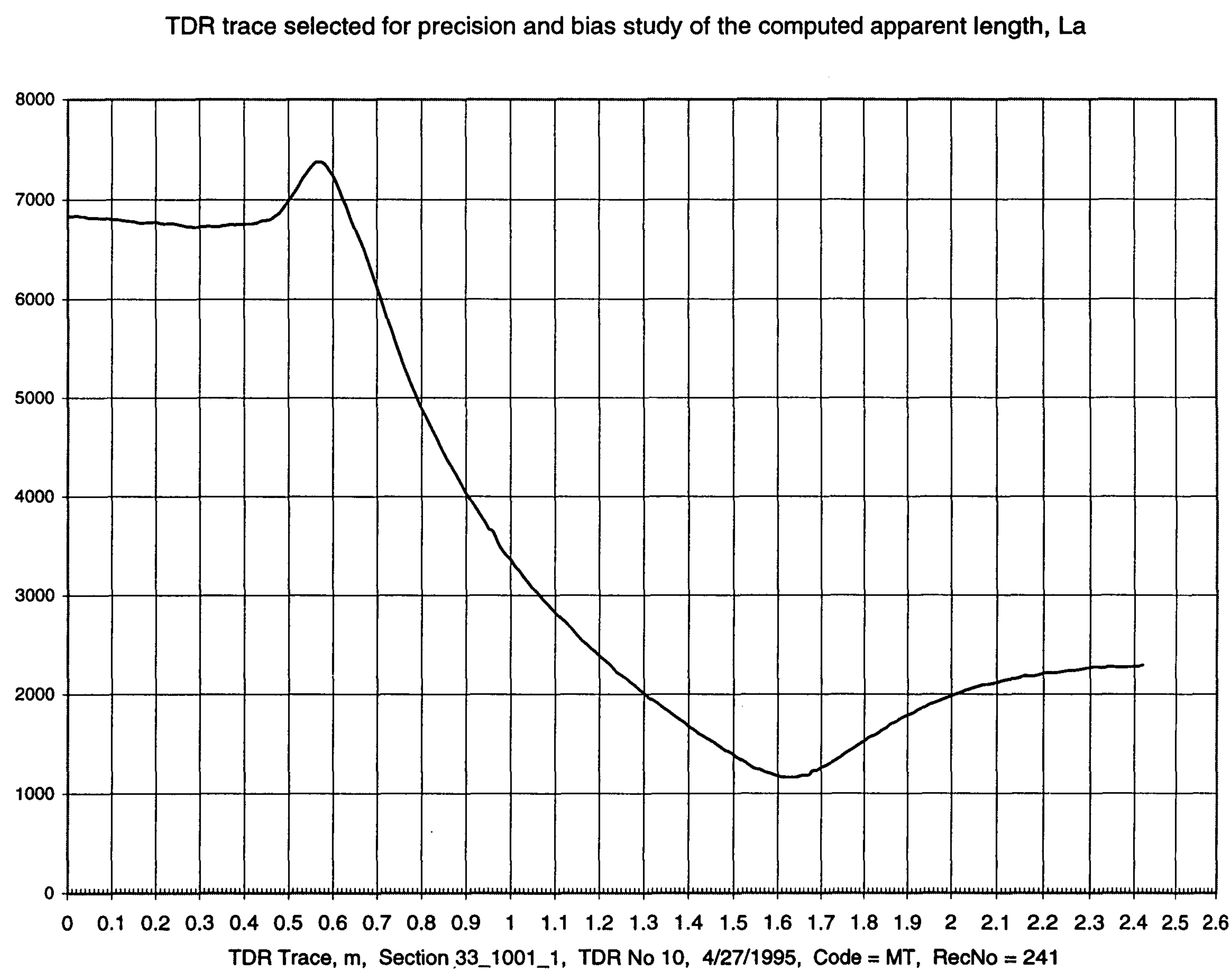


Figure 63. TDR trace 08 for precision and bias study.

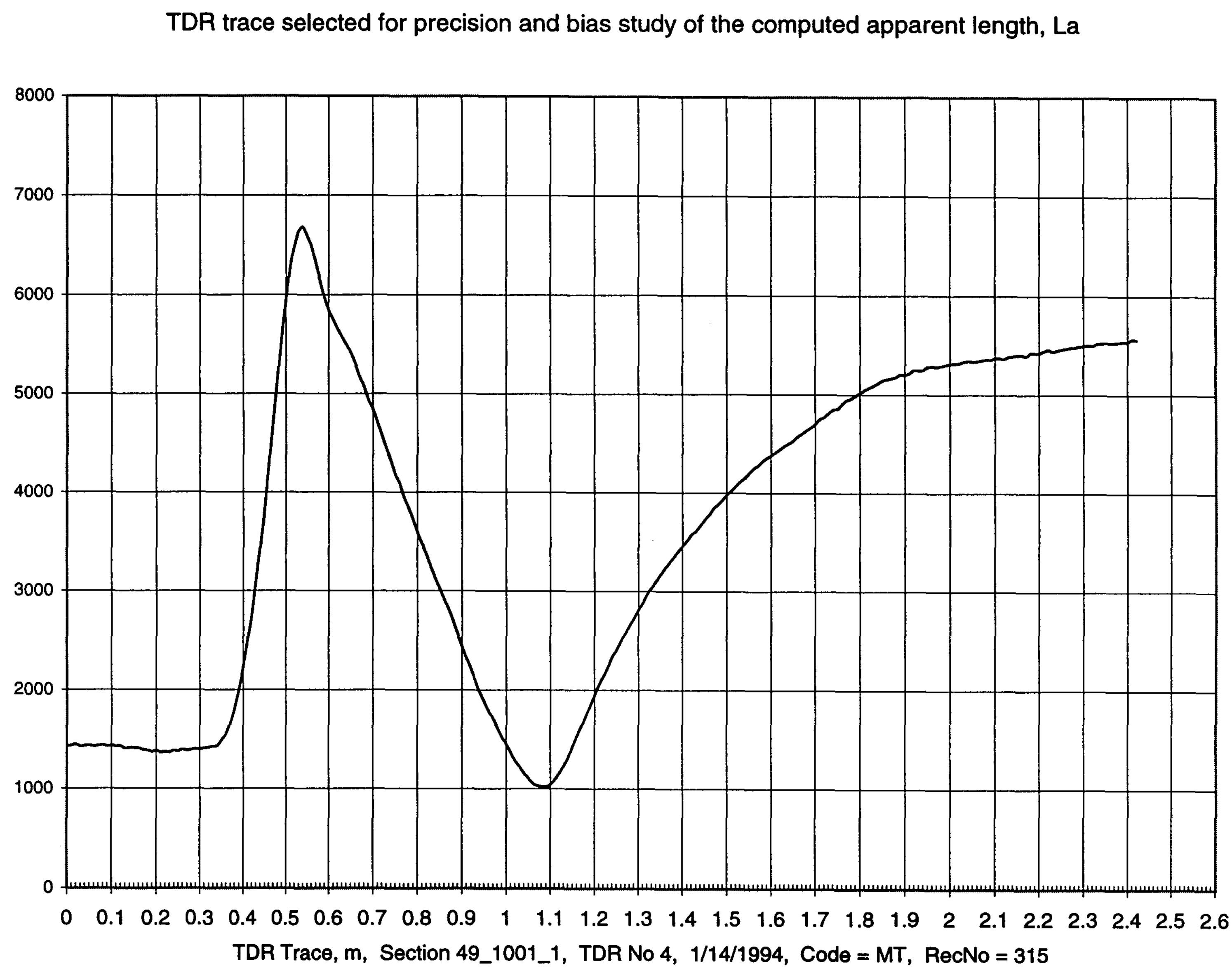


Figure 64. TDR trace 09 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

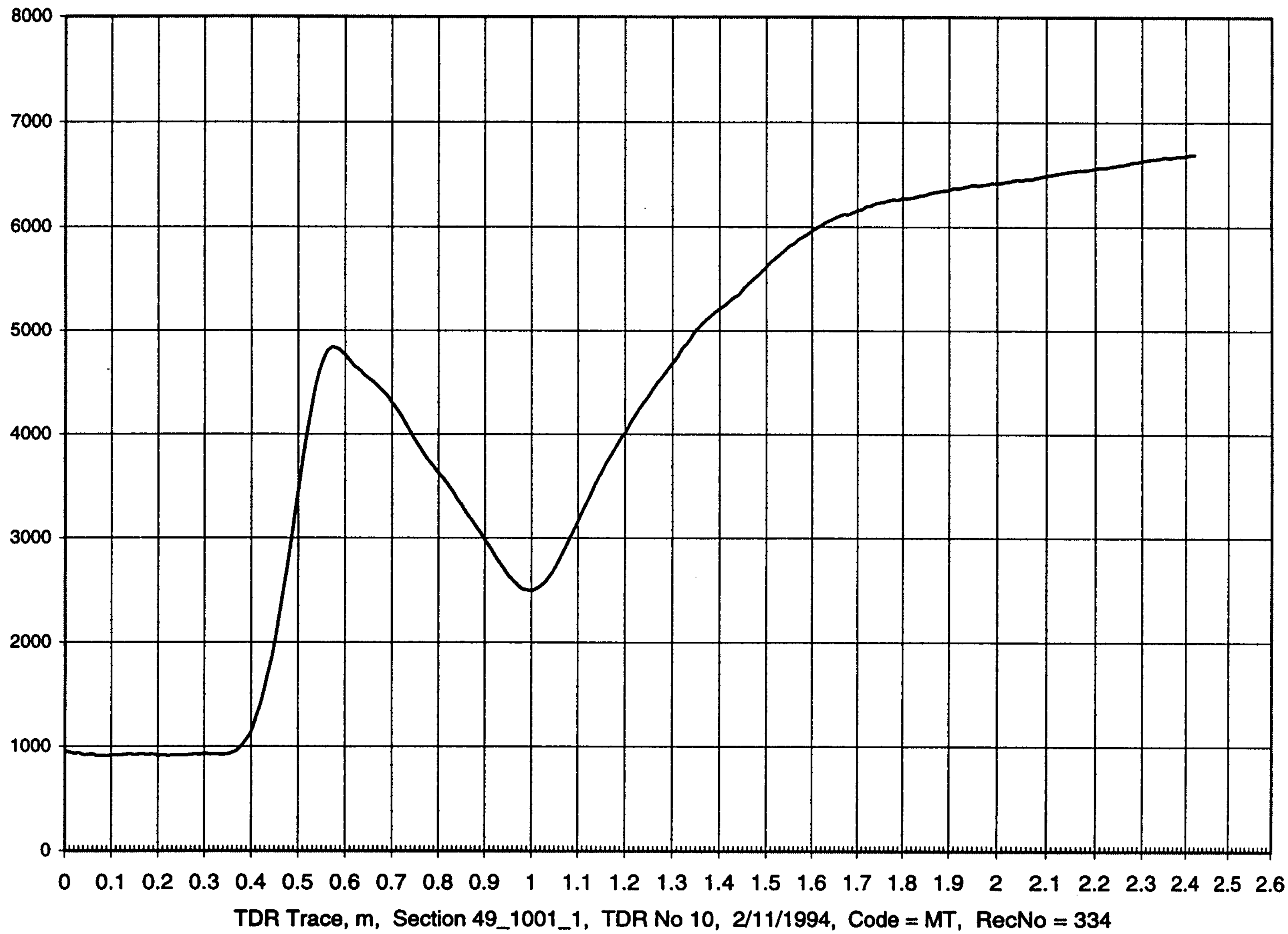


Figure 65. TDR trace 10 for precision and bias study.

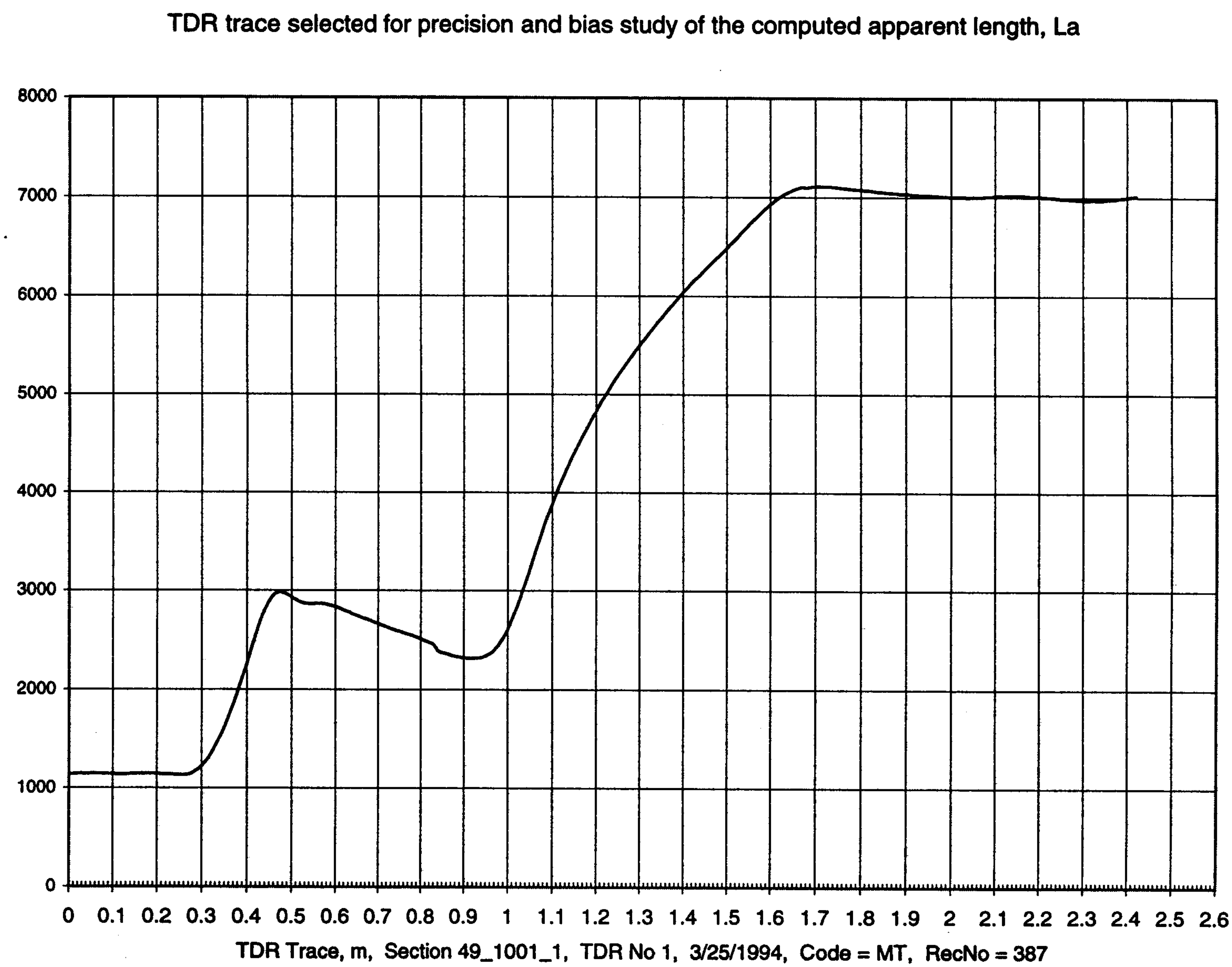


Figure 66. TDR trace 11 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

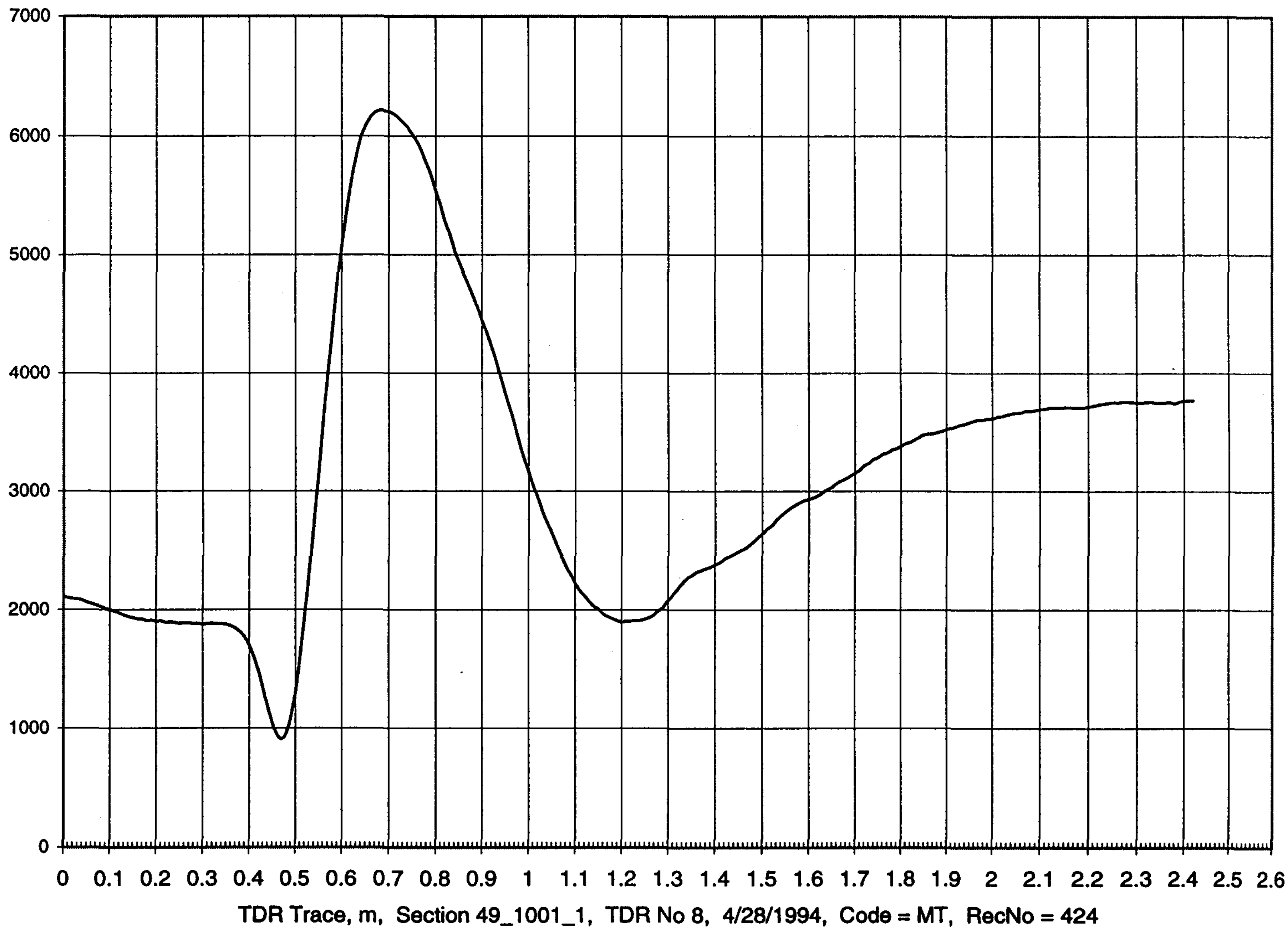


Figure 67. TDR trace 12 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

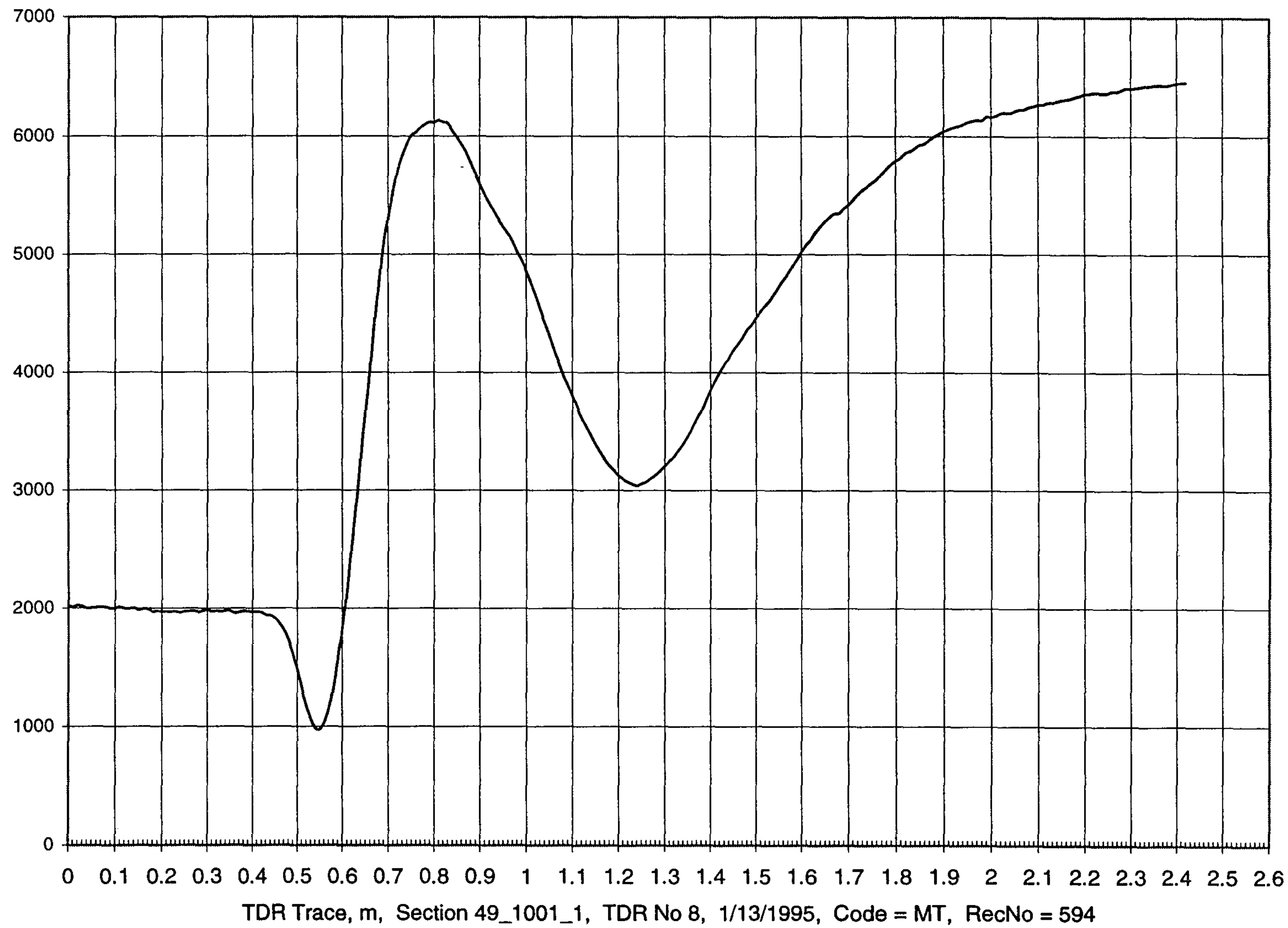


Figure 68. TDR trace 13 for precision and bias study.

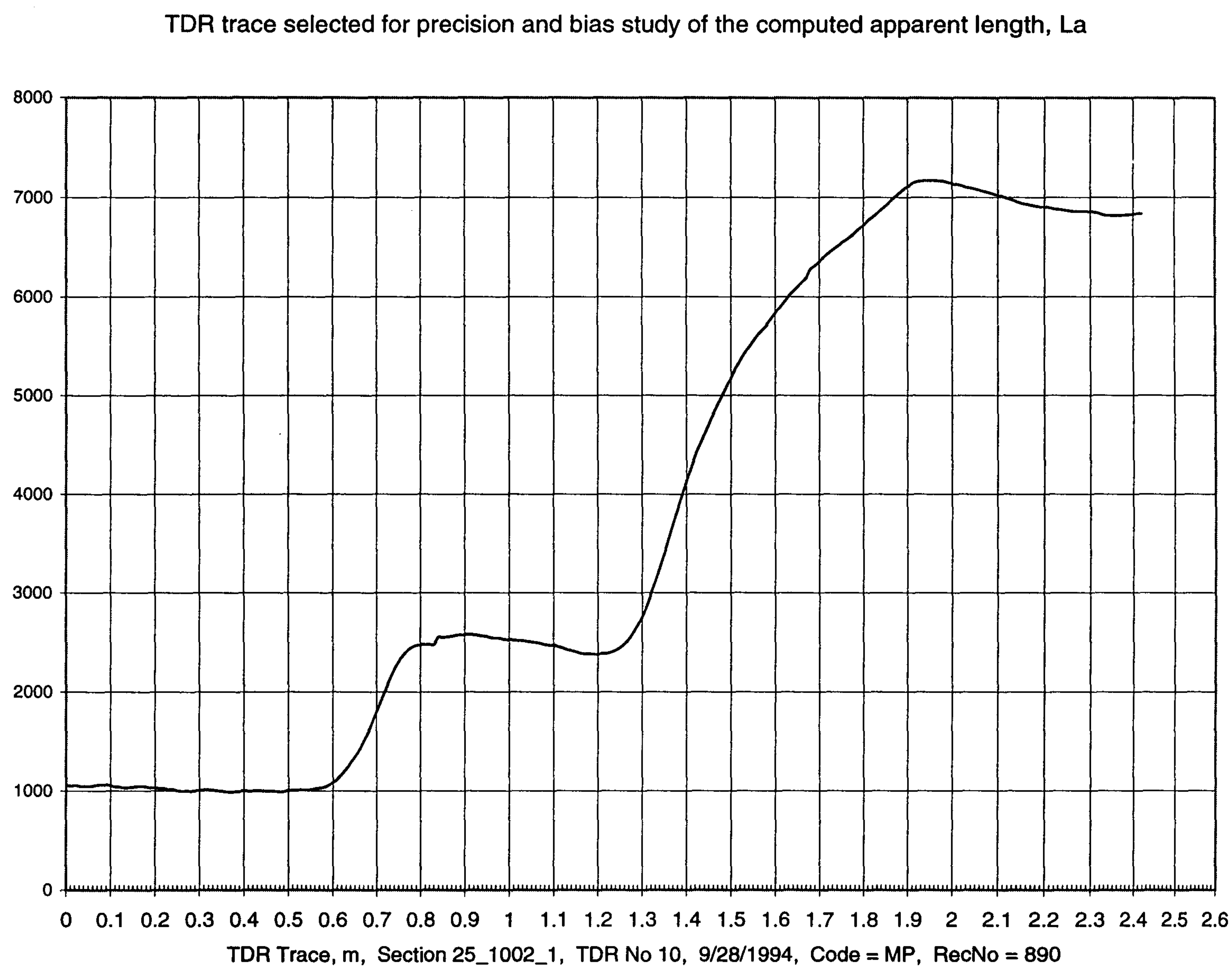


Figure 69. TDR trace 14 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

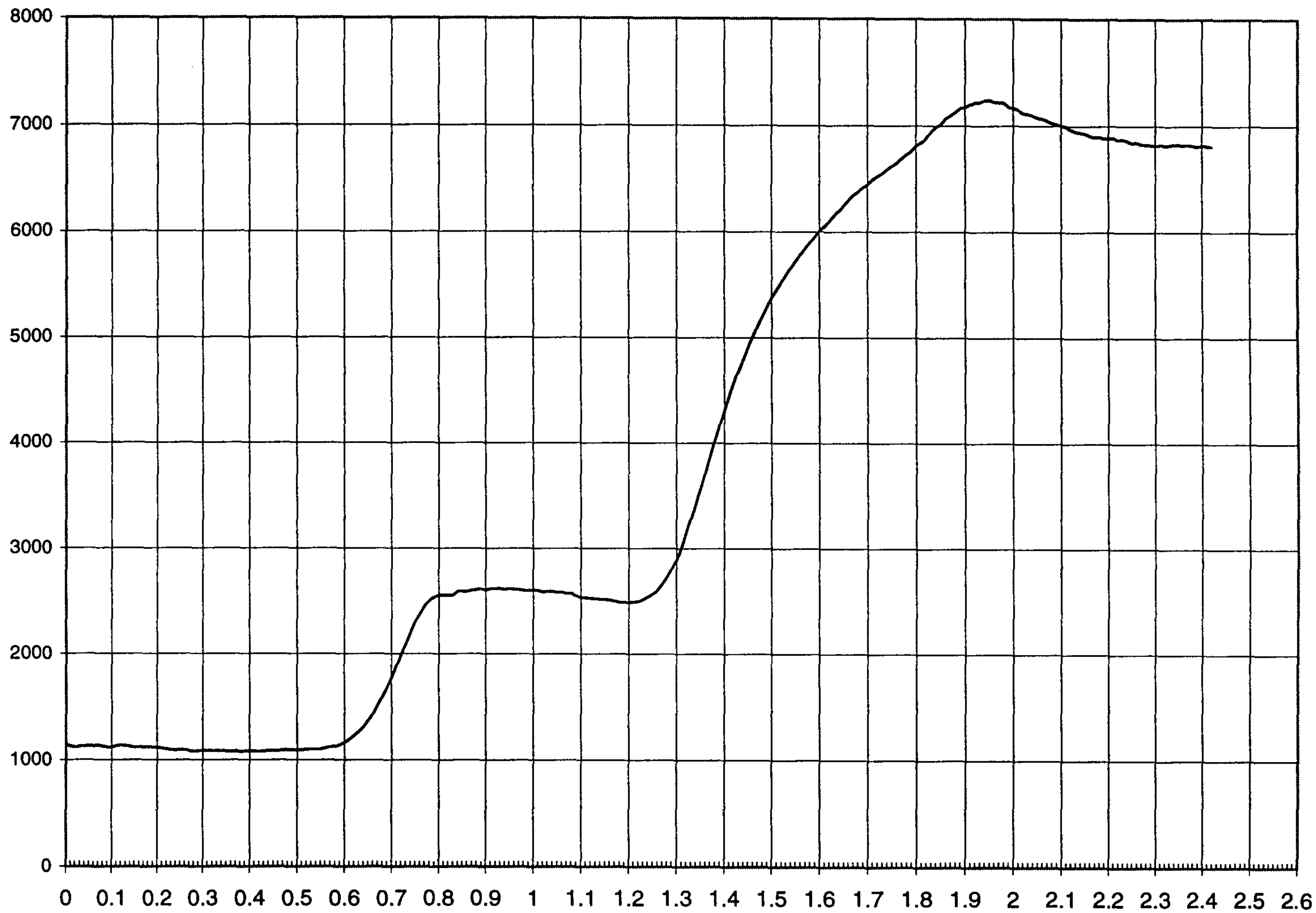


Figure 70. TDR trace 15 for precision and bias study.

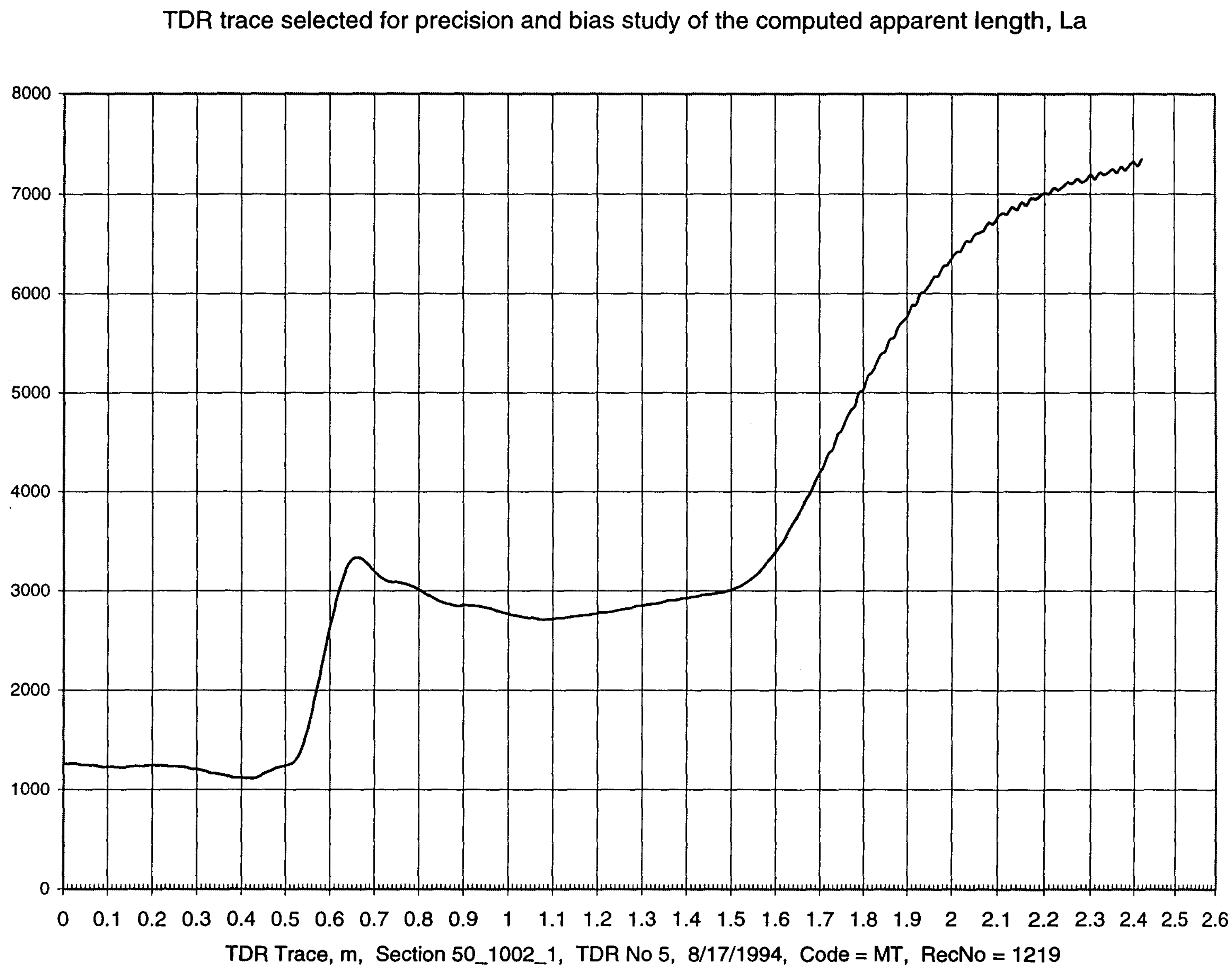


Figure 71. TDR trace 16 for precision and bias study.

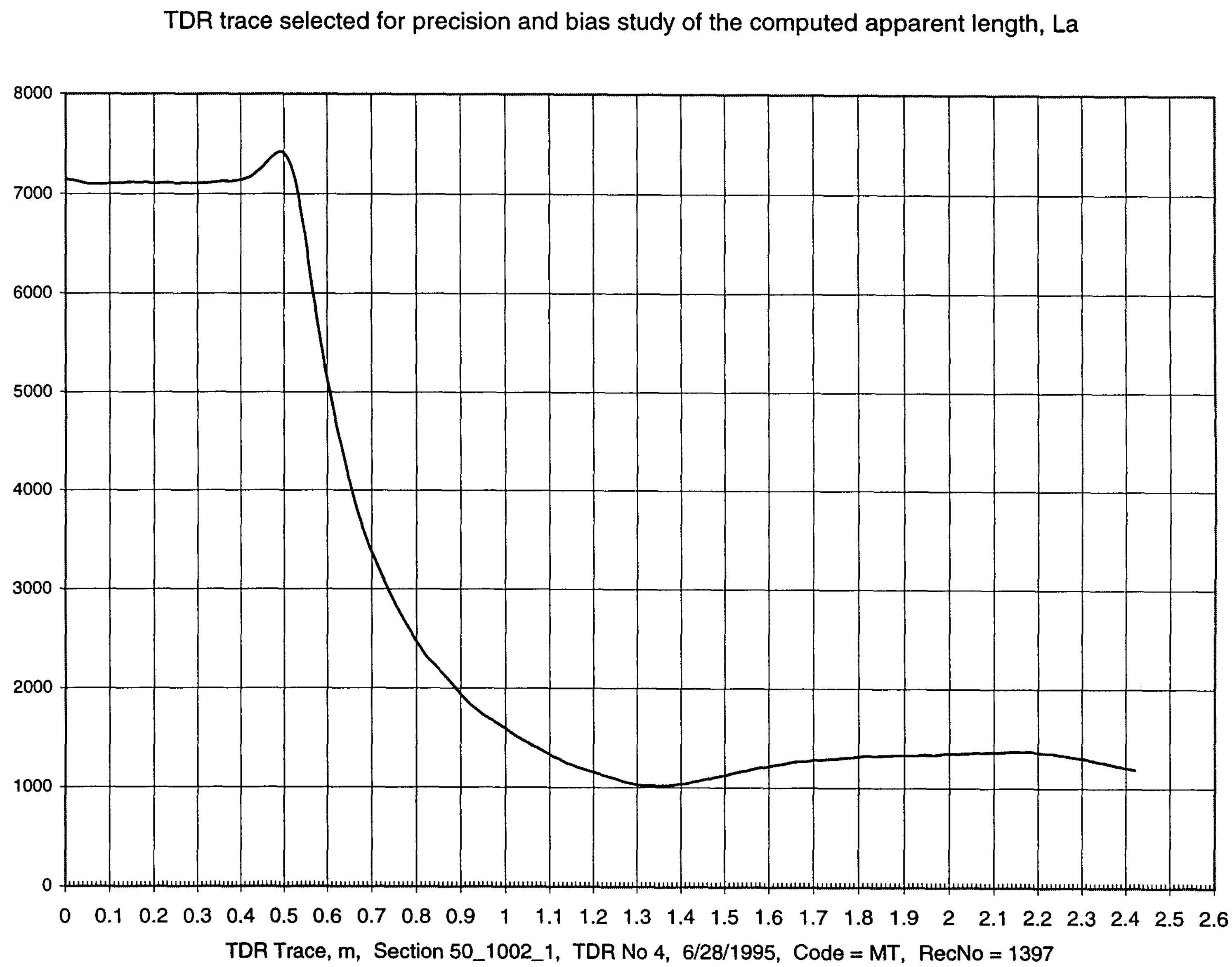


Figure 72. TDR trace 17 for precision and bias study.

