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FINAL REPORT

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A GEO-HYDROLOGIC STUDY OF THE SULPHUR ARTESIAN GROUNDWATER SYSTEMS AND ASSOCIATED WATERS AT THE CHICKASAW NATIONAL RECREATIONAL AREA, SULPHUR, OKLAHOMA

Submitted to

United States Department of the Interior

National Park Service

Prepared by

Dr. Jim F. Harp, Professor

and

Dr. Stephen G. McLin, Assistant Professor

School of Civil Engineering and Environmental Science
Bureau of Water and Environmental Resources Research
202 W. Boyd, Room 334
University of Oklahoma
Norman, Oklahoma 73019

ORA Project #155-421

Submitted by

Office of Research Administration
University of Oklahoma
1000 Asp Ave., Room 314
Norman, Oklahoma 73019

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I. INTRODUCTION

The School of Civil Engineering and Environmental Science at the University of Oklahoma in cooperation with the National Park Service has completed a three year program of research at the Chickasaw National Recreational Area, Sulphur, Oklahoma. This study was prompted by National Park Service concern of the continuing loss of springs within the Park. In 1906 the Park contained 33 springs. In 1939, 19 springs were present. In the early 1970's seven springs were flowing. Today, only 5 springs remain and observations indicate lessening of their flow rates.

This report document is the culmination of the study effort. The overall goals of this study have been as follows:

1. A study of the artesian well and spring flow cessation.
2. A flood analysis in the streamflow corridors of the Travertine District.
3. An assessment of climatological and aquifer data in order to analyze the statistical parameters over an extended study period.

In addition to direct observations and analysis by the Principal Investigators (Drs. Harp and McLin), the three year effort has been performed as a series of studies which have culminated in three theses by graduate students at the University of Oklahoma and this final report. The Principal Investigators of this study have prompted and directed these efforts, and have served on the thesis committees. These theses, which address various aspects of the study have been intensive and extensive. This element of the project has necessitated that the final re-

port be presented as a summary document with reference back to the theses. These documents of reference are the flood study by Harp (4), a thesis by Barthel (1), a thesis by Kamal (6), and a thesis by Wold (9). Copies of these documents have been presented to the National Park Service already, and must be utilized along with this summary report in order to fully assimilate the information and derive maximum benefit from the study results. There is some overlap of information within the theses. This has been necessary because each thesis has had to academically stand alone.

A. Research Period

The period of this research was from June 1983 to June 1986.

II. OBJECTIVES AND SCOPE OF THE STUDY

The specific objectives of this study as set out in the contractual obligations are as follows:

1. To assemble all hydrologic data for the contiguous Sulphur area in order to organize and synthesize the parametric information obtained into a useful form. The data expected to be analyzed over the period of the study will include, but not be limited to:

    1. rainfall records
    2. runoff records
    3. well flows
    4. spring flows
    5. observation wells
    6. water quality records as they relate to subsurface water movement
    7. Oklahoma Water Resources Board water use reported flows.

2. To conduct a thorough analysis of all data accumulated to determine means, trends, variances, and other useful statistical parameters. Analysis of periods of low or no flows will be performed in order to correlate flows, water usage and hydraulic deficiencies. Computer program SAS was available to perform this task.

3. The major project task will be to incorporate the data base into a computer-based mathematical model designed to simulate present groundwater conditions surrounding the Park area. This effort will assemble the overall data base into a single

interdependent evaluation of important hydrogeologic factors controlling water resources availability. Once this parameter dependency is fully understood, then meaningful impact analyses associated with future aquifer stress patterns will be completed. The end product of this task will be an identification of future hydrologic conditions leading to a temporary or permanent stoppage of spring flows within the Park area.

4. Perform a hydrograph analysis of the subsurface and surface flows to possibly ascertain the base flow and storage constants in the flow system. Utilizing surface flow records and the relationship $Q_t = Q_o K_r^t$, the aquifer storage coefficient ($S = -Q_t/\ln K_r$) can be obtained. From storage changes and rainfall volumes, an accurate recharge area should be estimable. Most prior estimates of the pertinent recharge area vary between 5 and 40 square miles. Project analysis of existing data indicate that the lower figure is probably correct. Additionally, determine the hydraulic aquifer properties of transmissivity and storage coefficient using a time series spectral analysis technique in the frequency domain. Input data requirements include rainfall, observation well water levels and streamflow.

5. To obtain the structural data from available geological maps and observation holes, which is the best method to locate the dip, strike, joint system and faults in the area.

6. An evaluation of potentiometric heads in available wells in and near the study area. The U.S. Geological Survey and Park project personnel have been active in recording well data in the area. A final compilation of this information and overall

evaluation should lend credence to the findings of the hydraulic gradients in the general area of the study. An accurate verification of ground elevations to within 1 foot at all water level measurement points is essential in this compilation process.

7. Primary inquiry indicates that some geophysical well logs are available. Interpretation by the study team is expected to help define the flow system and aquifer tiers in the area of the study. Short circuiting in the aquifer tier system is most likely responsible for the fresh water of the Arbuckle Group, the mineralized water of the Simpson Group and the contributions of the later-deposited Vanoss formation. Subsurface mixing of formation waters should be reflected in Piper diagrams of existing major water quality parameters. These analyses will be utilized to verify and refine modeling efforts under Tasks 3 and 8.

8. By analyzing the available data from Buffalo and Antelope Springs, in conjunction with the decrease of potentiometric head at the Vendome Well, the flow system can be modeled so that the predicted head changes which will result from restrictors and well closures can be accurately determined. The Vendome Well flows an approximate volume of water each day which is equal to that which the City of Sulphur uses each day. The Wyandotte well and the Belleview Plunge wells are both deemed to be scheduled for closure. Water conservancy measures are not reasonable whenever waste, or flow without benefit, is allowed to continue. The Oklahoma Corporation Commission regulates all injection wells and sets out rigid guidelines for users who expect to inject into the lower aquifer tiers. These activities in and

within the study area will be monitored for possible effect on the well flows and aquifer recharge volumes.

9. This effort will assemble the overall data base into a single interdependent evaluation of important hydrogeologic factors controlling water resources availability. Once this parameter dependency is fully understood, then meaningful impact analyses associated with future aquifer stress patterns will be completed. The end product of this task will be an identification of future hydrologic conditions leading to a temporary or permanent stoppage of spring flows within the Park area.

10. Recommendations for the location and installation of a rain gage network for the Antelope and Buffalo Springs recharge area will be made in order to accomplish the long term hydrologic monitoring and data collection input for future optimal system management decisions.

11. To provide the engineering design configuration for weir measurement stations at both Antelope and Buffalo Springs. Also, to design a relief channel in Travertine Creek and the Nature Center to prevent flooding within the center itself. This will require both hydrologic and hydraulic design aspects.

12. A useable resource document which will contain applicable data and information for future planning efforts will be derived, assembled, and published for scientific and lay audiences. The ideas and input of the entire team will contribute to the form, content, and data presentation format. The information to be contained in this document will provide the anticipated planning data for the management schemes and strategies into the year 2000 and beyond.

III. GENERAL STATEMENT

The dominant purpose of this study has been to develop the information and data necessary for planning and management of the waters of the contiguous Sulphur area. All available hydrological information and related data has been assembled bringing together an almost unique array of data for use by those that have need and use for such extensive data. This information is not generally available elsewhere, and constitutes the high value of this study and the report derived therefrom.

In summary this study has been performed to elucidate and accomplish the following tasks:

1. An appraisal of the water and related resources of the area;
2. A projection of the future needs and hydrological deficiencies as a basis for forecasting future demands upon the system in quantitative terms;
3. Translation of project data into useable terms and forms for scientific and lay audiences;
4. Identification of significant problems; and
5. A comprehensive document that will be useful in planning and management of the available water resources.

