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CORRELATION BETWEEN RAINFALL PATTERNS AND THE WATER TABLE IN THE GENERAL SEPARATIONS AREA OF THE SAVANNAH RIVER SITE

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ABSTRACT

The objective of the study was to evaluate rainfall and water table elevation data in search of a correlation that could be used to understand and predict water elevation changes. This information will be useful in placing screen zones for future monitoring wells and operations of groundwater treatment units. Fifteen wells in the General Separations Area (GSA) at Savannah River Site were evaluated from 1986 through 2001. The study revealed that the water table does respond to rainfall with minimal delay. (Water level information was available monthly, which restricted the ability to evaluate a shorter delay period.)

Water elevations were found to be related to the cumulative sum (Q-Delta Sum) of the difference between the average rainfall for a specific month and the actual rainfall for that month, calculated from an arbitrary starting point. Water table elevations could also be correlated between wells, but using the right well for correlation was very important. The strongest correlation utilized a quadratic equation that takes into account the rainfall in a specific area and the rainfall from an adjacent area that contributes through a horizontal flow. Specific values vary from well to well as a result of geometry and underground variations. R^2's for the best models ranged up to 0.96.

The data in the report references only GSA wells but other wells (including confined water tables) on the site have been observed to return similar water level fluctuation patterns.

1. STUDY PURPOSE

The purpose of this study is to provide information to assist in placement of well screens for future wells and operation of groundwater treatment units which are water table elevation sensitive by correlating water table elevations with rainfall data. Screen placement is important because SCDHEC wishes the screen to be 10' long and in some cases located so it intersects the water table surface. A screen is installed too high it will be above the water table at some time, and if too low, it will be below the top of the water table.

Predicting the movement of the water table is useful in determining which extraction wells to operate in precision extraction situations. Prediction of water table movement is important in setting screens for any groundwater treatment unit. Other uses include drought mitigation practices for shallow aquifer users such as individuals and small systems.

2. SITE DESCRIPTION

SRS occupies an area of approximately 768 km^2 (310 mi^2) on the Atlantic Coastal Plain and lies predominately on the Aiken Plateau (Figure 1). The Plateau is bounded to the north by the Piedmont Province at the Fall Line, the Savannah River to the west, the Congaree River to the east, and the Lower Coastal Plain to the south. The surface of the Aiken Plateau is highly dissected, characterized by broad inter-fluvial areas with narrow steep-sided valleys. Local relief is as much as 91 m (300 ft). The Savannah River forms the southwestern boundary of SRS and the Congaree River is approximately 96 km (60 mi) northeast of SRS. [Aadland, et al., 1995]

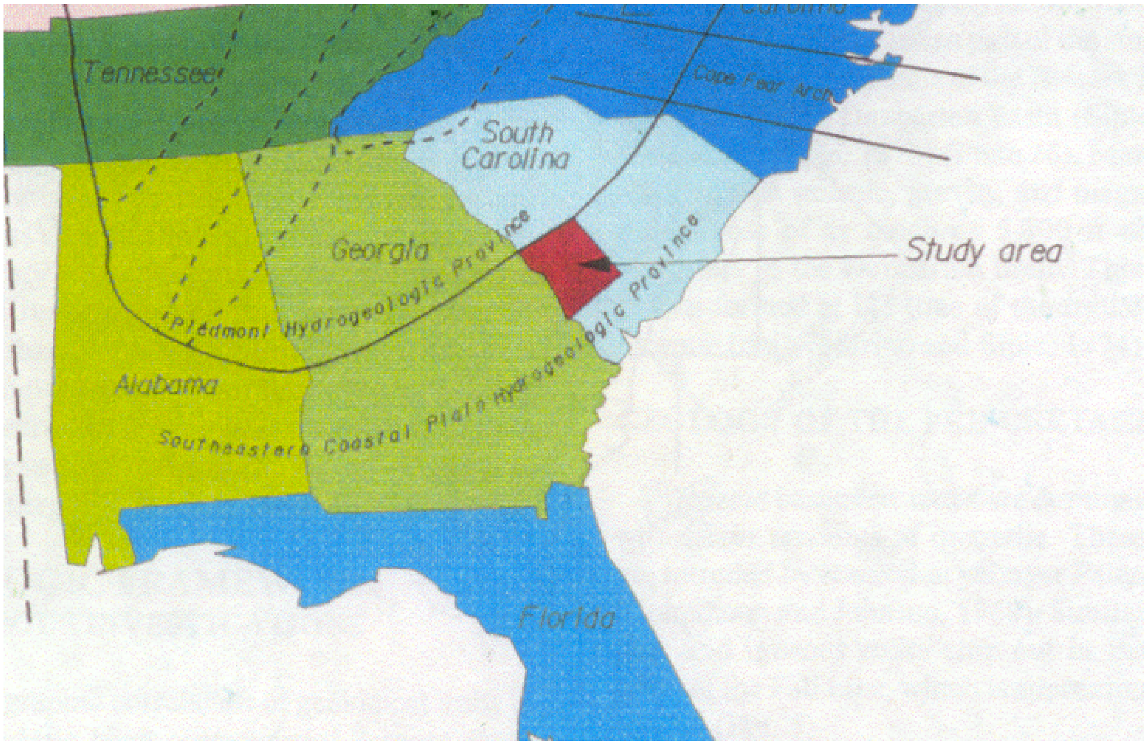

Figure 1. SRS and Southeast Physiographic Provinces [Aadland, et al., 1995]

2.1 Area Hydrogeology

Two hydrogeologic provinces are recognized in the subsurface beneath SRS. The uppermost province, which consists of the wedge of unconsolidated Coastal Plain sediments of Late Cretaceous and Tertiary age, is referred to as the Southeastern Coastal Plain hydrogeologic province. It is further divided into aquifer/confining systems, units, and zones. The underlying province, referred to as the Piedmont hydrogeologic province, includes Paleozoic metamorphic and igneous basement rocks and Upper Triassic lithified mudstone, sandstone, and conglomerate in the Dunbarton basin.