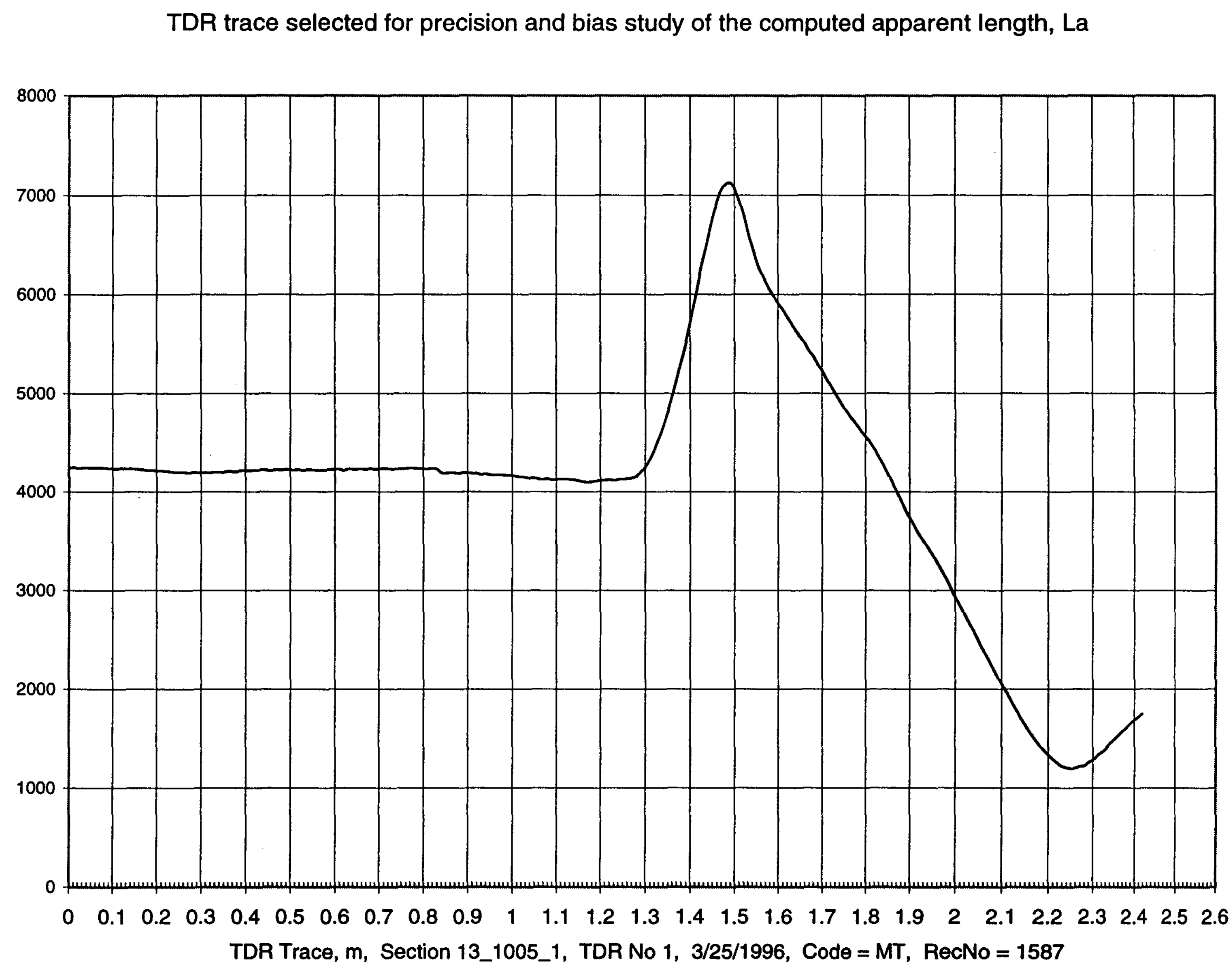


Figure 73. TDR trace 18 for precision and bias study.

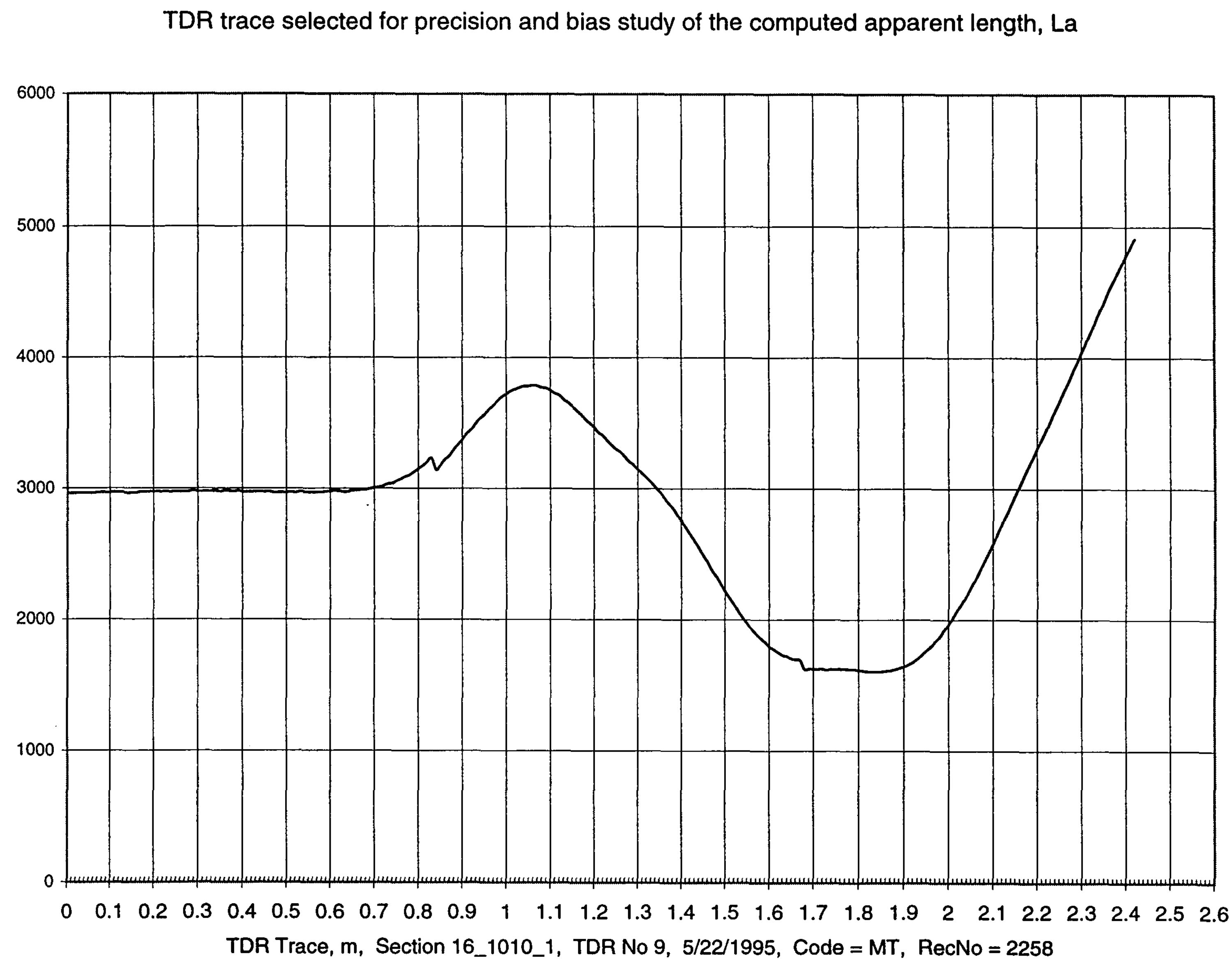


Figure 74. TDR trace 19 for precision and bias study.

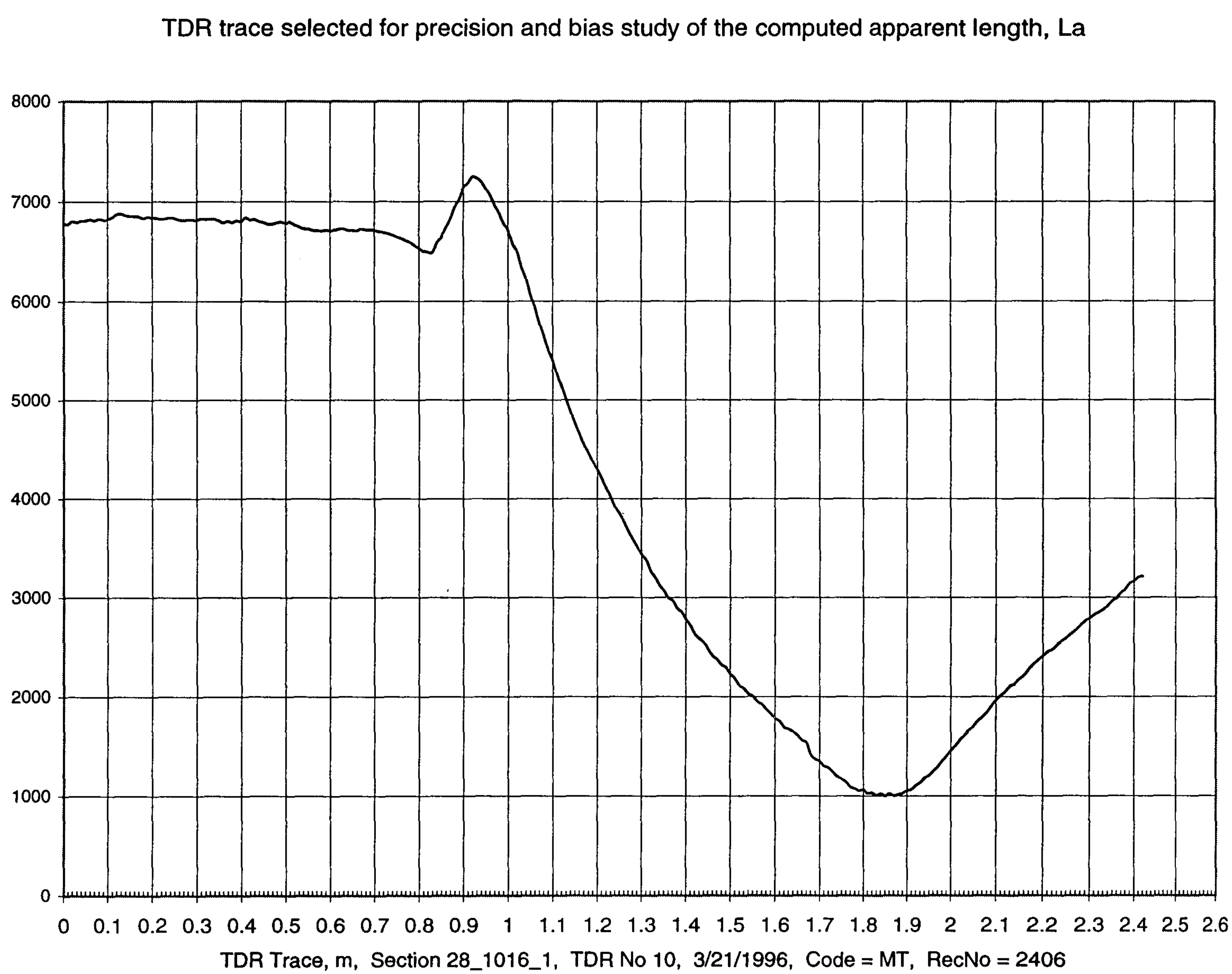


Figure 75. TDR trace 20 for precision and bias study.

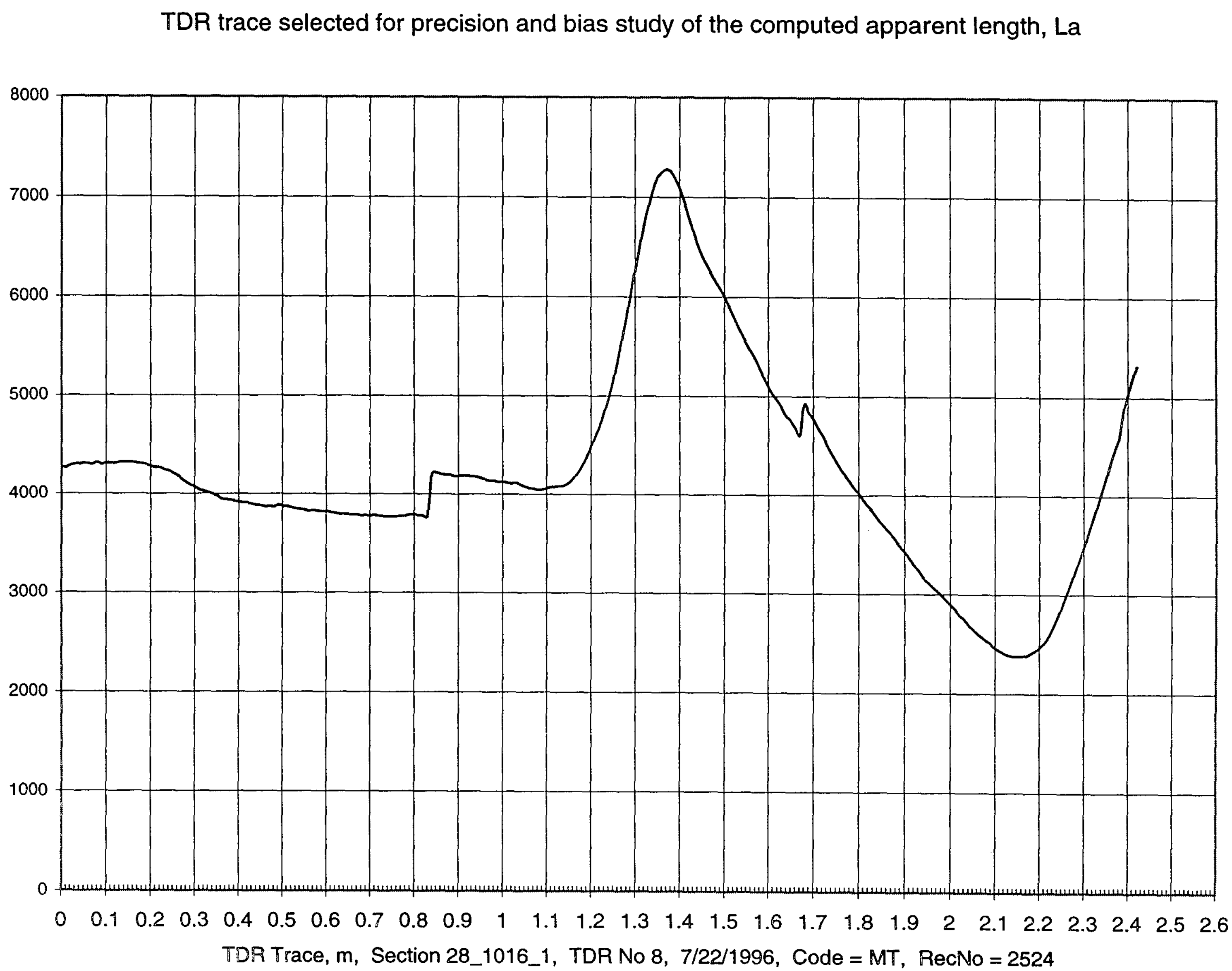


Figure 76. TDR trace 21 for precision and bias study.

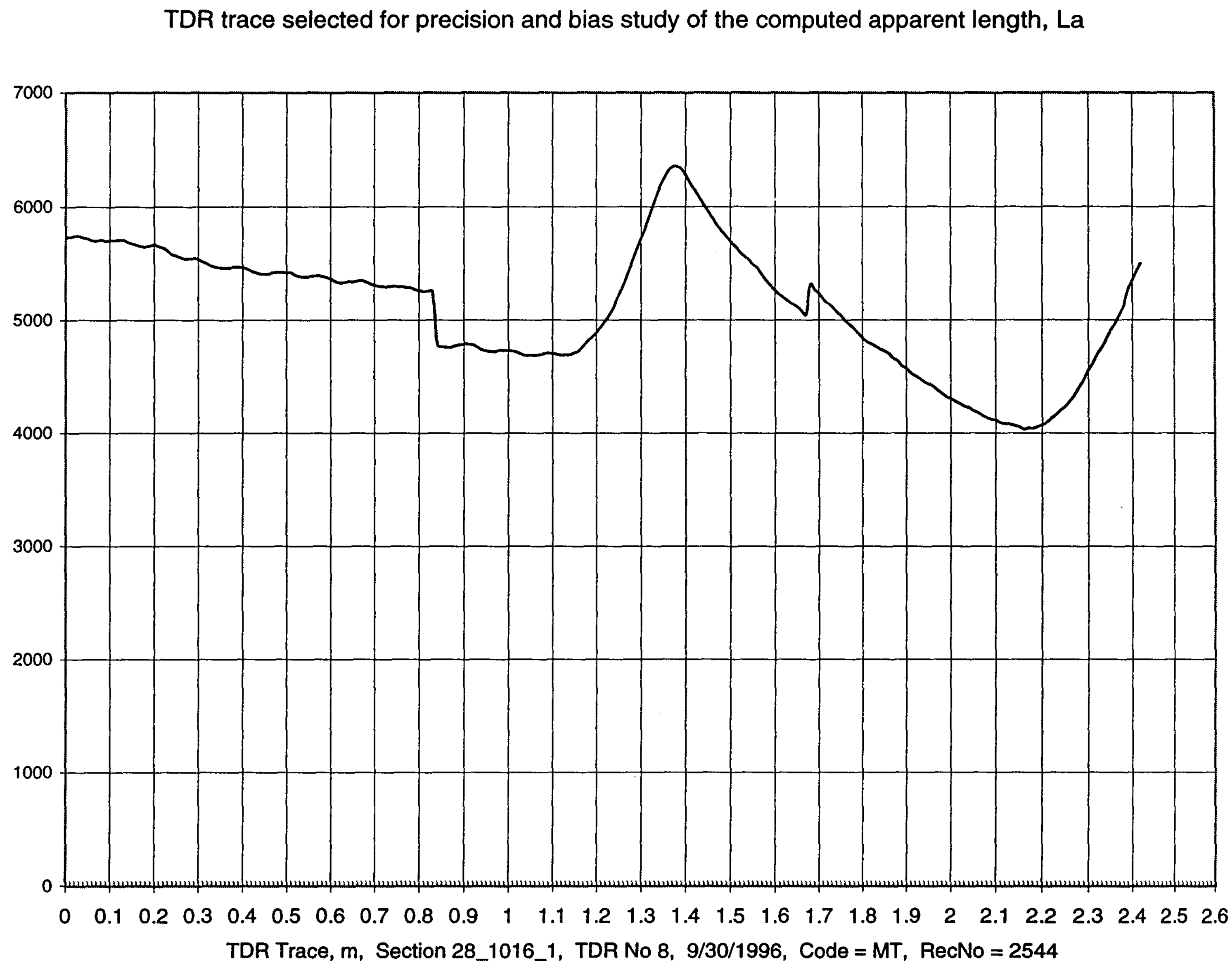


Figure 77. TDR trace 22 for precision and bias study.

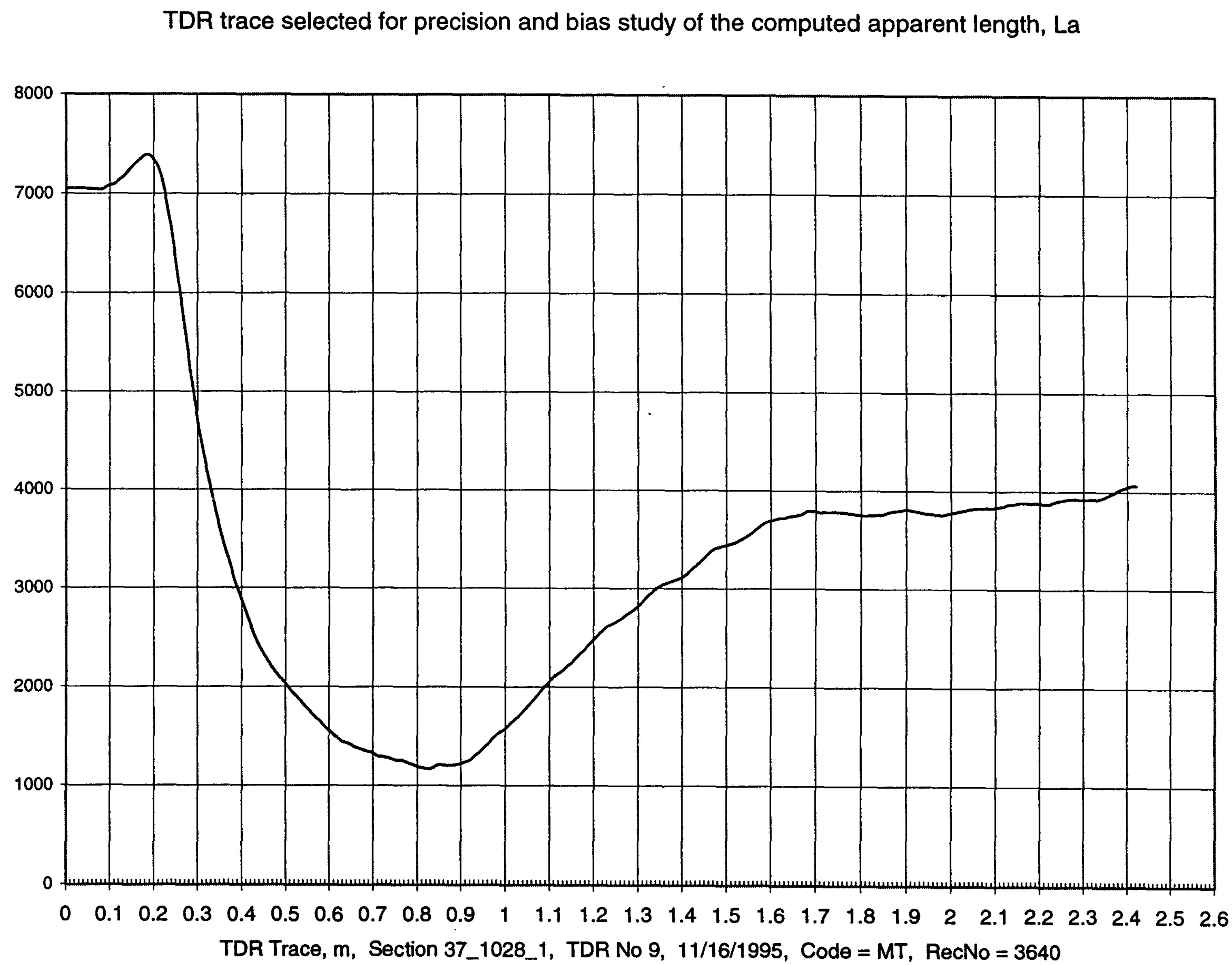


Figure 78. TDR trace 23 for precision and bias study.

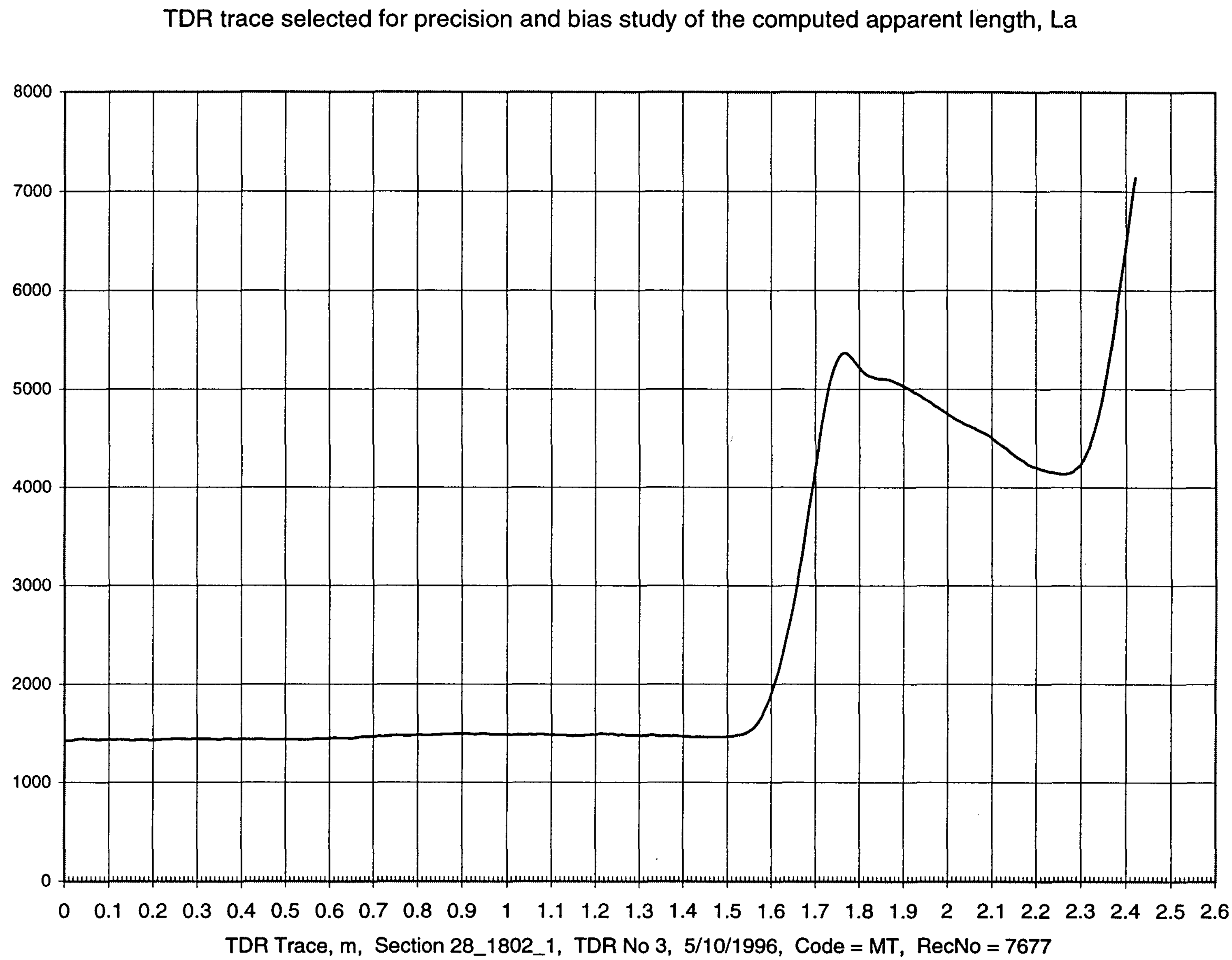


Figure 79. TDR trace 24 for precision and bias study.

TDR trace selected for precision and bias study of the computed apparent length, La

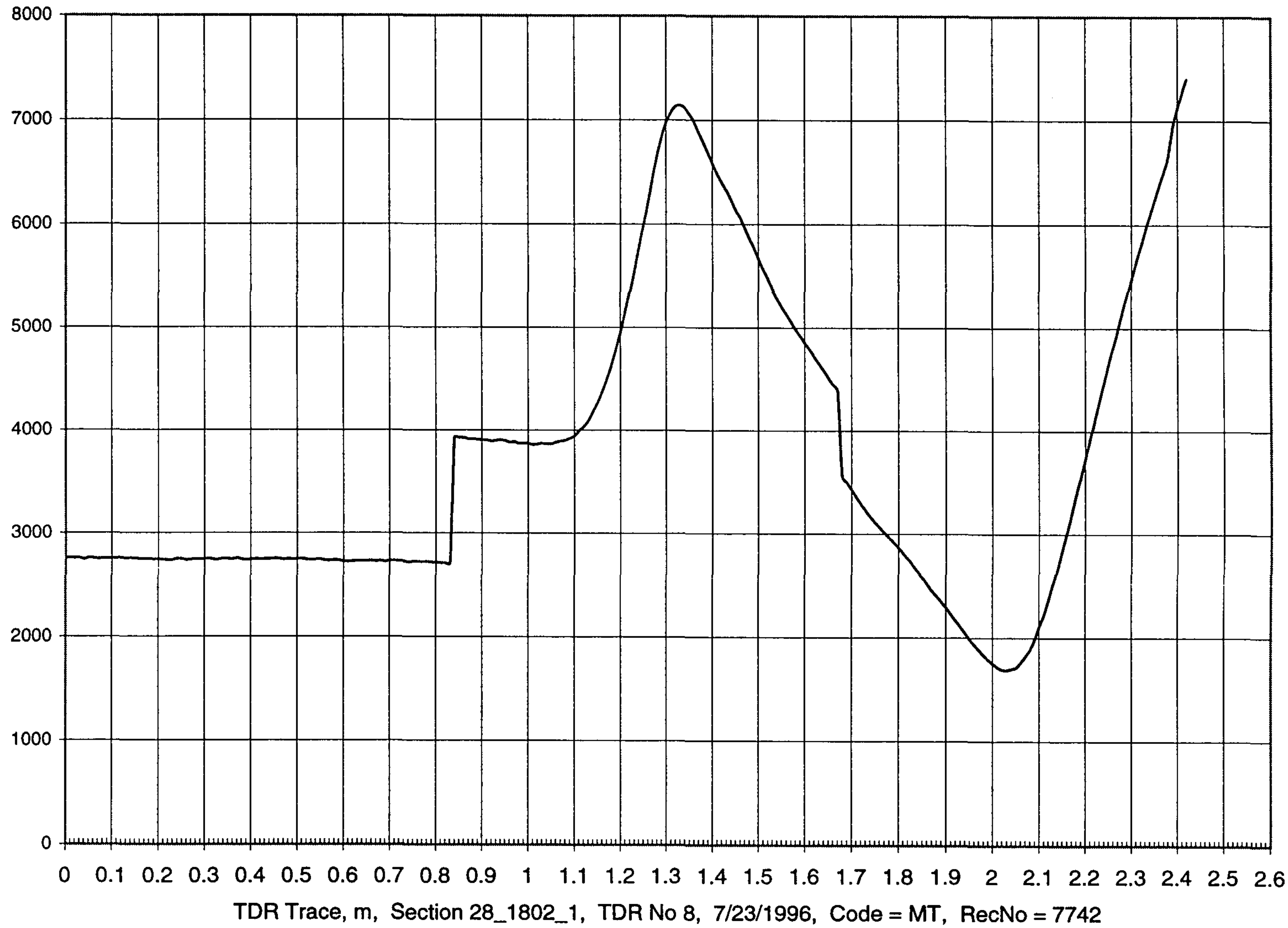


Figure 80. TDR trace 25 for precision and bias study.

APPENDIX C – LIST OF SOIL PROPERTIES USED IN THE MODEL DEVELOPMENT AND NEEDED SMP SOIL PROPERTIES

Table 20. Laboratory soil and property data used in the volumetric moisture model development.

State Code	SHRP ID	Soil Group	AASHTO Soil Class	Percent passing the following sieves 1 1/2 in	1/2in	No4	No10	No200	Plastic Limit	Liquid Limit
8	1053	fine	A-6	100	100	97	97	91.8	18	40
9	1803	fine	A-4	99	95	90	84	12.6	0	0
16	1010	coarse	A-2-4	100	100	97	88	13.1	25	25
23	1026	coarse	A-2-4	99	95	90	84	12.6	0	0
25	1002	coarse	A-3	100	100	99	98	7.1	0	0
27	1018	coarse	A-1-b	99	94	90	82	6.2	0	0
27	1028	coarse	A-1-b	100	93	87	80	4.9	0	0
27	6251	coarse	A-3	100	100	99	97	7	0	0
33	1001	coarse	A-3	100	99	98	96	7.9	0	0
35	1112	coarse	A-3	100	100	99	99	3.6	0	0
36	4018	coarse	A-2-4	100	84	64	49	15.9	0	0
40	4165	coarse	A-2-4	100	100	100	100	28.2	0	0
46	804	fine	A-6	100	99	98	98	45.5	17	36
46	9187	fine	A-7-6	100	100	100	99	85.7	19	51
48	1122	coarse	A-3	100	100	99	97	6.5	0	0
48	3739	coarse	A-3	100	100	99	99	6.2	0	0
48	4142	coarse	A-2-4	100	100	100	100	5.5	14	21
48	1068	fine	A-7-6	100	100	100	98	94	18	43
48	1077	fine	A-4	100	96	94	93	51.8	0	0
49	1001	coarse	A-2-4	100	100	100	100	26.8	0	0
49	3011	coarse	A-2-4	98	82	70	65	35.1	21	35
50	1002	fine	A-7-5	100	100	98	97	94.6	45	58
56	1007	coarse	A-2-4	100	91	75	74	23	0	0
83	1801	coarse	A-2-4	100	100	100	99	28.8	0	0
83	3802	fine	A-7-5	100	100	99	98	90.6	33	69
87	1622	fine	A-4	100	100	100	100	51.6	0	0
89	3015	coarse	A-3	100	95	91	89	2	0	0
90	6405	fine	A-4	100	99	96	92	40	14	19

Table 21. Needed soil properties for the SMP sites.

Section	Layer	Soil Type		Dry Density		Percent passing following sieves					Plastic	Liquid
ID	type	type	Source	g/cm^3	Source	11/2 in	1/2 in	No4	No10	No200	limit	limit
10101	Base	Coarse	2	2.13	11							
10101	Subgrade	Fine	2	1.68	2							
10101	Subgrade	Fine	2	1.68	10							
10102	Base	Coarse	2	2.13	11							
10102	Subgrade	Fine	2	1.67	2							
10102	Subgrade	Fine	2	1.67	10							
40113	Base	Coarse	2	2.25	1							
40113	Subgrade	Coarse	1	1.93	2							
40113	Subgrade	Coarse	1	1.93	10							
40114	Base	Coarse	2	2.27	1							
40114	Subgrade	Coarse	1	1.80	2							
40114	Subgrade	Coarse	1	1.80	10							
40215	Base	Coarse	2	2.29	1							
40215	Subgrade	Coarse	1	1.61	5							
40215	Subgrade	Coarse	1	1.61	10							
41024	Base	Coarse	2	2.28	6							
41024	Subgrade	Coarse	1	1.96	6							
41024	Subgrade	Coarse	1	1.96	10							
63042	Subgrade	Fine	1	1.65	7	100	100	99	99	64.5	20.5	30
63042	Subgrade	Fine	1	1.65	7	100	100	99	99	64.5	20.5	30
81053	Base	Coarse	2	2.16	1							
81053	Subgrade	Fine	1	1.63	1	100	100	97	97	91.8	18	40
91803	Base	Coarse	2	2.26	6							
91803	Base	Coarse	2	2.26	9							
91803	Subgrade	Fine	1	1.64	8							
100102	Base	Coarse	2	2.43	1							
100102	Subgrade	Coarse	2	1.90	1							
100102	Subgrade	Coarse	2	1.92	1							
131005	Base	Coarse	2	2.23	1							
131005	Subgrade	Coarse	1	1.69	2							
131005	Subgrade	Coarse	1	1.69	10							
131005	Subgrade	Coarse	1	1.83	1							
131031	Base	Coarse	2	2.17	1							
131031	Subgrade	Coarse	1	1.50	2							
131031	Subgrade	Coarse	1	1.50	10							
131031	Subgrade	Coarse	1	1.79	1							
133019	Base	Coarse	2	2.16	1							
133019	Subgrade	Fine	1	1.48	2	100	97.5	93.5	88	59.9	23	33
133019	Subgrade	Fine	1	1.48	10	100	97.5	93.5	88	59.9	23	33
133019	Subgrade	Fine	1	1.84	8	100	97.5	93.5	88	59.9	23	33
161010	Base	Coarse	2	2.05	1							
161010	Subgrade	Coarse	1	1.88	1							
183002	Base	Coarse	2	2.07	1							
183002	Subgrade	Fine	1	1.83	3	100	97.5	96	94.5	67.4	16.5	30.5
183002	Subgrade	Fine	1	1.83	10	100	97.5	96	94.5	67.4	16.5	30.5
204054	Subgrade	Fine	1	1.78	2	100	99.5	98	97.5	91.5	20	42.5
204054	Subgrade	Fine	1	1.78	10	100	99.5	98	97.5	91.5	20	42.5
231026	Base	Coarse	2	2.27	1							
231026	Subgrade	Coarse	1	1.96	1							
241634	Subgrade	Fine	1	1.79	2	100	100	99.5	99	98.5	0	0

Table 21. Needed soil properties for the SMP sites (continued).

