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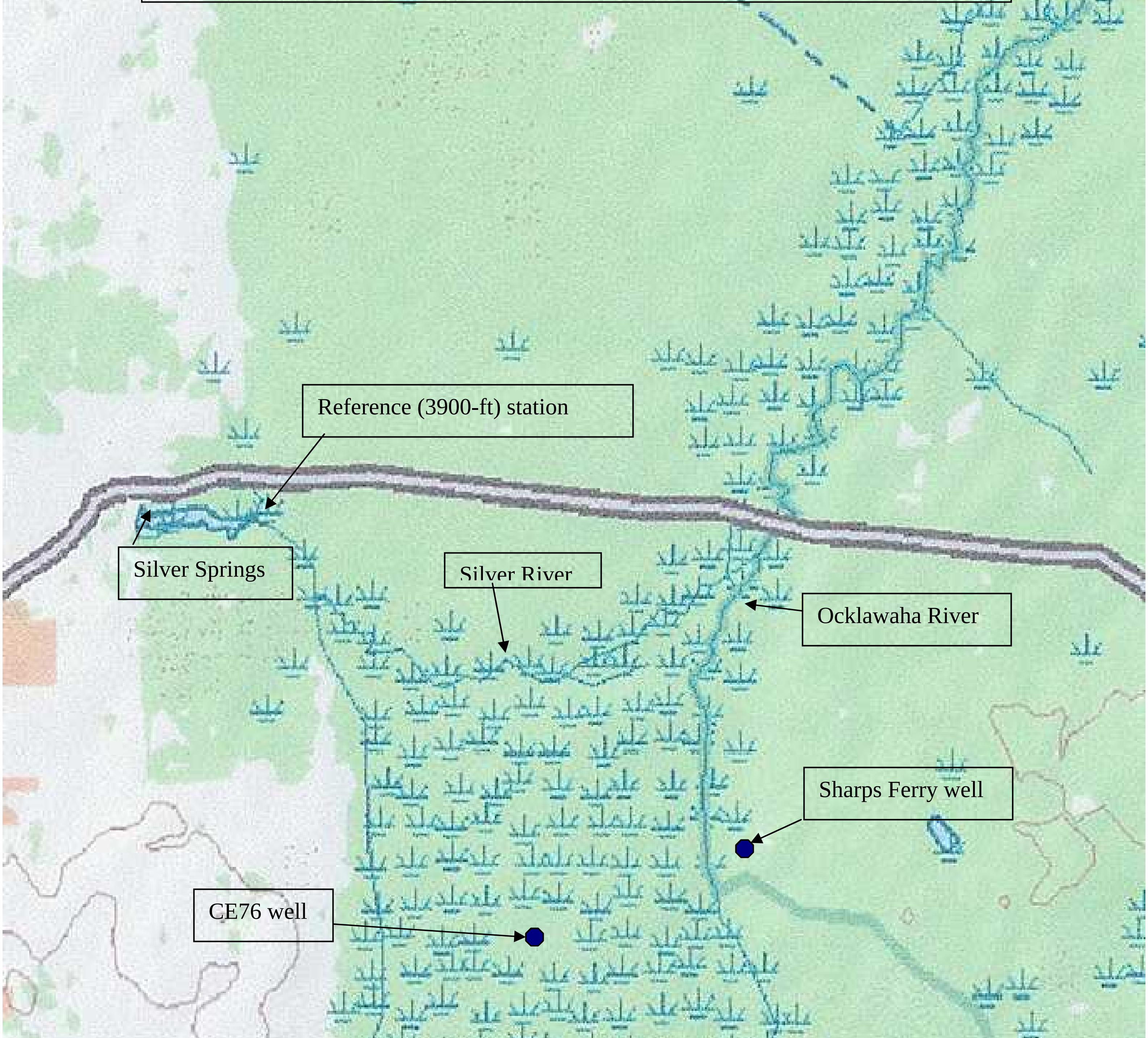
EVALUATION AND RECOMPUTATION OF DAILY-DISCHARGE FOR SILVER SPRINGS NEAR OCALA, FLORIDA

Evaluation and Recomputation of Daily-discharge for Silver Springs Near Ocala, Florida



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Executive Summary

SJRWMD has initiated data collection and analysis to determine minimum flows and levels (MFLs) for a number of priority springs. Determination of these MFLs requires an extensive review and evaluation of the historical database of spring discharge measurements that will be used during development of hydrologic models for each priority spring.

The original computation and publication of discharge by the U.S. Geological Survey (USGS) did not consider effects of measurement location on discharge computation. Inflow of water from surface tributaries and from spring vents in the river bed results in gain in discharge between the main boils and the mouth of Silver River. Thus the discharge measurements made at significant distances downstream from the main boils include water from these additional sources as well as water from the main boils. These discharge measurements must be adjusted to account for the additional inflow if they are to be used to develop the discharge rating curve to compute monthly and daily discharges from the spring.

Also, prior to 2005, USGS computation of daily spring discharge was based on daily record of aquifer head measured at a well near the spring. Spring discharge is a function of the aquifer head, but is more precisely a function of the difference in head between the spring pool and the Upper Floridan aquifer. This head difference can be affected by backwater from the Ocklawaha River, because the backwater may change the spring pool elevation without affecting the aquifer head. The effects of backwater can be taken into account by using spring discharge rating relationships that are based on head difference between the spring pool and the aquifer, rather than on aquifer head alone.

This report describes methods and results of re-computation of daily discharge from Silver Springs near Ocala, in an attempt to improve accuracy of existing records of daily discharge for the period 1933-2005. The daily discharges are specific to a single reference station located about 3900 ft downstream from the main spring boils.
This re-computation included consideration of effects of discharge-measurement location on rating-curve development. Also, new discharge rating curves based on head difference between the spring pool and the aquifer were used in the re-computation for the period 1948 - 2002.

Comparison of USGS original daily spring discharge with recomputed discharges indicates that the original USGS values are generally higher than the recomputed values. These differences are relatively small (less than 2 %) prior to 1960, and probably are caused by slight differences in the rating curve relationships used to calculate discharge from water level. The differences between the USGS data and the recomputed discharge are greater after 1960 and probably are the result of the normalization of the discharge-measurement data used to develop the relationship for re-computing the daily discharge values.

Comparisons of discharge computed from well water level (Qpw) with discharge computed from head differences (Qph) indicate that during the relatively infrequent periods of Ocklawaha River backwater effects there may be significant differences (more than 20 %) between the two calculated discharge values. These differences occur because well water level (aquifer head) is not likely to be affected significantly by backwater, while the head difference is directly affected by the backwater. Because spring discharge is more precisely a function of the difference in head between the spring pool and the Upper Floridan aquifer than just a function of aquifer head, it is recommended that the head-difference relationship rather than the well water-level relationship be used to compute Silver River discharges.

Comparison of daily discharge computed using hourly head differences with daily discharge computed using head differences calculated from daily average water levels indicate practically no difference between the two methods. During most days January 2003 through September 2005, the difference was 0.01 ft^3/s or less. Based on this comparison, there would seem to be no significant errors in daily mean discharges calculated using daily mean head or well water level, as was the practice before 2003.

This report describes methods of computation of discharge from Silver Springs. It does not address changes in spring discharge that have occurred over the period of record.

Table of Contents

List of Figures

List of Tables

Introduction

The St. Johns River Water Management District's (SJRWMD) Minimum Flows and Levels (MFLs) Program, implemented pursuant to Sections 373.042 and 373.042(1), *Florida Statutes,* establishes MFLs for lakes, streams and rivers, wetlands, and springs. MFLs define the frequency and duration of high, average, and low water events necessary to prevent significant ecological harm to aquatic habitats and wetlands from permitted water withdrawals. The MFLs Program is subject to the provisions of Chapter 40C-8, *Florida Administrative Code*, and provides technical support to SJRWMD's regional water supply planning process, and Consumptive Use and Environmental Resource permitting programs.

MFLs are represented by hydrologic statistics comprised of three components: a water level and/or flow, duration, and a return interval (frequency). MFLs designate hydrologic conditions below which significant harm is expected to occur and above which water is available for reasonable-beneficial use. As it applies to wetland and aquatic communities, significant harm is a function of changes in the frequencies of water level and/or flow events of defined durations causing unacceptable changes to ecological structures and/or functions. The determination of MFLs considers the protection of nonconsumptive uses of water, including navigation, recreation, fish and wildlife habitat, and other natural resources.

SJRWMD has initiated data collection and analysis to determine MFLs for a number of priority springs. Determination of these MFLs requires an extensive review and evaluation of the historical database of spring discharge measurements that will be used during development of hydrologic models for each priority spring.

This report describes methods and results of re-computation of daily discharge from Silver Springs near Ocala, in an attempt to improve accuracy of existing records of daily discharge for the period 1933-2005. This re-computation included consideration of effects of discharge-measurement location on rating-curve development. Also, new discharge rating curves based on spring pool head were used in the re-computation. These head-based computations should be less affected by backwater than the original computations, which were based on artesian pressure at a well near the spring pool for the period 1948 - 2002.

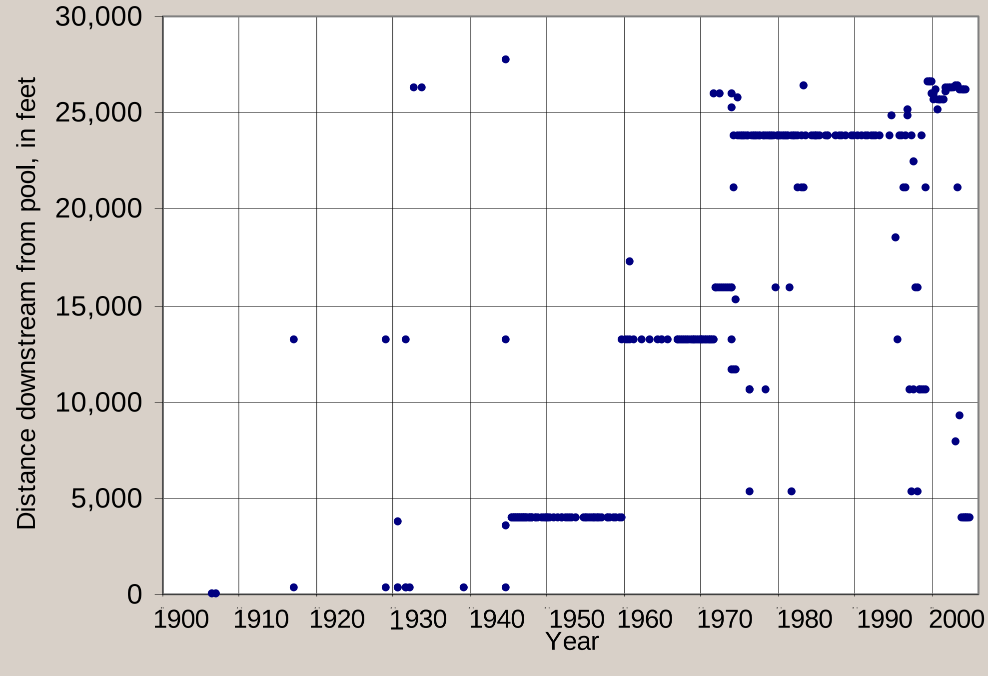
Background

Records of daily discharge of Silver Springs near Ocala have been computed from October 1932 to the present by the United States Geological Survey (USGS). Prior to October 2002, the daily discharges were computed with a rating curve relationship between artesian pressure measured in a well near the spring (Sharps Ferry Well) and measurements of discharge in the Silver River at various locations downstream from the main spring boils. Prior to 1947, only weekly or less frequent data were available for the Sharps Ferry well and daily discharges from Silver Springs were computed from the artesian pressure vs. discharge rating curve for days with potentiometric head measurements for the Sharps Ferry Well. Discharge for days with no artesian pressure measurements was estimated by linear interpolation of discharge between days with artesian pressure records.

Water level in the Sharps Ferry Well could not be measured continuously after September 2002, because water levels in the well often dropped below the bottom of the well. This drop in water level was the result of a regional decline in the artesian pressure in the Upper Floridan aquifer. Another well near the spring (Well CE-76) was used beginning in October 2002 for determination of artesian pressure near the spring. Along with the change in well, the method for computing daily discharge for Silver Springs was also changed to account for backwater effects from the Ocklawaha River on the spring pool elevation. The new method for computing daily discharges is based on relations of head as measured by the difference between water-surface elevation of the spring pool and artesian pressure in Well CE-76. Computations of discharge are made using hourly records of head, and daily discharge is then computed by averaging the hourly values.

This historical record of daily discharges furnished by USGS are probably subject to errors related to definition and application of the water level vs. discharge rating curve relationship. One source of error is the variation in location of discharge measurements used to develop the rating curve relationship. The locations where discharge has been measured have not been constant over the years (Figure 1.) Rather, locations have varied from just below the main spring boils to near the mouth of the Silver River, about 5 miles downstream from the boils. Inflow of water from surface tributaries and from spring vents in the river bed results in gain in discharge between the main boils and the mouth of Silver River. Thus, the discharge measurements made at significant distances downstream from the main boils include water from these additional sources as well as water from the main boils. These discharge measurements must be adjusted to account for the additional inflow if they are to be used to develop the discharge rating curve to compute monthly and daily discharges from the spring.