IV. RESULTS OF THE STUDY

A. Individual Efforts by Principal Investigators

1. <u>Flood Study of the Travertine District</u>

Early in the project an extensive and intensive flood study of Travertine and Rock Creek was performed by Harp (4) and oth-

ers. Drainage areas were measured from topographic maps, cross-sections were determined from field surveys, every hydraulic structure was measured for exact configuration, and the other data necessary for the computer solution to the problem, such as the hydraulic coefficients, were assembled. Computer program HEC-1 (10) was utilized to determine the flood flow magnitudes for the 10, 50, 100, and 500 year hydrologic events. Computer program HEC-2 (11) was utilized to compute the water surface elevations from lower Rock Creek stations upstream to the Travertine Nature Center. The natural and designated flood ways are also determined in the report document (4). The information from the Flood Study was tabulated in the Report (4) and the contours for the natural and designated flow ways were delineated onto the new two-foot contour maps made for National Park Service. Interested readers are referred to the formal study document (4) and the maps, presented to the Park Service in 1984.

2. Design of a Diversionary Channel Around the Nature Center

During periods of high flow, the Nature Center at the Chickasaw National Recreational Area has flooded on several occasions during the past dozen or so years. The channel over which the Nature Center was built is insufficient to carry these high flood flows without flooding the building. It is therefore proposed to construct a diversion channel around the Nature Center to reduce the likelihood of the Nature Center flooding again.

A topographic survey of channel cross sections was made upstream and downstream of the Nature Center. A natural depression exists about 250 ft to the south of the Nature Center which will

be the most logical path of the new diversionary channel. A natural exit point from Travertine Creek exists about 350 ft upstream from the Nature Center. A small bridge, or culvert will have to be built over the proposed new channel to allow visitor usage of the footpath. The downstream re-entry point for the diversionary channel into Travertine Creek should be situated about 250 ft downstream from the Nature Center, at a natural tributary inflow point, and is shown in Figure 1.

A trapezoidal diversionary channel of 10 ft width, with side slopes of 2:1 is sufficient. Computer runs using the HEC-2 program were made utilizing the 10, 50, 100 and 500 year flood flows. Even the 500 year flood flow peak can be successfully carried by this proposed diversionary channel. For this worst case, the computed water surface elevation at the Nature center is 1047.75 ft. The floor elevation of the Nature Center is approximately 1050.0 ft.

The hydrologic conditions as determined from the 1984 HEC-1 flood study were used in this analysis. They are repeated here as Table 1 for convenience. The summary information from the HEC-2 runs are also presented for clarity and convenience along with a sketch for identification of the cross sections. The HEC-2 computer runs have been previously submitted.

It is emphasized that the channel of 10 ft bottom width is the minimum required, and that a larger channel will provide more security, especially if the new channel is expected to be overgrown by vegetation at some future time. Such vegetation would retard any flow and thus reduce the effective carrying capacity

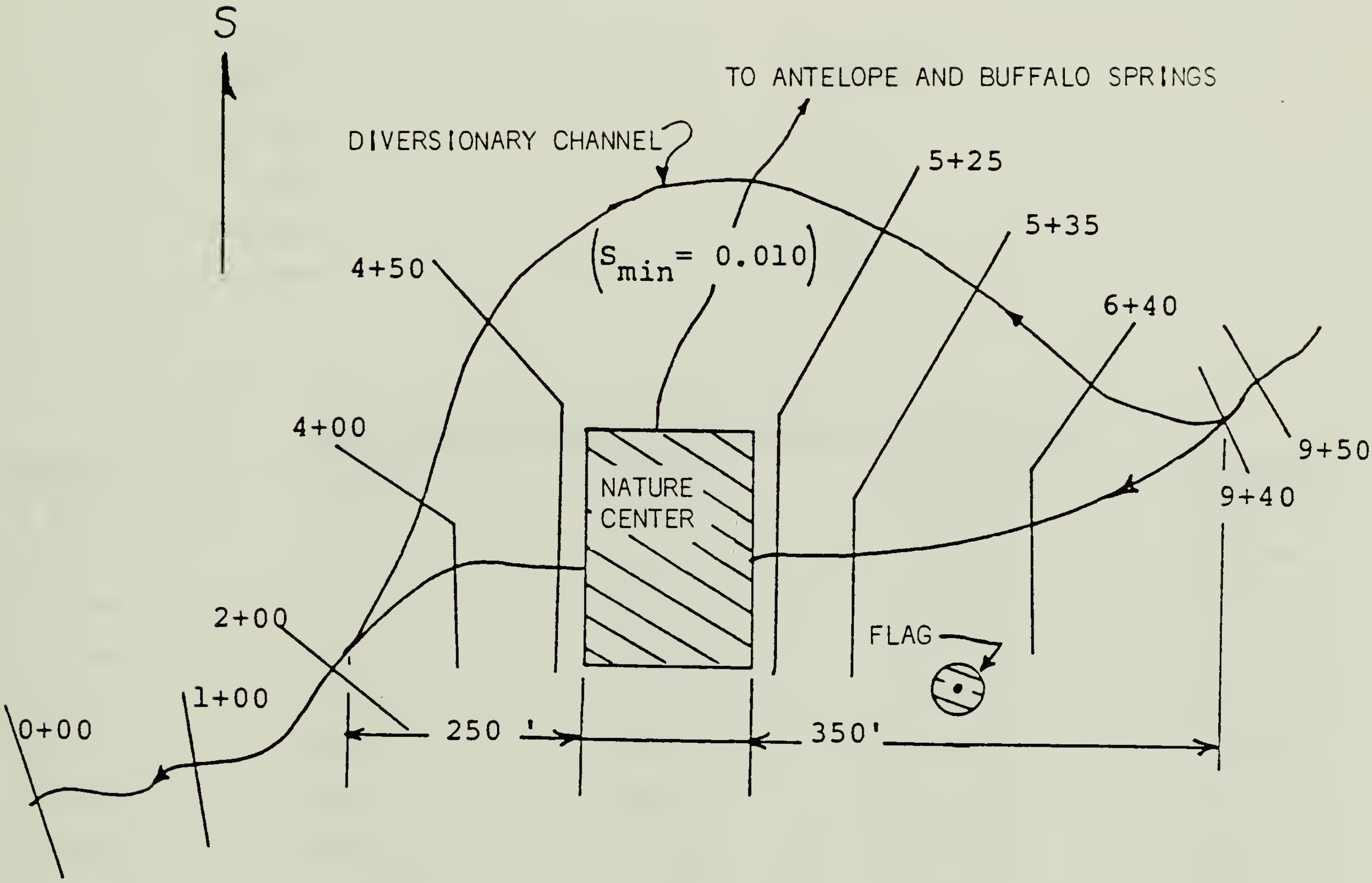

FIGURE 1 DIVERSIONARY CHANNEL AROUND TRAVERTINE NATURE CENTER

TABLE 1

HYDROLOGY

FLOOD	FLOW (CFS)
10 year	874
50 year	1121
100 year	1308
500 year	1695

STATION	COMPUTED WATER SURFACE ELEVATION FOR GIVEN FLOW			
	10 year	50 year	100 year	500 year
1 + 00	1042.43	1042.51	1042.59	1042.72
2 + 00	1043.58	1043.73	1043.81	1043.99
4 + 00	1046.67	1046.77	1046.90	1047.10
4 + 50	1047.15	1047.34	1047.45	1047.65
5 + 25	1047.17	1047.36	1047.48	1047.69
5 + 35	1047.17	1047.36	1047.48	1047.69
6 + 40	1047.17	1047.37	1047.48	1047.70
9 + 40	1047.17	1047.37	1047.49	1047.70
9 + 50	1047.18	1047.37	1047.49	1047.70

of the channel.

3. Hydrograph Analysis of Antelope and Buffalo Springs

Early in the project, it was thought that a hydrograph analysis of the Spring flows at Buffalo and Antelope would be productive in an effort to determine the storage volumes within the aquifer at any time.