Section	Layer	Soil Type		Dry Density		Percent passing following sieves					Plastic	Liquid
ID	type	type	Source	g/cm^3	Source	1 1/2 in	1/2 in	No4	No10	No200	limit	limit
241634	Subgrade	Fine	1	1.79	10	100	100	99.5	99	98.5	0	0
241634	Subgrade	Fine	1	1.90	2	100	100	99.5	99	98.5	0	0
241634	Subgrade	Fine	1	1.90	10	100	100	99.5	99	98.5	0	0
251002	Base	Coarse	2	1.94	1							
251002	Base	Coarse	2	2.03	1							
251002	Subgrade	Coarse	1	1.79	1							
271018	Base	Coarse	2	2.03	1							
271018	Subgrade	Coarse	1	1.83	3							
271018	Subgrade	Coarse	1	1.83	10							
271028	Subgrade	Coarse	1	2.02	3							
271028	Subgrade	Coarse	1	2.02	10							
274040	Base	Coarse	2	2.07	1							
274040	Subgrade	Fine	1	1.81	3	100	98	97	94.5	76.0	18.5	35.5
274040	Subgrade	Fine	1	1.81	10	100	98	97	94.5	76.0	18.5	35.5
276251	Base	Coarse	2	2.07	1							
276251	Base	Coarse	2	2.07	9							
276251	Subgrade	Coarse	1	1.86	3							
276251	Subgrade	Coarse	1	1.86	10							
281016	Base	Coarse	2	1.80	1							
281016	Subgrade	Coarse	2	1.83	2							
281016	Subgrade	Coarse	2	1.83	10							
281016	Subgrade	Coarse	2	1.91	1							
281802	Subgrade	Coarse	1	1.90	2							
281802	Subgrade	Coarse	1	1.90	10							
281802	Subgrade	Coarse	1	1.97	1							
308129	Base	Coarse	2	1.81	9							
308129	Subgrade	Fine	1	1.81	6	100	93.5	84.5	78	57.8	14.5	31
308129	Subgrade	Fine	1	1.81	10	100	93.5	84.5	78	57.8	14.5	31
310114	Base	Coarse	2	2.24	4							
310114	Subgrade	Fine	2	1.58	2							
310114	Subgrade	Fine	2	1.58	10							
313018	Subgrade	Coarse	1	1.82	2							
313018	Subgrade	Coarse	1	1.82	10							
320101	Base	Coarse	2	2.23	1							
320101	Subgrade	Coarse	2	1.97	1							
320204	Base	Coarse	2	2.23	1							
320204	Subgrade	Coarse	2	1.97	1							
331001	Base	Coarse	2	2.10	1							
331001	Base	Coarse	2	2.15	1							
331001	Subgrade	Coarse	1	1.86	1							
351112	Base	Coarse	2	1.72	1							
351112	Subgrade	Coarse	1	1.65	1							
360801	Base	Coarse	2	2.20	1							
360801	Subgrade	Coarse	2	1.92	2							
360801	Subgrade	Coarse	2	1.92	10							
360801	Subgrade	Coarse	2	2.10	1							
364018	Base	Coarse	2	2.13	11							
364018	Subgrade	Coarse	1	2.24	1							
364018	Subgrade	Coarse	1	2.24	1							
370201	Base	Coarse	2	2.36	1							

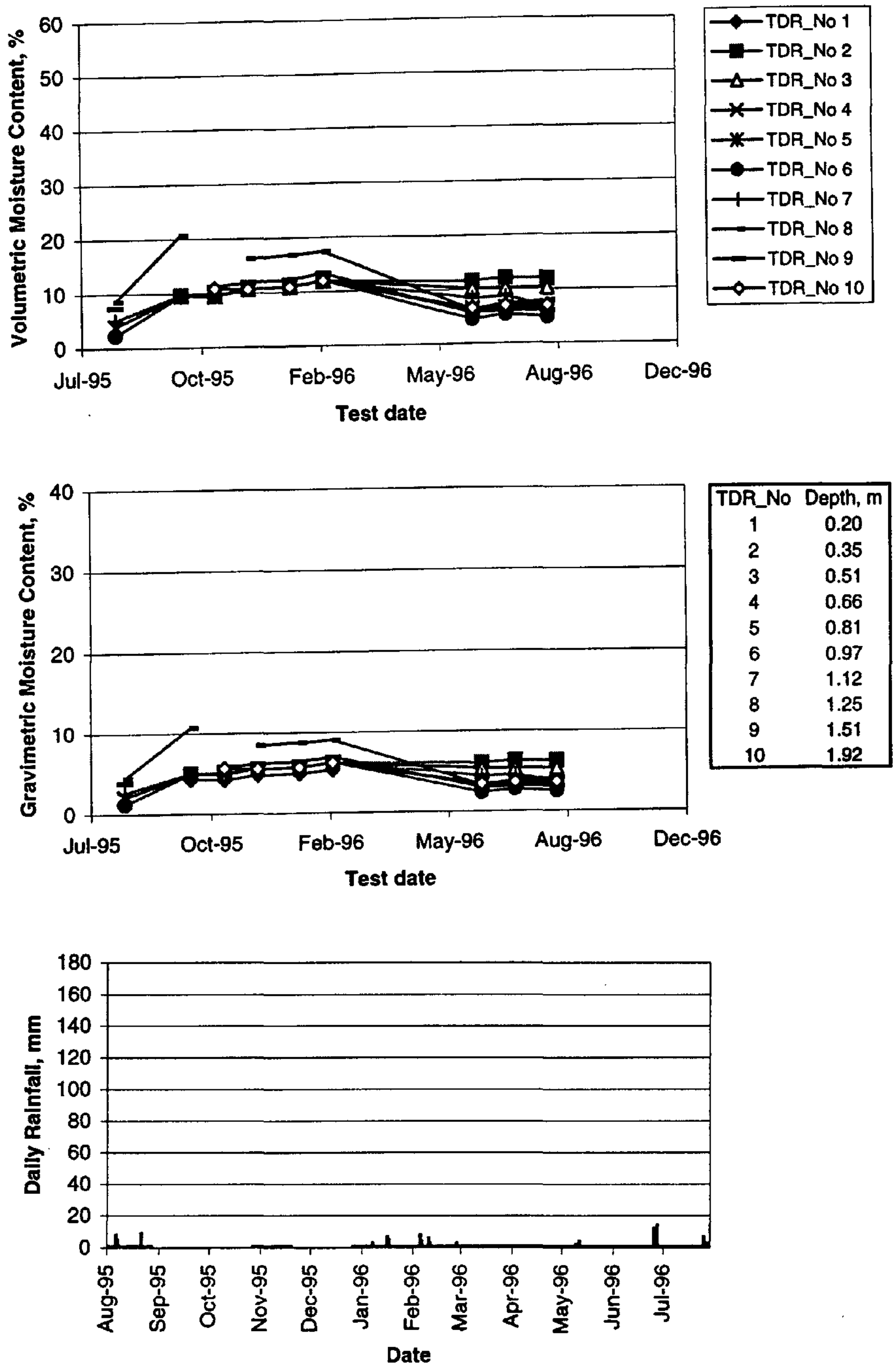
Table 21. Needed soil properties for the SMP sites (continued).

Section	Layer	Soil Type		Dry Density		Percent passing following sieves					Plastic	Liquid
ID	type	type	Source	g/cm^3	Source	11/2 in	1/2 in	No4	No10	No200	limit	limit
370201	Subgrade	Fine	1	1.30	1							
370201	Subgrade	Fine	1	1.30	10							
370205	Subgrade	Fine	1	1.44	1							
370205	Subgrade	Fine	1	1.44	10							
370208	Subgrade	Fine	1	1.41	1							
370208	Subgrade	Fine	1	1.41	10							
370212	Base	Coarse	2	2.16	1							
370212	Subgrade	Fine	1	1.42	1							
370212	Subgrade	Fine	1	1.42	10							
371028	Subgrade	Coarse	1	1.54	2							
371028	Subgrade	Coarse	1	1.54	10							
404165	Subgrade	Coarse	1	1.35	1							
421606	Base	Coarse	2	2.03	4							
421606	Subgrade	Fine	1	1.94	2	98.5	87.5	78.5	73	47.3	18.5	31.5
421606	Subgrade	Fine	1	1.94	10	98.5	87.5	78.5	73	47.3	18.5	31.5
460804	Base	Coarse	2	2.18	1							
460804	Subgrade	Fine	1	1.54	1							
469187	Base	Coarse	2	1.99	1							
469187	Base	Coarse	2	2.13	11							
469187	Subgrade	Fine	1	1.85	3							
469187	Subgrade	Fine	1	1.85	10							
481060	Base	Coarse	2	1.95	1							
481060	Subgrade	Coarse	1	1.66	1							
481060	Subgrade	Coarse	1	1.66	10							
481068	Base	Coarse	2	2.00	1							
481068	Subgrade	Fine	1	1.55	1	100	100	100	93	74.0	18	38
481068	Subgrade	Fine	1	2.00	1	100	100	100	93	74.0	18	38
481077	Base	Coarse	2	2.14	1							
481077	Subgrade	Fine	1	1.72	1	100	97.5	95.5	95	62.7	0	0
481122	Base	Coarse	2	1.82	1							
481122	Base	Coarse	2	1.85	1							
481122	Base	Coarse	2	2.15	1							
481122	Subgrade	Coarse	1	1.85	1							
483739	Base	Coarse	2	1.66	1							
483739	Base	Coarse	2	1.95	1							
483739	Subgrade	Coarse	1	1.66	1							
484142	Base	Coarse	2	1.85	1							
484142	Subgrade	Coarse	2	1.75	1							
484143	Subgrade	Fine	1	1.72	1	100	100	100	99	90.1	18	41
484143	Subgrade	Fine	1	1.72	10	100	100	100	99	90.1	18	41
491001	Base	Coarse	2	2.09	6							
491001	Subgrade	Coarse	1	1.81	6							
491001	Subgrade	Coarse	1	1.81	10							
493011	Base	Coarse	2	2.24	1							
493011	Subgrade	Coarse	1	2.00	1							
501002	Base	Coarse	2	2.09	1							
501002	Subgrade	Coarse	1	1.76	1							
510113	Base	Coarse	2	2.13	11							
510113	Subgrade	Fine	2	1.36	2							
510113	Subgrade	Fine	2	1.36	10							

Table 21. Needed soil properties for the SMP sites (continued).

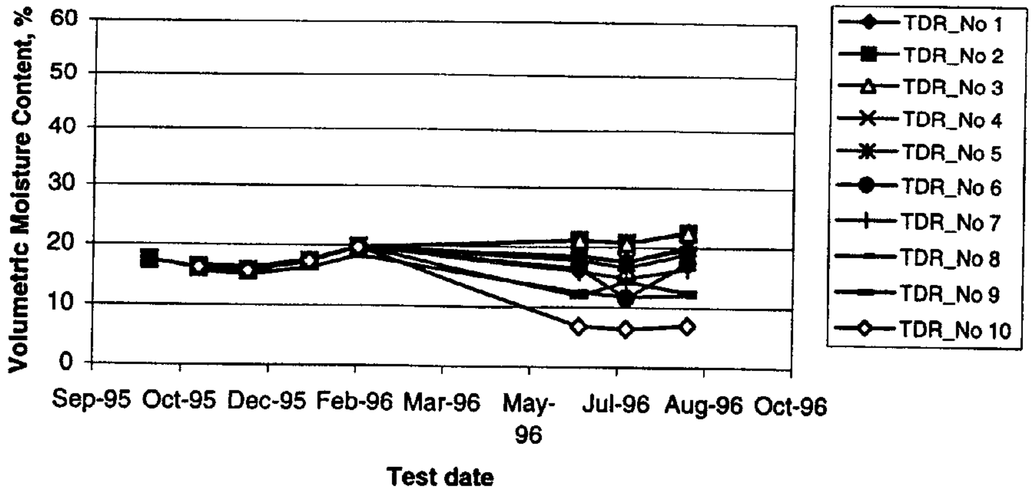
Section	Layer	Soil Type		Dry Density		Percent passing following sieves					Plastic	Liquid
ID	type	type	Source	g/cm^3	Source	11/2 in	1/2 in	No4	No10	No200	limit	limit
510114	Base	Coarse	2	2.13	11							
510114	Subgrade	Fine	2	1.86	2							
510114	Subgrade	Fine	2	1.86	10							
533813	Base	Coarse	2	1.88	1							
533813	Subgrade	Coarse	2	1.82	1							
561007	Base	Coarse	2	2.05	1							
561007	Subgrade	Coarse	2	1.92	1							
831801	Base	Coarse	2	2.08	1							
831801	Base	Coarse	2	2.08	9							
831801	Subgrade	Coarse	2	1.71	3							
831801	Subgrade	Coarse	2	1.71	10							
831801	Subgrade	Coarse	2	2.13	3							
831801	Subgrade	Coarse	2	2.13	10							
833802	Base	Coarse	2	2.13	1							
833802	Subgrade	Fine	1	1.28	3	100	100	99	98.5	91.5	32.5	74
833802	Subgrade	Fine	1	1.31	3	100	100	99	98.5	91.5	32.5	74
833802	Subgrade	Fine	1	1.41	3	100	100	99	98.5	91.5	32.5	74
833802	Subgrade	Fine	1	1.41	10	100	100	99	98.5	91.5	32.5	74
833802	Subgrade	Fine	1	1.44	3	100	100	99	98.5	91.5	32.5	74
871622	Base	Coarse	2	1.95	1							
871622	Base	Coarse	2	2.00	1							
871622	Subgrade	Fine	1	1.81	1	98.5	97.5	97	96	48.2	0	0
893015	Base	Coarse	2	2.20	1							
893015	Subgrade	Coarse	1	1.76	1							
906405	Base	Coarse	2	2.14	1							
906405	Subgrade	Coarse	1	2.03	3							
906405	Subgrade	Coarse	1	2.04	3							
906405	Subgrade	Coarse	1	2.04	10							

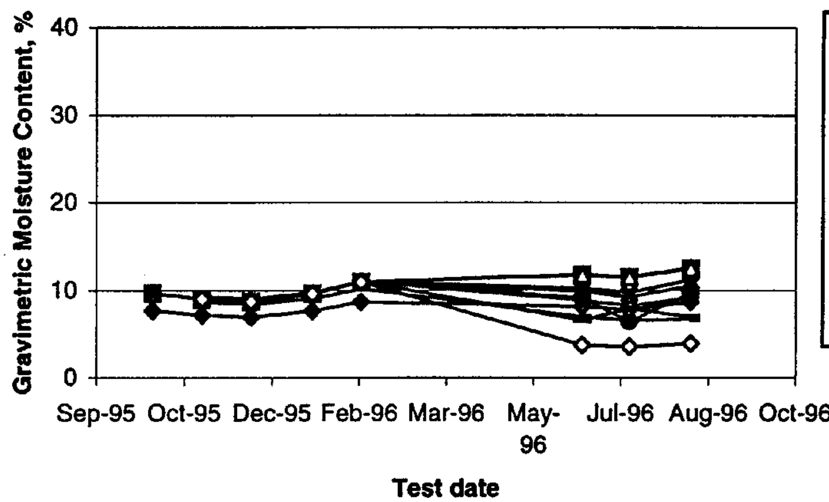
APPENDIX D – SEASONAL VARIATION IN VOLUMETRIC AND GRAVIMETRIC MOISTURE CONTENT AND DAILY RAINFALL



TDR_No	Depth, m
1	0.20
2	0.35
3	0.51
4	0.66
5	0.81
6	0.97
7	1.12
8	1.25
9	1.51
10	1.92

Figure 81. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 040113 in Arizona.





TDR_No	Depth, m
1	0.32
2	0.48
3	0.63
4	0.79
5	0.93
6	1.09
7	1.24
8	1.40
9	1.51
10	2.00

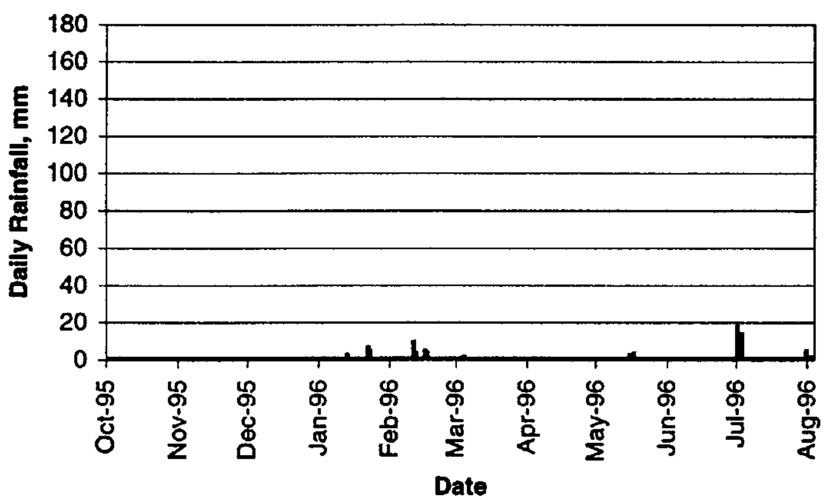
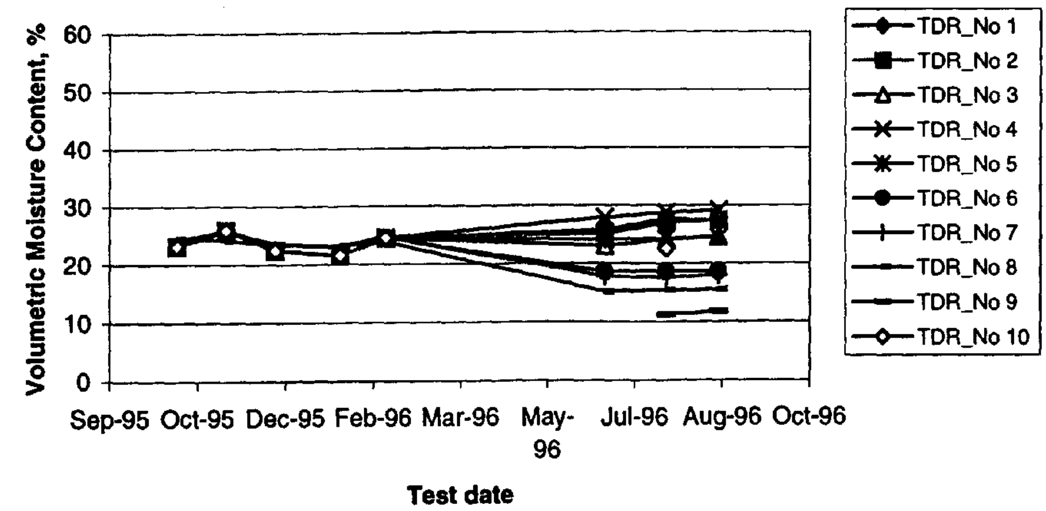
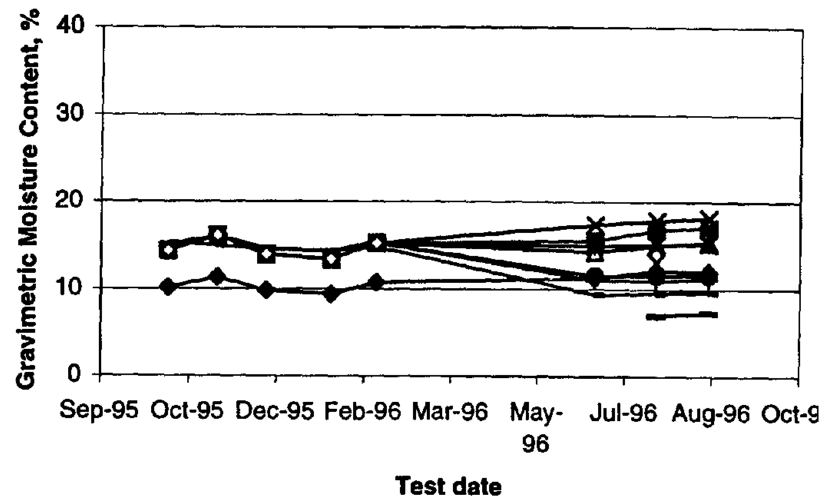


Figure 82. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 040114 in Arizona.





TDR_No	Depth, m
1	0.34
2	0.50
3	0.65
4	0.80
5	0.96
6	1.11
7	1.26
8	1.41
9	1.72
10	2.12

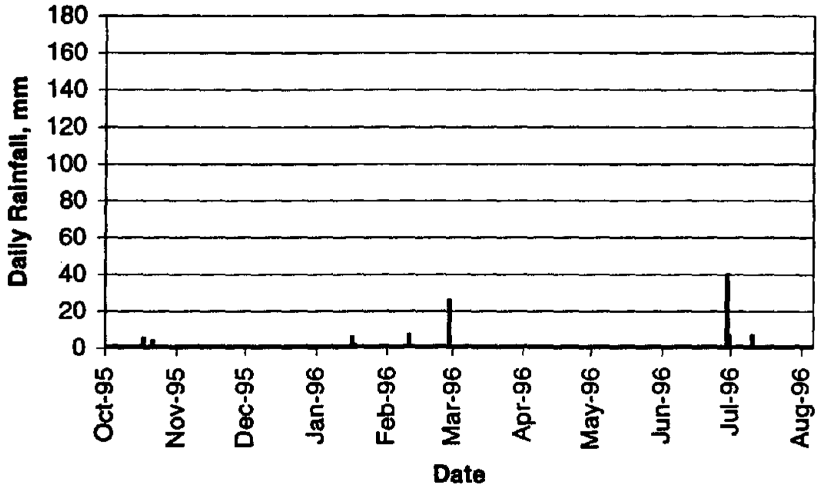


Figure 83. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 040215 in Arizona.

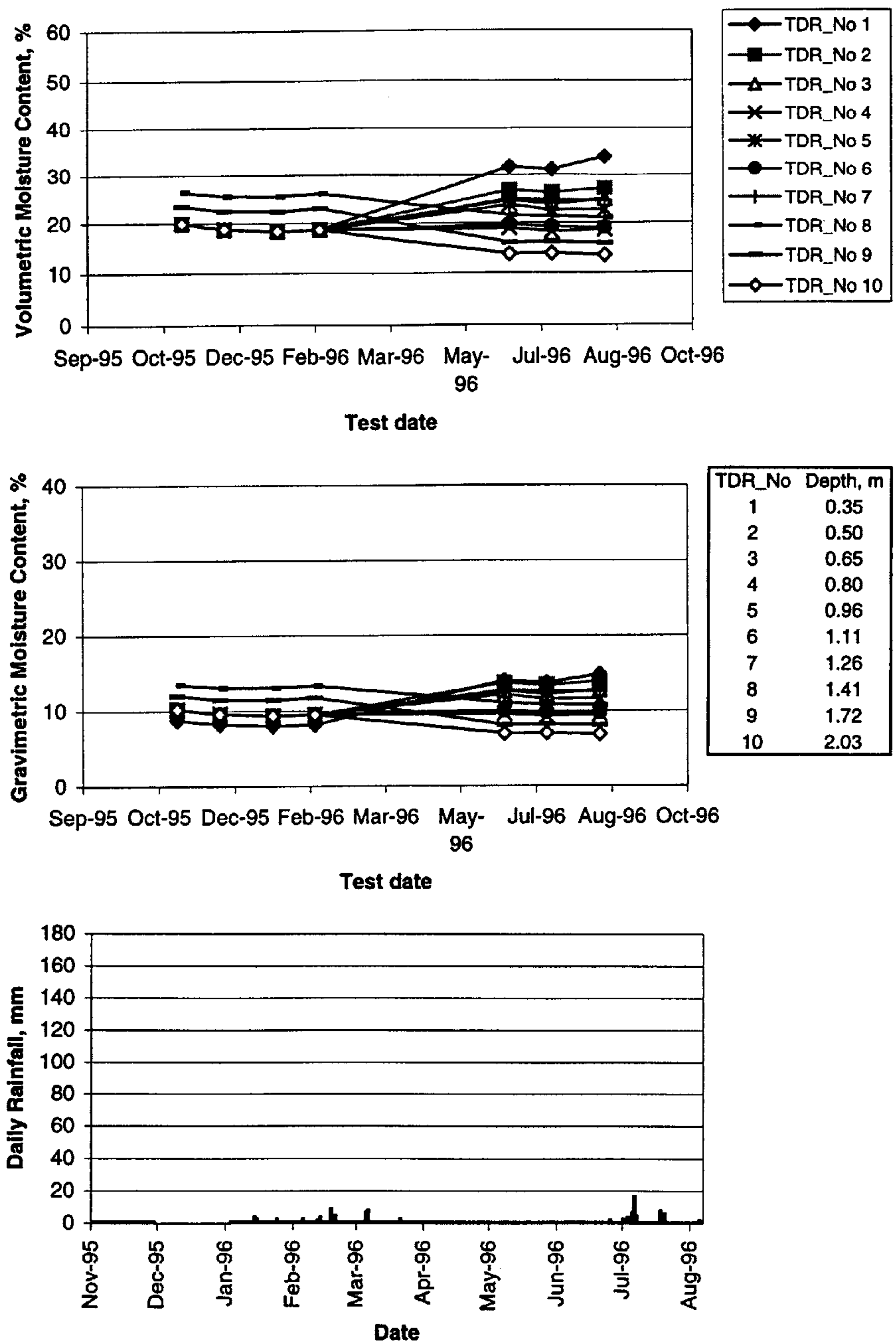
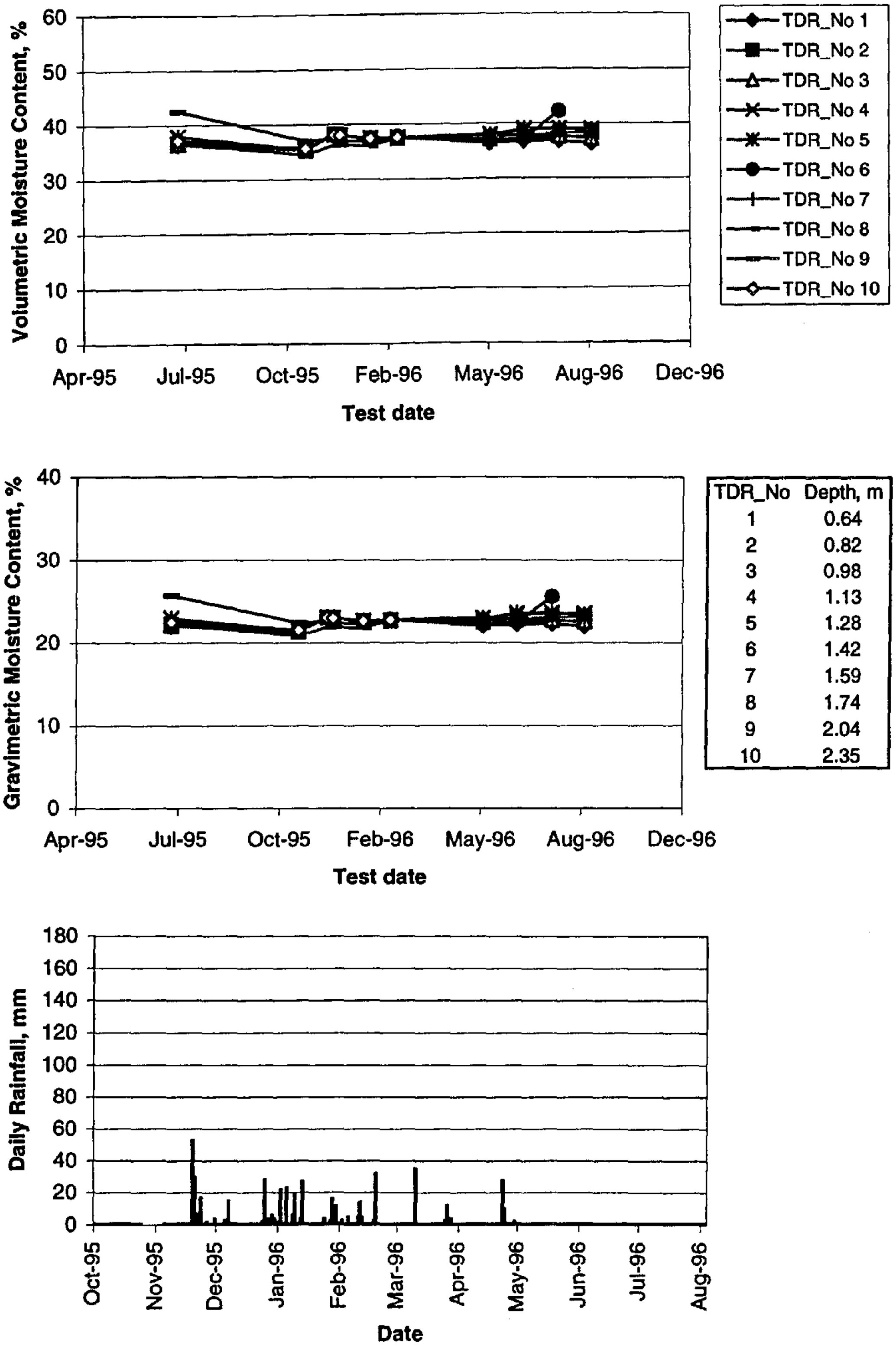
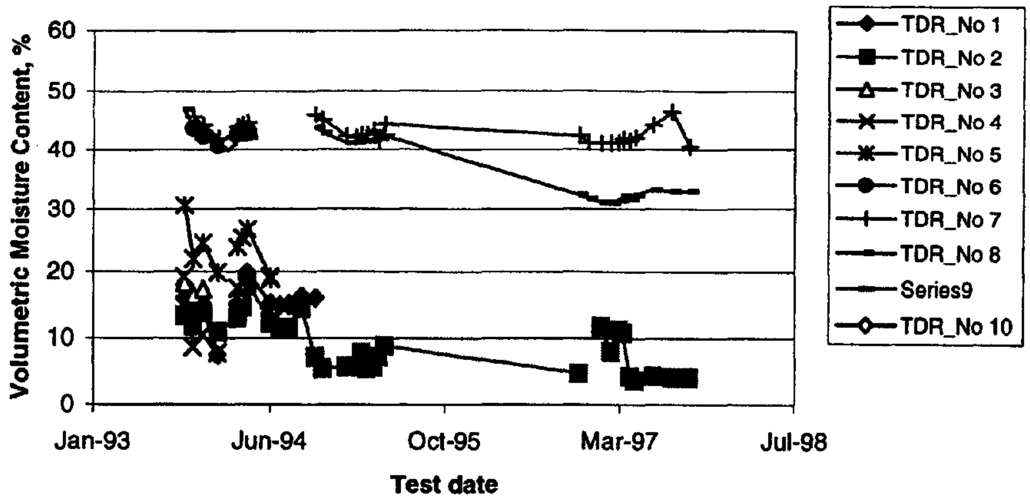


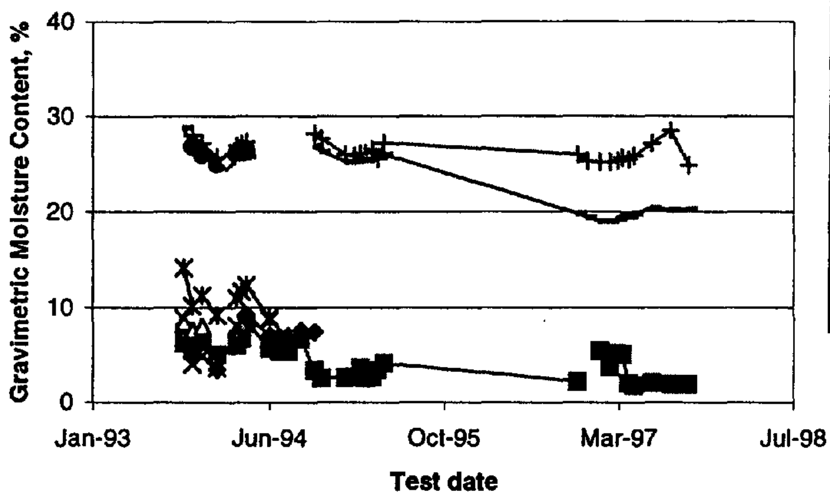
Figure 84. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 041024 in Arizona.



TDR_No	Depth, m
1	0.64
2	0.82
3	0.98
4	1.13
5	1.28
6	1.42
7	1.59
8	1.74
9	2.04
10	2.35

Figure 85. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 063042 in California.





TDR_No	Depth, m
1	0.18
2	0.33
3	0.49
4	0.64
5	0.80
6	0.93
7	1.10
8	1.25
9	1.56
10	1.86

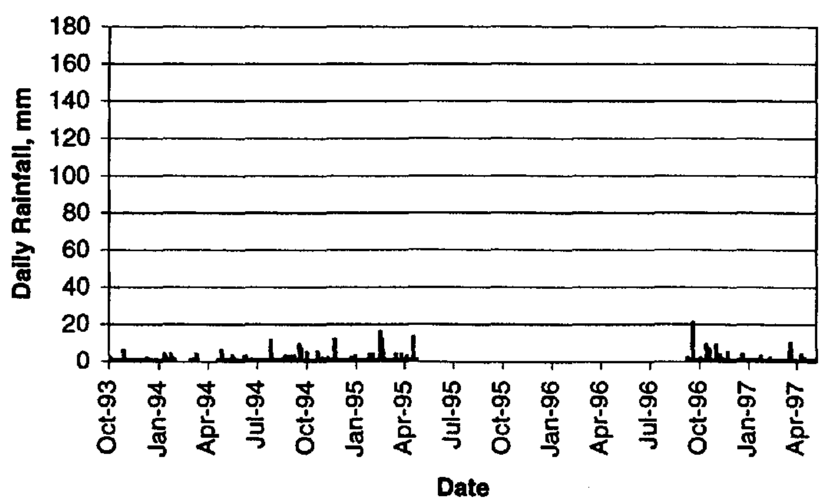
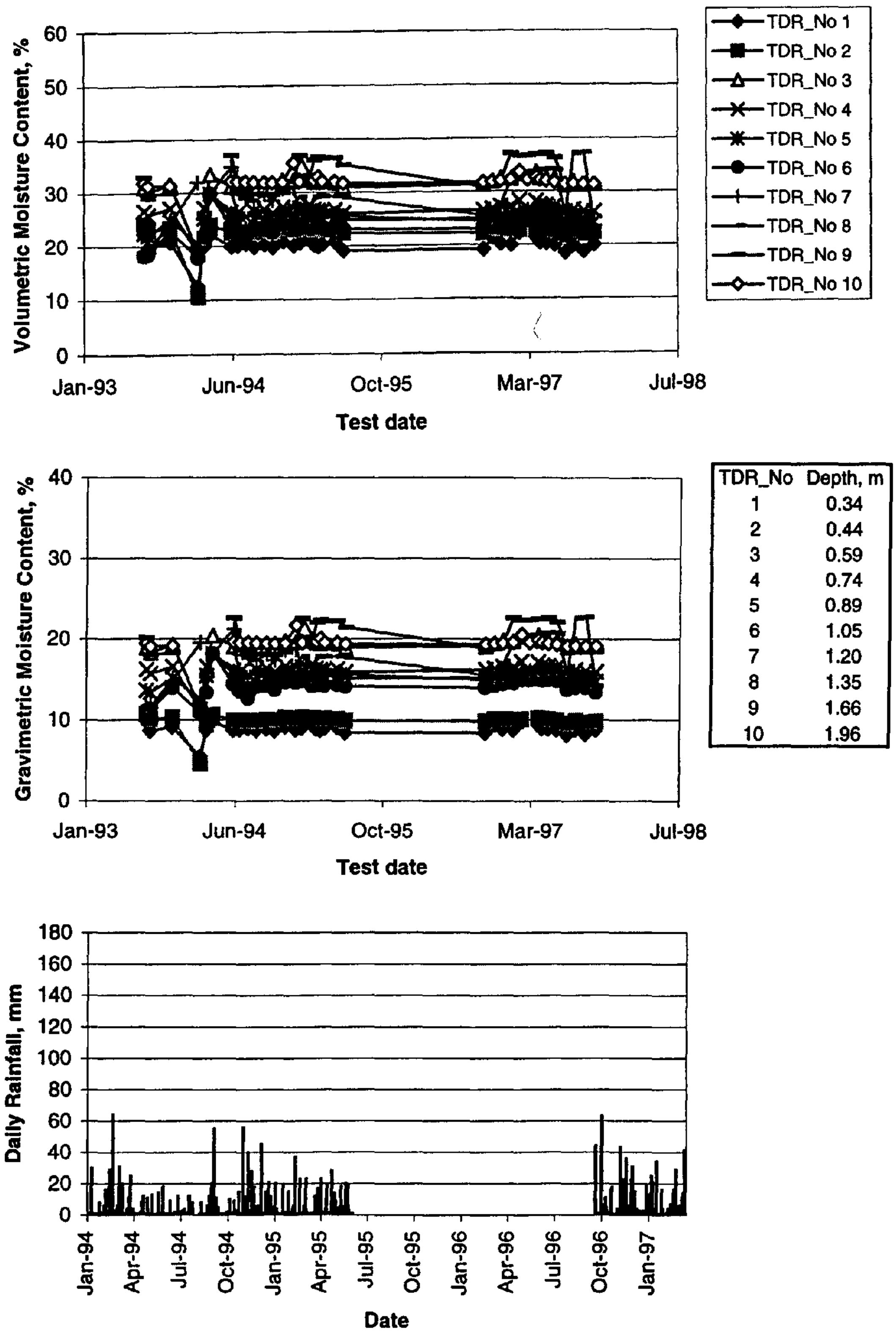
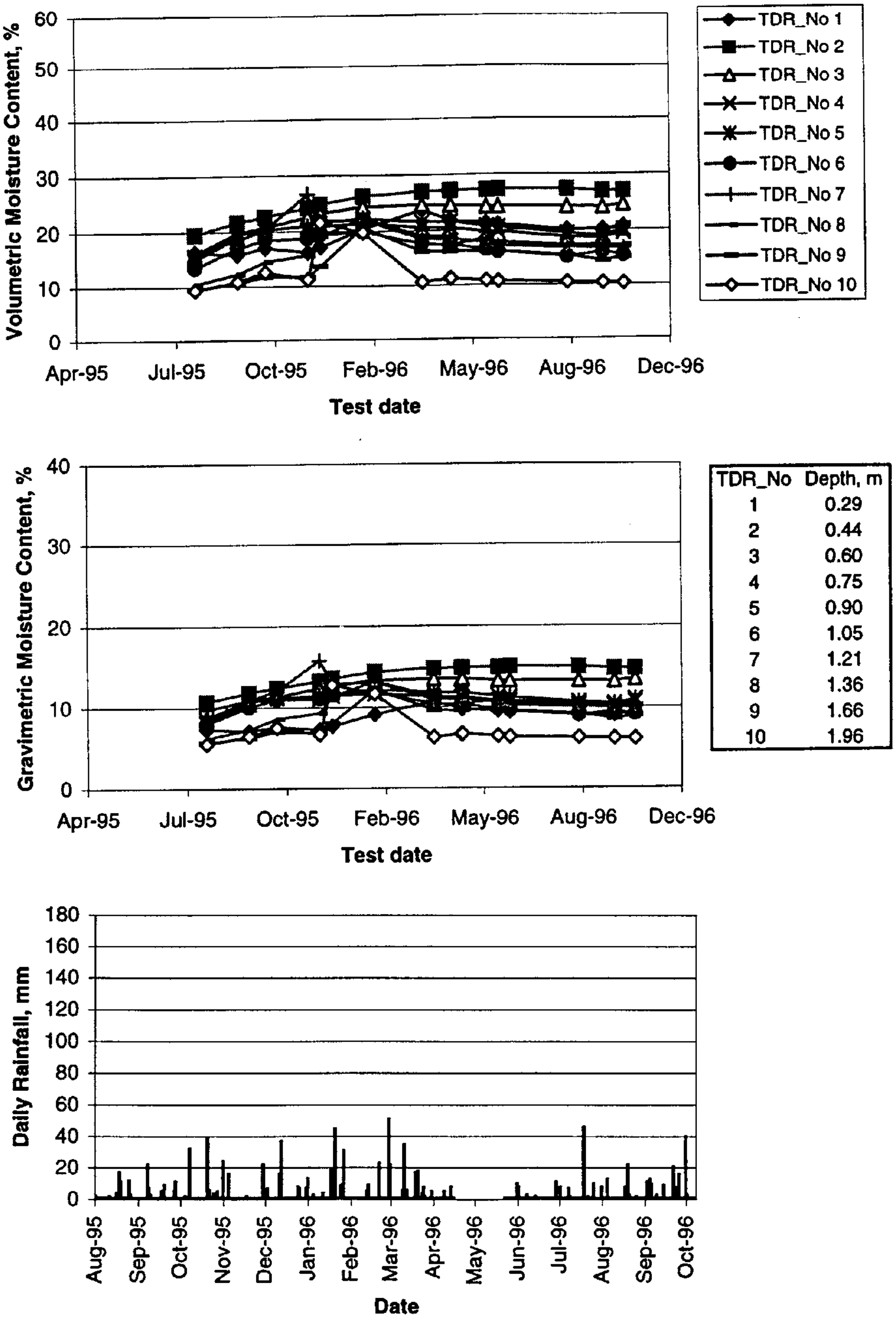


Figure 86. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 081053 in Colorado.