The Southeastern Coastal Plain hydrogeologic province underlies 120,000mi^2 of the Coastal Plain of South Carolina, Alabama, Mississippi, and Florida, and a small contiguous area of southeastern North Carolina. It extends from the Mississippi embayment in central Mississippi to the southwest flank of the Cape Fear arch in southeastern North Carolina. It comprises a multilayered hydraulic complex in which retarding beds of clay and marl are interspersed with beds of sand and limestone that transmit water more readily [Arnett, et al., 1999]. These beds are consistent with coastal depositional patterns, reflecting sea level changes over time. Groundwater flow paths and flow velocity for each of these units are governed by its hydraulic properties, geometry, and the distribution of recharge and discharge areas. Specifically, conductivity can vary significantly over location and direction of flow.

2.2 Site Hydrogeology

Subsurface topography at SRS consists of layers of sediments from 700 to 1200 feet deep. The sediments are composed of sand, clayey sand, and clay, with a small amount of limestone. Dense crystalline rock underlies the sediments. Groundwater in the vicinity moves through the sediments, rapidly in the sand layers. The clay layers slow groundwater flow; therefore, their presence between sand layers helps direct the flow of groundwater and contaminants. Clay layers are interspersed throughout the section, reflecting changes in deposition through time. These clay layers are considered “confining zones” which effectively separate various transmissive zones. See Figure 2 for a visual presentation of the various zones.

Slug tests, minipermeameter tests, pumping tests, and sieve analyses have been used to calculate hydraulic-conductivity values for the “upper” aquifer zone in thevicinity of the General Separations Area (GSA) [Holmes-Burnes, 2001]. The calculated value is in the range of 25 cm to 40 cm per year of vertical conductivity, with a significantly larger value for horizontal conductivity, as much as several hundred feet per year.

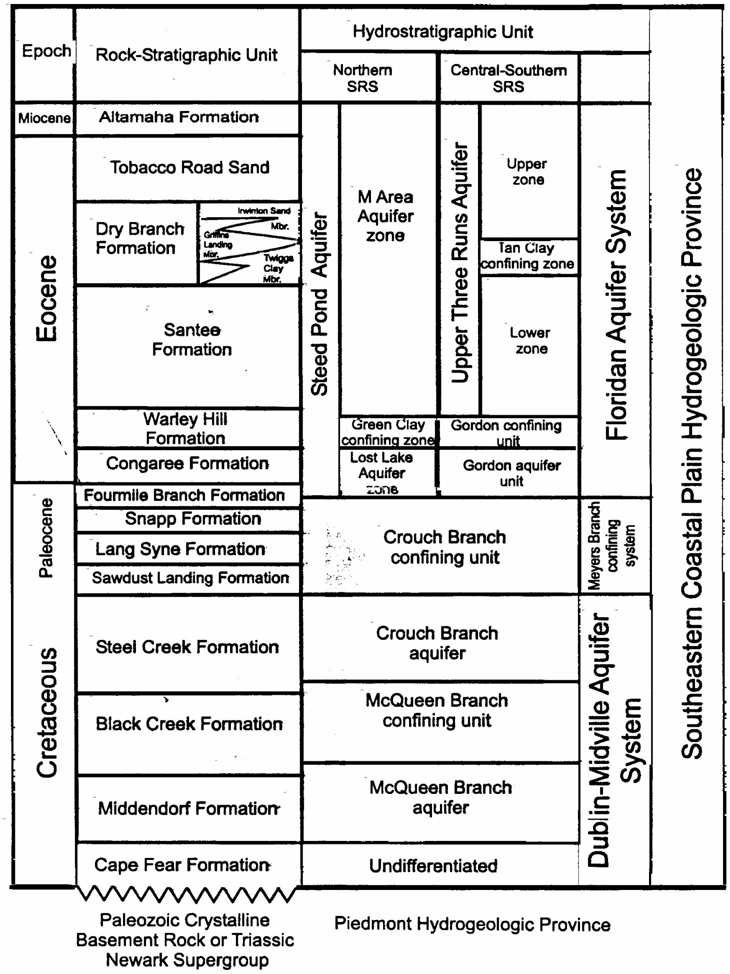

Figure 2. Site Hydrostratographic Units [Arnett, et al., 1999]

2.3 Site Wells

There are currently approximately 3000 monitoring wells on SRS, of which about 1700 are currently in working order. Groundwater monitoring of 1224 wells in 101 locations was done in 1999, with emphasis on results exceeding the Safe Drinking Water Act primary drinking water standards (DWS). There were 26,958 radiological analyses and 134,123 nonradiological analyses performed on these samples in 1999. Sampling wells have screens located in specific aquifers. [Arnett, et al., 1999]

Site monitoring wells are normally installed with a PVC shoe or foot and 10’ of screen at the desired elevation. See Figure 3. The wells to be considered in this report are used to monitor a RCRA regulated hazardous waste management facility and, as such, are maintained in accordance with the site RCRA permit. The wells are required by law to be able to provide representative samples of the aquifer of interest.

