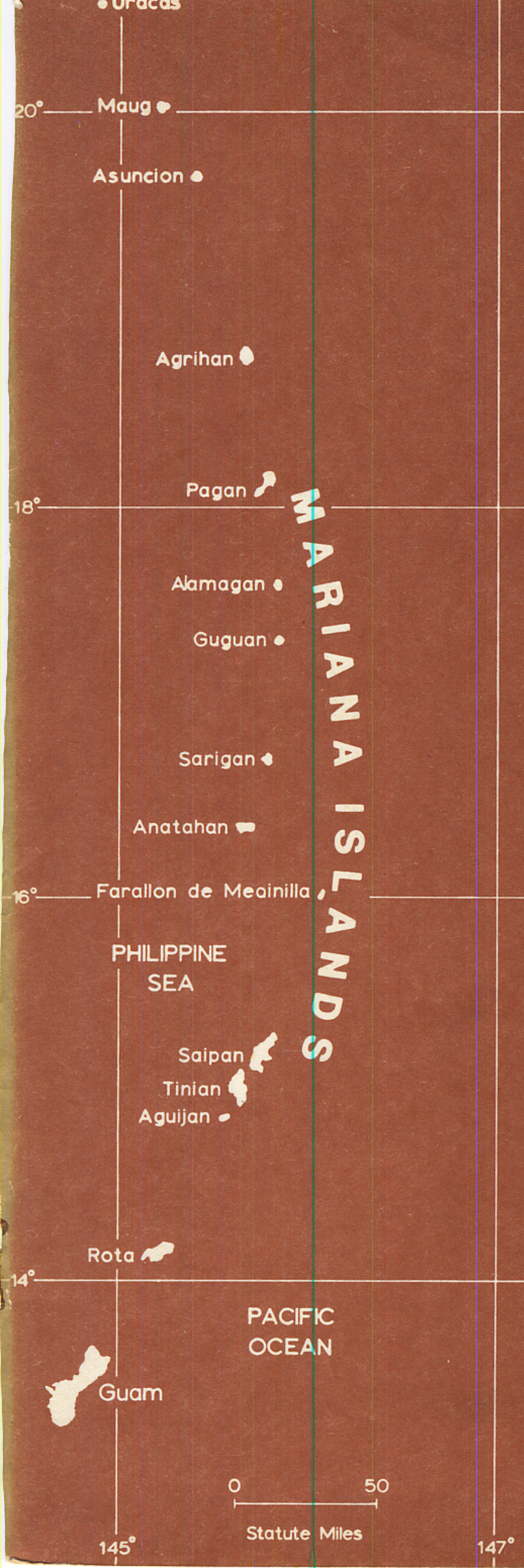

WELL WATER QUALITY ON MOEN ISLAND, TRUK

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Water Resources Research Center

UNIVERSITY OF GUAM

Technical Report No. 13

September 1980

DEPARTMENT OF THE INTERIOR · OFFICE OF WATER RESEARCH AND TECHNOLOGY

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INTRODUCTION

Truk Atoll, in the Eastern Caroline Islands, is comprised of 19 high volcanic islands and numerous small coral islands scattered over a large lagoon. A study of the quality of well water was conducted on Moen Island located in the eastern part of Truk lagoon. Moen, the second largest of the volcanic islands, is roughly triangular in shape and 11.7 square kilometers (km^2) in area (Fig. 1). The island is characterized by steep stream-dissected slopes and mountain peaks up to 370 m in elevation (Mount Teroken). The volcanic rocks are basalt, andesite and volcanic breccia (Davis, 1977). Low coastal terraces of variable width border the steep volcanic slopes. These terraces are composed of eroded alluvial deposits, calcareous beach and lagoon material and freshwater marsh deposits (Davis, 1977) (Fig. 1). Most of the commercial and residential development is associated with the coastal terraces. Lagoon fringing reefs border the shorelines at most places around the island with the most extensive development along the northern shorelines.

Moen's groundwater resources are found in deeply weathered zones in the volcanic rock (Valenciano and Takasaki, 1959). The primary area of groundwater development has been in the saddle between Tanaachau and Mount Teroken (Nepukos, Iras and Mechitiu villages). Twenty-two production wells have been constructed with 14 currently in service. Wells typically pump at rates ranging from 40-314 liters/minute (ℓpm). The chloride concentrations of the pumped water at the time of initial testing was generally low, ranging from 14 to 120 mg/ℓ. Subsequent pumping does not appear to have noticeably increased these chloride concentrations (Austin, Tsutsumi and Associates, Inc., 1980).

The quality of the groundwater resource in terms of chemical, physical and bacteriological constituents has not been extensively investigated. Valenciano and Takasaki (1959) recorded low levels of hardness, chloride and total dissolved residue in surface waters. The University of Hawaii in 1977 sampled five points in the distribution system for pH, temperature, turbidity, specific conductance, chlorides, nitrate-nitrogen, color, fluoride, hardness and total coliform bacteria (Austin, Tsutsumi and Associates, Inc., 1980). The Moen Department of Environmental Health has conducted periodic total bacteria, chloride and hardness analyses of pumped well water. A review of the available information dealing with the physical and chemical characteristics of the production wells is presented in a water resources development plan by Austin, Tsutsumi and Associates, Inc. (1980).

The development of a groundwater resource can be better achieved if the basic water quality of the resource is known. A study by the Water Resources Research Center (UOG) was begun in May 1979 to ascertain

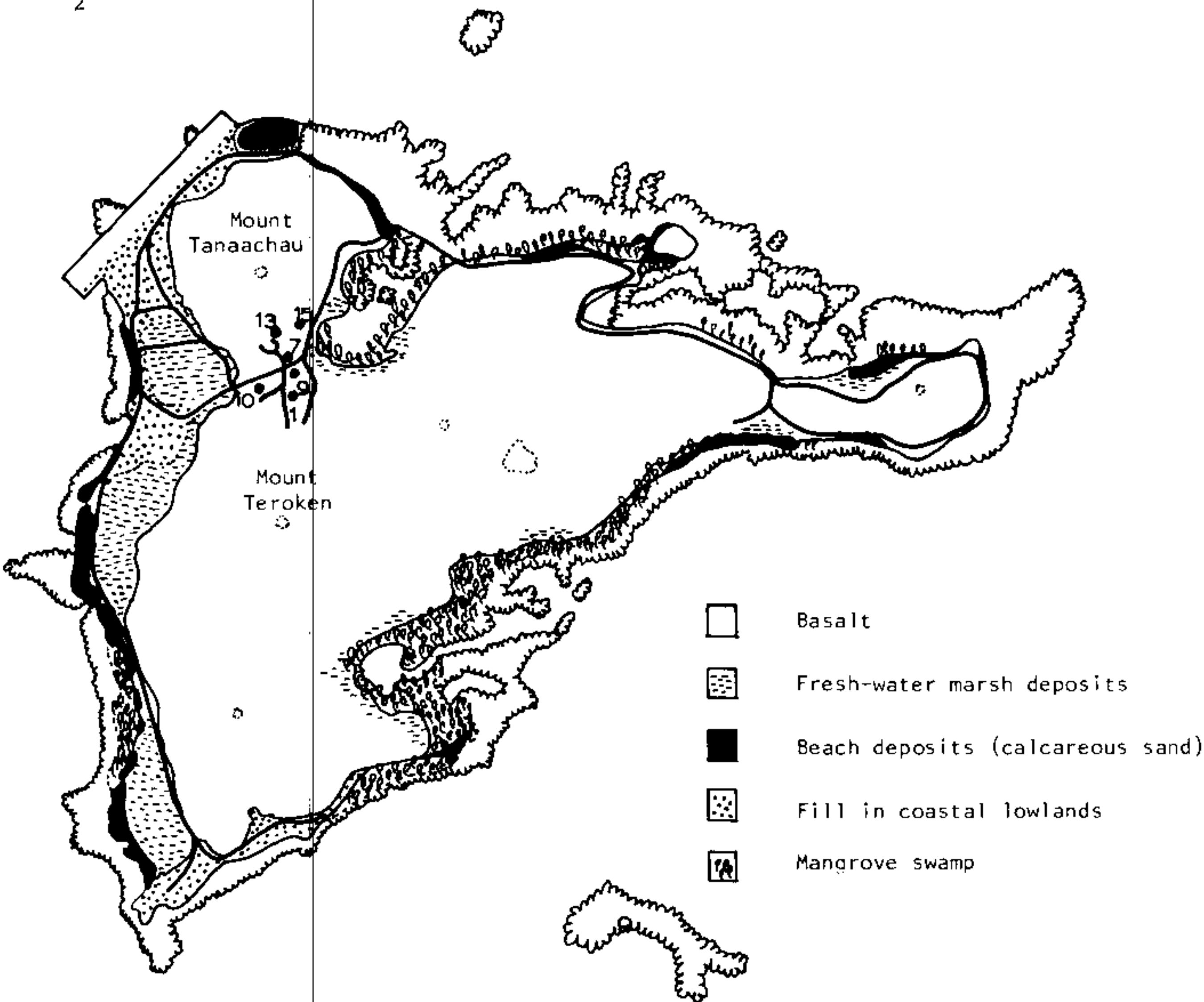

Figure 1. Moen Island with water well locations. The figure was adapted from Valenciano and Takasaki (1959).

the basic water quality of selected production wells connected to the distribution system. Six production wells were monitored on a monthly basis for a period of one year. Basic physical, chemical and bacteriological water quality parameters were measured for the pumped well water.

METHODS

Well Selection Criteria

All of the wells used in the study were connected to the distribution system. The selected wells ranged in test performance, relative to the local hydrological conditions, from poor to good with pumping rates varying between 95 to 303 ℓpm. Elevations of well bottoms ranged from 13 to 25 m below sea level. Wells 1, 5, 7, 9, 10, and 13 were selected for study (Fig. 1). Well 5 went off line after one month of analyses and was replaced by Well 15 (located below the girls' dormitory, Truk High School). Well 9 was selected primarily because it was showing signs of incrustation and corrosion. The well had a long history of severe corrosion problems (Mr. D. G. English, personal communication). See Table 1 for the physical characteristics of the monitored wells.

Physical and Chemical Analyses

The monthly water quality parameters measured were nitrate-nitrogen, nitrite-nitrogen, reactive phosphorus, chlorides, alkalinity, pH, turbidity (NTU), conductance, temperature, total residue, total non-filtrable residue, total soluble residue and carbon dioxide. Additional parameters analyzed on a less regular basis were total Kjeldahl nitrogen, total phosphorus, sulfate, and total and fecal coliform bacteria. Ammonia-nitrogen and reactive silicate were measured only one time.

The physical, chemical and bacteriological parameters were analyzed in accordance with *Standard Methods for the Examination of Water and Wastewater* (1975). Techniques presented in *A Practical Handbook for Seawater Analysis* (Strickland and Parson, 1971) were used to determine orthophosphate phoshorus, nitrate-nitrite nitrogen and reactive silicate. The indophenol technique (Solorzano, 1969) was used to determine ammonia nitrogen. Table 2 presents the methods of analysis used for each parameter.

Water samples were collected at the well head after a minimum one minute flushing period. The temperature of the running water was determined by mercury thermometer (20-50°C) and specific conductance by

Table 1. Physical characteristics of monitored wells. The information was adapted from Austin, Tsutsumi and Associates (1977), Austin, Tsutsumi and Associates (1980) and Davis (1977).