TDR_No	Depth, m
1	0.34
2	0.44
3	0.59
4	0.74
5	0.89
6	1.05
7	1.20
8	1.35
9	1.66
10	1.96

Figure 87. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 091803 in Connecticut.



TDR_No	Depth, m
1	0.29
2	0.44
3	0.60
4	0.75
5	0.90
6	1.05
7	1.21
8	1.36
9	1.66
10	1.96

Figure 88. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 131005 in Georgia.

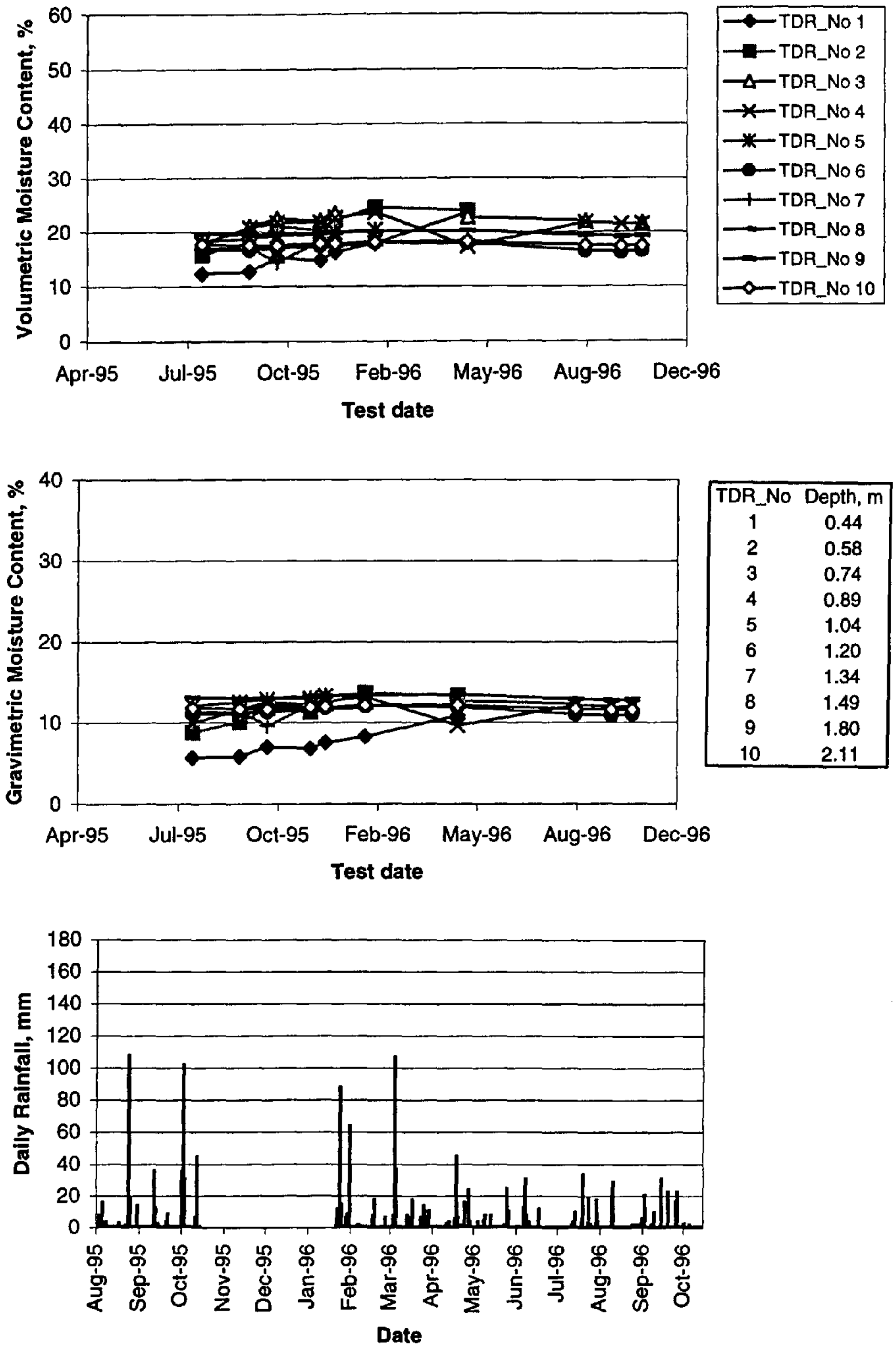
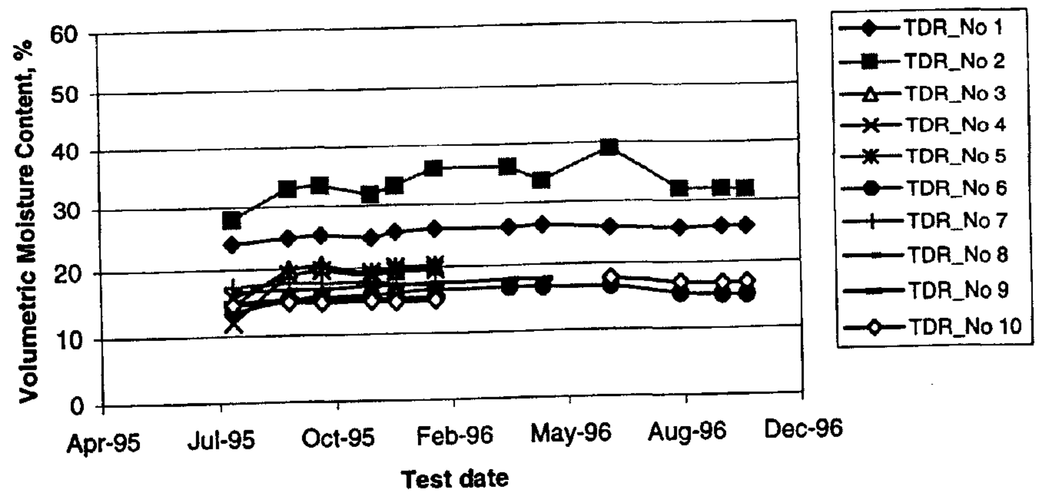
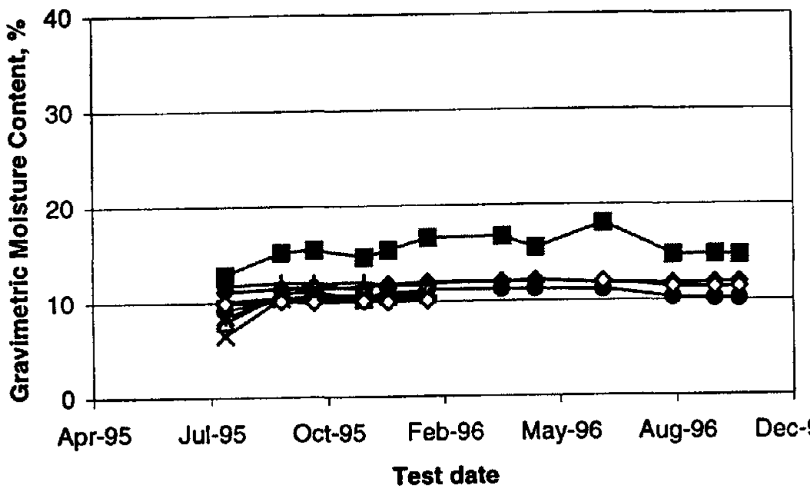


Figure 89. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 131031 in Georgia.





TDR_No	Depth, m
1	0.31
2	0.47
3	0.62
4	0.77
5	0.92
6	1.07
7	1.23
8	1.37
9	1.67
10	1.97

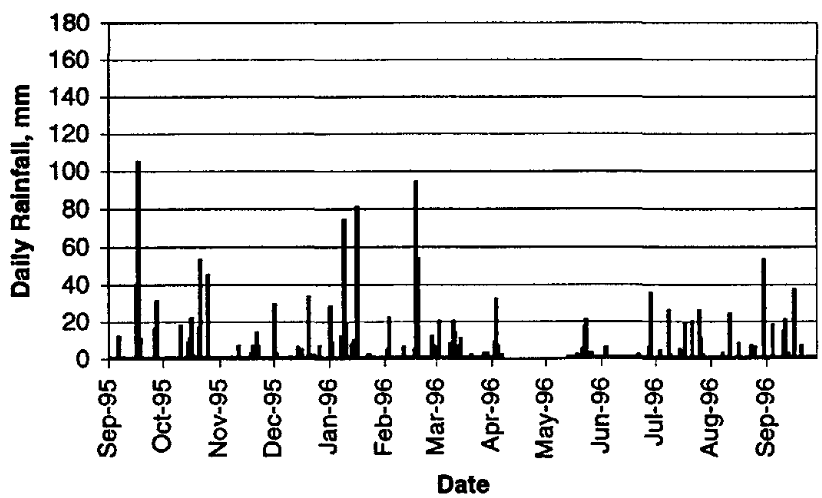
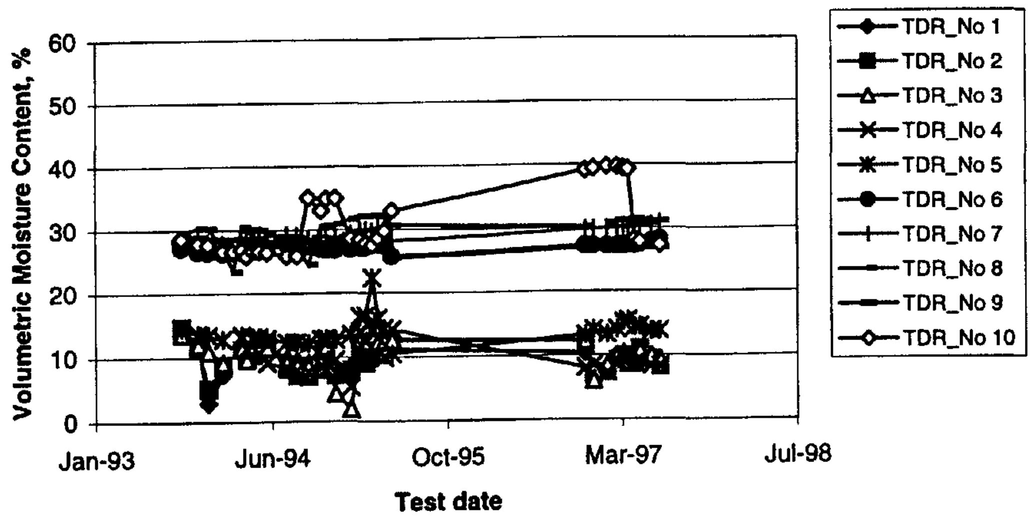
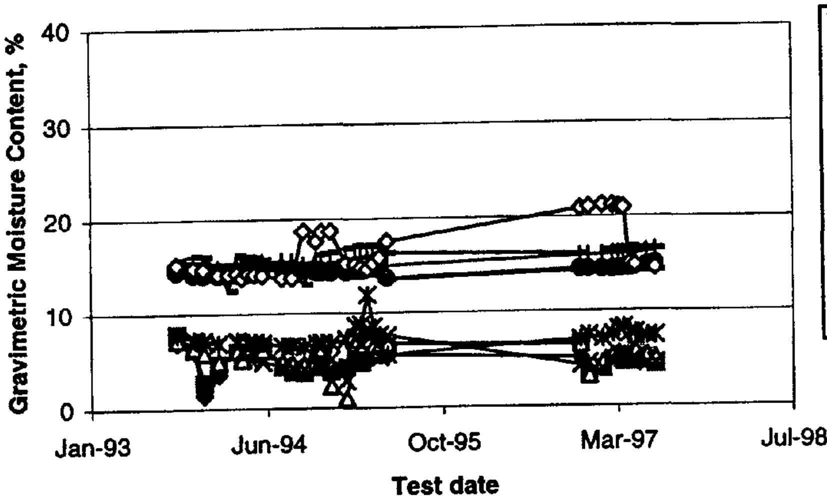


Figure 90. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 133019 in Georgia.





TDR_No	Depth, m
1	0.36
2	0.51
3	0.66
4	0.81
5	0.96
6	1.12
7	1.27
8	1.42
9	1.73
10	2.03

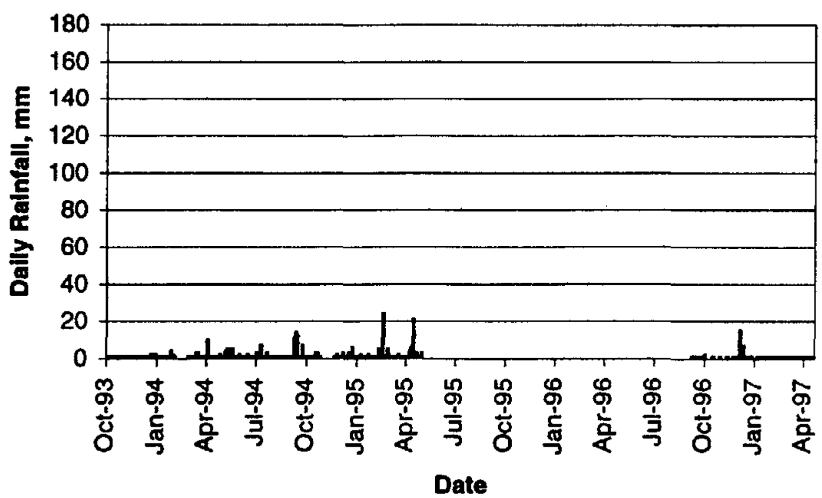
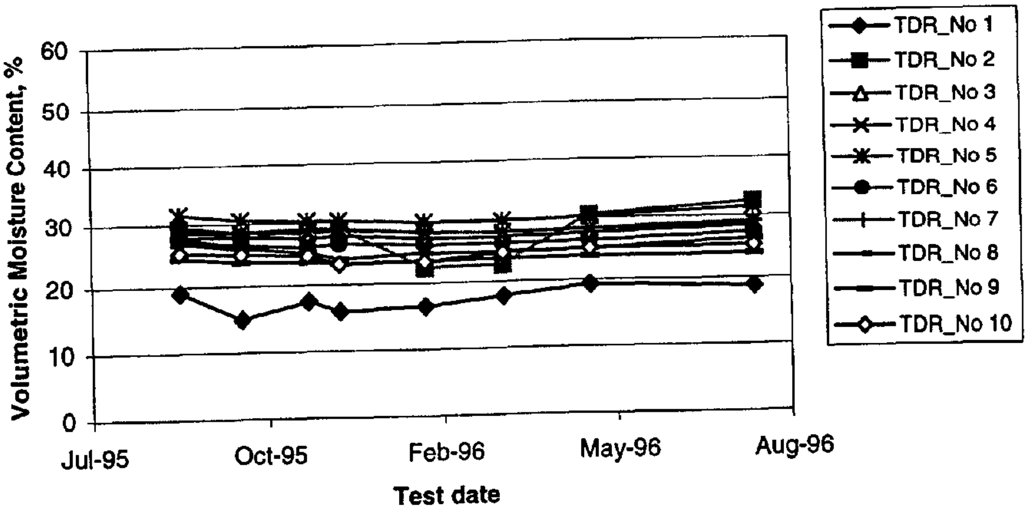
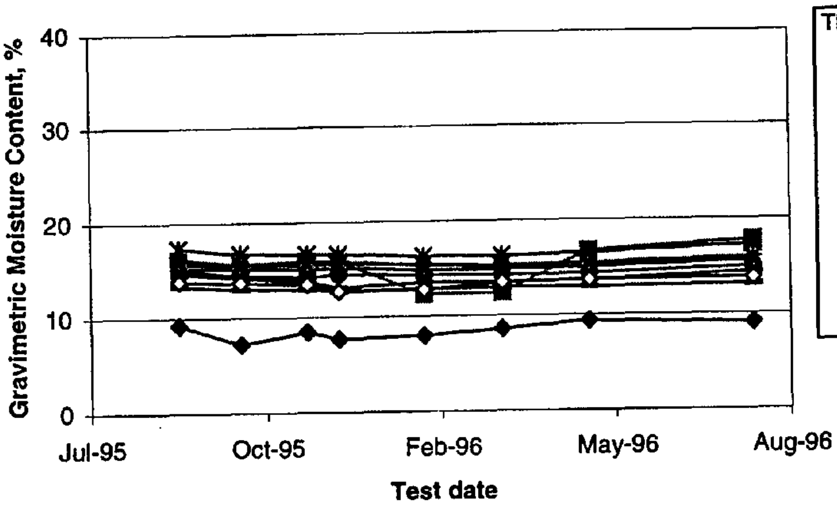


Figure 91. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 161010 in Idaho.





TDR_No	Depth, m
1	0.32
2	0.45
3	0.63
4	0.76
5	0.91
6	1.08
7	1.23
8	1.37
9	1.70
10	1.93

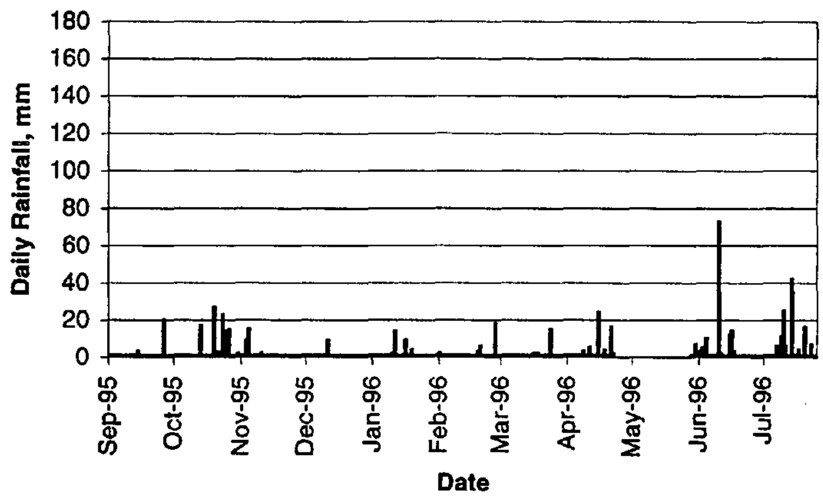


Figure 92. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 183002 in Indiana.

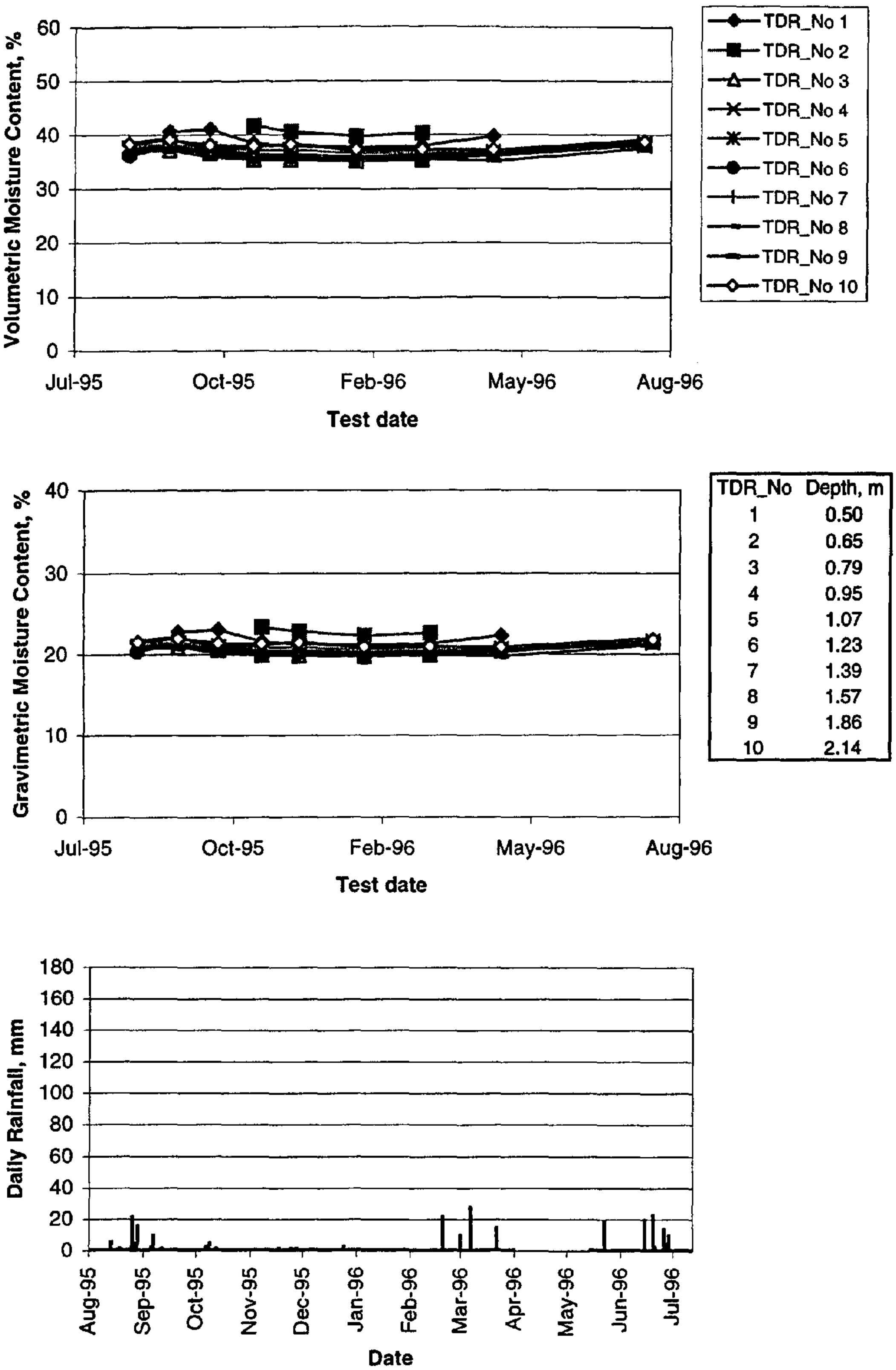
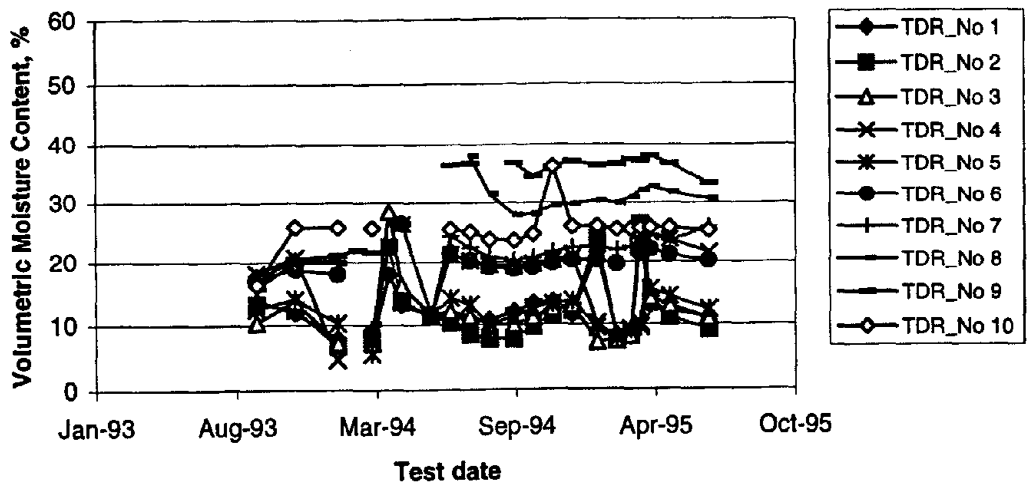
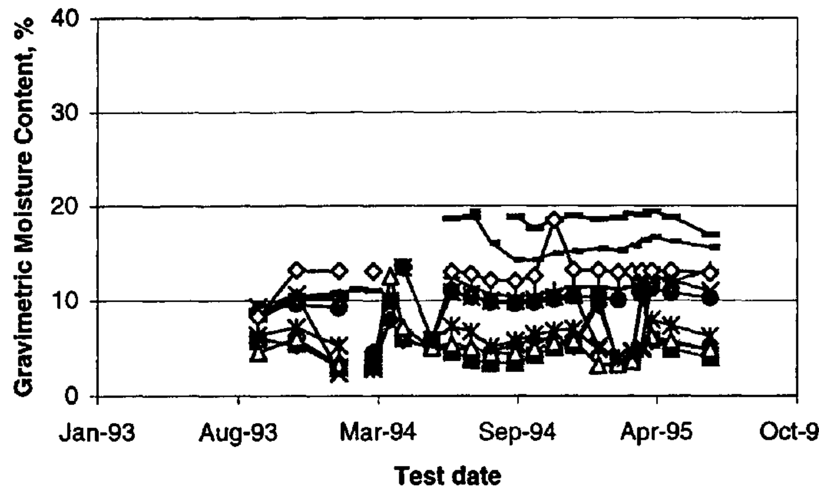


Figure 93. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 204054 in Kansas.





TDR_No	Depth, m
1	0.30
2	0.46
3	0.61
4	0.77
5	0.91
6	1.06
7	1.22
8	1.39
9	1.66
10	1.97

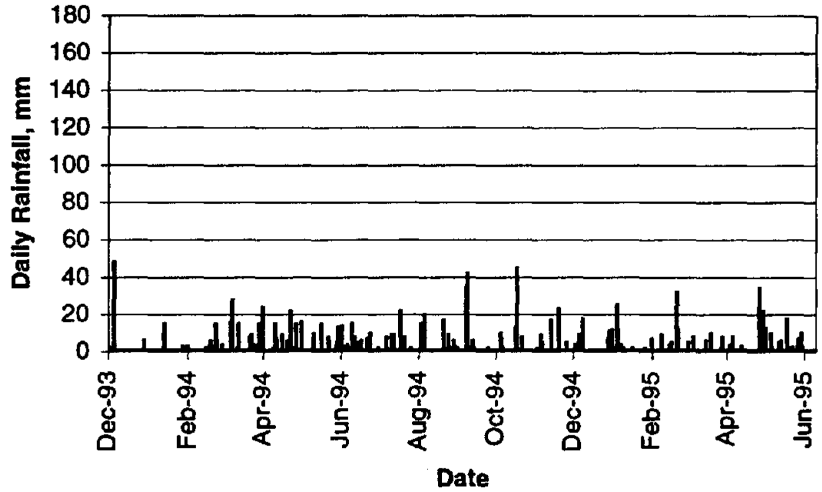
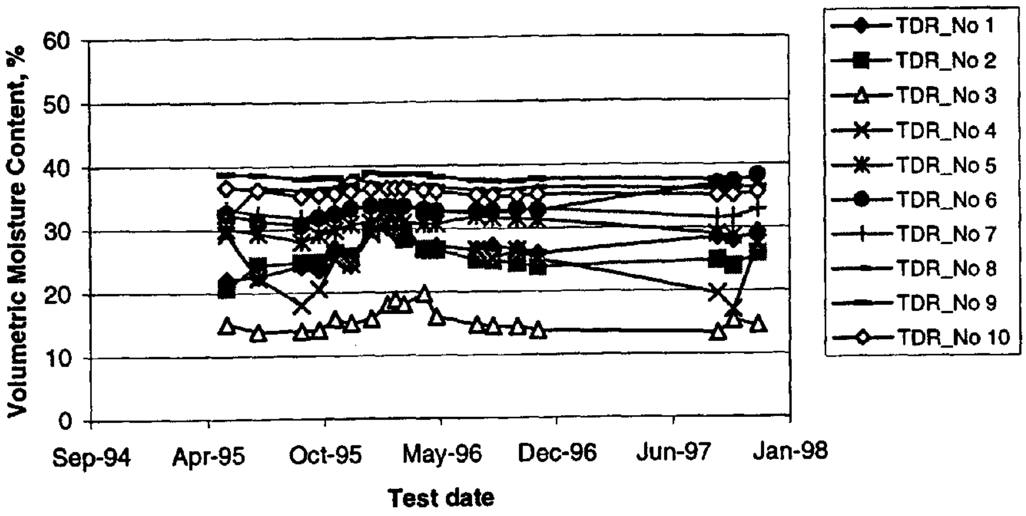
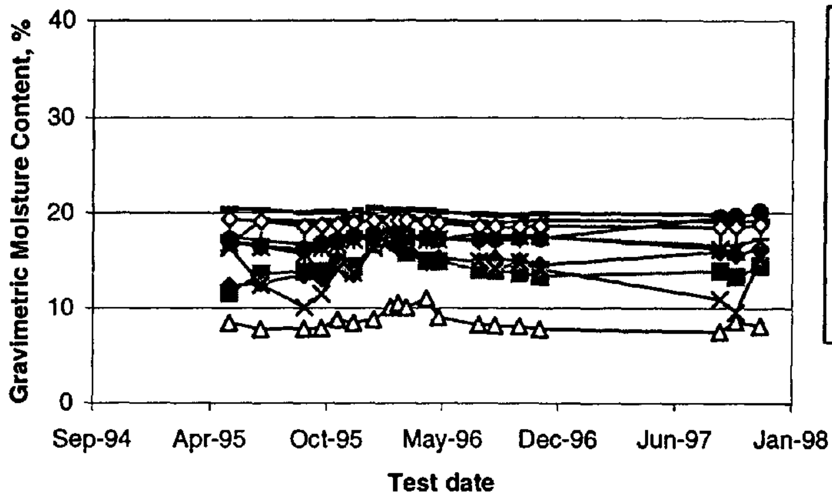


Figure 94. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 231026 in Maine.





TDR_No	Depth, m
1	0.37
2	0.51
3	0.66
4	0.81
5	0.99
6	1.12
7	1.29
8	1.42
9	1.73
10	2.18

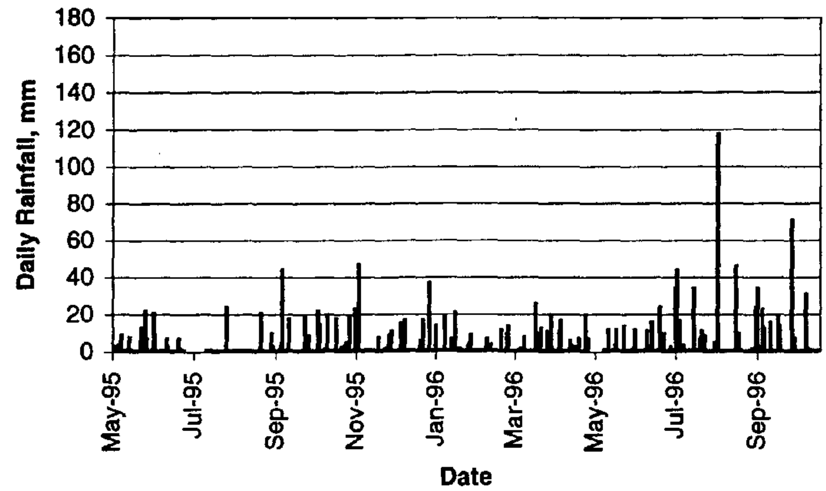
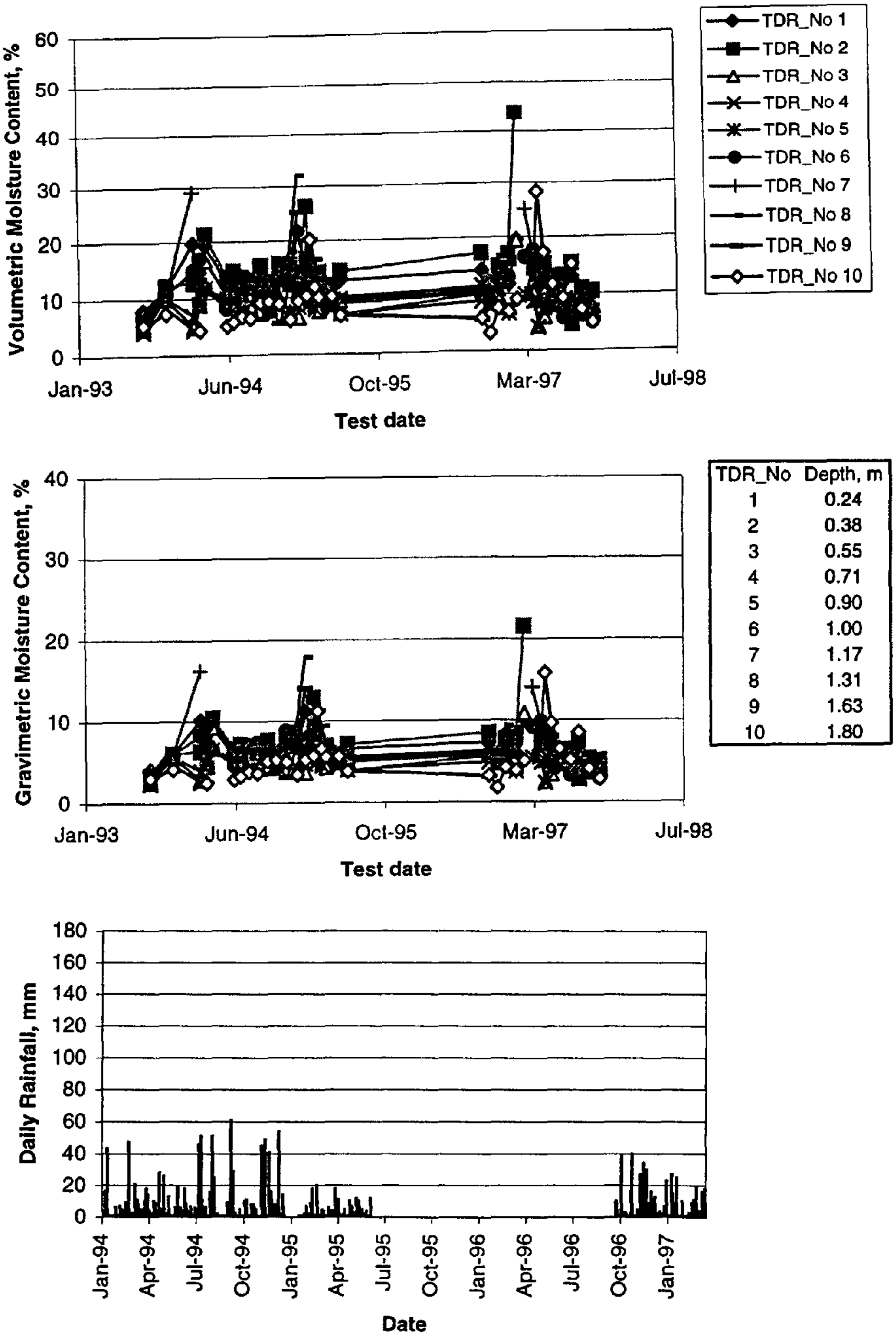


Figure 95. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 241634 in Maryland.



TDR_No	Depth, m
1	0.24
2	0.38
3	0.55
4	0.71
5	0.90
6	1.00
7	1.17
8	1.31
9	1.63
10	1.80

Figure 96. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 251002 in Massachusetts.