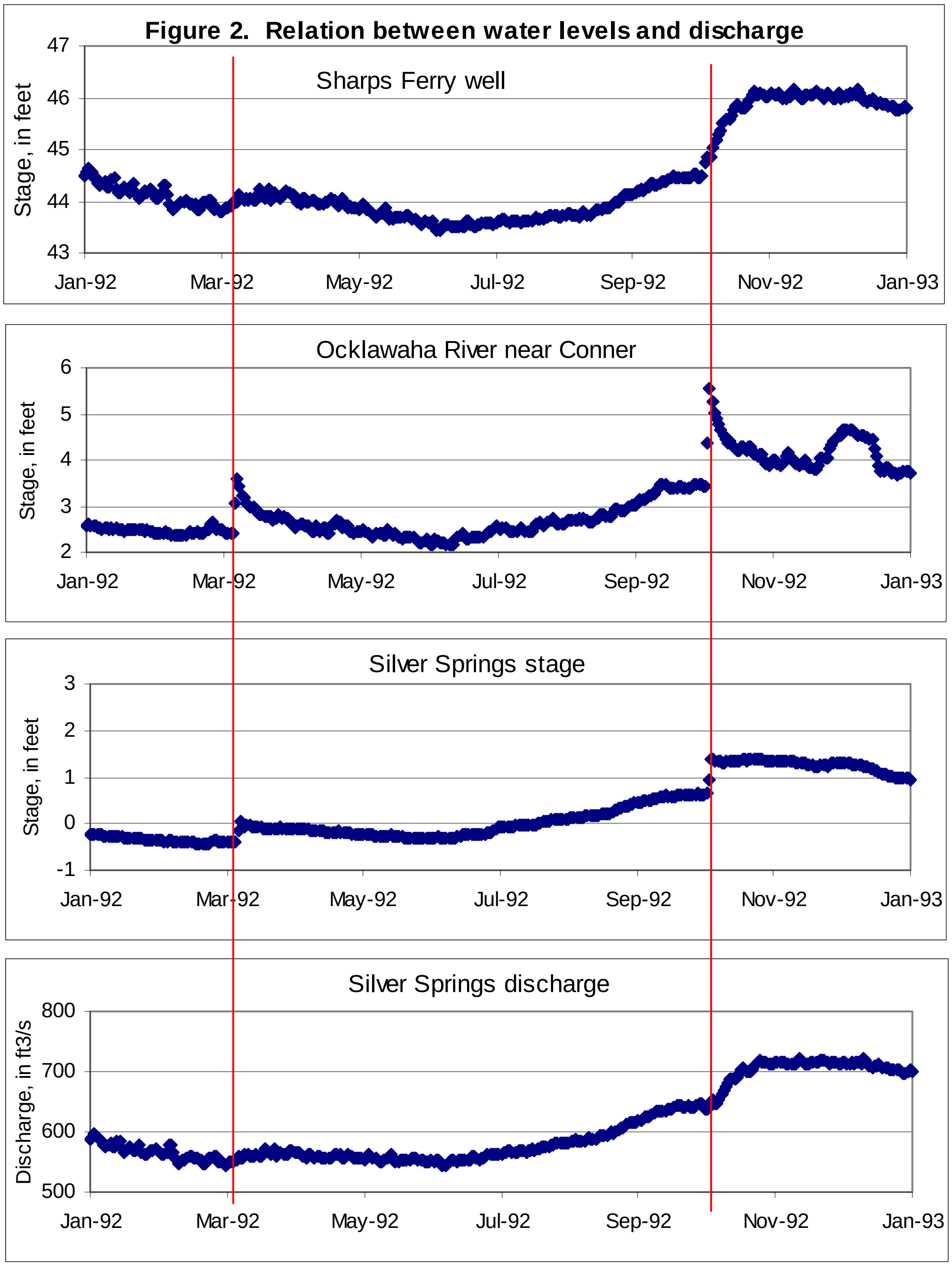
Figure 1. Location of discharge measurements in the Silver River



Another source of error in computed discharges prior to 2003 is related to the backwater effects from the Ocklawaha River. Water releases from the Moss Bluff dam on the Ocklawaha River (about 13 miles upstream from the mouth of the Silver River) can cause a rapid increase in river stage, both in the Ocklawaha River and in the Silver River all the way up to the main spring boils. This backwater decreases the difference, or head, between the artesian ground-water pressure at the spring and the spring pool elevation. Therefore, because discharge from the springs is directly related to the head, the backwater would have the effect of decreasing the discharge. The discharges computed from the Sharps Ferry artesian pressure record would not reflect the actual decrease in spring discharge that would be expected to occur as a result of the Ocklawaha River backwater, because the artesian pressure of the well is largely unaffected by the backwater.

To illustrate the effects that water releases from Moss Bluff have on water-surface elevations in the Ocklawaha River and the Silver River, water level and discharge data for the year 1992 were plotted (Figure 2). Two relatively large water releases are evident during 1992: one in March and a larger water release in October. In both cases, water levels in the Ocklawaha River increased rapidly over a period of about 2 days. Water level at the Silver Springs pool responded almost instantaneously (on a daily time step), though to a lesser magnitude. However, the computed daily discharge from Silver Springs does not reflect this rapid increase in water surface elevation that should decrease the head (and hence the discharge) from the spring. After the

Moss Bluff water releases, both well water level and springs discharge increase over a period of several weeks, probably as the result of rainfall.



Purpose and Scope

Re-computation of Silver Springs discharge was done to take into account variation in location of measuring sections used to establish rating relations and to minimize or eliminate effects of backwater from the Ocklawaha River by using spring discharge relations based on head difference between artesian pressure at the spring vents and the spring pool water level. The daily discharges were re-computed at a fixed reference station located about 3900 ft downstream from the main spring boils, henceforth referred to as the 3900 ft station (Figure 1).

Methods used for discharge recomputation are described in this report, and hydrographs and summary tables of daily discharges are presented. The recomputed daily discharges are compared with the original USGS data.

Daily data summaries are included in a spreadsheet that was compiled as part of this project. This spreadsheet includes the original (USGS) and recomputed Silver Springs discharge, artesian pressures for the Sharps Ferry well and the CE-76 well, and pool elevation and heads for the Silver Springs pool for 1933 – 2005.

Discharge and water surface elevation data from three USGS stations were analyzed during this project (Table 1). The station locations are shown on the cover page.

Table 1. USGS data sites
(USGS station identifiers are used to retrieve data from the USGS NWIS computer files. Latitude/longitude are in degrees, minutes, seconds format.)

Site name	**USGS station identifier**	**Latitude/ longitude**	**Type of data**
Silver Springs	02239500	291244/820315	Water surface elevation and discharge
CE76 well	291100082010003	291100/820100	Water-surface elevation, Upper Floridan aquifer
Sharps Ferry well	291115081592501	291115/815925	Water surface elevation, Upper Floridan aquifer

Daily water-surface elevation and discharge data are published by the USGS in a series of annual water data reports. These reports are available through the Internet at the following URL:

http://fl.water.usgs.gov/Pubs_products/online.html

Alternately, these data may be retrieved and downloaded through the Internet by station identifier, type of data, and desired period of record at the following URL:

http://waterdata.usgs.gov/fl/nwis

Discharge-measurement data and annual station analysis documents were reviewed for discharge measurement and station operation details. These documents are in files maintained at the USGS office in Orlando. The 18 measurements listed in Table 2 were not used to develop rating curve relationships, either because they are replicate measurements made during a single day or because the measurements were determined to be inaccurate, according to the annual station analysis documents. In the case of replicate measurements for a day, the measurement taken closest to the 3900 ft station was used. A total of 299 measurements were then available for rating curve development for the period October 1, 1933 through September 30, 2005.

Table 2. Measurements that were not used in rating development
(N_m refers to measurement number in USGS files

N_m	Date	N_m	Date	N_m	Date	N_m	Date
--	04-03-1939	--	09-23-1944	2	09-23-1944	4	09-23-1944
146	01-09-1974	148	01-28-1974	153	07-29-1974	165	05-25-1976
187	10-15-1979	188	12-03-1979	191	04-04-1980	206	07-14-1982
209	03-01-1983	210	05-05-1983	211	07-12-1983	215	12-14-1984
273	01-09-2001	10	06-27-2005				

This evaluation and the discharge recomputation involved completion of the following tasks:

1. ***Normalization of discharge measurements in the Silver River to discharge at the 3900 ft station:*** The reference station is the one presently used for instantaneous discharge measurements (about 3900 ft downstream from the main spring boils).

2. ***Development of a set of well water level vs. discharge ratings and head difference vs. discharge ratings based on discharge measurements normalized to the 3900 ft station:*** For October 1932 to September 2002, data for the Sharps Ferry well were used to represent artesian pressure at the spring vents. From October 2002 through September 2005, data for the CE-76 well were used. Ratings based on head difference between the artesian pressure and the spring pool were used from February 1948 through September 2005.

3. ***Recomputation of daily discharges at the 3900 ft station for the period 1933 – 2005 using the rating of well water level and head difference to normalized discharge:*** Ratings based on head difference were not used to compute discharges prior to 1948 because daily values of Silver Springs water-surface elevation are not available.

4. ***Comparison of discharges computed from hourly record of head with discharges computed from daily values of head:*** From water year 2003 on, the USGS used hourly water-level records to compute hourly heads and discharge. Daily discharge was then computed from the hourly discharge values. The recomputation of daily discharge was done using daily head values for 1933 – 2002, and hourly head values from 2003 on, and also using daily head values from 2003 on, to determine the difference between daily discharges computed using hourly head values and daily discharges computed using daily head values.

5. ***Preparation of a report describing results of this evaluation:*** Methods used for discharge recomputation are described and hydrographs and summary tables of daily discharges for the reference location are presented. Results obtained using artesian

pressure ratings are compared with results from head ratings. The daily reference-location discharges are compared with the original daily discharge data.

6. ***Preparation of spreadsheets including daily data:*** The spreadsheet includes artesian pressures for the Sharps Ferry well and the CE-76 well, and pool elevation and heads for the Silver Springs pool for 1933 – 2005.

Methods

The first step in data-processing task included normalizing discharge measurement data from all measuring locations to a single reference location about 3900 ft downstream from the spring pool. Then a series of ratings were developed to estimate discharge at the reference location from Floridan aquifer artesian pressure (well water level), and from head difference (difference between spring pool water-surface elevation and Floridan aquifer artesian pressure). Finally, discharges representative of the reference location were computed using these ratings.

1. *Normalization of discharge measurements in the Silver River to discharge at a reference location*

From 1933 to 2005 there have been more than 300 measurements of discharge in the Silver River. The location of these measurements has ranged from about 300 ft downstream from the spring pool to just upstream from the confluence of the Silver River and Ocklawaha River, about 5.7 miles downstream from the spring pool (Figure 1).

Methods developed in a previous project were used to normalize discharge measurements made at any location from 3900 ft downstream from the spring pool to equivalent discharge at the mouth of the Silver River, about 5.7 mi downstream from the spring pool (German, 2006). Then the discharges normalized to the mouth of the river were multiplied by a constant ratio (0.90) to represent discharge at the 3900 ft station.

The normalization procedure is based on the average relative gains between measuring points and the mouth of Silver River, as indicated by simultaneous measurements at two commonly-used discharge-measuring locations (3900 ft and 13,200 ft downstream from the spring pool) and the mouth. The average ratio of discharge at the 13,200 ft location to discharge at the mouth is 0.97, and the average ratio of discharge at the 3,900 ft location and the mouth is 0.90 (Table 3). A set of interpolation equations were derived by using these average ratios and assuming that inflow increases linearly between a measuring point and the next point downstream. The equations are:

From 3900 ft to 13200 ft: $Q_{mouth} = Q(1.145 - 8.613x10^{-6} D)$
From 13201 ft to mouth: $Q_{mouth} = Q(1.059 - 2.161x10^{-6} D)$

where Q_{mouth} is estimated discharge at the mouth of Silver River, Q is the measured discharge at distance D, and D is the distance downstream from the boil, in feet.

Estimates made using the above equations should be regarded as approximations because the equations were derived with a limited amount of data, especially at the 13,200 ft location where only two simultaneous measurements have been made. Also, surface runoff from tributaries, such as the one about 4100 ft below the boil, would likely be seasonally variable and would require more data to evaluate.

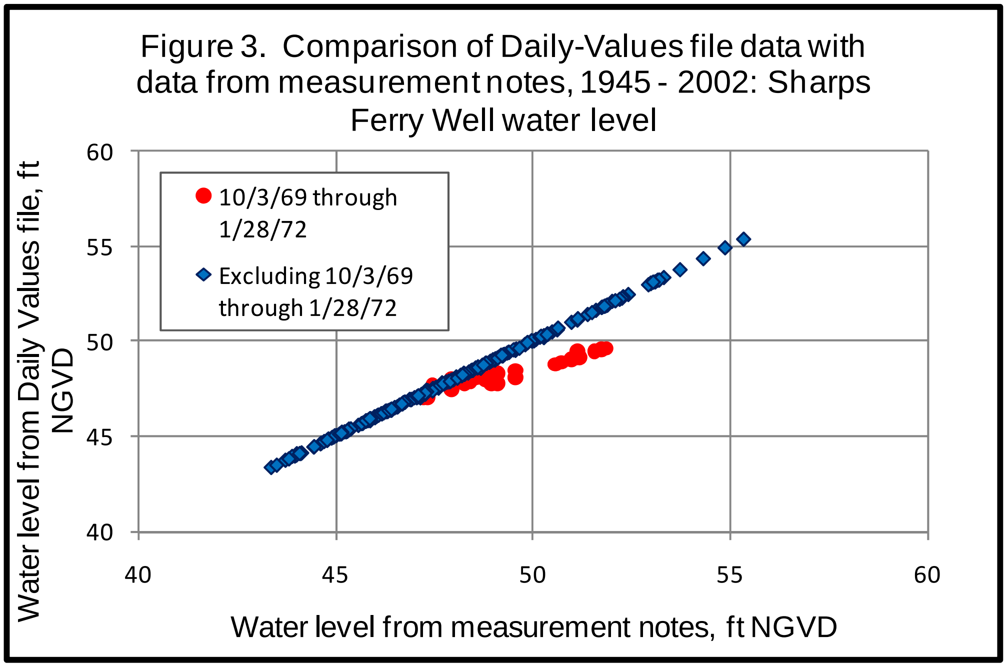
The ratio of discharge at the mouth to discharge at other locations is probably not a constant but rather varies in response to runoff, surface and ground water levels, and perhaps other factors. Variation in the ratio of discharge at the 3900 ft location and the mouth is discussed later in this report.

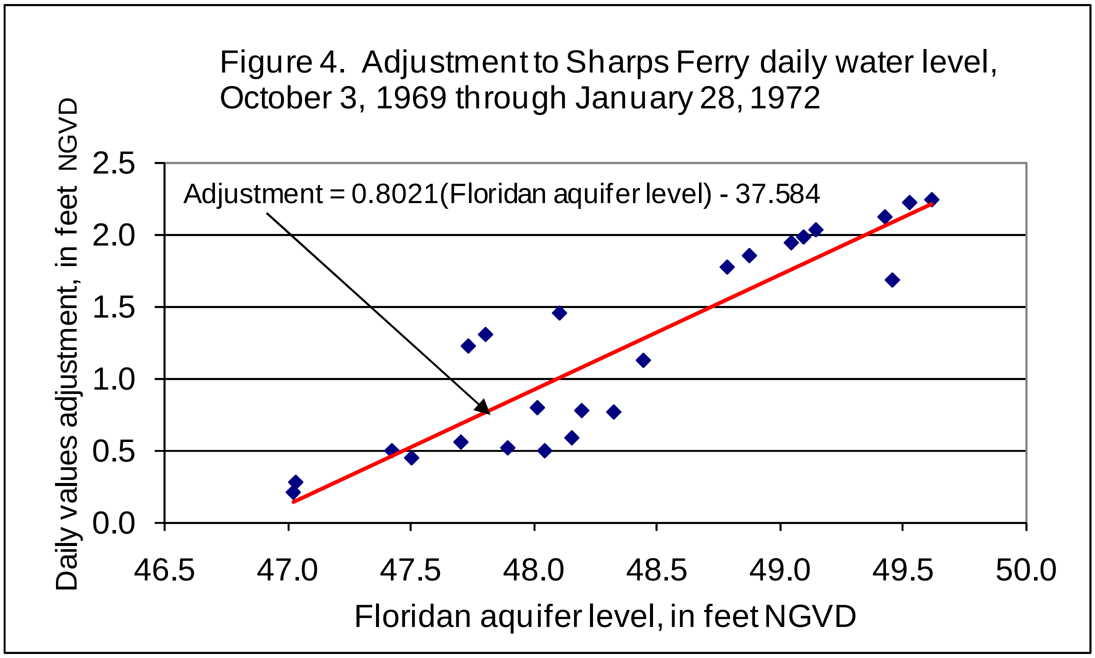
Table 3. Simultaneous measured discharge at the 3900 ft station, 13,200 ft station, and at mouth of the Silver River.