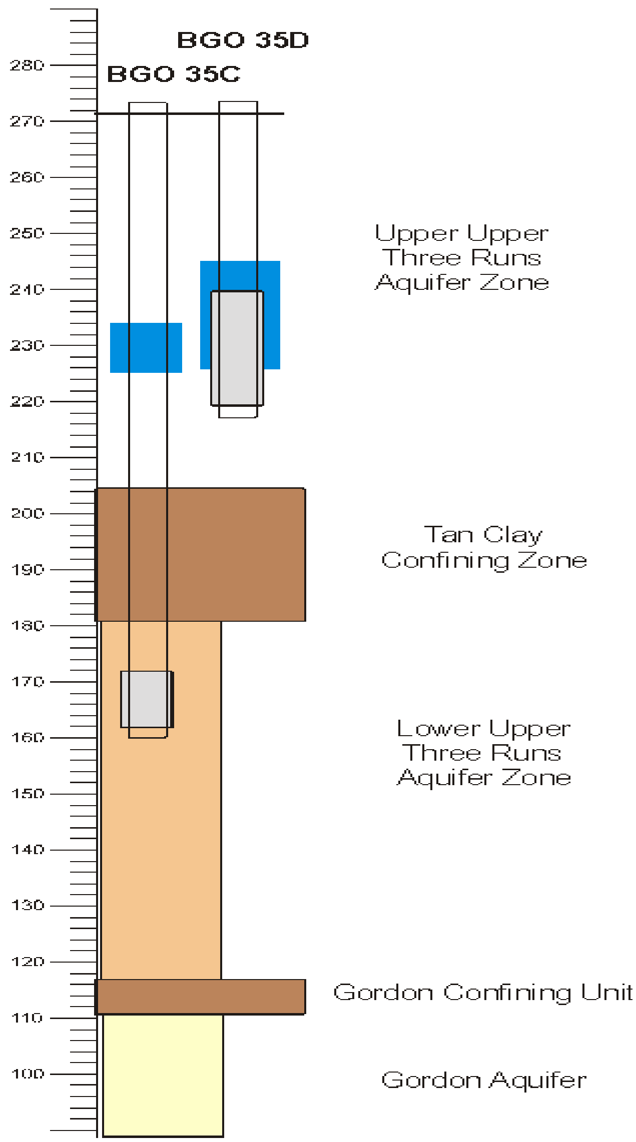

Figure 3. Typical Monitoring Well Configuration

There are eight domestic water production wells with a typical depth of screens between 600' and 800' below grade. Some pilot holes were installed as deep as 1000' prior to development of the well. There are an additional twenty wells used for process water with screens between 300' and 800' deep.

Additional monitoring of the site will be driven by the environmental restoration program which includes characterization of waste units, and remediation programs in accordance with SCDHEC and EPA requirements. Monitoring is also performed to meet DOE orders. There is no current expectation of significant well installations over the next several years, but more wells will be required as various operating units are retired and those areas undergo remediation.

Site monitoring wells are commonly drilled in clusters with each well in the group screened across a different aquifer or zone. Thus, well group BGO 37 consists of two wells, BGO 37C and BGO 37D, installed per Table 1 below. Well BGO 37C has an effective well depth of 117.5 ft., and is screened in the Lower Zone of the Upper Three Runs Aquifer. Well BGO 37D has an effective depth of 69.3 ft., and is screened in the Upper Zone of the Upper Three Runs Aquifer, which makes it the surface water table, the unit of interest for this report. All of the wells to be considered in this report are located in the General Separations Area (GSA) and those screened in the surface water table which will generally have the suffix D.

Table 1. BGO Well Series Details

Well ID	SRS North Coordinate	SRS East Coordinate	Screen Zone Top (ft MSL)	Screen Zone Bottom (ft MSL)	Ground Elevation (ft MSL)	Eff. Well Depth (ft)	Casing Dia (in)	Casing Type	Installed
BGO 37C	73498.2	57279.2	178.8	168.8	284.3	117.5	4	PVC	12-8-88
BGO 37D	73490.8	57292.9	346.1	226.1	285.1	69.3	4	PVC	12-8-88

The wells are tested for a full range of analytes; pH, temperature, water level, and organic, metallic, and nuclear contaminants. Additional constituents may be analyzed by request of various site organizations and may include suites of herbicides, pesticides, additional metals, volatile organics and others. Radioactive constituents that may be analyzed by request include gamma emitters, iodine-129, strontium-90, radium-228, uranium isotopes, and other alpha and beta emitters. The monitoring program has changed over the years, during some time frames information is available on a monthly basis and during others it is available quarterly or even more infrequency. The parameter of interest to this study is water elevation.

2.4 Site Rainfall

Rainfall data is available on site from 1952 onward. It is available in monthly increments from the A-Area climatology station, located approximately six miles from the Separations areas where the BGO, FSB, and HSB wells are located. Rainfall data is obtained through tipping bucket monitors, which are considered very accurate.

3. MODEL

3.1 Conceptual Model

There are a number of factors which can impact the movement of water from the ground surface through the vadose zone to the water table.

- Soil type
  - Sandy soils allow water to be transmitted into the vadose zone.
  - Clayey soils retard water movement.
- Horizonal depositional pattern.
  - Horizontal layers of clay are interspersed with layers of sand.
  - These layers are usually discontinuous in nature.
  - This makes it more difficult to predict movement to the water table.
- Vegetation.
  - Grasses, pine forest, or hardwood forests.
  - Actively growing or dormant.
- Surface slopes
  - Steeper slopes == more runoff

    - Flat or low-lying areas facilitate recharge areas.
- Recharge area
    - Size impacts amount of water in specific portion of water table.
    - Location of discharge trace or outcrop.
- Rainfall patterns
    - Summer rainfall is short and relatively violent with rainfalls rates up to 4" per hour over a short time. This is not a pattern which would be expected to deliver much water to the water table; instead runoff to area streams.
    - Winter rainfalls can be long gentle soaks, typically 1/4" per hour over a longer time frame, allowing for greater soaking.
- Season
    - Summer heat tends to draw moisture from the soil.

