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Clayton
ENVIRONMENTAL
CONSULTANTS

Low and High Tide Groundwater Elevation Monitoring Report 4930, 5050, 5051, and 5200 Coliseum Way Properties Oakland, California

Clayton Project No. 70-97203.00.500
August 1997

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1.0 INTRODUCTION

This report presents the data and results of the low and high tide groundwater elevation monitoring event conducted at the 4930, 5050, 5051, and 5200 Coliseum Way properties in Oakland, California (Figure 1). The coordinated monitoring event was conducted in response to the October 10, 1996 request from Mr. Dale Klettke of the Alameda County Department of Environmental Health (ACDEH). The objective of the coordinated monitoring was to determine if the shallow groundwater gradient and flow direction is influenced by tidal fluctuations.

2.0 DESCRIPTION OF WORK

As requested by the ACDEH, the scope of work included measuring the depth to groundwater in wells at the four adjoining properties within a one-hour time frame. The measurements were obtained on December 10, 1996 during the new moon at times corresponding to low and high tide in nearby San Leandro Bay.

The depth to groundwater data were collected by others because the coordinated field effort required monitoring at sites with different property owners. The environmental consultants and corresponding property which was monitored is as follows:

Consultant	Property
Geomatrix Consultants	4930 Coliseum Way 5051 Coliseum Way
Levine-Fricke-Recon	5050 Coliseum Way 750 50th Avenue
Subsurface Consultants	5200 Coliseum Way

Note: For purposes of this report, the monitoring wells located at 750 50th Avenue have been included with the wells located at 5050 Coliseum Way.

3.0 FINDINGS

The field data collected during the low and high tide coordinated monitoring event are summarized in Tables 1 and 2, respectively. Field data sheets provided to Clayton by others are included as Appendix A to this report.

Potentiometric surface maps were prepared using the low and high tide data collected on December 10, 1996 and are included as Figures 2 and 3, respectively. A comparison of Figures 2 and 3 shows that groundwater flow direction for both the low and high tide events is to the west-southwest over a majority of the properties with a southerly flow component at 4930 Coliseum Way. Hydraulic gradient across the properties range from 0.009 ft/ft to 0.024 ft/ft during low tide and from 0.006 ft/ft to 0.015 ft/ft during high tide.

Groundwater elevations in wells located immediately adjacent to the stormwater drainage channel along 5051 Coliseum Way (MWA-1 and MW-4) show an increase during high tide. Water levels in wells located away from the drainage channel do not increase significantly.

4.0 DISCUSSION AND CONCLUSIONS

The results of the December 10, 1996 coordinated low and high tide depth to water monitoring event indicate that groundwater flow direction and gradient are not significantly influenced by tidal fluctuations. While there is some localized response in wells located immediately adjacent to the stormwater drainage channel, tidal fluctuations do not significantly influence other wells at the site.

During the Summer of 1996, Weiss Associates performed a long-term groundwater elevation study at the site. Groundwater levels were continuously recorded over an approximate 40-day period using down-hole pressure transducers in groundwater monitoring wells at the 5050 and 5051 Coliseum Way properties. Groundwater level data collected by Weiss Associates were provided to Dr. Tadeusz Patzek for analysis.

The results of Dr. Patzek's analysis is documented in his April 23, 1997 report entitled "Analysis of Tidal Response at the Volvo GM Site (5050 Coliseum Way) and PG&E Site (5051 Coliseum Way)". A copy of the report is included as Appendix B to this report.

The findings of Dr. Patzek's analysis of the long-term data are as follows:

- the well with the greatest fluctuations, MW-4, is located on the 5051 Coliseum Way site about 40 feet east from a stormwater channel and has a response amplitude of about ±1 foot;
- the adjacent stormwater channel is concrete-lined and contains weep holes to allow water to enter and exit the channel;
- surface water in this adjacent stormwater channel is tidally influenced, with fluctuations in water levels of about ±2-3 feet; and
- wells located farther away from the stormwater channels have much lower response amplitudes than MW-4.

Based on his findings, Dr. Patzek concluded that:

- groundwater level fluctuations in some of the wells at the four sites are the result of tidally-influenced seawater, present in adjacent stormwater channels, entering the subsurface through weep holes or other openings. San Leandro Bay is too far away to significantly influence groundwater levels at the site.

- local fluctuations in groundwater levels in wells near the stormwater channels do not correspond to a flow of groundwater between the stormwater channels and these nearby wells. Rather, these oscillations in groundwater levels represent a diffuse pressure wave transmitted through the water.

Note that Dr. Patzek's conclusion is supported by other studies of tidal influence which demonstrate that tidally-influenced lateral groundwater flow decreases rapidly away from a tidal zone (see *Simulation of Tidal Effects on Contaminant Transport in Porous Media*, C. S. Yim and M.F.N. Mohsen, 1992, Ground Water, v. 30, no. 1, pp. 78-86).

The results of the December 10, 1996 low and high tide depth-to-water coordinated monitoring event demonstrate that groundwater flow direction and gradient are not significantly influenced by tidal fluctuations. Additionally, analysis of long-term data indicates that the only wells which are tidally influenced are located immediately adjacent to the stormwater drainage channel. While water levels in these wells increase during high tide events, the increase is not caused by the flow of groundwater. The water levels increase in response to a diffuse pressure wave.

This report prepared by:

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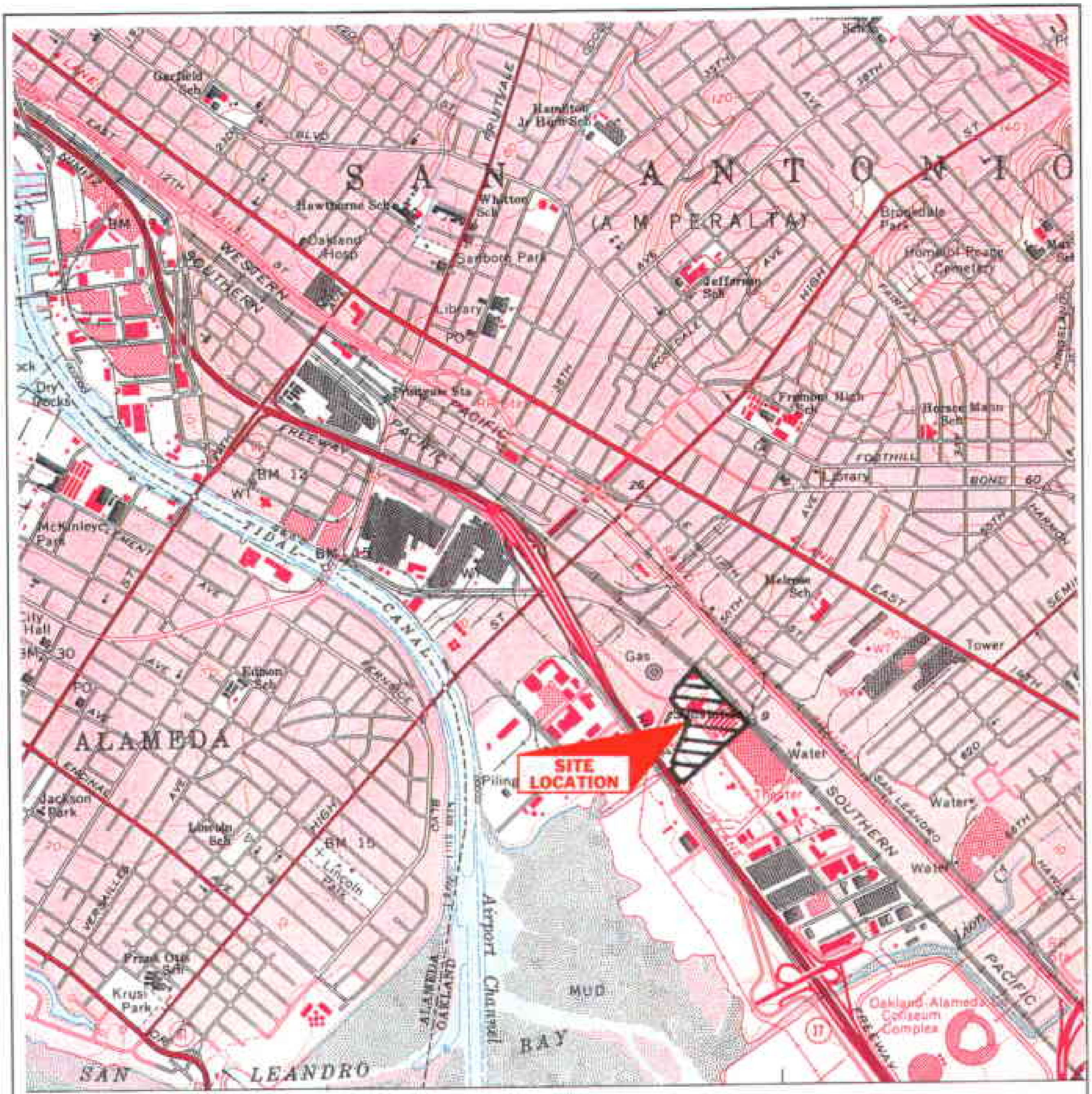
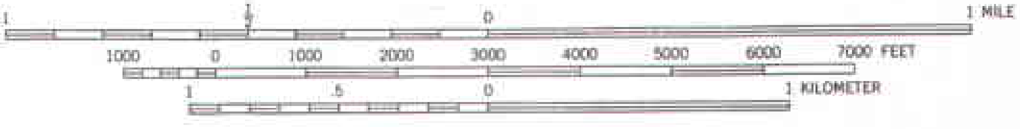
Environmental Management and Remediation
San Francisco Regional Office

This report reviewed by:

Dwight R. Hoenig
Vice President, Western Regional Director
Environmental Management and Remediation
San Francisco Regional Office





SITE LOCATION MAP

50th AVENUE STORM DRAIN
OAKLAND, CALIFORNIA

Clayton Project No. 70-97203.00.500

Figure
1

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FIG500.CDR

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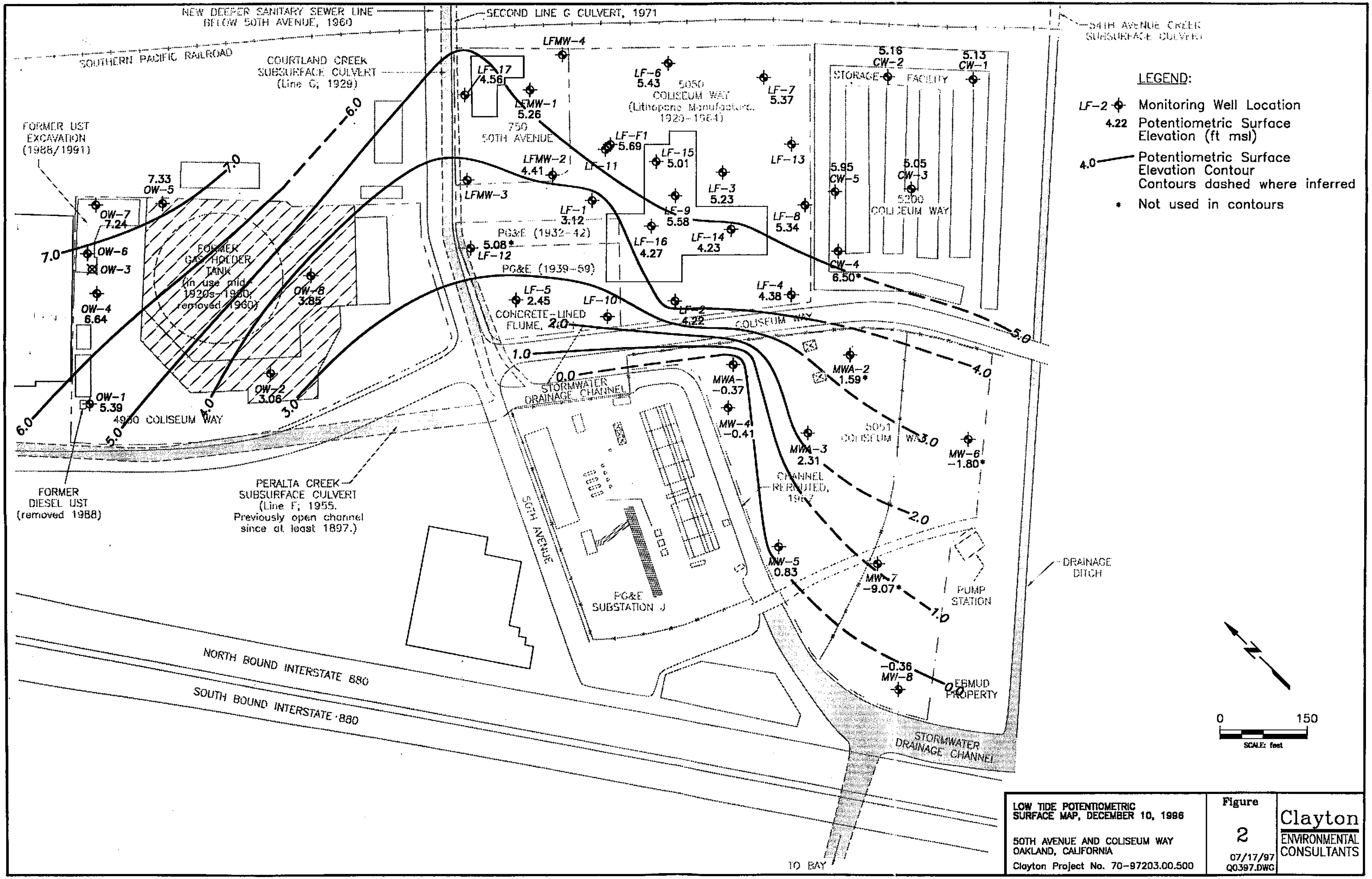

LOW TIDE POTENTIOMETRIC SURFACE MAP, DECEMBER 10, 1996

50TH AVENUE AND COLISEUM WAY
OAKLAND, CALIFORNIA

Clayton Project No. 70-97203.00.500

Figure
2
07/17/97
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Clayton
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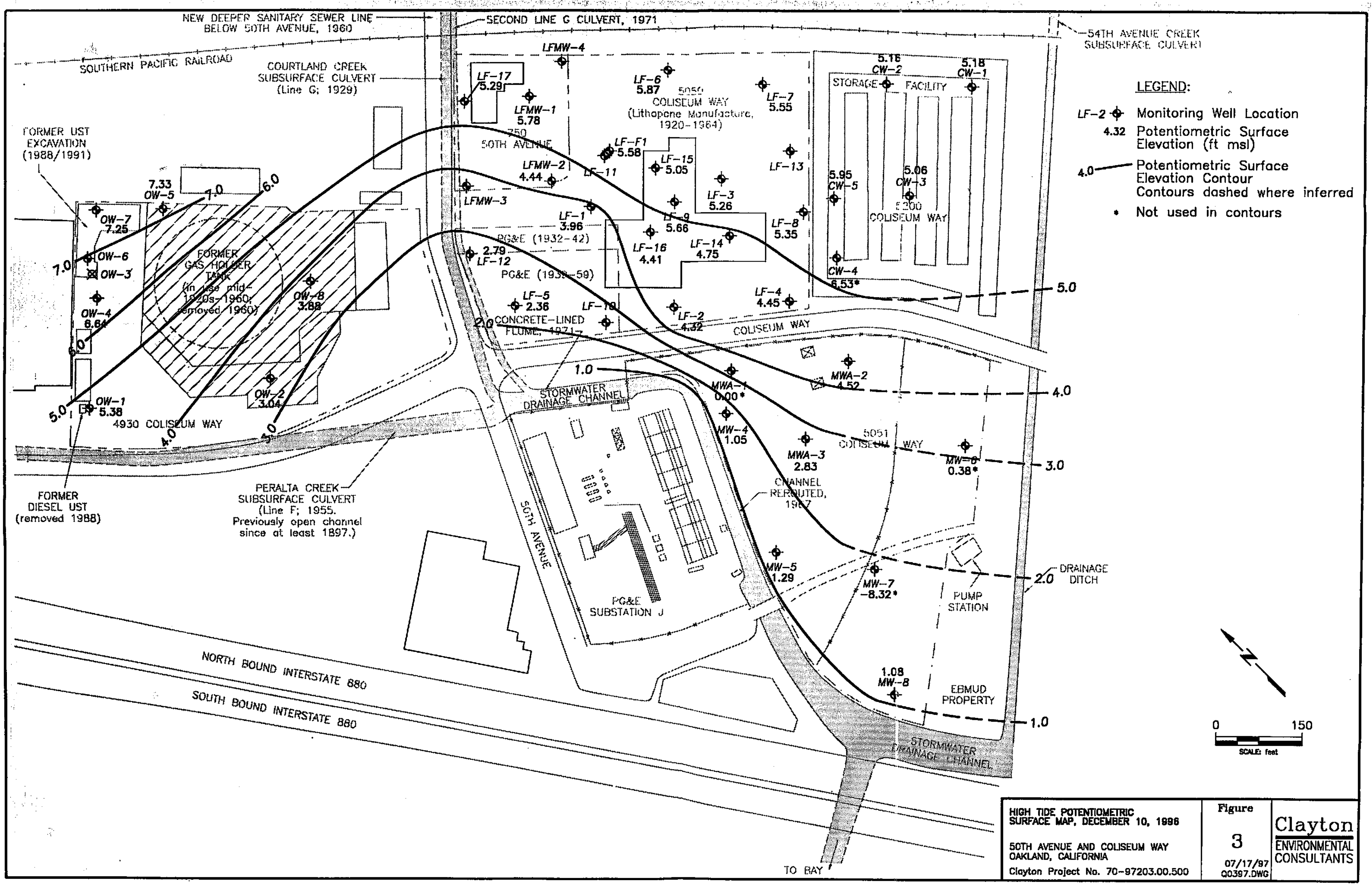