WELL NO.	YEAR COMPLETED	ALTITUDE (m)	ELEVATION BELOW SEA LEVEL (-m)	TOTAL WELL DEPTH (m)	INITIAL PUMPING RATE ℓpm (gpm)	PUMPING RATE 1979-1980 ℓpm (gpm) (N, $\bar{x}\pm$s.d.)	WELL PERFORMANCE ℓpm @ N/cm² (gpm @ psi)	SPECIFIC CAPACITY (ℓpm/m)
1	1970	23	16	39	303 (80)	11,219±57 (58±15)	170 @ 38 (45 @ 53)	11
5*	1970	15	16	31	76 (20)	1,246 (65)	--	--
7	1970	9	23	31	303 (80)	10,185±60 (49±16)	208 @ 59 (55 @ 83)	4
9	1971	9	25	25	110 (29)	10,110±49 (29±13)	114 @ 51 (30 @ 72)	<4
10	1976	4	14	18	189 (50)	12,204±19 (54±5)	167 @ 73 (44 @102)	4
13	1976	12	13	25	227 (60)	11,238±57 (63±15)	204 @ 63 (54 @ 88)	8
15	1976	5	16	21	140 (37)	8,148±91 (39±24)	114 @ 61 (30 @ 86)	4

*Pump burned out July 2, 1979.

Table 2. Physical, chemical and bacteriological parameters and methods used in analyses. All Standard Methods of analyses were performed according to the 14th edition (1975).

PARAMETER	METHOD	REFERENCE
Physical		
Temperature	20-50°C Mercury Thermometer	Standard Methods
Turbidity	Nephelometer (NTU)	Standard Methods
pH	Specific Ion Meter/Combination Electrode	Standard Methods
Total Residue	Total Residue Dried at 103-105°C	Standard Methods
Total Filtrable Residue	Glass fiber filter at 103-105°C	Standard Methods
Specific Conductance	Wheatstone bridge	Lectro-Mho Meter
Chemical		
Chloride	Specific Ion Meter/Chloride Electrode	Orion
Total Alkalinity		
Free Carbon Dioxide	Nomographic Calculation	Standard Methods
Sulfate	Turbidometric	Standard Methods
Reactive Silicate	Molyodosilicate	Strickland & Parson, 1971
Total Phosphorus	Persulfate Digestion/Ascorbic Acid Reduction	Standard Methods
Ortho-phosphate Phosphorus	Ascorbic Acid Reduction	Strickland & Parson, 1971
Nitrate-Nitrite Nitrogen	Cadmium Reduction	Strickland & Parson, 1971
Ammonia Nitrogen	Indophenol	Solorzano, 1969
Total Kjeldahl Nitrogen	Digestion/Distillation/Nesslerization	Standard Methods
Bacteriological		
Total and Fecal Coliform Bacteria	Membrane Filtration	Standard Methods

electrical probe (Wheatstone bridge). Coliform bacteria samples were collected in sterilized wide mouth bottles. Water samples for coliform bacteria, turbidity, pH, chlorides and alkalinity were taken within one hour of collection to the Moen Department of Environmental Health for analyses. Samples for the determination of phosphorus and nitrogen components were collected in precleaned bottles, frozen at the refrigeration plant and shipped to the Water Resources Research Center laboratory for analyses. The orthophosphate-phosphorus, nitrate-nitrite and ammonia nitrogen samples were filtered through a .45 μm millipore filter prior to freezing. Samples for residue, sulfate and silicate were not frozen for shipment.

The 24-hour precipitation levels (Fig. 2) were obtained from the National Oceanic and Atmospheric Administration weather station on Moen Island.

RESULTS

The mean physical water quality parameter measurements (pH, temperature, turbidity, specific conductance, total residue, total filtrable residue and total non-filtrable residue) are presented in Table 3. The mean chemical water quality parameter measurements (chloride, total alkalinity, free carbon dioxide, nitrogen, phosphorus, sulfate and reactive silicate) are presented in Table 4. Arithmetic and geometric means for total and fecal coliform bacteria are presented in Table 5. Monthly data sets for Wells 1, 7, 9, 10, 13 and 15 are presented in Tables 6 to 11, respectively.

The territorial safe drinking water standard (Territorial Register, 1978) for turbidity is established at 1 NTU. The mean turbidity levels of Wells 7, 9, 13 and 15 were in violation of this standard. Wells 1 and 10 each had a single violation (Fig. 3). Mean turbidity of the well water ranged from 0.52 (Well 1) to 31 NTU (Well 15). Wells 7 and 15 consistently had the highest turbidity levels with Well 15 having a recorded high of 160 NTU (Fig. 3). Frequently the higher turbidity levels were associated with slight to highly colored (white to red/brown) water. Occassionally rust-like fragments were present in the higher turbidity samples (e.g., the 160 NTU, Well 15 sample).

Mean total residue ranged from 145 mg/ℓ (Well 10) to 695 mg/ℓ (Well 9). Mean total residue levels were similar for Wells 1, 10, 13 and 15. Generally all the well water had higher total residue (TR) levels around July and November 1979 and January 1980. Well 9 had an additional peak residue level in April 1980. These trends were also reflected in the total filtrable residue (TFR) levels of the well waters (Figs. 4-9). Total non-filtrable residue (TNFR) levels were similar, although

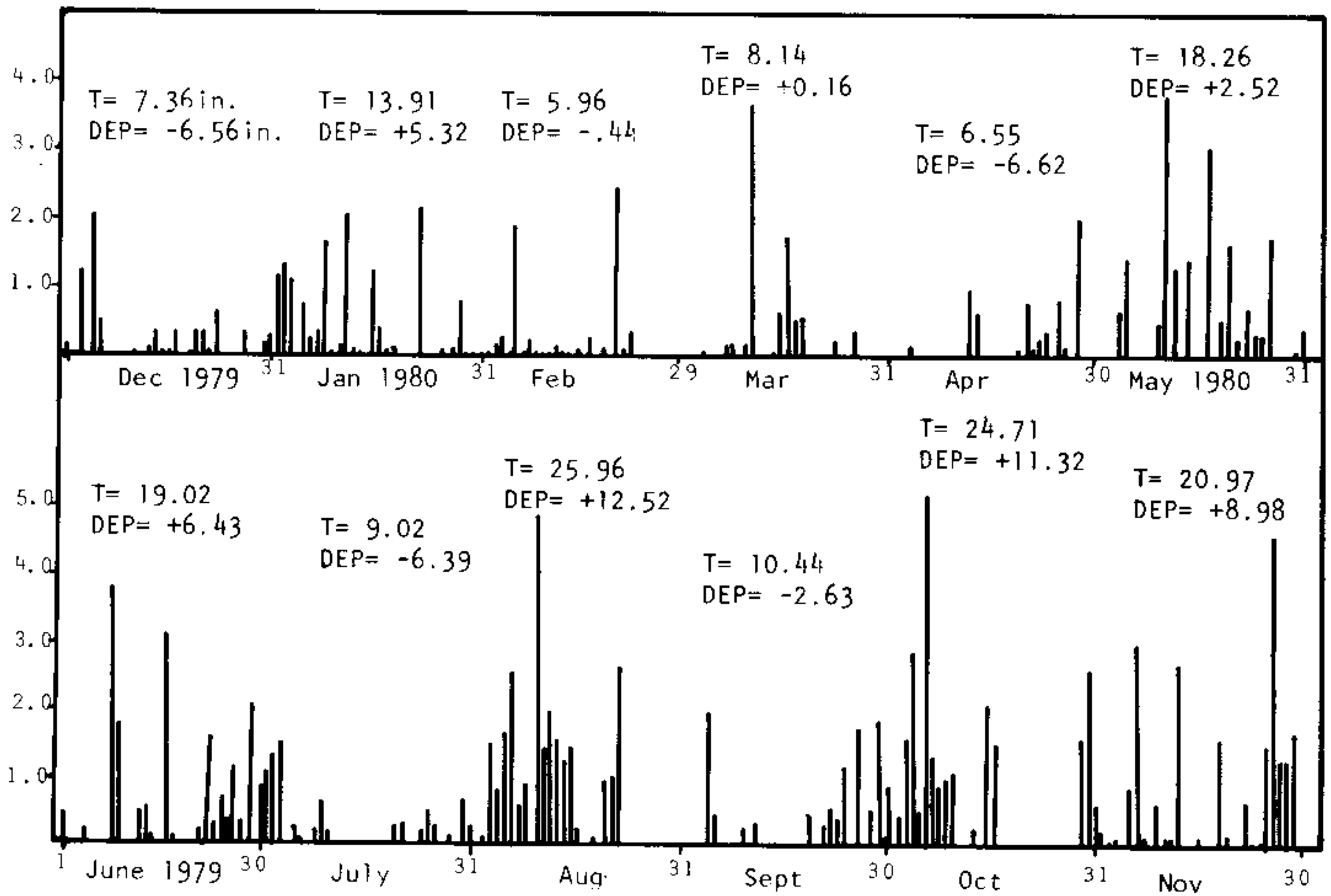

Figure 2. 24-hour rainfall levels, total monthly rainfall and departure from grand means.

Table 3. Physical water quality parameters. The number of samples, mean and standard deviation are presented for the monitored wells. Safe drinking water standards are from the Trust Territory of the Pacific Islands Territorial Register (1978).

	WELL 1 (N,x̄±s.d.)	WELL 7 (N,x̄±s.d.)	WELL 9 (N,x̄±s.d.)	WELL 10 (N,x̄±s.d.)	WELL 13 (N,x̄±s.d.)	WELL 15 (N,x̄±s.d.)	WELL 5 6/79	STORAGE TANK 8/79	SAUPUK SPRING WATER 2/79	SAFE DRINKING WATER STANDARDS
pH	11,6.39±.29	11,6.54±.32	12,6.44±.43	12,6.52±.31	11,6.39±.33	10,6.21±.21	7.00	6.70	6.10	None
Temp (°C)	11,27.5±.6	10,27.7±.9	12,28.0±.7	12,27.6±.5	11,27.7±.23	10,27.9±.8	28.8	25.4	26.6	None
Turbidity (NTU)	11,0.52±.24	12,19±31	13,12.6±10	13,.89±.59	12,2.4±4.9	11,31±50	0.81	14	2.6	1
Specific Conductance (μmho/cm)	10,195±110	9,374±95	10,1400±534	10,200±72	10,256±60	8,279±127	400	70	100	None
Total Residue (mg/ℓ)	9,153±131	10,237±119	10,695±202	12,145±108	10,152±81	9,224±151	318	80	65	None
TNFR (mg/ℓ)	11,14.5±18.7	11,21±30	12,70.2±122	12.11.9±18	11,4.7±3.6	10,29.0±30	3.4	5.3	24	-
Total Filterable Residue (mg/ℓ)	9,142±121	10,215±121	10,617±211	12,133±100	10,147±80	9,192±143	315	75	41	--

Table 4. Chemical water quality parameters. The number of samples, mean and standard deviation are presented for the monitored wells. Safe drinking water standards are from the Trust Territory of the Pacific Islands Territorial Register (1978).