Date	Stage, Ft	Stage, previous day, ft	Rate of change, ft	Q_{3900}, ft3/s	Q_{13200}, ft3/s	Q_{mouth}, ft3/s	Ratio of Q_{13200} to Q_{mouth}	Ratio of Q_{3900} to Q_{mouth}	Remark
9/23/1944				795	802	832	0.96	0.96	
1/28/1974					689	702	0.98		
4/14/2004	40.13	40.13	0.00	542		606		0.89	
6/1/2004	39.95	39.94	0.01	523		553		0.95	
7/21/2004	40.18	40.18	0.00	473		540		0.88	
8/2/2004	40.27	40.27	0.00	429		519		0.83	
9/16/2004	42.24	42.21	0.03	643		896		0.72	
3/14/2005	40.97	40.96	0.01	613		669		0.92	
5/10/2005				623		742		0.84	Mouth measured 5/9/05
6/29/2005	40.58	40.60	-0.02	670		1068		0.63	Mouth measured 6/27/05
8/23/2005	41.92	42.02	-0.10	766		913		0.84	Mouth measured 8/22/05
11/17/2005	41.48	41.49	-0.01	678		734		0.92	
12/6/2005	41.41	41.43	-0.02	637		732		0.87	Mouth measured 12/5/05
1/24/2006	41.05	41.05	0.00	671		662		1.01	
3/21/2006	40.99	40.99	0.00	643		684		0.94	
5/19/2006	40.62	40.63	-0.01	568		630		0.90	
7/12/2006	40.62	40.61	0.01	541		588		0.92	Mouth measured 07/12/06
7/31/2006	40.64	40.63	0.01	490		587		0.83	
9/8/2006	40.67	40.67	0.00	483		577		0.84	
10/26/2006	40.48	40.49	-0.01	539		501		1.08	
11/8/2006	40.44	40.44	0.00	511		491		1.04	
1/9/2007	39.98	39.99	-0.01	452		478		0.95	Mouth measured 01/10/07
1/30/2007	39.83	39.84	-0.01	526		473		1.11	
3/7/2007	40.2	40.21	-0.01	489		553		0.88	Mouth measured 03/06/07
5/9/2007	39.91	39.92	-0.01	483		507		0.95	
6/26/2007	39.79	39.79	0.00	407		441		0.92	
N							2	25	
Mean							0.97	0.90	
Median							0.97	0.92	

Note: Simultaneous measurements are considered to be made at different stations within no more than 2 days.
Stage is the water surface elevation of the spring pool. Rate of change of stage is the difference between stage on day given and the previous day. Positive rates of change indicate a rising stage.
Q_{3900} is the measured discharge at the 3900 ft station station.
Q_{13200} is the measured discharge at a location about 13,200 downstream from the spring pool.
Q_{mouth} is measured discharge near the mouth of the Silver River.

There are discrepancies between some water-level measurements for the Sharp Ferry well stored in the USGS daily-value file and those recorded on the discharge measurement field sheets at the time of measurement. These discrepancies, shown by the red line in Figure 3, are all within the period October 3, 1969 through January 28, 1972, and indicate that water levels in the daily-values file appear to be too low. The differences between the two sources of data are not constant, and are proportional to magnitude of the water level. A relation of the difference between the daily values data and the measurement note data, and the well water level data from the daily-values file was used to estimate an adjustment to the daily-values data (Figure 4). The adjustment calculated from the relation shown in Figure 4 was added to daily values of water level for the Sharps Ferry well for the period October 3, 1969 through January 28, 1972.These corrected water levels were then used to calculate discharge from the relationship between discharge and water level or head differences.





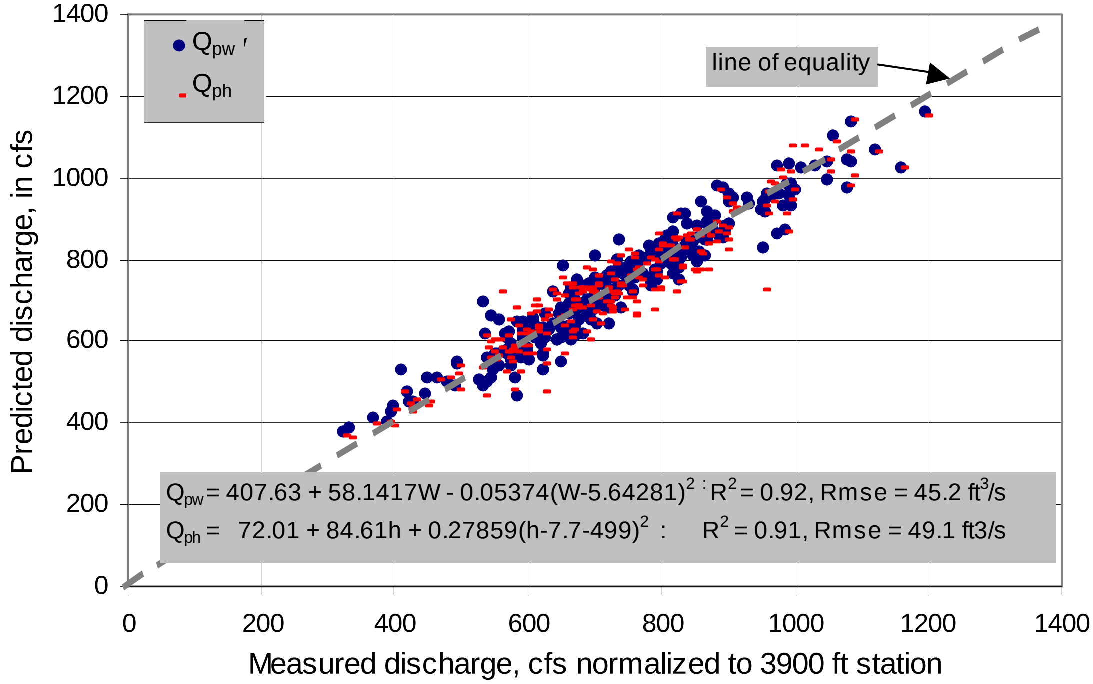
2. Development of a set of well water level vs. discharge rating curves and head difference vs. discharge rating curves based on discharge measurements normalized to the 3900 ft station

The first step in developing a set of relationships (or rating curves) for estimating discharge from the Sharps Ferry well water level, or head difference between the spring pool and the well, was to determine a single relationship for the entire period of record (January 1933 through September 2002 for the Sharps Ferry well.) This was done so that the residuals (difference between measured discharge and rating-estimates of discharge) could be examined to determine when changes in the relationship between discharge and water level occurred. Based on the pattern of the residuals, rating curves were developed to more accurately represent selected time periods.

The plot of measured and calculated discharges (Figure 5) shows that a single relationship of discharge as a function of well water level or head difference for the period 1933 – 2002 provides a good estimate of discharge in both cases, though both tend to underestimate discharge slightly at discharges greater than about 1000 cfs. The relationship using well water level provides a slightly lower standard error of regression compared to the relation using head difference.

Figure 5. Measured and predicted discharge, 1933 - 2002

(Q_{pw} is discharge calculated using polynomial function of Sharps Ferry well water level, Q_{ph} is discharge calculated using polynomial function of head difference, W is water level (in feet above gage datum), h is head difference between well and pool water level (in feet), R^2 is the coefficient of determination, and Rmse is the standard error of the regression.)



Date plots of the residuals (Figure 6) and cumulative residuals (Figure 7) show patterns in the residuals that indicate there are changes in the relationships of measured vs. calculated discharges over time. Therefore, several relationships, each for a specific time period, would provide a more unbiased estimate of discharge than would one single relationship for the entire period of record. For example, the residuals for the well water level relationship tend to be greater than 0 for the time period 1947-69, less than 0 for the time period 1970-75, and less than 0 for the period 1996 and after. The reason for these changes is probably complex and may be related to patterns in rainfall that are in turn related to long-term changes in sea-surface temperatures such as the Atlantic Multidecadal Oscillation (Enfeld et al. 2001).

The cumulative residual plots (Figure 7) show more clearly the time patterns in the residuals. Changes in slope of the residual points indicate a change in the relationship between discharge and the terms used to calculate discharge (i.e., well water level or head.) A period of time with a constant slope can be represented without a time-related bias using a relationship between discharge and well water level or head fitted for that time period. Although there are frequent changes in slope of the plotted residuals over short time periods, it is not practical to fit a relation to some time periods because they do not include enough discharge measurements to define a relationship. A criterion of a minimum of 20 measurements was used in selecting time periods to be represented by a single relationship. This criterion was selected based on professional judgment to ensure that the number of measurements was probably sufficient to define the relationships over the seasonal range in flow. Therefore it was necessary to generalize somewhat in selecting time periods to be represented by separate relationships.

The period from January 1933 through September 2002 was divided into six time intervals (Figure 7) based on the relatively constant slope of the residual plots and the need to include at least 20 discharge measurements in each time interval. Regression analysis was used with data for these selected time intervals to develop relationships for calculating discharge from the Sharps Ferry well water level, and also from the head difference between the spring pool and the Sharps Ferry well. A relationship between discharge and head was not developed for the 1933 – 46 time period because there are no daily values of spring pool elevation prior to February 1947.

The Sharps Ferry well was abandoned in September 2002 because the water level in the well became too low for continuous water-level recorder operation. From October 2002 through September 2005, well CE76 was used to develop relationships between well water level and head difference. Single relationships between discharge and well water level or head difference were used to represent that time period.

The details of each regression analyses are given in Appendix A. These details include plots of measured discharge vs. the predictor variable (i.e., well water level or head difference), measured vs. predicted discharge, tables summarizing model fit, and plots of the residuals.

1936

Figure 6. Residuals of relation between measured and calculated discharge

(Res_{pw} is the residual of Q_{pw}, and Res_{ph} is the residual of Q_{ph}. Residuals are the difference between Q_{norm} and Q_{pw} or Q_{ph}.)

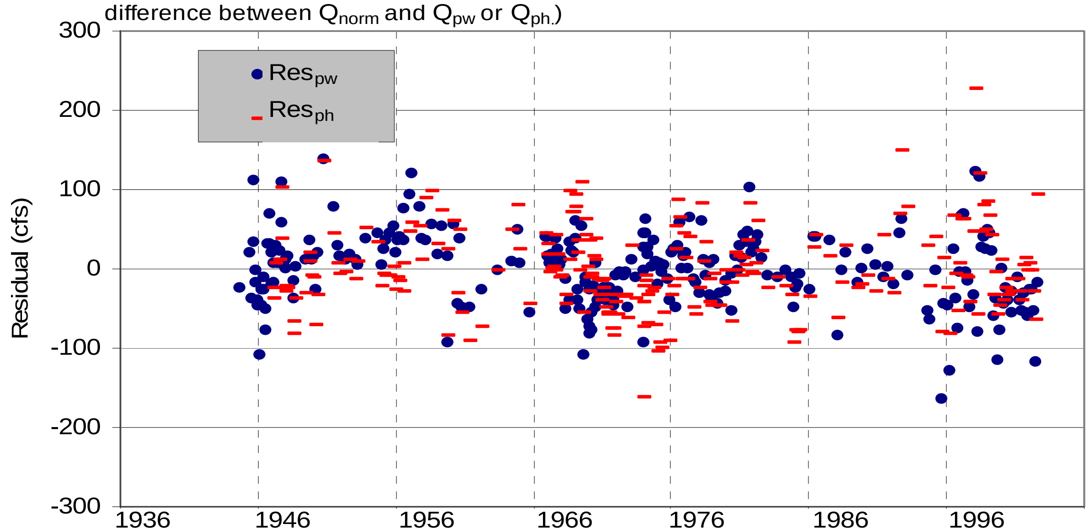
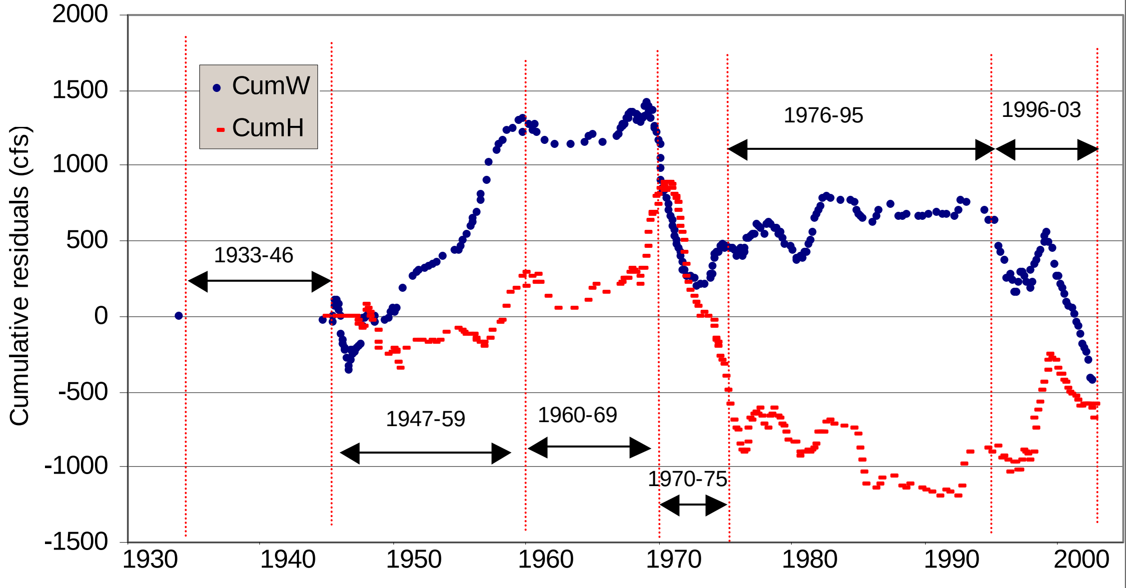


Figure 7. Cumulative residuals of relation between measured and calculated discharge.