HIGH TIDE POTENTIOMETRIC
SURFACE MAP, DECEMBER 10, 1996

50TH AVENUE AND COLISEUM WAY
OAKLAND, CALIFORNIA

Clayton Project No. 70-97203.00.500

Figure
3
07/17/97
Q0397.DWG

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CONSULTANTS

TABLE 1
LOW TIDE WATER LEVEL MEASUREMENT DATA
Coliseum Way Properties, Oakland, California

Property	Monitoring Well	Date	Time	TOC (ft, msl)	Depth to Water (ft)	Water Surface Elevation (ft, msl)
4930 Coliseum Way (Data provided by Geomatrix)						
	OW-1	10-Dec-96	7:20	9.06	3.67	5.39
	OW-2	10-Dec-96	7:25	8.49	5.43	3.06
	OW-4	10-Dec-96	7:30	10.06	3.42	6.64
	OW-5	10-Dec-96	7:50	10.48	3.15	7.33
	OW-7	10-Dec-96	7:44	12.24	5.00	7.24
	OW-8	10-Dec-96	7:10	8.43	4.58	3.85
5051 Coliseum Way (Data provided by Geomatrix)						
	MWA-1	10-Dec-96	6:39	9.27	9.64	-0.37
	MWA-2	10-Dec-96	6:46	7.79	6.20	1.59
	MWA-3	10-Dec-96	6:51	10.50	8.19	2.31
	MW-4	10-Dec-96	6:30	10.27	10.68	-0.41
	MW-5	10-Dec-96	6:35	9.45	8.62	0.83
	MW-6	10-Dec-96	7:01	7.14	8.94	-1.80
	MW-7	10-Dec-96	7:05	8.78	17.85	-9.07
	MW-8	10-Dec-96	7:10	6.69	7.05	-0.36

TABLE 1
LOW TIDE WATER LEVEL MEASUREMENT DATA
Coliseum Way Properties, Oakland, California

Property	Monitoring Well	Date	Time	TOC (ft, msl)	Depth to Water (ft)	Water Surface Elevation (ft, msl)
5050 Coliseum Way (Data provided by Levine-Fricke-Recon)						
	LF-1	10-Dec-96	7:09	7.56	4.44	3.12
	LF-2	10-Dec-96	7:13	9.84	5.62	4.22
	LF-3	10-Dec-96	7:57	10.98	5.75	5.23
	LF-4	10-Dec-96	7:14	10.36	5.98	4.38
	LF-5	10-Dec-96	6:55	8.03	5.58	2.45
	LF-6	10-Dec-96	8:01	11.59	6.16	5.43
	LF-7	10-Dec-96	7:52	10.65	5.28	5.37
	LF-8	10-Dec-96	7:55	10.91	5.57	5.34
	LF-9	10-Dec-96	7:35	11.70	6.12	5.58
	LF-12	10-Dec-96	7:00	8.70	3.62	5.08
	LF-14	10-Dec-96	7:25	11.72	7.49	4.23
	LF-15	10-Dec-96	7:42	11.62	6.61	5.01
	LF-16	10-Dec-96	7:46	11.56	7.29	4.27
	LF-17	10-Dec-96		9.71	5.15	4.56
	LF-F1	10-Dec-96		8.82	3.13	5.69
	LFMW-1	10-Dec-96		10.21	4.95	5.26
	LFMW-2	10-Dec-96	7:05	8.86	4.45	4.41

TABLE 1
LOW TIDE WATER LEVEL MEASUREMENT DATA
Coliseum Way Properties, Oakland, California

Property	Monitoring Well	Date	Time	TOC (ft, msl)	Depth to Water (ft)	Water Surface Elevation (ft, msl)
5200 Coliseum Way (Data provided by Subsurface Consultants)						
	CW-1	10-Dec-96	6:41	14.11	8.98	5.13
	CW-2	10-Dec-96	6:45	14.88	9.72	5.16
	CW-3	10-Dec-96	6:52	14.07	9.02	5.05
	CW-4	10-Dec-96	6:58	14.76	8.26	6.50
	CW-5	10-Dec-96	7:03	14.36	8.41	5.95

TABLE 2
HIGH TIDE WATER LEVEL MEASUREMENT DATA
Coliseum Way Properties, Oakland, California

Property	Monitoring Well	Date	Time	TOC (ft, msl)	Depth to Water (ft)	Water Surface Elevation (ft, msl)
4930 Coliseum Way (Data provided by Geomatrix)						
	OW-1	10-Dec-96	13:06	9.06	3.68	5.38
	OW-2	10-Dec-96	13:13	8.49	5.45	3.04
	OW-4	10-Dec-96	13:00	10.06	3.42	6.64
	OW-5	10-Dec-96	13:05	10.48	3.15	7.33
	OW-7	10-Dec-96	13:20	12.24	4.99	7.25
	OW-8	10-Dec-96	13:25	8.43	4.55	3.88
5051 Coliseum Way (Data provided by Geomatrix)						
	MWA-1	10-Dec-96	13:06	9.27	9.27	0.00
	MWA-2	10-Dec-96	13:13	7.79	3.27	4.52
	MWA-3	10-Dec-96	13:09	10.50	7.67	2.83
	MW-4	10-Dec-96	13:00	10.27	9.22	1.05
	MW-5	10-Dec-96	13:05	9.45	8.16	1.29
	MW-6	10-Dec-96	13:16	7.14	6.76	0.38
	MW-7	10-Dec-96	13:20	8.78	17.10	-8.32
	MW-8	10-Dec-96	13:25	6.69	5.61	1.08

TABLE 2
HIGH TIDE WATER LEVEL MEASUREMENT DATA
Coliseum Way Properties, Oakland, California

Property	Monitoring Well	Date	Time	TOC (ft, msl)	Depth to Water (ft)	Water Surface Elevation (ft, msl)
5050 Coliseum Way (Data provided by Levine-Fricke-Recon)						
	LF-1	10-Dec-96	13:26	7.56	3.60	3.96
	LF-2	10-Dec-96	13:29	9.84	5.52	4.32
	LF-3	10-Dec-96	13:47	10.98	5.72	5.26
	LF-4	10-Dec-96	13:32	10.36	5.91	4.45
	LF-5	10-Dec-96	13:10	8.03	5.67	2.36
	LF-6	10-Dec-96	14:02	11.59	5.72	5.87
	LF-7	10-Dec-96	13:52	10.65	5.10	5.55
	LF-8	10-Dec-96	13:49	10.91	5.56	5.35
	LF-9	10-Dec-96	13:41	11.70	6.04	5.66
	LF-12	10-Dec-96	13:14	8.70	5.91	2.79
	LF-14	10-Dec-96	13:36	11.72	6.97	4.75
	LF-15	10-Dec-96	13:45	11.62	6.57	5.05
	LF-16	10-Dec-96	13:59	11.56	7.15	4.41
	LF-17	10-Dec-96	14:25	9.71	4.42	5.29
	LF-F1	10-Dec-96		8.82	3.24	5.58
	LFMW-1	10-Dec-96	14:15	10.21	4.43	5.78
	LFMW-2	10-Dec-96	13:18	8.86	4.42	4.44

TABLE 2
HIGH TIDE WATER LEVEL MEASUREMENT DATA
Coliseum Way Properties, Oakland, California

Property	Monitoring Well	Date	Time	TOC (ft, msl)	Depth to Water (ft)	Water Surface Elevation (ft, msl)
5200 Coliseum Way (Data provided by Subsurface Consultants)						
	CW-1	10-Dec-96	13:00	14.11	8.93	5.18
	CW-2	10-Dec-96	13:04	14.88	9.72	5.16
	CW-3	10-Dec-96	13:08	14.07	9.01	5.06
	CW-4	10-Dec-96	13:11	14.76	8.23	6.53
	CW-5	10-Dec-96	13:17	14.36	8.41	5.95

APPENDIX A

FIELD DATA SHEETS

Post-it™ brand fax transmittal memo 7671

	# of pages ▸ 1
To Mark Maloney (?)	From Sally Gordon
Co. Clayton	Co. Geomatrix
Dept.	Phone #
Fax # 510 426 0106	Fax #

Pacific Gas and Electric Water Level Elevations
5051 Coliseum Way
Oakland, California

Low Tide

Well No.	Date	Time	MP Elevation (feet)	Water Level Below MP (feet)	Water Level Elevation (feet)
MWA-1	12/10/96	639	9.27	9.64	-0.37
MWA-2	12/10/96	646	7.79	6.20	1.59
MWA-3	12/10/96	651	10.50	8.19	2.31
MW-4	12/10/96	630	10.27	10.68	-0.41
MW-5	12/10/96	635	9.45	8.62	0.83
MW-6	12/10/96	701	7.14	8.94	-1.80
MW-7	12/10/96	705	8.78	17.85	-9.07
MW-8	12/10/96	710	6.69	7.05	-0.36

High Tide

Well No.	Date	Time	MP Elevation (feet)	Water Level Below MP (feet)	Water Level Elevation (feet)
MWA-1	12/10/96	1306	9.27	9.27	0.00
MWA-2	12/10/96	1313	7.79	3.27	4.52
MWA-3	12/10/96	1309	10.50	7.67	2.83
MW-4	12/10/96	1300	10.27	9.22	1.05
MW-5	12/10/96	1305	9.45	8.16	1.29
MW-6	12/10/96	1316	7.14	6.76	0.38
MW-7	12/10/96	1320	8.78	17.10	-8.32
MW-8	12/10/96	1325	6.69	5.61	1.08

WATER LEVEL MONITORING RECORD

GEOMATRIX

Project 29CC **Project No.** PG+E

Date 12/10/96 **Recorded By** MRK

Note: Use these abbreviations to make your life easier:
P = Pumping SC = Specific Conductance Measured
I = Inaccessible WS = Water Sample Collected

	morning		afternoon			
Well No.	~~**Date**~~ time	**Water Level Below MP (feet)**	**Corrections (feet)** time	**Water Level Below GL (feet)**	**Water Level Elevation (feet, MSL)**	**Remarks**
MWA-1	639	9.64	1306	9.27		
MWA-2	646	6.20	1313	3.27		← Pressure on wells when 1st opened
MWA-3	651	8.19	1309	7.67		
MW-4	630	10.68	1300	9.22		
MW-5	635	9.62	1305	8.16		
MW-6	701	8.94	1316	6.76		← pressure when first opened
MW-7	705	17.85	1320	17.10		
MW-8	710	7.05	1325	5.61		
MW-1	720	3.67	1329	3.68		
MW-2	725	5.43	1345	5.45		
MW-4	730	3.42	1333	3.42		
MW-5	750	3.15	1350	3.15		
MW-6	NA					
MW-7	737	5.00	1342	4.99		
MW-8	744	4.58	1355	4.55		← pressure in well

Water Level Elevations
PG and E
4930 Coliseum Way
Oakland, California

Low Tide

Well No.	Date	Time	MP Elevation (feet)	Water Level Below MP (feet)	Water Level Elevation (feet)
OW-1	12/10/96	720	9.06	3.67	5.39
OW-2	12/10/96	725	8.49	5.43	3.06
OW-4	12/10/96	730	10.06	3.42	6.64
OW-5	12/10/96	750	10.48	3.15	7.33
OW-6	12/10/96	NA	NA	NA	NA
OW-7	12/10/96	744	12.24	5.00	7.24
OW-8	12/10/96	710	8.43	4.58	3.85

High Tide

Well No.	Date	Time	MP Elevation (feet)	Water Level Below MP (feet)	Water Level Elevation (feet)
OW-1	12/10/96	1306	9.06	3.68	5.38
OW-2	12/10/96	1313	8.49	5.45	3.04
OW-4	12/10/96	1300	10.06	3.42	6.64
OW-5	12/10/96	1305	10.48	3.15	7.33
OW-6	12/10/96	NA	NA	NA	NA
OW-7	12/10/96	1320	12.24	4.99	7.25
OW-8	12/10/96	1325	8.43	4.55	3.88

5050

WATER-LEVEL MEASUREMENTS

Project Name: [illegible]
Project No.: [illegible]
Field Personnel: [illegible]
Date: 12/10/96
General Observations:

WELL NO.	WELL ELEVATION TIME	DEPTH TO WATER MEASUREMENTS 6:30.0	13:00	WATER ELEVATION	REMARKS (UNITS = FEET)
LF-1		4.94	~~9.49~~ 3.60		7:09 / 13:26
LF-2		5.62	5.52		7:13 / 13:29
LF-3		5.75	5.72		7:57 / 13:47
LF-4		5.98	5.91		7:14 / 13:32
LF-5		5.58	5.67		6:55 / 13:10
LF-6		6.16	5.72		8:01 / 14:02
LF-7		5.28	5.10		7:52 / 13:52
LF-8		5.57	5.56		7:55 / 13:49
LF-9		6.12	6.04		7:35 (MID BAY / 13:41)
LF-10	~~0.0~~	0.0	0.0		THESE WELLS INUNDATED
LF-11	~~[illegible]~~	0.0	0.0		WITH RAINWATER RUNOFF
LF-12		3.62	5.91		7:00 / 13:14
LF-13		~~6.12~~			~~7:35 (MID BAY)~~
LF-14		7.49	6.92		7:25 / 13:3[illegible] (SOUTH BAY)
LF-15		6.61	6.57		7:42 / 13:45 (NORTH BAY)
LF-16		7.29	7.15		7:46 / 13:55
LF-17		5.15	4.42		/ 14:25
LF-F1	0.0 (W)	3.13	3.24		
MW-1		4.95	4.43		/ 14:15
MW-2		4.45	4.42		7:05 / 13:18
MW-3		NM			
MW-4		NM			

6.22 LF
6.24 SS

LEVINE·FRICK
CONSULTING ENGINEERS AND HYDROGEOLOGISTS

GROUNDWATER DEPTHS

ect Name: 5200 Coliseum Way

Job No.: 97.002

Measured by: DWA

Well	Date	Time	Groundwater Depth (feet)	Comments
CW-1	12/10/96	0641	8.98	new locks
CW-2	↓	0645	9.72	↓
CW-3	↓	0652	9.02	↓
CW-4	↓	0658	8.26	↓
CW-5	↓	0703	8.41	↓
CW-1	12/10/96	1300	8.93	
CW-2	↓	1304	9.72	
CW-3	↓	1308	9.01	
CW-4	↓	1311	8.23	
CW-5	↓	1317	8.41	

APPENDIX B

ANALYSIS OF TIDAL RESPONSE PREPARED BY DR. TAD PATZEK

PV TECHNOLOGIES, INC.
6585 Ascot Dr., Oakland CA 94611-1708
(TEL) 510-531-5104 (FAX) 510-530-2125

April 23, 1997

Mr. Dwight Hoenig
Clayton Environmental Consultants
1252 Quarry Line
Pleasanton, CA 94566
Tel: 510-426-2600, Fax: 510-426-0106

Dear Mr. Hoenig:

Enclosed is my report "**Analysis of Tidal Response at the Volvo GM Site (5050 Coliseum Way) and PG&E Site (5051 Coliseum Way)**". If you have any questions, please feel free to call me.

