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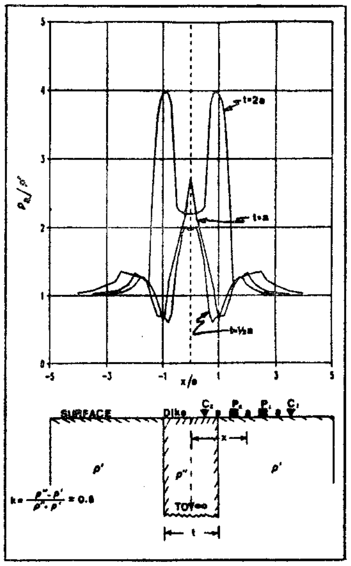

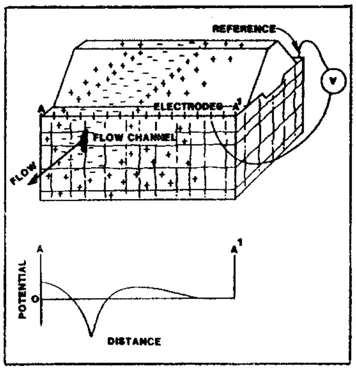

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TECHNICAL REPORT REMR-GT-6

GEOTECHNICAL APPLICATIONS OF THE SELF POTENTIAL (SP) METHOD

Report 1

THE USE OF SELF POTENTIAL IN THE DETECTION OF SUBSURFACE FLOW PATTERNS IN AND AROUND SINKHOLES

by

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COVER PHOTOS:

TOP — Theoretical Wenner resistivity profile across a high-resistivity vertical fault

MIDDLE — Idealized Self Potential (SP) Anomaly Generation

BOTTOM — SP Anomaly Plot

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Self potential (SP) measurements were effectively used in the detection of surface and subsurface drainage around a sinkhole. The same SP technique was also able to track an apparent subsurface flow path for over 600 ft from one sinkhole into another sinkhole. Confirmation of the SP data was obtained by visual observation, electrical resistivity measurements and geological studies. The use of this geophysical technique was evaluated in and around sinkholes in a karst area of west central Virginia.

The SP electrode configuration consisted of a double ring of electrodes circumferentially located around each sinkhole. Two reference electrodes were used in taking SP measurements. One reference electrode was located outside the rings of electrodes, and the other was located in the center of one of the sinkholes. Once a major drainage path around the sinkhole was detected, an array of electrodes was used to track the flow path.

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Although SP data varied significantly for individual electrodes during the 6-month testing period, the relative values between electrodes were consistent. This finding was also true if the position of the reference electrode was changed. It appeared that changes in precipitation and temperature had a great affect on the variation of SP data over the testing period.

Preface

The work described herein was performed during the period June 1985 through January 1986 by Dr. Ronald A. Erchul under an Interagency Personnel Agreement (IPA) with the Virginia Military Institute, Lexington, Virginia. The work was funded by the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research program sponsored by Headquarters, US Army Corps of Engineers (USACE). The work was performed under Civil Works Research Work Unit 32315, "Geophysical Techniques for Assessment of Existing Structural Foundations." The REMR Overview Committee consists of Mr. James E. Crews and Dr. Tony C. Liu, Headquarters, USACE. The Technial Monitor was Mr. Ben Kelly.

Field work was performed by Dr. Erchul and students of his engineering geology classes at the Virginia Military Institute. This report was prepared by Dr. Erchul. Mr. William F. McCleese is REMR Program Manager, and Mr. Jerry S. Huie is the problem area leader. Principal Investigator for this REMR research project is Dr. Dwain K. Butler, Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES). Dr. Arley G. Franklin is Chief, EEGD, and Dr. William F. Marcuson III is Chief, GL. The report was edited by Ms. Odell F. Allen, Information Products Division, Information Technology Laboratory, WES.

COL Dwayne G. Lee, CE, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

Contents

Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	2.54	centimetres
miles (US Statute)	1.609347	kilometres

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F - 32). To obtain Kelvin (K) readings, use: K = (5/9) (F - 32) + 273.15.

GEOTECHNICAL APPLICATIONS OF THE SELF POTENTIAL (SP) METHOD

THE USE OF SELF POTENTIAL IN THE DETECTION OF SUBSURFACE FLOW PATTERNS IN AND AROUND SINKHOLES

Introduction

1. The purpose of this research was to test and evaluate an indirect geophysical measuring technique called self or spontaneous potential (SP) on a newly developed sinkhole to determine if this method would be able to detect the direction of ground-water flow. This study represents a novel application of the SP method; and this report, preliminary in nature, presents a proof test of the application and concept.

2. The SP method measures natural electrical potential field differences at the earth's surface. Anomalies in the electric field can be produced by ore bodies, heat flow, or subsurface fluid flow. SP has been used widely in oil well logging to detect permeable zones, and it has also been used to delineate conductive ore deposit. The SP method has been used for many years in the USSR for geotechnical applications such as seepage analysis and study of landslide processes. Publication of papers by Soviet researchers Ogilvy, Ayed, and Bogoslovsky (1969) and Bogoslovsky and Ogilvy (1972) led to a number of geotechnical applications in the United States.

3. Recently the US Army Engineer Waterways Experiment Station (WES) has used SP measuring techniques at Gathright Dam in Virginia (Cooper and Koester 1982), Clearwater Dam in Missouri (Koester et al. 1984) and Mill Creek Dam in Walla Walla, Washington, (Butler, Wahl, and Sharp 1984) to determine the abnormalities created in the ambient electric field in cases where water was known to be flowing through porous zones of subsurface material but the location of these zones was not well defined. WES has greatly simplified the SP measuring technique by using copper clad steel grounding rods as electrodes rather than the nonpolarizing electrodes that many investigators have used in the past. For the scope of the Army projects the copper clad electrodes were very cost effective, and they detected relative potential difference

successfully. It was this simplification of the SP measuring technique that encouraged the present investigation.