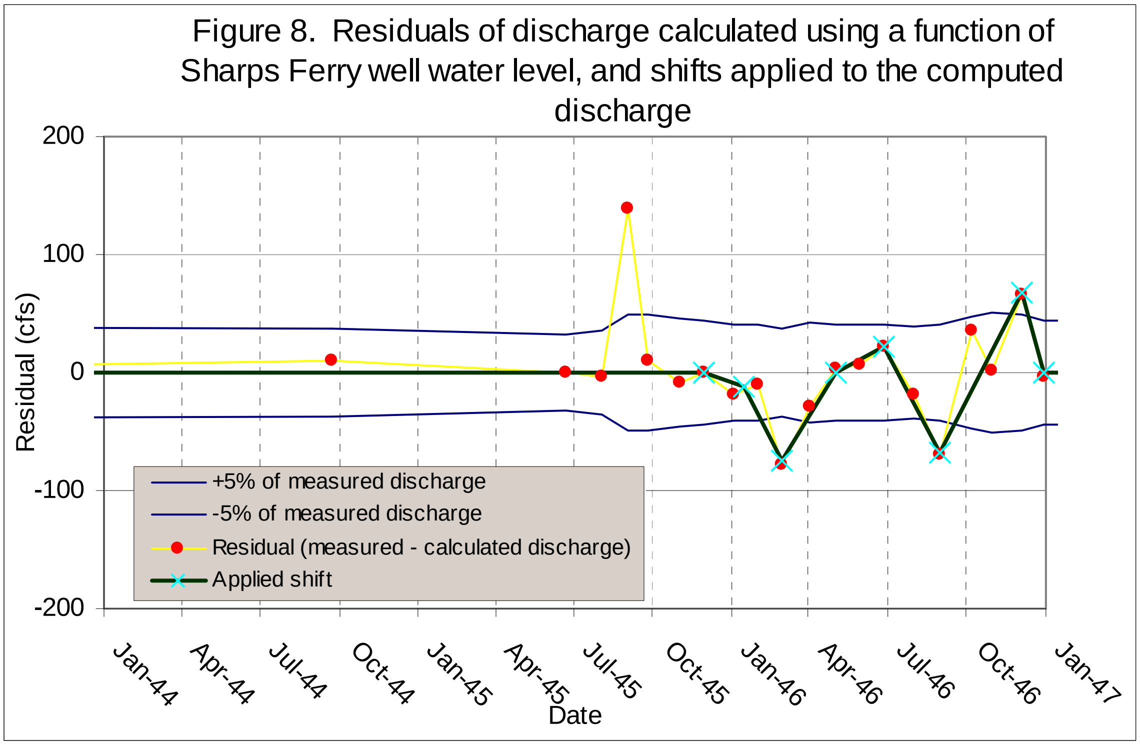
(CumW is the cumulated residual for Q_{pw}, and CumH is the cumulated residual for Q_{ph}. Q_{pw} and Q_{ph} are calculated discharges as a function of Sharps Ferry well water level or head difference. Residuals are the difference between Q_{norm} and Q_{pw} or Q_{ph}.



3. Re-computation of daily discharges at the 3900 ft station for the time period 1933 – 2005 using the ratings of well water level and head difference to normalized discharge

Subdividing the data into specific time periods helps remove cyclic patterns in residuals but does not completely eliminate them. For example, the residuals of discharges calculated using a function of well water level for the period 1933-46 tend to be less than 0 for measurements made between January 1946 and April 1946 (Figure 8). This pattern of negative residuals indicates a possible positive bias (i.e., discharges are calculated too high) in daily discharges calculated between these dates.

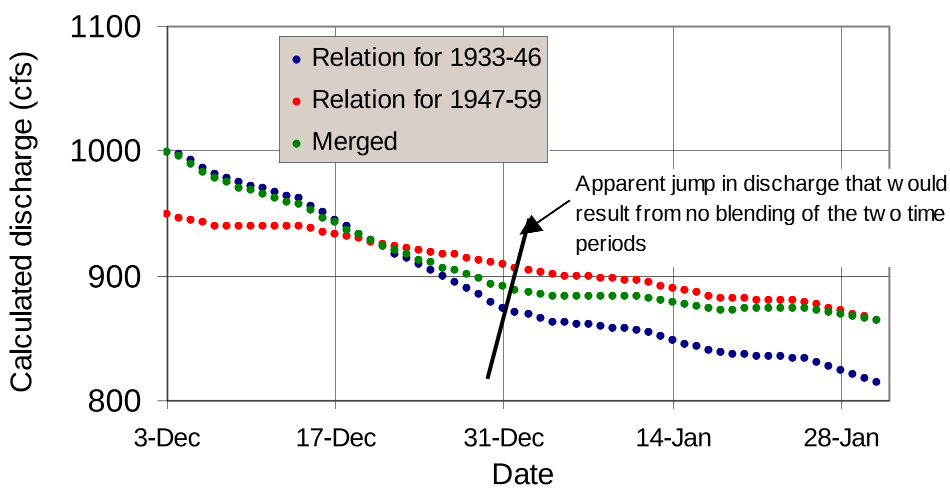
Shifts were applied to the daily discharges calculated from the regression-defined relationships to correct for these cyclic bias patterns (see Figure 8 for shifts applied to calculated discharge for the 1933-46 data). Selection of the shifts is subjective, and shifts were not used unless the measurements seemed to indicate the presence of a continuing trend in residuals. Thus, shifts were not made based on individual measurements, even though these measurements might be associated with a relatively large residual. For example, the measurement on September 1,1945 (974 ft^3/s) was much greater than that predicted by the well water-level relationship (835 ft^3/s), but measurements made 3 or 4 weeks before and after the September 1, 1945 measurement did not indicate a continuing bias in the residuals, and no shifts were made based on the September 1945 measurement. In general, shifts were only used when the residual plots suggest short-term but persistent patterns in residual bias, such as those occurring between November 29, 1945 and December 31, 1946 (Figure 8). These patterns in residuals may be the result of change in measuring conditions, such as weed growths in the measuring section, that can affect measurement accuracy. Other possibilities include small datum shifts in the Sharps Ferry well water-level recorder or an actual change in the discharge-water level relationship for some reason, such as a change in hydraulic conductivity of the spring-vent system. The residual patterns for the November 29, 1945 to December 31, 1946 are not related to measuring-station location, because all measurements were made at the 3900 ft station. Plots of residuals and shifts for all of the other time periods are given in Appendix B.



The final step in creating a re-computed record of daily discharge was to join the individual relationships together into a continuous time series of the shifted calculated daily discharges based on the regression relationships of discharge to well water level, and discharge to head difference. A simple concatenation of the individual time series would result in abrupt changes in calculated discharge between the last day in one time interval and the first day in the succeeding time period, because these two days are calculated using different relationships . For example, the calculated discharge for the last day of the 1933-1946 time period (December 31, 1946) is 874 ft3/s calculated with the relationship of discharge to well water level fitted for that time period. The calculated discharge for January 1, 1947 is 906 ft3/s, calculated with the relationship of discharge to well water level fitted for that time period. Concatenation of the old and the new time series implies a jump in discharge that is only an artifact of the differences in the two predictive relationships (note the change from the blue line to the red line in Figure 9).

A weighted merge of calculated discharges from one time period to the next was used to produce a smooth transition between periods. This was done by calculating a merged discharge that was weighted with 98% of the early-period relationship and 2 % of the next-period relationship 30 days before the end of the early period, 96% of the early-period relationship and 4 % of the next-period relationship on the following day, and so on until the merged discharge was weighted with 98% of the next-period relationship and 2 % of the early-period relationship 30 days after the beginning of the next period. This weighting method results in a smooth transition between the two adjacent discharge relationships (see green line Figure 9).

Figure 9. Example of merging calculated discharges from adjacent time periods



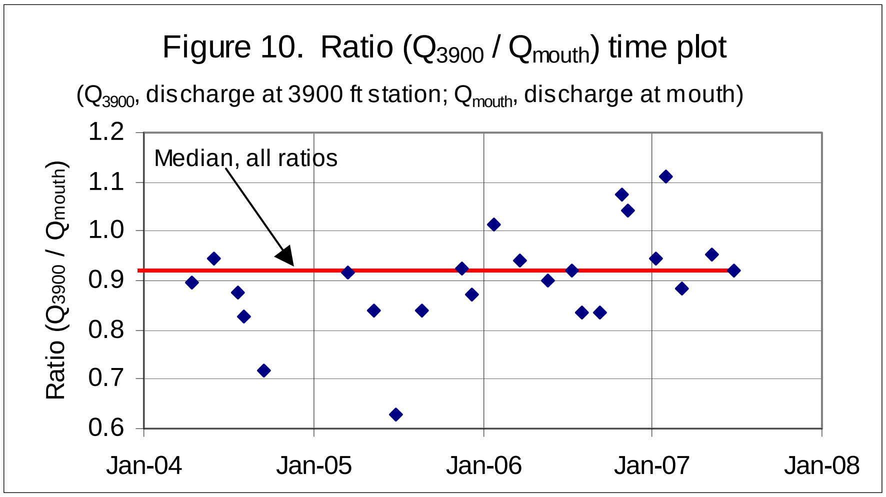
Spreadsheets and data graphs were prepared using Microsoft Excel 2000 (Blattner and others, 1999). Rating development and statistical analyses were done using the SAS JMP software (SAS Institute, Inc. 2002).

Results and Discussion

Characteristics of the Ratio of Discharge of Silver River at the 3900 ft Station to Discharge at Mouth

There have been 25 simultaneous measurements of discharge at the 3900 ft station on the Silver River and at the mouth of the river between September 1944 and June 2007. Measurements are considered simultaneous if they were made within two days of one another. Most were made on the same day. All but one of these measurements were made since April 2004 (Table 3).

Ratios of discharge at the 3900 ft station to discharge at the mouth (Q_{3900} / Q_{mouth}, called the Q ratio in the following discussion) have ranged from 0.63 to 1.11 (Figure 10). The mean ratio is 0.90 and the median ratio is 0.92. The plot does not indicate a time trend in the ratio, nor does a Kendall Tau test indicate a trend (P-value = 0.16).



Q ratio plots suggest that the ratio may be lower for high spring pool levels (Figure 11) or for relatively rapid rates of water-level rise (Figure 12). However, since the highest water level and the highest rate of water-level rise are for the same measurement (made on Sept. 16, 2004), the condition is most likely to affect the ratio is not determinable.

Days for which both rate of water-level rise at the spring pool is 0.03 ft/d or greater and pool water level exceeds 42 ft are relatively rare: out of nearly 59 years of water-level record (1947 – 2005) this combination of conditions occurred on 64 days, or less than 1% of the days of record. Thus, if the Q ratio is affected by a combined high pool water level and rate of water level rise, this effect is probably rare.

Pool water levels exceeding 42 ft occurred on 531 days, or about 2.5 % of the days of record. Rates of pool water-level change exceeding 0.03 ft/d occurred on 1,958 days, or about 9.2 % of the days of record. Thus, a high rate of pool water-level change (exceeding 0.03 ft/d) may be the most significant factor in terms of potential effect on the Q ratio, simply because this condition occurs relatively frequently.

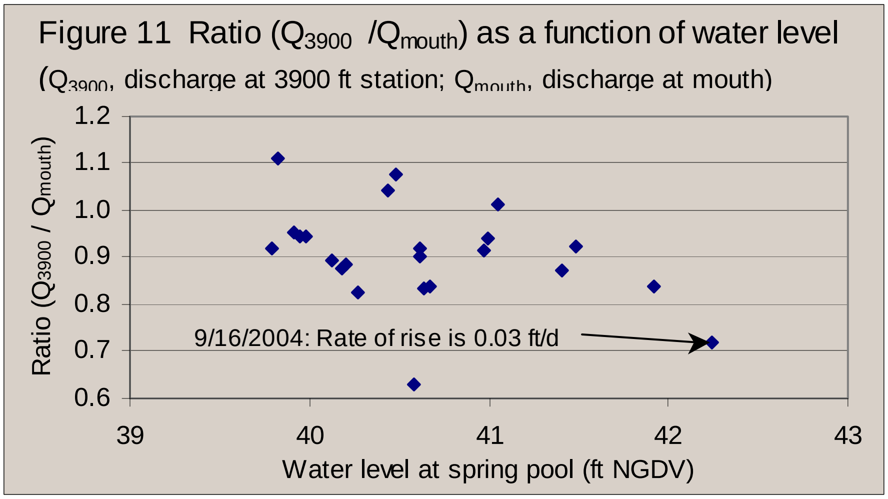


Figure 11 Ratio (Q3900 /Qmouth) as a function of water level
(Q3900, discharge at 3900 ft station; Qmouth, discharge at mouth)
Ratio (Q3900 / Qmouth)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
9/16/2004: Rate of rise is 0.03 ft/d
39
40
41
42
43
Water level at spring pool (ft NGDV)

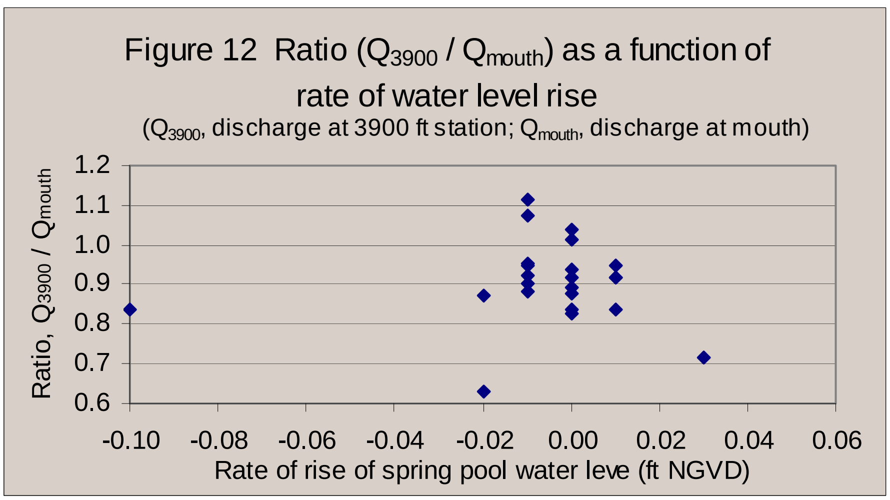
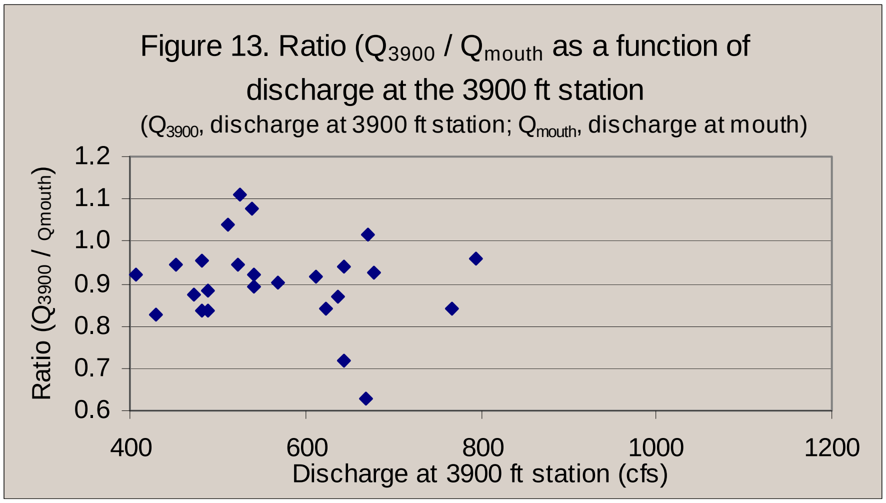
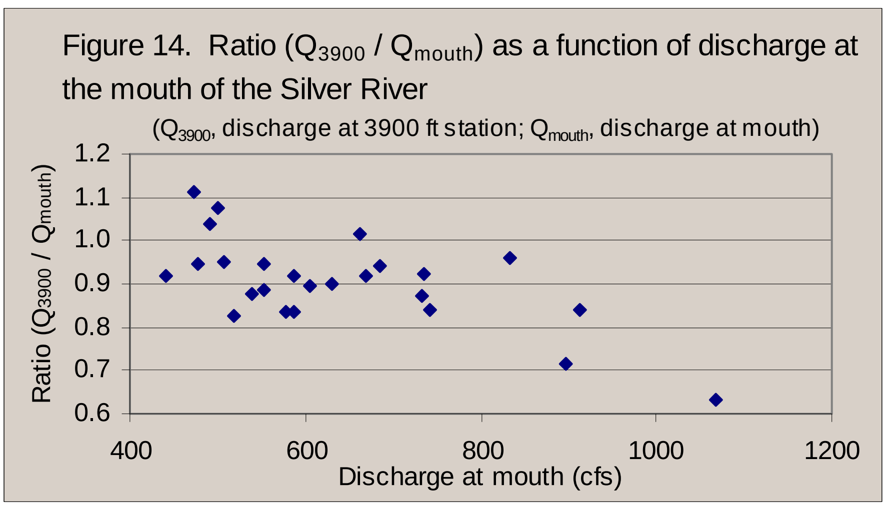


Figure 12 Ratio (Q3900 / Qmouth) as a function of rate of water level rise
(Q3900, discharge at 3900 ft station; Qmouth, discharge at mouth)
Ratio, Q3900 / Qmouth
1.2
1.1
1.0
0.9
0.8
0.7
0.6
-0.10
-0.08
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
Rate of rise of spring pool water leve (ft NGVD)

The plot of the Q ratio as a function of discharge at the reference location (Figure 13) does not indicate a clear relationship between the ratio and discharge. The plot of the Q ratio as a function of discharge at the mouth of the Silver River does indicate that the ratio may be lower at higher discharges (Figure 14). However, this apparent relationship is largely the result of a single measurement and more measurements at high discharges are needed to confirm the relationship.