Very truly yours,

Tad Patzek

Tadeusz W. Patzek
President

Analysis of Tidal Response at the Volvo GM Site (5050 Coliseum Way) and PG&E Site (5051 Coliseum Way)

by

Dr. Tad W. Patzek

Summary of Conclusions

1. Flow of sea water through weep-holes in the concrete-lined walls of the storm channel on the PG&E property is responsible for tidal responses in wells MW-4 and MWA-1 there. This opinion is consistent with a more permeable silty-sand and gravel fill that surrounds wells MW-4 and MWA-1. Oscillations of sea water, in-and-out of the weep-holes every six hours, are confined to the vicinity of the storm channel and do not result in water flow to-and-from MW-4 or MWA-1. These oscillations are felt by *other* water particles near the wells as a diffusive pressure wave.

2. There is no such response in another PG&E well, MWA-2.

3. There is no such response in Volvo/GM wells MW-3 and LF-12, next to an underground concrete channel *without* weep-holes.

4. In fact, wells MW-3 and LF-12 have no connection whatsoever to the storm channel or the Bay; they do respond to earth tides, just as well LF-7 far away from any channel.

5. Therefore, tidal responses in wells MW-4 and MWA-1 are an indication of **local coupling** with the stormwater channel on the PG&E site and in no way can be regarded as a "proof" of a continuous path of aqueous contaminant transport from the Volvo/GM site to the Bay.

Observations

1. The fluctuations of groundwater level beneath the PG&E property are caused by a local source, not by the Bay. The Bay is simply too far to cause significant tidal oscillations beneath this property. The closest distance between the Bay and MW-4 is more than 2000 ft.

2. Bay tides do travel, however, up an unlined channel which connects with the stormwater channel on the PG&E Property.

3. The fluctuations of surface water level in the stormwater channel, the main source of water fluctuations in nearby wells, are about ±2-3 ft (Figures 1-3).

4. Well MW-4, some 40 ft from the concrete-lined portion of the storm channel shows by far the strongest response to tides. The amplitude of this response is ±1 ft or 40-50 percent of the forcing surface water amplitude (Figures 4-7).

5. In comparison, the second strongest response, in well MWA-1, is only ±0.15 ft or 5-7 percent of the surface water amplitude (Figures 8-10).

6. There are two possibilities of coupling the surface water fluctuations to the surrounding soils and the monitoring wells:

   - The first, most likely possibility, involves water in the storm channel flowing into the soil through weep-holes. The side walls of the channel have 2-inch weep-holes, spaced every 10 ft. These weep-holes are under water except during the lowest tide. Therefore, the weep-holes act as reciprocating pumps. They inject small slugs of sea-water into fill surrounding the channel over 6 hours of high tide and then withdraw these slugs over the following six hours of low tide.

   - The second, unlikely, possibility involves cracks in joints between sections of the concrete channel walls. These cracks would also act as sea-water pumps, just as the weep-holes, but would have to be closer to well MW-4 than to well MWA-1. However, a visual inspection of the lining concrete and the joints did not reveal such cracks.

7. To estimate the likelihood of these two possibilities, Equation (1.1.5) in Appendix A was solved, with the input parameters listed in Table 1 below. The results are shown in Figures 29 and 30. It is entirely possible that a sandy-silty fill between the channel and the two monitoring wells could transmit tidal amplitudes seen in these wells. Indeed, the distance of the pulsating flow between the weep-holes and MW-4 is 40 ft (13 meters) and the average hydraulic conductivity of soil between the storm channel and MW-4 is 0.0001 cm/s (cf. Figure 29), corresponding to silty sand. For well MWA-1, the shortest distance to the channel weep-holes is 67 ft or 20 m. The average soil permeability is then 0.00002 cm/s, corresponding to silt or silty clay.

8. Of course, sea water oscillating in-and-out of the weep-holes every six hours, cannot and does not flow all the way to MW-4 or MWA-1. This water motion is purely oscillatory and is felt at these wells by *other* water particles as a diffusive pressure wave.

9. On the west side of the Volvo/GM property, there is an underground concrete channel which does not have weep-holes. Let's then consider wells MW-3 and LF-12 right next to this channel. Well MW-3 is completed only below the Bay Mud and well LF-12 is also completed above the Bay Mud.

10. The tidal response in MW-3 is ±0.015 ft (±5 mm of water) or 0.5-0.7% of the surface water amplitude. This response is close to the detection limit of pressure transducers and, in fact, it represents elastic seismic waves in soil, or "earth-tides," described briefly in Appendix A.

11. The tidal response in LF-12 is ±0.06 ft (±18 mm of water) or 2-3% of the surface water amplitude. This response also represents earth-tides and there is no coupling to the channel.

12. To prove further that neither well MW-3 nor well LF-7 are in any way connected to the underground channel, let's consider well LF-7, far away from this channel. This well is completed below the Bay Mud, just as well MW-3. Hence, its response and that of MW-3 should be similar. In fact these two responses are almost identical, compare Figures 16 and 22.

13. A third, and most unlikely, explanation of tidal response in MW-4 is a direct interaction of the unlined portion of the storm channel, some 330 ft (100 meters) down-gradient from MW-4, with the soils below and up-gradient from it. This interaction would occur first *along* the sand and gravel fill surrounding the concrete-lined portion of the storm channel and then *away* from the channel and towards well MW-4. In order for this response to occur, the entire 330 ft pathway would have to have an average intrinsic permeability of 6 darcy or a hydraulic conductivity of 0.006 cm/s, corresponding to a continuous layer of well-sorted gravel. Such a high conductivity is consistent with a buried bed of a high-energy river or creek, or a rather coarse fill. It is unlikely that a high energy river flowed down the tidal flats, *and* along the storm water channel during the last century or so. If, on the other hand, there were a highly permeable fill along the storm channel, then one would expect it to continue north to the Volvo/GM property. The negligible magnitude of tidal response in MW-3 contradicts this hypothesis.

The Fast Fourier Transforms and Power Spectra of tidal responses were calculated using MATLAB®, and the linear high-pass filter was implemented in LOTUS-123©.

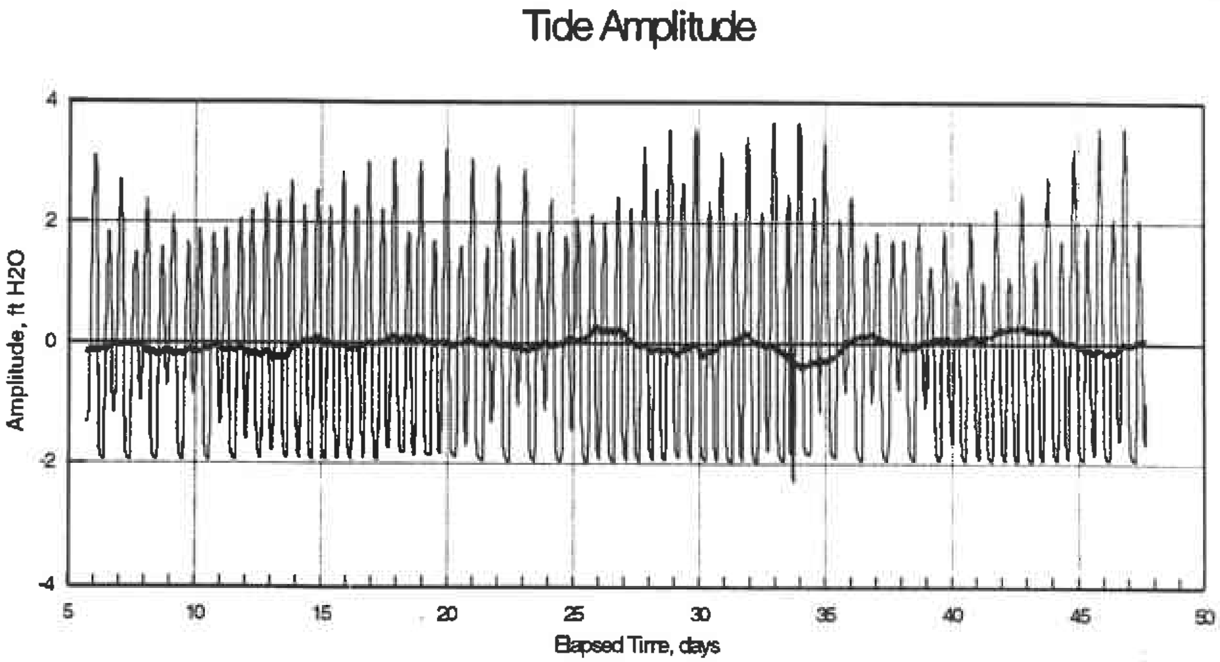

Figure 1. Tidal response (blue curve) in the open storm water channel, with its mean subtracted. The tidal amplitude is ±2-3 ft with some low-frequency modulation. The green line is the atmospheric pressure fluctuation about its mean. This fluctuation is negligible when compared with the tide amplitude and has been neglected. The time series consists of 4330 data points.

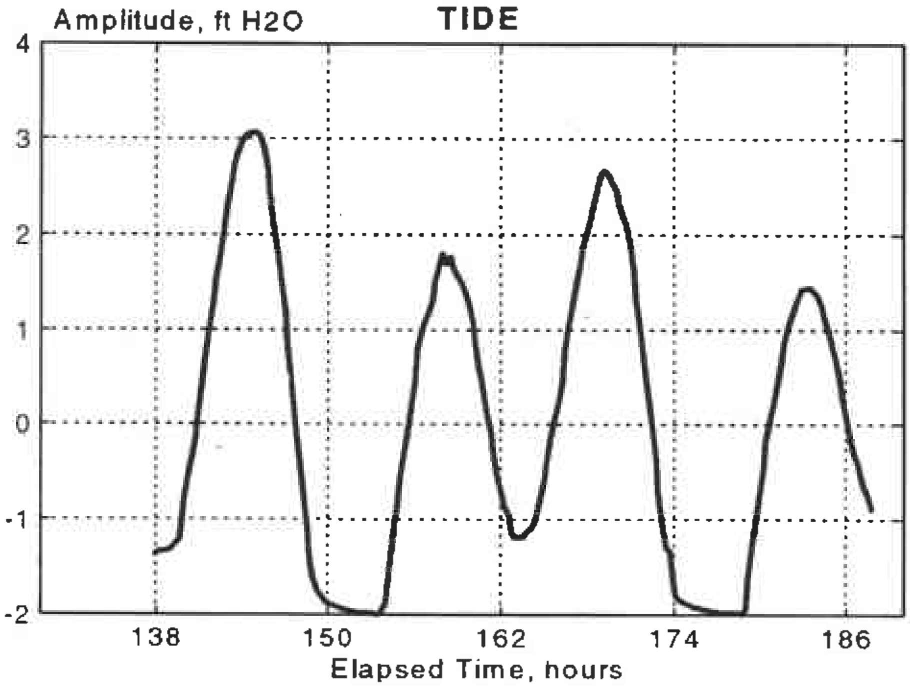

Figure 2. Tidal amplitude on an expanded scale. Now it is clear that the period of the dominant tide component is somewhat longer than 12 hours, as expected (cf. Table A.1. in Appendix A.)

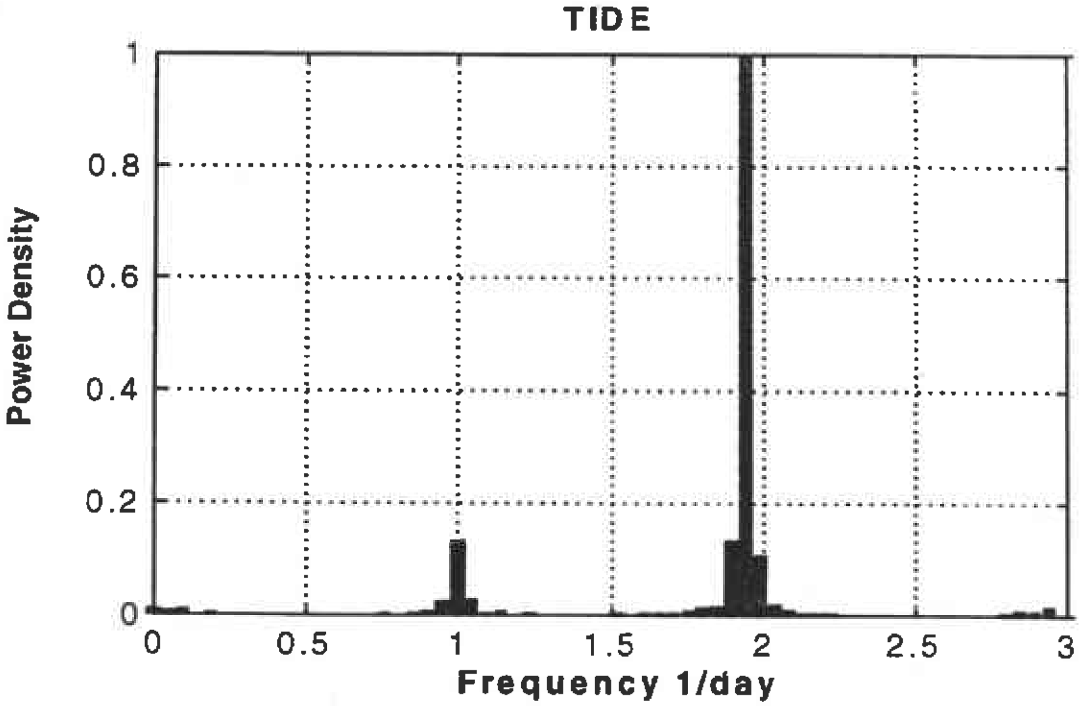

Figure 3. The relative Fourier power spectrum of tidal response in the storm water channel. The 12-hour component (2 1/day) carries most energy. The 24-hour component (1 1/day) carries only 15 percent of the peak energy. Therefore, it is safe to assume that the tidal response period is somewhat less than 12 hours or twice a day.

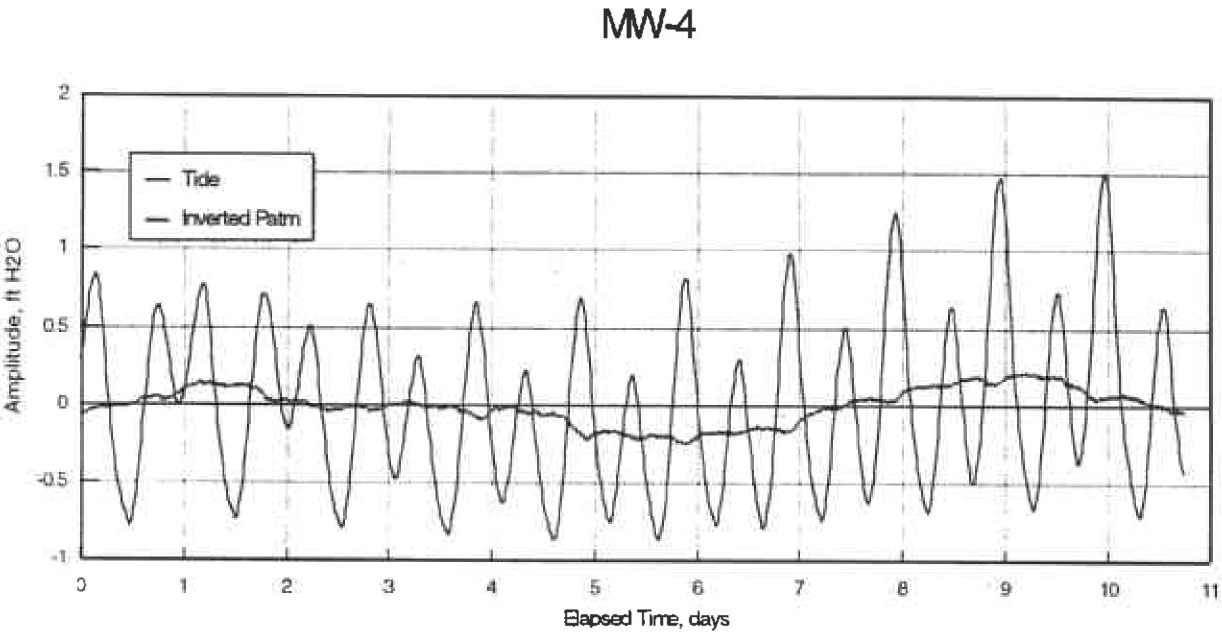

Figure 4. The raw tidal response measured in well MW-4. The inverted barometric pressure fluctuations about its mean are small compared with the groundwater level

fluctuations in MW-4. However, they do modulate the groundwater oscillation amplitude. Barometric efficiency of MW-4 has been assumed to be 1.