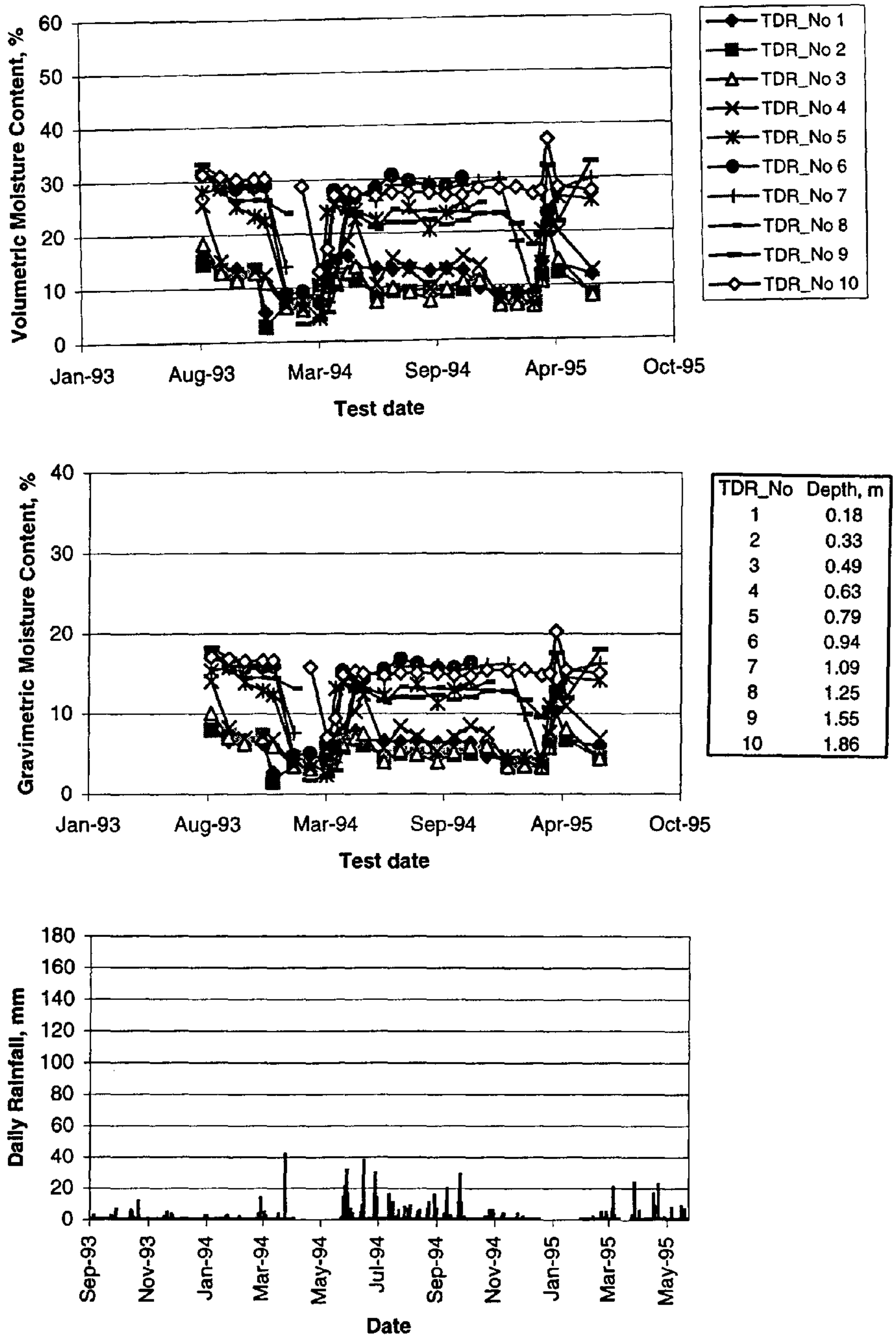
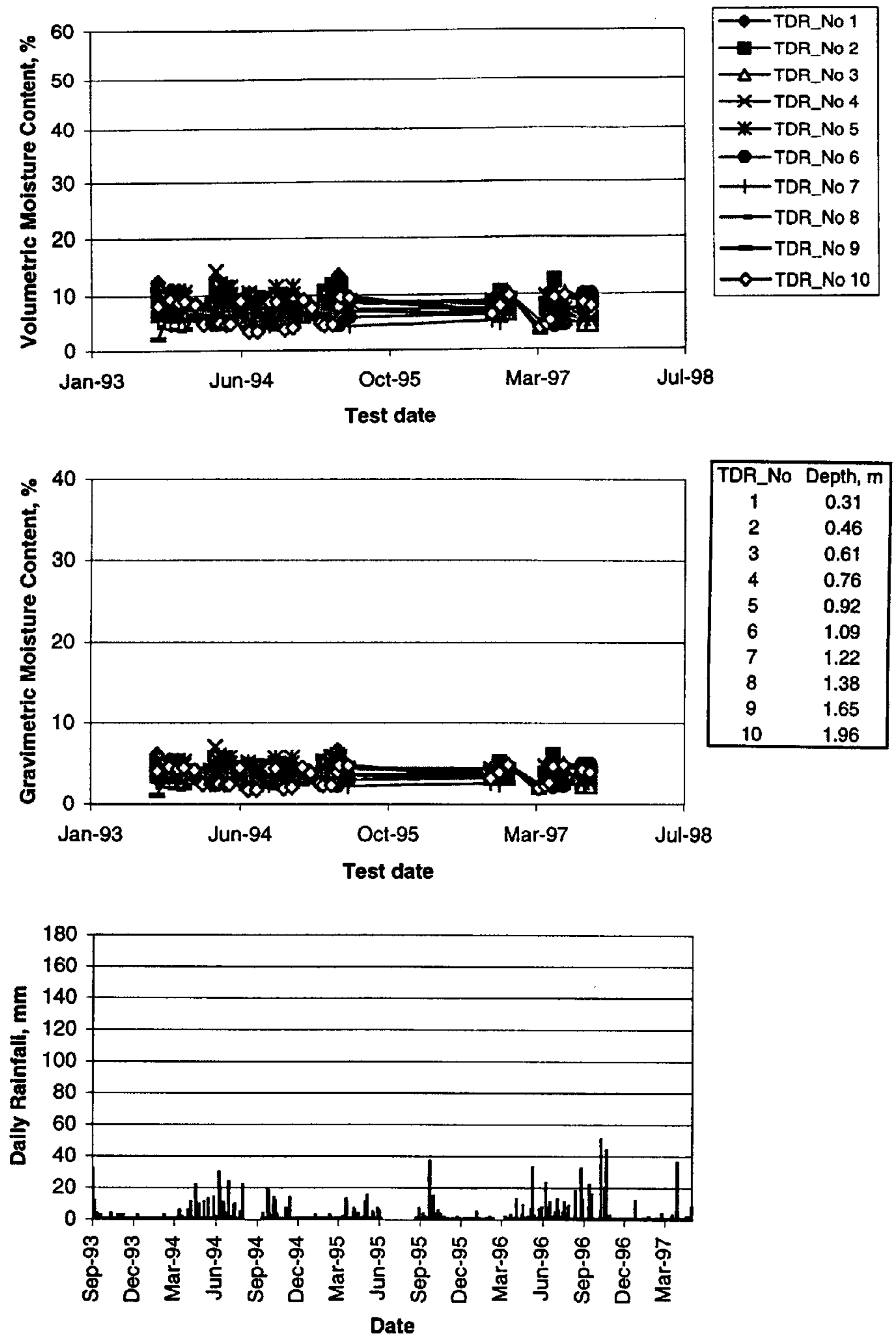
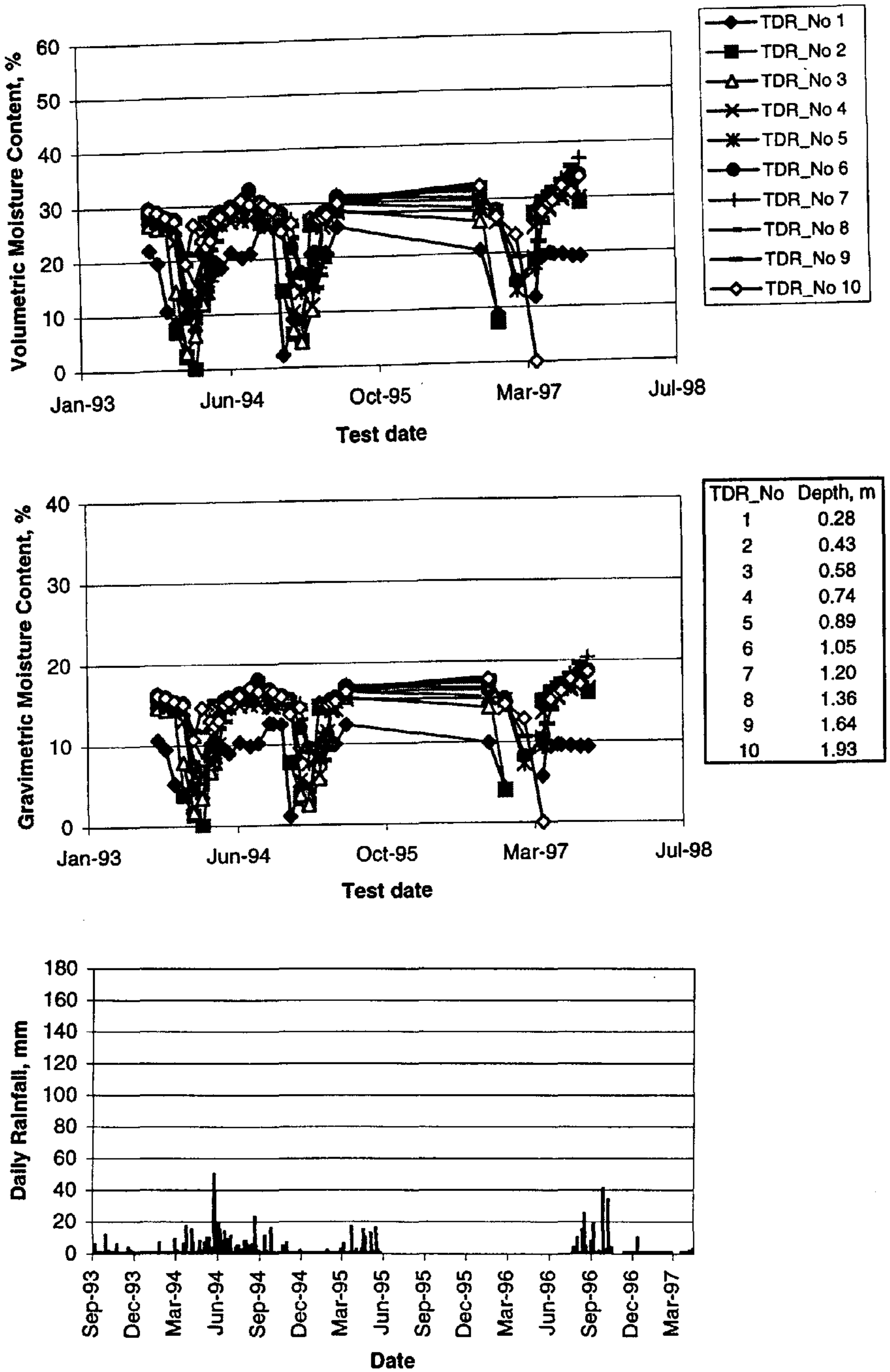


Figure 97. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 271018 in Minnesota.



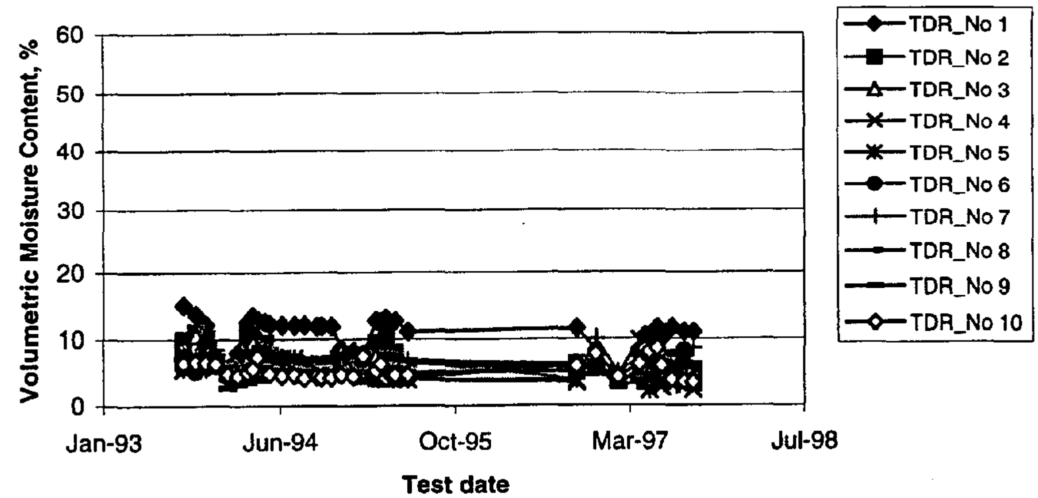
TDR_No	Depth, m
1	0.31
2	0.46
3	0.61
4	0.76
5	0.92
6	1.09
7	1.22
8	1.38
9	1.65
10	1.96

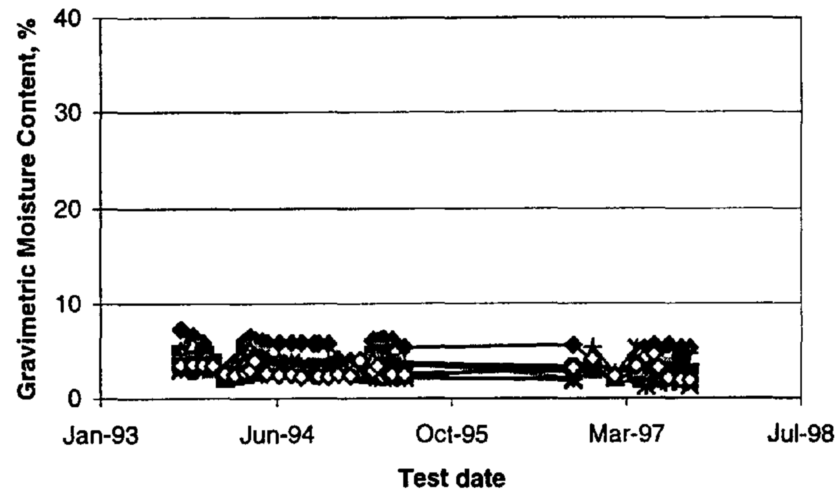
Figure 98. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 271028 in Minnesota.



TDR_No	Depth, m
1	0.28
2	0.43
3	0.58
4	0.74
5	0.89
6	1.05
7	1.20
8	1.36
9	1.64
10	1.93

Figure 99. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 274040 in Minnesota.





TDR_No	Depth, m
1	0.29
2	0.44
3	0.61
4	0.75
5	0.90
6	1.06
7	1.22
8	1.37
9	1.67
10	1.97

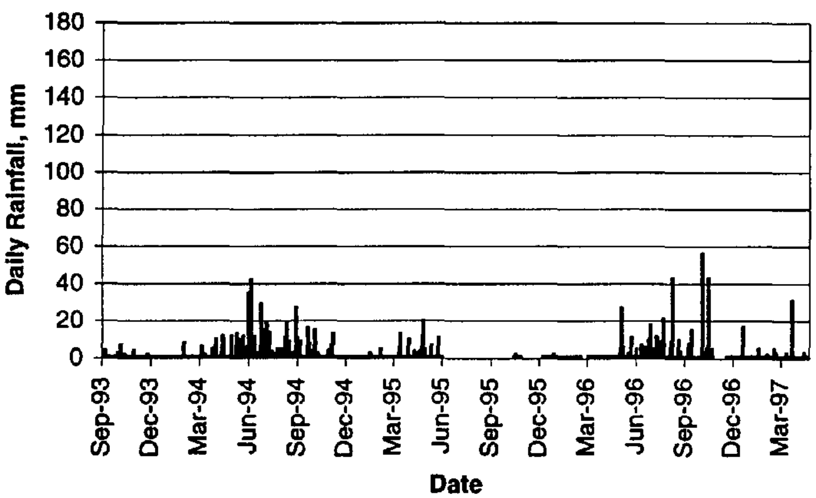
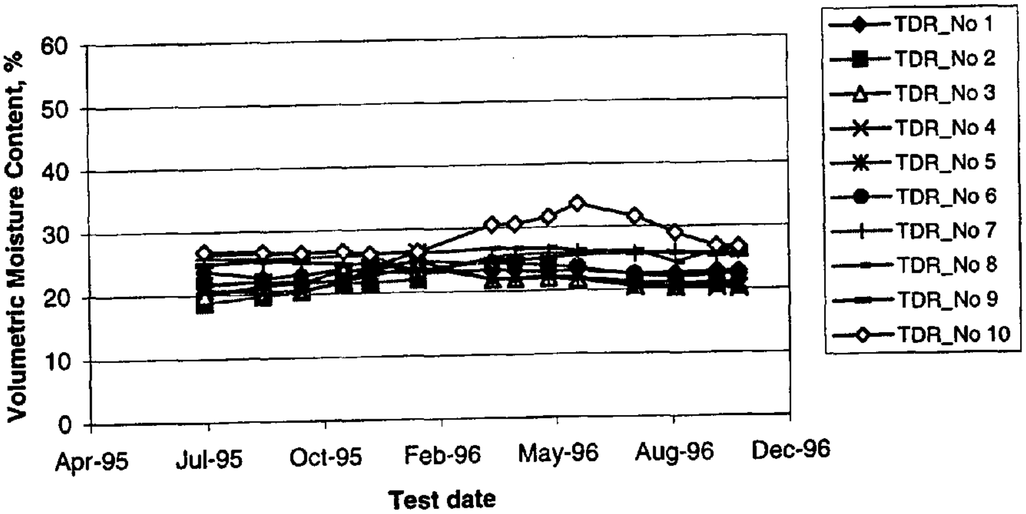
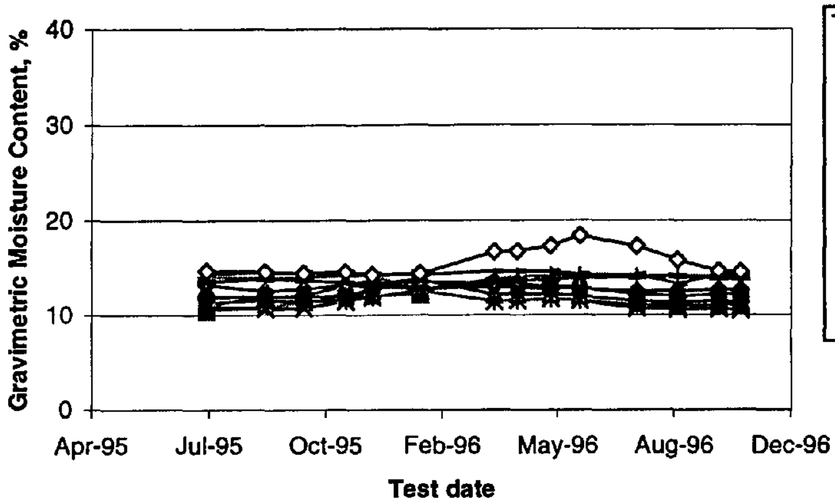


Figure 100. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 276251 in Minnesota.





TDR_No	Depth, m
1	0.35
2	0.51
3	0.65
4	0.81
5	0.95
6	1.11
7	1.26
8	1.41
9	1.71
10	1.96

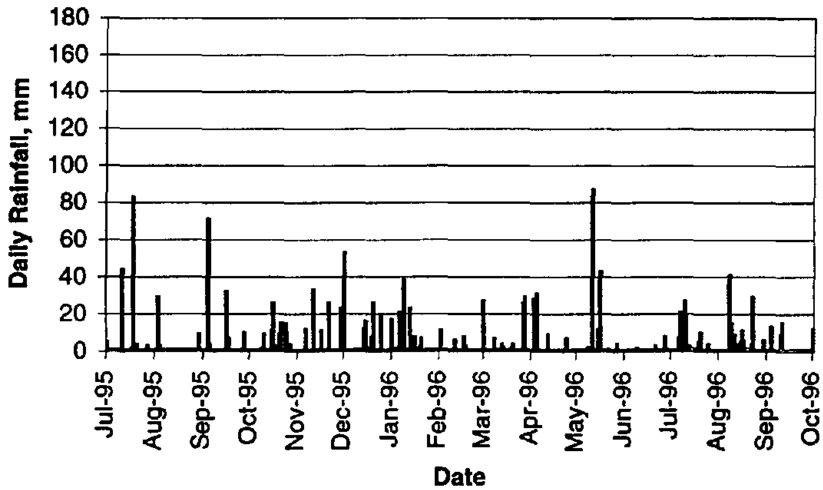
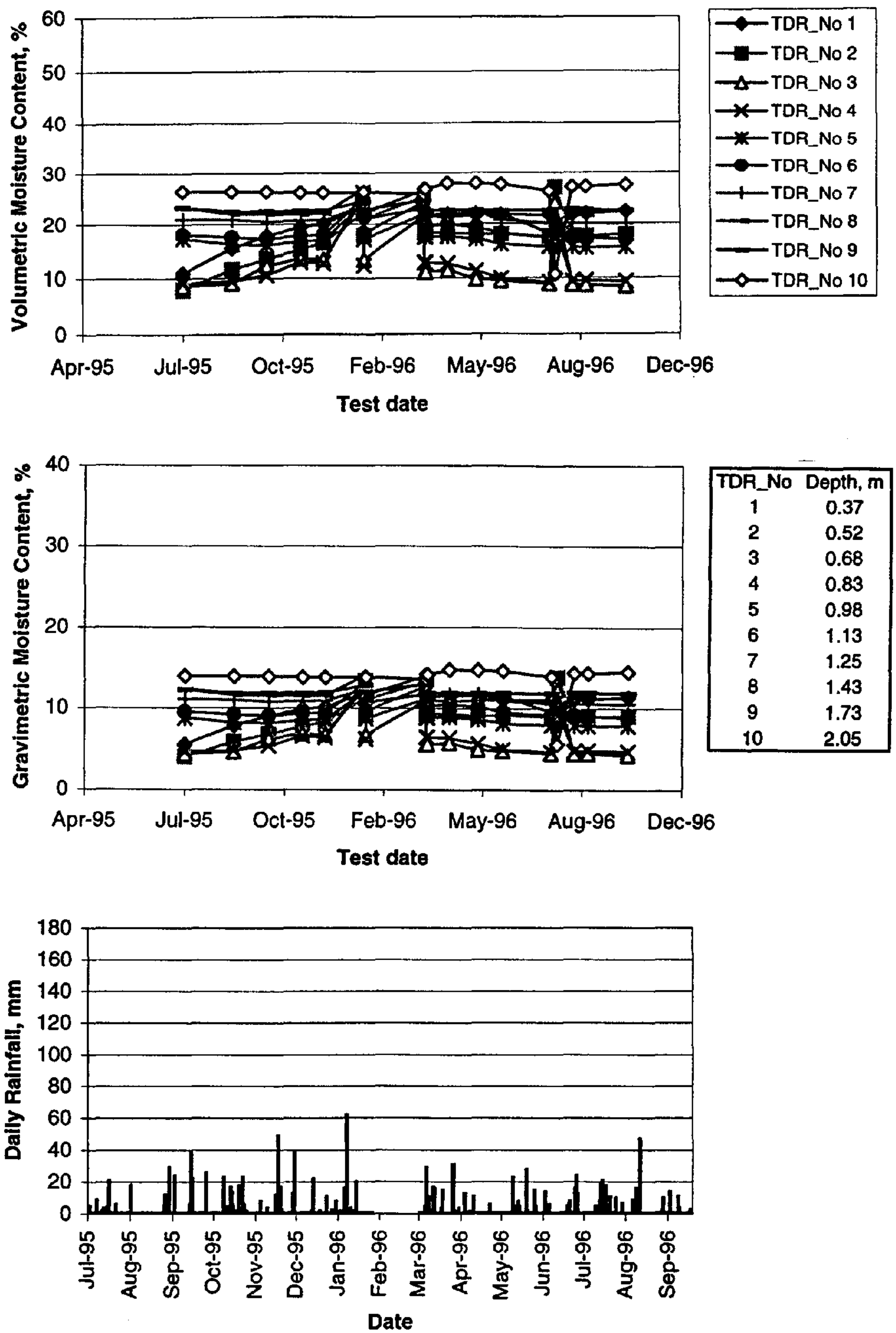
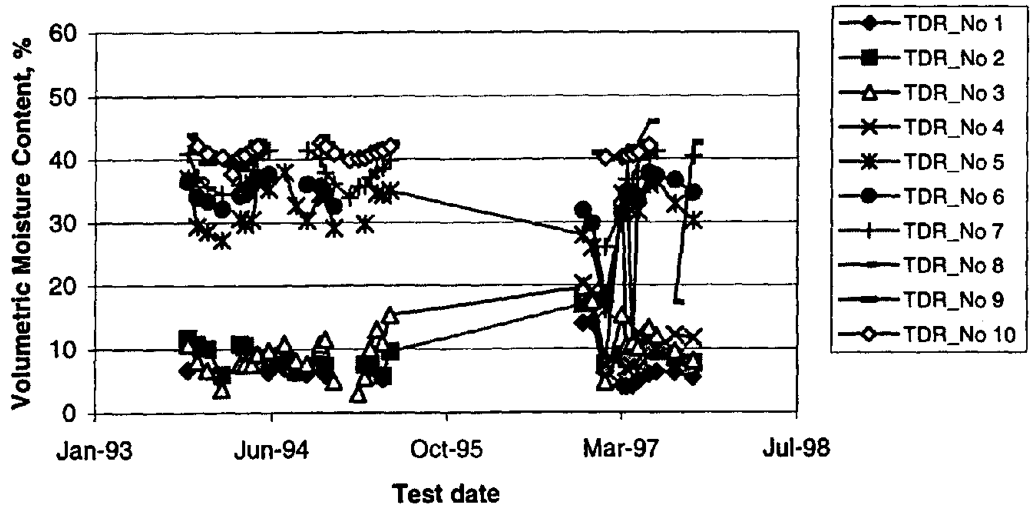


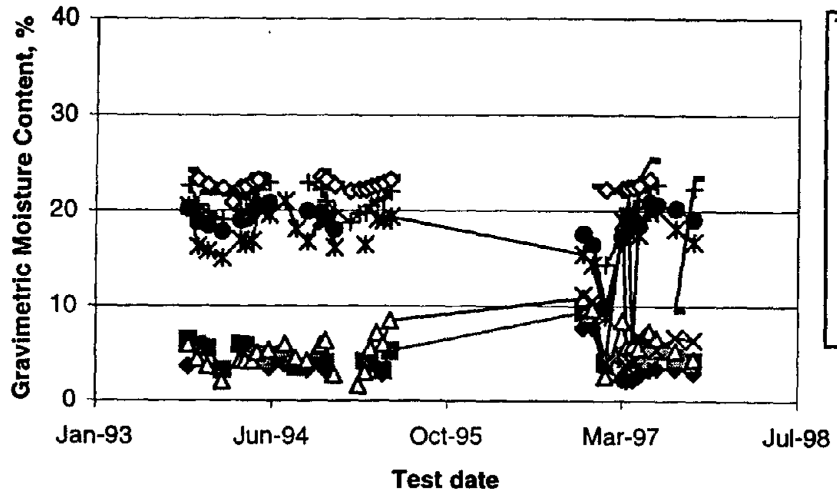
Figure 101. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 281016 in Mississippi.



TDR_No	Depth, m
1	0.37
2	0.52
3	0.68
4	0.83
5	0.98
6	1.13
7	1.25
8	1.43
9	1.73
10	2.05

Figure 102. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 281802 in Mississippi.





TDR_No	Depth, m
1	0.23
2	0.38
3	0.53
4	0.69
5	0.84
6	0.99
7	1.14
8	1.28
9	1.45
10	1.60

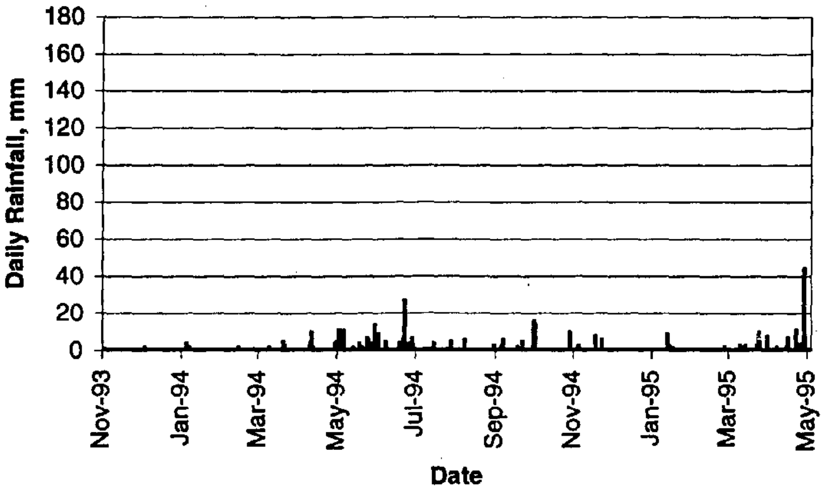


Figure 103. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 308129 in Montana.

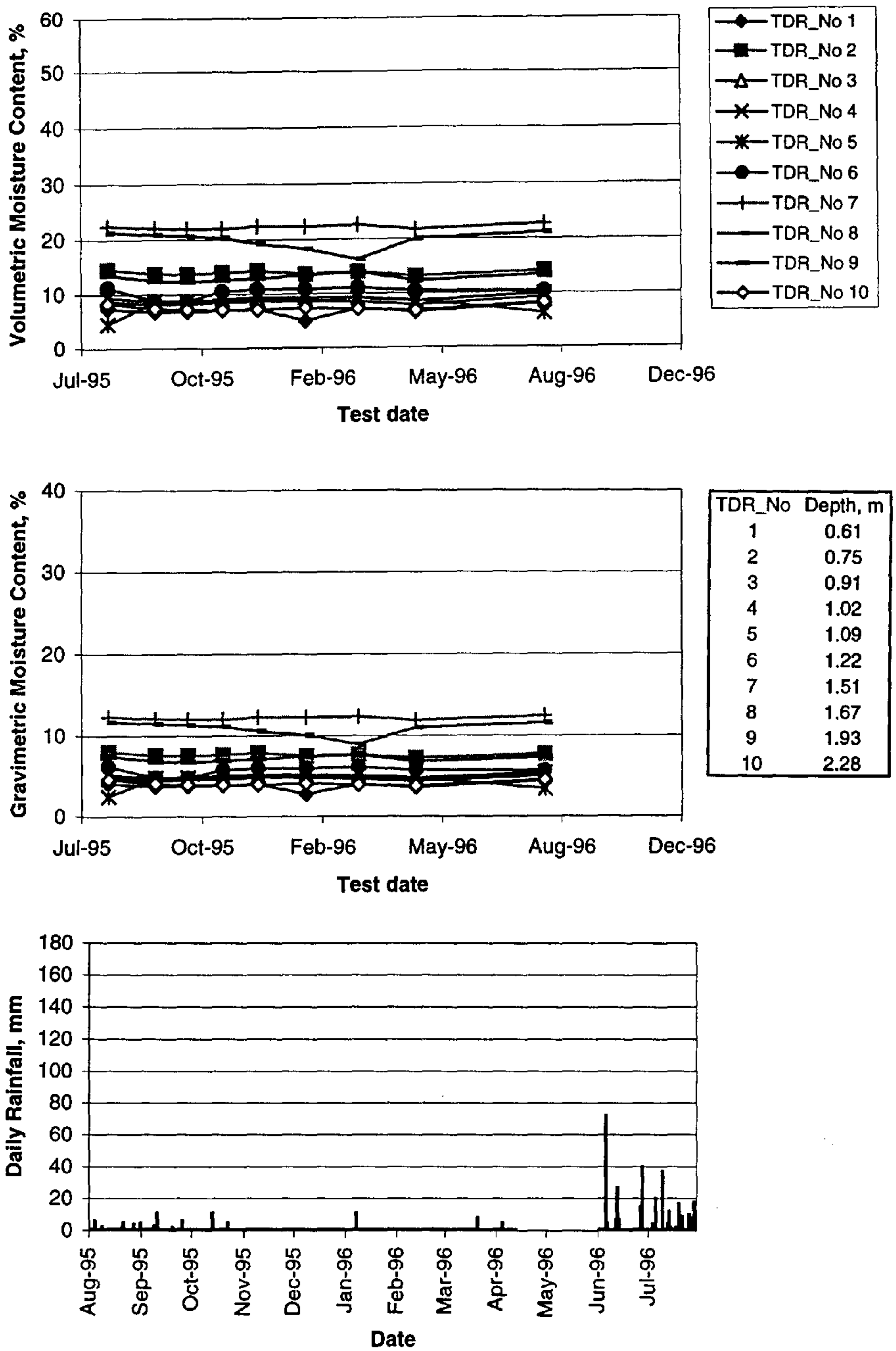
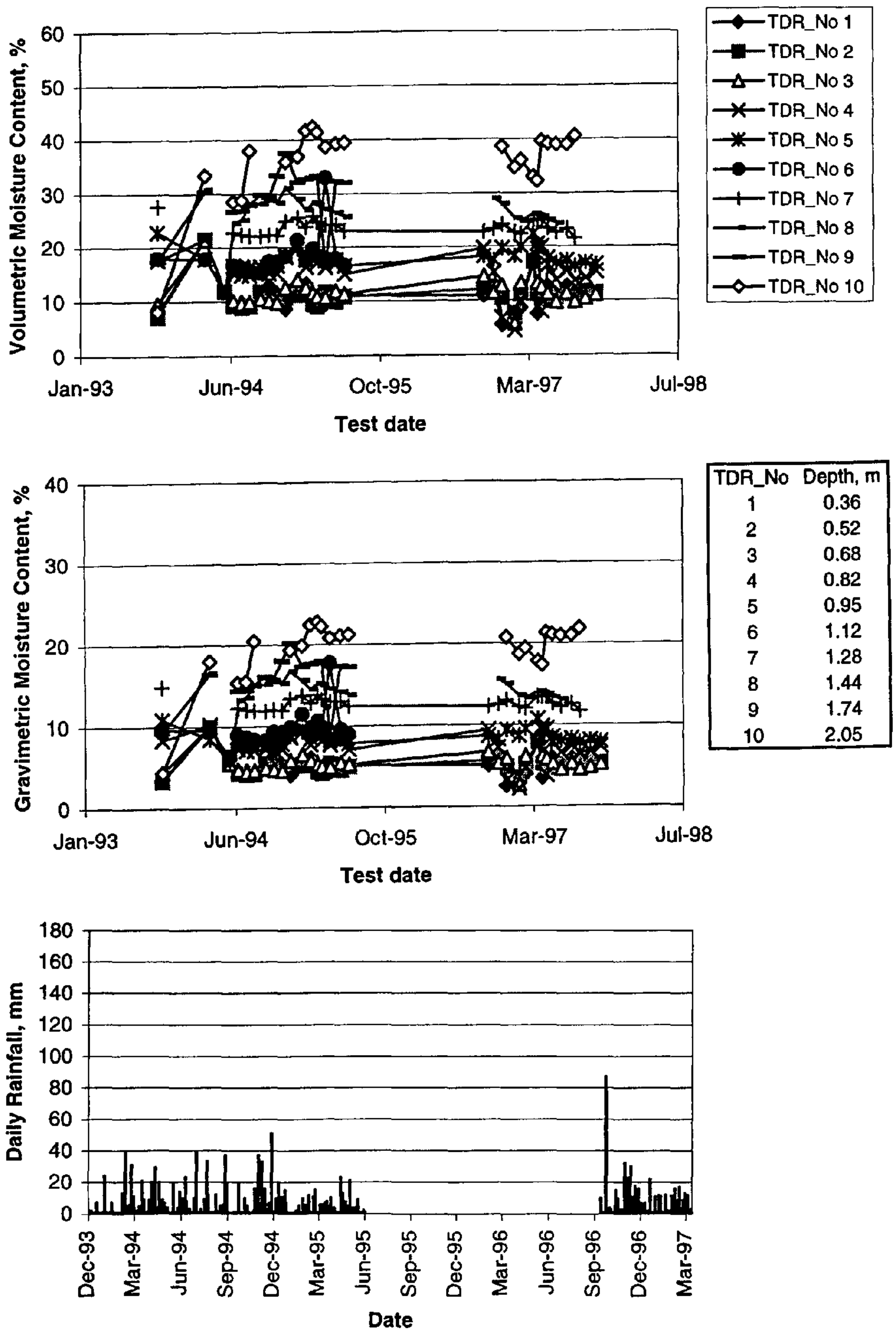
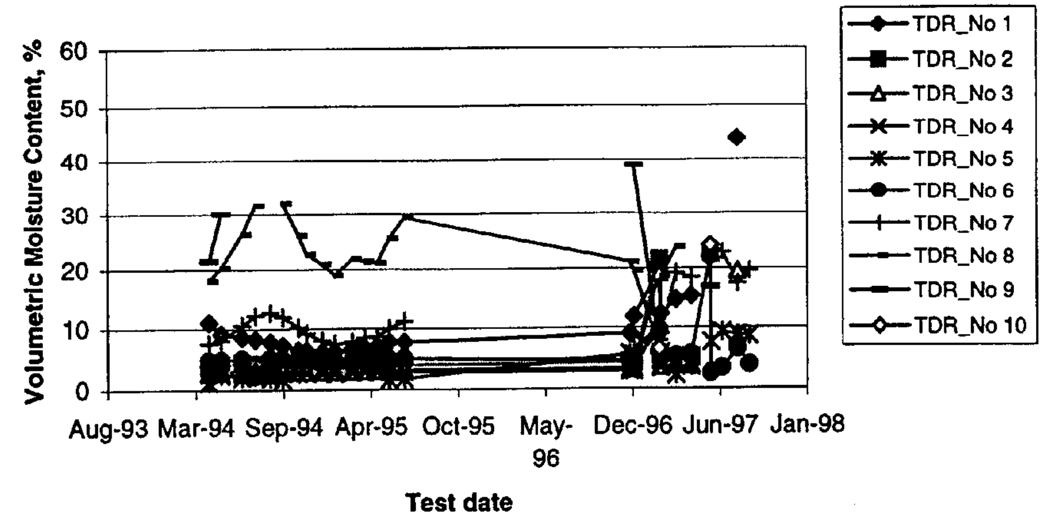


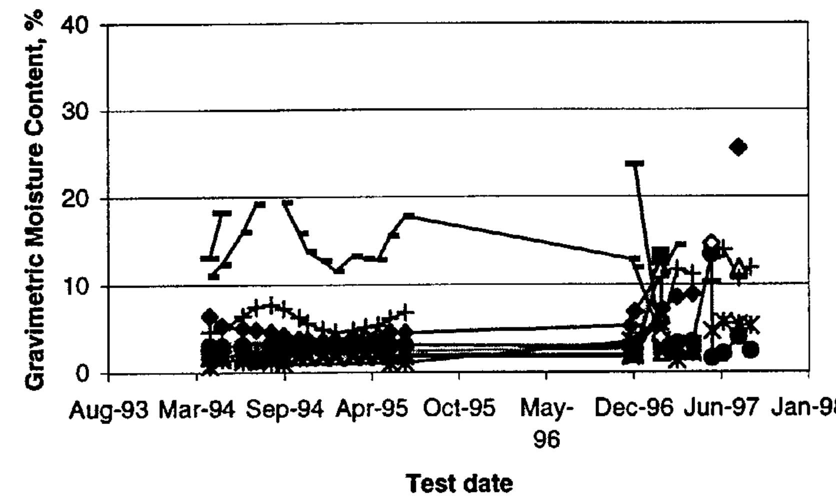
Figure 104. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 313018 in Nebraska.