After reviewing all of the variables which could be involved in predicting the water table movement, it is obvious that we do not have sufficient data to cover all of the possibilities. Therefore I attempted to remove some of the variables. The variables related to factors other than rainfall such as vegetation type, soil, drainage area, and soil depositional patterns were assumed constant over the study.

There may be a significant seasonal component that cannot be assumed as insignificant. The water table elevation could be considered over the long-term to be in equilibrium condition forced to change by rainfall events. It would be stable if, during a given time, rainfall balanced discharge. Thus, equilibrium would be maintained by average rainfall.

Dr. John Reed, a geologist at Savannah River Site, suggested that an attempt to quantify the recharge-discharge rates for the surface water table, using transfer function theory (Dooge) might be practical. A transfer function is a device commonly used by hydrologists (Jury) to characterize a system whose internal mechanisms are unknown, due to lack of data, or unknowable, due to extreme variability and complexity of the system. The system, in this case the Vadose zone, is characterized entirely in terms of its method of transforming an input function (in this case rainfall) into an output function (a well-response hydrograph).

The water table's response to rainfall can be characterized by rainfall and the water table gradient between given wells or between a well and a discharge point.

Rainfall is the origin of all near-surface groundwater, whether it is directly from rainfall or from recharge from a river or lake. The General Separations Area has no rivers or lakes, only a few small streams, so recharge is from rainfall, infiltrating the root area and then through the Vadose zone. In the GSA, the distance to the watertable ranges up to approximately 100'.

Movement of water through the saturated zone is simply a function of Darcy's Law, being related to the permeability of the medium and the gradient. Water movement in the Vadose zone is a function of capillary action, or negative pressure. Water moves in the saturated zone as a result of pressure gradient and permeability and in the Vadose zone as a result of overcoming capillary forces to allow water to move into the saturated zone. The entire system would look something like Figure 5 below.

Mathematically we can state that the change in elevation is a function on rainfall (infiltration) and groundwater movement (in and out), or

$$\frac{dh}{dt} = \frac{dr}{dt} + \frac{di}{dt} - \frac{do}{dt}$$

or

$$h = \int (r + i - o)dt$$

Where h = water table elevation

r = infiltration through the Vadose zone

o = downgradient water table flow (out of area of interest)

i = upgradient water table flow (into area of interest)

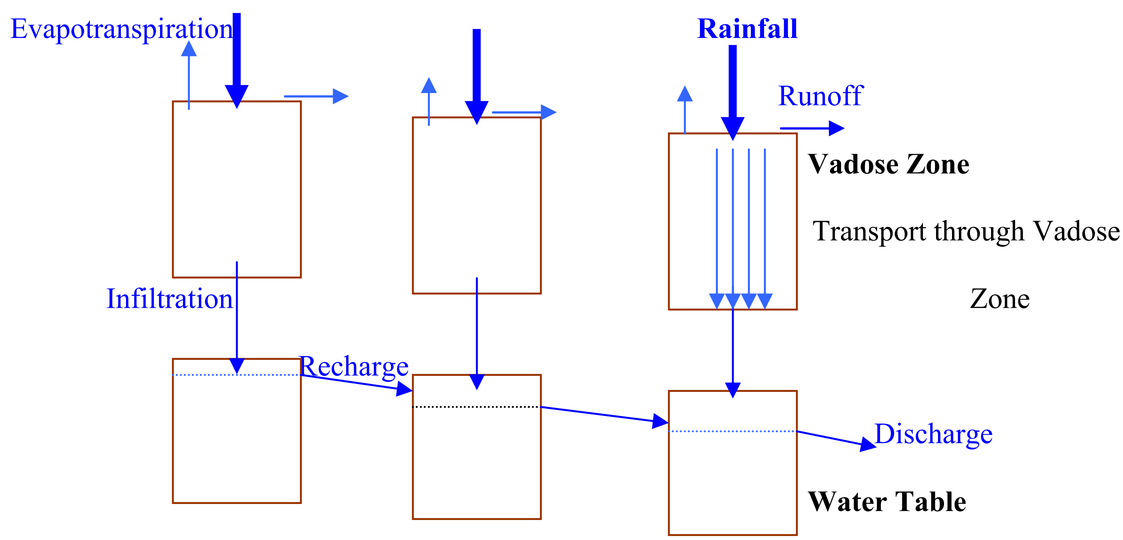

Figure 4. Groundwater Recharge System

3.2 Study Methodology

The objective of this study is to try to correlate water table movement with rainfall data using the simply available information of monthly rainfall data over time and water levels in specific wells over time. We will try various regressions, to include linear, non-linear, transformed regressions, quadratic, and cubic regressions, to identify patterns which correlate the rainfall and well elevation data. This information will be useful in determining how much screen to install in monitoring wells and where to install it based on the found water table in a newly-drilled well and the current and future expected behavior of the water table.

4. Data

4.1 Well Data

The first step in evaluating the data is to examine the well water depth data from the site groundwater database. Since we are interested in a series of wells in the vicinity of the separations areas, choose and graph the surface aquifer movement over time. Three sets of wells were chosen which are aligned along known subsurface water flow gradients. They include (1)

FSB108D , FSB109D, and FSB120D, (2) BGO 37D and BGO 32D, and (3)HSB 105D, HSB 106D, and HSB 116D. Water elevations in the wells were average-adjusted for convenience of display. The plots for the HSB wells noted above are shown in Figure 5. Other well plots were similar.

Even a casual observation reveals a pattern of lowering and recharge over time in these wells. The data was analyzed for seasonal component, such as consistent rise during fall or winter months. There is no evidence of a seasonal recharge. The various discharge/recharge patterns appear to be over a longer period of time, so additional analysis of data, to include rainfall data, was required.