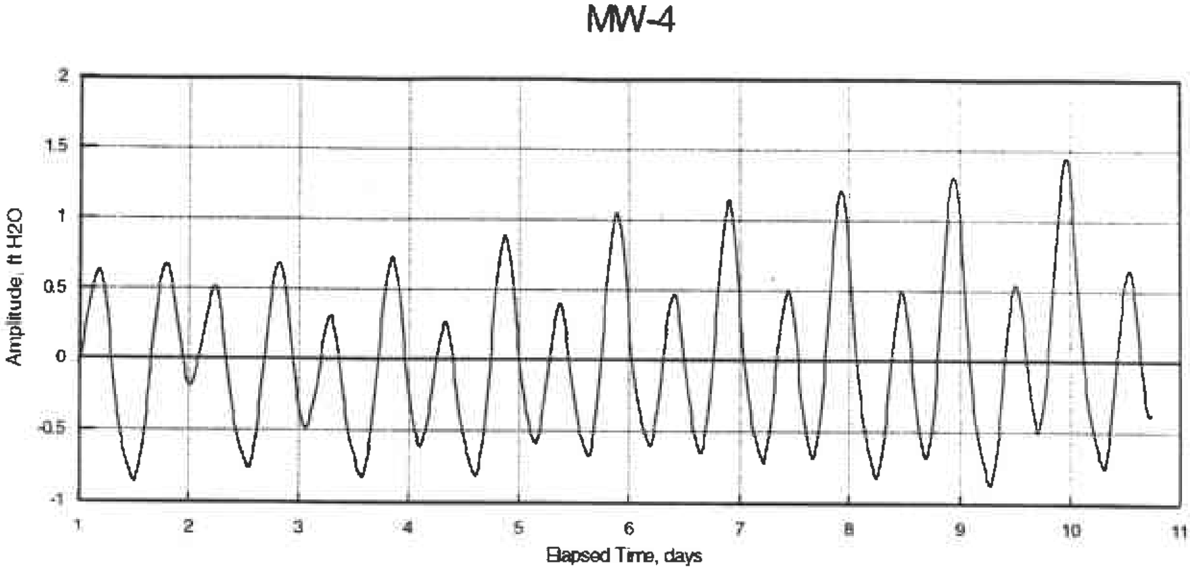

Figure 5. The raw tidal response in MW-4 with the atmospheric pressure effects removed.

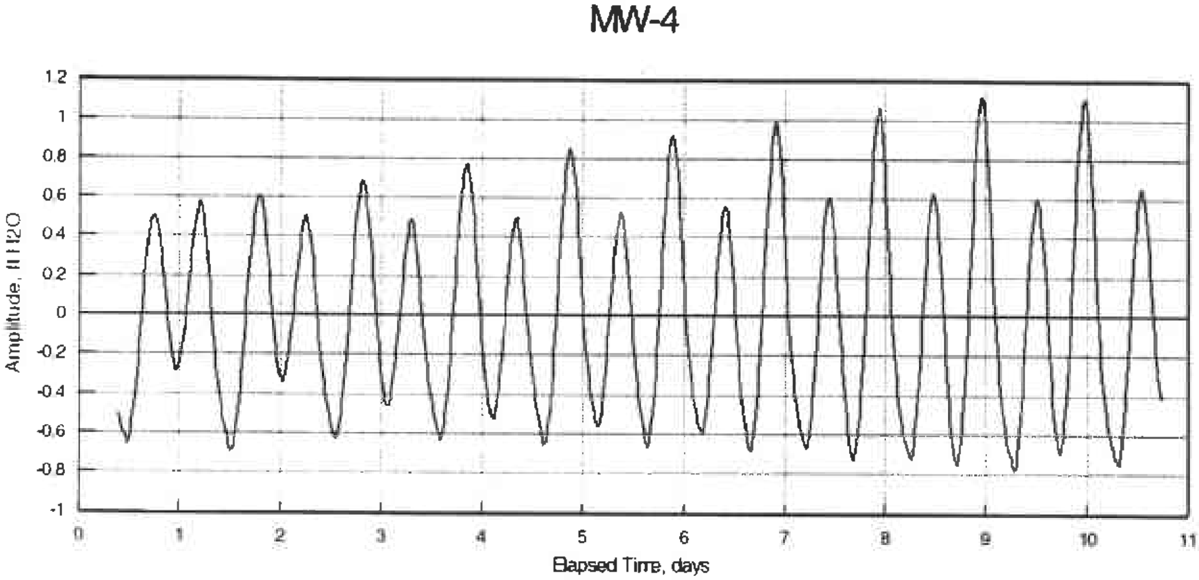

Figure 6. After removal of the atmospheric pressure effects from the MW-4 response, a zero phase shift, high-pass filter of Pertsev[1] was applied to the raw tidal response. As can be visually verified, this filter does not change the high-frequency amplitude of tidal response, but it removes the slow fluctuations. These slow fluctuations are negligible for

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[1] K. L. Hildebrand, "Hydraulic Characterization of An Aquifer Through Passive Monitoring: A Case Study." M.S. Thesis, University of California at Berkeley, 1995.

MW-4. The maximum ground water level fluctuation in MWA-4 is roughly ±1 ft or 40-50% of the storm channel amplitude.

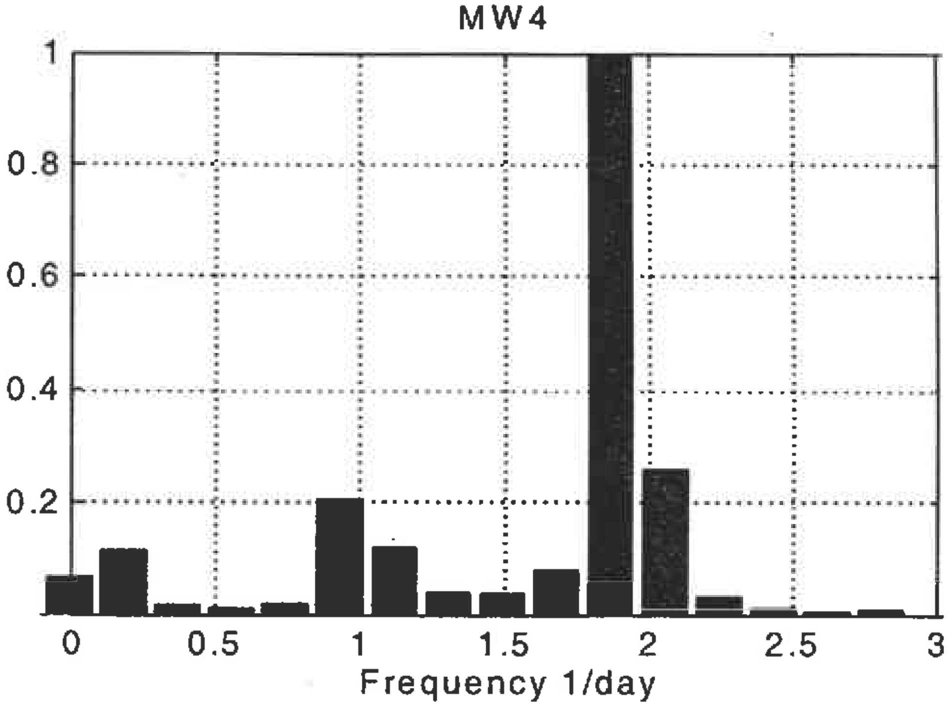

Figure 7. Relative power spectrum of tidal response in MW-4. The 12-hour component (2 1/day) carries most energy as expected. The 24-hour component (1 1/day) carries 20 percent of the peak energy. It has been amplified relative to the 12-hour component because of weaker attenuation of lower frequencies. Note that the power spectrum in MW-4 is coarser because of fewer (1032) data points.

+

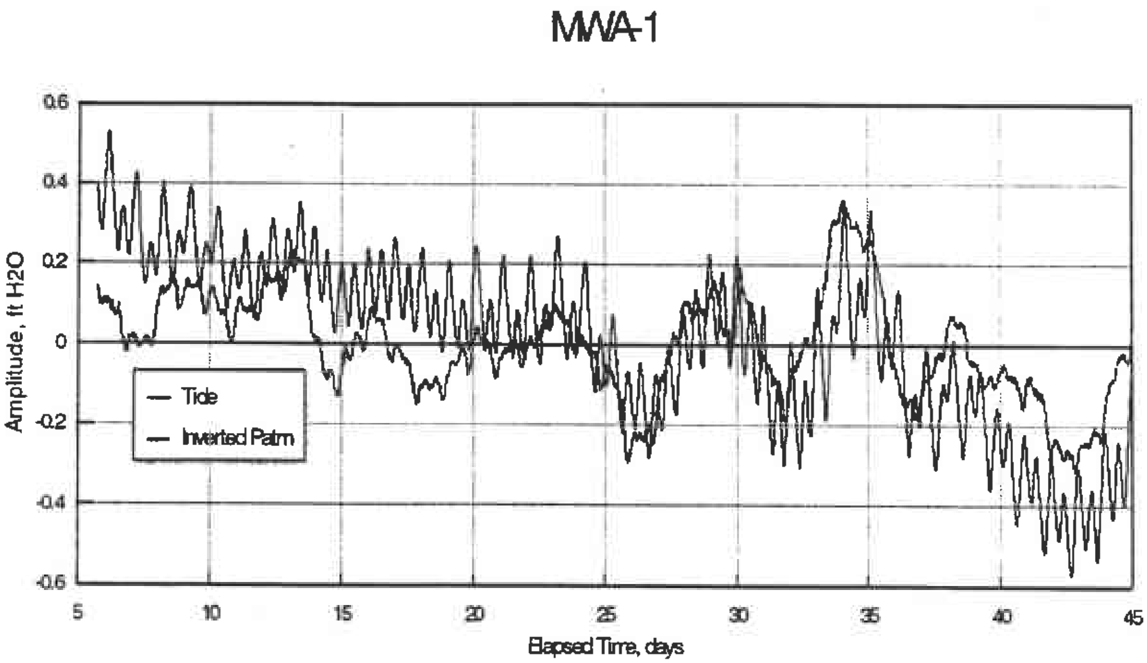

Figure 8. A plot of raw tidal response in MWA-1 (blue curve) and the inverted barometric pressure (red curve) adjusted by barometric efficiency coefficient, here 0.8. Both curves have their means subtracted. The raw tidal response is the sum of atmospheric pressure and tidal influence. The effect of atmospheric pressure must be removed. To achieve this, the adjusted inverted barometric pressure is subtracted from the raw tidal response.

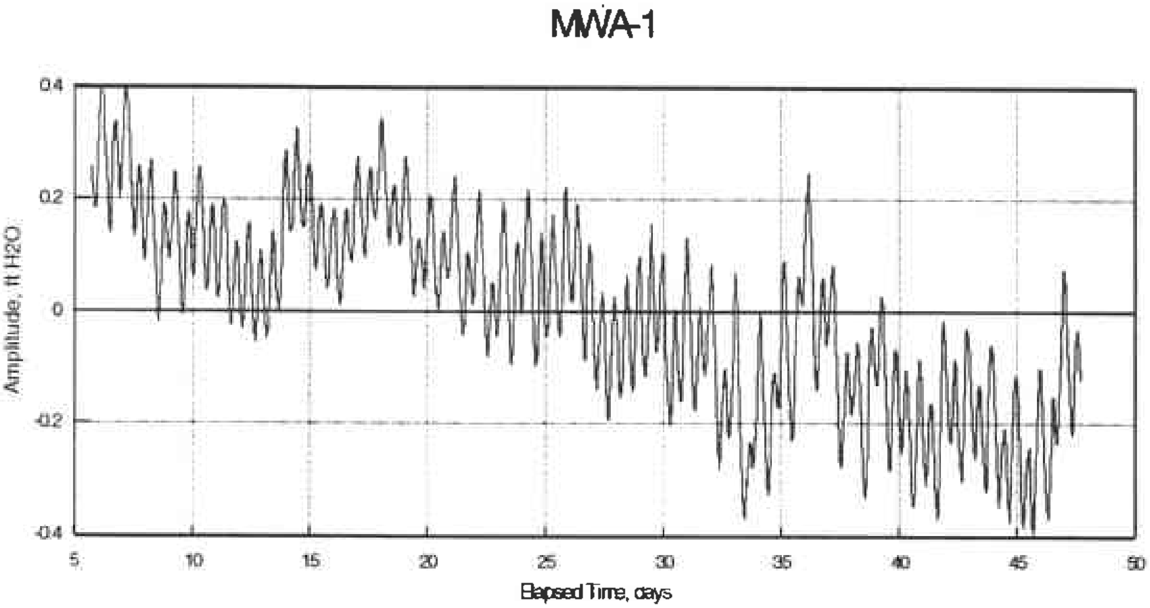

Figure 9. The raw tidal response in MWA-1 with the atmospheric pressure effects removed. This tidal response is still subject to slow fluctuations with periods of the order of 15 days and a drift of the mean. These slow fluctuations can be removed by applying a high-pass filter.

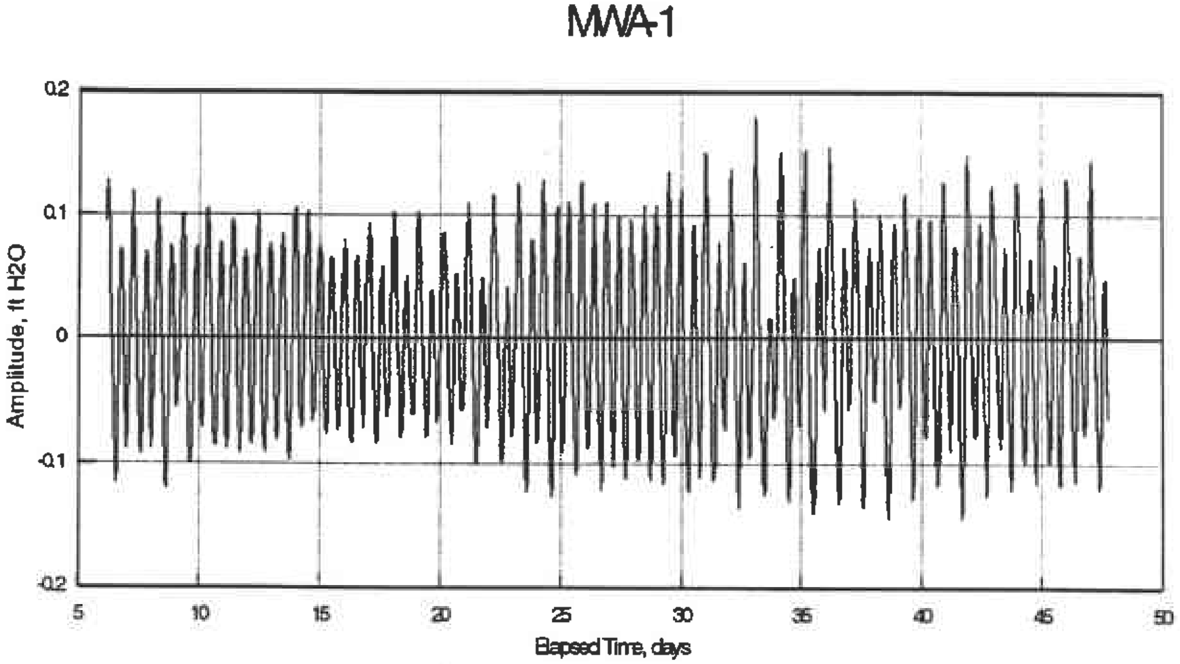

Figure 10. After removal of the atmospheric pressure effects from the MWA-1 response, a zero phase shift, high-pass filter of Pertsev was applied to the raw tidal response. As can be visually verified, this filter does not change the high-frequency amplitude of tidal response, but it removes the slow fluctuations. Therefore, the true tidal response in MWA-1 has been extracted. The maximum ground water level fluctuation in MWA-1 is roughly ±0.15 ft or 7% of the storm channel amplitude.