Baseflow recession values from both Antelope and Buffalo Springs were difficult to establish because there has been no hydraulic structure of standard, or calibrated, configuration at either Spring from which to determine flow rates. Also, it was difficult to determine from the data available just when recession flows are present at Antelope Spring. A long conveyance channel connects the spring outlet with a downstream outfall. At Buffalo, a rustic weirlike outlet exists but local influx of about 4-6 times the weir overflow is estimated to enter the natural channel just downstream of the weir.

The flows at Antelope and Buffalo Springs have been calculated from the physical configurations of the springs and the pin readings, depth measurements to a pin set-up by Park personnel earlier. This procedure has been used since 1969 to establish the estimated flows at the major openings at Buffalo and Antelope Springs.

The existence of these two springs has been documented since the early 1900's. Antelope Spring may be described as a free-flowing spring which issues from a small, protruding bluff, into a shallow, irregular pool of approximately a hundred square feet surface area. The flow from this spring exits through a rough

opening in the pool, about 5 feet wide, and then flows about 100 feet to the west before passing under a crosswalk bridge, and emptying into a pond. The flow continues out of this pond, eventually into Travertine Creek.

Buffalo Spring wells up from beneath the ground surface into a circular, rock-lined, man-made pool of about 25 feet diameter and 2.5 feet depth. The water exits this pool by a somewhat irregular shaped rock formed overflow channel about 5 feet wide which was built as part of the pool. Water then flows in a natural channel for some 60 feet before entering Travertine Creek. Immediately below Buffalo Spring proper, there is considerable additional water welling up into the creek bed, which increases flow substantially (roughly by a factor of about 6, according to U.S.Geological Survey estimates).

Measurements of the water surface elevations are made at both springs by Park employees. During the first years of data collection, measurements were made monthly. For the past several years data has been collected on a weekly basis. These measurements have been made since mid-1969 at Antelope Springs, and mid-1972 at Buffalo Spring.

The exits from the spring pools are only roughly weir-shaped, they were not constructed by engineering standards as weirs. However, flow calculations were made as follows:

1. The flow from Buffalo Spring was calculated, assuming the exit from the pool acted as a broad, rectangular weir. Flows were calculated for several measured depths, and a least squares linear regression of computed discharge versus

measured depth was made. This calibration curve allowed direct estimates for discharge at other depths recorded at later times.

2. For Antelope Spring, the process was somewhat more difficult. The configuration of the natural channel at the pool exit varies widely from that of a weir. However, about twenty yards downstream, the channel is reasonably regular, and is a close approximation to a broadcrested weir. Data assembled from the physical configuration were used to establish an approximate flow-vs.-depth relationship. Although a new Stevens water surface recorder was established in November 1985 at Antelope, compilation of the data has not been made as of this date.

For both springs it may be assumed that the flow may be described by the weir equation of the following form:

Q = (C) * (b) * (H) ** 1.5,

where

Q = Flow, in cfs

C = a constant, dependent upon the channel or weir shape,

b = the width of the channel or weir in ft., and

H = the head in ft. on the weir at the point in question.

Alternatively, C and b may be combined into a single term, say "K", reducing the equation to:

Q = (K) * (H) ** 1.50

If the flow at a given depth can be determined by other means,

such as critical flow equations, it is then possible to back-calculate "K" for the equation, and the specifics of "C" and "b" are not essential.

One other aspect of these particular springs must be taken into account, and that is the fact that there must be a finite depth in both springs before flow will occur. This depth will appear in the above equations as a correction to the height value, as follows:

$$H = P.R.-d$$

where

H = the head on the weir, as before,

P.R. = the actual pin reading of the depth of the stream, at the point of measurement, and

d = the depth at which flow actually begins over the exit "weir" from the springs.

The equation is now reduced to:

Q = K * (P.R.-d) ** 1.5.

To use the equation, it is first necessary to establish the "d" components of the separate equations for each spring. For Buffalo, there is a notation in the October 1978 Park data files that the depth at which flow began was 1.82 feet; this established "d" for Buffalo. For Antelope, a study was made of flow depths, from the old field notes, and pin readings taken by the Park employees. These, with some engineering judgement, established a "d" value of 0.6 feet for Antelope. It should be noted that the pin at Buffalo Spring was discovered to be missing in October of 1981, after an extended dry spell. The pin was

replaced, but is not at exactly the same height as the original; based upon field observations and conversations with Park personnel (Mr. Randy Fehr), it appears that the new correction factor, "d", should now be 1.97 feet.

Using these "d" values, flow calculations were made using the older field notes, and data from recent trips to the area. This resulted in the "K" value of 10.44 for Buffalo and 8.69 for Antelope.

As a result, the following equations have been developed, and have been used in calculating spring flows for usage throughout this project:

For Antelope Spring;

$$Q = 8.69 * (P.R.-0.6) ** 1.5.$$

For Buffalo Spring;

$$Q = 10.44 * (P.R.-1.97) ** 1.5.^{\dagger}$$

Area well usage data, obtained from the Oklahoma Water Resources Board for the period of 1964 through 1985, partial, are summarized by Kamal (6). The blanks in the data indicate no data were reported to the State Water Board. These data are highly suspect in that they are reported by laymen, having little background, or knowledge of how to compute these values. The U.S. Geological Survey deems that these values are only rough approximations and should be used accordingly. Generally, within the State, crop production, etc. are better indicators of water usage.

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† For data prior to October 1981, "d" should be taken as 1.82.

4. Recession Hydrograph for Buffalo and Antelope Springs

The hydrograph is widely used to indicate the flow rate and volume of water through a drainage basin over a period of time. The descending leg of the hydrograph, to the right of the peak, is termed the recession curve, and represents surface water runoff, interflow, and actual groundwater discharge to the stream in question, termed base flow. Over time, the direct runoff ceases first, followed by the interflow, eventually leaving the base flow as the only component of flow. The base flow recession constant, K_r, was determined graphically by plotting a straight line onto the graph where it is judged that only base flow recession conditions exist. Given the shapes of the recession portions of the flow curves for these two springs, this method was deemed unsatisfactory. Readings of water height, and consequently flow, are too far apart to yield a useful graph.

Instead, a method proposed by Langbein (7) was used. This method is also reported by De Wiest (2). Using this method, Barthel (1) plotted a number of points from the recession portions of the flow curves, plotting q_n vs q_{n+1}. In this study, it was uncertain exactly where the groundwater portion of the recession curve started, so that the selection of data was somewhat arbitrary. The points selected indicate some data "scatter"; however, both sets of points yielded essentially the same recession coefficient, a K_r of 0.7, based upon a "best fit" by eye. The numerical value of K_r has no direct meaning. The importance is that each data set produced the same K_r value, which given the relative closeness of the springs to each other, their common

source, and near-identical elevation, is not surprising. The result of this analysis is shown in Figures 2 and 3.

5. Calibrated Weir Design for Antelope and Buffalo Springs

As part of this study it was important to design outlet hydraulic structures at both Antelope and Buffalo Springs. At the time of this writing, a new stage recorder has been installed at Antelope Spring. However, a new calibrated weir structure is essential for continuing data accumulation and ongoing analysis of spring flows. A summary design for both the weir structure at Antelope and Buffalo respectively are presented below in Table 2. From past records, and an application of weir fundamentals, the various flow magnitudes have been estimated below.