4. The application of SP in this study is based on the established observation that the amount and the direction of fluid (ground-water) flow sets up electromotive forces in the surrounding media with resulting variations in potential which are detectable as anomalies at the surface. Negative anomalies are associated with seepage areas (Ogilvy, Ayed, and Bogoslovsky 1969) and with water flowing in solution channels (Cooper and Koester 1982). Water flowing in a solution channel at a depth of 90 ft in Manatee Springs, Florida, was readily detectable by SP (Cooper 1983). In Cooper and Koester (1982) negative anomalies of 500 mv were observed and assumed to be paths of ground-water flow. Electrical resistivity, dye injections, and bore holes confirmed this model.

5. When water flows through underground channels, the flowing fluid forms a double boundary layer at the channel wall which results in a net negative electrical charge in the geological material surrounding the channel (Butler, Wahl, and Sharp 1984). This accumulation of negative ions at the solid-liquid phase interface is then detected as anomalous to the positively charged surrounding rock bodies, and these areas are taken to be the preferred paths followed by ground water as it flows through conduits, fissures, and fractures.

Site Description

6. The study area is 6 miles* south of Lexington, Virginia, in the southern Shenandoah Valley. This is an area of karst topography and contains many sinkholes, which range in diameter from 8 to 300 ft and in depth from 3 to 50 ft. Within the study area of 2 miles by 1/2 mile, 25 sinkholes occur (see Figure 1). Two of these sinkholes were instrumented for this study (Harris and Hunter sinkholes). The Harris sinkhole had experienced a catastrophic collapse during a heavy rainfall in August 1984; hence, it displays a fresh aven (opening) at its bottom. The Hunter sinkhole is a shallow feature typical of subsidence development.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

Figure 1. Topographic map of the study area and the sinkholes in this area

7. Developed in the upper portion of the Ordovician aged Beekmantown Formation, the Hunter and Harris sinkholes occur at an elevation of approximately 1,200 ft. The Beekmantown, a thick bedded, finely grained dolomite is approximately 1,500 ft thick in the study area. The structure of the area is in the form of an anticlinal fold that plunges to the southwest (Spencer 1968). The Beekmantown is considered to be one of the most important cave bearing strata in Virginia. Some of the more notable commercial caves, (Endless and Skyline) as well as many of Virginia's long caves, occur in the Beekmantown; within a mile of the study area there are five caves.

8. The area is mostly open pasture, but exposed bedrock outcrops (karren) of the Beekmantown Formation are common in the study area. These

exhibit evidence of extensive solutional weathering, especially along joints. Base level is Buffalo Creek, a perennial stream located 1/2 mile northeast of the study area at an elevation of approximately 1,000 ft (200 ft below the studied sinkholes).

9. The two sinkholes which were studied were selected because of their location at the low end of a large uvala or karst depression (they therefore receive maximum runoff from the surface watershed), their convenient access, their representation of both collapse and subsidence forms, and their proximity to each other (600 ft).

Methodology

10. A double ring of electrodes was placed circumferentially around the sinkholes, using copper-clad steel grounding rod cut into 2-ft lengths and 5/8 in. in diameter. These electrodes were driven into the ground to a depth of 18 in. At the Harris sinkhole, the inner ring consisted of eight electrodes, 50 ft in diameter, and the outer ring consisted of 16 electrodes 150 ft in diameter. At the Hunter sinkhole the inner ring of electrodes consisted of 16 electrodes in a 30-ft diameter, and the outer ring consisted of 16 electrodes 150 ft in diameter. The measuring electrodes were numbered starting with electrode 1 as the northern electrode in the inner ring and increasing to 8 or 16, proceeding clockwise, for the Harris or Hunter sinkholes, respectively. In the outer ring the most northern electrode was numbered 9 or 17 and increased to number 24 or 32 proceeding clockwise for the Harris or Hunter sinkholes, respectively.

11. Two reference electrodes were used. The first (reference electrode 1) was located 21.5 ft due west of electrode 21 of the Harris sinkhole. The second (reference electrode 2) was located in the center of the Harris sinkhole approximately 19 ft below surface elevation. The reference electrodes were the same size and material as the other electrodes, and they were also installed in the same manner.

12. SP measurements were obtained by using a high impedance, digital voltmeter. The meter was connected between one of the reference electrodes and a reel of wire. One member of the measuring team laid out wire from the reel to one of the numbered electrodes located around the sinkhole. The wire was then clipped onto the electrode, thus completing the measurement half of

the circuit (the earth being the other half), and the individual relayed by voice the number of the specific electrode to the person reading the voltmeter. The person reading the voltmeter recorded the measurement, disconnected the reference electrode, and took a second measurement using the second reference electrode. Upon completion of this procedure, the instrument reader relayed by voice to the reel person who then proceeded to the next numbered electrode where the measurement procedure was repeated. This method was continued until all electrode readings using both reference electrodes were taken.

13. Data were collected approximately biweekly for a 6 month period. When SP data around a sinkhole revealed a consistent and repetitious pattern, a tracking array of electrodes was installed beyond the edge of the sinkhole to determine if the inferred flow patterns could be detected at some distance away. The lowest SP readings were inferred to be subterranean drainage paths. The tracking array consisted of a grid of 16 electrodes spaced on 50 ft centers. The 16 electrodes in a tracking array were alphanumerically labeled A1 through P1 in the array's first position and A2 through P2 in the array's second position.

14. Each array consisted of four rows of four electrodes. The northernmost row for tracking array one was labeled from left to right A1 through D1. The other rows were labeled consistent to this pattern with the southernmost row having electrodes labeled from left to right M1 through P1. As the array was advanced to a second position, the same numbering pattern was followed. Once a repetitious pattern was discerned, the array was advanced in the preferred direction and the measurements repeated. In this way it appeared that a subsurface flow path between the Harris and Hunter sinks was discernible.

15. In addition to SP data, electrical resistivity measurements were taken at the site for the purpose of providing some confirmation of the SP results. Using the already implanted electrodes, azimuthal measurements were obtained by rotating a 50 ft spacing Wenner electrode array 22.5 deg until eight readings were taken. This rotational measurement scheme resulted in a characterization of the resistivity variation as a function of azimuth around the sinkhole and reflected the electrical anisotrophy of the underlying bedrock and regolith.