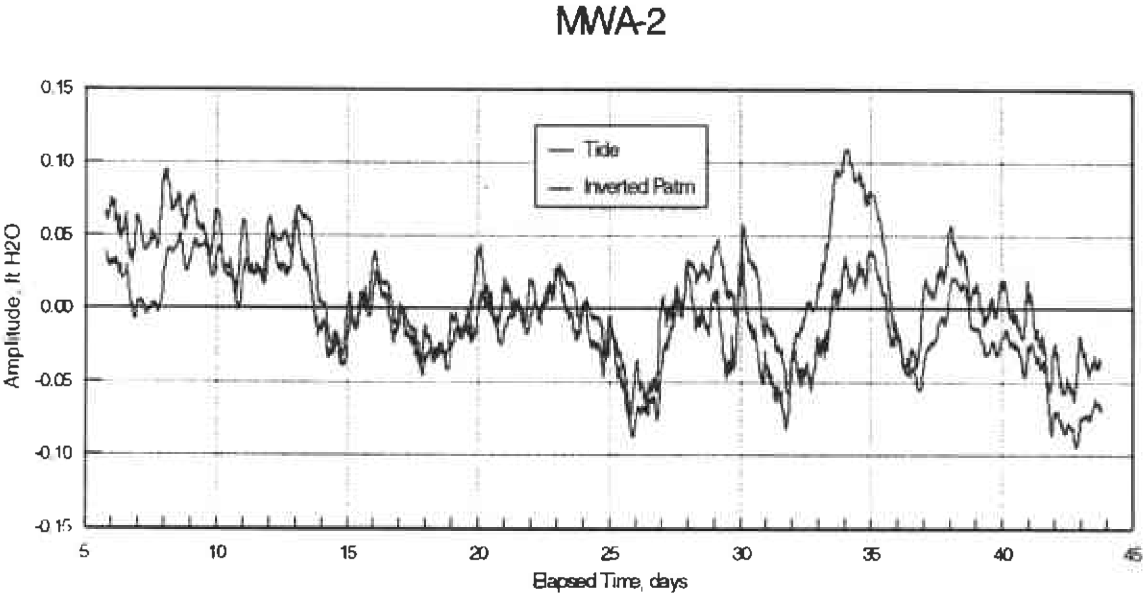

Figure 11. A plot of raw tidal response in MW-2 (blue curve) and the inverted barometric pressure (red curve) adjusted by barometric efficiency coefficient, here 0.30. Both curves

have their means subtracted. The raw tidal response is the sum of atmospheric pressure and tidal influence.

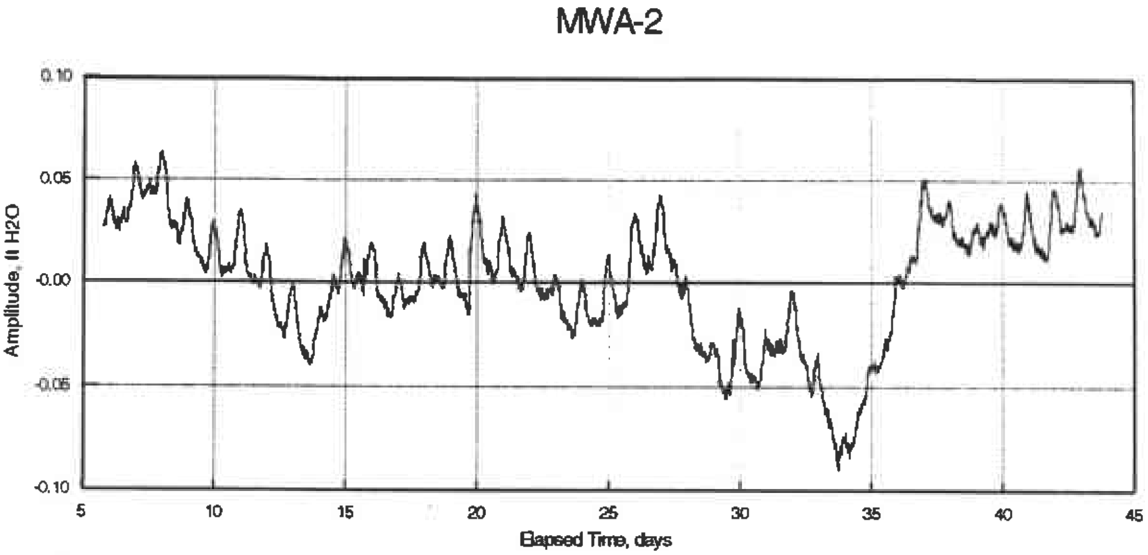

Figure 12. The raw tidal response in MW-2 with the atmospheric pressure effects removed. This tidal response is still subject to slow fluctuations. The 0.1 ft "recharge" between 33 and 37 days is caused by an overestimated effect of the atmospheric pressure drop. The slow fluctuations are removed by applying a high-pass filter.

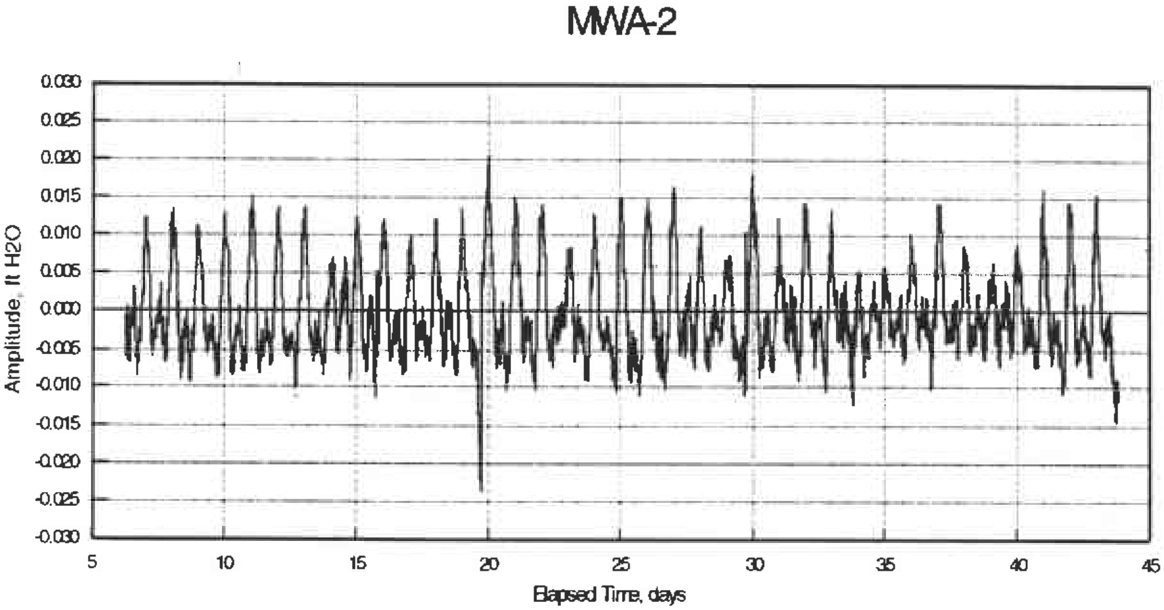

Figure 13. After removing the atmospheric pressure effects from the MWA-2 response, a zero phase shift, high-pass filter of Pertsev is applied to the raw tidal response, yielding its

true tidal response. The water level fluctuations in MWA-2 are ±0.015 ft or 0.7% of the storm channel amplitude.

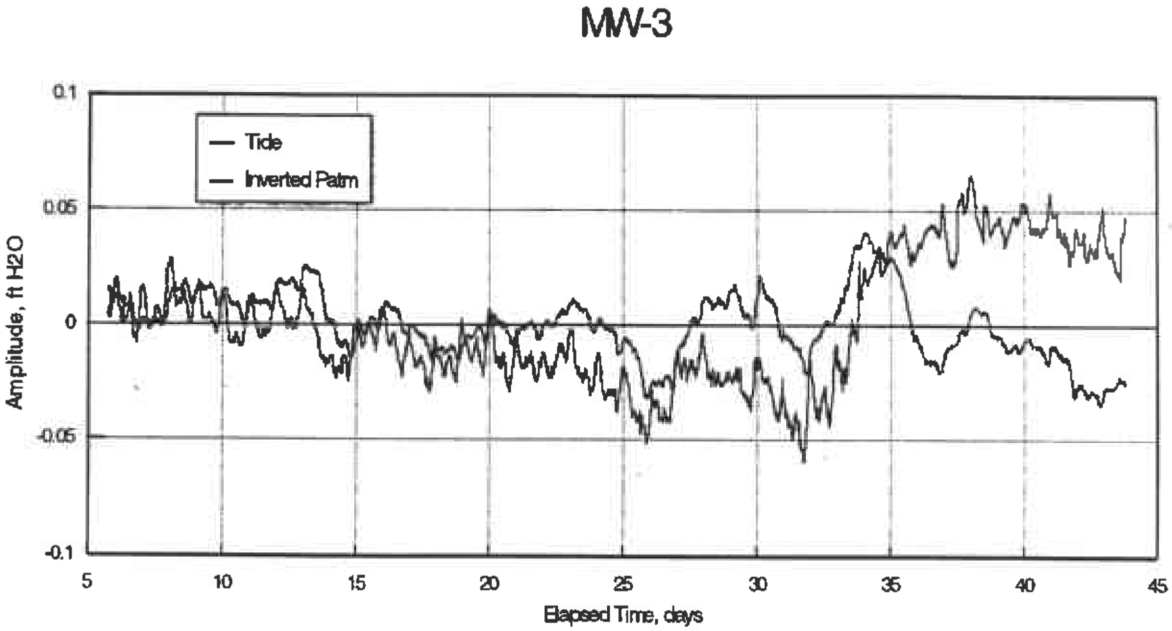

Figure 14. A plot of raw tidal response in MW-3 (blue curve) and the inverted barometric pressure (red curve) adjusted by barometric efficiency coefficient, here 0.15. Both curves have their means subtracted. The raw tidal response is the sum of atmospheric pressure and tidal influence. The effect of atmospheric pressure must be removed. To achieve this, the adjusted inverted barometric pressure is subtracted from the raw tidal response.

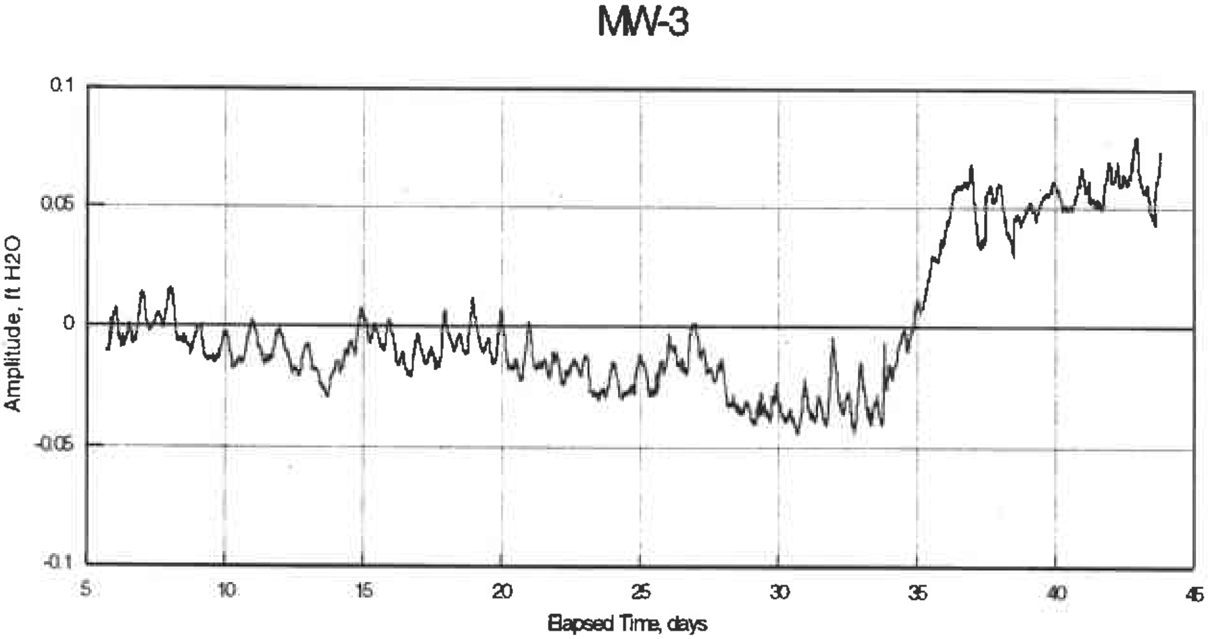

Figure 15. The raw tidal response in MW-3 with the atmospheric pressure effects

removed. This tidal response is still subject to slow fluctuations. There is also a 0.1 ft recharge between 33 and 37 days. The slow fluctuations are removed by applying a high-pass filter.

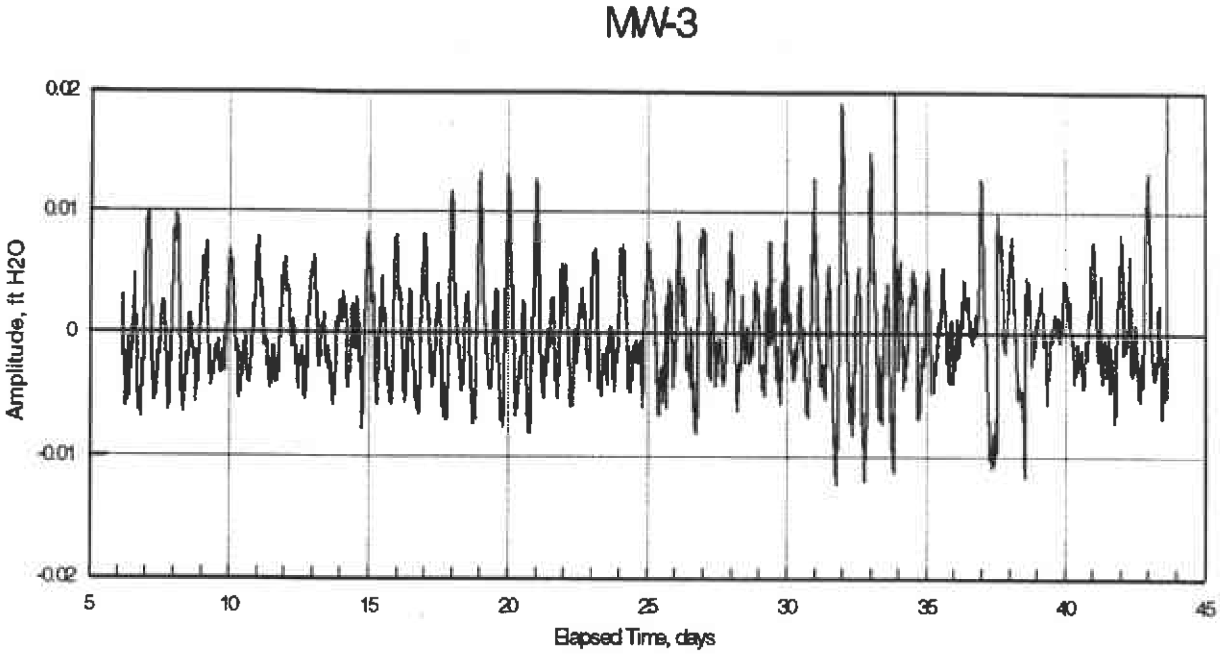

Figure 16. After removal of the atmospheric pressure effects from the MW-3 response, a zero phase shift, high-pass filter of Pertsev is applied to the raw tidal response, yielding its true tidal response. The water level fluctuations in MW-3 are ±0.015 ft or 0.7% of the storm channel amplitude.