It seems possible that the variation in the Q ratio among the set of 25 measurements (Table 3) could simply be the result of random measurement errors. The measurement accuracy is probably no better than 5 % of the measured discharge, and could be poorer in some cases due to prolific weed growths in the measurement sections. This error could obscure effects of hydrologic conditions such as water level and rate of water-level change on the ratio. Therefore, assumption of a constant Q ratio seems appropriate at this time. Additional sets of measurements, especially at extreme hydrological conditions, may result in a more accurate description of the Q ratio.

Characteristics of the Regression Relationships for Calculating Spring Discharge

A set of relationships for seven different time periods was developed to calculate spring discharge from well water level or head difference between well water level and spring pool water level. The time periods are 1933-1946, 1947-1959, 1960-1969, 1970-1975, 1976-1995, 1996-2002, and 2003-2005. The well water level is from the Sharps Ferry well for the period 1933-2002, and from well CE76 for the period 2003-2005.

The coefficient of variation ranged from 3.8 % to 8.8 % for the eight relationships using water level as the predictor, and from 4.5 to 9.2 % for the seven relationships using head difference as the predictor (Table 4). The coefficient of determination ranged from 0.71 to 0.95 for the relationships using water level as the predictor, and from 0.81 to 0.92 for the relationships using head difference as the predictor. Details of the regression analyses for the rating development are given in Appendix A.

The purpose of the ratings is to calculate spring discharge for each day, using daily values of well water level and head difference. However, the ratings were developed using relatively few days (N in Table 4). Well water levels or head differences on some days in each period were outside the range of those values used to define the rating relationships. Therefore, extrapolation of the rating beyond the lowest or highest predictor variable value was necessary. Overall, the total number of extrapolated days for discharges calculated from well water level was 706 (2.6 % of the days) for the period 1933 – 2005. The maximum water-level extrapolation was 1.72 ft. Generally, the magnitude of the extrapolation was much less: 0.33 ft or less for 99.5 % of the days, and 0.19 ft or less for 99 % of the days. The total number of extrapolated days for discharges calculated from head difference was 361 days (1.7 %) for the period 1947 – 2005. The maximum head difference extrapolation was 1.41 ft., and was 0.19 ft or less for 99.5 % of the days, and 0.07 ft or less for 99 % of the days The magnitude and time distribution of the extrapolations are shown in Figure 15 and 16.

It is difficult to estimate the magnitude of uncertainty in calculated discharges that results from extrapolation of ratings, and no attempt to do so has been made here. Discharges calculated from extrapolation of a rating should be regarded as tentative and less accurate than those calculated using independent variable values that are within the range of the rating used. The discharges that have been calculated using extrapolation are flagged in the spreadsheet of daily values that was prepared as an accompaniment to this report.

Table 4 Summary of regression relationships used to calculated spring discharge

(Predictor, the independent variable in the relationship used to calculate discharge; N, the number of discharge measurements defining the relationship; Range, the range in water level or head difference for the set of measurements used to develop the relationship; CV, the coefficient of variation for the regression; R^2 , the coefficient of determination; Days outside, the number of days in the daily record for which the predictor value was lower or higher than all values used in relationship development, and in parentheses, the days outside as the % of the total number of days in the period)

Period	Predictor	N	Range (ft)	CV (%)	R^2	Days outside (number, %)
1933-46	Water level	21	3.80 to 9.70	5.5	0.80	198 (3.8)
1947-59	Water level	52	0.99 to 10.94	4.3	0.95	27 (0.6)
1947-59	Head difference	51	5.32 to11.79	4.5	0.92	44 (0.9)
1960-69	Water level	37	2.85 to 12.96	4.8	0.93	67 (1.8)
1960-69	Head difference	37	5.92 to 12.62	5.9	0.90	134 (3.7)
1970-75	Water level	48	2.92 to 9.50	3.8	0.92	65 (3.0)
1970-75	Head difference	48	6.37 to 10.12	4.5	0.88	38 (1.7)
1976-95	Water level	70	1.35 to 9.12	5.7	0.84	294 (4.0)
1976-95	Head difference	69	4.61 to 10.12	6.4	0.80	94 (1.3)
1996 –2002 (Sept)	Water level	43	-0.48 to 9.71	8.9	0.91	34 (1.4)
1996 –2002 (Sept	Head difference	43	3.38 to 10.31	9.2	0.91	32 (1.3)
2002 (Oct) - 2005(Sept)	Water level	28	41.63 to 46.23	8.8	0.71	21 (1.9)
2002 (Oct) - 2005(Sept)	Head difference	28	1.64 to 3.90	7.2	0.81	19 (1.7)
Entire (1933 – 2005)	Water level					706 (2.6)
Entire (1947 – 2005)	Head difference					361 (1.7)

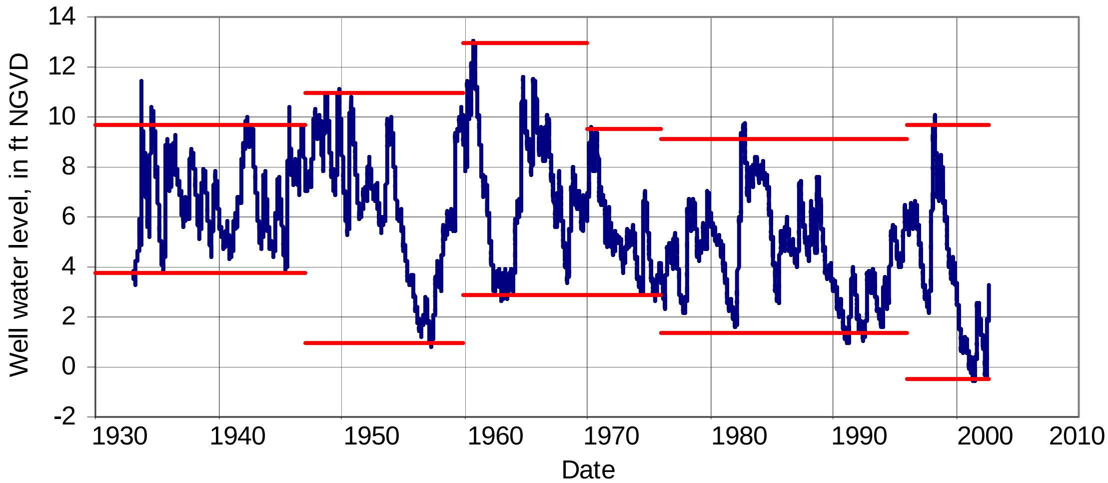


Figure 15. Daily well water level used to calculated discharge

(Well w ater levels are for Sharps Ferry w ell. Red lines show range of w ell w ater levels used in rating development.)

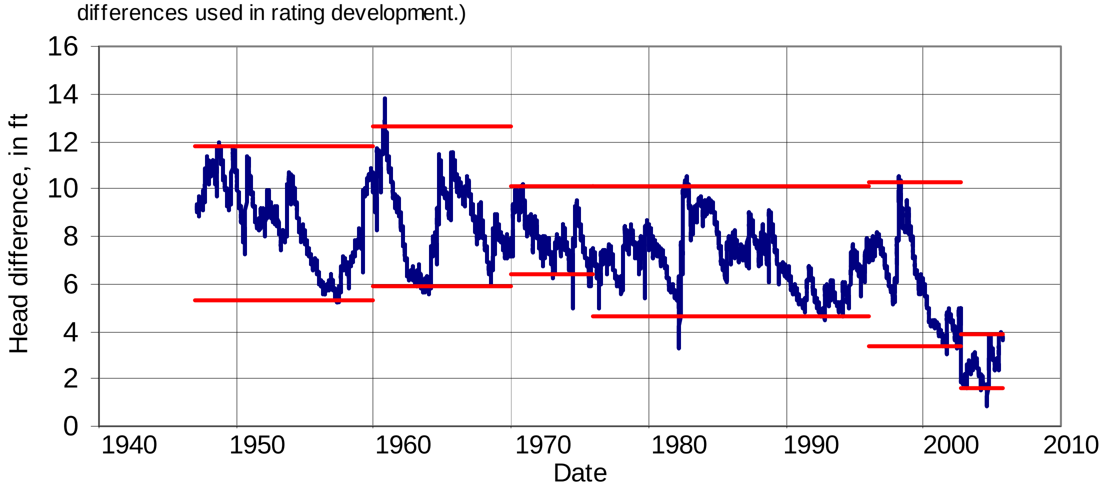


Figure 16. Daily head difference used to calculate discharge

(Head differences are difference betw een Sharps Ferry w ell w ater level and the spring pool. Well CE76 w as used for calculation of head after September 2002. Red lines show range of head differences used in rating development.)

Analysis of Residuals from the Discharge Re-calculating Relationships

Each set of relationships for estimating discharge from well water level or head difference for a specific time period was developed using discharge measurements made at more than one location. This is especially true for the relationships for the periods 1970-1975, 1996-2002, and 2003-2005 when several measurement locations were used.

Residual patterns seem to be related to measurement location in some cases. Reasons for this measurement location effect on residual patterns might include the following:

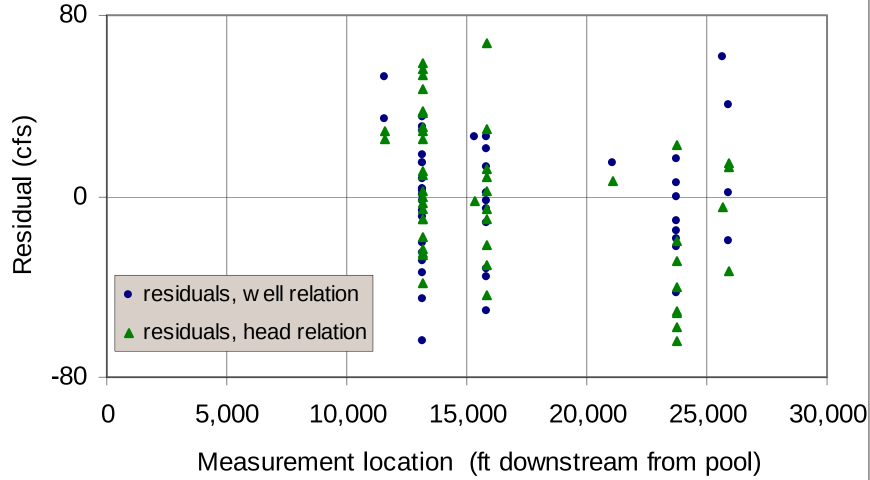
1. The normalization of measured discharge from the measurement location to the 3900 ft station is not accurate, so that normalized discharges are lower or higher than the actual discharge. The normalization procedures are based on a few measurements made at different downstream distances on the same day.

2. Measurement section characteristics result in measurement bias. For example, dense weed growth in a measurement section could interfere with proper operation of the water-velocity meter and result in lower than actual measured velocities and discharge.

3. The use of measurement locations is not generally random in time, so that for some rating periods measurements made early in the period were generally at one location, and measurements made late in the period were generally at a different location. Thus, the apparent effect of measurement location could actually be due to a pattern of residuals that is related to time and perhaps changes in magnitude of discharge.

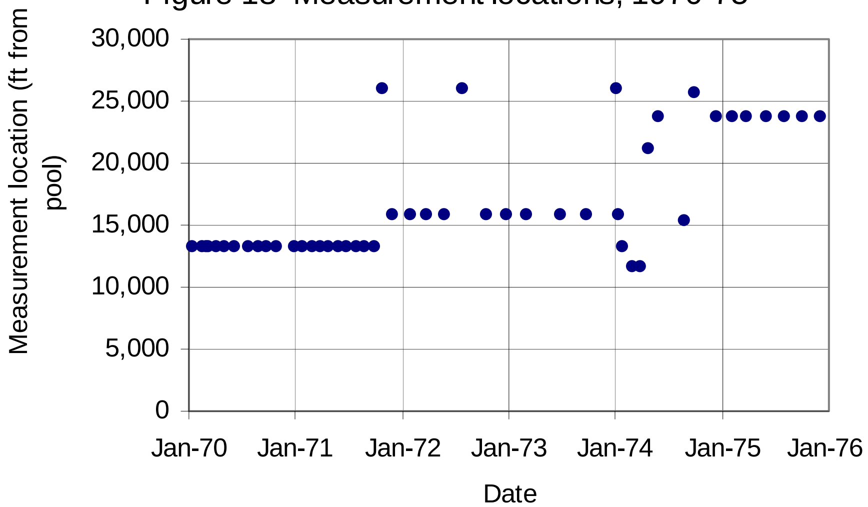
Residuals for the eight measurements made at the 24,000 ft station during the 1970-1975 period tend to be negative, indicating that the measured discharge is lower than the discharge calculated using the predictive relations for that time period (Figure 17). The four measurements made at the 26,000 ft station during this time period do not appear to have this negative bias in residuals. Because the two locations are so close together, the normalization of measured discharges to the 3900 ft station could not explain the difference in the residual patterns for the two locations.

Figure 17. Residuals of relationship between measured and calculated discharge, 1970-75



The apparent bias in measurements made at the 24,000 ft station may be related to the date of the measurements. All but one of the measurements made at the 24,000 ft station were made at the end of the 1970-1975 period (Figure 18). Thus, any time-related bias could have affected these measurements.

Figure 18 Measurement locations, 1970-75



There was a pattern of decreasing water level in the Sharps Ferry well, and in the head difference between the well and the spring pool from 1970 through 1975 (Figure 19). The annual averages of well water level and head are given in Table 5. The lowest annual mean values occurred in 1975, when all measurements were made at the 24,000 ft station. Thus, it seems possible that residuals from the relationships between measured discharge and well water level or head could be related to magnitude of the well water level or head. However, a relationship between the residuals and water level or head is not clearly indicated by the plots of residuals (Figures 20 and 21), and the reason for the apparent bias in measurements made at the 24,000 ft location is not clear. A possible explanation is that characteristics of the measuring section, such as abundant weed growth or some other characteristic, may tend to cause measurements to be a little lower than the actual discharge.