	WELL 1 (N,x±s.d.)	WELL 7 (N,x±s.d.)	WELL 9 (N,x±s.d.)	WELL 10 (N,x±s.d.)	WELL 13 (N,x±s.d.)	WELL 15 (N,x±s.d.)	WELL 5 6/79	STORAGE TANK 8/79	SAUPUK SPRING WATER 2/79	SAFE DRINKING WATER STANDARDS
Chloride (mg/ℓ)	10,12.4±4.9	10,30.5±8.7	11,260±151	11,25.5±24	11,16.9±5.4	9,21.0±15.3	48.5	12.5	11.2	400
Total Alkalinity (mg/ℓ)	11,116±43	11,230±95	12,189±85	12,117±48	11,129±51	10,124±41	172	26	24	--
Free CO_2 (mg/ℓ)	9,108±115	10,145±154	10,115±106	12,71±56	10,123±98	9,135±80	28	11	28	None
Nitrite-Nitrate Nitrogen (mg/ℓ)	11,2.51±5.0	11,.52±.46	11,.66±.27	12, .35±.24	11,1.01±.61	10,.60±.46	.27	.03	.11	10
TXN (mg/ℓ)	3,.38±.38	3,.35±.29	3,.37±.35	3,.25±.23	3,.16±.13	2, .43	.20	--	--	--
Ammonia-Nitrogen (mg/ℓ)	1, .01	1, .01	1, .02	1, .01	1, .02	1, .01	--	--	--	--
Orthophosphate Phosphorus (mg/ℓ)	11,.12±.02	10,.06±.03	11,.07±.06	11,.05±.01	10,.09±.05	9,.07±.06	.07	.01	.07	None
Total Phosphorus (mg/ℓ)	5,.13±.01	5,.12±.09	5,.11±.07	5,.07±.01	5,.09±.04	4,.07±.05	.08	--	--	None
Sulfate (mg/ℓ)	2,<1.0	2,5.1	2,30.8	1, 3.1	2, 6.5	2, 6.7	--	1.0	--	250
Reactive Silicate (mg/ℓ)	1, 8.75	1, 9.60	1, 8.65	1, 11.8	1, 9.85	1, 8.60	--	--	--	None

Table 5. Bacteriological water quality. The number of samples, mean, standard deviation and geometric mean are presented for monitored wells. Safe drinking water standards are from the Trust Territory of the Pacific Islands Territorial Register (1978).

	WELL 1	WELL 7	WELL 9	WELL 10	WELL 13	WELL 15	SAFE DRINKING WATER STANDARDS
Total Coliform							
$(N,\bar{x}$, s.d.)	5,9±7	5,5±5	5,1003±2234	5,3±3	4,10±8	4,30±60	4/100 mℓ for a single sample
Geometric mean	7	4	11	3	7	3	
Fecal Coliform							
$(N,\bar{x}$,s.d.)	5,24±43	5,4±2	5,23±39	5, 1±1	4, 1±1	4,50±87	0/100 mℓ
Geometric mean	7	4	6	1	1	8	

Table 6. Well 1 physical, chemical and bacteriological data.

Date	6/79	7/79	8/79	9/79	10/79	11/79	12/79	1/80	2/80	4/80	5/80
pH	6.48	6.40	6.69	6.63	5.80	6.59	6.25	6.50	6.00	6.71	6.25
Temp. °C	28.4	27.5	27.7	28.4	26.9	26.7	27.3	27.6	27.4	26.7	27.7
Turbidity (NTU)	1.0	0.32	0.82	0.40	0.5	0.4	0.70	0.43	0.32	0.59	0.20
Specific Conductance (μmhos)	155	160	150	190	175	---	100	500	180	160	185
Total Alkalinity (mg/l)	99	114	100	106	221	145	120	144	80	75	72
Chloride (mg/l)	11.8	11.8	10.4	12.4	12.4	---	7.1	20.6	7.3	8.9	21.3
Sulfate (mg/l)			<1.0								<.01
Total Residue (mg/l)		222	22	60	84	398	72	324	92	108	---
Total Non-filtrable Residue (mg/l)	14.4	2.3	2.4	20.0	3.2	55	10.4	3.8	1.3	2.1	45.1
Total Filtrable Residue (mg/l)		220	20	40	81	343	62	320	91	106	---
Total Nitrogen (TKN) (mg/l)	0.24			0.10							0.82
Nitrate Nitrogen (mg/l)	17.5	2.30	0.89	0.63	0.75	0.71	0.66	0.74	1.09	1.12	1.24
Total Phosphorus (mg/l)	0.12			0.12			0.13	0.14			0.14
Ortho-Phosphate (mg/l)	0.11	0.10	0.10	0.11	0.14	0.15	0.13	0.14	0.12	0.13	0.13
Total Coliform (col./100 ml)	8			10		20				0	6
Fecal Coliform (col./100 ml)	8			100		4				0	6
Nitrite Nitrogen (mg/l)	<.001	.003	.001	0	.000	<.001	<.001	---	---	---	.001
Pumping Rate (GPM)	46	47	60	68	50	80	85	56	64	44	40
Free CO_2 (mg/l)		75	40	35	400	62	120	85	130	26	---

Table 7. Well 7 physical, chemical and bacteriological data.

Date	6/79	7/79	8/79	9/79	10/79	11/79	12/79	1/80	3/80	4/80	5/80
pH	6.63	6.40	6.50	6.55	6.10	6.61	7.01	7.00	5.95	6.70	6.50
Temp. °C	28.0	27.8	27.7	29.7	28.3	26.7	27.5	50	27.2	26.7	27.8
Turbidity (NTU)	0.62	0.60	1.3	2.7	93	28	70	24	1.8	0.8	1.1
Specific Conductance (μmhos)	420	300	250	440	323	---	300	550	---	345	440
Total Alkalinity (mg/l)	252	138	156	288	371	319	317	308	124	134	124
Chloride (mg/l)	35.1	19.4	19.8	30.5	41.9	---	30.5	19.9	40.8	28.4	39.1
Sulfate (mg/l)			7.6								2.7
Total Residue (mg/l)		272	74	178	172	510	212	352	208	188	204
Total Non-filtrable Residue (mg/l)	5.0	3.3	6.8	4.2	30.0	33.6	104	5.8	0.8	6.2	36.4
Total Filtrable Residue (mg/l)		269	67	174	142	476	108	346	207	182	178
Total Nitrogen (TKN) (mg/l)	0.28			0.10							0.66
Nitrate Nitrogen (mg/l)	0.18	1.75	0.60	0.32	0.44	0.30	0.25	0.22	0.28	0.43	0.90
Total Phosphorus (mg/l)	0.08			0.07			0.08	0.29			0.10
Ortho-Phosphate (mg/l)	0.08	0.10	0.09	0.05	0.05	0.02	0.08	0.09	---	0.06	0.07
Total Coliform (col./100 ml)	8			9		0				1	9
Fecal Coliform (col./100 ml)	3			2		5				3	6
Nitrite Nitrogen (mg/l)	.001	.001	.022	.001	.000	<.001	.003	---	---	---	<.001
Pumping Rate (GPM)	54	75	65	27	30	56	---	38	56	35	58
Free CO_2 (mg/l)		95	95	160	550	130	50	34	230	50	60

Table 8. Well 9 physical, chemical and bacteriological data.

Date	6/79	7/79	8/79	9/79	10/79	11/79	12/79	1/80	2/80	3/80	4/80	5/80
pH	6.50	6.08	6.82	6.68	5.80	6.69	7.30	6.60	5.80	6.21	6.50	6.30
Temp. °C	28.6	27.7	27.8	28.4	27.8	27.2	29.5	27.9	27.9	27.2	27.2	28.3
Turbidity (NTU)	26	28	9.2	20	4.0	19	26	15	9.5	0.40	1.2	3.9
Specific Conductance (μmhos)	2000	1480	1060	900	990	---	640	1300	2000	---	1375	2250
Total Alkalinity (mg/l)	208	108	210	188	251	219	407	183	88	122	129	158
Chloride (mg/l)	222	165	104	224	256	---	46.9	206	312	373	352	604
Sulfate (mg/l)			14.5									47
Total Residue (mg/l)		726	340	516	620	728	824	540	860	744	1056	---
Total Non-filtrable Residue (mg/l)	40.2	81.1	38.9	60.0	17.2	104	43.2	1.3	443	1.1	2.9	8.9
Total Filtrable Residue (mg/l)		645	301	456	603	624	781	539	427	743	1053	---
Total Nitrogen (TKN) (mg/l)	0.31			0.05								0.75
Nitrate Nitrogen (mg/l)	1.34	0.56	0.82	0.56	0.62	0.64	---	0.62	0.63	0.32	0.38	0.83
Total Phosphorus (mg/l)	0.10			0.08			0.07	0.24				0.08
Ortho-Phosphate (mg/l)	0.10	0.13	0.05	0.22	0.06	0.04	0.06	0.04	0.04	---	0.04	0.03
Total Coliform (col./100 ml)	5000			12		0					0	3
Fecal Coliform (col./100 ml)	91			20		3					0	1
Nitrite Nitrogen (mg/l)	.001	.005	.004	.001	.000	.003	---	---	---	---	---	0
Pumping Rate (GPM)	38	21	16	23	11	---	---	25	44	56	29	28
Free Co_2 (mg/l)		140	60	70	380	60	30	55	200	105	55	---

Table 9. Well 10 physical, chemical and bacteriological data.

Date	6/79	7/79	8/79	9/79	10/79	11/79	12/79	1/80	2/80	3/80	4/80	5/80
pH	6.68	7.08	6.63	6.63	6.33	6.23	6.33	6.90	6.54	5.90	6.44	6.52
Temp. °C	28.3	27.9	27.8	28.2	27.2	26.7	27.7	27.8	27.8	27.2	27.2	27.8
Turbidity (NTU)	0.75	2.5	0.78	0.45	0.90	0.62	0.75	0.80	1.3	0.50	0.9	0.50
Specific Conductance (µmhos)	220	200	210	190	271	---	140	330	60	---	180	200
Total Alkalinity (mg/l)	138	121	122	127	226	138	139	138	68	61	67	60
Chloride (mg/l)	18.3	18.3	19.9	24.1	20.2	---	14.7	12.4	13.1	22.2	19.9	97.6
Sulfate (mg/l)												3.1
Total Residue (mg/l)	236	266	40	116	72	394	30	192	68	108	108	108
Total Non-filtrable Residue (mg/l)	2.9	3.4	2.7	10.0	3.0	62.2	26.8	0.8	1.3	2.1	0.4	27.1
Total Filtrable Residue (mg/l)	233	263	37	106	69	332	3	191	67	106	108	81
Total Nitrogen (TKN) (mg/l)	0.17			0.07								0.50
Nitrate Nitrogen (mg/l)	0.18	0.21	0.16	0.24	0.30	0.25	0.19	0.33	0.92	0.38	0.27	0.77
Total Phosphorus (mg/l)	0.07			0.05			0.06	0.08				0.08
Ortho-Phosphate (mg/l)	0.08	0.04	0.04	0.05	0.04	0.05	0.05	0.05	0.05	---	0.05	0.04
Total Coliform (col./100 ml)	6			4		0					6	1
Fecal Coliform (col./100 ml)	3			2		0					0	0
Nitrite Nitrogen (mg/l)	<.001	.001	.004	.000	.000	<.001	.002	---	---	---	---	.000
Pumping Rate (GPM)	54	60	60	53	60	60	60	47	50	48	50	48
Free CO_2 (mg/l)	42	17	50	40	160	140	160	30	28	120	38	25

Table 10. Well 13 physical, chemical and bacteriological data.

Date	6/79	7/79	8/79	9/79	10/79	12/79	1/80	2/80	3/80	4/80	5/80
pH	7.00	6.40	6.50	6.42	6.15	6.22	6.50	6.33	5.65	6.50	6.60
Temp. °C	28.3	27.8	27.7	28.8	27.8	27.7	27.9	27.7	26.7	26.7	27.9
Turbidity (NTU)	0.60	0.60	1.3	1.0	0.37	18	2.0	1.5	0.40	1.2	0.60
Specific Conductance (μmhos)	260	300	250	240	223	180	400	240	---	210	260
Total Alkalinity (mg/l)	140	138	156	153	247	146	122	76	69	82	88
Chloride (mg/l)	20.5	19.4	19.8	15.7	15.8	6.2	12.4	14.2	20.9	14.6	26.6
Sulfate (mg/l)			7.6								5.4
Total Residue (mg/l)		272	74	130	108	48	188	96	136	172	296
Total Non-filtrable Residue (mg/l)	1.8	3.3	6.8	4.4	4.0	6.8	5.0	4.7	0.6	1.0	13.8
Total Filtrable Residue (mg/l)		269	67	126	104	41	183	91	135	171	282
Total Nitrogen (TKN) (mg/l)	0.15			0.04							0.29
Nitrate Nitrogen (mg/l)	2.51	1.75	0.60	0.72	0.73	0.53	0.68	1.05	0.58	0.82	1.12
Total Phosphorus (mg/l)	0.08			0.09		0.03	0.12				0.13
Ortho-Phosphate (mg/l)	0.08	0.10	0.09	0.09	0.10	0.02	0.09	0.08	---	0.20	0.10
Total Coliform (col./100 ml)	18			14						0	8
Fecal Coliform (col./100 ml)	0			1						1	3
Nitrite Nitrogen (mg/l)	<.001	.001	.022	.000	.000	.006	---	---	---	---	.000
Pumping Rate (GPM)	55	75	65	75	60	80	88	40	52	56	48
Free CO_2 (mg/l)		95	95	100	340	160	60	55	240	45	40

Table 11. Well 15 physical, chemical and bacteriological data.