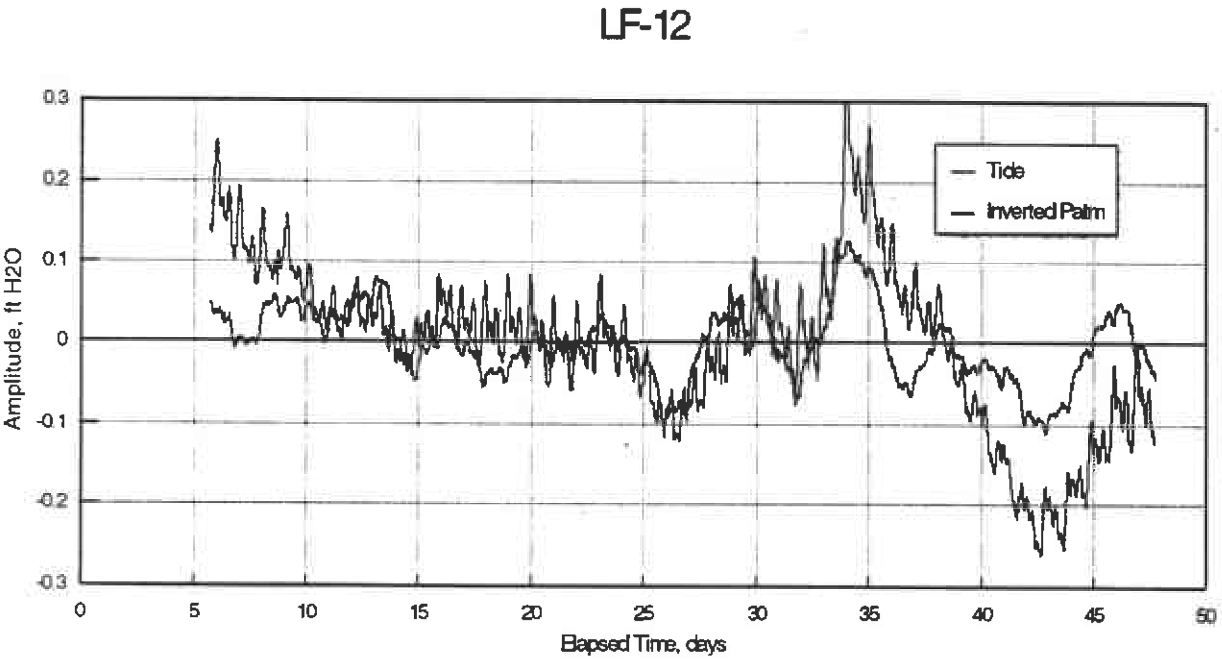

Figure 17. A plot of raw tidal response in LF-12 (blue curve) and the inverted barometric

pressure (red curve) adjusted by barometric efficiency coefficient, here 0.35. Both curves have their means subtracted.

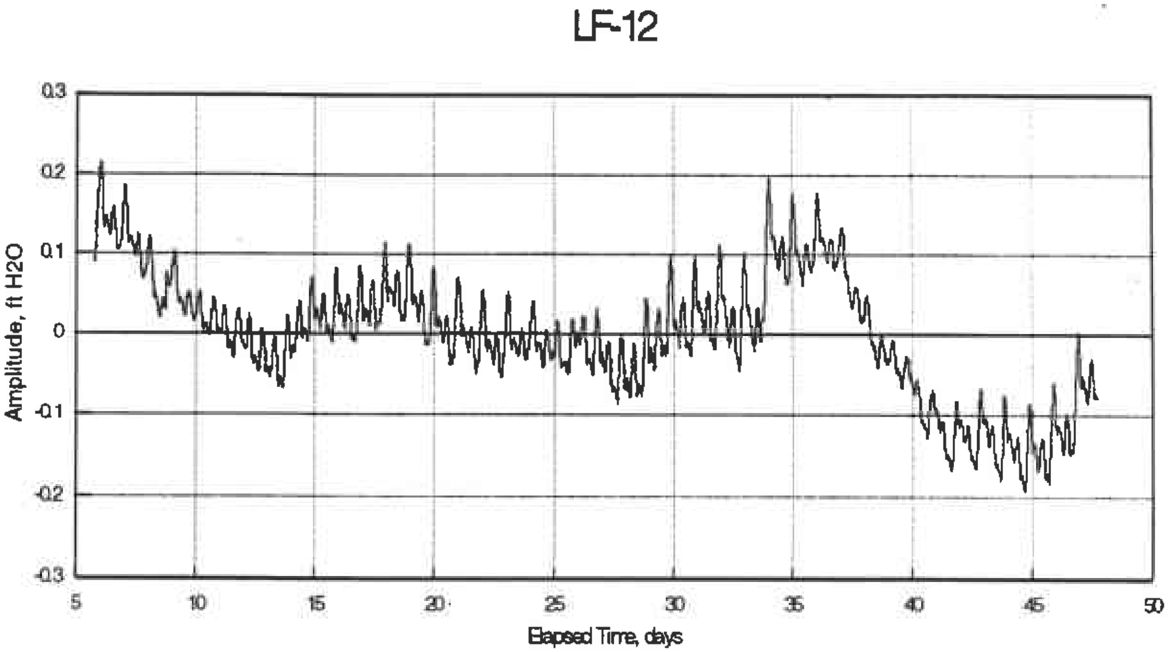

Figure 18. The raw tidal response in LF-12 with the atmospheric pressure effects removed. This tidal response is still subject to slow fluctuations with periods of the order of 15 days. These slow fluctuations are removed by applying a high-pass filter.

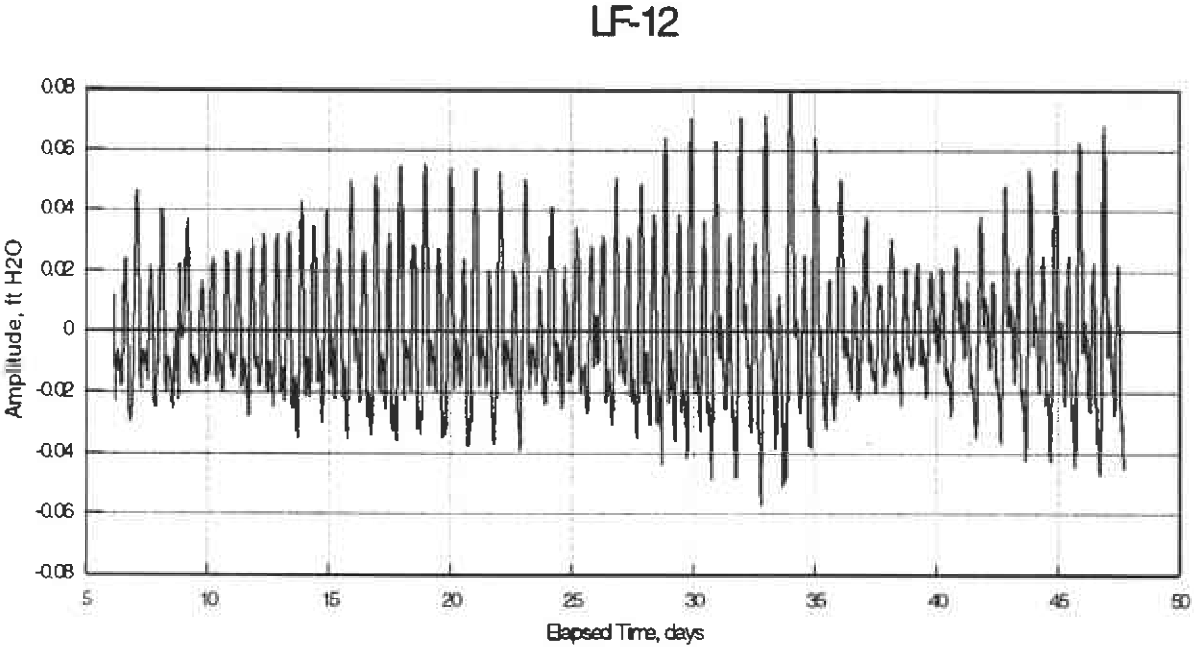

Figure 19. After removal of the atmospheric pressure effects from the LF-12 response, a zero phase shift, high-pass filter of Pertsev is applied to the raw tidal response, yielding the

true tidal response in LF-12. The water level fluctuation in LF-12 is ±0.06 ft or 3% of the storm channel amplitude.

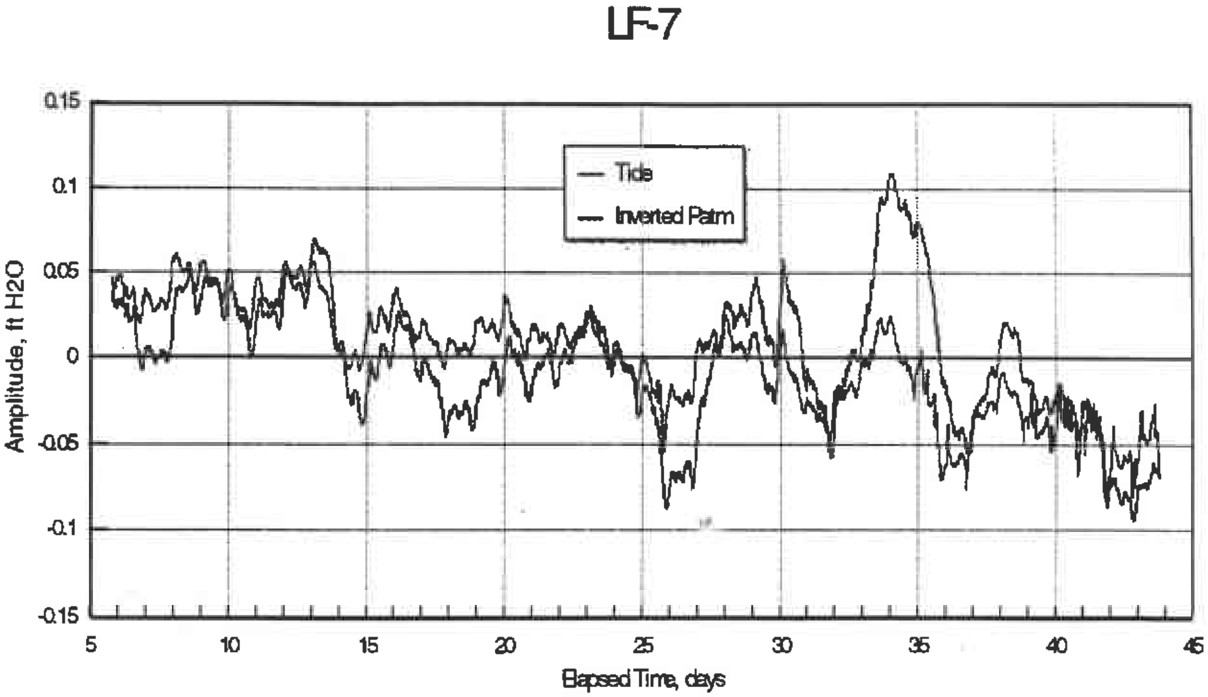

Figure 20. A plot of raw tidal response in LF-7 (blue curve) and the inverted barometric pressure (red curve) adjusted by barometric efficiency coefficient, here 0.25. Both curves have their means subtracted.

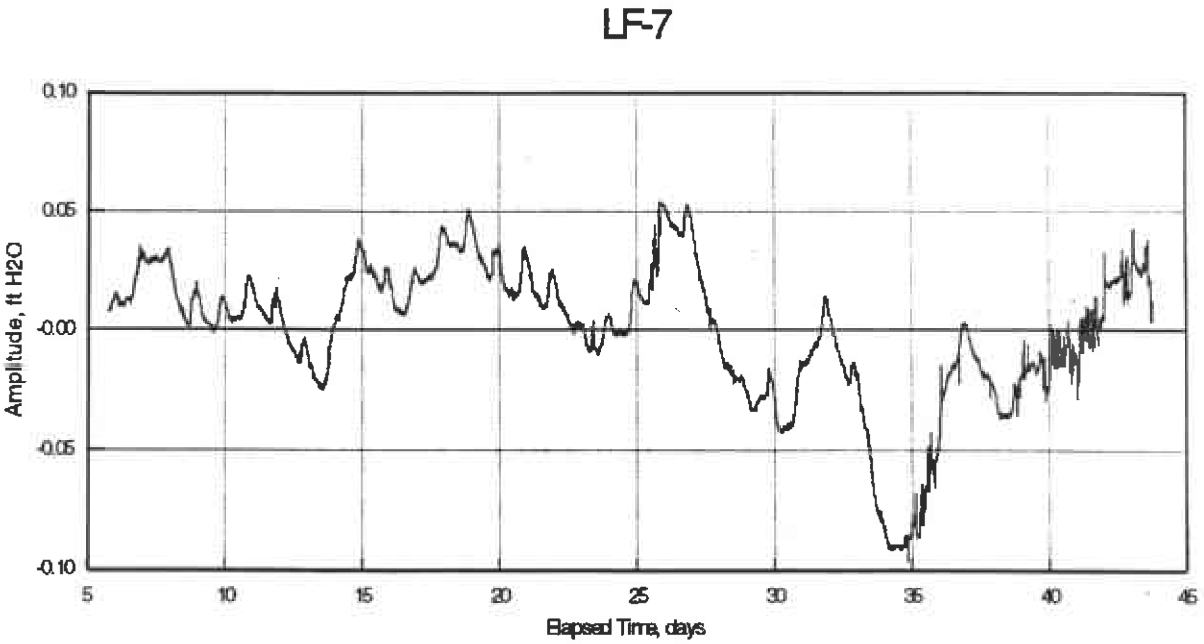

Figure 21. The raw tidal response in LF-7 with the atmospheric pressure effects removed. This tidal response is still subject to slow fluctuations with periods of the order of 15 days. These slow fluctuations can now be removed by applying a high-pass filter.

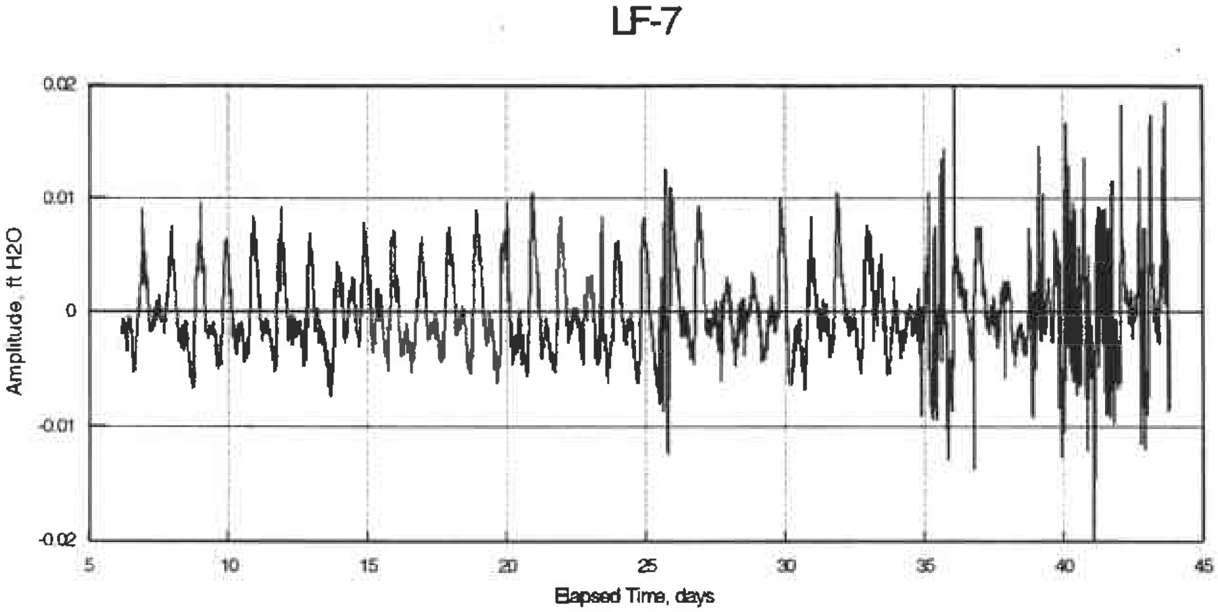

Figure 22. After removal of the atmospheric pressure effects from the LF-7 response, a zero phase shift, high-pass filter of Pertsev is applied to the raw tidal response, yielding the true tidal response in LF-7. The water level fluctuation in LF-7 is ±0.015 ft or 0.7% of the storm channel amplitude. In fact, tidal responses in MW-3 and LF-7 are similar.