16. Since the study area is located in a very rural area, no studies were conducted for stray currents or interference. Most readings were very

stable. Occasional erratic readings were a result of cattle rubbing on the electrode and loosening it in the soil. Further tamping corrected these problems. Air temperature and precipitation data from an official station at Lexington (6 miles from study area) are used to evaluate the effects of these parameters on the SP readings.

Results and Discussion

17. The SP data from both sinkholes that were studied are given in Tables 1, 2, and 3. Table 4 lists the SP values for electrodes in the two tracking arrays that were used between the sinkholes. The SP data for a given electrode varied greatly over time, but variation between electrodes remained relatively constant. Changes in ground-water flow as well as surface ground temperature and precipitation or a combination of these and other factors are probably responsible for fluctuating SP values.

18. Since the raw data shown in Tables 1, 2, 3, and 4 indicate variability over the collection period, an effort was made to filter the data by using ranks to preserve the ability of the data to document consistent negative anomalies and to remove seemingly erratic swing in the raw data. Negative SP readings for a given collection day would be given a low ranking, e.g. the electrode having the most negative value for the day would be given a rank of one, and the electrode having the most positive value would be given a rank of 24 at the Harris sinkhole or 32 at the Hunter sinkhole.

19. An example of the ranked data and the average value and standard deviation of the rank data over the collection period for the Harris sinkhole using reference electrode 1 is presented in Table 5. Negative readings are shown as low rankings and positive readings are shown as high rankings. The standard deviation of the ranking shows the relative sensitivity of an electrode to time varying effects such as water flow while systematic changes that are believed to be associated with temperature effects are filtered out by the ranking procedure.

20. The ranking procedure has both advantages and limitations. The major advantage is the removal of systematic changes in the data. These systematic changes translate the origin for the data. The major disadvantage is the insensitivity to factors which exaggerate scale. Increased ground-water flow may make the most negative readings more negative. This change is not

Table 1

Values of Spontaneous Potential in Millivolts Between Reference Electrode 1 and Circumferential Positioned Electrodes Around the Harris Sinkhole, July 1985-December 1985

	Harris Sinkhole Data, Reference Electrode 1																
El No.	7/24	7/25	7/26	8/7	8/8	8/10	9/2	9/17	9/30	10/22	10/30	11/1	11/6	11/30	12/23	12/27	12/30
1	85	-5	8	--	12	15	--	--	492	111	197	72	85	50	4	-49	-42
2	-333	-268	-215	-178	-187	-161	193	345	527	88	193	36	16	-33	-95	-167	-170
3	-85	-88	-54	-11	-16	-7	126	279	452	49	133	-27	4	-38	-20	-96	-83
4	89	-24	-5	30	28	27	46	238	386	44	65	-1	-41	-29	-119	-163	-166
5	-35	-78	-36	-20	-19	-8	36	162	350	81	167	49	68	57	60	7	11
6	-114	-91	-34	-66	-86	-36	-326	-262	62	-124	-223	-225	-238	-224	-395	-393	-415
7	109	6	17	25	21	22	197	346	501	103	183	77	100	102	55	2	9
8	111	3	16	30	22	25	240	346	515	119	217	86	110	98	50	0	4
9	27	-31	7	34	28	29	169	313	474	101	181	68	76	73	5	-57	-43
10	-99	-84	-35	6	4	3	101	139	278	68	126	14	3	-1	-74	-116	-95
11	8	-54	-32	-13	-15	-7	151	223	221	47	100	-9	26	24	-22	-65	-78
12	-31	-90	-42	8	3	8	204	319	478	101	177	-51	50	67	23	-34	-25
13	-25	-59	-188	-136	-127	-111	80	155	234	-18	55	-78	-7	-18	-22	-88	-77
14	-264	-149	-160	-278	-293	-230	48	-127	9	-60	-111	-82	-103	-137	-291	-372	-410
15	-20	-45	-44	6	-23	-11	51	82	182	-19	6	-65	-35	-51	-135	-185	-198
16	114	-23	-6	5	4	6	129	721	389	71	116	33	63	66	17	-24	-13
17	-329	-232	-287	-325	-365	-368	-58	-70	36	-166	-242	-165	-184	-212	-321	-387	-396
18	-55	-111	-115	-93	-99	-87	-43	174	226	-7	-88	-51	-77	-149	-267	-345	-353
19	110	4	9	30	26	22	-61	54	230	56	62	22	81	83	21	-4	-43
20	100	0	12	19	33	31	--	334	524	-146	175	69	38	50	-11	-12	-55
21	-31	-66	-63	-80	-79	-63	201	282	427	102	175	74	77	82	21	-14	-74
22	-4	-12	-19	32	14	38	146	226	313	39	75	11	44	51	0	-40	-25
23	-41	-11	1	53	32	31	152	268	427	98	187	74	93	93	31	-15	-11
24	-97	-122	-81	-12	-12	-1	75	52	175	2	25	-36	6	-5	-96	-161	-150

Table 2

Values of Spontaneous Potential in Millivolts Between Reference Electrode 2 and Circumferential Positioned Electrodes Around the Harris Sinkhole, August 1985-December 1985