Date	7/79	8/79	9/79	10/79	11/79	12/79	1/80	3/80	4/80	5/80
pH	6.30	6.14	6.38	5.83	6.19	6.30	6.20	5.90	6.40	6.50
Temp. °C	27.9	28.2	28.7	27.5	29.4	27.2	28.0	26.7	27.2	28.0
Turbidity (NTU)	6.0	0.48	52	20	22	77	160	0.60	0.44	1.8
Specific Conductance (μmhos)	315	280	530	192	---	150	270	---	185	210
Total Alkalinity (mg/l)	126	163	136	201	130	152	96	77	80	84
Chloride (mg/l)	25.0	59.2	20.2	14.6	---	7.8	12.5	22.0	11.7	16.5
Sulfate (mg/l)		9.4								4.1
Total Residue (mg/l)	266	292	140	336	532	26	164	---	124	136
Total Non-filtrable Residue (mg/l)	2.6	48.7	80.0	5.8	76.0	18.8	36.3	0.8	1.2	20.2
Total Filtrable Residue (mg/l)	263	243	60	330	456	7	128	---	123	116
Total Nitrogen (TKN) (mg/l)			0.07							0.79
Nitrate Nitrogen (mg/l)	1.73	0.76	0.53	0.41	0.26	0.24	0.15	0.47	0.56	0.92
Total Phosphorus (mg/l)			0.08			0.01	0.06			0.14
Ortho-Phosphate (mg/l)	0.09	0.02	0.20	0.05	0.03	0.01	0.01	---	0.11	0.10
Total Coliform (col./100 ml)			1		0				0	120
Fecal Coliform (col./100 ml)			20		0				0	180
Nitrite Nitrogen (mg/l)	.003	.002	.002	.001	.003	.004	---	---	---	.000
Pumping Rate (GPM)	90	46	42	10	---	---	18	36	35	35
Free CO_2 (mg/l)	105	200	130	300	160	135	100	---	48	40

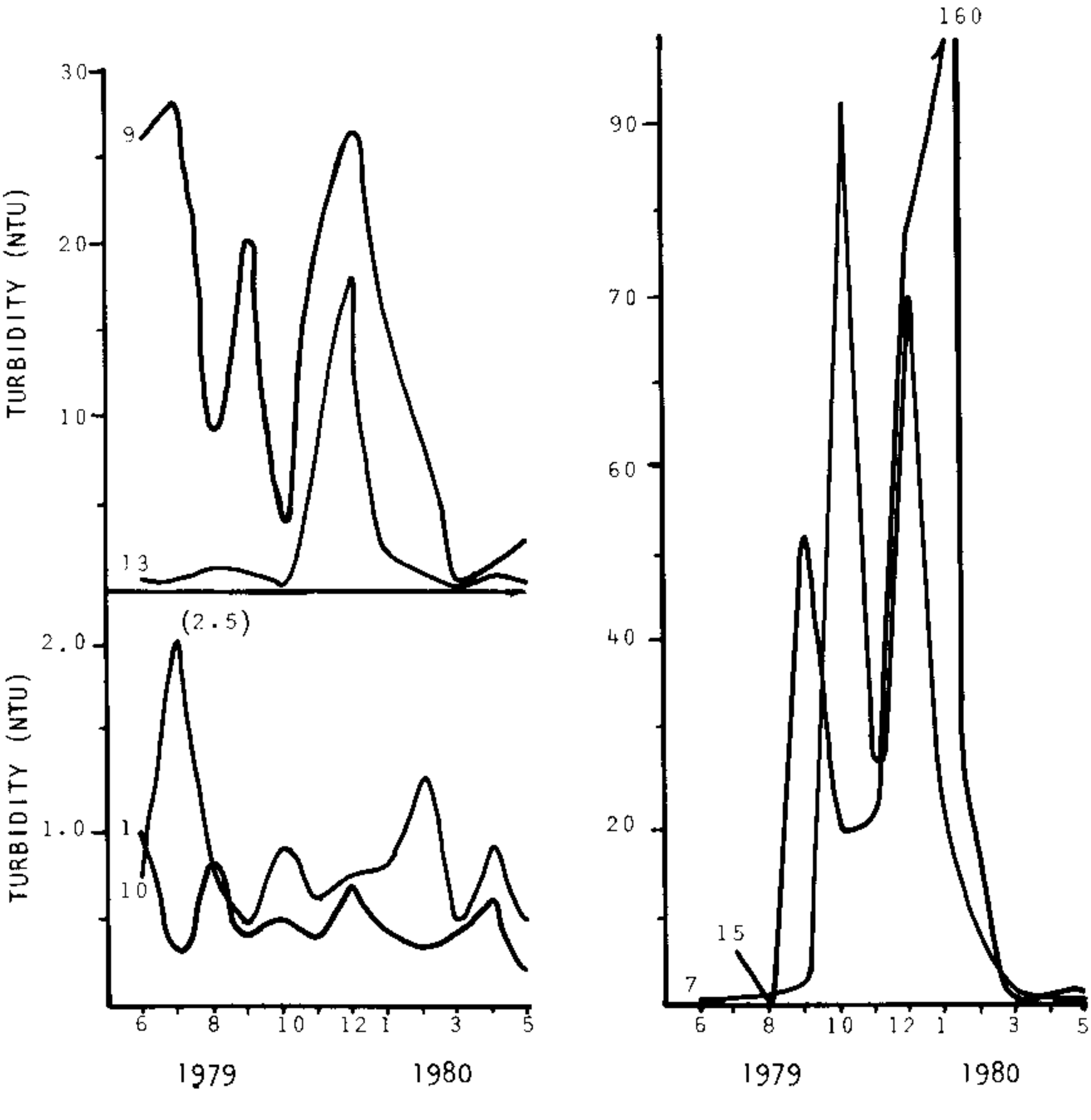

Figure 3. Monthly turbidity levels of well waters from June 1979 to May 1980.

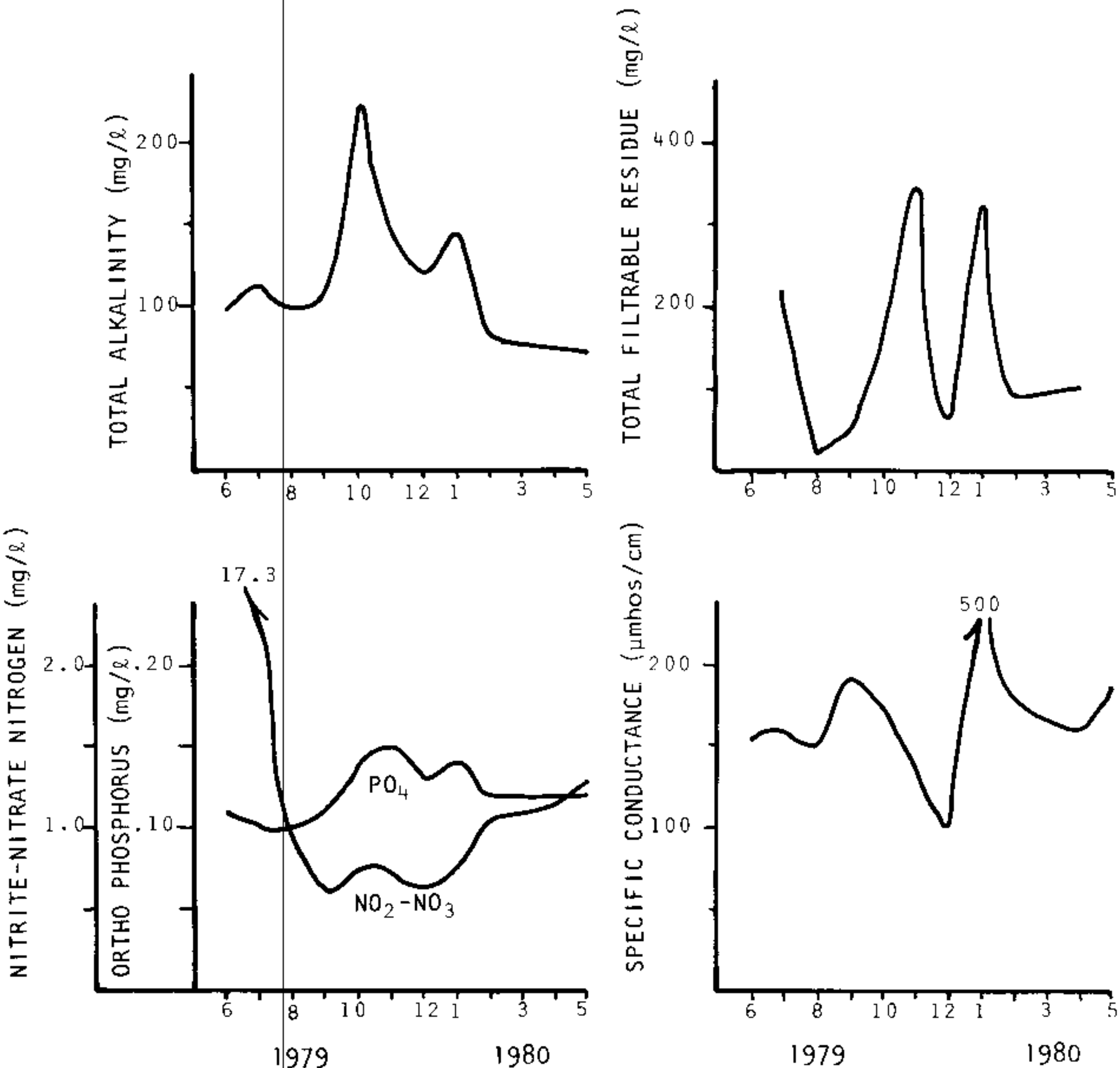

Figure 4. Well 1 physical and chemical water quality.