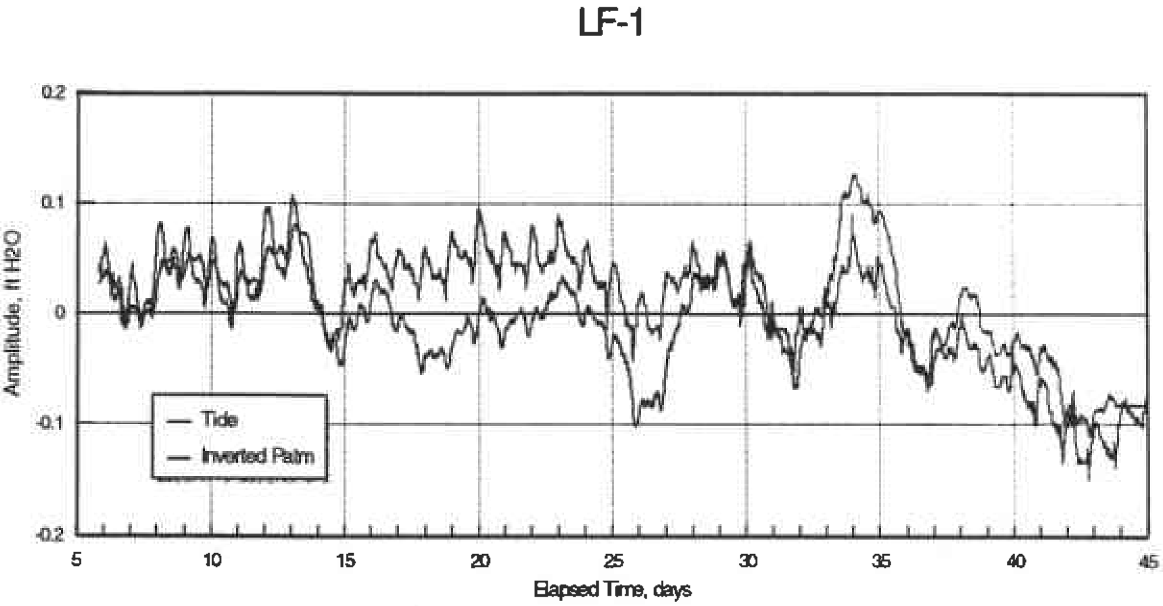

Figure 23. A plot of raw tidal response in LF-1 (blue curve) and the inverted barometric pressure (red curve) adjusted by barometric efficiency coefficient, here 0.35. Both curves have their means subtracted.

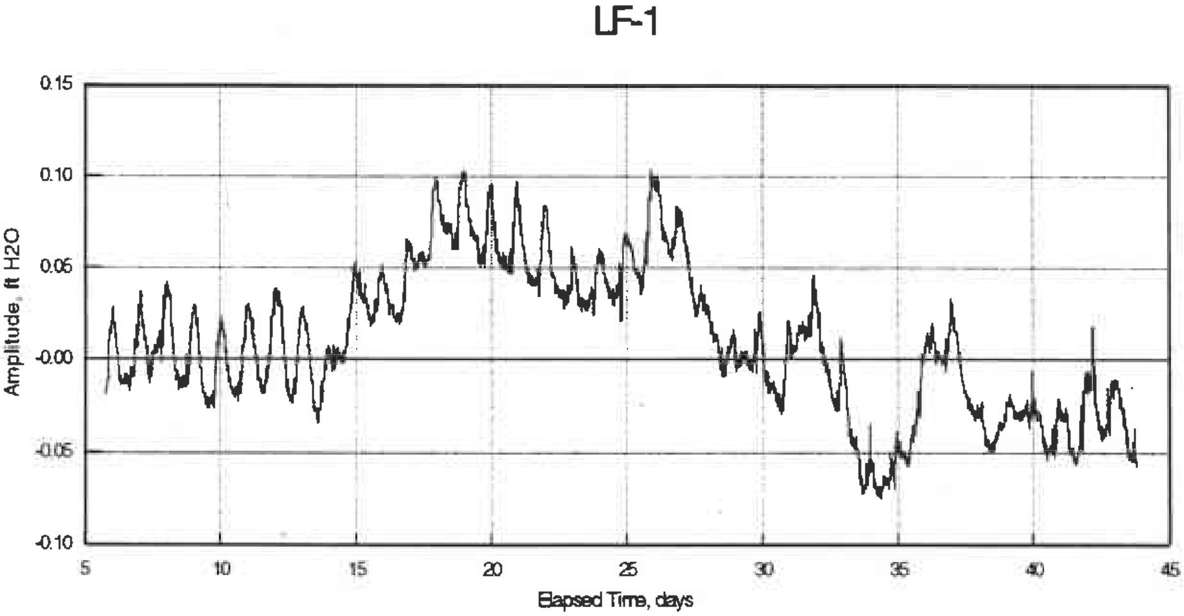

Figure 24. The raw tidal response in LF-1 with the atmospheric pressure effects removed. This tidal response is subject to slow fluctuations which are removed by applying a high-pass filter.

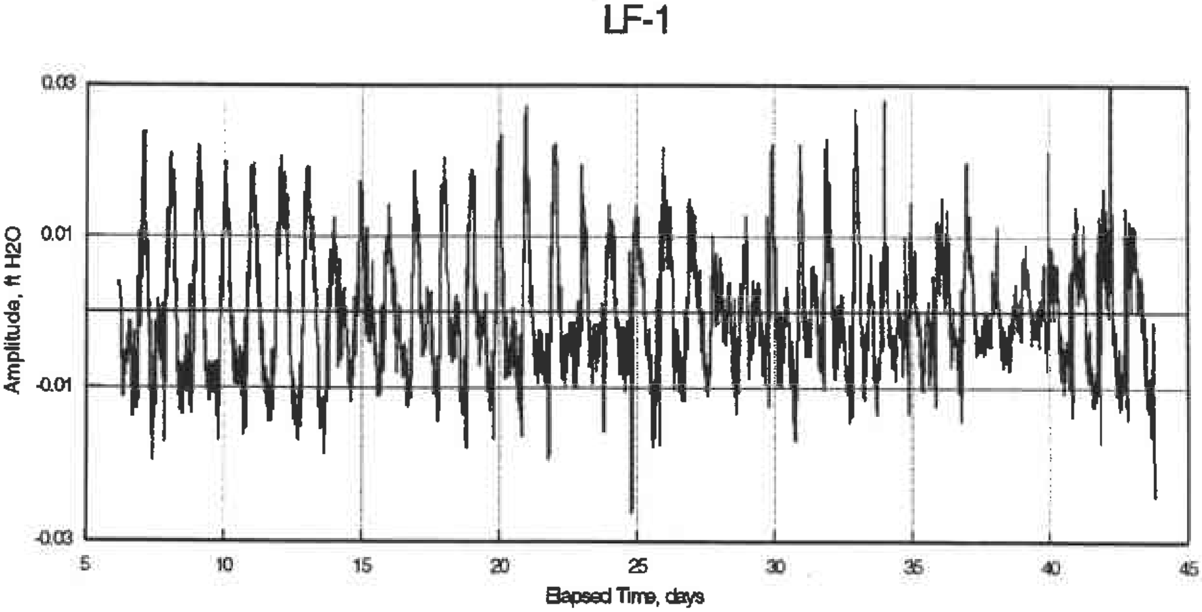

Figure 25. After removing the atmospheric pressure effects from the LF-1 response, a zero phase shift, high-pass filter of Pertsev is applied to the raw tidal response, yielding the true tidal response in LF-1. The water level fluctuation in LF-1 is ±0.03 ft or 1.5% of the storm channel amplitude.

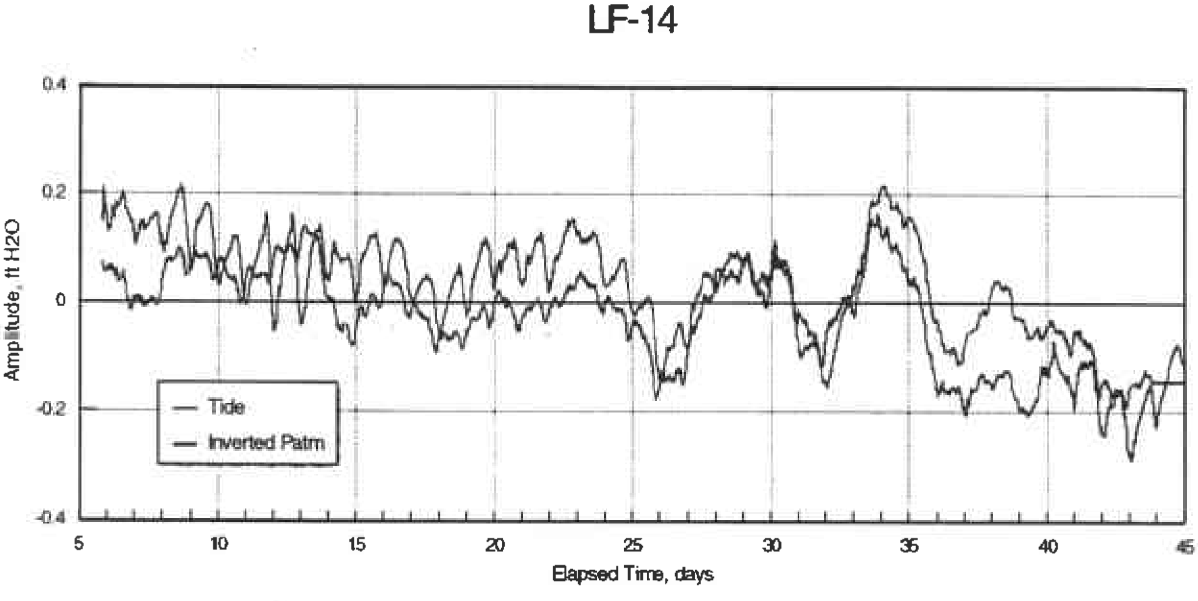

Figure 26. A plot of raw tidal response in LF-14 (blue curve) and the inverted barometric pressure (red curve) adjusted by barometric efficiency coefficient, here 0.6. Both curves have their means subtracted.

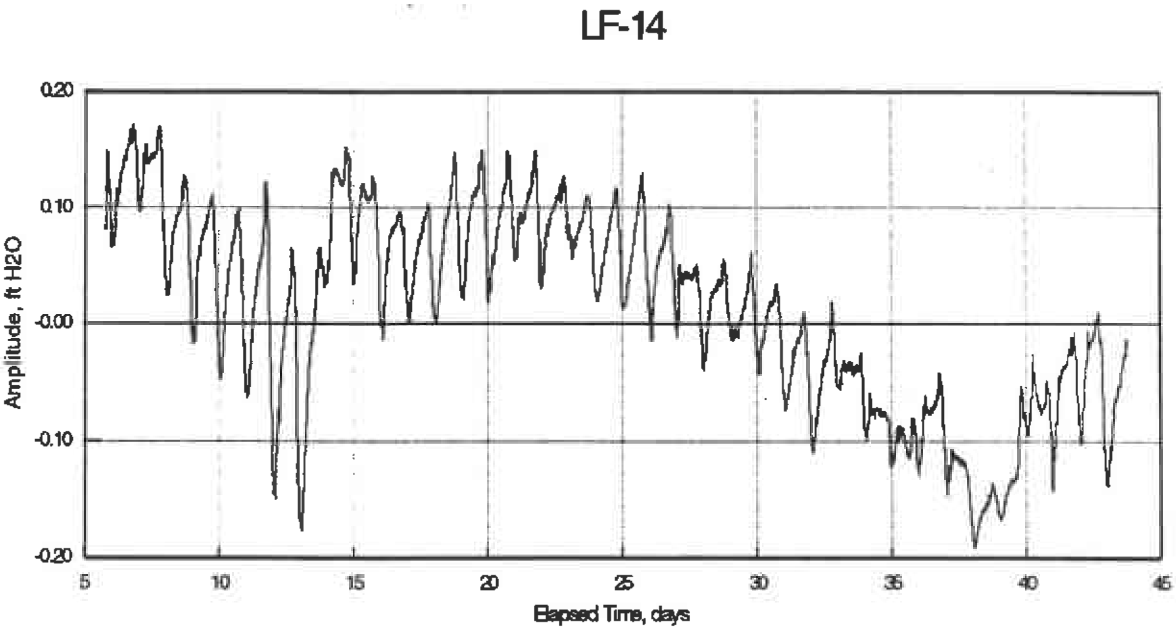

Figure 27. The raw tidal response in LF-14 with the atmospheric pressure effects removed. This tidal response is subject to slow fluctuations which are removed by applying a high-pass filter.

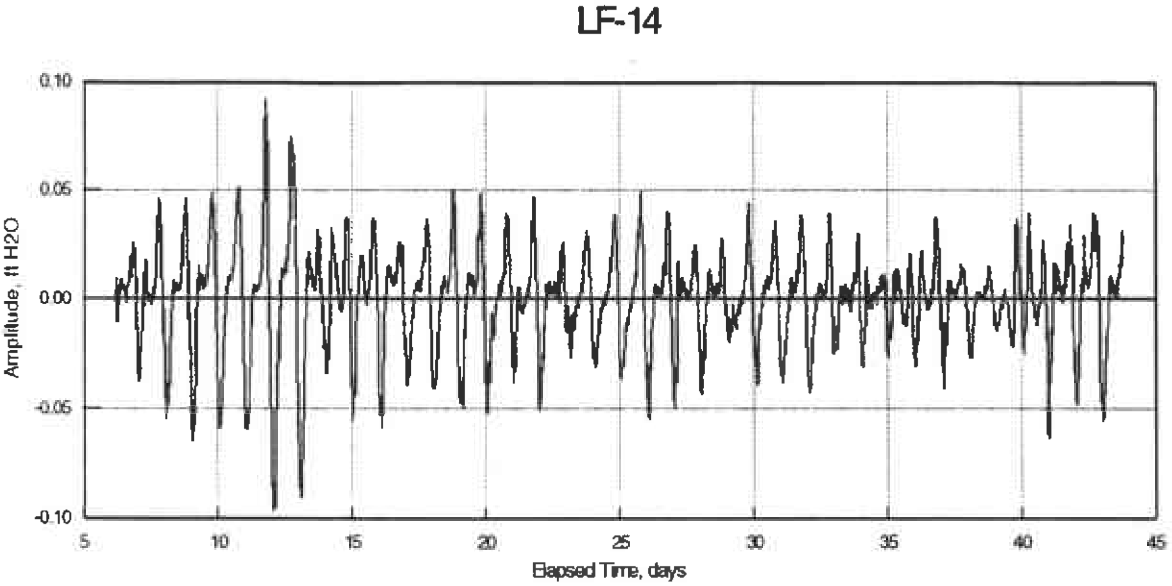

Figure 28. After removing the atmospheric pressure effects from the LF-14 response, a zero phase shift, high-pass filter of Pertsev is applied to the raw tidal response, yielding the true tidal response in LF-1. The water level fluctuation in LF-1 is roughly ±0.05 ft or 2.5% of the storm channel amplitude.