Harris Sinkhole Data, Reference Electrode Two

El No.	8/7	8/8	8/10	9/2	9/17	9/30	10/22	10/30	11/1	11/6	11/15	11/30	12/23	12/27	12/30
1	--	401	413	--	--	266	314	276	235	220	197	193	-2	-1	-34
2	218	202	237	342	285	302	285	268	214	151	183	108	-105	-120	-161
3	383	373	392	275	227	227	247	207	129	141	163	102	-30	-47	-75
4	426	418	426	196	187	160	241	143	157	93	52	111	-129	-114	-158
5	381	370	390	191	108	138	280	242	167	203	182	201	50	55	19
6	329	304	363	-191	-339	-165	72	-143	-68	-101	-227	-79	-398	-344	-400
7	422	411	422	339	267	275	303	269	235	234	216	246	45	51	16
8	424	412	425	382	291	288	312	297	274	244	221	242	41	45	12
9	431	418	426	314	249	251	299	264	226	212	195	212	0	7	-38
10	400	392	402	245	76	56	263	209	169	139	103	140	-82	-64	-88
11	383	372	390	297	163	-1	245	182	147	162	132	167	-32	-17	-70
12	402	392	406	351	261	254	299	258	210	187	185	210	13	12	-17
13	258	262	286	226	98	11	176	135	94	125	142	121	-31	-37	-70
14	114	95	164	196	-183	-214	134	-31	77	31	-83	3	-301	-325	-401
15	391	366	387	197	8	-36	175	87	85	98	62	87	-144	-135	-190
16	399	394	405	272	196	164	270	200	196	200	182	209	7	22	-6
17	45	24	28	86	-144	-187	25	-160	-11	-50	-165	-68	-331	-337	-389
18	302	291	312	99	101	1	186	-6	110	53	-36	-4	-277	-295	-344
19	424	416	422	78	-23	7	256	146	180	217	195	230	16	42	-39
20	416	422	435	258	258	298	51	250	220	171	168	194	-18	36	-44
21	315	309	335	343	214	200	299	256	231	212	197	225	14	34	-1
22	428	402	436	288	155	88	237	155	170	179	136	195	-4	7	-17
23	446	420	429	293	196	202	295	271	235	228	203	238	23	32	-3
24	383	376	396	219	-13	-48	199	105	118	142	116	135	-104	-112	-142

Table 3

Values of Spontaneous Potential in Millivolts Using Reference Electrodes 1 and 2 and the Circumferential Positioned Electrodes Around the Hunter Sinkhole

	Oct 22		Dec 18	Jan 14	
	Reference 1	Reference 2	Reference 1	Reference 1	Reference 2
1	208	107	125	19	15
2	129	28	45	-17	-21
3	127	28	52	-43	-47
4	68	-32	18	-72	-76
5	199	99	113	9	5
6	59	-40	-32	-165	-168
7	136	36	69	-52	-56
8	9	-90	-28	-154	-158
9	177	77	90	-46	-53
10	174	74	36	-359	-360
11	181	81	86	-27	-31
12	109	70	78	-7	-10
13	127	27	65	-36	39
14	199	99	23	-293	-299
15	190	90	106	5	2
16	173	73	92	-9	13
17	56	44	-43	-148	-152
18	18	-82	-24	-109	-113
19	182	83	101	12	8
20	-285	-383	-261	-338	-336
21	29	-71	-87	-276	-278
22	187	87	66	-71	-77
23	140	40	41	-34	-38
24	160	60	83	-6	-10
25	124	24	-17	-118	-121
26	149	50	37	-82	-85
27	171	71	71	-88	-91
28	142	42	-2	-1	-5
29	162	62	45	-85	-89
30	35	-64	-26	-143	-149
31	-45	-144	-167	-252	-256
32	137	37	67	-8	-12

Table 4

Spontaneous Potential Values in Millivolts for Tracking Arrays One and Two Using Reference Electrode 1, August 1985–January 1986

TAE1*	8/7	8/8	8/10	8/13	TAE2*	9/30	10/22	10/30	11/1	11/6	1/14
A1**	-230	-222	-207	-154	A2	-53	-82	-179	-63	-27	-107
B1	-87	-33	-1	9	B2**	49	-246	-294	-105	-130	-479
C1	299	-53	-8	13	C2	177	32	30	-38	-73	-45
D1	-80	-33	1	4	D2	255	94	175	12	-218	-292
E1	-172	-100	-41	-15	E2	-83	-114	-200	-55	10	-334
F1**	-206	-308	-266	-259	F2	492	-5	86	-18	-121	-60
G1	-186	-202	-160	-217	G2**	151	-1	-202	-198	-275	-206
H1	-185	-160	-71	-29	H2	544	107	194	6	-151	-328
I1	-154	-98	-29	-8	H2	335	79	136	12	-41	-60
J1	-160	-122	-73	-61	J2**	537	-220	-190	-362	-297	-390
K1**	-168	-351	-284	-313	K2	355	69	176	44	-301	-425
L1	-207	-183	-93	-72	L2**	-14	-96	-269	-57	-121	-386
M1	-160	-112	-65	-101	M2	391	-45	-14	14	34	-179
N1**	-222	-294	-246	-217	N2**	2	-114	-105	-112	-143	-426
O1	-170	-84	8	30	O2	36	23	-159	-119	-167	-223
P1	-299	-80	29	68	P2**	143	-24	-194	-223	-216	143

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* Tracking Array Electrode.

** Is the electrode in the row with the lowest ranking value. A tracking array consisted of 16 electrodes on 50 ft spacings. Four rows had four electrodes alphanumerically labeled, e.g. tracking array one, row one, was labeled A1 through D1 starting from left to right continuing to row four where electrodes were labeled M1 through P1.

Table 5

Ranked Values of Spontaneous Potential Data and the Average and Standard Deviation of this Data Between Reference Electrode 1 and the Circumferential Positioned Electrodes Around the Harris Sinkhole, July 1985-December 1986