TDR_No	Depth, m
1	0.36
2	0.52
3	0.68
4	0.82
5	0.95
6	1.12
7	1.28
8	1.44
9	1.74
10	2.05

Figure 105. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 331001 in New Hampshire.





TDR_No	Depth, m
1	0.25
2	0.41
3	0.56
4	0.72
5	0.86
6	1.02
7	1.17
8	1.32
9	1.63
10	1.90

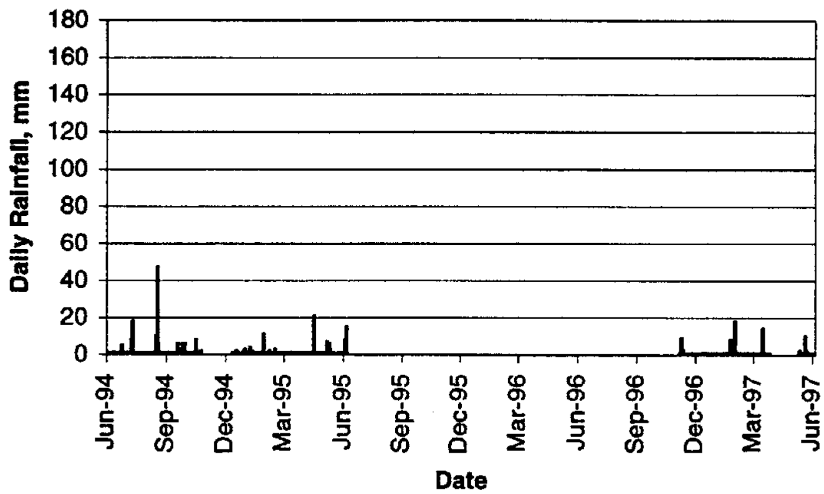


Figure 106. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 351112 in New Mexico.

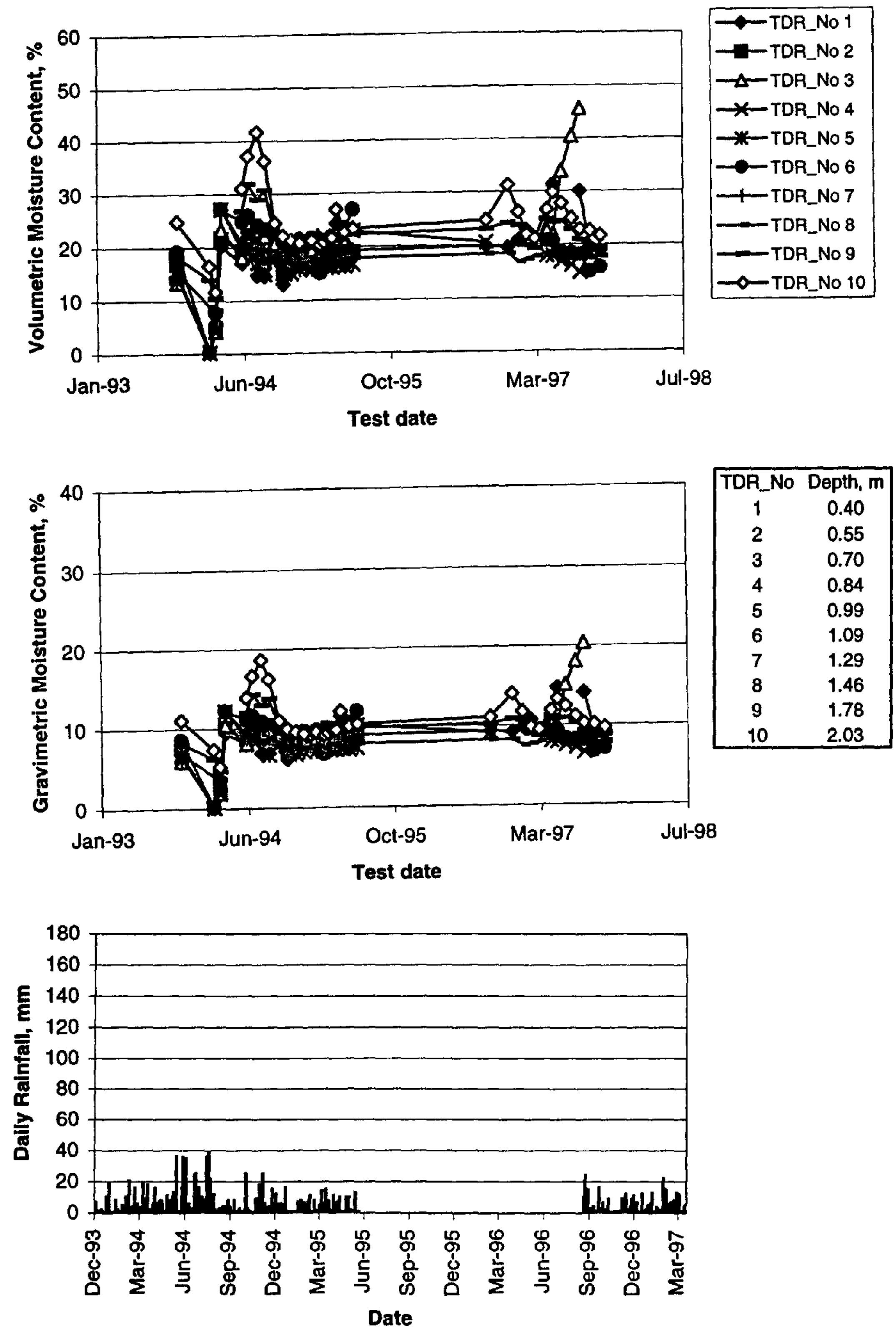
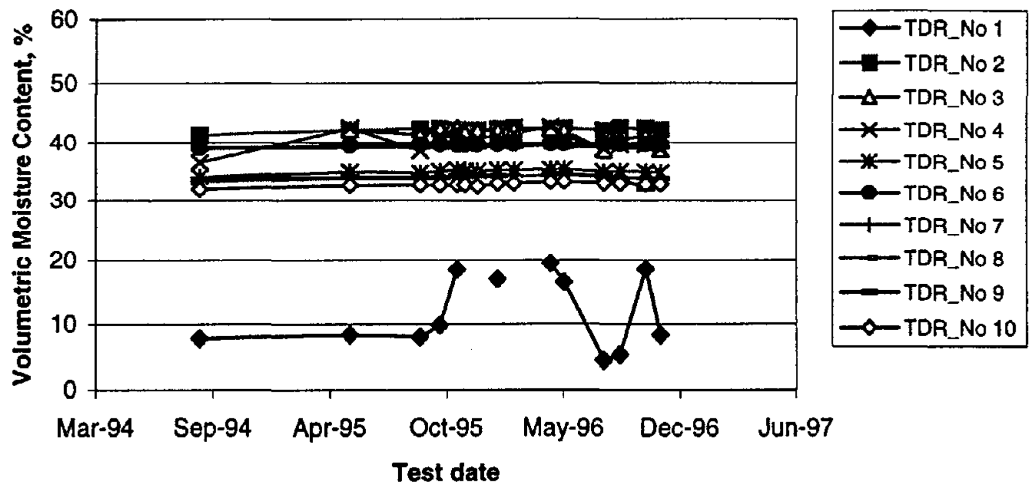
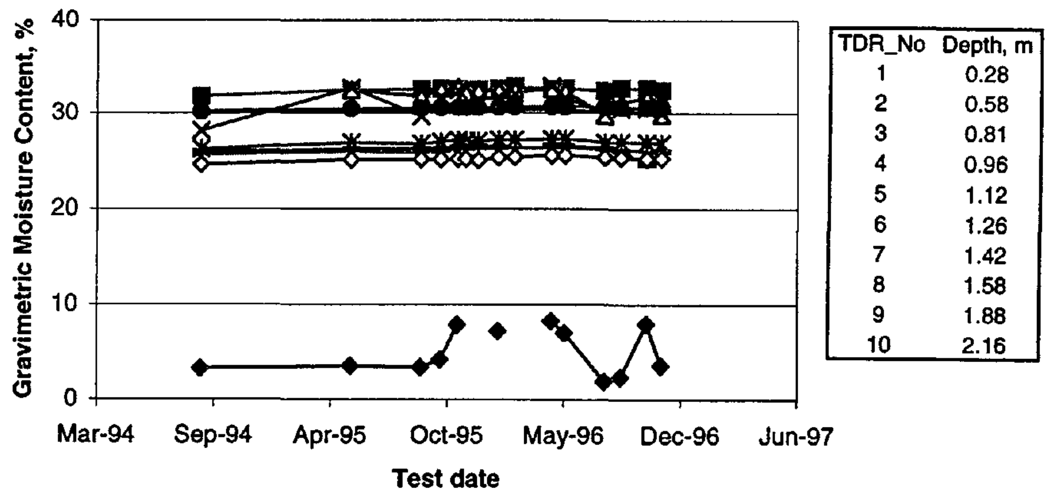


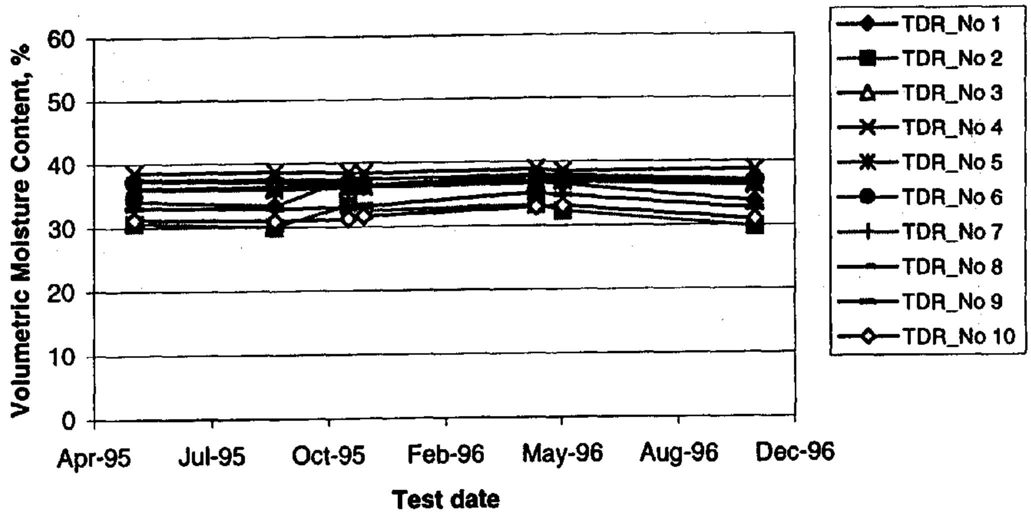
Figure 107. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 364018 in New York.

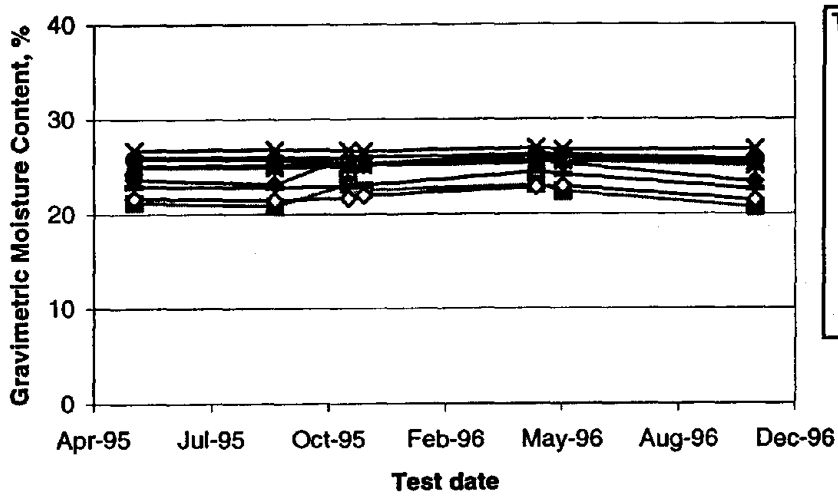




NO DAILY RAINFALL DATA WAS AVAILABLE AT THE TIME OF THIS STUDY.

Figure 108. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 370201 in North Carolina.





TDR_No	Depth, m
1	0.51
2	0.65
3	0.81
4	0.96
5	1.10
6	1.26
7	1.42
8	1.58
9	1.88
10	2.16

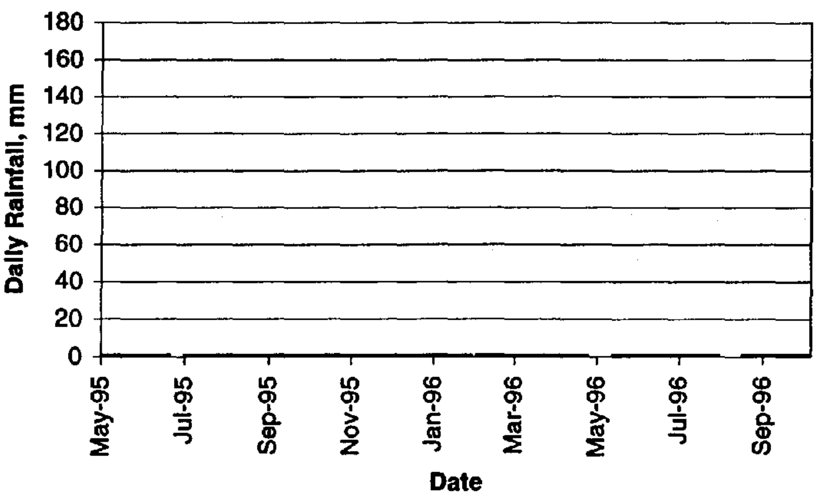
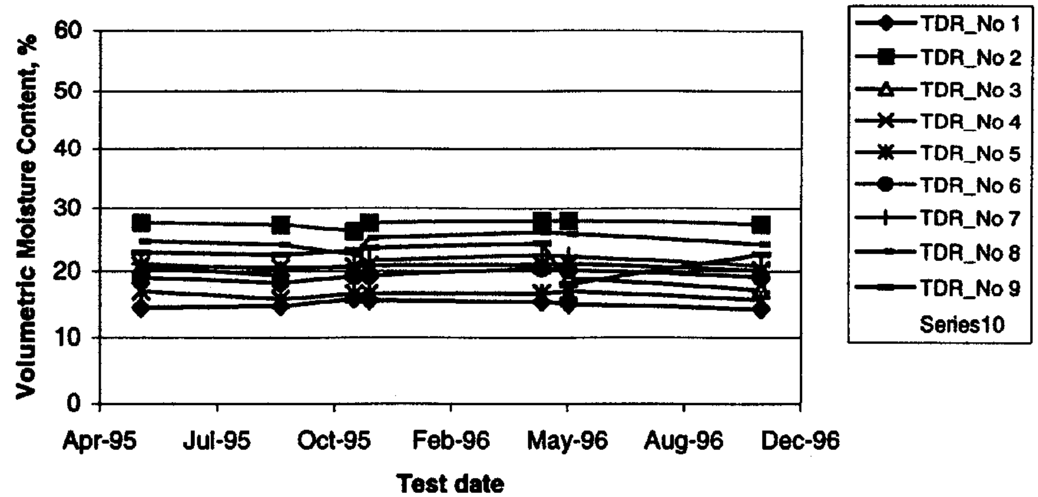
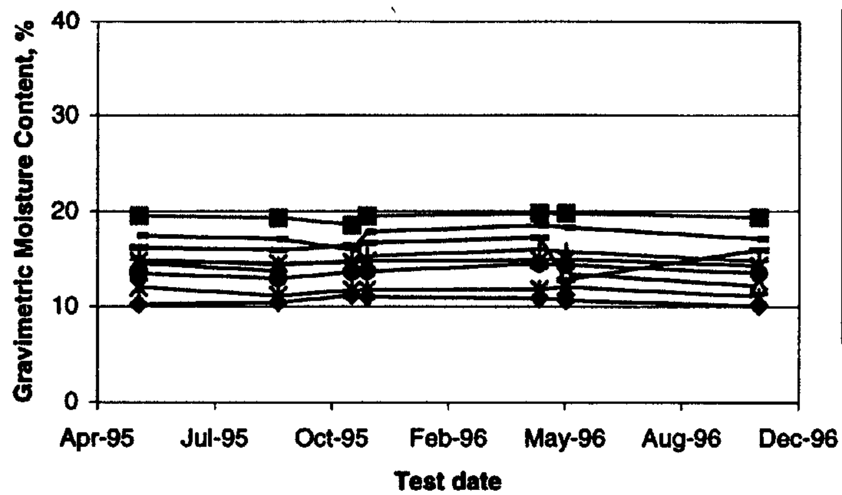


Figure 109. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 370205 in North Carolina.





TDR_No	Depth, m
1	0.58
2	0.74
3	0.89
4	1.04
5	1.20
6	1.35
7	1.50
8	1.70
9	1.96
10	2.23

NO DAILY RAINFALL DATA WAS AVAILABLE AT THE TIME OF THIS STUDY.

Figure 110. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 370208 in North Carolina.

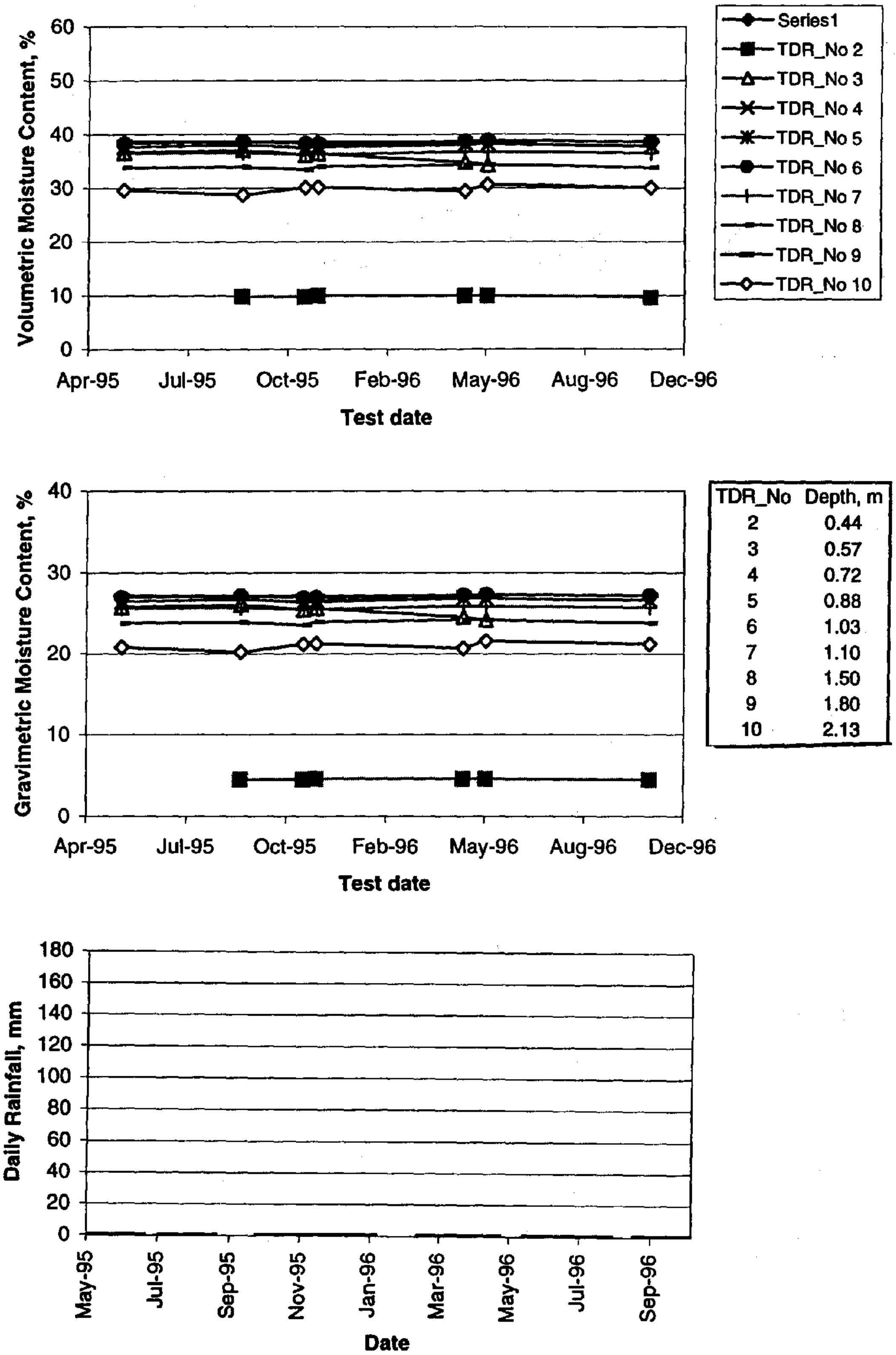


Figure 111. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 370212 in North Carolina.

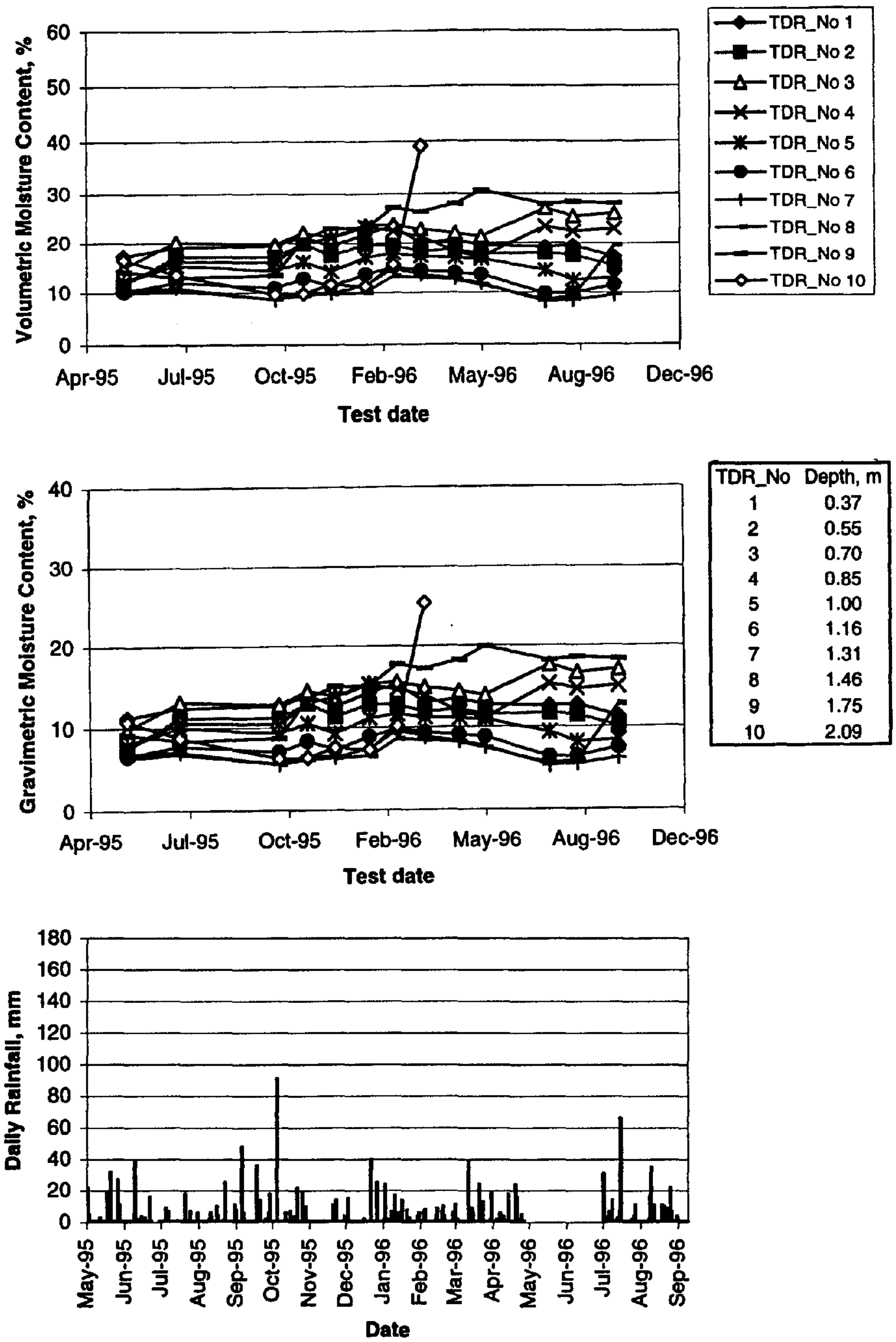


Figure 112. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 371028 in North Carolina.

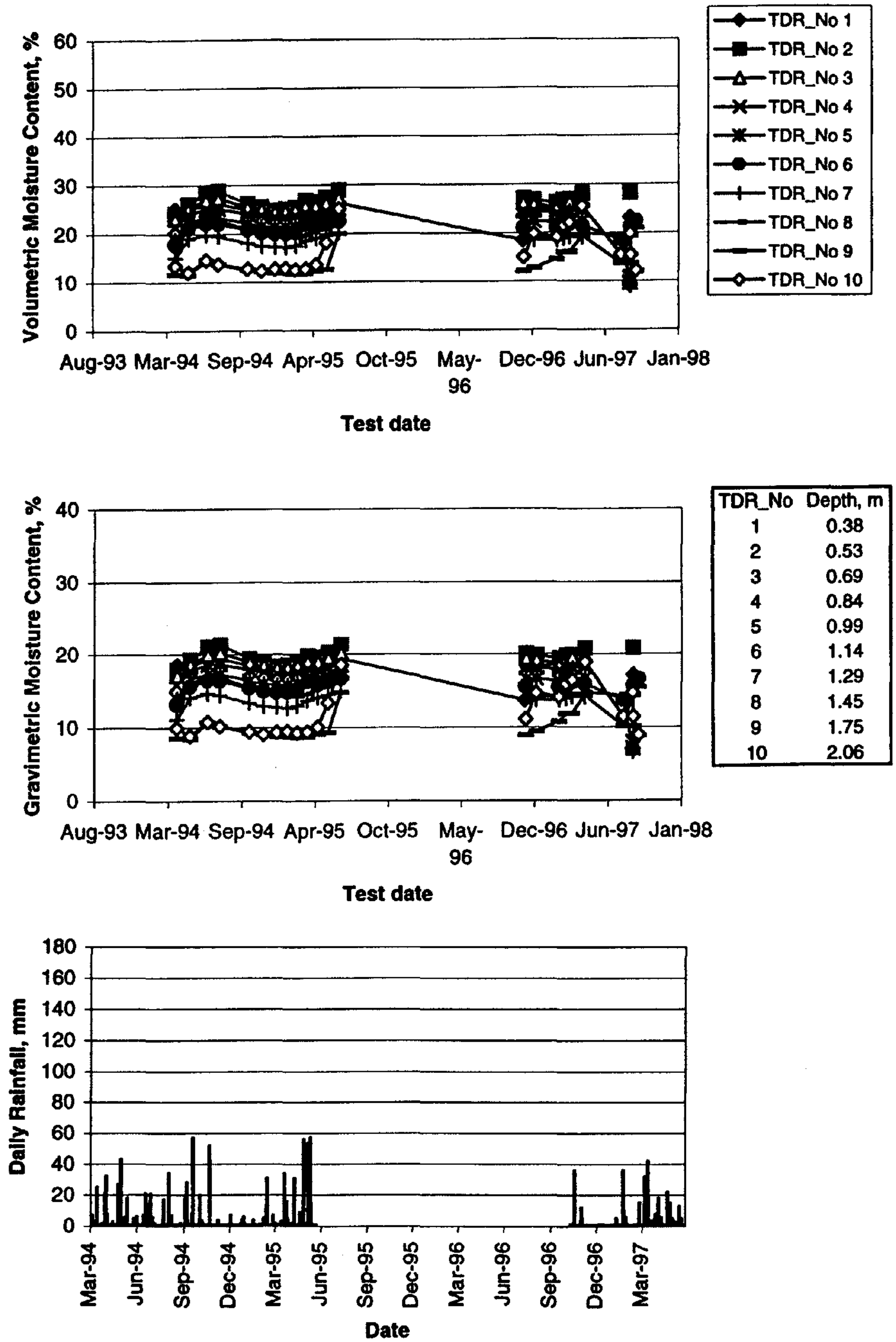
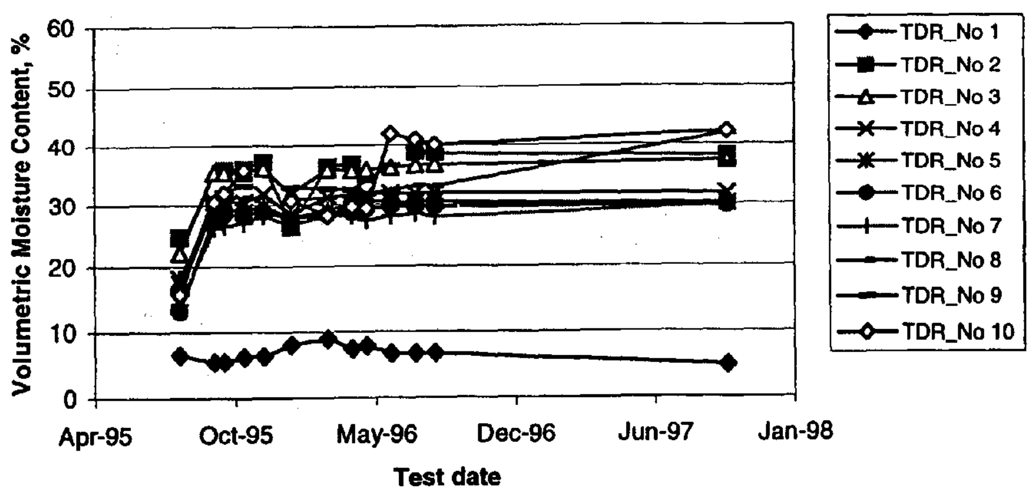
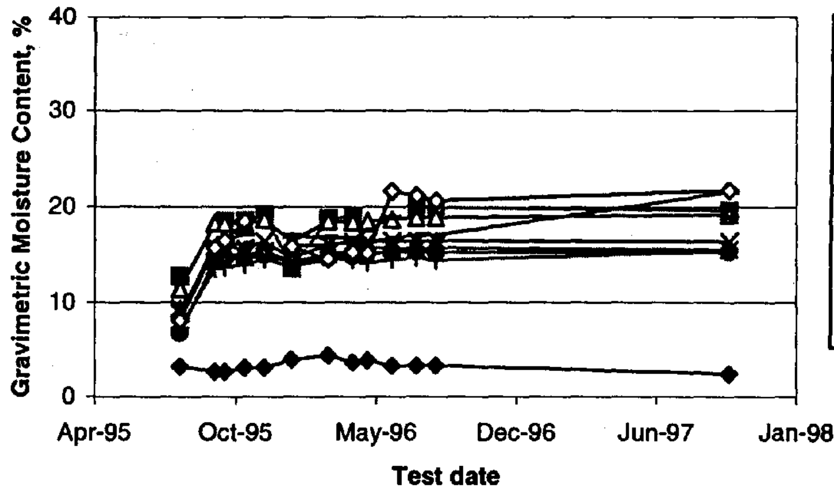


Figure 113. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 404165 in Oklahoma.





TDR_No	Depth, m
1	0.38
2	0.55
3	0.69
4	0.85
5	1.00
6	1.16
7	1.30
8	1.46
9	1.78
10	2.03

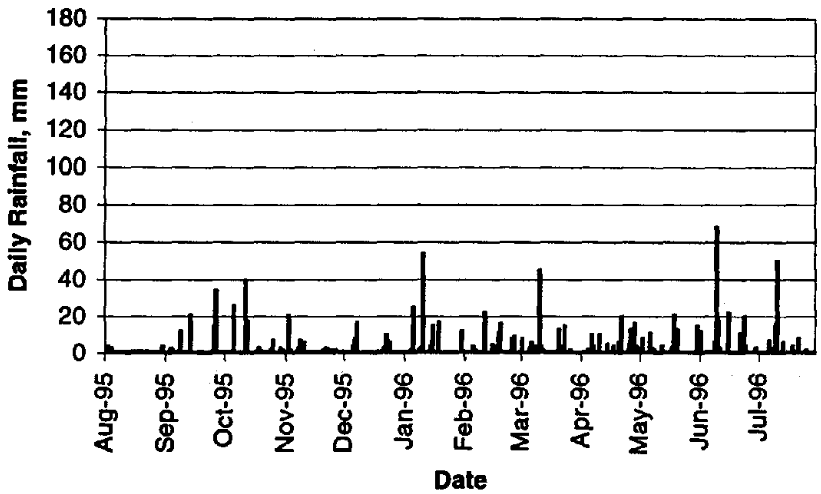
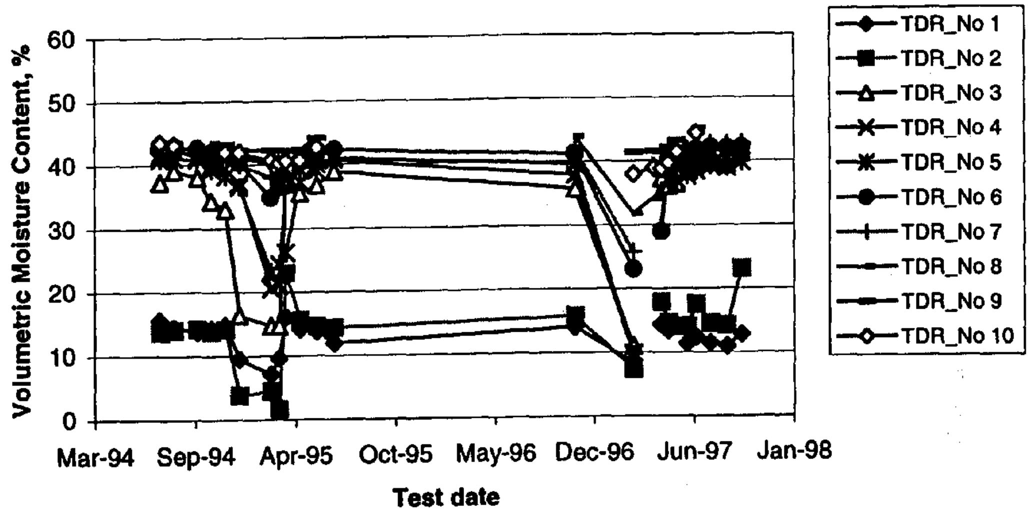
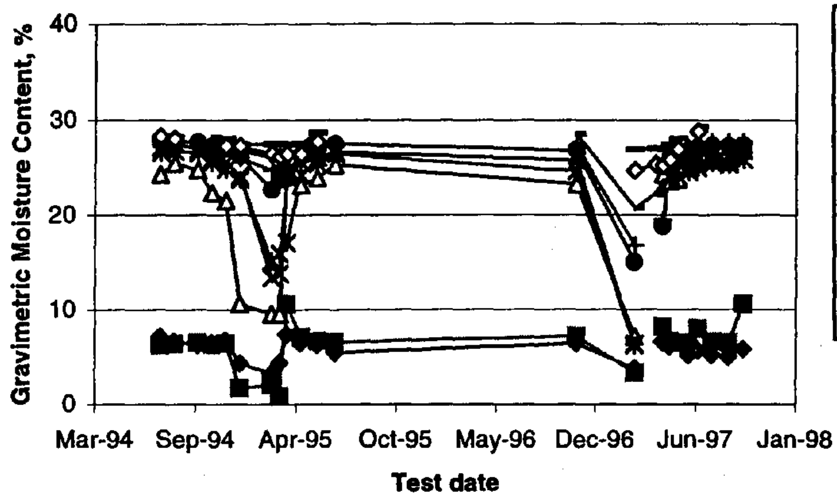


Figure 114. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 421606 in Pennsylvania.