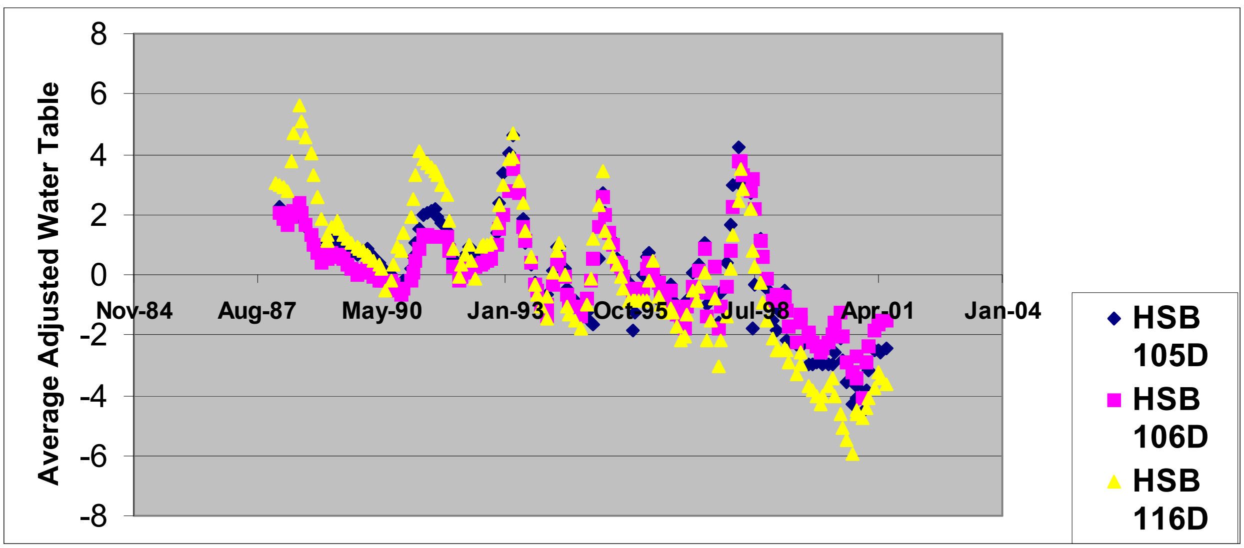

Figure 5. Selected HSB Well Water Table Trace

4.2 Rainfall Data

Monthly rainfall data is available from 1952 to the present. Data from 1986 through 2001 (the time frame for most of the well data) can be plotted as shown on Figure 9. The plot shows no significant pattern; it appears random. Another method of analyzing the data is to calculate the difference between the average rainfall for a particular month and the actual for that month. The plot for that data is shown on Figure 6. Again, no obvious pattern is detectable. The cumulative sum of the difference between average and actual monthly rainfall (Q-Delta Sum) is plotted as Figure 7. A pattern emerged in this figure similar to the patterns of the hydrographs. The next step will be to plot both well water elevations and rainfall data on the same graph as shown in Figure 8.