El	Dates																	
No.	7/24	7/25	7/26	8/7	8/8	8/10	9/2	9/17	9/30	10/22	10/30	11/1	11/6	11/30	12/23	12/27	12/30	Average	SD*
1	18	20	20	24	16	15	24	24	20	23	23	20	21	13	15	14	17	19.2	3.6
2	1	11	2	3	3	3	18	20	24	17	22	16	11	7	8	6	6	10.4	7.7
3	7	8	8	11	10	9	12	15	17	12	14	9	9	6	12	10	10	10.5	2.8
4	19	16	17	19	22	19	6	13	13	10	9	11	5	8	6	7	7	12.1	5.4
5	10	10	11	8	9	8	5	9	12	16	15	17	17	16	24	24	24	13.8	5.8
6	4	6	13	7	6	6	1	1	3	3	2	1	1	1	1	1	1	3.4	3.2
7	21	24	24	17	18	16	19	22	21	20	23	23	24	24	23	23	23	21.3	2.4
8	23	22	23	18	19	18	22	21	22	24	24	24	24	23	22	22	22	21.9	1.9
9	17	15	19	22	21	29	17	17	18	19	19	18	18	19	16	13	15	18.3	2.2
10	5	9	12	13	14	12	11	7	10	14	13	13	8	11	9	9	9	10.5	2.4
11	16	13	14	9	11	10	15	11	6	11	11	10	12	12	11	12	11	11.4	2.2
12	11	7	10	15	13	14	21	18	19	20	18	6	15	18	20	16	18	15.2	4.4
13	13	12	3	4	4	24	10	8	9	6	7	4	7	9	10	11	12	9.0	4.8
14	3	3	4	2	2	2	7	2	1	4	3	3	3	4	3	3	2	3.0	1.3
15	14	14	9	14	8	7	8	6	5	5	5	5	6	5	5	5	5	7.4	3.3
16	24	17	16	12	15	13	13	23	14	15	12	15	16	17	17	17	20	16.2	3.3
17	2	2	1	1	1	1	3	3	2	1	1	2	2	2	2	2	3	1.8	0.7
18	8	5	5	5	5	4	4	10	7	7	4	7	4	4	4	4	4	5.2	1.8
19	22	23	21	20	20	17	2	5	8	13	8	14	20	21	18	21	16	15.8	6.3
20	20	21	22	16	24	21	23	19	23	2	16	19	13	14	13	20	14	17.6	5.3
21	12	11	7	6	7	5	20	16	15	21	17	21	19	20	19	19	13	14.5	5.5
22	15	18	15	21	17	23	14	12	11	9	10	12	14	15	14	15	19	14.9	3.7
23	9	19	18	23	23	22	16	14	16	18	21	22	22	22	21	18	21	19.1	3.6
24	6	4	6	10	12	11	9	4	4	8	6	8	10	10	7	8	8	7.7	2.4

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* SD = standard deviation.

visible in the rankings. Only when readings (raw data) pass each other do changes in ranking occur.

21. Figure 2 shows the electrode pattern and the average ranked SP values at the Harris sinkhole using reference electrode 1. A preferred drainage pattern, based on selection of electrodes with the lowest ranked values, is indicated in Figure 2. Figure 3 is an enlarged topographic map of the study area which incorporates data from both sinkholes, the tracking arrays between them, and the inferred subsurface flow path.

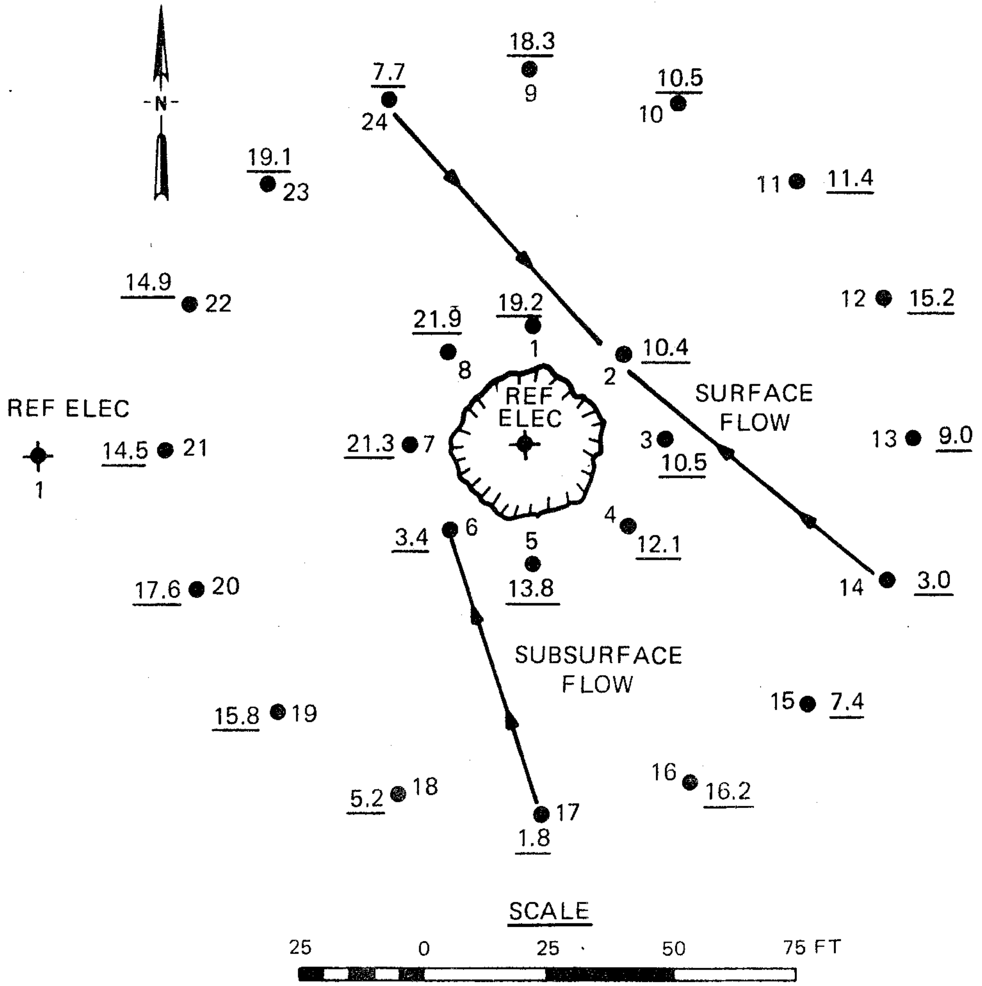

Figure 2. Electrode pattern spacing, average ranked spontaneous potential values, and the inferred flow pattern at the Harris sinkhole using reference electrode 1