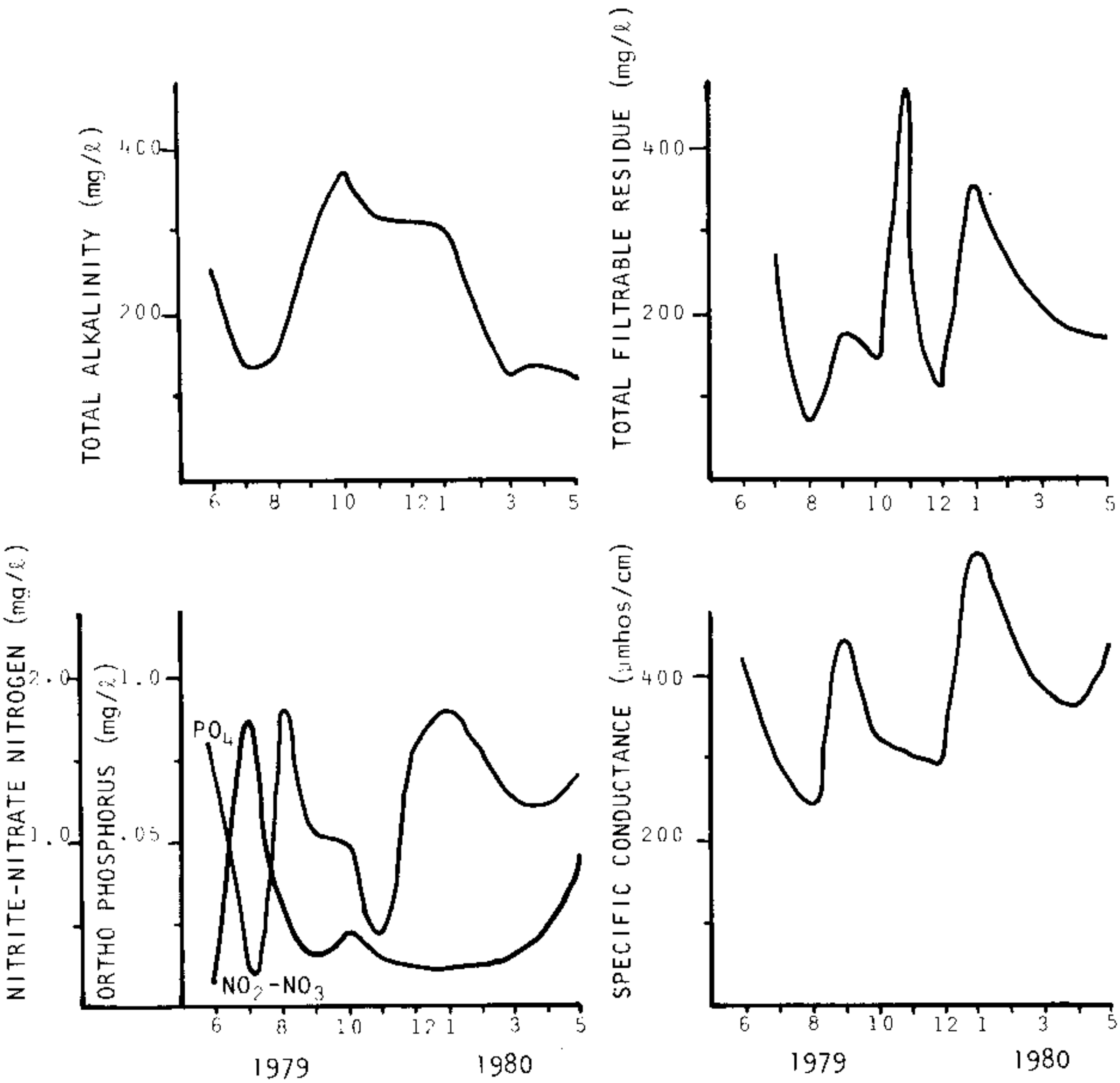

Figure 5. Well 7 physical and chemical water quality.

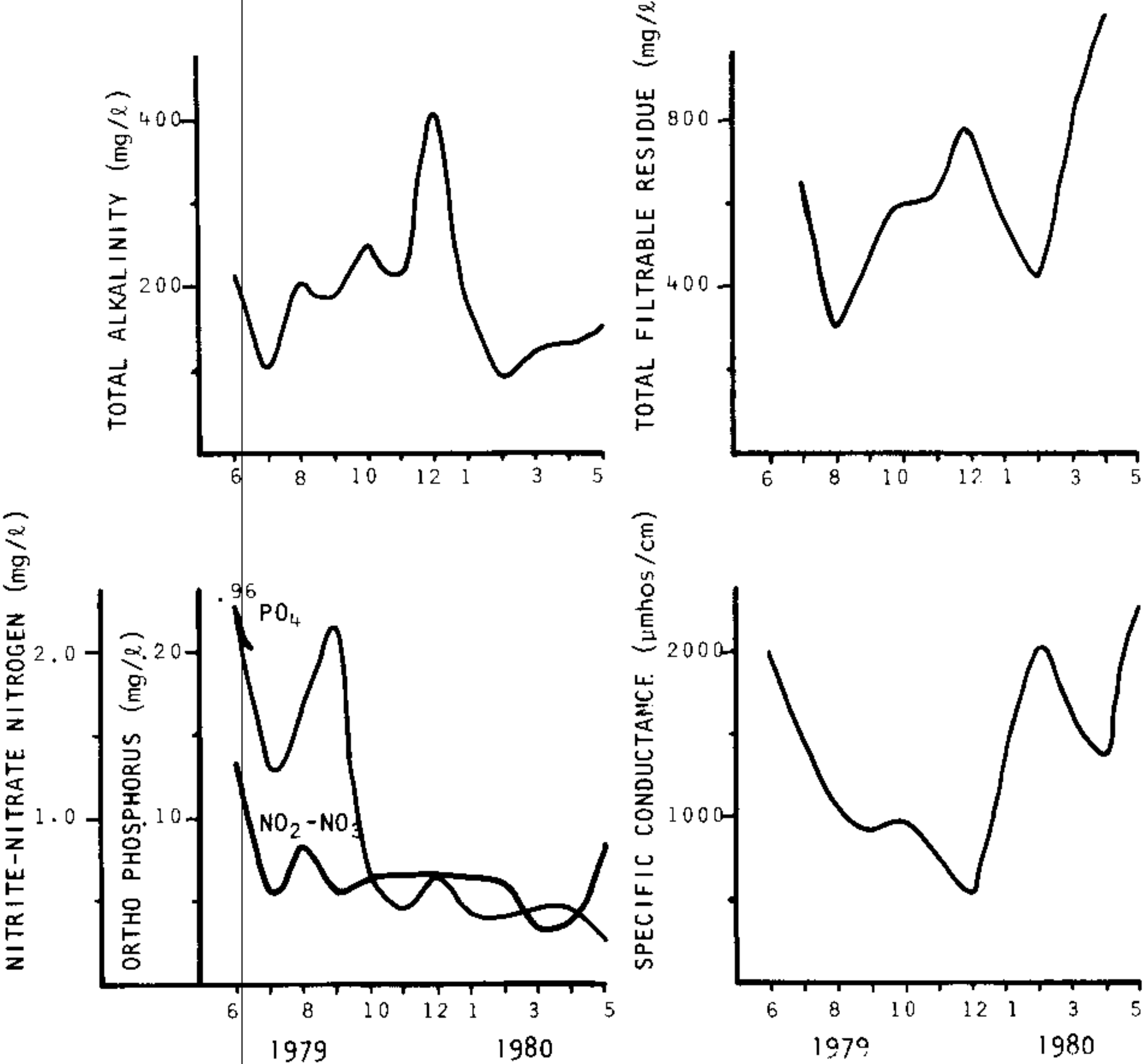

Figure 6. Well 9 physical and chemical water quality.

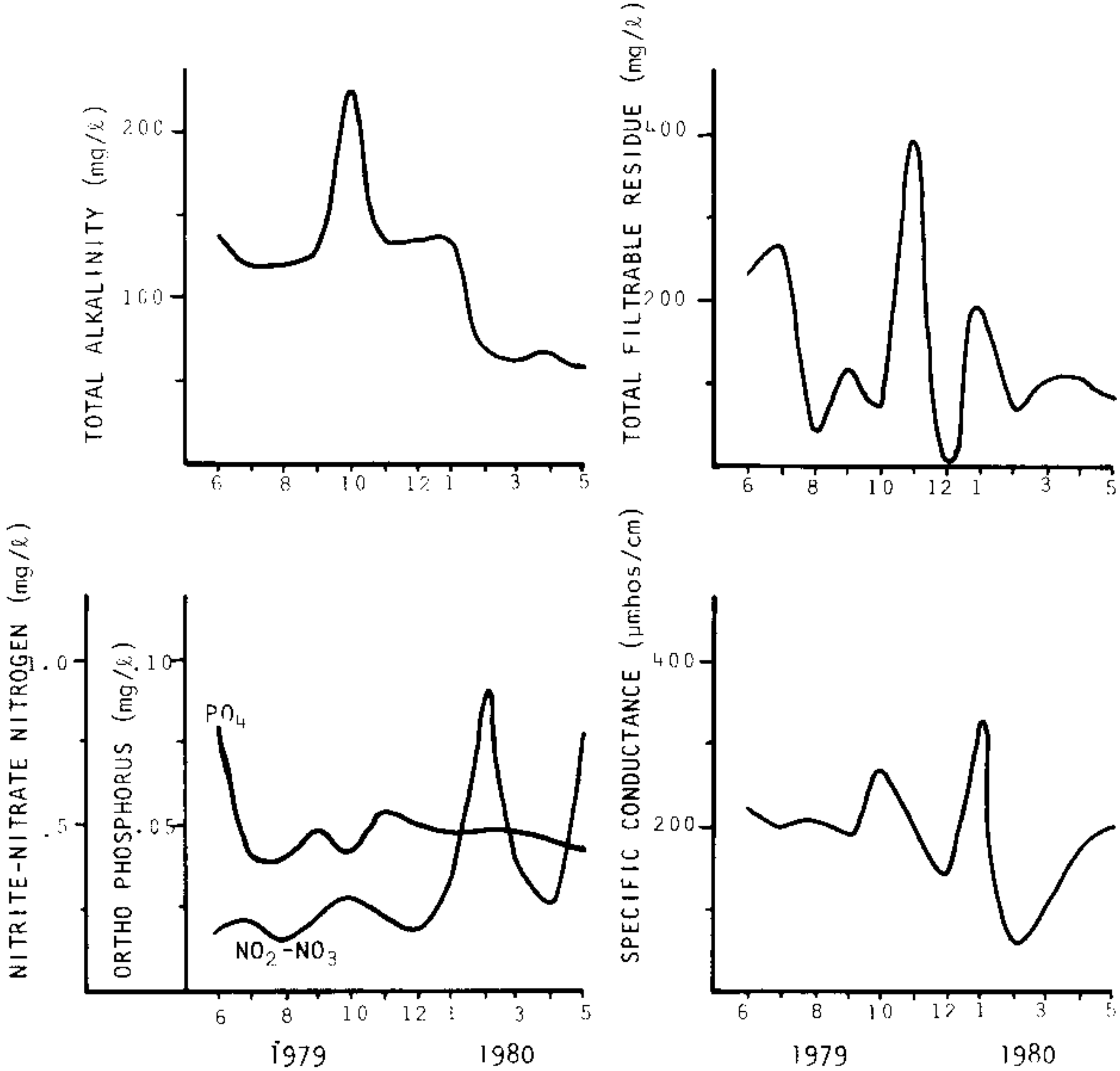

Figure 7. Well 10 physical and chemical water quality.