TABLE 2

PARAMETERS	ANTELOPE	BUFFALO
Q_{max}	4.35 cfs	8.0 cfs
Q_{min}	0 cfs	0 cfs
Q_{avg}	1.81 cfs	6.0 cfs
Weir width	4 ft	6 ft
Weir Constant K (Q=K*H ** 1.5)	12.83	19.26

The weir at Antelope should be placed near the walkway area outfall. The weir at Buffalo must be placed where the small tributary runs into Travertine Creek. This is about 40 yards downstream from the circular pool area. This is due to the local inflow that enters the stream downstream from the existing weir at the pool exit. The U.S.Geological Survey has recently estimated the local inflow to be about 5-6 times the flow rate which

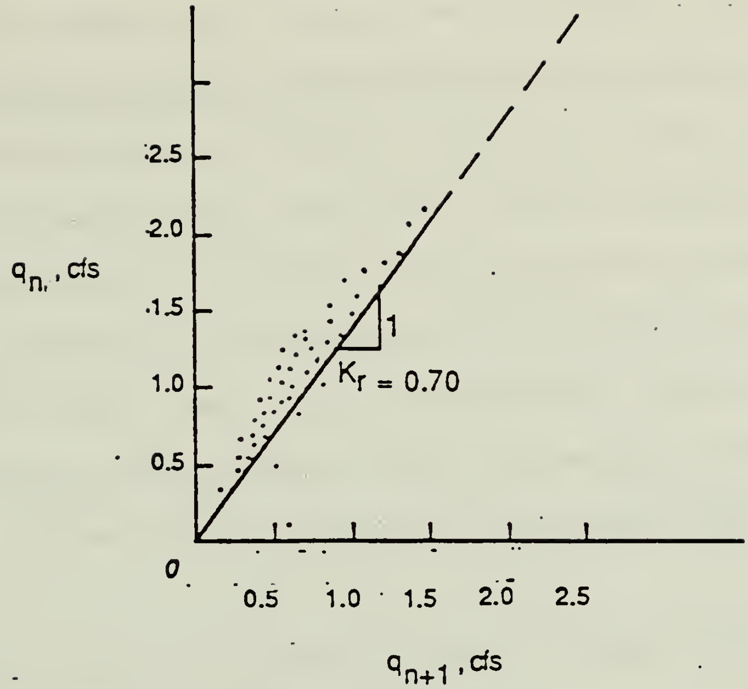

FIGURE 2 BUFFALO SPRING
ANALYSIS OF BASE FLOW DATA (SHOWN AS POINTS)

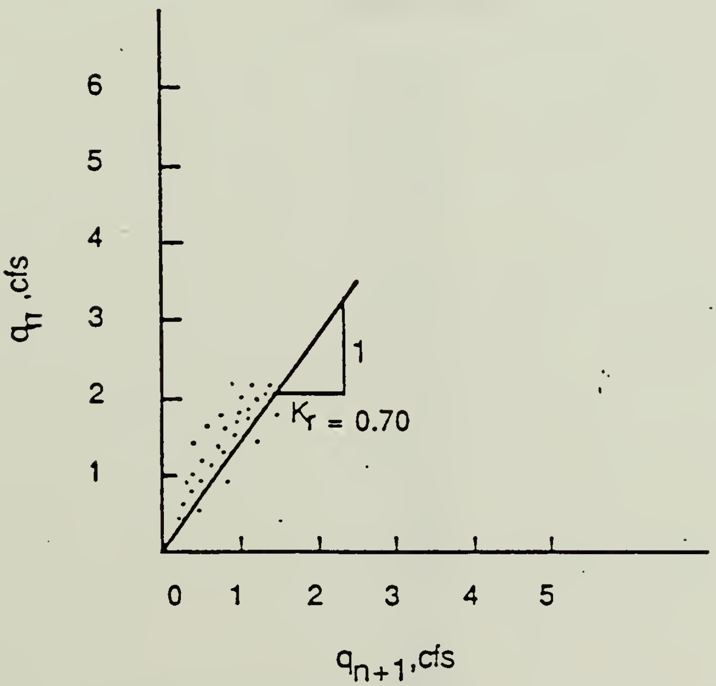

FIGURE 3 ANTELOPE SPRING
ANALYSIS OF BASE FLOW DATA (SHOWN AS POINTS)

which exits the pool area proper. The flows at Buffalo will not be accurately known until the new weir is built and calibrated.

6. Miscellaneous Observations at the Vendome Well

The Vendome Well is the most famous artesian well in the area. It is located near the Park's north boundary, about 10,000 feet west-northwest of Buffalo and Antelope Springs, and about 1600 feet northwest of Pavilion and Hillside Springs. This well is about 365 feet deep and was reportedly drilled about 1922. The piezometric head readings shown below were recorded occasionally. The computed well flows were obtained from the relationship

$$Q = C_D * A * (2gH) ** 0.5 = 1.5 (H) ** 0.5$$

where $C_D = 0.9$

$A = 0.25 * PI * (0.5 ft) ** 0.5$

$g = 32.2$ ft/sec/sec

Date	Head (ft.)*	Q(cfs)*
Oct 1972	1.5	1.85
Jan 1973	1.6	1.90
Jun 1974	1.6	1.90
Feb 1975	1.5	1.80
May 1976	1.4	1.80
Jul 1977	1.4	1.80
Mar 1978	1.1	1.60
Jul 1979	1.2	1.70
Jun 1980	1.0	1.50
Oct 1981	1.1	1.50
Feb 1982	1.0	1.50
Dec 1982	1.0	1.50
Feb 1983	0.9	1.40
Dec 1983	0.9	1.40
Feb 1984	0.8	1.30
Jun 1984	0.8	1.30
Dec 1984	0.7	1.20
Jun 1985	0.7	1.20
Sep 1985	0.7	1.20
Dec 1985	0.8	1.30
Jan 1986	1.1	1.60
Mar 1986	1.0	1.50

* (This data is deemed to be of poor accuracy.)

The Vendome Well flows a volume of water each day which is about equal to that which is pumped by the City of Sulphur during the sample period. The various other surrounding wells add significantly to this depletion process. It is highly possible that if the Vendome Well were partially shut-in that the flows might be increased in other artesian springs such as the Wyandotte and the Belleview Plunge, not to mention the other private wells that flow near the Park.

The Principal Investigators believe that if the Vendome Well were partially shut in and that the Wyandotte well, the Belleview Plunge wells, and other nearby private free flowing wells were closed off completely that the aquifer could recharge and either eliminate the flow cessations at Antelope and Buffalo Springs, or lengthen the time between flow cessations, assuming that external pumping is disregarded. The complicated aquifer tier arrangement makes exact prediction impossible, but the Principal Investigators believe that the aquifer reservoir system could be replenished and produce a positive effect upon the Park water inventory resources and the important spring flows.

From photographs taken in the 1930's, the Vendome Well issued to a height of more than 20 ft. Today the jet issues about 1 ft in height and has been lower than 1 ft. So, based upon historical observations, the fresh water from the lower Arbuckle aquifer possibly could show an increase in potentiometric head if all nearby Arbuckle wells were shut-in. It is reasonable to anticipate that such action would improve spring flows originating from the lower Arbuckle aquifer.

Improvements in Antelope and Buffalo Spring flows originating in the upper Arbuckle aquifer may also be possible if sufficient hydraulic communication exists between the upper and lower portion of the aquifer.

The water quality of the lower aquifer system could be adversely affected if lower Arbuckle wells are closed, but it is felt that this is unlikely. The specific gravity of fresh water is less than that of mineralized or upper solution-dissolved, cavity-produced, reservoir quantities. Upper to lower Arbuckle aquifer recharge and subsurface water circulation will tend to further pressurize these lower zones and prevent undesirable quality problems from arising, if prudent management policies are monitored and performed.

7. Rain Gage Network for Recharge Area

The rain gage network necessary to measure the average depth of precipitation over the area of recharge for Antelope and Buffalo is suggested in Figure 4. This recharge area was determined by Barthel (1) and deemed to be reasonably accurate. This area was determined by a well survey and potentiometric isoline separation. The area is only about 6 square miles, in contrast with an area about 7 times larger than was suggested by previous investigators. This smaller recharge area for Buffalo and Antelope Springs is consistent with recent flow cessations, especially in low rainfall years.