TDR_No	Depth, m
1	0.33
2	0.48
3	0.64
4	0.79
5	0.93
6	1.10
7	1.25
8	1.39
9	1.70
10	1.99

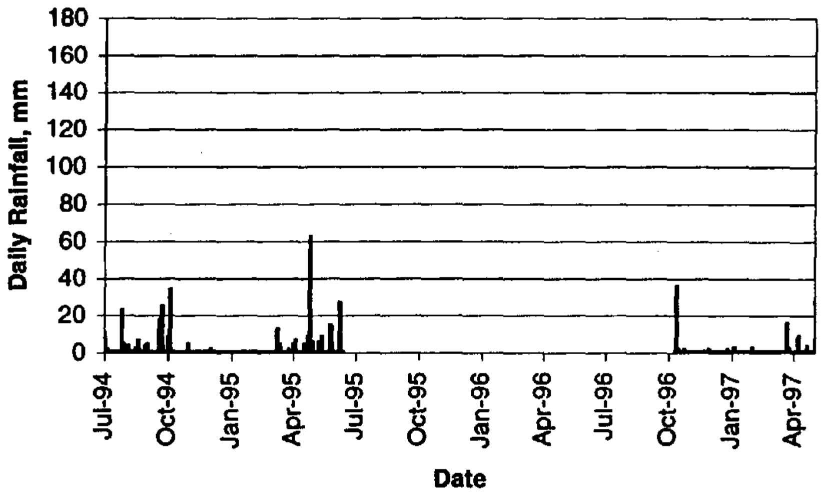
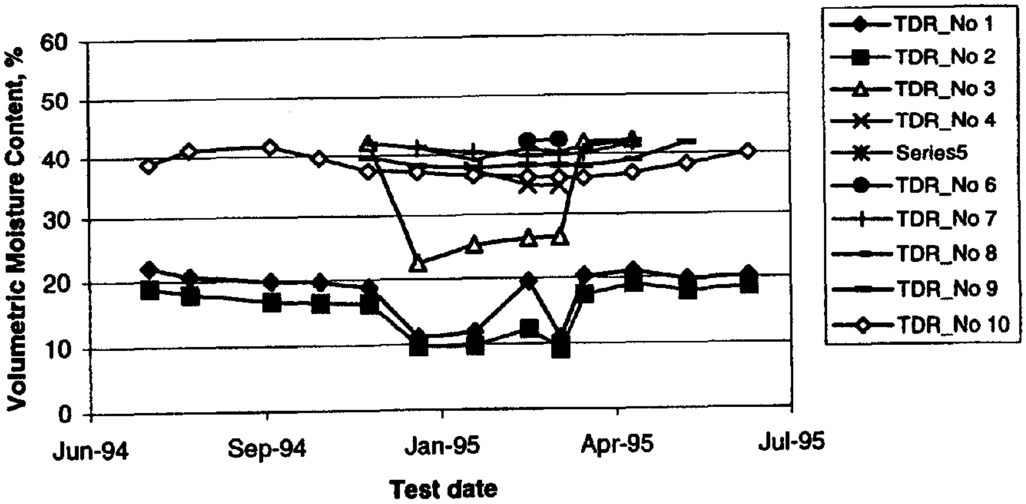
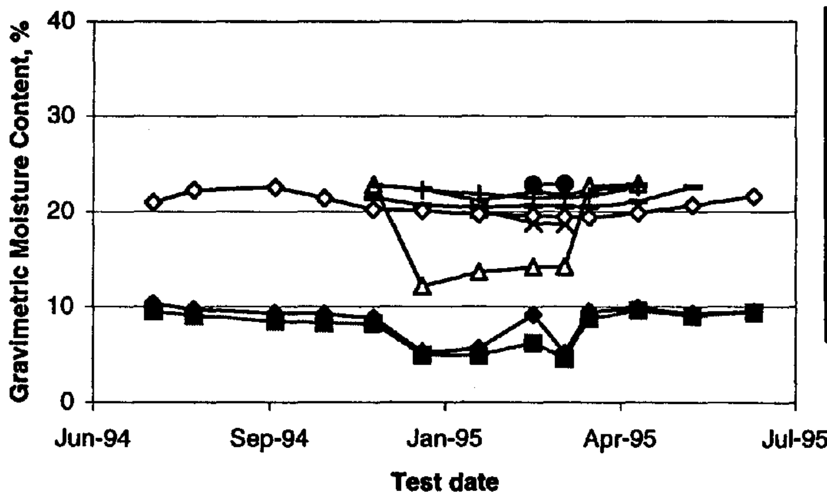


Figure 115. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 460804 in South Dakota.

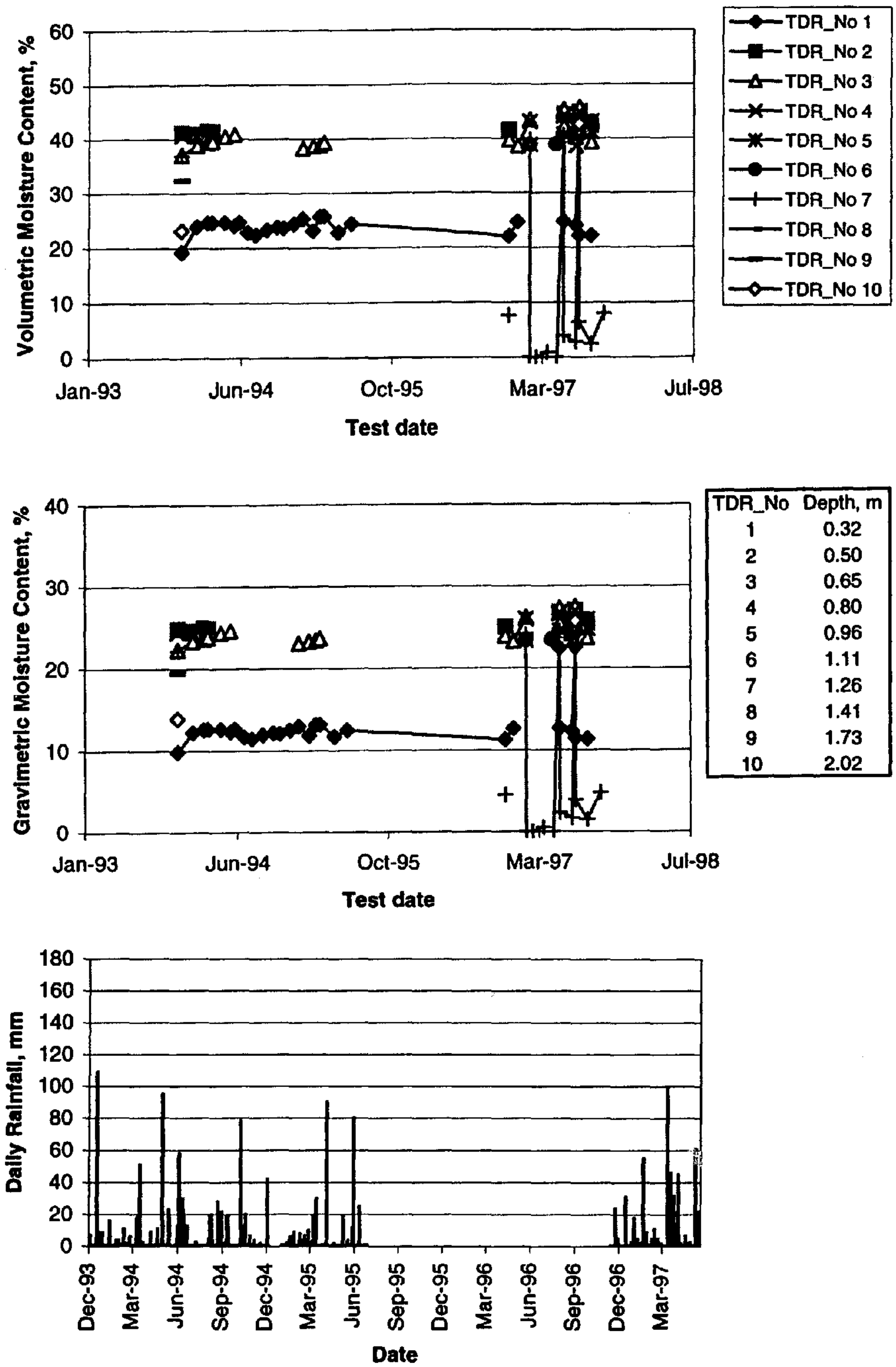




TDR_No	Depth, m
1	0.21
2	0.37
3	0.51
4	0.68
5	0.83
6	0.97
7	1.13
8	1.28
9	1.58
10	1.90

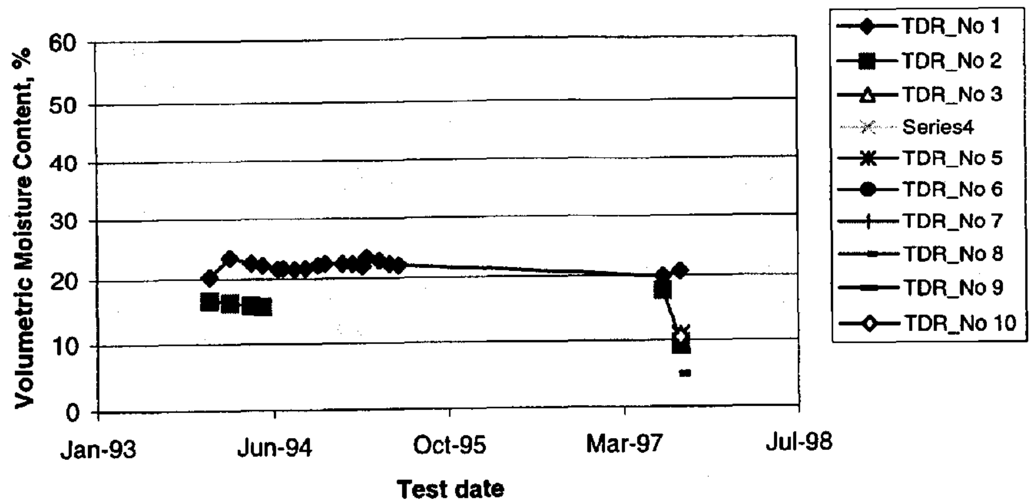
NO DAILY RAINFALL DATA WAS AVAILABLE AT THE TIME OF THIS STUDY.

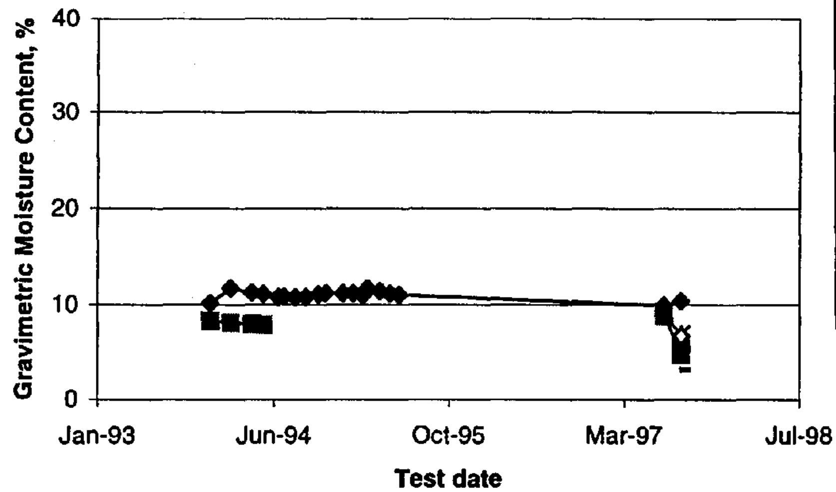
Figure 116. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 469187 in South Dakota.



TDR_No	Depth, m
1	0.32
2	0.50
3	0.65
4	0.80
5	0.96
6	1.11
7	1.26
8	1.41
9	1.73
10	2.02

Figure 117. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 481060 in Texas.





TDR_No	Depth, m
1	0.35
2	0.50
3	0.65
4	0.81
5	0.96
6	1.11
7	1.26
8	1.40
9	1.72
10	2.01

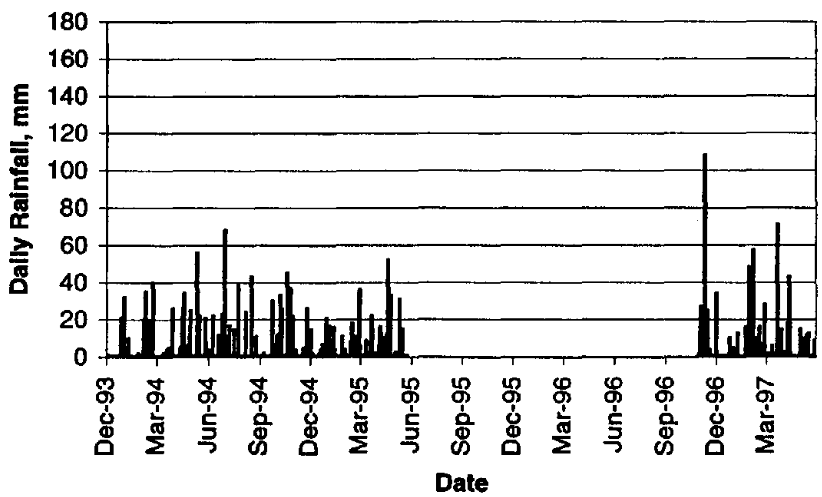
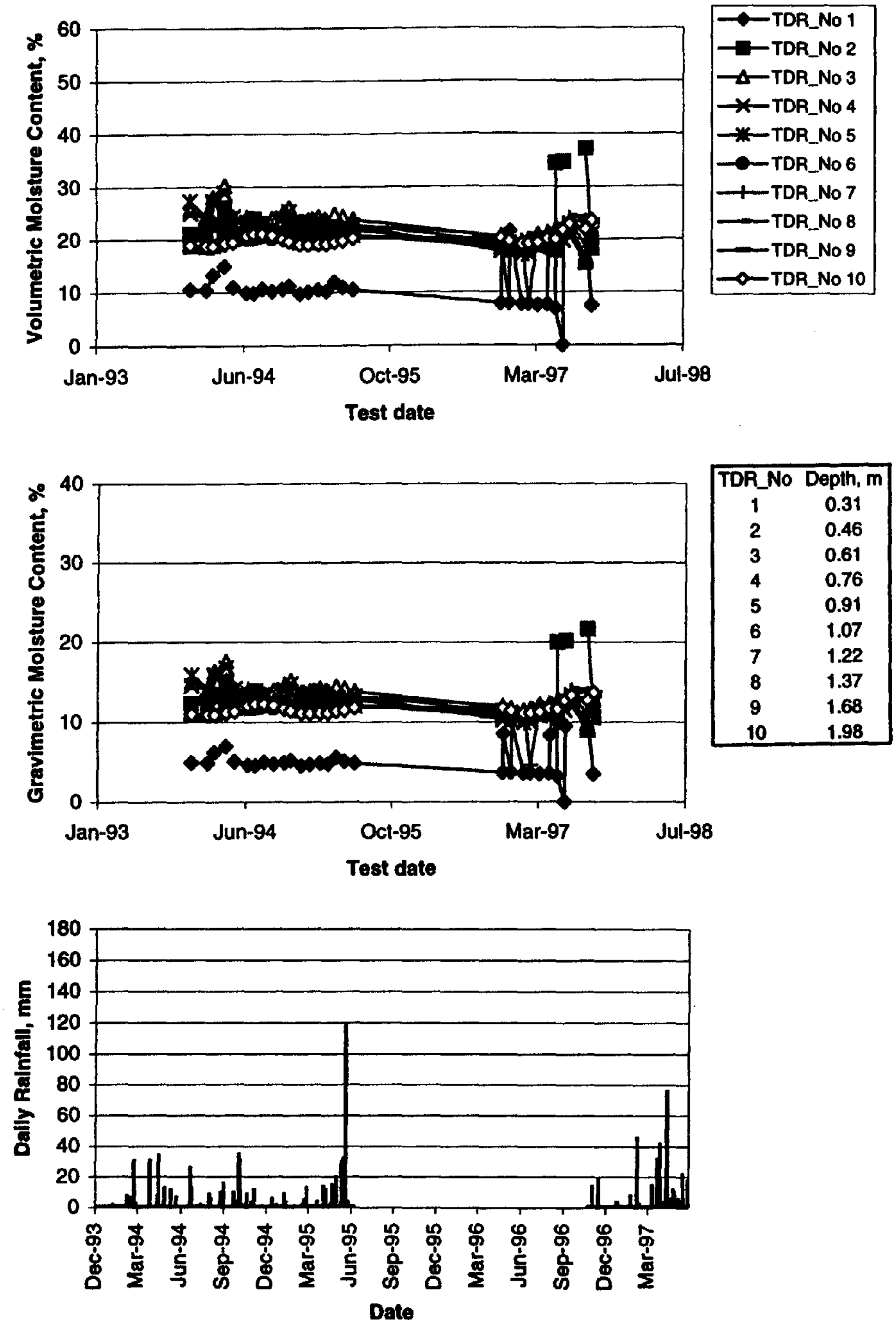


Figure 118. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 481068 in Texas.



TDR_No	Depth, m
1	0.31
2	0.46
3	0.61
4	0.76
5	0.91
6	1.07
7	1.22
8	1.37
9	1.68
10	1.98

Figure 119. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 481077 in Texas.

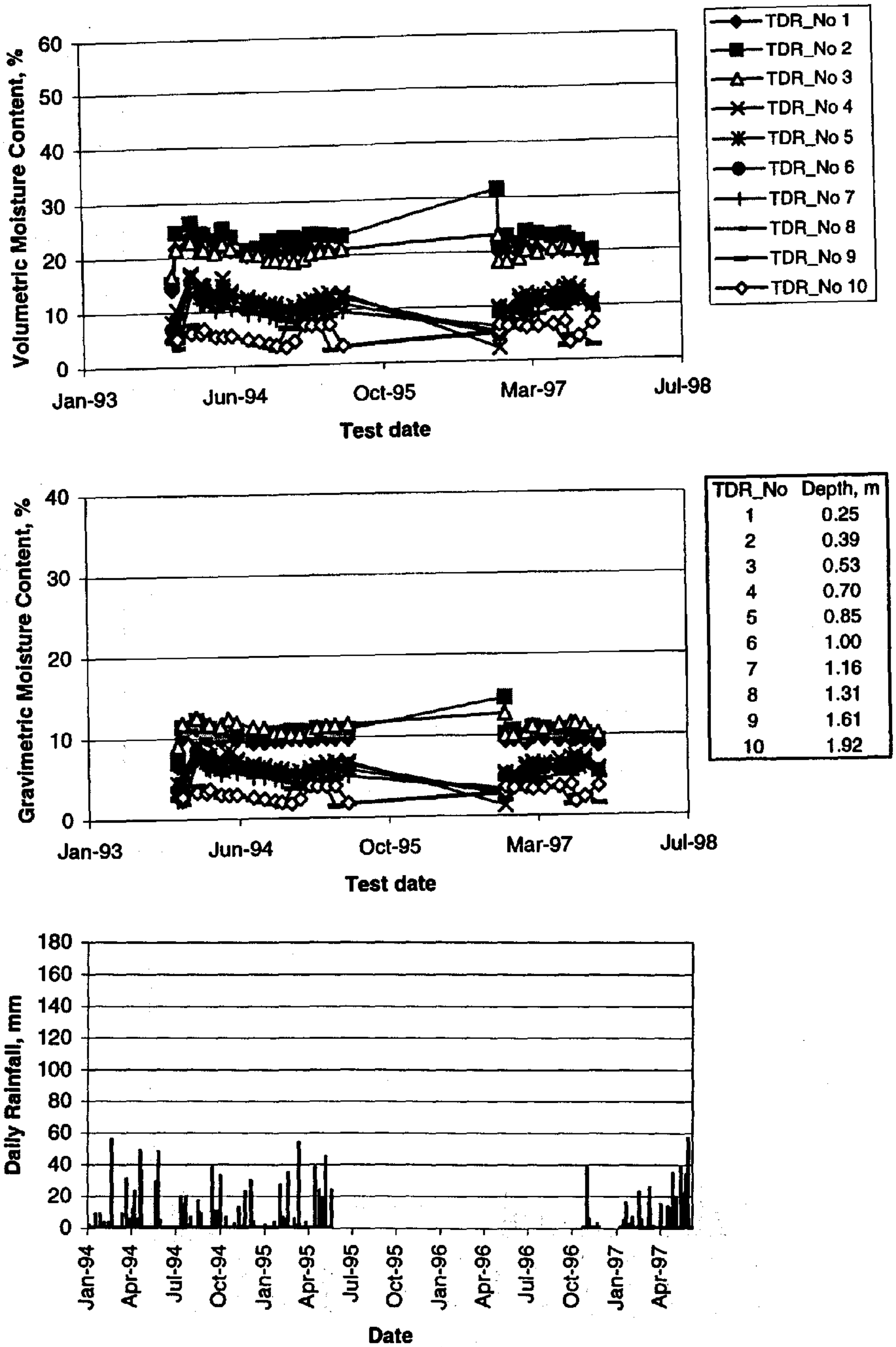


Figure 120. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 481122 in Texas.

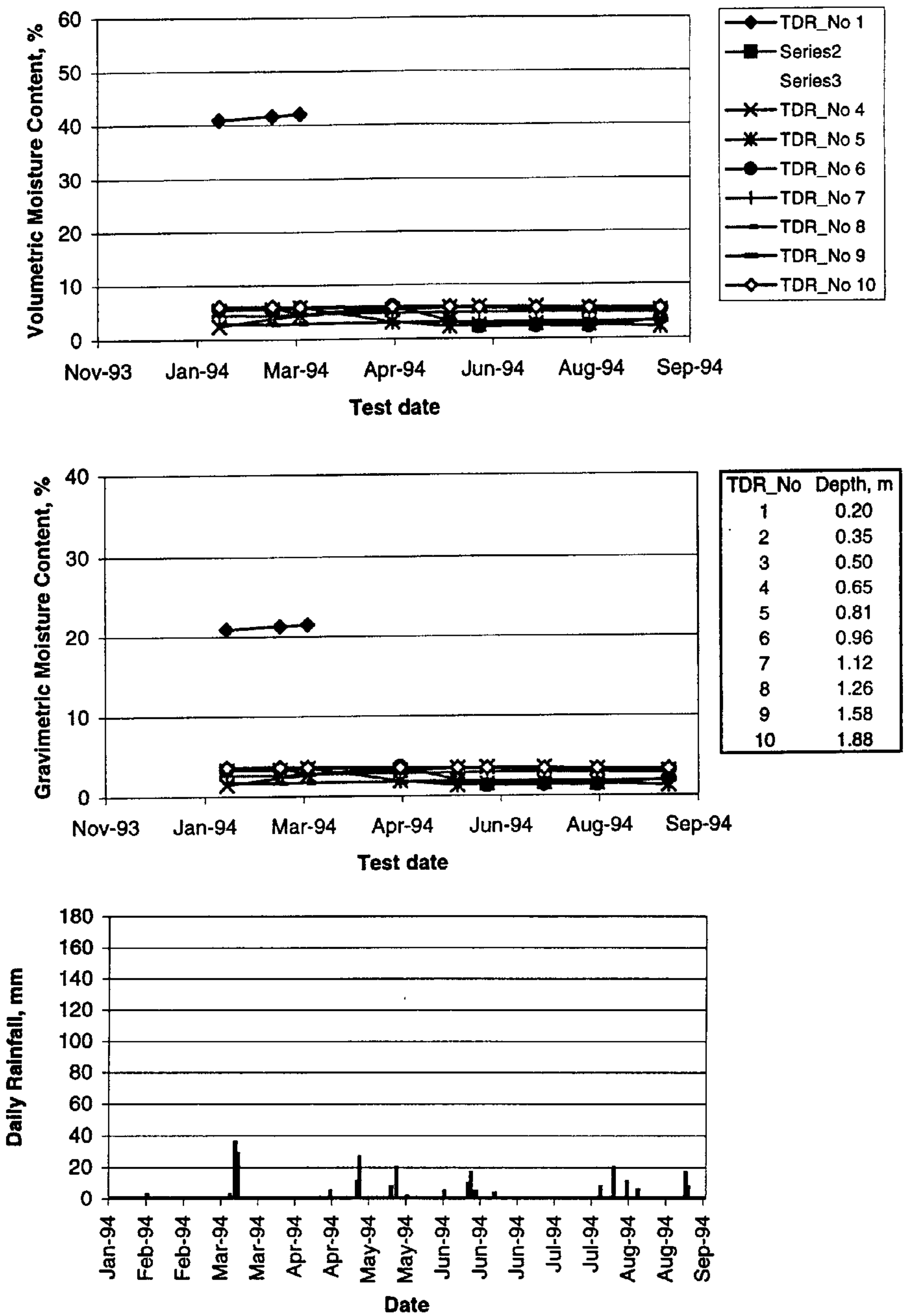
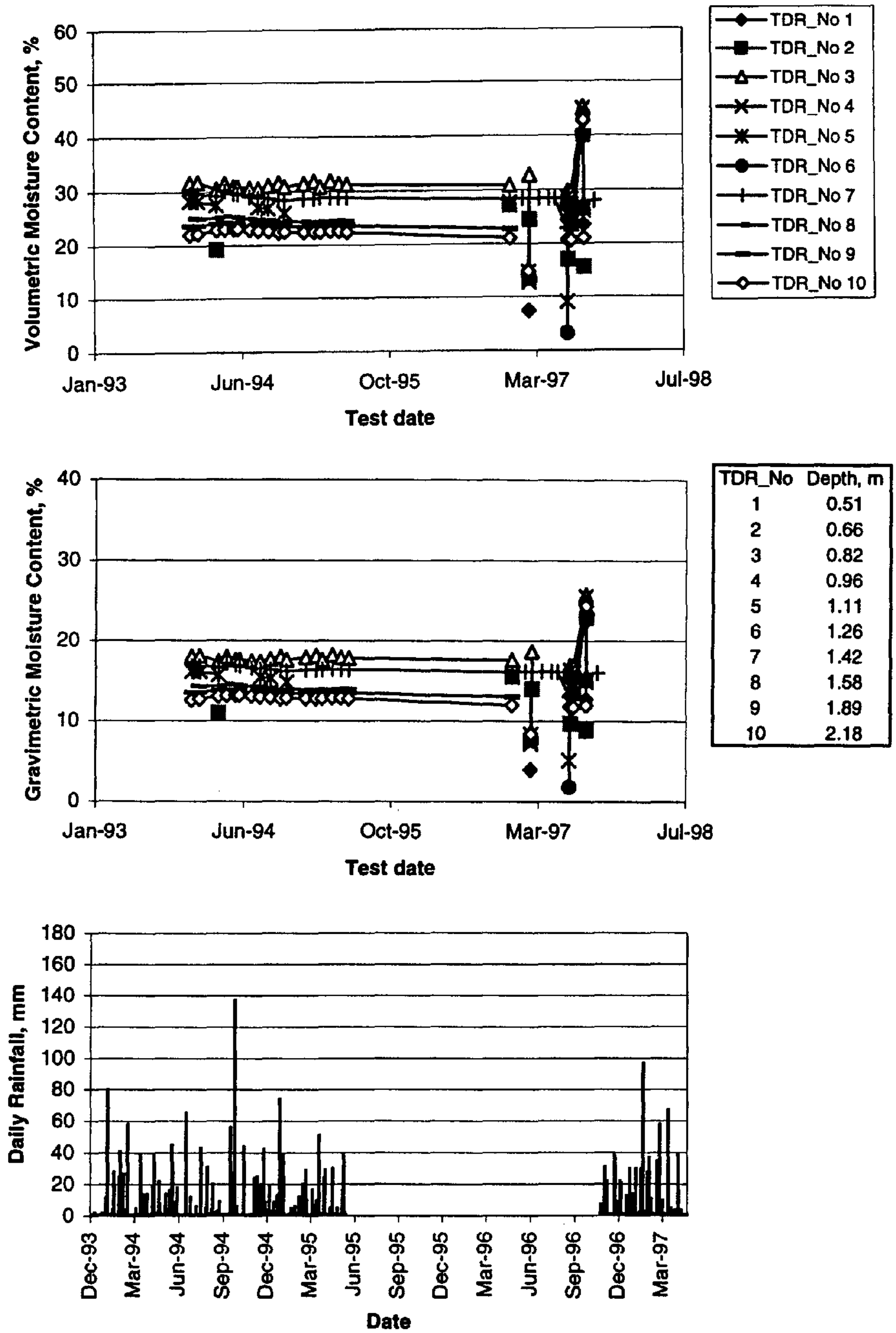
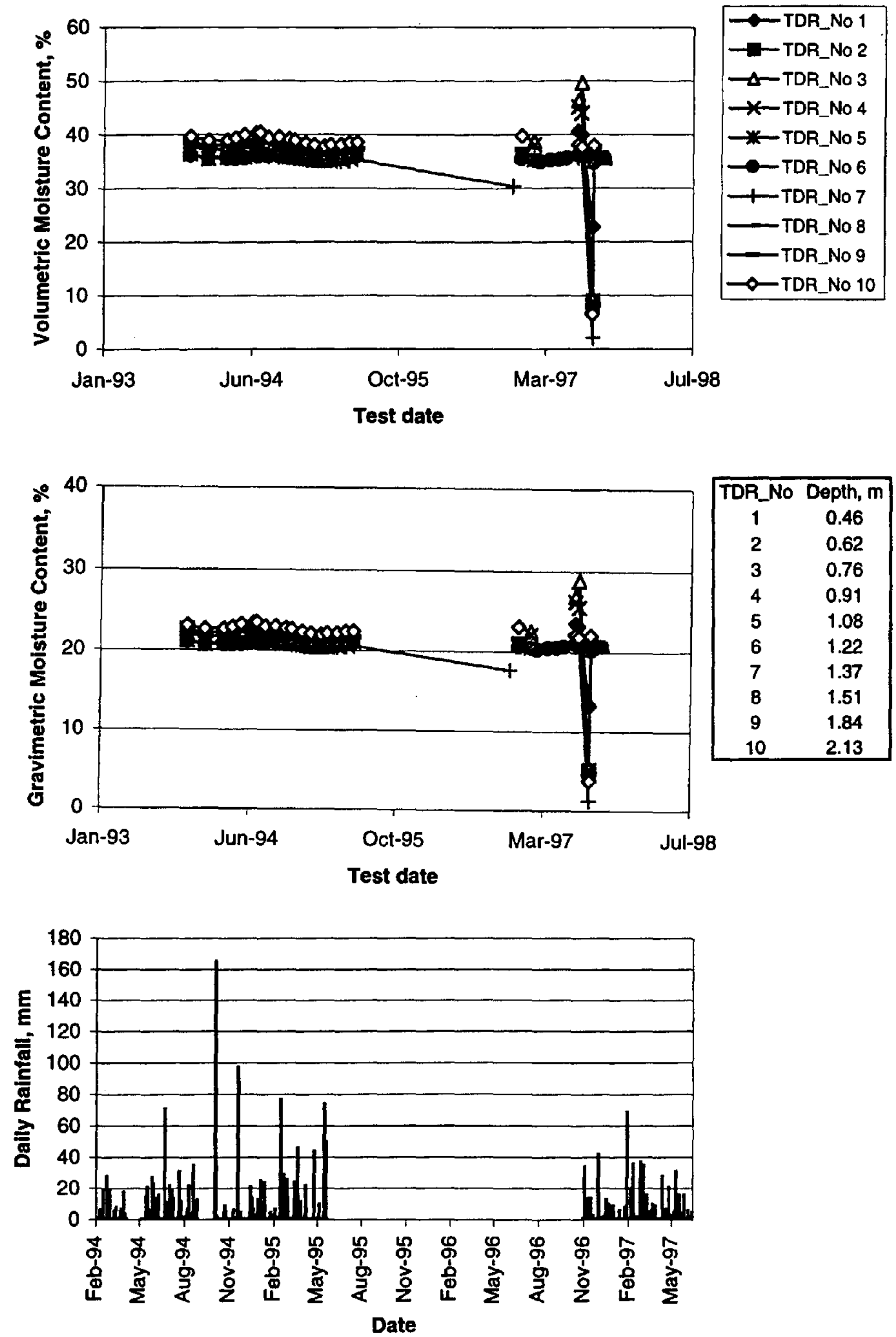


Figure 121. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 483739 in Texas.



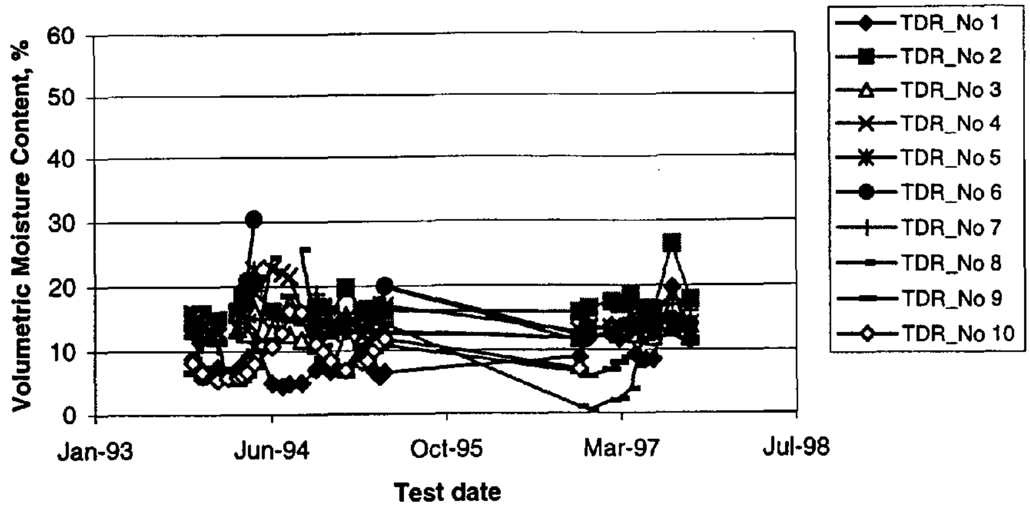
TDR_No	Depth, m
1	0.51
2	0.66
3	0.82
4	0.96
5	1.11
6	1.26
7	1.42
8	1.58
9	1.89
10	2.18

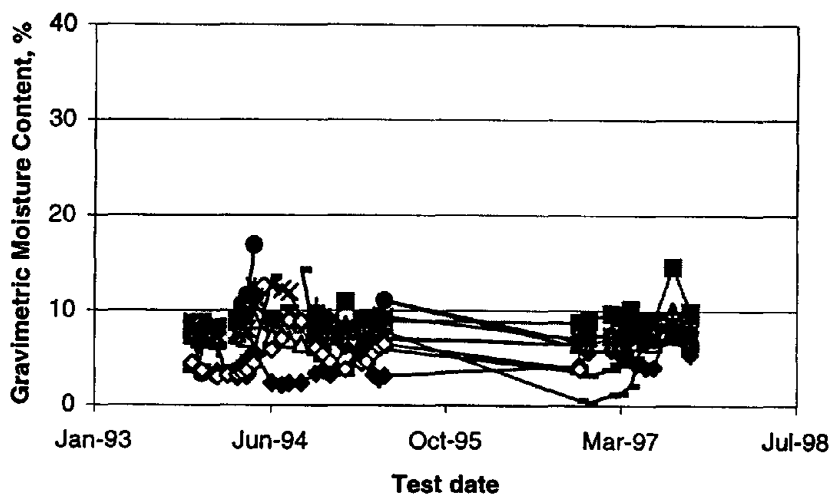
Figure 122. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 484142 in Texas.



TDR_No	Depth, m
1	0.46
2	0.62
3	0.76
4	0.91
5	1.08
6	1.22
7	1.37
8	1.51
9	1.84
10	2.13

Figure 123. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 484143 in Texas.