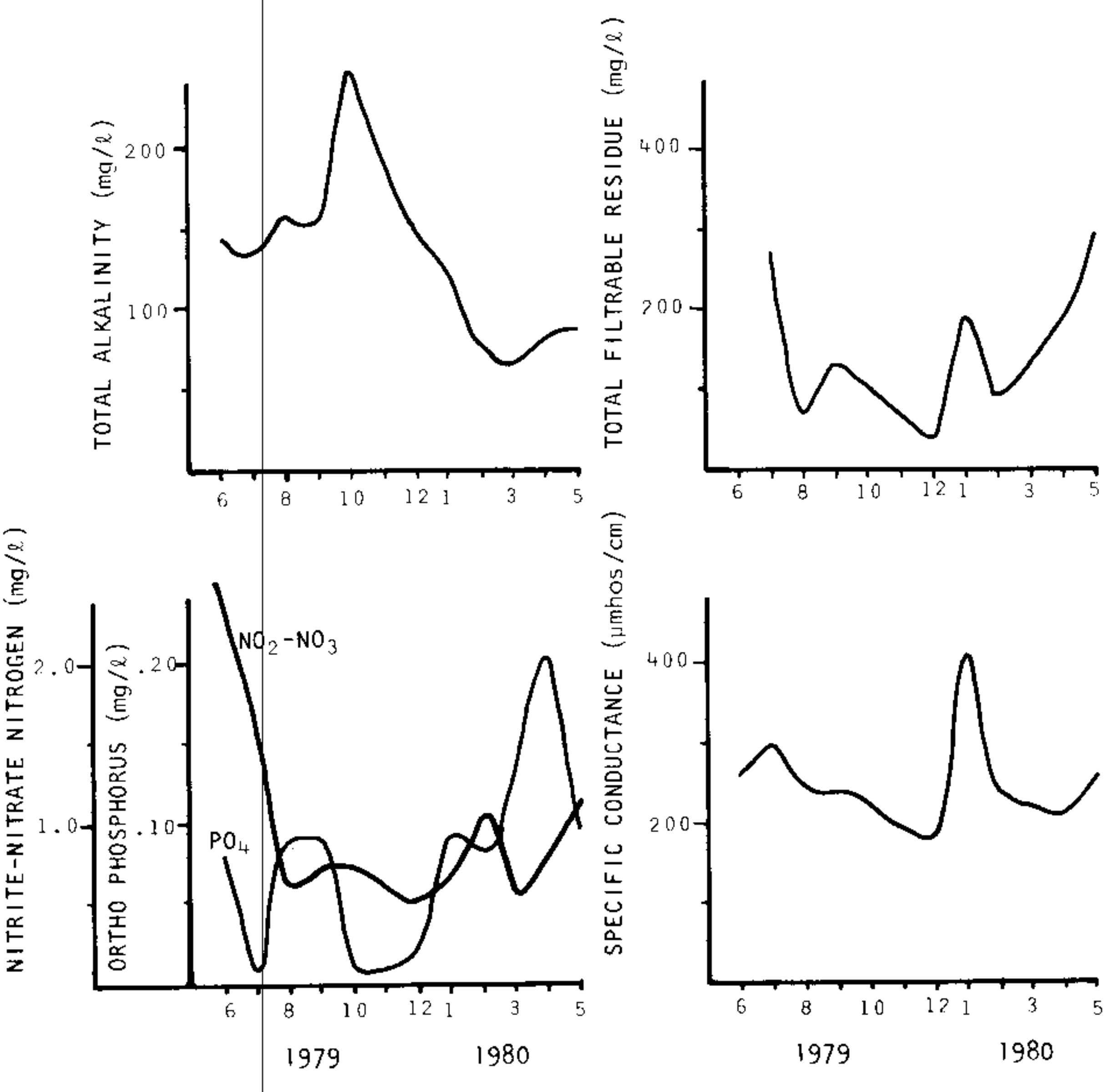

Figure 8. Well 13 physical and chemical water quality.

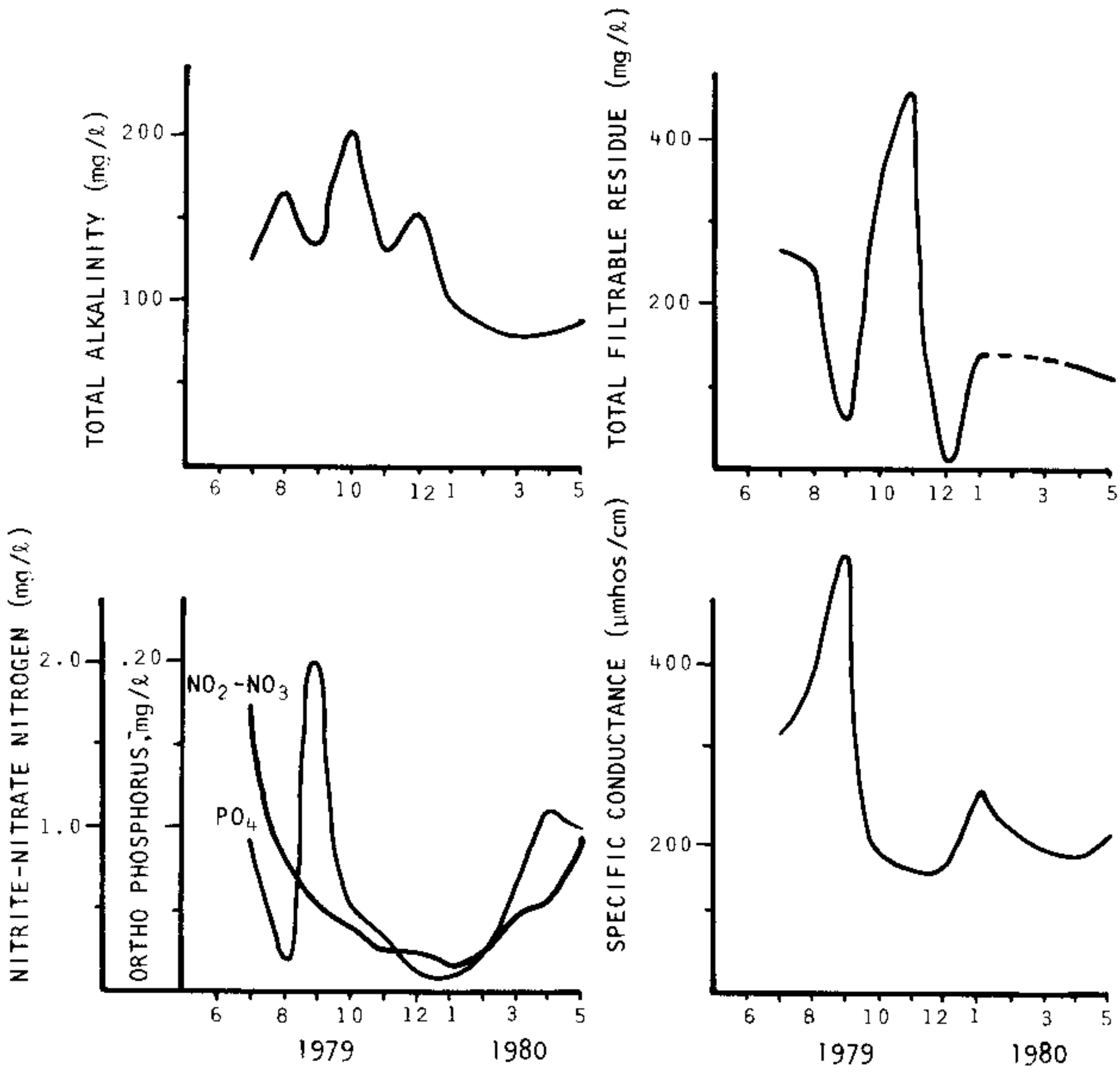

Figure 9. Well 15 physical and chemical water quality.

variable, for all the wells, except Well 9. The mean TNFR level in Well 9 was 70.2 mg/ℓ with the remaining wells ranging from 4.7 to 29.0 mg/ℓ. The TNFR particles in Well 15 water were generally a fine white chalk-like material, presumed to be a calcium carbonate. The TNFR particles in Wells 7 and 9 were usually a fine brown to red particulate material.

Specific conductance of the well water ranged from 195 (Well 1) to 1400 μmhos/cm (Well 9) (Figs. 4-9). Specific conductance readings taken at 1 to 5 minute intervals at the well heads usually were steady values for all wells except 9. Well 9 conductance values continually fluctuated. As a result, a median value at the 1 minute interval was used as the recorded value. The following set of timed conductance readings were obtained for Well 9 in July 1979: 0 minutes, 1480 μmhos/cm; 1 minute, 860 μmhos/cm; 3 minutes, 960 μmhos/cm; 4 minutes, 1080 μmhos/cm; 5 minutes, 1100 μmhos/cm. All of the wells had a peak conductance period in January 1980 (Figures 4-9). The wells had an additional peak conductance period occurring in the time interval between July to October, 1979.

Mean well water pH ranged form 6.21 to 6.54 (Fig. 10). Reduced pH periods occurred in October 1979 and February to March 1980. Peak pH periods occurred in July to September 1979 and November 1979 to January 1980. Well 9 had the widest range of pH values, 5.80 to 7.30. Well 13 had the lowest recorded pH value at 5.65.

Mean temperature values ranged from 27.5 (Well 1) to 28.0°C (Well 9). The high value (+50°C) for Well 7 was a result of pump malfunction and therefore was not used in the mean calculation.

Mean chloride levels ranges from 12.4 (Well 1) to 260 mg/ℓ (Well 9). Chloride levels in Well 9 show a large increase beginning in January 1980 (Fig. 11). A chloride concentration of 604 mg/ℓ was measured in May 1980. This value is in violation of the territorial safe drinking water standard (Territorial Register, 1978) which is 400 mg/ℓ. There is also a possible positive increase in chloride levels occurring in Wells 1 and 10 from February to May 1980. Wells 7, 13 and 15 fluctuated with variable peak periods.

The total alkalinity (expressed as $CaCO_3$) was always in the form of bicarbonate alkalinity (HCO_3^-). The mean total alkalinity ranged from 116 (Well 1) to 230 mg/ℓ (Well 7) (Figs. 4-9). Well 9 had a peak total alkalinity (407 mg/ℓ) in December 1979 (Fig. 6). The remaining wells had peak alkalinities in October 1979. Alkalinity values in all the wells showed decreases beginning in January 1980 and remained low through May 1980.

Free carbon dioxide (CO_2) was generally high in the well water with mean values ranging from 71 (Well 10) to 145 mg/ℓ (Well 7). Two periods of elevated CO_2 levels were recorded for all the wells, October

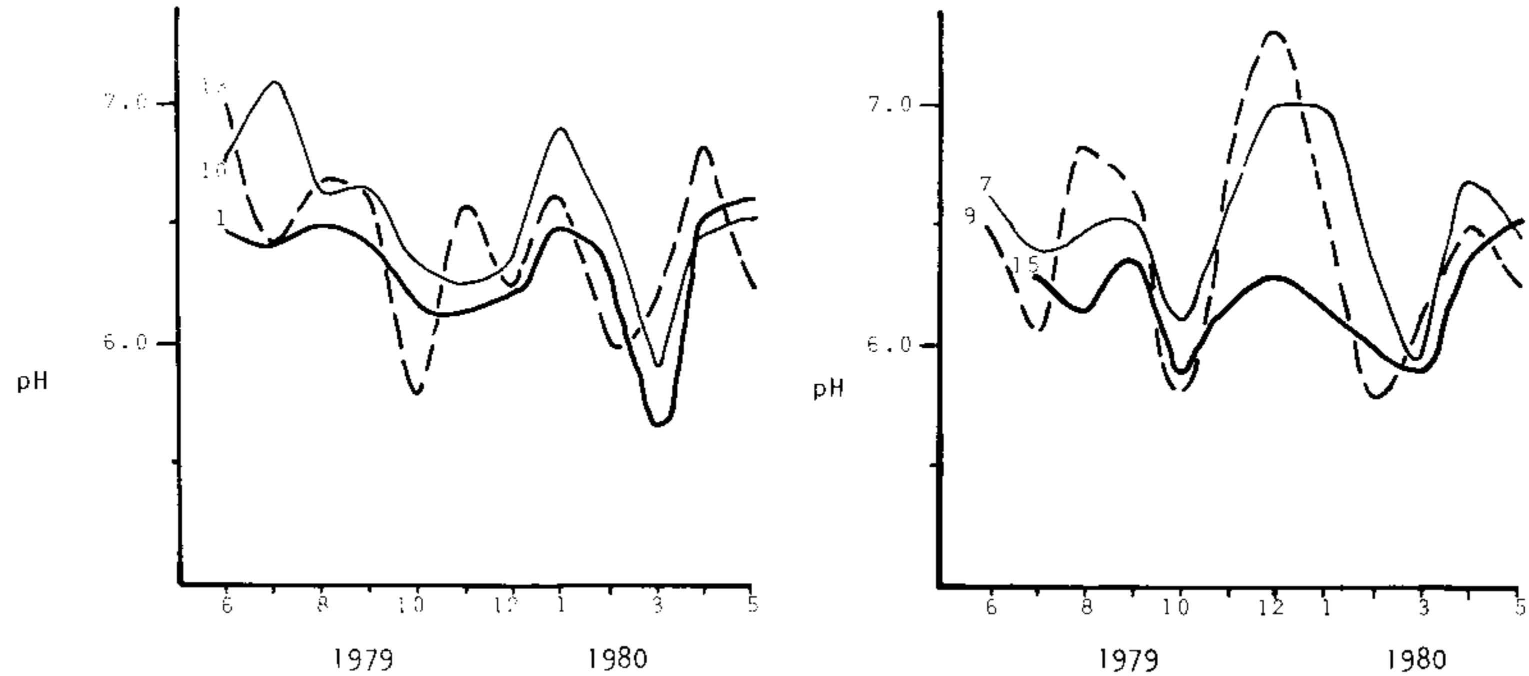

Figure 10. Monthly pH of well waters.