It can be noted that a number of rain gages could be placed in the area, at great expense. Actually only two gages are necessary to measure the rainfall over both the Arbuckle and Simpson

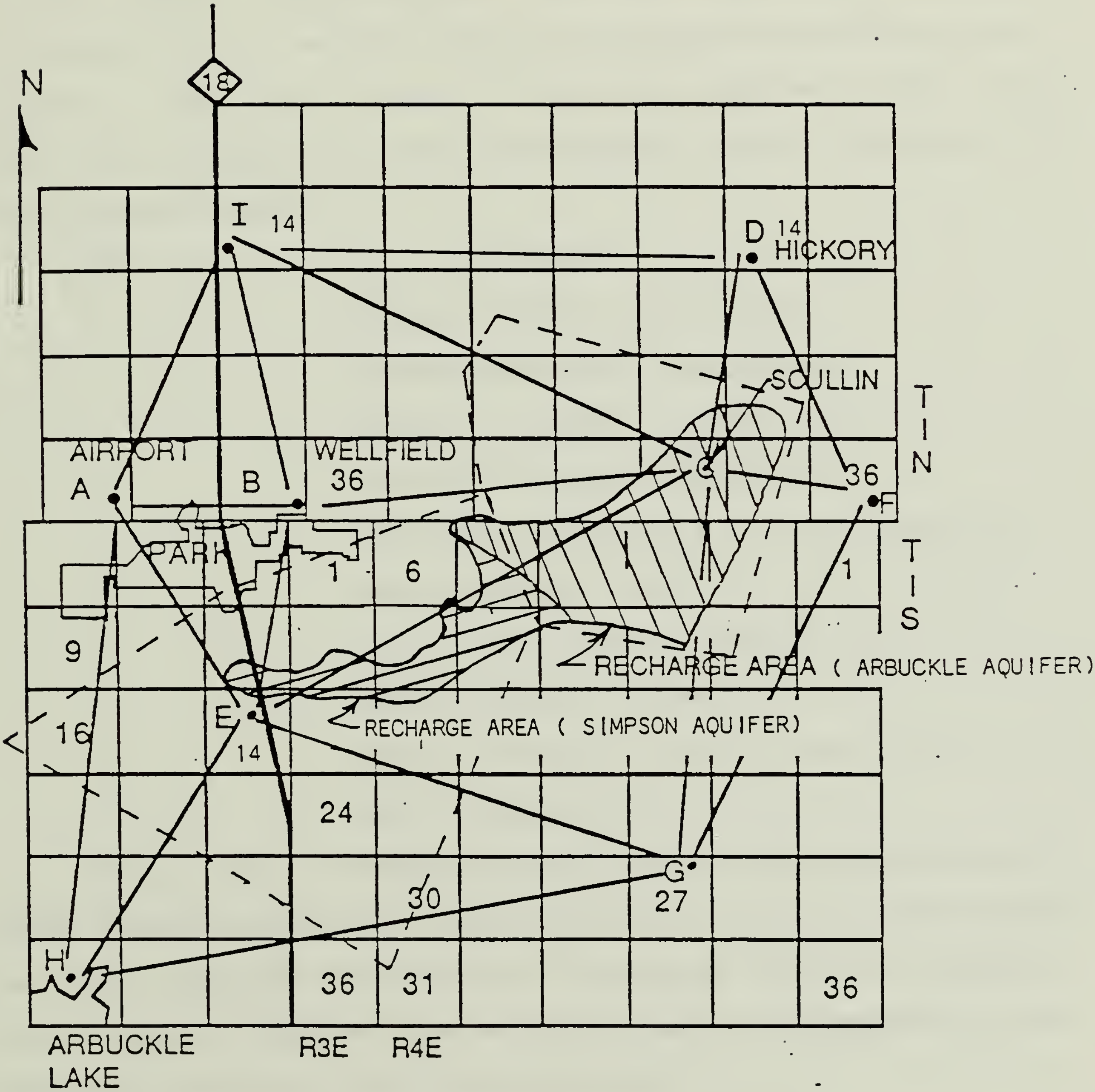

FIGURE 4 PROPOSED RAINGAGE NETWORK

(LETTERS REFER TO RAINGAGE SITES)

(NUMBERS REFER TO LEGAL SECTIONS)

(------ DASHED LINES REPRESENT THEISSEN POLYGONS)

Group recharge areas. These gages, C and E, as shown in Figure 4, are the only ones that are needed. Rain gage C will provide data for the Arbuckle Group aquifer which contributes water to both Antelope and Buffalo Springs. Rain gage E will provide data for the Simpson Group aquifer. The other gages are ultimately recommended for an ongoing program of detailed precipitation measurement. They are located at the most expedient sites. The sites were established using the Theissen polygon technique and are tabulated below:

SITE	LOCATION
A	Sulphur Airport, Section 33
B	Sulphur Well Field, Section 35
C	Scullin, Oklahoma, Section 34
D	Hickory, Oklahoma, Section 14
E	South Park Entrance on H.W.18, Section 14
F	Winrock Ranch, Section 36
G	Section Line road in Section 27.
H	Arbuckle Lake, Section 33
I	North of Sulphur on HW 18 near O.G.& E. Wells, Section 14

These sites, in combination with another gage located someplace between Sulphur and Davis along the interconnecting highway at a site adjacent to the water conservancy district standpipe, are the most convenient ones available and are recommended as the official network for long range planning.

The two gages, letters C and E, are the vital components of an essential network for near-term precipitation measurement, and

ultimate assessment of the recharge rate for both aquifer systems which are responsible for all spring flows within the Park.

For the network shown, the average precipitation P_x is given by:

$$P_X = [(P_C * 6.0 + P_E * 2.1)/8.1]$$

where P_x is the average precipitation in inches,

P_C and P_E are the respective gage recorded amounts, in inches, and where 6.0 and 2.1 square miles are the respective Theissen polygon areas surrounding gages C and E. If possible, recording gages should be used, but nonrecording gages will suffice if read daily, and used as daily rainfall amounts. Actually, the present rainfall data that is being collected by the Park Service is recorded in daily amounts, and averaged as monthly variates.

8. <u>Reports</u>

In addition to two previously submitted project progress reports, this Final Report of the project which contains an overview of the above efforts (including the theses) has been prepared.

B. Theses Derived from the Project Research Effort

The following material is a brief synopsis of the theses as directed by the principal investigators:

1. <u>Thesis by Barthel</u>

A thesis by Charles Barthel, Jr. (1) concentrates on the study of the flows of Antelope and Buffalo Springs, although all spring flows within the Park were studied.

The principal objectives of this thesis were: (1) review all

past data and reports pertinent to the study; (2) determine the origin of the waters of Antelope and Buffalo Spring; (3) classify Antelope and Buffalo Springs in technical terms; (4) assess the geologic and hydrologic characteristics or parameters of the aquifer which provides water to Antelope and Buffalo Springs; (5) determine the recharge area(s) of all springs within the Park; and (6) utilize a ground water model (Prickett-Lonnquist) to quantify the aquifer characteristics at various sites.

A definite correlation between flow data of Antelope and Buffalo springs and water level data of the two Park Service observation wells was established. Additionally, through statistical analysis it was shown that the peak discharge of Antelope and Buffalo Springs closely correlates with peak rainfall events in the spring and fall. Water level data of the two National Park Service observation wells provided the basis for long term hydrograph analysis which indicate that the ground water level is decreasing at a rate of 0.65 feet per year. It was determined that continuation of this trend will result in the springs becoming permanently dry in about 40 years.