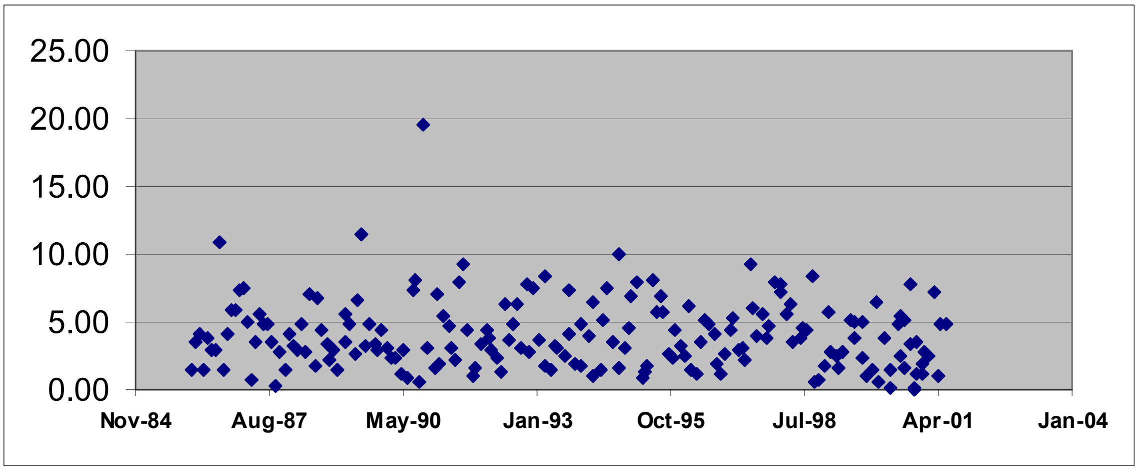

Figure 6. Monthly Rainfall

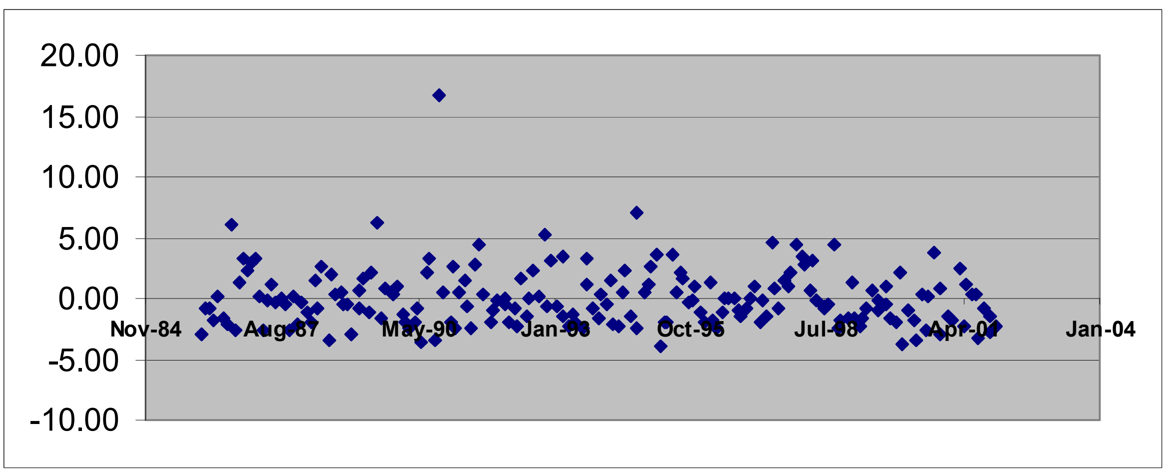

Figure 7. Difference Between Average and Actual Monthly Rainfall

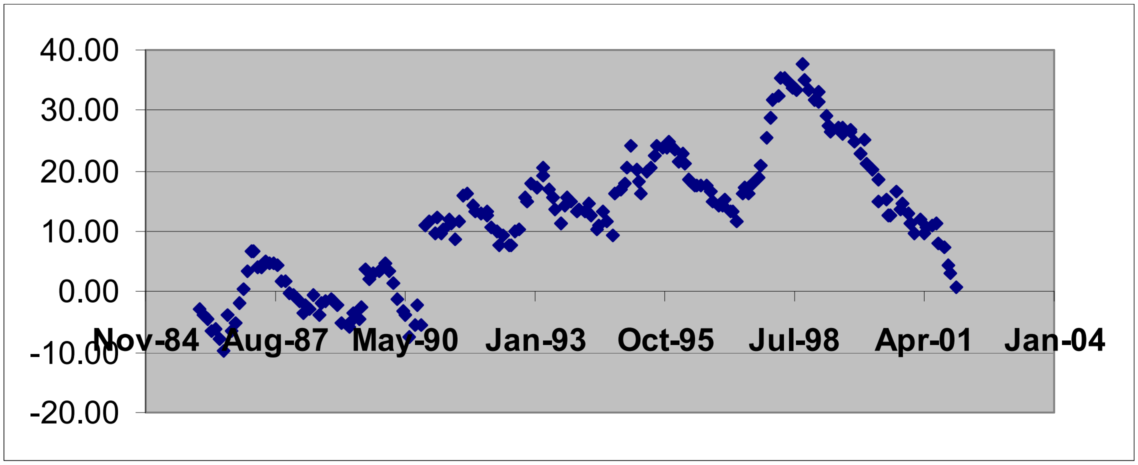

Figure 8. Cumulative Summary Difference Between Average and Actual Rainfall, 1986 through 2001(Q-Delta Sum)

4.3 Well and Rainfall Data

The cumulative sum of the difference (Q-Delta Sum) between the monthly average and monthly rainfall is plotted with the differences between the well water levels and the average for the specific wells in Figure 9. Here we can see that the Q-Delta Sum of the rainfall follows a similar pattern to the hydrographs. An interesting point to note is that there is no obvious lag from rain to water table reaction. This is a point which cannot be verified any further because well data is no more frequent than monthly. More nearly continuous data could be used in conjunction with daily rainfall to verify time to response.