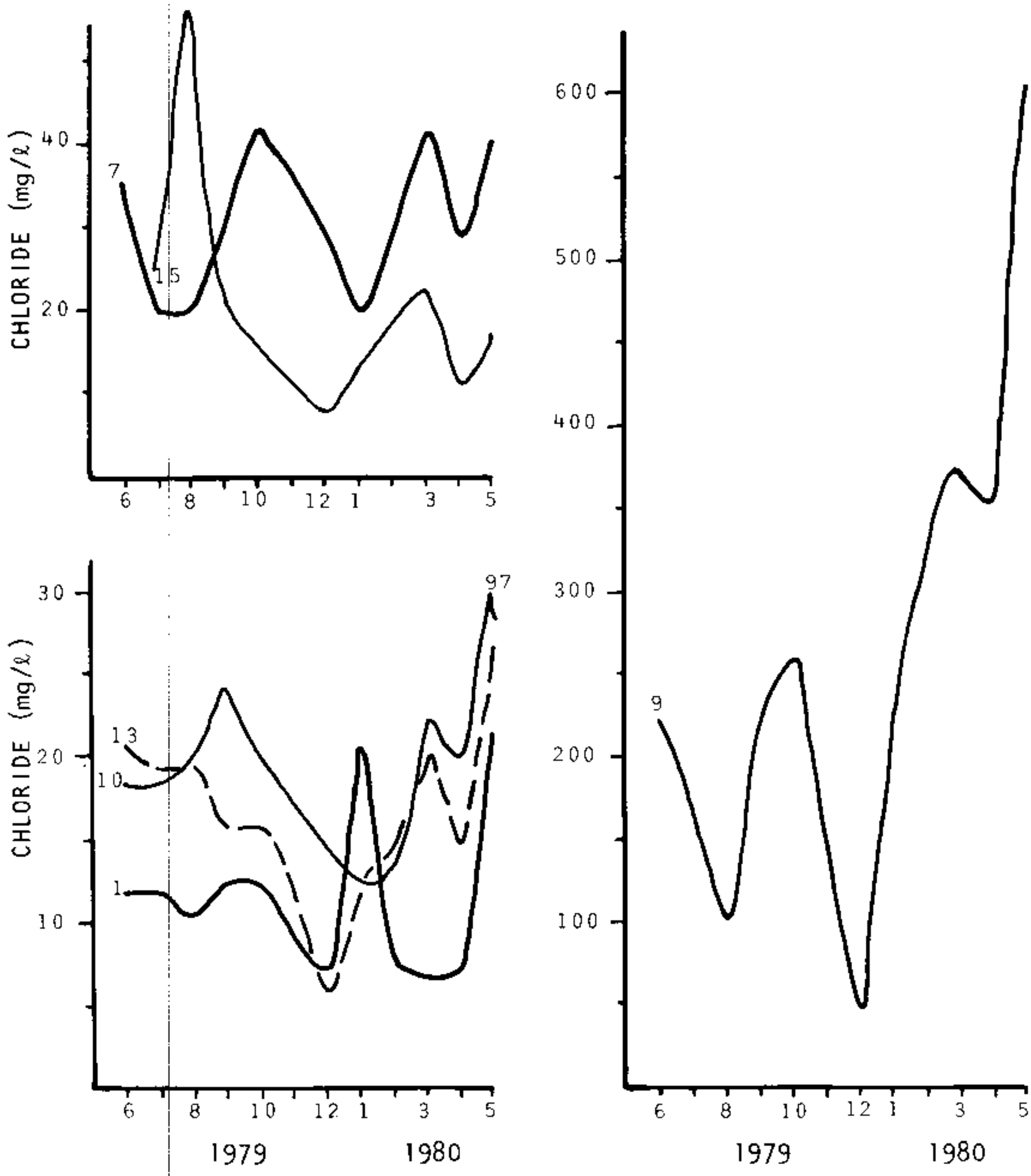

Figure 11. Monthly chloride levels of well waters.

1979 and March 1980 (Fig. 12). CO_2 levels in October ranged from 160 (Well 10) to 550 mg/ℓ (Well 7). The high CO_2 content in water pumped during the October peak from Wells 7, 9, and 15 caused the sampled water to effervesce. The March 1980 peak period had lower values ranging from 120 (Well 10) to 240 mg/ℓ (Well 13). The CO_2 value for the March 1980 peak period of Well 15 water was not obtained.

The principle form of nitrogen in the well water was nitrate-nitrogen. Nitrite-nitrogen levels were generally below detectable limits. Mean nitrite-nitrate nitrogen values ranged from 0.35 (Well 10) to 2.51 mg/ℓ (Well 1) (Figs. 4-9). The mean value of Well 1 was high due to a 17.5 mg/ℓ nitrate-nitrogen concentration measured in June 1979. Attributing the 17.5 mg/ℓ value to sample contamination and disregarding it, the mean nitrite-nitrate nitrogen value of Well 1 would become 1.01±.50 mg/ℓ. The ammonia-nitrogen concentration of the well water was sampled in May 1980 and was found to be negligible. Mean total kjeldahl nitrogen (TKN = organic nitrogen + ammonia nitrogen) ranged from 0.16 (Well 13) to 0.38 mg/ℓ (Well 1), excluding Well 15 which had only two measurements, 0.07 and 0.79 mg/ℓ. The TKN values of all the well waters were variable with large concentration deviations between sampling periods. Total nitrogen (TKN + nitrite-nitrate nitrogen) concentrations of the well waters were approximately 1 mg/ℓ.

Mean phosphorus levels ranged from 0.07 (Wells 10 and 15) to 0.13 mg/ℓ (Well 1). The phosphorus was primarily in the form of orthophosphate-phosphorus with the organic phosphorus (Total minus orthophosphate phosphorus) generally negligible. Mean orthophosphate values ranged from 0.05 (Well 10) to 0.12 mg/ℓ (Well 1) (Figs. 4-9).

Sulfate and reactive silicate concentrations were low in all of the well waters. The highest sulfate values were in Well 9 water with values ranging from <1.0 (Well 1) to 6.7 mg/ℓ (Well 15). Reactive silicate levels in the well waters ranged from 8.6 (Well 15) to 11.8 mg/ℓ (Well 10).

Total and fecal coliform bacteria contamination was present in all of the well waters as evidenced by the arithmetic and geometric means (Table 5). Total coliform arithmetic means ranged from 3 (Well 10) to 1003 colonies/100 mℓ (Well 9) with the geometric means ranging from 3 (Well 10) to 11 colonies/100 mℓ (Well 9). Fecal coliform arithmetic means ranged from 1 (Wells 10 and 13) to 50 colonies/100 mℓ (Well 15) with the geometric means ranging from 1 (Wells 10 and 13) to 8 colonies/100 mℓ (Well 15). The occurrence of fecal coliforms in the well water was in violation of the territorial safe drinking water standards (Territorial Register, 1978). The presence of fecal coliforms in the well waters indicated contamination of the well waters with surface water. The contaminated water entered the wells either by seepage around the well casing or through back-flow from the distribution system.

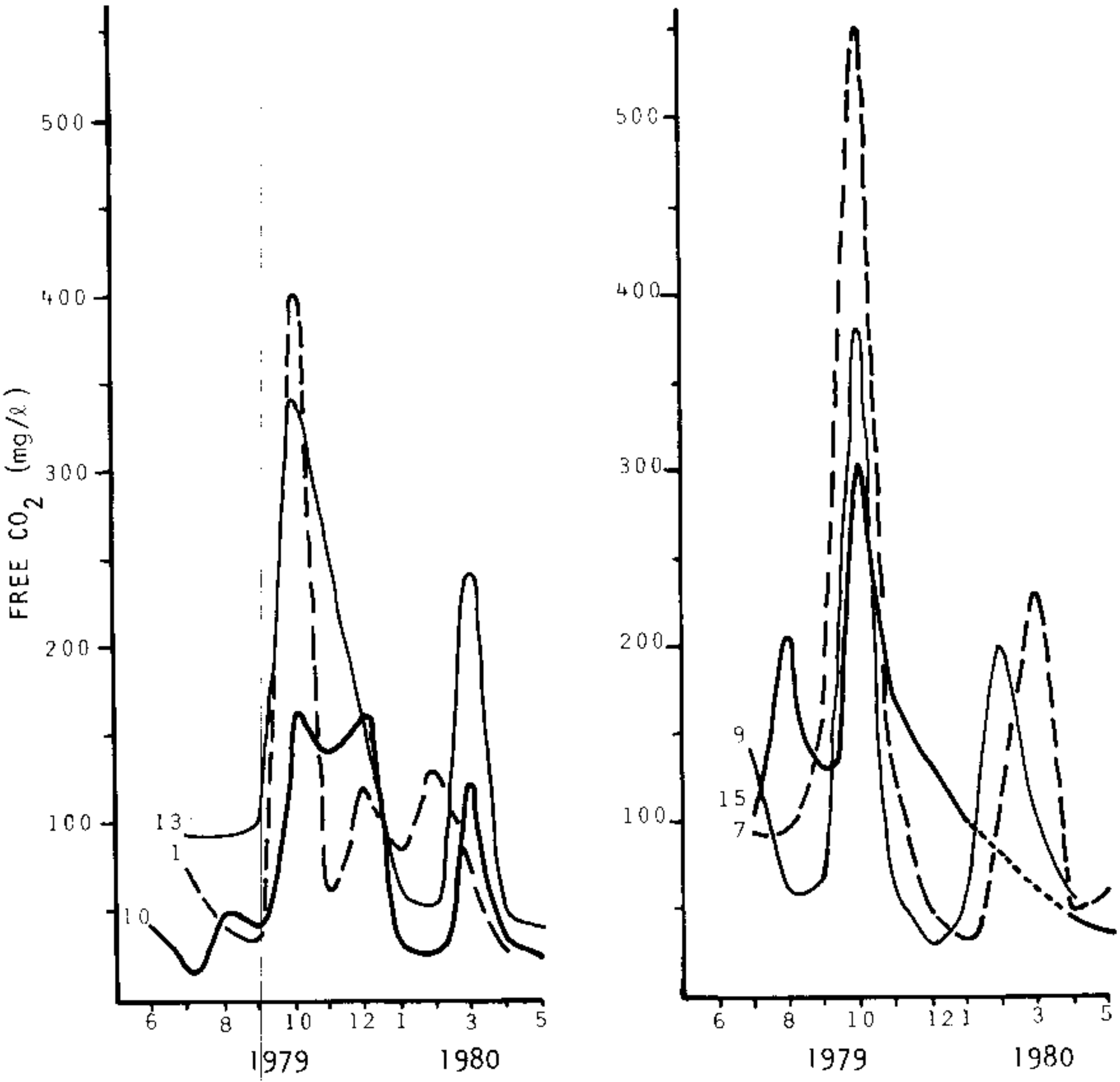

Figure 12. Monthly carbon dioxide content of well waters.