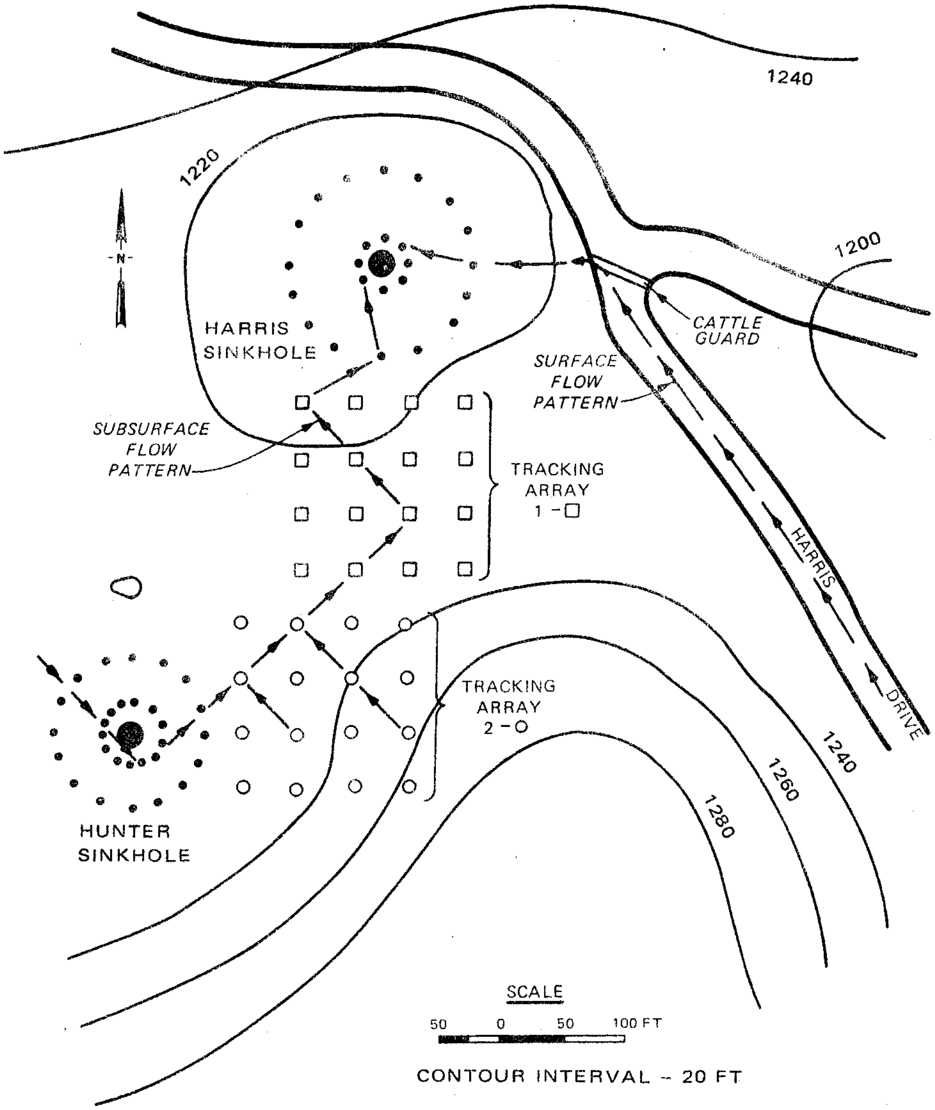

Figure 3. Topographic map of the Harris and Hunter sinkholes and their associated circumferential ring electrodes, tracking arrays, and the drainage path as inferred by SP data

22. The inferred subsurface flow path connecting the Harris and Hunter sinkholes is over 600 ft in length. It does not follow the direction of surface drainage but appears to be oriented along strike of the underlying bedrock (approximately N 50 deg E). This strike direction also appears to control passage development of nearby caves as well as sinkhole distribution. Most of the sinkholes in the general area are aligned in this preferred orientation (see Figure 1). The Hunter sinkhole is located about 20 ft higher than the Harris sinkhole, and from observation during runoff events it apparently

intercepts surface drainage and conducts the water subterraneanly (via strike controlled fissures) into the lower Harris sinkhole. SP data appear to confirm this model.

23. Further confirmation of the SP data was obtained from observation of surface runoff that is channeled by a road and cattle guard into the Harris sinkhole during periods of heavy precipitation. SP data (from electrode 14 to electrode 2) detected this flow path long after surface runoff had ceased flowing. This flow path is inferred to be a recharge path within the regolith as well as a surface runoff path.

24. Table 6 lists the averages and standard deviations of the ranked SP data at the Harris sinkhole for reference electrodes 1 and 2. From Table 6 it is evident that low ranked measuring electrodes, i.e., those electrodes having low or negative SP values, are generally consistent even though different reference electrodes are being used. Actual differences in SP values may be due to the elevation difference of 32 ft between reference electrodes (reference electrode 2 being at the bottom of the aven in soil which had recently collapsed into the bottom of the sinkhole). Differences in soil moisture or structure of the in situ soil at reference electrode 1 and the collapsed soil at reference electrode 2 may also explain the range of SP values.

25. Azimuthal electrical resistivity data from the Harris sinkhole is shown in Figure 4. Although this represents only one set of data, it is interesting to note that the major axis of the elliptical plot reflects the strike direction. Taylor (1985)* has shown that joint orientation is one of the most useful and reliable parameters that can be obtained from azimuthal resistivity measurements. The character of this ellipse may be interpreted to determine the transverse and longitudinal resistivity for the subsurface material at the site. Dominant strike controlled jointing and secondary dip control (bedding plane) of ground-water movement are suggested by the resistivity data as well as the SP data and observation of outcrops and cave passages in the area.

26. Figure 5 relates precipitation, average daily air temperature, and SP values from a randomly chosen electrode. The qualitative trends of SP data

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* R. W. Taylor. 1985. "The Determination of Joint Orientation and Porosity from Azimuthal Resistivity Measurement," a paper presented at the Annual Meeting of the Association of Engineering Geologists, Raleigh, N.C.