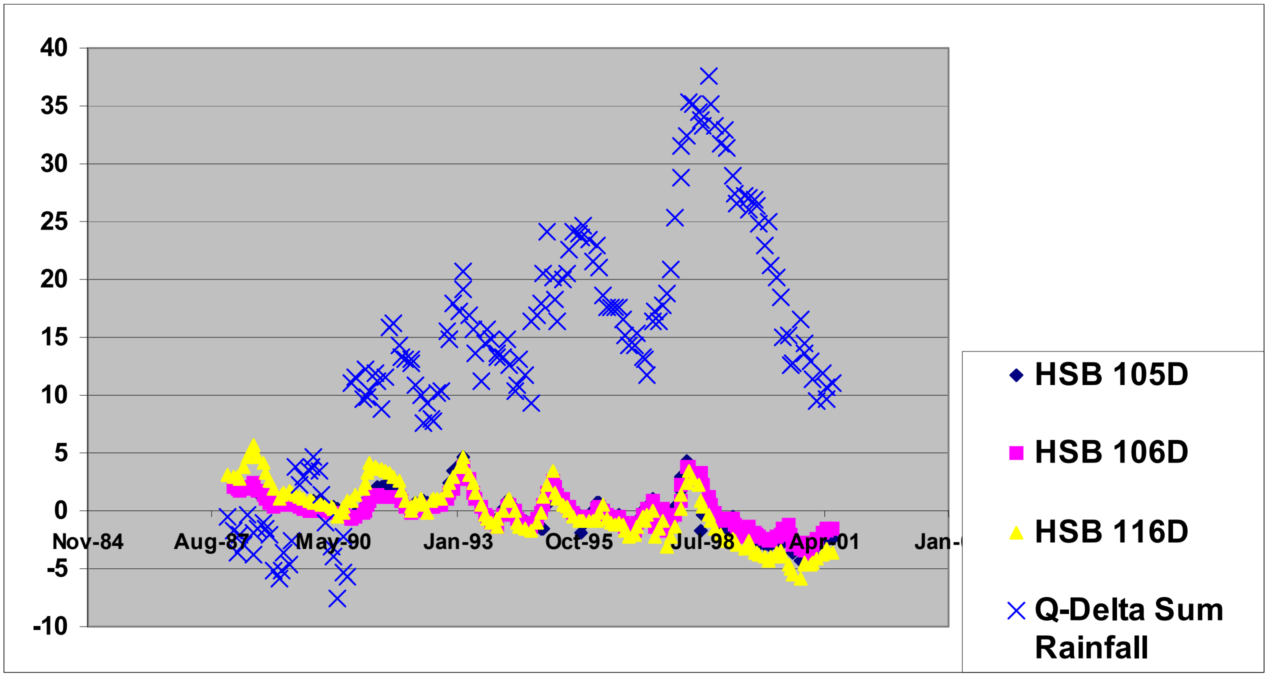

Figure 9. Q-Delta Sum Rainfall and Water Table Movement for Selected HSB Wells

A number of evaluations using the Q-Delta sum rainfall data and well water elevations were investigated, including simple linear relationships, correlation with adjacent wells, and modifying the Q-Delta sum to reflect critical rainfall levels rather than averages. All techniques utilized showed some promise but the quadratic model showed the strongest correlations. This actually makes sense since the rainfall near the well point might be considered the linear portion and the addition of that rainfall plus gradient flow is the quadratic portion, being related to rainfall in the general area, rainfall up and down gradient, and the subsurface conditions.

Table 2 summarize the linear regression as a quadratic relationship between rainfall and well water levels covering a rising water table and Table 3 a falling water table. The form of the equation is Well Level = Constant + Coefficient_1 x Q-Delta Sum rain + Coefficient_2 x Q-Delta Sum rain^2. Therefore Well level BGO 32D = -3.619 + 0.065 Q-Delta Sum rain + .00346 Q-Delta Sum rain^2.

Column one is the constant for each well. Columns two through four are the linear coefficient, its F-value and associated p. There is only one well, HSB 102D on a falling water table, which does not have a statistically significant linear coefficient. Columns five through seven are the quadratic coefficient, its F-value and associated p. A good number of wells did not have a significant coefficient with a rising water table, but more were significant with a falling water table. It is interesting to note that HSB 102D's quadratic coefficients are significant in both a rising and falling water table. Columns eight and nine are the ANOVA F-value and associated p for the quadratic coefficient. All are significant. Columns ten and eleven are the R^2's for the models, column ten for the instance where we have a quadratic model, and column eleven for a linear model. R^2 is better in all cases for the quadratic model, but only marginally so if the quadratic portion is not statistically significant (e.g. FSB 104D).

Table 2. Correlation of Wells With Rainfall Using Quadratic Function on Rising Water Table

Rising	5/97 - 9/98	Linear	F	p	Quadratic	F	p	ANOVA F	p	Quadratic Equation R^2	Linear Equation R^2
BGO 32D		-0.245	61.37		0.012	11.73		58.50		89	80
BGO 35D		-0.278	38.20		0.011	12.93		40.75		85	72
BGO 36D		-0.350	34.08		0.014	13.45		37.90		84	69
BGO 37D		-0.524	40.05		0.021	17.13		50.12		88	73
FSB 104D		-0.064	40.91		0.0068	1.67	0.22	22.20		76	73
FSB 105D		-0.459	100.53		0.0059	1.82	0.20	53.92		88	87
FSB 108D		-0.587	9.16		0.0019	11.72		13.71		66	38
FSB 109D		-0.542	29.05		0.0021	11.30		30.15		81	66
FSB 120D		-0.773	13.09		0.0026	13.28		18.55		73	47
HSB 102D		-0.341	57.35		0.0163	10.84		52.91		88	79
HSB 105D		-0.027	6.85		0.004	0.21	0.65	3.35		32	31
HSB 106D		-0.150	24.50		0.0088	1.97	0.18	14.03		67	62
HSB 116D		-0.233	15.34		0.0106	2.17	0.16	9.36		57	51
HSB 130D		0.127	17.37		-0.0014	0.15	0.71	8.26		54	54
HSB 138D		-0.001	15.90		0.0053	0.33	0.58	7.76		53	52
BGO 29D		-0.052	190.09		0.0074	11.54		172.37		96	93
BGO 30D		0.071	162.29		0.0039	1.64	0.22	85.65		93	92
BGO 31D		0.101	142.23		0.0034	0.92	0.36	71.65		92	91
BGO 46D		0.159	165.80		0.0016	0.23	0.64	78.44		92	92
BGO 50D		0.134	180.00		0.0024	0.58	0.46	87.63		93	93

Table 3. Correlation of Wells With Rainfall Using Quadratic Function on Falling Water Table

Falling	9/98 - 6/01	Linear	F	p	Quadratic	F	p	ANOVA F	p	Quadratic Equation R^2	Linear Equation R^2
BGO 32D		0.065	188.42		0.0035	3.57		103.59		87	86
BGO 35D		-0.090	78.39		0.0066	17.39		67.96		81	71
BGO 36D		-0.155	40.13		0.0076	30.69		54.04		78	56
BGO 37D		-0.164	35.80		0.0083	21.56		40.18		72	53
FSB 104D		0.289	353.96		0.003	0.95	0.34	177.20		92	92
FSB 105D		0.013	431.85		0.005	38.31		512.87		97	94
FSB 108D		0.117	223.35		0.019	1.17	0.29	112.86		88	88
FSB 109D		-0.016	25.24		0.0033	1.67	0.20	13.72		47	44
FSB 120D		0.123	421.36		0.0046	6.47		249.89		94	93
HSB 102D		-0.320	1.00	0.33	0.0111	17.23		9.37		38	3
HSB 105D		-0.196	42.93		0.0101	25.48		50.63		77	57
HSB 106D		-0.192	30.89		0.0092	22.11		36.69		70	49
HSB 116D		-0.138	54.33		0.0083	17.86		50.40		76	63
HSB 130D		-0.011	20.72		0.0012	1.94	0.18	11.69		47	43
HSB 138D		-0.315	10.64		0.0012	46.11		35.88		70	25
BGO 29D		-0.011	297.29		0.0052	52.58		414.50		96	90
BGO 30D		-0.046	201.82		0.0055	75.37		373.12		96	86
BGO 31D		-0.031	248.93		0.0052	75.31		451.15		97	89
BGO 46D		-0.055	162.44		0.0057	55.83		248.29		94	84
BGO 50D		-0.063	167.00		0.0060	72.20		305.37		95	84