Although total bacteria was not quantified, it was believed to have been present in moderate to heavy levels in most of the well waters during the bacteriological sampling periods. This was indicated by the presence of many non-coliform colonies in the cultured samples.

DISCUSSION

Groundwater pollution is defined as an impairment of water quality by chemicals, heat or bacteria to a degree that does not necessarily create a public health hazard, but does affect such waters for normal use. Contamination implies an impairment of water quality by chemicals or bacteria to a degree that creates a public health hazard (Campbell and Lehr, 1973).

Total and fecal coliform bacteria are used as indicators of the possible presence of disease-producing organisms of human or animal origin. The frequent presence of total coliform and turbidities in excess of 1 NTU in well water at Wells 7, 9, 13 and 15 constitutes localized pollution of the groundwater resource. The occurrence of fecal coliform bacteria implies groundwater contamination.

Bacteriological contamination of the production wells with coliform and non-coliform bacteria poses not only a potential health hazard but can cause extensive corrosion and incrustation of well structures. Sulfate-reducing bacteria as indicated by rusty colored water and the slight odor of hydrogen-sulfide (rotten egg smell) was suspected of growing in the well waters, particularly Well 9. These anaerobic (do not use free oxygen) bacteria utilize sulfate as their primary food source. A major source of corrosion in Well 9, which had the highest sulfate levels, was possibly due to sulfate-reducing bacteria.

Disinfection of the water in the well with chlorinated water is required to control the bacteriological contamination. Generally chlorine solutions of 50 to 200 mg/ℓ are sufficient to sterilize the bacteria component in the well water. Sulfate-reducing bacteria may require 400 mg/ℓ chlorine concentration and six hours contact time (Campbell and Lehr, 1973). Additionally, highly turbid groundwater can reduce the effectiveness of normal chlorination, requiring larger doses of chlorine to ensure disinfection of the well. See Appendix A for general disinfection procedures.

Chemical and physical characteristics of the well water can cause corrosion and incrustation in production wells. According to Campbell and Lehr (1973) the following chemical and physical conditions can be considered as indicators of corrosive groundwater:

pH below 7.0
presence of dissolved oxygen
hydrogen-sulfide
total filtrable residue (TFR) in excess of 1000 mg/ℓ
carbon dioxide in excess of 50 mg/ℓ
chloride in excess of 300 mg/ℓ
increased or abnormally high temperatures

The monitoring wells all had pH values below 7.0 and frequent carbon dioxide levels in excess of 50 mg/ℓ. Well 9 had 4 chloride values in excess of 300 mg/ℓ and 1 TFR value in excess of 1000 mg/ℓ. The groundwater temperatures were slightly higher than surface spring water and catchment/storage water (Table 3). The mean water temperatures were consistent between the wells and were not considered abnormally high. The well waters were not analyzed for dissolved oxygen or hydrogen-sulfide.

The high levels of free carbon dioxide periodically measured in the well waters were possibly related to short periods of intense rainfall (Fig. 2). Since the time lag for surface or rain water to percolate into the aquifer was not known, it was difficult to assess the relationship between CO_2 levels and 24-hour rainfall. Tropical rain forests produce large quantities of CO_2 with a considerable part released directly to the atmosphere (Hem, 1970). A portion of this CO_2 is dissolved in the water as H_2CO_3 (carbonic acid) and retained in the soil layer (Freeze and Cherry, 1979). During periods of intense rainfall the soil-water with the accumulated dissolved constituents is flushed into the aquifer zone. Peak CO_2 levels should occur when there has been a period of low rainfall followed by heavy 24-hour rainfall. Peak CO_2 periods result in elevated carbonic acid concentrations in the well waters which can cause incrustation (Campbell and Lehr, 1973).

Incrustation as defined by Campbell and Lehr (1973) is a clogging, cementation or stoppage of a well screen and/or water-bearing formation. It is caused by precipitation of materials, deposition of silt to clay sized particles and bacteria or slime forming organisms. Bacterial contamination and silt deposition are potentially the major factors causing incrustation in the monitored wells. Groundwater in weathered basalt formations may have higher levels of turbidity, particularly after rainy periods (Bouwer, 1978). The high mean levels of TNFR, silt and residue resulting from corrosion, in the well waters (Table 3) can potentially clog the well screens. Periods of increased turbidity coincided with the highest TNFR levels. Incrustation from bacterial contamination can be eliminated by routine disinfection of the well water.

The dissolved nitrogen and phosphorus concentrations in the well waters were low. Discounting the high (17.5 mg/ℓ) nitrite-nitrate measurement in Well 1, the dissolved nutrients did not present a health hazard. Dissolved nutrients do not effect the structural components of the wells. The chloride levels in the wells were low except for Well 9. An increase in chloride concentration of 600 mg/ℓ occurred in Well 9 over a 4 month period (Fig. 11). Continued monitoring of this well would be required to ascertain if the measured increases in chloride levels were a seasonal or long term trend.

Wells 7, 9, 13 and 15 were surged in February and Well 1 in March 1980. Wells 7 and 15 had pumps replaced. Well 10 was not surged. The variation in physical and chemical water quality parameters of Well 10 showed a similar pattern as the surged wells. The well water parameter trends in the surged wells for the April and May sampling periods could have been seasonal changes. There was no obvious basis for distinguishing an improvement in water quality as strictly a result of surging. Except for turbidity, surging does not appear to have greatly improved well water quality. There was an apparent improvement in turbidity levels in Wells 7, 9 and 15 after the surging process (Fig. 3).

Bacterial contamination was found in the well water from Wells 7, 10 and 13 in the April sampling period. No total or fecal coliform bacteria were detected in water from Wells 1, 9 and 15. However, these samples did contain noncoliform bacteria. Wells 7 and 13 had both total and fecal coliform contamination. Well 10 had only total coliform contamination. The presence of coliform bacteria in the surged wells during the May sampling period indicated that the wells were not properly disinfected or contaminated surface water had entered the wells subsequent to surging.

All wells had coliform bacteria contamination in the May sampling period. Well 10 had only total coliform contamination. All surged wells had fecal coliform contamination with the highest count in Well 15 (180 colonies/100 mℓ) (Table 11). Well 15 water had more fecal than total coliform bacteria which indicated sewage contamination from human or animal sources.

RECOMMENDATIONS

Bacterial contamination is the major problem associated with the production wells. Disinfection of the groundwater in the wells is essential to eliminate a potential health hazard and bacterial corrosion of well structures. Contaminated water is entering the production wells through seepage around the casing seal or from pipeline back-flow. A bacteriological study should be established to determine the contamination sources. Total bacteria and total and fecal coliform bacteria levels should be monitored for a minimum period of five days in all the production wells and in the pipeline leading from the wells to the storage tanks.

This would establish the bacterial level of the wells and identify the sources of contamination in the wells. The detection of any fecal coliform would require disinfection of the contaminated well. A total coliform level of 4 colonies/100 mℓ in more than one sample indicates a contaminated well that requires disinfection. Wells that have excessively high total bacteria levels with observable turbidity levels (>1 NTU) should be disinfected. After disinfection of a well, total coliform bacteria should be monitored for a period of 5 days. The presence of total coliform in excess of the standards (Territorial Register, 1978) would require disinfection of the well with either a stronger chloride dose or a longer contact period. The total coliform bacteria and turbidity levels in the production wells should be routinely monitored as designated inthe territorial safe drinking water standards (Territorial Register, 1978).

The chloride concentration in Well 9 should be monitored on a weekly basis to determine the chloride trend. In the case that the chloride level in Well 9 continues to climb, it is recommended that the well be shut off for at least a one month recovery period. This would presumably help reduce the seawater intrusion.

In addition to the required monthly well water monitoring, water wells should be analyzed once a year for a wide range of bacteriological, chemical and physical water quality parameters. Total bacteria and total and fecal coliform bacteria should be determined with the membrane filter technique. Microscopic examinations of the well water should be made for the presence of iron and sulfate-reducing bacteria. Chemical parameters should include chloride, total alkalinity, total hardness, calcium hardness, free CO_2, hydrogen sulfide, dissolved oxygen, total and orthophosphate phosphorus, total nitrogen (TKN + nitrite-nitrate nitrogen), and ammonia nitrogen. The physical parameters should include turbidity, temperature, pH, specific conductance and total filtrable residue.

Background heavy metal levels should be determined for all the production wells. Metal analyses should include arsenic, barium, chromium, lead, mercury, silver and iron.

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APPENDIX A

WELL DISINFECTION PROCEDURE

The disinfection procedure, chlorine dosages and contact times are adapted from Campbell and Lehr (1973) and EPA Office of Water Supply (1977).

Chlorine disinfection effeciency is dependent on pH, temperature, initial chlorine concentration, bacterial type and number and contact time. Organic and particulate matter can reduce the chlorine to less efficient combined chlorine compounds. Generally, an initial chlorine concentration of approximately 50 mg/ℓ will most likely inactivate any known disease-producing organisms. Sulfate-reducing, iron and non-coliform bacteria, usually not a health hazard, may require up to 400 mg/ℓ chlorine dose with at least 6 hours of contact time.

A chlorine disinfection solution is made with either calcium hypochlorite of sodium hypochlorite. Sodium hypochlorite should be used when concentrations greater than 300 mg/ℓ are required. Calcium hypochlorite is a dry powder containing approximately 70 percent "available" chlorine by weight. Sodium hypochlorite, as laundry bleach, generally contains 12 to 15 percent by weight of available chlorine. The chlorine solution is made by dissolving calcium or sodium hypochlorite in two to three gallons of water.

Table A-1 presents the recommended amount of chlorine solution for the production wells based on well depth and casing diameter. Since bacterial contamination was shown in the monitored wells, a single shock chlorination treatment of 400 mg/ℓ may be required to eliminate bacterial growth. Initial contact times should range between 8 to 12 hours. A residual chlorine level of 1.0 mg/ℓ should be measured in the well 2 hours after chlorination. If no residual remains after 2 hours, additional chlorine solution should be added to the well.

The chlorine solution should be introduced into the well so that all well surfaces above the static levels will be completely flushed with the solution. The dispersion of the solution can be aided by pouring into the well a volume of water equal to the volume of the screen. This will result in an overflow of the disinfection solution into the area around the screen. After the contact period the well is pumped to clear it of the disinfection solution.

Table A1. Recommended dosage of calcium and sodium hypochlorite to disinfect the production wells.

MOEN WELLS	DEPTH RANGE m (ft)	VOLUME OF WELL ℓ (gal)	CALCIUM HYPOCHLORITE (dry weights-grams) 50 mg/ℓ	100 mg/ℓ	SODIUM HYPOCHLORITE* ℓ (gal) 400 mg/ℓ	CONTACT TIME
1-7, 9	30-39 (100-127)	984-1257 (260-332)	8.5	17	8.5 (2 1/4)	8-12 hours with a chlorine
12,13,15,18	23-29 (74-99)	730-984 (193-260)	5.7	12.7	6.3 (1 2/3)	residual of
8,10,11,14, 16,17	14-22 (47-73)	466-723 (123-191)	4.3	8.5	4.3 (1 1/8)	1.0 mg/ℓ @ end of 2 hours.

*The sodium hypochlorite liquid measurements are based on the available chlorine levels found in commercial bleaches like clorox or purex.