Table 6

The Averages and Standard Deviations of the Ranked Spontaneous Potential Data at the Harris Sinkhole for Reference Electrodes 1 and 2

	Reference Electrode 1		Reference Electrode 2	
EL No.	Average Ranking	Standard Deviation	Average Ranking	Standard Deviation
1	19.2	3.6	19.4	0.4
2	10.4	7.7	12.1	7.3
3	10.5	2.8	11.4	2.9
4	12.1	5.4	10.7	5.7
5	13.8	5.8	14.2	5.8
6	3.4	3.2	2.5	2.2
7	21.3	2.4	21.0	1.9
8	21.9	1.9	22.1	0.2
9	18.3	2.2	18.2	0.2
10	10.5	2.4	10.7	2.4
11	11.4	2.2	10.8	2.3
12	15.2	4.4	17.3	2.2
13	9.0	4.8	7.8	2.6
14	3.0	1.3	2.8	1.4
15	7.4	3.3	6.2	0.2
16	16.2	3.3	15.0	1.8
17	1.8	0.7	1.8	0.7
18	5.2	1.8	5.0	1.5
19	15.8	6.3	14.8	6.2
20	17.6	5.3	15.9	5.4
21	14.5	5.5	15.9	5.4
22	14.9	3.7	14.4	4.1
23	19.1	3.6	20.2	2.7
24	7.7	2.4	8.4	2.3

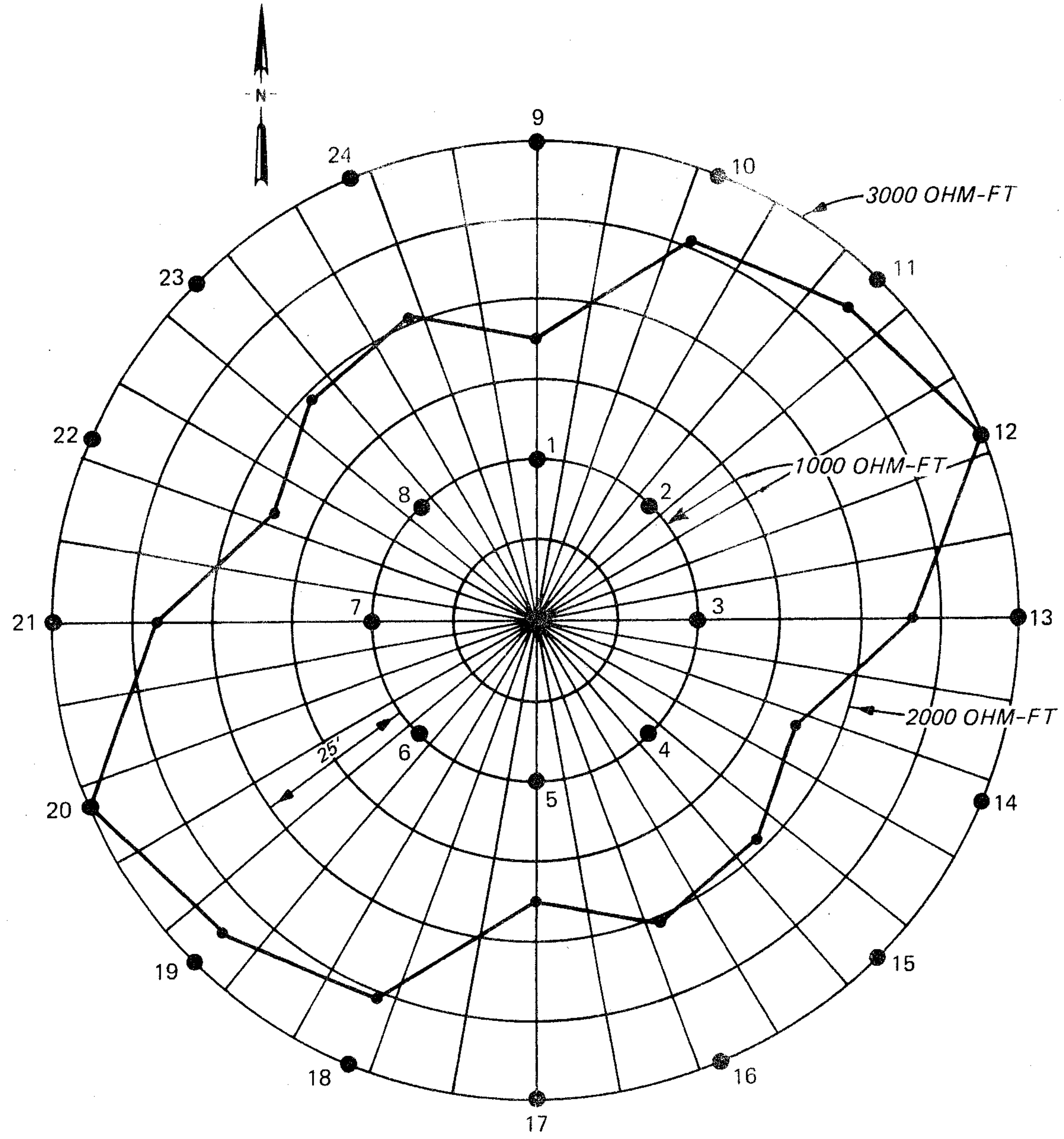

Figure 4. Azimuthal resistivity results in ohm-ft taken at the Harris sinkhole site

for other electrodes are similar. Temperature and precipitation data are from an official weather station in Lexington, 6 miles from the study area. Precipitation values are total 5-day accumulations up to the date on which SP data were taken. The monthly accumulations are represented by horizontal lines. Average daily air temperature is assumed to give an indication of surface ground temperature. In general, it seems that SP values decrease with a decrease in temperature or an increase in precipitation. This finding is