The R^2's are distributed as follows for the quadratic:

	Excellent	Good	Fair	Poor
Rising	5	9	5	1
Falling	8	9	0	3

4.4 Water Level Predictions

The objective of the study is to make predictions on water levels based on rainfall data and current water table information. Figure 10 below shows a scatter diagram using the actual water levels for well BGO 30D, the calculated water level for BGO 30D using the formula calculated from the actual water levels, and the projected (expected) water table based on an expected regression based on the four nearest wells (BGO 29D, BGO 31D, BGO 46D, and BGO 50D). (The equation for the expected regression is: $0.0055x^2 -0.039x -1.46$ and the actual regression equation for BG 30D well is: $.0055x^2 - 0.046x - 1.52$.) The results show that the

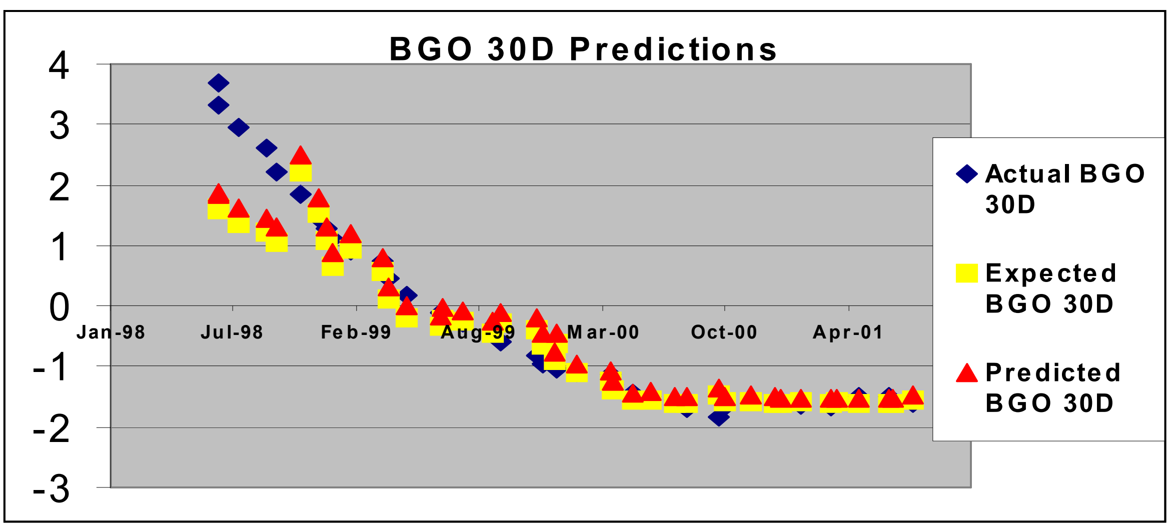

Figure 10. BGO, Expected BGO 30D, and Predicted BGO 30D Water Levels From 6/98 through 6/01

projection from the four nearest wells is very close to both the actual levels and the expected levels using the BGO 30D well. (quadratic) regression. Figure 18 shows the trace of the same information through time. That also shows that the projection is a good estimate of the water level of an unknown well. Note that all Q-Delta Sums in the report are positive numbers. If the current drought continues, they will become negative numbers. The calculations using the quadratic may not be representative of the real world. An adjustment may be required to handle negative Q-Delta Sums, such as changing the arbitrary starting point to keep all numbers positive.

4.5 Analysis of Data

An analysis of wells using a quadratic equation is shown of the in Tables 2 and 3. Analysis is as follows:

- The linear portion of the quadratic expression was significant in all but one case.
- The quadratic portion of the equation was significant more frequently on a falling water table than on a rising water table.
- The coefficient of determination was higher in all cases when the quadratic function was used.

Wells were analyzed with cubic relationships, normal and log normal transforms, and inverse relationships. None of these methods produced better models and results than those discussed in detail in this paper.

The best way to predict the water table is by using a quadratic function of the rainfall. The best correlations occurred when both the rainfall and the groundwater flow components are included in the model. The quadratic portion of the quadratic expression expresses the up (or down) gradient flow and the linear portion is the rainfall falling in the vicinity of the well.

The values for the coefficients vary from well to well and also vary depending on whether the water table is rising or falling. This study did not try to evaluate these differences or why they exist.

5. Conclusions

The objective of this study was to evaluate rainfall data to see if any predictions could be made concerning water table elevations from that data. A number of wells were evaluated on the Savannah River Site and a strong correlation between a rainfall metric and water table elevation was developed. The rainfall metric was called the Q-Delta Sum because it involved using the cumulative difference between actual and average rainfall over the time frame. The correlation equation was a quadratic which makes sense since there are two components to be considered in groundwater movement; the direct rainfall (from immediate area) transmitted through the vadose zone, and the cross-flow from up gradient flow (rainfall from nearby). The specific values varied from well to well and are likely to be functions of the subsurface conditions which were not modeled in this evaluation.

The water table movement in a given well can be modeled by using rainfall data. Predicting future well movement can be done using the same metrics, along with the long-term rainfall predictions. These metrics can be of use in planning water treatment unit operations and in determining where to place monitoring well screens in the surface water table, if the variable of interest is the top of the water table. Wells being used for dissolved plumes and LNAPL evaluations would require the water table surface to be intersected by the screen zone, while a well which is expected to be used for DNAPL's would not be correlated to the water table movement, merely the top of the lower confining zone.

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