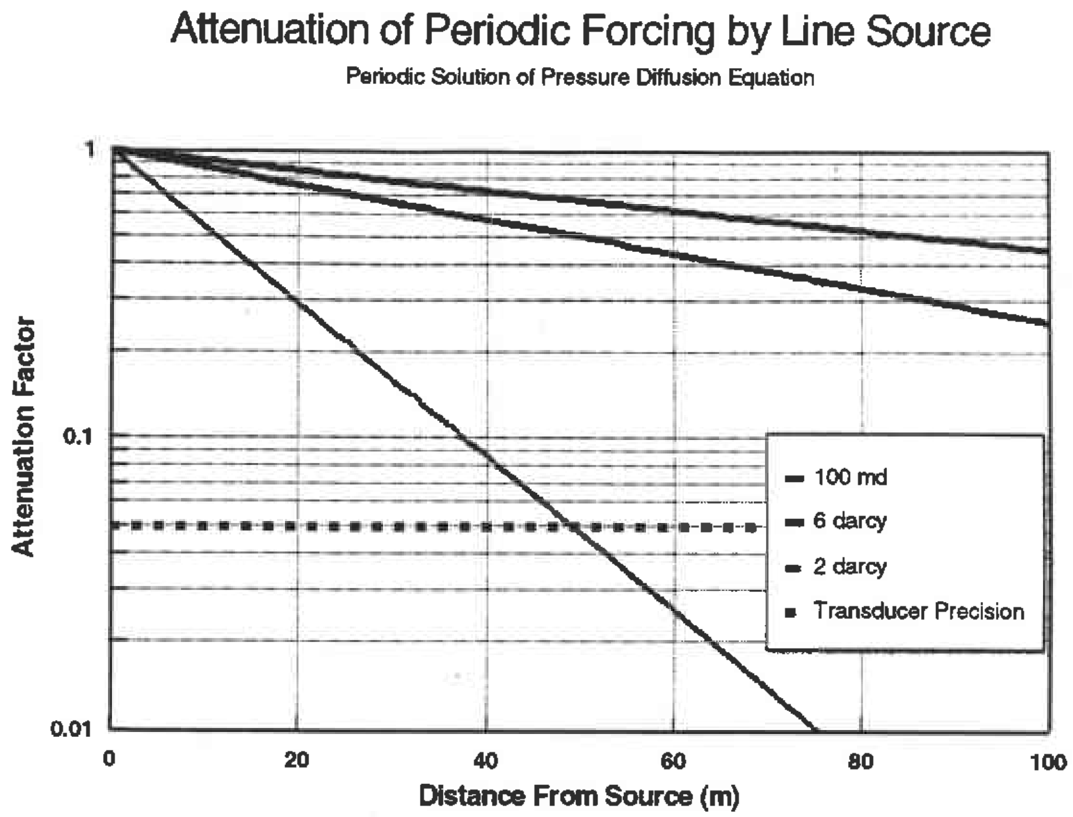

Figure 29. The attenuation of water amplitude in the storm channel (the source of fluctuations) as a function of distance in soil and average soil permeability. The intrinsic soil permeability of 100 millidarcy corresponds to the hydraulic conductivity of 0.0001 cm/s: 2 darcy = 0.002 cm/s; and 6 darcy = 0.006 cm/s. Well sorted sands and gravels have hydraulic conductivities of 0.001-1 cm/s. For example, over a distance of 100 m (330 ft) from the source, 0.45 of the forcing amplitude would be observed in a gravel with average hydraulic conductivity of 0.006 cm/s. This is unlikely, unless the storm channel is next to, or above, an old creek bed, or there is a coarse fill surrounding the channel.

Table 1. Parameters used to generate Figure 29

Porosity, fraction	0.35
Compressibility 1/(dyne/cm²)	1.450E-09
Compressibility 1/(psi)	1.000E-04
Ref. Permeability, cm²	9.896E-09
Ref. Permeability, darcy	1.00
Tide period, hours	12.00
Tide angular velocity, rad/s	1.454E-04
Hydraulic diffusivity, cm²/s	1949

Hydraulic diffusivity, m²/day	16843
Water viscosity μ, poise	0.01

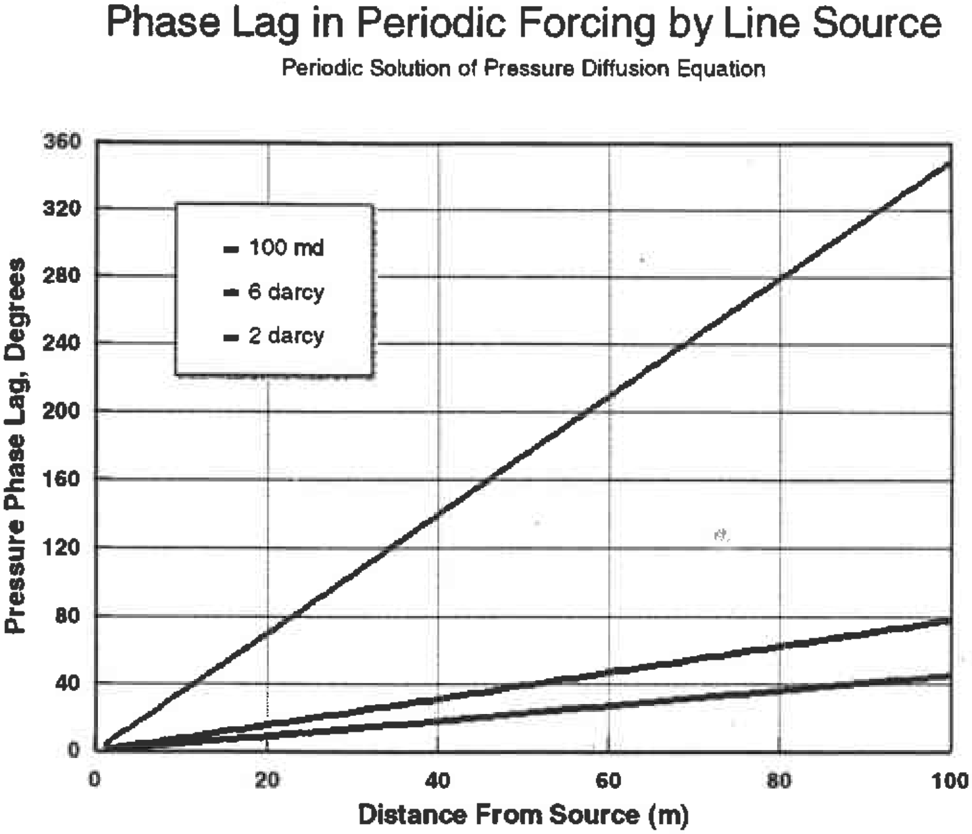

Figure 30. A delay ("phase lag") between tidal response in a well and surface water fluctuations in the storm channel ("line source"). In a 100 millidarcy sand (K=0.0001 cm/s) the phase lag is 40 degrees over a distance of 40 ft or 13 meters. Hence, if the amplitude of water in the channel is +2ft, the water amplitude in the well is $0.8\times\cos(40^0)=+0.61$. The average hydraulic gradient due to tides is (2-0.61)/40=0.03 ft/ft. This gradient is, however, directed perpendicularly away from the channel, i.e. NE and SW over a 6-hour period. In reality, sea water, oscillating in-and-out of a weep hole, flows only centimeters into the fill near the channel walls.

APPENDIX A: Measurement of Shallow Coastal Aquifer Permeability From Ocean Tides

1. Transient Linear Flow in a Confined Aquifer

An idealized shallow aquifer-ocean system at the 5050 Coliseum Way site, "Volvo Site," is shown in **Figure A1.** The shallow system depicted in Figure A1 is <u>**different**</u> than the confined, deep inland aquifers modeled by, e.g., Hsieh*et al.*, 1987, and many others.

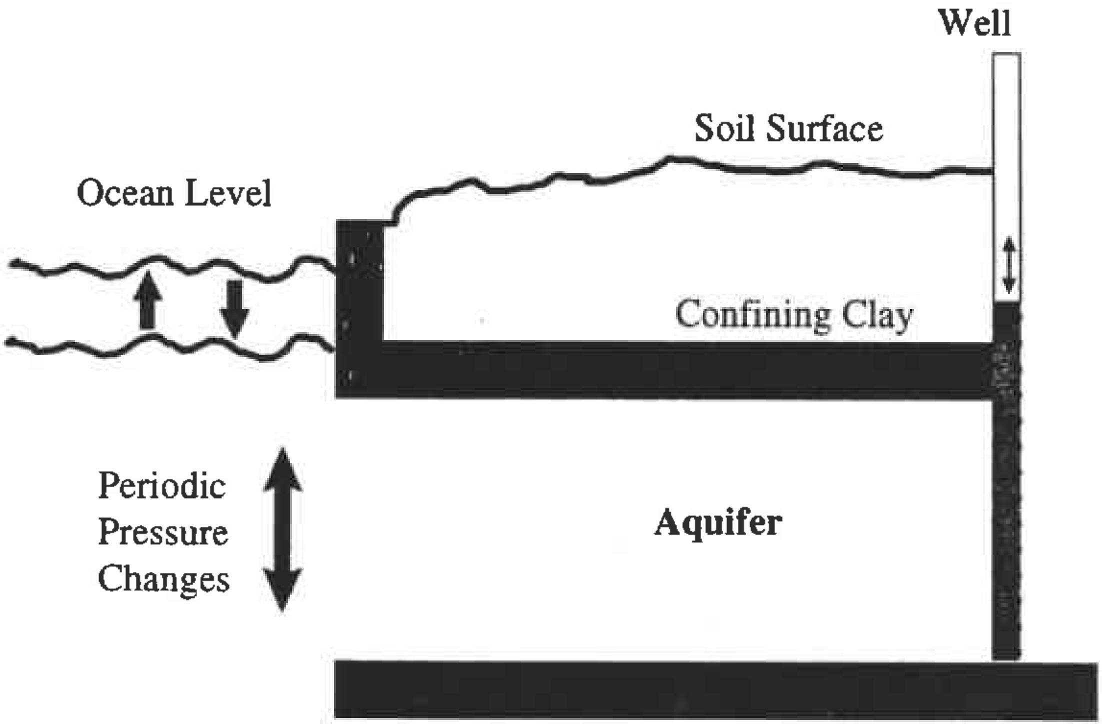

Figure A-1. Shallow aquifer open to the ocean.

I will assume, for the time being, that the shallow aquifer is confined and its width is very large compared to its thickness. As the average level of ocean water oscillates due to tides, the aquifer is subjected to periodic pressure changes along its ocean side. In other words, the water pressure in the aquifer is driven by the periodically changing hydrostatic pressure of the ocean water. This picture should be contrasted with periodic changes in deep aquifer pressure caused by elastic seismic waves ("Earth tides"), which in turn are generated by the oscillating overburden weight. In this latter case, water flows between a uniformly compressing and dilating pore space of the aquifer rock and a wellbore. There is a small and negative phase lag between the highest level of water in the wellbore and the highest level of pore pressure.

In the case of ocean tides in contact with a shallow aquifer, there is a planar pressure wave diffusing inland with an increasing phase lag between the ocean water level and the levels of water in observation wells. Locally, there is no phase lag between the aquifer pressure and water level.

If the aquifer is unconfined, then its analysis is considerably more complicated and, probably, must be done numerically.

1.1. Model

The simplest model of periodic water level changes caused by ocean tides is one of transient one-dimensional water flow caused by a periodic line source at the boundary:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{\eta}\frac{\partial p}{\partial t}; \quad \eta = \frac{k}{\varphi \mu c} \tag{1.1.1}$$

where x is the direction of water flow, perpendicular to the coastline; p is water pressure at a fixed depth; and η is the hydraulic diffusivity, i.e., the ratio of formation permeability, k, to its porosity, φ, water viscosity, μ, and the total soil compressibility, c.

The initial condition is that of uniform water pressure,

$$p(x > 0, t = 0) = p_i, \tag{1.1.2}$$

and the boundary conditions are

$$\begin{aligned} p(x = 0, t) &= p_{\max}\cos(\omega t) \\ p(x \to \infty, t) &= p_i \end{aligned} \tag{1.1.3}$$

where

$$\omega = \frac{2\pi}{T} = 2\pi f \tag{1.1.4}$$

is the angular velocity of tides, T is the tidal period and f the tidal frequency.

The steady-state periodic solution of Eq. (1.1.1) with the initial condition (1.1.2) and boundary conditions (1.1.3) was given by Carslaw and Jaeger (1959) as

$$p(x,t) = p_{\max} e^{-\kappa x}\cos(\omega t - \kappa x); \qquad \kappa = \sqrt{\tfrac{\omega}{2\eta}} \tag{1.1.5}$$

Equation (1.1.5) represents a pressure wave of wave number κ and wavelength

$$\lambda = \frac{2\pi}{\kappa} = \sqrt{\frac{4\pi\eta}{f}} \tag{1.1.6}$$

The important properties of the steady-state periodic pressure are the following:

(i) The amplitude of the oscillation is attenuated as

$$e^{-\kappa x} = e^{-x\sqrt{\omega/2\eta}} \tag{1.1.7}$$

and thus falls off more rapidly for higher forcing frequencies.

(ii) There is a progressive lag

$$\kappa x = x\sqrt{\frac{\omega}{2\eta}} = x\sqrt{\frac{\omega\varphi\mu c}{2k}} \tag{1.1.8}$$

in the phase of the pressure wave. This lag increases with the forcing frequency and with the diminishing formation permeability.

(iii) The pressure fluctuations, e.g., the positions of the maxima and minima of pressure, are propagated into the soil with velocity

$$v = \sqrt{2\omega\eta} \tag{1.1.9}$$

1.2. Cumulative Influx During 1/2 of Tide Period

The Darcy velocity of water at plane x=0 of the confined aquifer is

$$u = -\frac{k}{\mu}\frac{\partial p(x,t)}{\partial x}\bigg|_{x=0} = -\frac{k\kappa p_{\max}}{\mu}\left(\sin(\omega t) - \cos(\omega t)\right) \tag{1.2.1}$$

The average inflow/outflow Darcy velocity is

$$u_{T/2} = \frac{\omega}{\pi}\int_{0}^{\pi/\omega} u(0,t)\,dt = \frac{2k\kappa p_{\max}}{\pi\mu} \tag{1.2.2}$$

Since the maximum pressure is forced by the maximum hydrostatic pressure at plane x=0, then we can assume that

$$p_{\max} = \rho_w g h_{\max} \tag{1.2.3}$$

where $h_{\max}$ is the tide amplitude.

Substituting Eqs (1.2.3) and (1.1.5) into Eq. (1.2.2) yields

$$u_{T/2} = \frac{2\rho_w g h_{\max}}{\pi}\sqrt{\frac{\omega\varphi c k}{\mu}} \tag{1.2.4}$$

The average mass flux of water is then

$$\dot{m}_w = u_{T/2}\rho_w \tag{1.2.5}$$

2. Sampling Frequency

Water fluctuations with periods between 26 and 8 hours, or with 0.9 - 3 cycle/day frequencies, have been observed in wells penetrating confined aquifers (e.g., Hildebrand, 1995), see Table A.1.

Table A1. Important tidal constituents and their periods

Tidal Constituent	Period, hrs	Frequency, 1/day
Q1	26.8684	0.8932
O1	25.8193	0.9295
S1	24.0000	1.0000
K1	23.9345	1.0027
J1	23.0985	1.0390
OO1	22.3061	1.0759
MU2	12.8718	1.8645
N2	12.6583	1.8960
M2	12.4206	1.9323
L2	12.1916	1.9686
S2	12.0000	2.0000
K2	11.9600	2.0067
M3	8.2804	2.8984
S3	8.0000	3.0000

Only two frequencies - near 2 and 1 cycle/day - are low enough, see Eg. (1.1.7), and have enough power to be useful for measuring the aquifer soil permeability. For shallow aquifers (5-20 ft of depth), the atmospheric pressure changes may be more significant, as they represent a higher fraction of the overburden pressure and the hydrostatic pressure of ocean water, than in deep aquifers. These latter changes occur at frequencies lower than 0.5 cycle per day. Locally, there may be other, lower, frequencies because of water flow restrictions in the San Francisco Bay.

In a classical Earth tide analysis (Hsieh *et al.*, 1987), two sets of data are needed to determine the phase shift: (1) water level fluctuations in the wells and (2) pressure disturbance in the aquifer. The first set of data is acquired by use of pressure transducers immersed in open wells. The second set of data is acquired by measuring the water pressure in a packed-off interval. In a shallow coastal aquifer, the phase shift is between the level of ocean water and the wellbore water levels. Hence, the second data set must be acquired at a reference point in the ocean.

2.1. Required Resolution

With the elapsed time of measurement $T = 30$ days and the data acquisition frequency of every **30 minutes**, the sampling time interval is

$$\Delta = \frac{T}{N-1} \approx \frac{1}{48} \text{ day}, \qquad (2.1.1)$$

where N is the number of points in the time series.

The Nyquist frequency is

$$f_c = \frac{1}{2\Delta} = 24 \quad 1/\text{day} \qquad (2.1.2)$$

Hence the Nyquist frequency is still 8 times higher than the highest tidal frequency.

2.2. Miscellaneous Requirements

- To acquire 2048 data points for the fast Fourier analysis, it will take about 42 days.
- The ocean water pressure must be monitored separately to determine phase lag.
- All pressure transducers must be calibrated side-by-side at the site before placement in the observation wells.
- Transducer drift should be estimated.
- A separate transducer should record changes in atmospheric pressure to unbias the water level data.

4. References

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