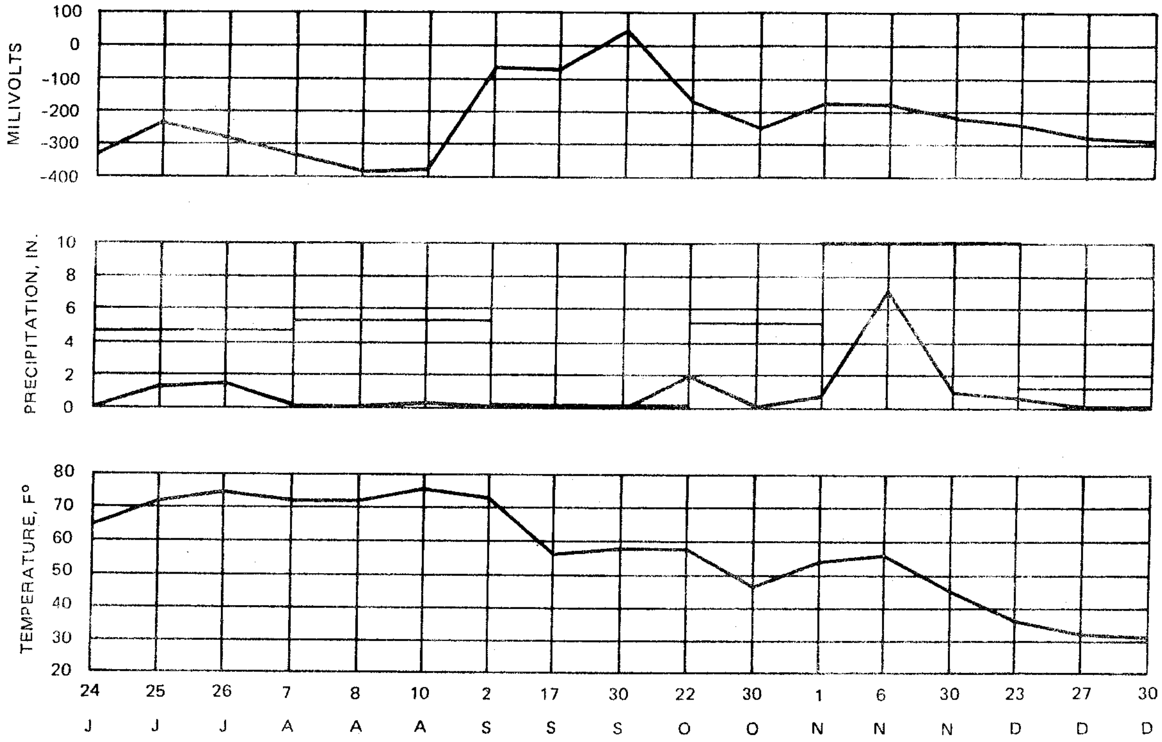

Figure 5. Precipitation, air temperature, and self potential value for electrode 17 taken over the measurement dates conducted during this study

consistent with work presented by other investigators in that an increase in water flow resulted in a lowering of SP values. The effects of temperature fluctuation on SP values have been studied by Corwin and Hoover (1978). They have noted a coupling effect and describe a decrease in SP values over geothermal areas (where temperature extremes are high). In this study area, as surface temperatures decrease in winter months, a thermal couple develops between the cool surface and warmer ground at depth. This thermal difference may approximate the effects of geothermal areas, and thus SP values decrease as surface temperature decreases. In summer months the temperature differences between surface and subsurface are reversed. A similar correspondence between temperature and SP is noted, although the response is not as marked; this could probably be due to a greater lag time in ground warming for these months.

Conclusions

27. The major conclusions from this research are the following:

a. The SP technique used in this study was effective in detecting SP anomalies which were inferred to represent surface and subsurface drainage or flow paths around a sinkhole. In addition, the SP technique was able to track one anomaly (flow path) for over 600 ft into another sinkhole.

b. Confirmation of the interpretation of the SP data was obtained by visual observation of surface runoff into the instrumented sinkhole, by electrical resistivity measurements, and by geological studies.

c. Although SP values varied significantly during the 6-month (July to December 1985) testing period for individual electrodes, the ranking values between electrodes were consistent. This was also true if the position of the reference electrode was changed. It appeared that changes in precipitation and surface ground temperature had the greatest affect on the variation of SP data over the testing period.

Future Studies

28. The results of this preliminary, proof of concept research for studying flow patterns around sinkholes and for geotechnical applications of the SP method in general will be greatly enhanced by studies to:

a. Confirm and quantify the effects of major environmental factors on SP measurements by monitoring electrode arrays over long periods of time (> 6 months).

b. Instrument and monitor SP electrodes around sinkholes under the controlled release of known quantities of water and at a sinking stream site with known flow rate in attempts to relate SP response to flow rate.

c. Compare and quantify differences in the response of metallic and non-polarizing electrodes to environmental factors and assess the utility of the different electrode types for long term monitoring applications.

d. Develop a library of SP modeling tools (computer programs) for predicting SP response and for interpreting field survey data.

Items a, b, and c will be addressed in Report 2 in this series, and items a, c, and d will be the subject of Report 3 in this series.

Synopsis of Recommended Field Procedure

29. It is clear from the proceeding section that field procedures for geotechnical applications of the SP method are still evolving. Environmental factors such as vegetation, cultural features, and variations in temperature, soil type, and moisture content over the survey site and during the period of a long-term monitoring effort can apparently effect metal electrodes, such as the copper clad steel rods used in the present study, to a much greater extent than non-polarizing electrodes. While it may be possible to compensate for the environmental effects on metal electrodes by careful field procedures and data processing techniques such as presented by Butler et al. (1984), the extra time and effort involved may obviate the advantages of lower cost, easy availability and simplicity of installation and maintenance of the metal electrodes compared to non-polarizing electrodes. With due consideration to the above reservations regarding the use of metal electrodes, the following is an abbreviated field procedure recommendation, with a more detailed and definitive set of recommendations to be given in Reports 2 and 3 of this series:

a. Plan the SP survey to use a single fixed reference electrode if at all possible.

b. Use electrodes which have constant length and install (drive) each to a constant depth.

c. Install the electrode array at least 48 hours before the first set of SP measurements are acquired.

d. Carefully record any variations in soil type along the survey lines and the locations of any cultural features such as piezometer pipes or buried pipes or conduits.

e. Note any unstable readings during SP surveys.

f. Keep a record of rainfall times and amounts during the course of an SP monitoring study.

g. Examine each set of SP measurements for correlations with known conditions and for evidence of reference level shifts compared to previous survey results.

h. Use the procedure presented in Butler et al. (1984) to process SP monitoring data to compensate for reference level shifts and variations in soil type, moisture content, and other non-seepage related SP variations; this procedure produces an SP anomaly data set.

i. Correlate the SP anomaly data with reservoir pool level.

j. Anomaly features which correlate directly or inversely with pool level can be flagged as significant.

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