TDR_No	Depth, m
1	0.25
2	0.41
3	0.56
4	0.71
5	0.86
6	1.02
7	1.17
8	1.32
9	1.63
10	1.93

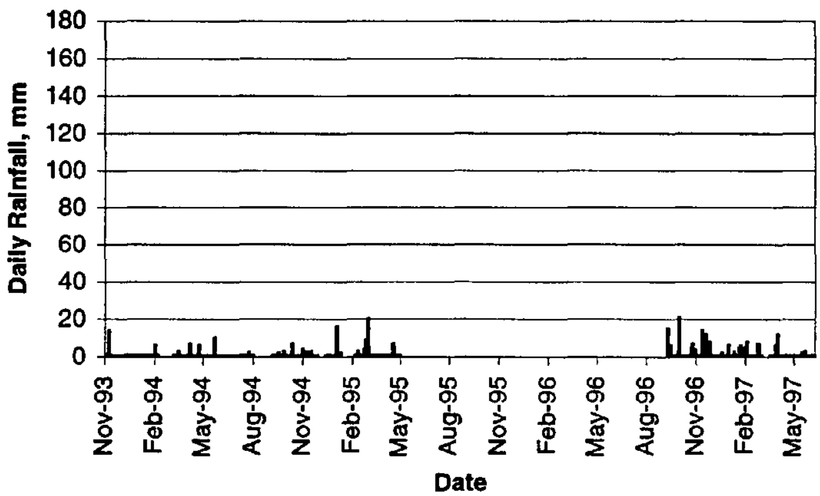
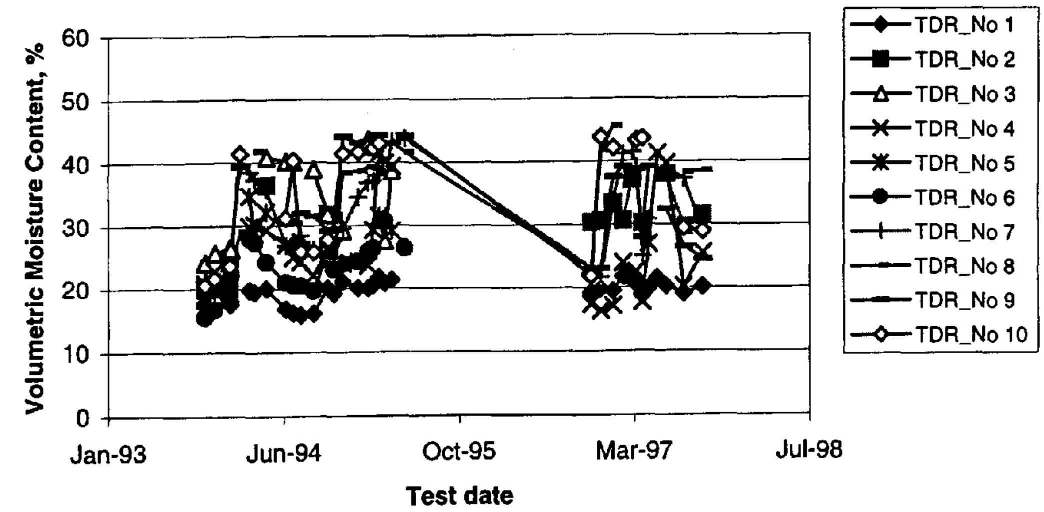
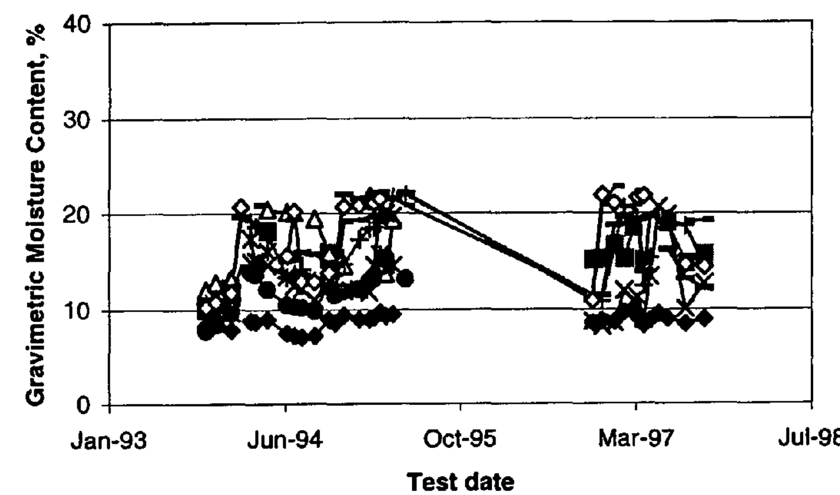


Figure 124. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 491001 in Utah.





TDR_No	Depth, m
1	0.39
2	0.55
3	0.70
4	0.85
5	1.00
6	1.16
7	1.31
8	1.46
9	1.76
10	2.07

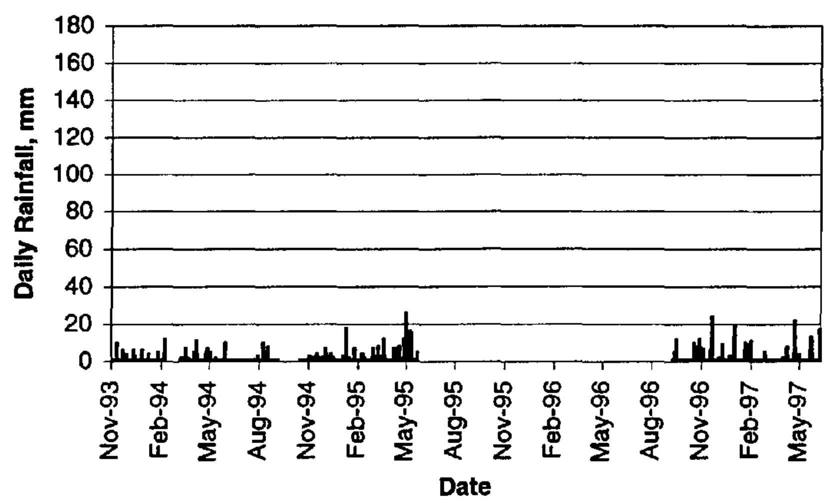
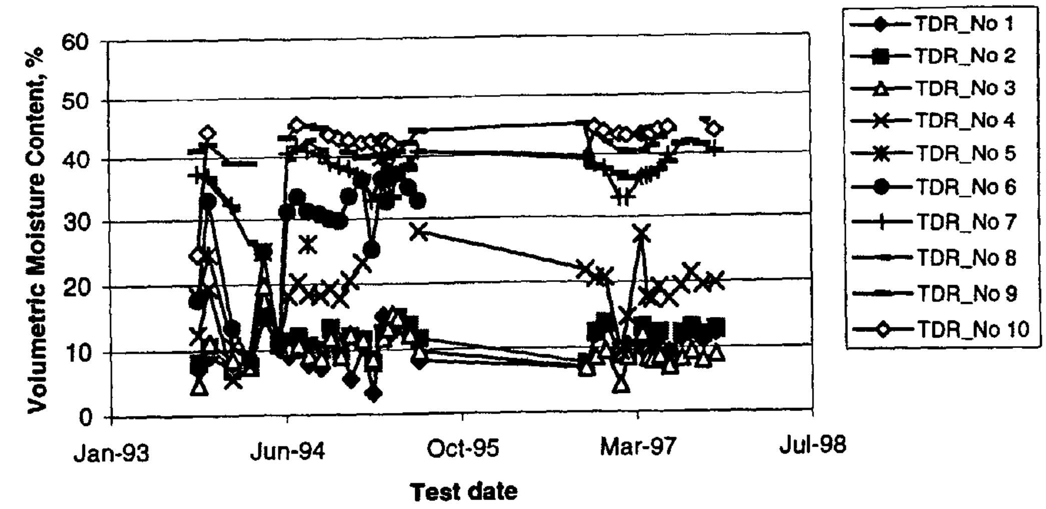
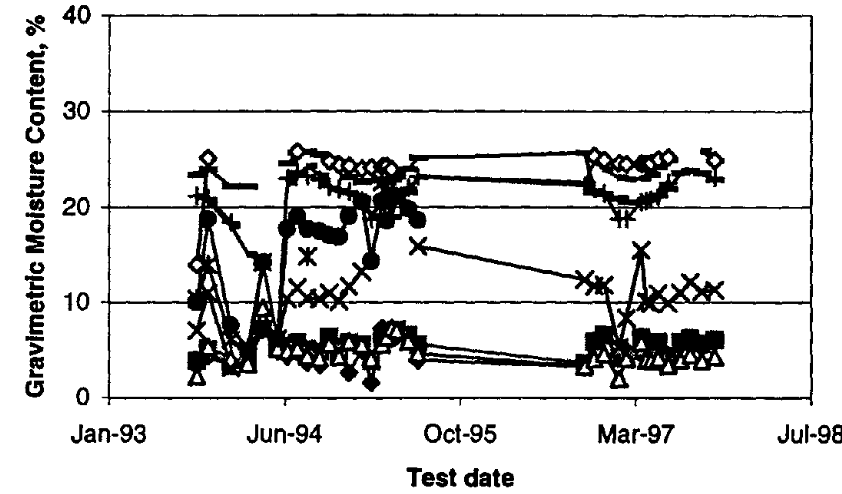


Figure 125. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 493011 in Utah.





TDR_No	Depth, m
1	0.37
2	0.52
3	0.66
4	0.81
5	0.95
6	1.12
7	1.27
8	1.43
9	1.76
10	2.05

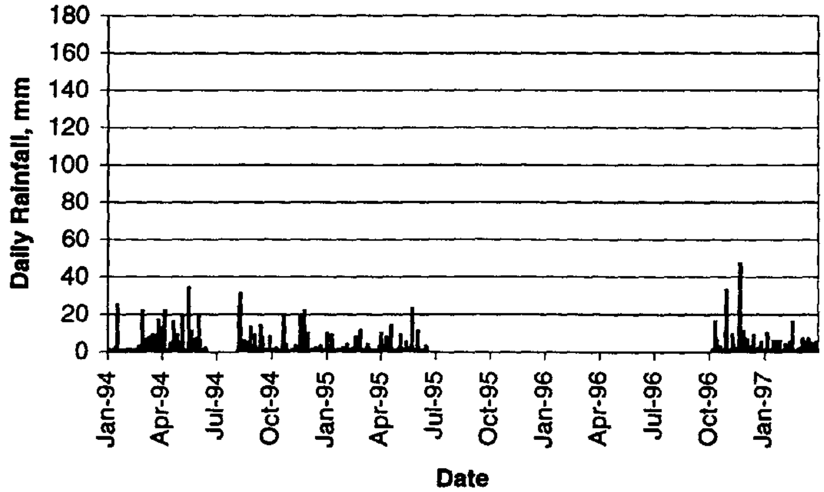


Figure 126. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 501002 in Vermont.

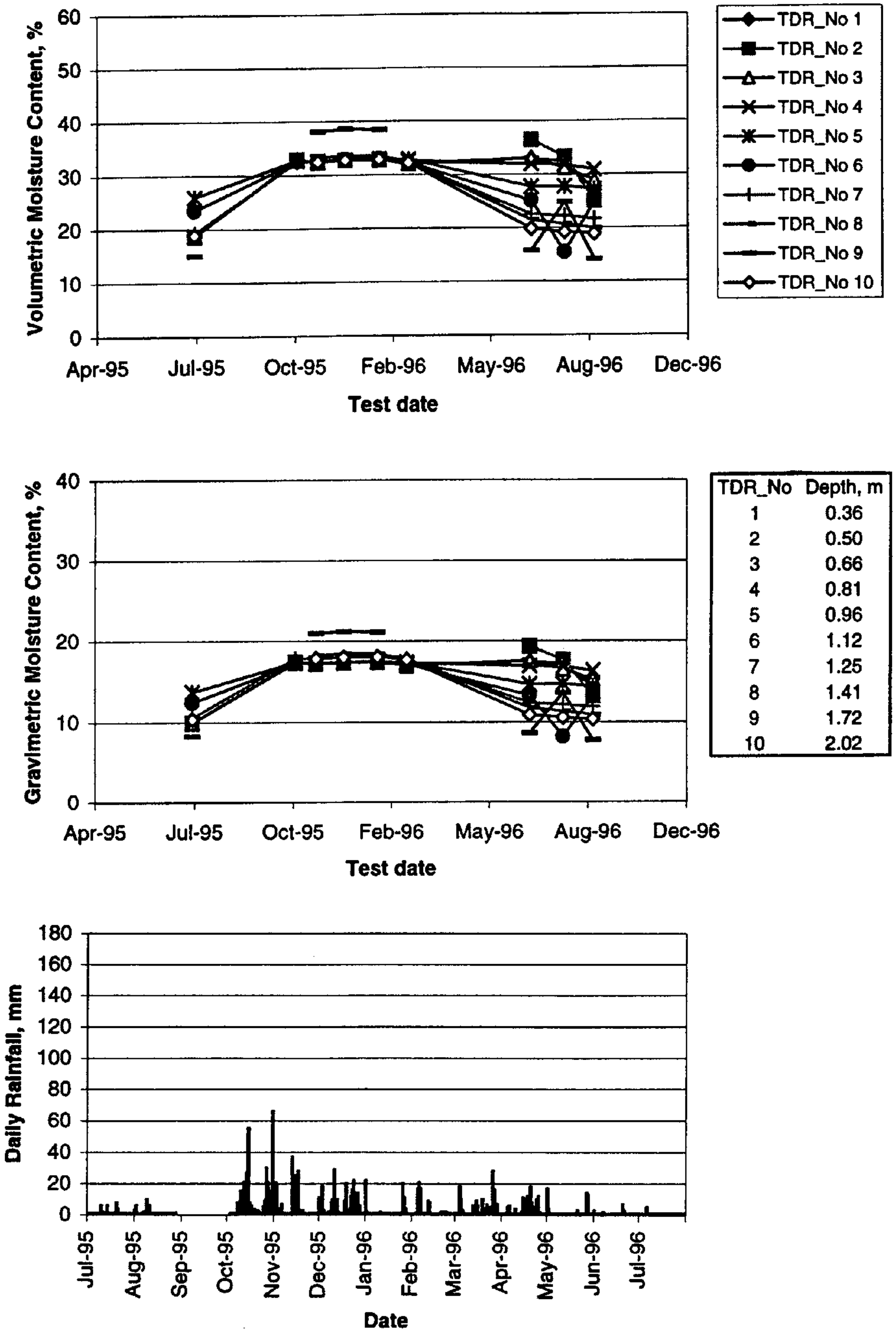
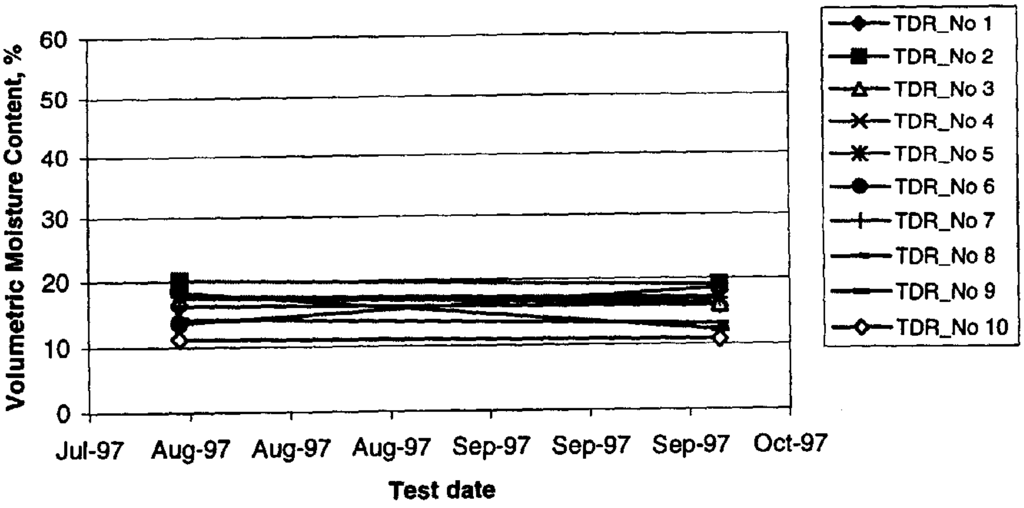
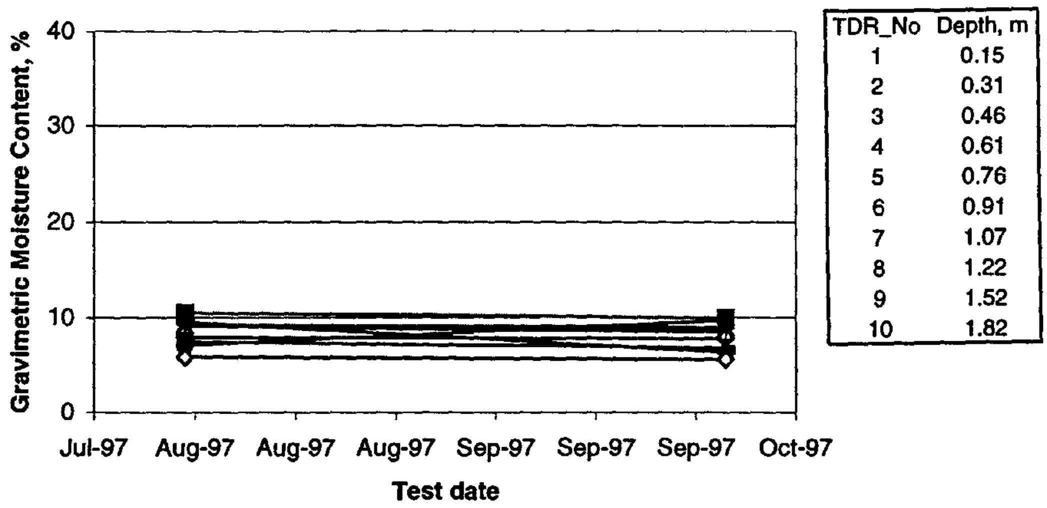


Figure 127. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 533813 in Washington.





NO DAILY RAINFALL DATA WAS AVAILABLE AT THE TIME OF THIS STUDY.

Figure 128. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 561007 in Wyoming.

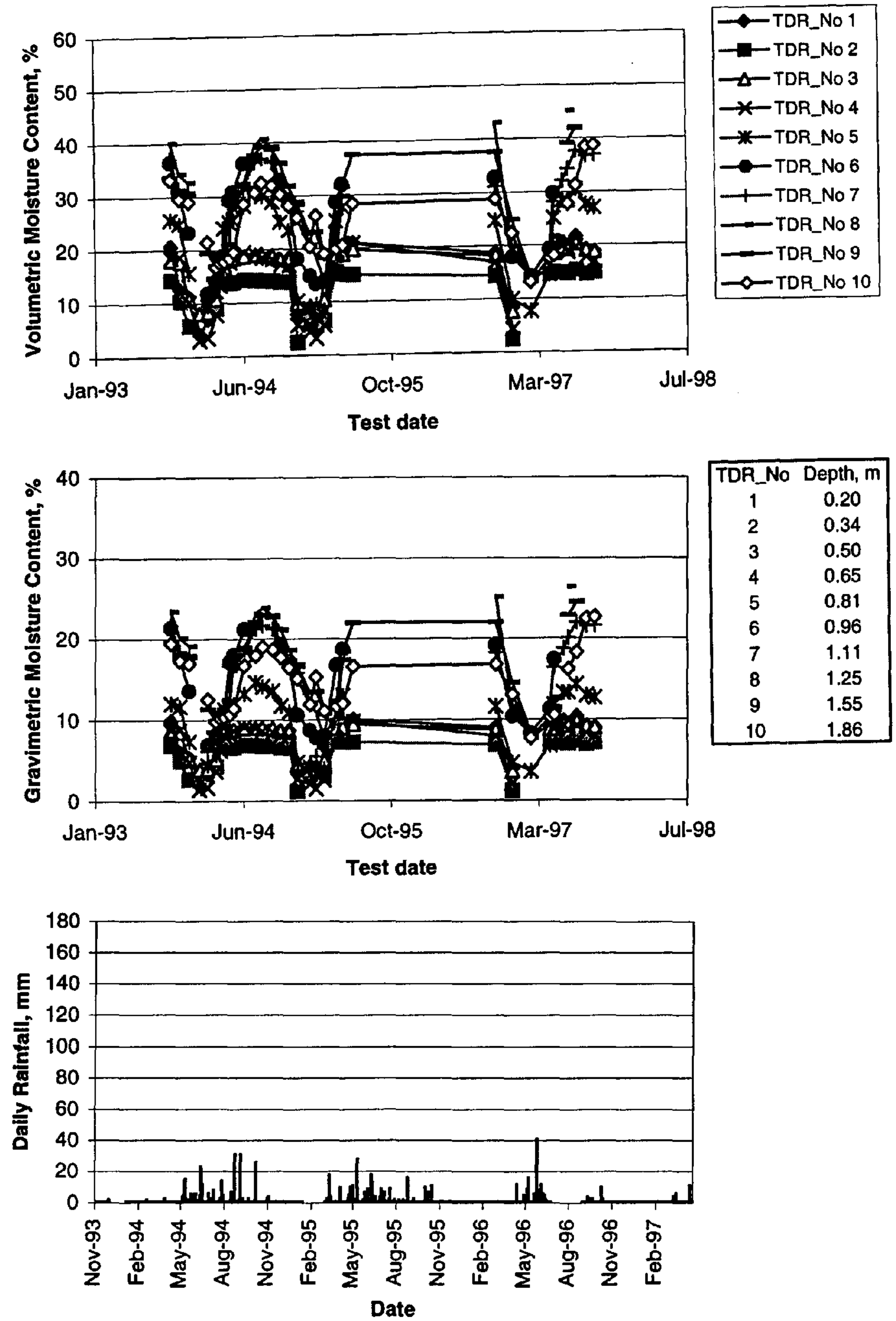
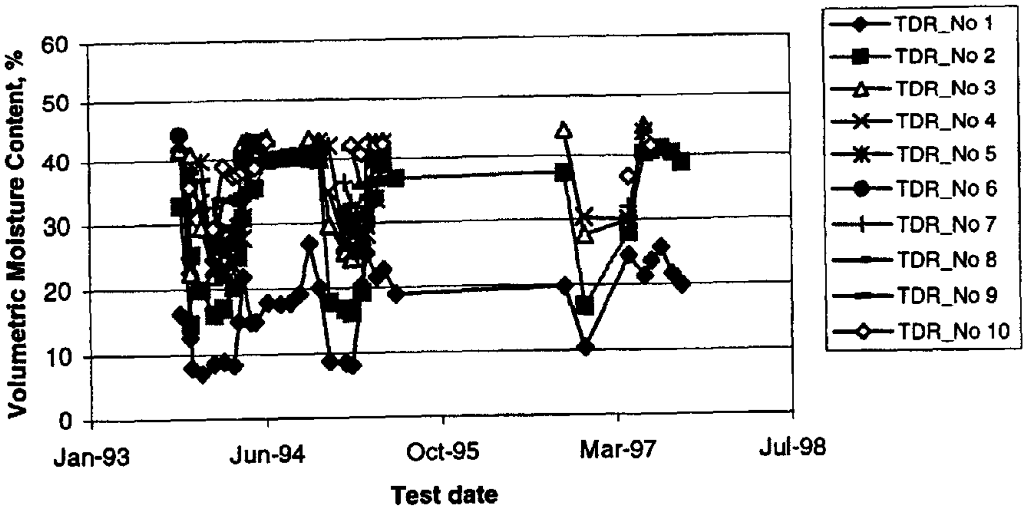
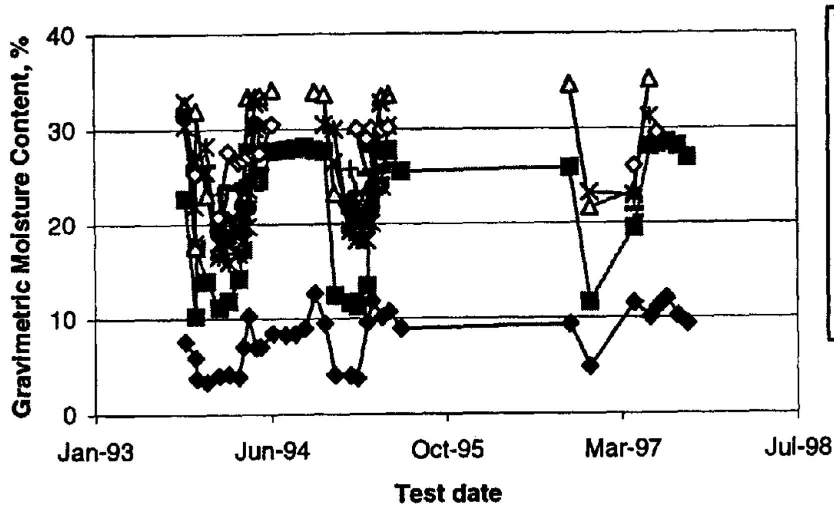


Figure 129. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 831801 in Manitoba.





TDR_No	Depth, m
1	0.32
2	0.44
3	0.61
4	0.76
5	0.92
6	1.05
7	1.21
8	1.35
9	1.66
10	1.96

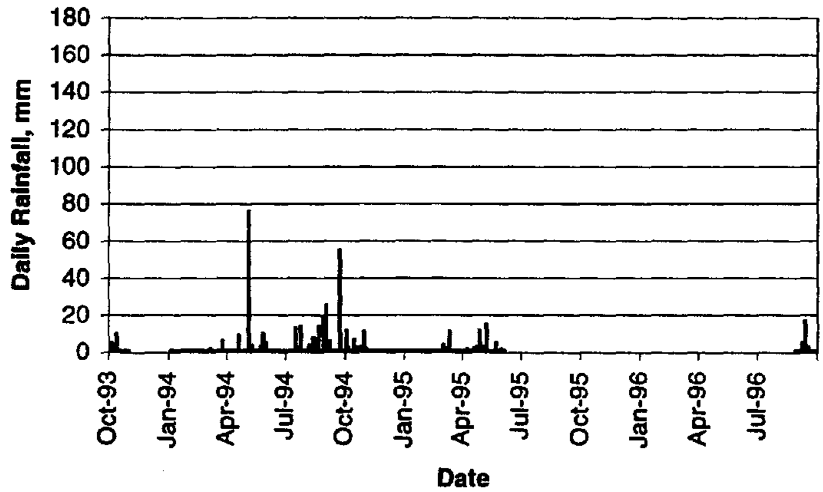
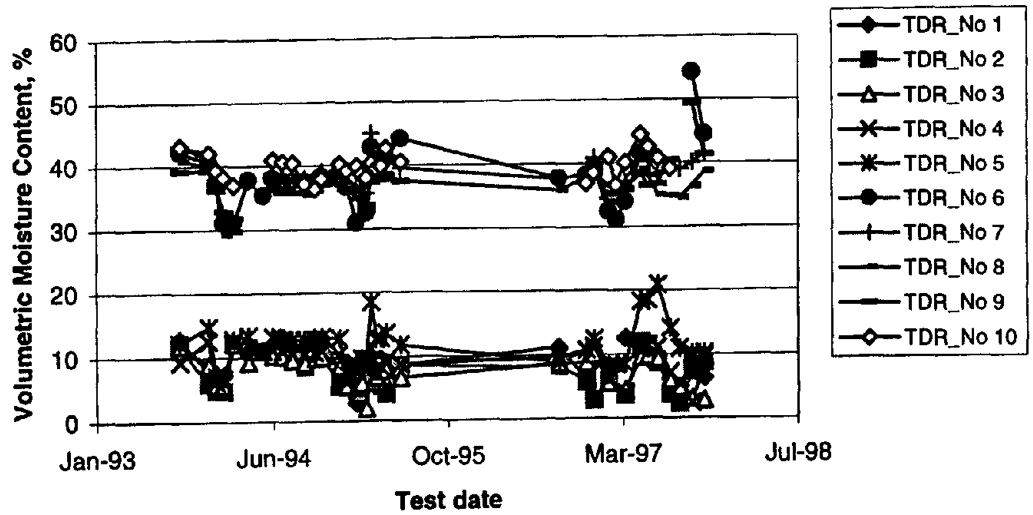
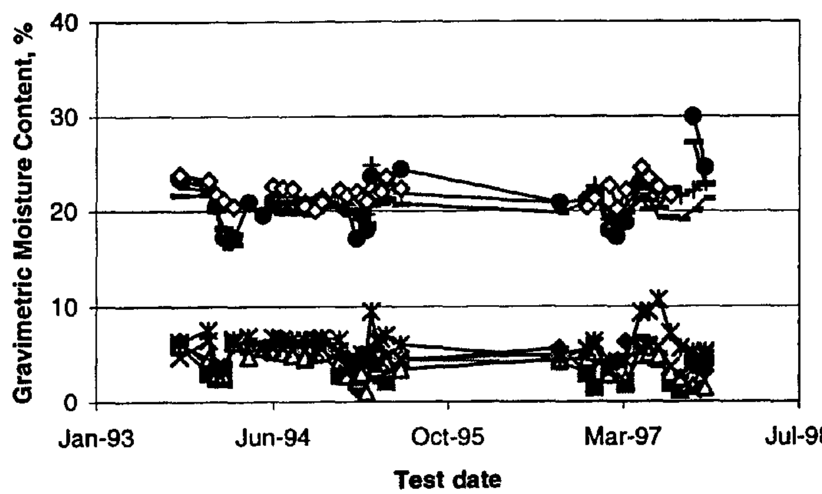


Figure 130. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 833802 in Manitoba.





TDR_No	Depth, m
1	0.23
2	0.38
3	0.55
4	0.70
5	0.79
6	0.99
7	1.09
8	1.29
9	1.58
10	1.89

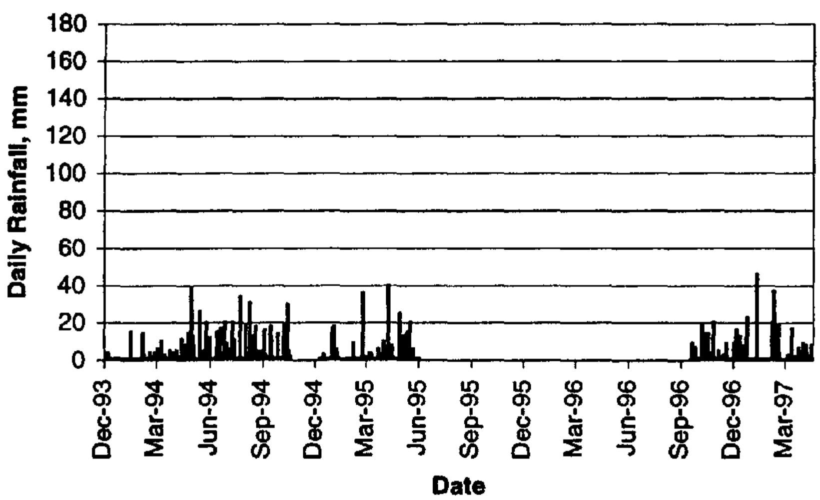
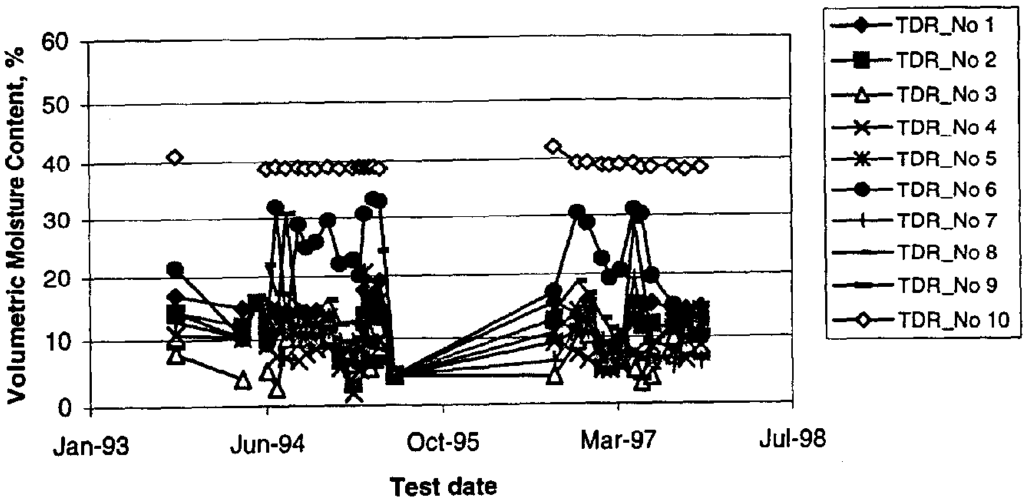
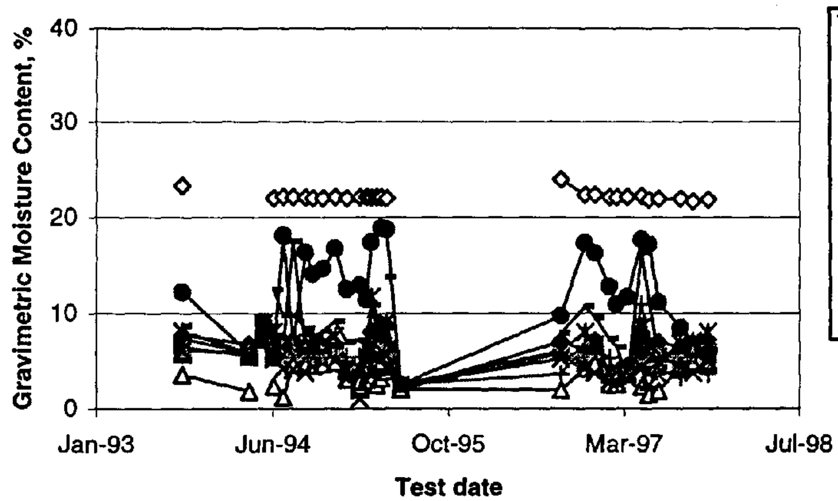


Figure 131. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 871622 in Ontario.





TDR_No	Depth, m
1	0.28
2	0.41
3	0.56
4	0.72
5	0.88
6	1.02
7	1.17
8	1.35
9	1.64
10	1.93

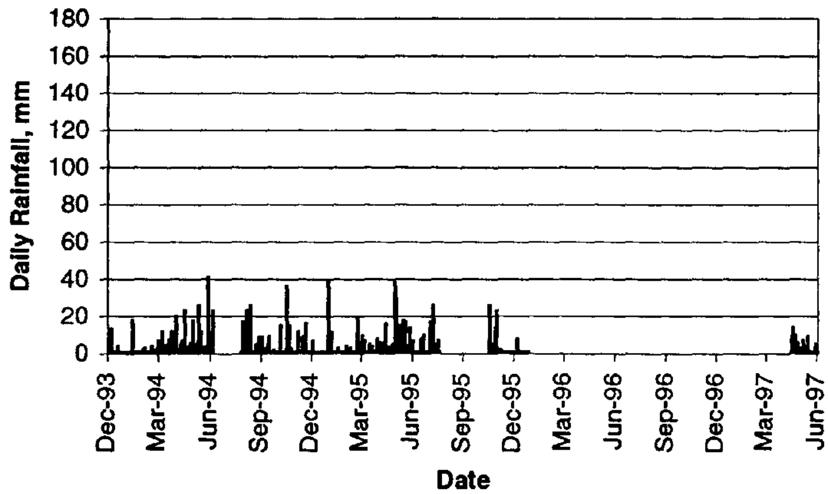


Figure 132. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 893015 in Quebec.

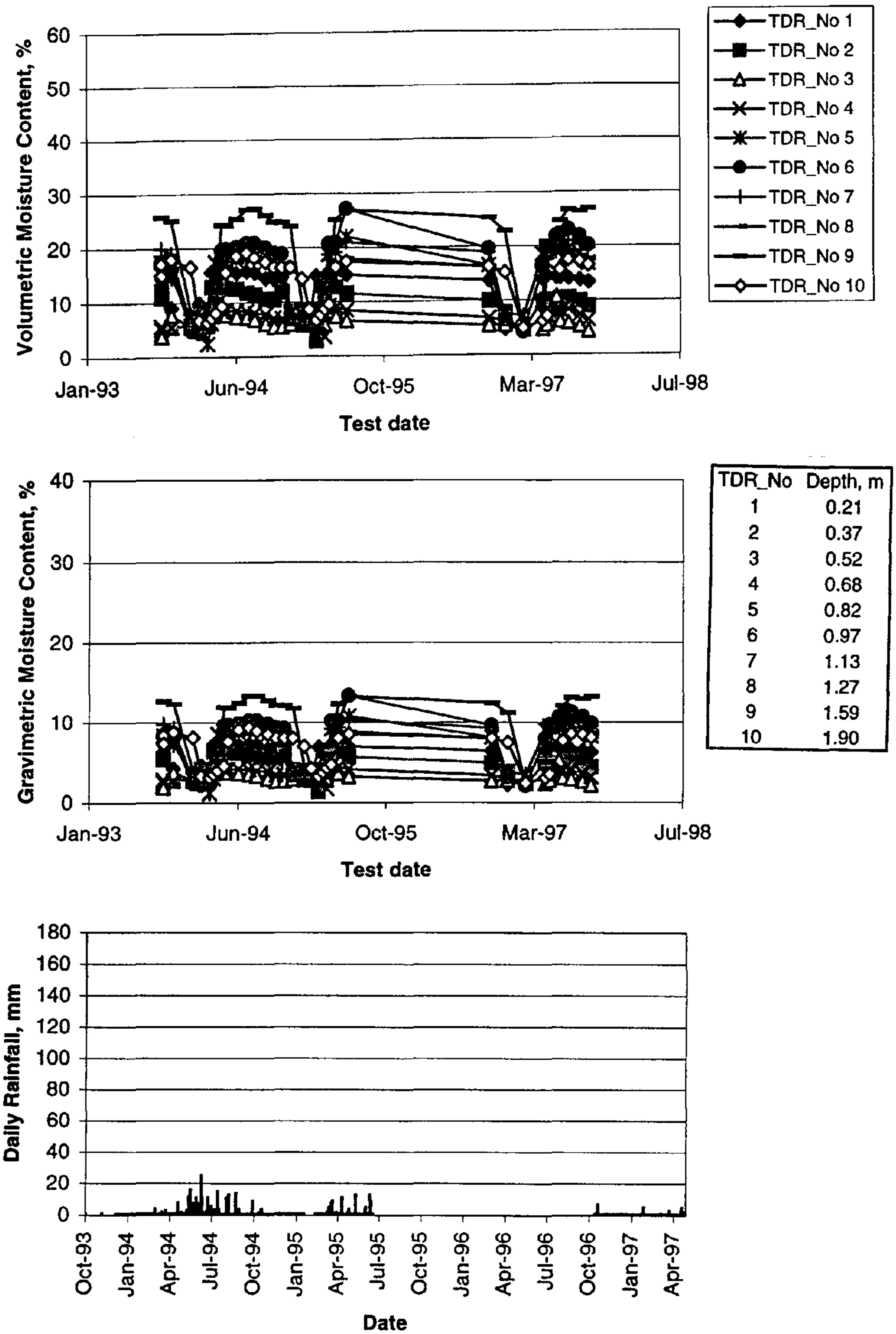


Figure 133. Seasonal variation in volumetric and gravimetric moisture content and daily rainfall for section 906405 in Saskatchewan.

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