As a further study of the long term trend of the flow of Antelope and Buffalo Springs, rainfall records and the recorded times when the springs have been dry were analyzed. Data evaluated extend from 1919 to 1984. Barthel divided the data into four portions as follows: (1) from 1919 to 1934 the average rainfall was about 10% above normal and the springs were dry 0.58 years, (2) from 1934 to 1949 the average rainfall was about 70% above normal and the springs were dry 1.83 years, (3) from 1949

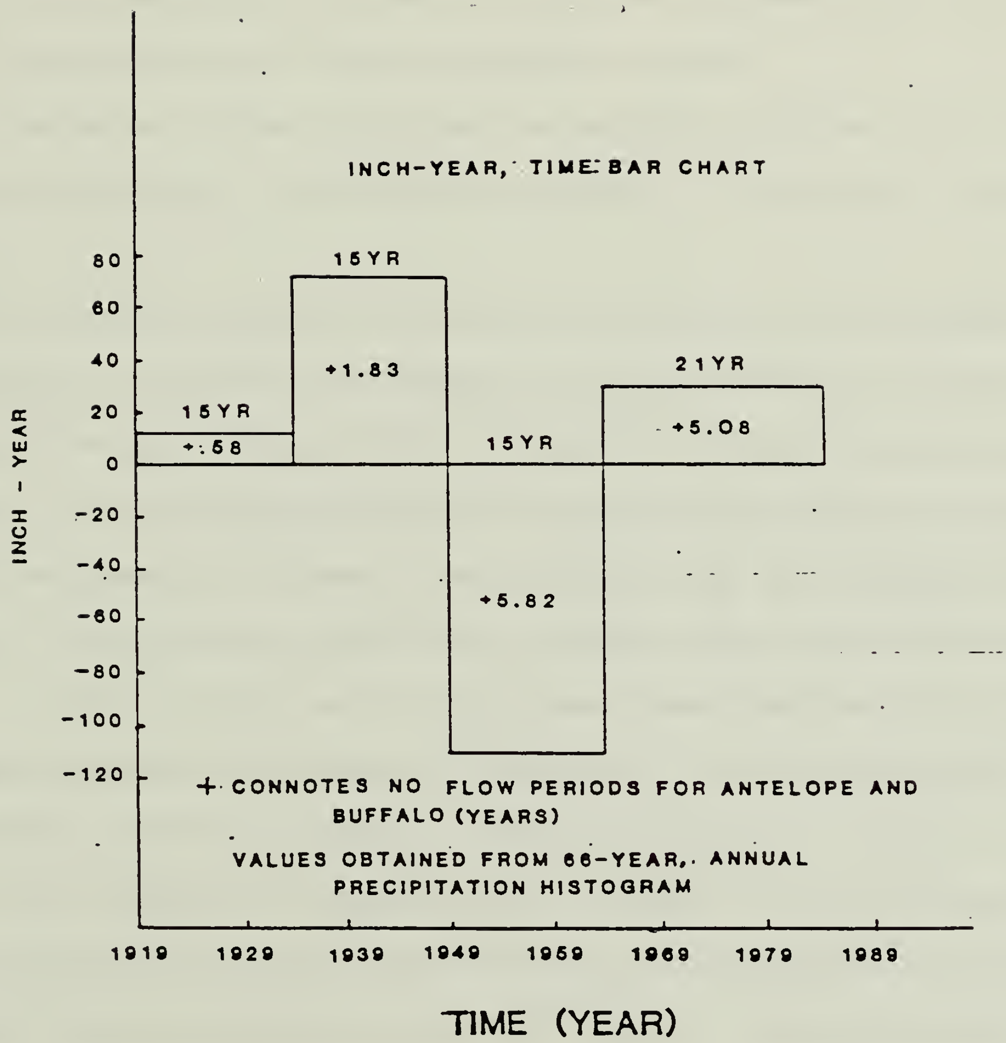

FIGURE 5 INCH-YEAR, TIME BAR CHART THAT DEPICTS ABOVE OR BELOW NORMAL PRECIPITATION AMOUNTS FOR A SPECIFIED PERIOD, IN RELATION TO NO-FLOW PERIODS AT ANTELOPE AND BUFFALO SPRINGS. (AFTER BARTHEL)

to 1964 the rainfall was about 110% below normal and the springs were dry 5.82 years, and (4) from 1964 to 1984 the rainfall was about 25% above normal and the springs were dry 5.08 years (see Figure 5). This analysis supplements the long term hydrograph analysis in showing that these springs are increasingly going dry - even during periods of above average rainfall.

In technical terms Antelope and Buffalo Springs are classed as third-magnitude, intermediate-response, freshwater artesian springs.

The Arbuckle aquifer was studied by porosity measurements of core samples, barometric efficiency tests on the two Park Service observation wells, "slug tests" on these wells and the results of the model. These efforts involved testing the aquifer to determine in mathematical terms the transmitting and storage properties of the geologic formations through which the ground water moves. A water table map of the area was prepared from water level measurements collected by Barthel. It was concluded that the overall average aquifer transmissivity is about 43,000 ft^2/day, the hydraulic conductivity is about 1.6 ft/day, and the storage coefficient ranges from 0.0012 to 0.0001 near the spring. Also, the study indicates that the aquifer characteristics are not the same at every place. Instead, the ability of the aquifer to allow water to flow (hydraulic conductivity) decreases near the Park.

The authors conclude that the ground water of the Arbuckle Group is responsible for the flow of Antelope and Buffalo Springs. Further, the flow regime of this aquifer is greatly

controlled by the regional dip of the geologic formations to the northwest in combination with effects caused by the Sulphur fault. These effects include the fault plane proper and the surface exposure of the Simpson Group which, as the result of fault displacement, is present to the south of the fault. The Simpson Group is shown to be much less permeable than the Arbuckle and thus flow to the south, beyond the fault, is retarded.

The location of the Sulphur fault in the vicinity of the Park is inferred by field geologic examination of the area, the location of the springs in the Park, ground water flow parameters as determined in this work, analysis of water level data, similarities of water chemistry at various springs and wells, and water level data of wells throughout the area. The location of Antelope and Buffalo Springs is believed to be the combined result of the Sulphur fault in the immediate area, and the relatively impermeable nature of the Simpson aquifer.

The recharge area of the ground water system from which Antelope and Buffalo Springs derive their flow was mapped and determined to be about 6 square miles as shown in Figure 4. This recharge area is composed of the Arbuckle Group, a highly fractured limestone aquifer, which is exposed at the surface to the east of the Park. This aquifer system is also the water source for the City of Sulphur well field. In all probability, waters from the Arbuckle aquifer combine with those of the Simpson aquifer to provide the water source for the Vendome well, artesian wells within the town, Oklahoma Gas and Electric wells,

and Hillside, Pavilion and Black Sulphur Springs within the Park. It is believed that subsurface mixing of lower quality Simpson waters with higher quality Arbuckle waters is more pronounced as one moves down-dip, toward the west, from the recharge area into the Arbuckle aquifer. The recharge area of the ground water system of the Simpson Group was mapped and determined to be about 2 square miles. It is exposed at the surface to the southeast of the Park. These ground waters are believed to be partly responsible for the flow of Hillside, Pavilion and Black Sulphur Springs and were the source of water for Medicine and Bromide Springs, which are now dry. Recharge to both the Arbuckle and Simpson Groups is by precipitation. The recharge area for both of these aquifer systems is outside the Park.

2. <u>Thesis by Kamal</u>

A thesis by Mostafa Kamal (6) is a study of Antelope and Buffalo Springs as related to the Arbuckle aquifer.

The objectives of the thesis were to:

(1) Study the relationship of rainfall, depth of spring flow of Antelope and Buffalo Springs, and water levels within both the east and west National Park Service observation wells using spectral analysis. Monthly values of the data were used in this effort.

(2) To develop and use an amplitude transfer function for a linear aquifer system in order to more accurately determine aquifer transmissivity, (T), and storage coefficient, (S).

(3) To further refine aquifer properties of the Arbuckle

Group in the eastern portion of the Park by correlating them with precipitation percentages becoming aquifer recharge.

This spectral analysis by Kamal is an extension of the work by Barthel. This earlier work indicted that the groundwater regime in the eastern portion of the Travertine District is not artesian. The assumptions necessary for Kamal's model analysis are that the linear aquifer system is infinite in areal extent and that the aquifer has negligible slope. It is realized that these assumptions do not exactly correspond to the actual physical conditions but are a close approximation. The results for T and S are considered to be superior to previous values of aquifer characteristics determined by other methods.