Figure 19 Well water level and head difference, 1970-76
(W,ShF is water level in the Sharps Ferry Well. Head is the difference between W,ShF and the spring pool water level)

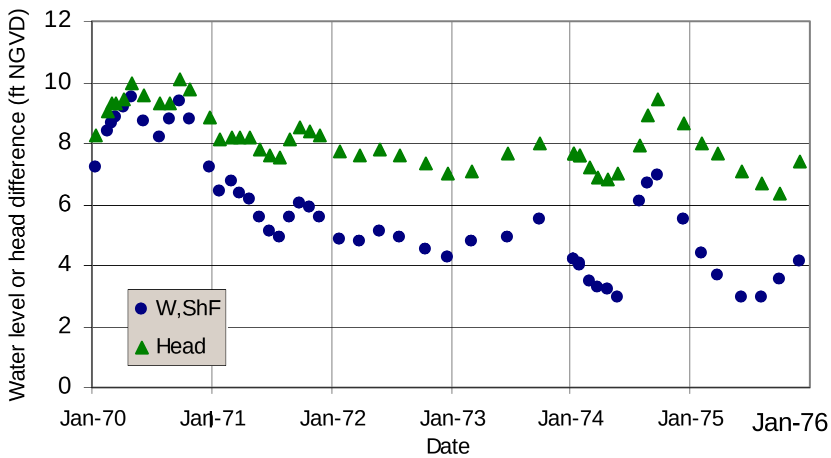


Table 5. Average well water level and head difference, 1970-75 (Water levels and head differences are in feet.)			
Year	Number of measurements	Sharps Ferry Well water level	Head (difference between spring pool and well water level)
1970	12	8.56	9.36
1971	11	5.86	8.08
1972	6	4.73	7.52
1973	3	5.08	7.59
1974	10	4.46	7.79
1975	8	3.60	7.20

Figure 20 Residuals of relationship between discharge and well water level, and well water levels, 1970-75

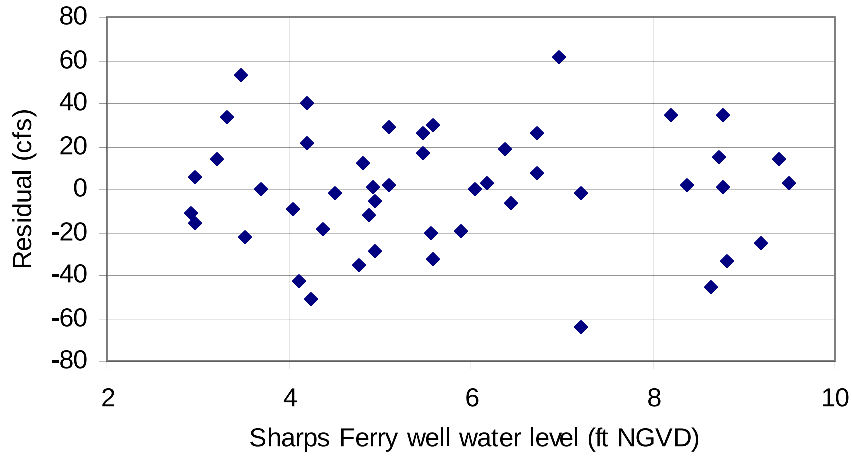
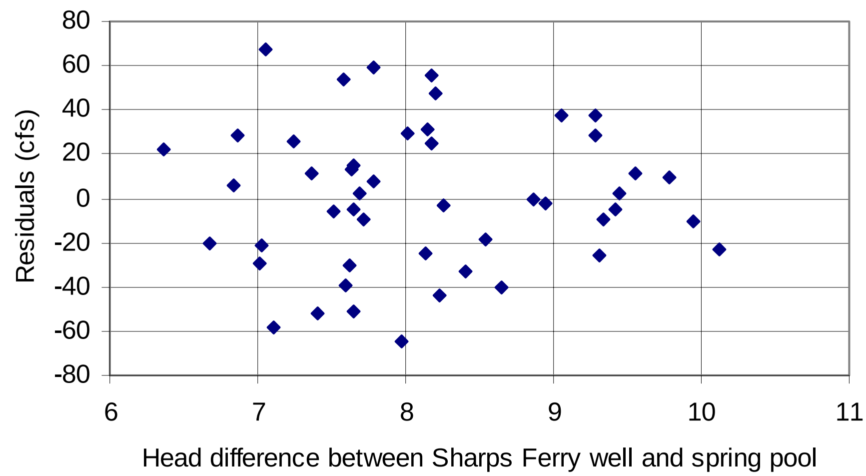


Figure 21 Residuals of relationship between discharge and head difference, and head differences, 1970-75



Residuals for the nine measurements made at the 11,000 ft station to 5,000 ft station during the 1996-2002 period tend to be positive, indicating that the measured discharge is higher than the discharge calculated using the predictive relations for that time period (Figure 22). Residuals for measurements made at stations more than 20,000 ft downstream have little or no bias. However, there is little or no evidence of location-dependent bias in the 2003-2005 period (Figure 23), indicating that the normalization procedure is not a source of significant bias in normalized discharge.

Figure 22. Residuals of relationships between discharge and well water levels or head, and measurement location, 1996-2002

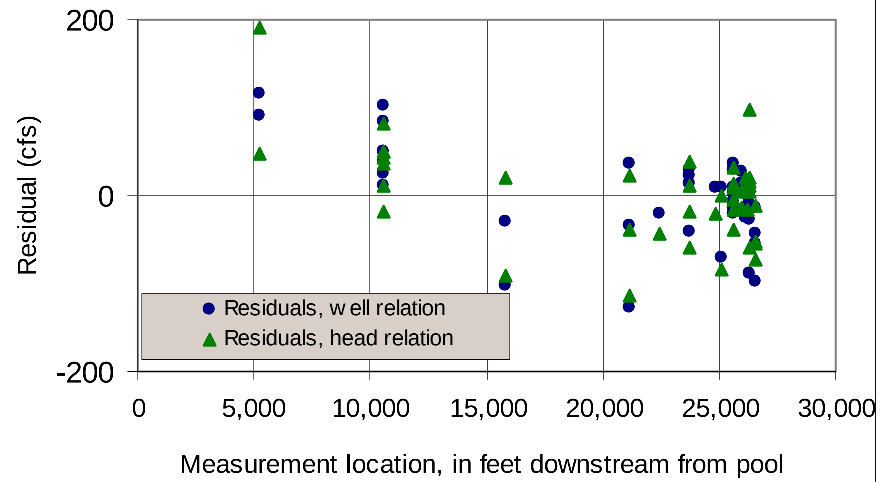
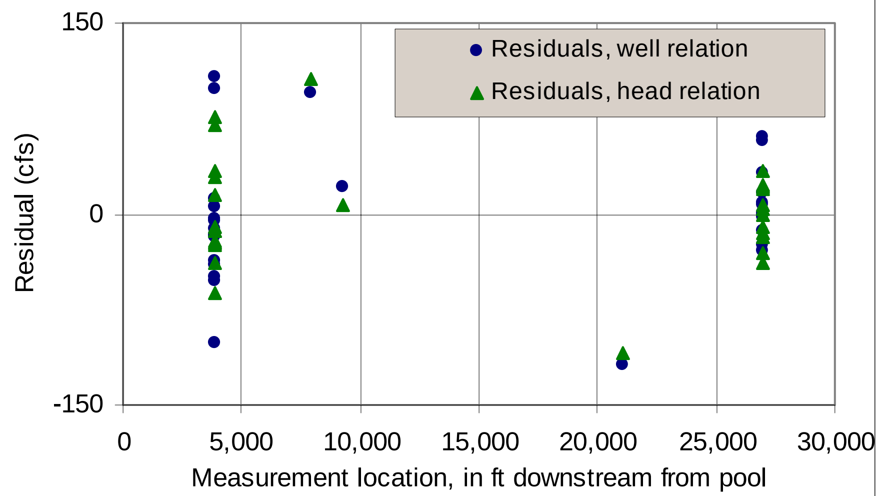


Figure 23. Residuals of relationships between discharge and well water level or head, and measurement location, 2003-2005



Comparison of Daily Discharge from USGS Files, and Discharge Re-calculated Using a Well Water-level Relation and a Head-difference Relationship

Comparison of 10-year averages of USGS original daily spring discharge with the recomputed discharges indicates that the original USGS values are generally higher than the recomputed values (Figure 24). These differences are relatively small (less than 2 %) prior to 1960, and probably are caused by slight differences in the rating curve relationships used to calculate discharge from water level. Greater differences between the USGS original discharges and the recomputed discharges from 1960 on probably reflect the lack of normalization of the USGS original discharges to a specific location on the Silver River.

From the 1960s through the 1990s, the differences between 10-year averages of original and re-computed discharges are as much as 11 %. These larger differences may result from normalization of the discharge-measurement data used in the re-computed values (Q_{pw} and Q_{ph}). The rating relationships for Qpw and Qph were developed using measured discharge that was normalized to the 3900 ft station. Prior to 1960, most discharge measurements were made at or near the 3900 ft station, so differences between normalized and unnormalized discharge are relatively small (Figure 1). During the 1960s and early 1970s, discharge measurements were generally made at the 13,000 to 16,000 ft stations, and could include additional inflow which occurred downstream of the 3900 ft station. From the mid 1970s on, most discharge measurements were made near the mouth of the Silver River and, therefore, include inflows between the 3900 ft station and the mouth.

The differences between original and re-computed discharges are relatively small (about 5 %) for the 2000s (Figure 24). The USGS reconstructed rating curves to represent discharge at the 3900 ft station from October 1, 2003 on. Most of the difference in the averages for the 2000s results from the difference in the earlier (before the USGS reconstruction) data. The USGS reconstructed data for the period January 1, 2004 through September 30, 2005 differed from Qpw and Qph by about 2 %.

The recalculated discharges were less than the original USGS-computed discharges for the entire range of discharge (Figure 25). The maximum differences between original and re-computed discharges were for the middle of the discharge range and for the very low discharges. For example, the re-computed discharges were about 8 % lower than the original discharges for the 50^{th}-percentile discharge, and also for 1-percentile discharge. At the higher discharge rates (greater than 60 percentile), the re-calculated discharges were lower than the original USGS discharges generally by 4 to 6 %.

Figure 24. Average daily discharge for 10-year periods

(Qorg, Qp,w and Qp,h are calculated discharge from Silver Springs. Qorg is the orginal USGS data, Qp,w is discharge calculated from Sharps Ferry well water level, and Qp,h is discharge calculated from head difference between the Sharps Ferry well and the spring pool. Well CE76 was used for calculation of head after September 2002. Record for the 1930's period begins October 1, 1932. Record for the 2000's period ends September 2005.)

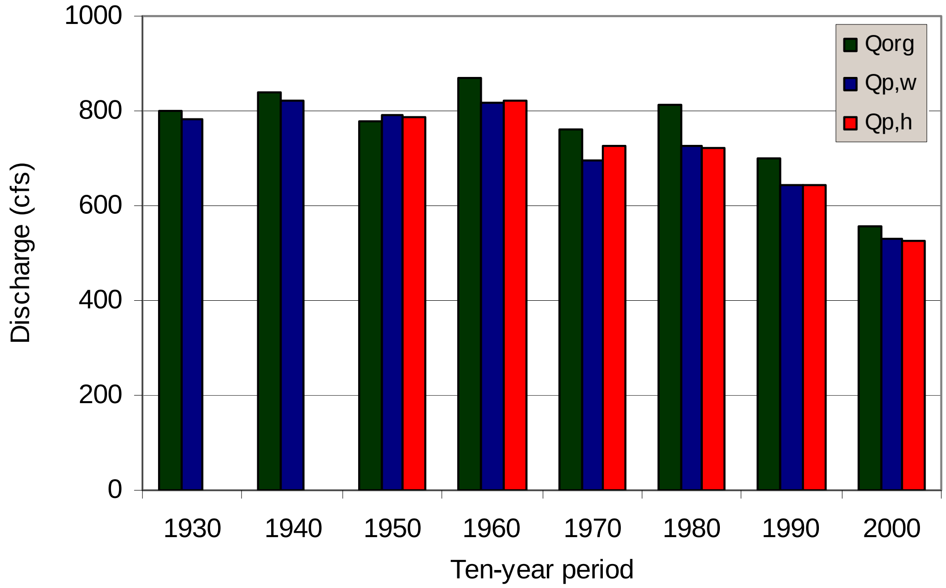
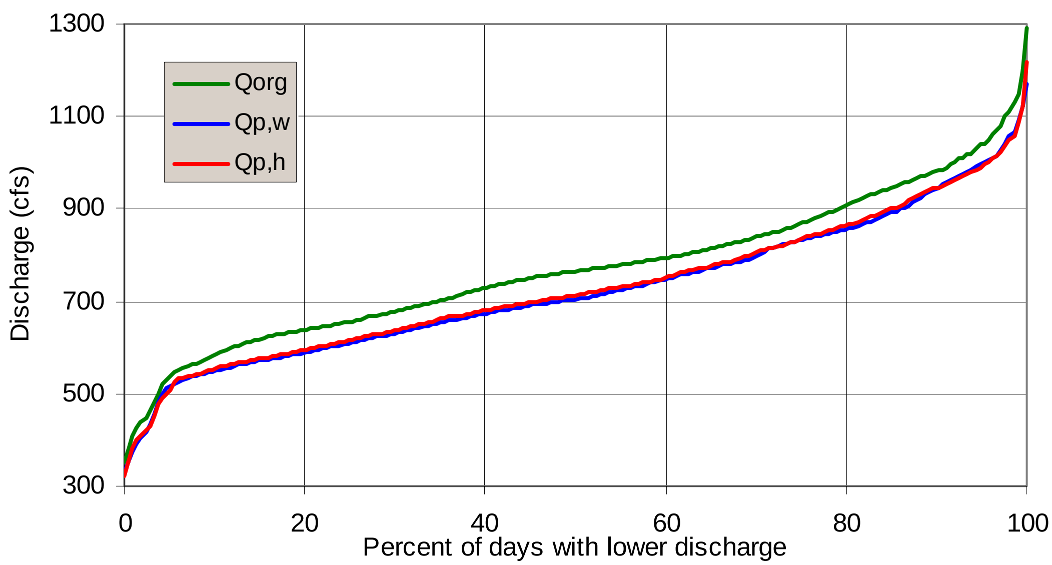


Figure 25. Discharge duration for Silver Springs

(Qorg, Qp,w and Qp,h are daily discharge from Silver Springs. Qorg is the original USGS data. Qp,w is discharge calculated from Sharps Ferry well water level, and Qp,h is discharge calculated from head difference between Sharps Ferry well and the spring pool. Qp,w and Qp,h are for the 3900 ft station on the Silver River. Well CE76 was used for calculation of head after September 2002. This plot includes only Febrruary 1947 through September 2005, when both well water level and head data are available.)



The differences between discharges calculated using well water level (Qpw) and discharges calculated using head difference (Qph) were generally less than 1 %. However, during the 1970s this difference was nearly 4 % (Figure 24).
The differences between these calculated discharges may be relatively large during periods of rapid head change due to backwater effects. An example is given in the plot of data for April 1982 (Figure 26). In early April 1982 there was a rapid drop in head difference, even though the water level in the Sharps Ferry well was rising. This drop in head difference was probably caused by backwater from the Ocklawaha River as a result of release of water from the Moss Bluff dam on the Ocklawaha River. A decrease in spring discharge would be expected to accompany this decrease in head difference, and this expected decrease is shown in the plot of Qph (see red line in Figure 26). However, Qpw (blue line) does not decrease, rather it continues to increase, following the increase in the Sharps Ferry well water level (green line). On April 8, just before the rapid fall in head difference, the difference between Qpw and Qph was about 12 ft^3/s or 2 %. The next day the difference between Qpw and Qph was 116 ft^3/s, or about 21 %. Several days later after the head difference and the Sharps Ferry well water level had stabilized the difference between Qph and Qpw was much smaller. On May 1 this difference was about 51 ft^3/s, or 7 %.

A similar effect is seen near the end of May 1982, when the head difference (purple line) decreases over a period of several days. This decrease in head difference is reflected in the decrease in Qph (red line), but not in Qpw (blue line).

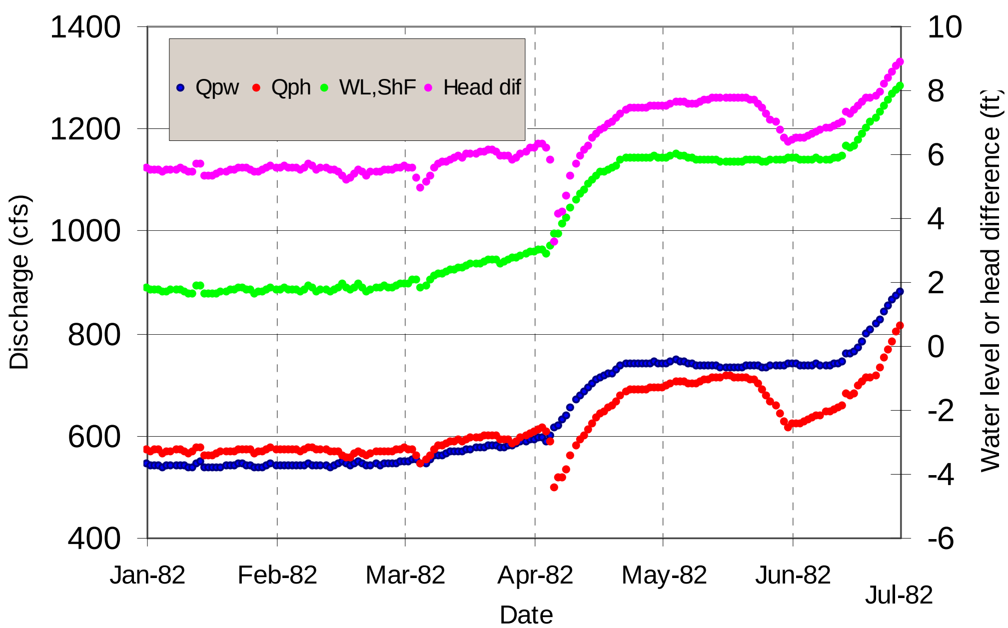
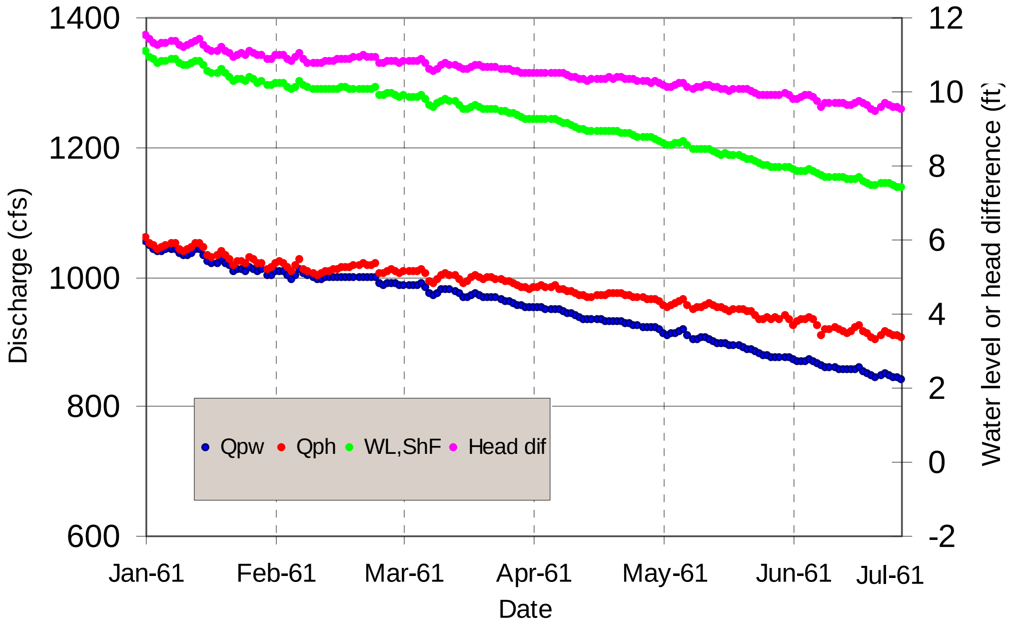


Figure 26. Calculated discharge, water level and head difference, 1982
(Qpw is spring discharge calculated from Sharps Ferry well water level. Qph is discharge calculated from head difference. WL,ShF is Sharps Ferry well water level. Head dif is the difference between well and the spring pool water surface elevation.)

Longer-term differences between trends in well water level and trends in head difference will cause the difference between Qph and Qpw to change (Figure 27). For the period January 1961 through June 1961 the decline in head difference was relatively small compared to the decline in Sharps Ferry well water level. This difference in trends could result from a decline in backwater effects so that the Silver Springs pool water level declined more slowly than the Sharps Ferry well water level. At the end of this period, the head difference had declined to about 96 % of the starting head difference, while the well water level had declined to 78 % of the starting level. These changes are reflected in Qph and Qpw, which were nearly the same on January 1, 1961. By June 30, the difference between Qph and Qpw was 47 ft^3/s or about 7 %.

Figure 27. Calculated discharge, water level and head difference, 1961
(Qpw is spring discharge calculated from Sharps Ferry well water level. Qph is spring discharge calculated from head difference. WL,ShF is Sharps Ferry well water level. Head dif is the difference between well and spring pool water surface elevation)



These comparisons of Qph and Qpw indicate that during periods of backwater there may be significant differences (more than 20 %) in daily discharge calculated using well water level (Qpw) and discharges calculated using head difference (Qph). The backwater events are relatively infrequent, however, so the mean difference in Qph and Qpw over a long time period is probably insignificant compared with errors in making discharge measurement used to construct the relations between discharge and water level or head. However, use of the head-difference relation, rather than the well water-level relation, is recommended, because the head-difference relationship provides a less biased estimate of discharge, especially during times when head changes are changing rapidly.

Comparison of Daily Discharge Calculated Using Daily Water-level and Head Difference Data with Discharge Calculated Using Hourly Data

The USGS began using hourly values of head difference to calculate daily spring discharge in October 2002. Before then, daily average well water levels were used.

The re-computation of daily discharge from January 2003 through September 30, 2005 was done using both hourly and daily head values, to determine whether there is a significant difference in calculated discharge from the two procedures. The possibility of there being a difference between the two procedures results from changes in head during a day. Using the older procedure, the hourly head measurement records are used to calculate a mean head for each day. The mean head is then used in the discharge-head relationship to calculate daily mean discharge. Using the newer procedure, discharges are calculated from each hourly head measurement and then averaged to get the daily mean discharge. Both procedures would be expected to produce identical results if head were constant throughout the day or if the relationship between discharge and head were linear, even if the head was changing. Since some of the discharge-head relationships have some degree of curvature, there should be some difference in discharge calculated using the two procedures when heads are not constant during a day.

There is generally a diurnal cycle in well water level and head difference due to barometric pressure changes (Figure 28). These head difference fluctuations generally span about 0.05 ft or less, apart from the day-to-day trend in head difference. The changes in head difference result in a diurnal fluctuation in calculated spring discharge (Figure 28). This fluctuation in discharge due to barometric pressure changes probably is generally less than 10 ft^3/s. Of course, much greater changes in head difference and calculated discharge can occur during the day due to changes in water levels both in the Floridan aquifer and in the surface water system in response to hydrologic events such as rainfall and water releases from the Moss Bluff dam.

There were only very small differences between the mean daily discharges calculated with the two procedures (Figure 29). During most days, the difference was 0.01 ft^3/s or less. The maximum difference was 0.5 ft^3/s on September 6, 2004, when a head drop of about 0.6 ft occurred (Figure 30). Based on this comparison, there would seem to be no significant errors in daily mean discharges calculated using daily mean head or well water level, as was the practice before 2003.

Figure 28. Head difference and calculated discharge, September 10-15, 2004

(Qph is discharge calculated from head difference between spring pool and CE76 well.)

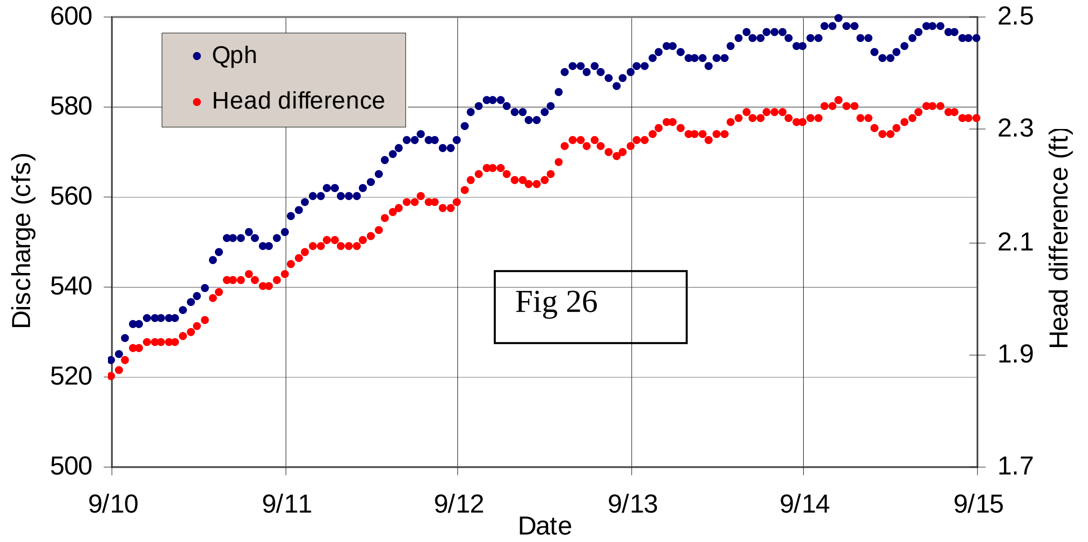
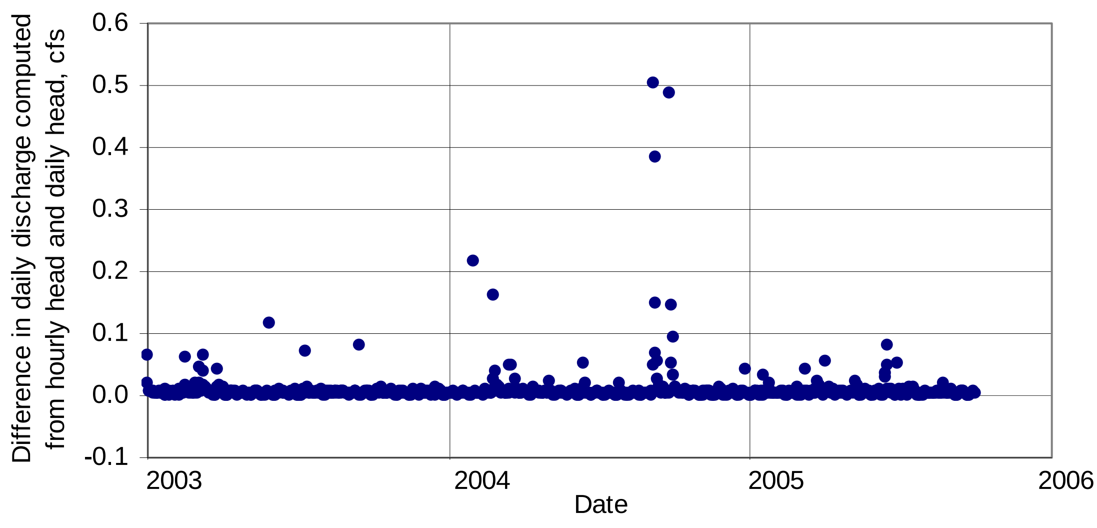


Figure 29 Difference in daily discharge calculated using hourly head and daily head



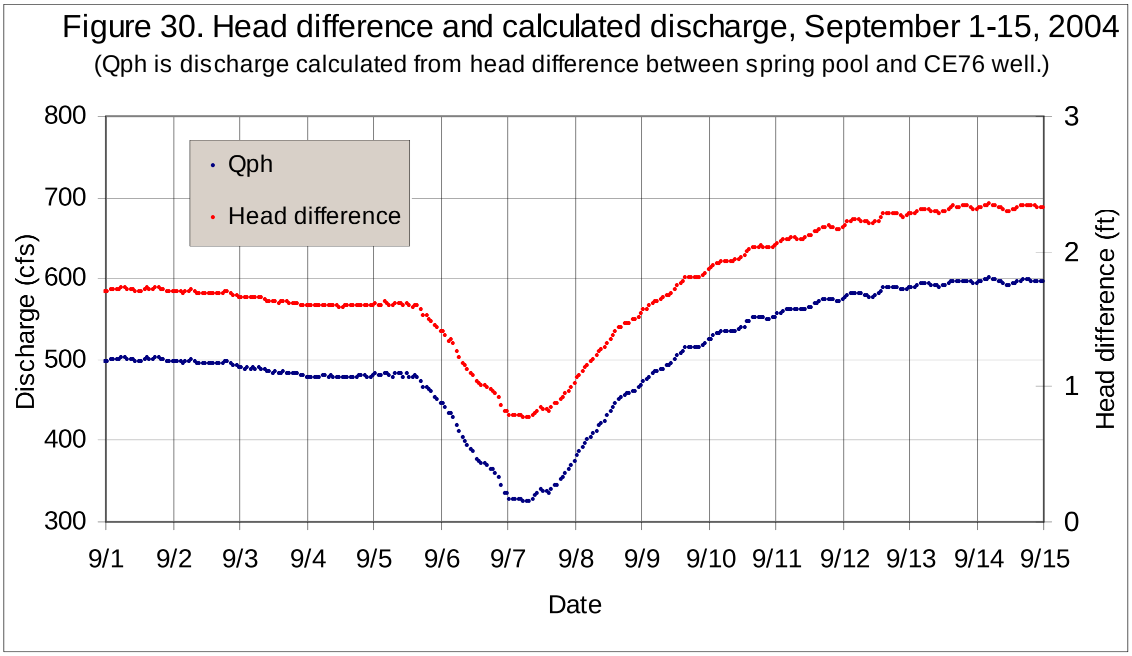


Figure 30. Head difference and calculated discharge, September 1-15, 2004
(Qph is discharge calculated from head difference between spring pool and CE76 well.)
Qph
Head difference
Discharge (cfs)
Head difference (ft)
800
700
600
500
400
300
3
2
1
0
9/1
9/2
9/3
9/4
9/5
9/6
9/7
9/8
9/9
9/10
9/11
9/12
9/13
9/14
9/15
Date

Verification of Re-calculated Discharges Using a Subset of Measurements to Develop Alternative Well Water-level Relations and Head-difference Relationships

A second set of well water level vs. discharge rating curves and head difference vs. discharge rating curves was developed to eliminate possible effects of inaccuracies in the distance-normalization of measured discharges on the rating relations, and to provide another set of re-calculated discharges for comparison with the first set. The second set of ratings was developed using only measurements at single selected locations. Actual measured discharges were used rather than normalized discharges. Comparison of the two sets of re-calculated discharge gives some indication about the sensitivity of the re-calculation procedure to rating curve development.