This complex mathematical/statistical study of these data allowed the determination of an array of aquifer characteristics. Kamal lists the determined array with corresponding realistic recharge values as 4 to 15% of rainfall which directly enters the ground water as recharge. The determination of the actual recharge value is beyond the scope of this thesis. His overall analysis indicated that the aquifer characteristics are that the transmissivity ranged from 1080 ft^2/day to 10,200 ft^2/day, and that the corresponding storage coefficients ranged from 0.09 to 1.0. However, considering all combinations of the individual data base, Kamal believes that the best data set for analysis of the Arbuckle aquifer is obtained by the use of the data of Buffalo Spring, the east observation well and rainfall. These data indicate a transmissivity of 13,000 gpd/ft and a storage

OR 1740 ft^2/day

coefficient of 0.248, for the "correlated input case" and correspond to 6% of precipitation entering the aquifer as recharge.

The analysis provides guidance for future efforts in refining the aquifer characteristics as well as the mathematical development of the equations necessary to evaluate future data. It is vital to independently determine an accurate estimate of recharge as a percentage of precipitation in future work.

3. Thesis by Wold

The thesis by Steven Wold (9) concentrates on an examination of anticipated flow of Antelope and Buffalo Springs which would occur if additional pumping wells, recently permitted by the State of Oklahoma to the Roos Ranch, are drilled and pumped at the permitted rate.

The first objective of the thesis was to determine if the proposed Roos Ranch wells would, with time, result in Antelope and Buffalo Springs going permanently dry. The second objective was to evaluate the effect, if any, that the proposed Roos Ranch wells would have on the recharge area of these springs.

Several models of the local ground water system were developed to allow various evaluations. The first model (Prickett-Lonnquist) was utilized to simulate the known ground water configuration of the area, using both a "mathematical simulation" and a "physical simulation". In each case the model was run to predict the resulting ground water conditions under three separate conditions: (1) the full pumping of all wells including the proposed Roos Ranch wells, (2) plugging the Vendome Well before

the Roos Ranch wells begin pumping, and (3) plugging both the Vendome Well and the Oklahoma Gas and Electric Wells before the Roos Ranch wells begin pumping. In each case the model indicates that Antelope and Buffalo Springs will permanently go dry within ten years.

The Theis method, another model, predicts sufficient lowering of the water table at Buffalo and Antelope Springs to cause cessation of flow due solely to the effect of the proposed Roos Ranch wells. This model assumes that all proposed wells are placed in operation at the same time. The results of the model indicate that the springs would go permanently dry in one to five years.

The last model is similar to the one discussed above, however, the production mode of the proposed wells at the Roos Ranch is modified to allow the pumpage of a single well for two years, then an additional well would be placed in service sequentially until all wells are in full production. This is believed to be the most practical and realistic scenario of possible future development at the ranch. Under these conditions the springs would become permanently dry in two to twenty years.

It was determined that the pumpage of the proposed Roos Ranch wells would have an adverse effect upon the recharge area of the Arbuckle aquifer system. This effect would result due to the lowering of the ground water levels near the large production wells. This local lowering aspect, technically called the "cone of depression", would extend far beyond the wells themselves and would result in the change of the location of the ground water

divide. Thus, the ground water divide would move to the west toward the City of Sulphur and the Park. The hydrologic consequences of this shift in the position of the divide would drastically reduce the area of rainfall capture that feeds recharge waters to both Antelope and Buffalo Springs and the City of Sulphur well fields. These simulations indicate that shortly after the Roos Ranch wells have begun pumping the recharge area of the Arbuckle aquifer will be decreased in size. This action will result in a lowering of the water table in the general Sulphur area and permanent loss of the artesian flows from Antelope and Buffalo Springs.

The above models utilize an array of ground water or aquifer characteristics/parameters, transmissivities and storage coefficients, as determined by various authors utilizing different methods. The variations in predicted times, as given by the models above, are to some extent, a reflection of the different aquifer parameters used. However, the necessary simplification of the models is due to a lack of completely adequate overall data of the geology/aquifer. The author presents six recommendations for future study.

V. ANALYSIS OF THE STUDY

A. Analysis of the Data

The Simpson-Arbuckle aquifer at the eastern boundary of the Chickasaw National Recreational area demonstrates the characteristics of an unconfined aquifer even though it is overlain by the impermeable Vanoss Conglomerate. This phreatic

(non-artesian) behavior is deemed to be in response to the presence of faults and fractures which apparently extend laterally for several miles under the Vanoss Conglomerate. The Springs unquestionably emerge from these faults and fracture extensions within the eastern Recreational Area boundaries.

In an effort to analyze historical data for this study, it was decided that the most productive analysis possible, and the best method available would be to use a relatively new technique called spectral analyses. A complete description of the aquifer spectral response has been performed by Kamal (6) and the reader is referred to this thesis for complete details. Spectral analysis response has been performed for rainfall, Antelope and Buffalo spring stages, and water table elevation of the two Park Service observation wells, using monthly data. Data were analyzed on the IBM 3081 mainframe computer available at the University of Oklahoma using a time series analysis in the frequency domain. This procedure utilizes bivariate analysis which yields amplitude transfer functions which are then used in a demonstrative graphical solution to ultimately determine the transmissivity and storage coefficient of the Arbuckle aquifer. These results were comparable to other studies performed earlier using more simplified means. In the present study, time series of complex events are used. Time series data of rainfall, spring stage, and water table elevation, as extracted on a monthly basis, were used. Analysis in the frequency domain was carried out to find the hydraulic transmitting properties of a ground water aquifer in a linear system.

Although the exact rate of groundwater recharge was indeterminable, values of from 4 to 15 percent of rainfall are deemed to be reasonable. From Kamal (6) the reader can make a determination of aquifer characteristics over a range of recharge fraction magnitudes. For example, if one assumes a recharge fraction of say 6% of annual rainfall, the transmissivity and storage constant are 13,000 gpd/ft and 0.248 respectively, assuming correlated input data. This value of recharge provided suitable calibration of the Prickett-Lonnquist Model. These values are reasonable and compare favorably with previous work. The values obtained in this way, using spectral analyses, should be the most accurate values possible because all of the data collected over the entire time period of monitoring was utilized.

B. Structural and Geological Findings

An excellent summary of the structural geology of the area has been presented by Barthel (1). This study found extensive limestone formations in the Arbuckle Group outcrop areas. From video analysis obtained from a downhole television camera log at the Vendome and Horsman wells, massive solution cavities can be seen. The dissolution of the limestone formation has long been reputed to be the explanation of the mineralized content of the various wells and spring water quality. As mentioned earlier, the apparently confined Arbuckle aquifer near the eastern Park boundary behaves as though it were unconfined. The studies of Barthel (1), Kamal (6), and Wold (9) have all demonstrated that the structural history of the Simpson-Arbuckle Aquifer reflected in numerous faults and fractures explains this behavior.

The recharge area for Antelope and Buffalo Springs was originally thought by early investigators to be about 40 square miles. This was stated by Hart (5) and others on several occasions. A survey of the surface features tends to lead one to the conclusion that this is accurate. However, Barthel (1) has demonstrated that this estimate is much too high and the actual recharge area is only about 8 square miles for both the Arbuckle and Simpson aquifers. Barthel demonstrated the correctness of this estimate by using a well survey to construct a potentiometric map. On this map the ridge line delineation leaves little doubt that the recharge area is much smaller than historically stated by those who had no access to the data which was available in this study. This area is shown in Figure 4.

C. Water Quality Analysis

Water quality records within the Park area are sparse and there is no ongoing program of water quality analysis. Barthel (1) provides a summary of the available water quality data and the respective locations as shown in the form of Stiff Diagrams. Generally, the results depict a higher than normal amount of sodium and chloride from the Simpson aquifer region. However, lower than average amounts of sodium and chloride exist in the Arbuckle Aquifer. The dissolved solids content of Simpson derived water is about 500-800 mg/l, while the Arbuckle derived water is about 200 mg/l. An analysis of Vendome Well water indicates a high total dissolved solids content of about 1200 mg/l. As indicated by Barthel (1) these values have been nearly constant over the period of available data. Previous investigators, namely Hart (5) have used water quality as a basis of as-

certaining the spring source delineation.

Hart (5) concluded that the Sulphur Fault is the primary controlling feature isolating the freshwater springs, Antelope and Buffalo, from the remainder of the springs in the Park. He attributed the occurrence of mixed waters in the center of the Park and north of the Park to waters from the small veneer of Simpson sediments overlying the elevated Arbuckle dolomites. He determined that Bromide and Medicine Springs originated from the sandstone of the Simpson Group. Both have been dry for a decade. He substantiated this particular finding by conducting a water quality analysis of the Simpson Group. Harp and Laguros (3) concurred with previous investigators that the occurrence of artesian springs in the Park was the result of pressurized water flowing upward through fractures and joints in the younger, overlying formations; ultimately discharging from the Pontotoc Group.

Harp et al. (3), conducted an investigation primarily to determine the deprivation effects of production wells on spring flows in the Park. Also, the authors presented additional information to clarify and elucidate upon Hart's (5) findings.

D. Projected Life of the Aquifer

Barthel (1) analyzed the aquifer using well flows as reported by well owners to the Oklahoma Water Resources Board, as required by Law. He deduced from his aquifer calibration and computer results from the Prickett-Lonnquist Model that flow cessation of both Buffalo and Antelope Springs could occur in as little as 20 years, and as much as 40 years, depending upon

interpretation of data and results. The Barthel study did not consider the presently proposed pumping from the Roos Ranch wells because the wells were approved by the Oklahoma Water Resources Board near the end of his thesis work. Yet, the analysis of that aquifer stress condition was absolutely essential to the project in order to provide a complete analysis of the aquifer.

Thus, a year later the Principal Investigators directed Wold (9) to study the expected aquifer response to simulated pumping from the proposed Roos wells utilizing the Prickett-Lonnquist model (8) to expand upon the analyses and work of Barthel (1).

Wold assumed three scenarios under which he analyzed the response to the Roos Ranch pumping operations. These scenarios are listed below:

1. All wells and springs flowing and the Roos wells in full operation.
2. All wells and springs flowing except the Vendome Well.
3. All wells and spring flowing except the Vendome Well and the Oklahoma Gas and Electric wells.

In all three scenarios, cessation of flows at Antelope and Buffalo Springs was expected to occur within ten years. This is predicated upon continuous pumping rates. Actually, flows and pumping rates will probably not be constant, and thus the time may be longer than the ten year exhaustion period predicted by the computer model.

Another scenario assuming all wells producing at the present rate and all springs flowing, except the Roos ranch wells, was performed by Barthel (1). That result was that flow cessation at

Antelope and Buffalo would occur in as little as 20 years. An additional interpretation of Barthel's data was that the Springs would cease to flow in as short a time as 40 years assuming no Roos Ranch well flows. The principal investigators feel that the best estimate from the data and analysis is that spring flow cessation will occur somewhere between 20 and 40 years without the Roos wells in operation, and about 10 years or less with the Roos wells in full operation.

Relatedly, the time before the aquifer will cease to provide artesian water for the City of Sulphur may be only slightly longer than the time of cessation of the Park springs and should be of great concern for the City of Sulphur. The analysis for the City of Sulphur Well Field exhaustion prediction was not made, but the background and data are now available for a computer analysis of this event.

VI. SUMMARY STATEMENT

The research project, which lasted for three years, began with the intensive flood study which was performed using the approved Federal Emergency Management Agency (FEMA) procedures. This phase of the project was important for two reasons: (1) it established the floodways and flood fringe areas for purposes of safety and park management information, and (2) it determined the complete surface water hydrologic and hydraulic aspects for future design and operation purposes. The results were presented in great detail (4) and the document provides a uniqueness not available prior to the study.

The other project efforts to determine hydrograph analysis, weir designs, a diversionary channel around the Travertine Nature Center, and important recharge areas have all been fruitful and present with rigor, accuracy, and detail, useful information heretofore not available.

The three theses constitute the principal project effort, in that each thesis dealt with extensive data, predictive analysis, and quantitative results utilizing state-of-the-art techniques.

The total project reports, data, and theses have provided, in a useful form and manner, the data and information for both present and subsequent study and analyses whereby, management decisions can be made with certainty of purpose and proper orientation of goals.

VII. RECOMMENDATIONS

The following recommendations are made from a geohydrologic perspective for the general area of study.

1. Establish a rain gage network, at least gages C and E near the Park South Entrance and at Scullin to accurately assess the recharge in the Antelope and Buffalo recharge area.
2. Perform water quality analyses at all the springs and along Travertine and Rock Creek seasonally. The Environmental Protection Agency at Ada, Oklahoma can perform these analyses at minimum cost.
3. The City of Sulphur should have the Prickett-Lonnquist model applied immediately to their wells to determine future water levels and/or the length of time before appropriate

cessation of their water wells will occur. This is particularly important in light of the proposed Roos Ranch Well field, which has already been permitted by the Oklahoma Water Resources Board.

4. Establish a ground water monitoring well near Scullin, which is in the middle of the Antelope and Buffalo recharge area. A recording type of measurement device similar to the East and West Observation wells of the Park is recommended. This will provide long range water level data in response to Roos Ranch well pumping.
5. Construct the proposed weirs at both Antelope and Buffalo Springs, as designed during this study. This will provide more accurate spring flow data than is presently available.
6. Shut-in the Vendome Well, except for just enough water to sustain Flower Park and to maintain visibility for visitors. This will likely slow down the depletion of the aquifer.
7. Shut-in the Wyandotte, Belleview Plunge, and other free-flowing wells immediately. This will also reduce depletion of the aquifer.
8. Encourage a new water treatment plant at Arbuckle Lake for the City of Sulphur water supply. This will slow down the depletion of the aquifer and will provide protection for the City of Sulphur. This is especially true since the Roos wells have been already permitted.
9. Discourage any more well permits that will impact the Park. This might be accomplished by publicity and City involvement. The City of Sulphur might consider purchasing the land overlying the established aquifer recharge area in order to protect the Park and The City of Sulphur.

REFERENCES

1. Barthel, C.J., 1985. "Hydrogeologic Investigation of Artesian Spring Flow, Sulphur, Oklahoma, Area," unpublished Master's Thesis, University of Oklahoma.

2. De Wiest, R.G.M., 1966. Geohydrology, John Wiley & Sons, New York.

3. Harp, J.F. and Laguros, J.G., 1976. "Subsurface and Surface Water Flows of Platt National Park, Sulphur, Oklahoma, Final Report," unpublished, University of Oklahoma.

4. Harp, J.F., Laguros, J.G., McLin, S.G and West, L.B., 1984. "A Comprehensive Flood Study of the Travertine and Rock Creek Areas within the Chickasaw National Recreational Area, Sulphur, Oklahoma," O.R.A. 155-421, University of Oklahoma.

5. Hart, D. L., 1977. "Hydrology of the Platt National Park Area, Murray County, Oklahoma," U.S. Geological Survey Administrative Report, Oklahoma City, Oklahoma, 1977.

6. Kamal, M., 1986. "Time Series Analysis of Water Level and Spring State Data from the Simpson-Arbuckle Aquifer," unpublished Master's Thesis, University of Oklahoma.

7. Langbien, W.B., 1940. "Some Channel Storage and Unit Hydrograph Studies," Transactions of the American Geophysical Union, Vol. 21.

8. Prickett, T.A. and Lonnquist, C.G., 1971. "Selected Digital Computer Techniques for Groundwater Resource Elevation," Illinois State Water Survey Bulletin 55.

9. Wold, S., 1986"Hydrologic Simulations of the Simpson-Arbuckle Aquifer, Sulphur, Oklahoma, Area," unpublished Master's Thesis, University of Oklahoma.

10. HEC-1, Generalized Computer Package, 1982. Corps of Engineers Hydrologic Engineering Center, Davis, California.

11. HEC-2 Generalized Computer Package, 1982. Corps of Engineers Hydrologic Engineering Center, Davis, California.