As with the first set of rating curves, the period from 1933 through 2005 was divided into time intervals (Table 6). These time intervals are similar to the periods used in the first set of ratings except that the period 1960-1995 was divided into two intervals (Table 6) rather than the three intervals used in the first set. Only two intervals were used because there are not enough measurements at a single location to define the period 1970-1975.

Table 6. Time intervals and locations used to construct set of alternative ratings

Begin date	End date	Measurement location (feet downstream from spring pool)	Number of measurements for time period	Number of measurements for location	Normalization factor for converting to discharge at the 3900 ft station
1-22-1933	12-31-1946	3900	21	19	1
1-1-1947	12-31-1959	3900	52	51	1
1-1-1960	9-30-1971	13600	59	58	0.97
10-1-1971	12-31-1995	>20,000	97	75	0.90
1-1-1996	9-30-2002	>20,000	43	32	0.90
10-1-2002	9-30-2005	>20,000	28	12	0.90
10-1-2002	9-30-2005	3900	28	14	1

Two sets of ratings were developed for 10-1-2002 through 9-30-2005, one using measurements from the reference location and the other using measurements made near the mouth of the river (Table 6). This was done to test the normalization factor (0.90) used to estimate discharge at the 3900 ft station from discharge at the mouth of the Silver River.

As for the first set of ratings, regression analysis was used with selected measurement data to develop relationships for calculating discharge from the Sharps Ferry well water level, and also from the head difference between the spring pool and the Sharps Ferry well. A relationship between discharge and head was not developed for the 1933 – 1946 time period because there are no daily values of spring pool elevation prior to February 1947. From October 2002 through September 2005 well CE76 was used to develop a relationship between well water level and head difference.

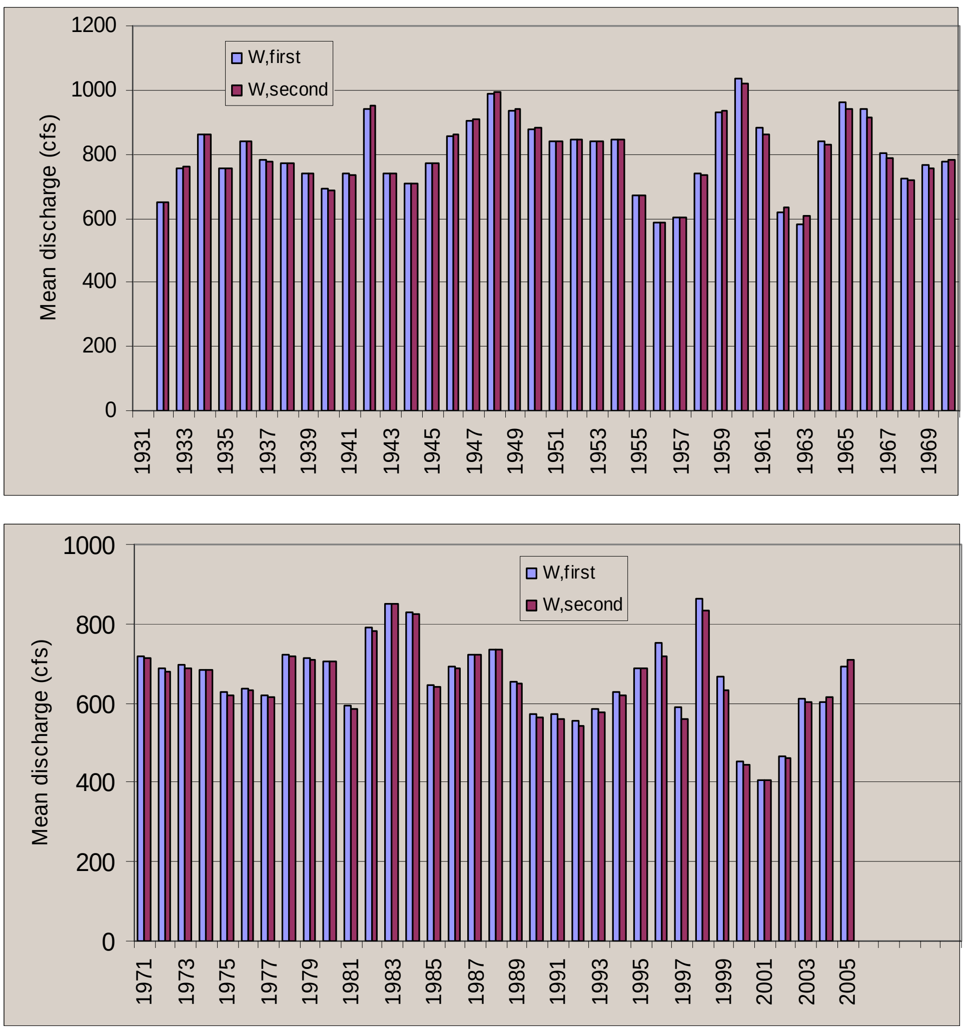
Use of measurements from a single location to develop rating relationships does not remove uncertainty regarding normalization of computed discharges to the 3900 ft station. This uncertainty is especially applicable to the 1960-1971 period when nearly all measurements were made at the 13,200 ft station. The normalization of discharge at the 13,200 ft station to the 3900 ft station is tentative because only two sets of measurements were made at these stations on the same day. The two sets that have been made indicate that discharge at the 13,200 ft station is about 97 % of the discharge at the mouth of the Silver River, and thus a factor of about 1.08 greater than discharge at the 3900 ft station.

Some indication of the possible range in the factor for normalizing discharge at the 13,200 ft station to the 3900 ft station is given by the upper and lower bounds for this factor. The upper bound for the normalization factor follows from an assumption that there is no gain in discharge between the 3900 ft and 13,200 ft stations. In this case the normalization factor is 1. The lower bound follows from an assumption that all gain in discharge downstream from the 3900 ft station occurs between the 3900 ft station and the 13,200 ft station. Therefore, the discharge at the 13,200 ft station is the same as at the mouth. Numerous measurements made during the same day (Table 3) have indicated that the normalization factor for adjusting discharge at the mouth to discharge at the 3900 ft. station is probably about 0.90. Therefore, the lower bound for the normalization factor for the 13,200 ft station is 0.90. These upper and lower bounds indicate that, for example, a discharge of 1,000 ft^3/s at the 13,200 ft station would be between 900 ft^3/s and 1,000 ft^3/s at the 3900 ft station. This implies a range in normalized discharge that is about 10 % of the discharge at the 13,200 ft station. If the normalization factor for the mouth is less than 0.90 as some measurements in Table 3 indicate, then the range in the normalization factor for the 13,200 ft station would be larger, between 0.90 to 1.

There is no uncertainty in normalization of calculated discharge for 1931-1959 because measurements were made at the 3900 ft station. Uncertainty in normalization for the 1972-2005 period (for discharges calculated from the rating relationship for the mouth of Silver River) is indicated by the numerous measurements made at the mouth and the 3900 ft station on the same day (Table 3). These measurements indicate that the ratio of discharge at the 3900 ft station to discharge at the mouth of the Silver River is probably within the range of 0.85 to 0.95. A ratio of 0.9 was used to normalize discharges near the mouth (greater than 20,000 ft downstream from the spring pool) to the 3900 ft station.

The two sets of regressions based on well water levels generally produced annual mean discharges that differed by less than 10 ft^3/s (Figure 31). The greatest difference was 36 ft3/s (about 5 **%**) for 1996.

Figure 31 Calculated mean annual discharge from relations based on well water level
(W,first is mean annual discharge from set of regression relations using location normalized discharges;
W,second is mean annual discharge from set of regression relations using measurements made at selected locations.)

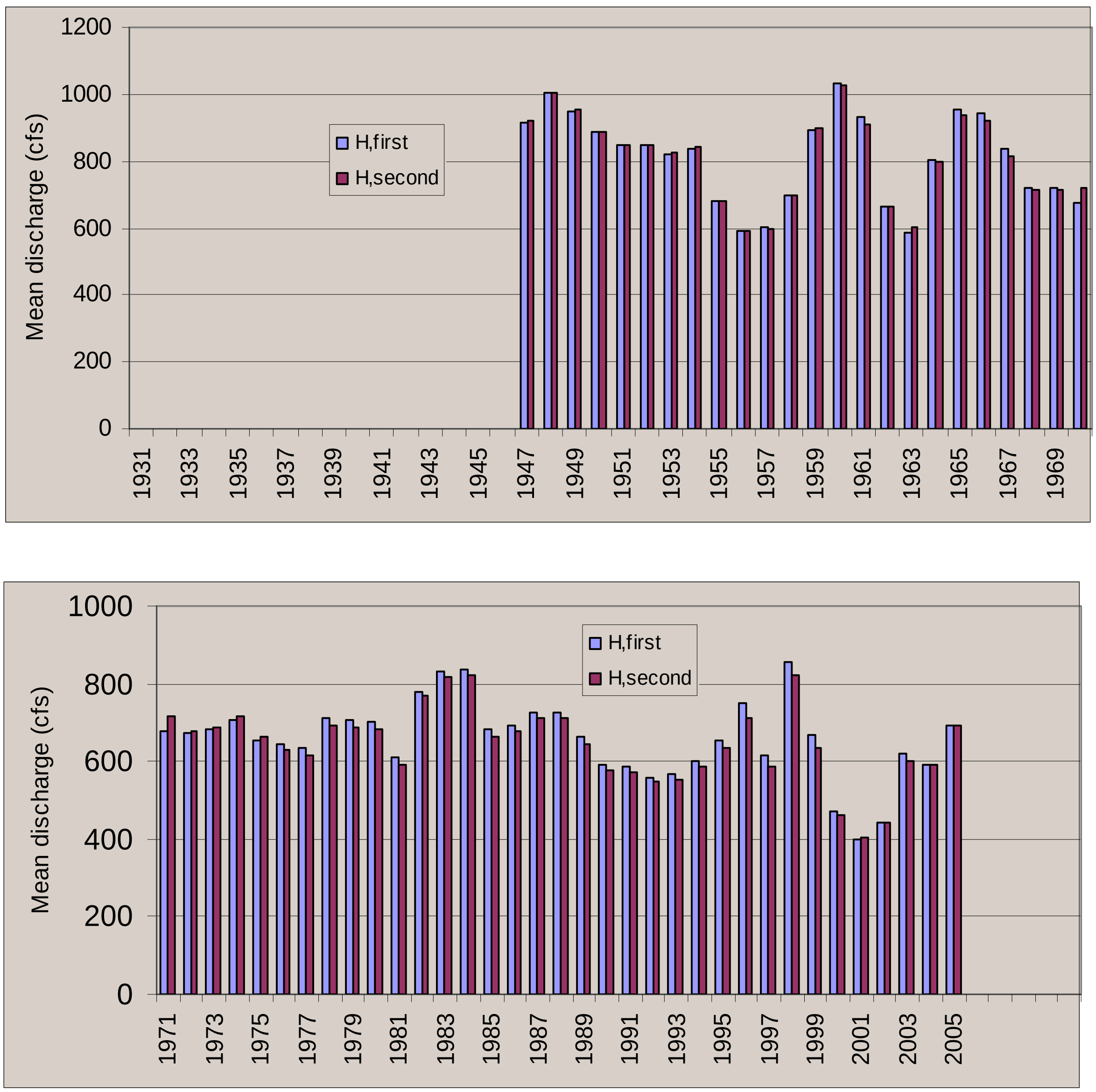


The two sets of regressions based on head differences also generally produced annual mean discharges that differed by less than 10 ft^3/s (Figure 28). The greatest difference was 44 ft3/s (about 6 percent) for 1970.

The two sets of regressions based on head differences also generally produced annual mean discharges that differed by less than 10 ft^3/s (Figure 32). The greatest difference was 44 ft ft^3/s (about 6 %) for 1970.

Figure 32 Calculated mean annual discharge from relations based on head difference

(H,first is mean annual discharge from set of regression relations using location normalized discharges; H,second is mean annual discharge from set of regression relations using measurements made at selected locations.)



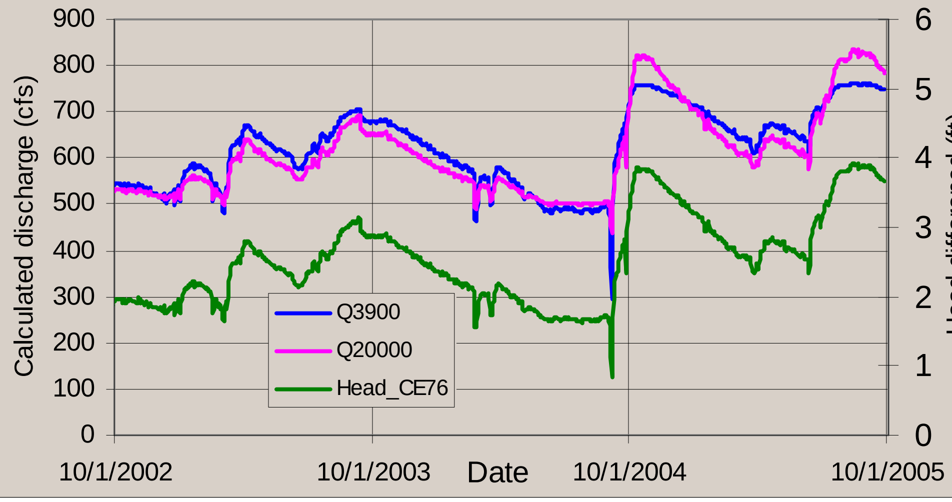
The mean difference in daily discharge was 8 ft^3/s between the sets of relationships based on well water level, and 14 ft^3/s between the sets of relationships based on head difference. The maximum difference in calculated daily discharge was nearly 100 ft^3/s for both water level and head difference relationships.

A comparison of discharge calculated using the two single-location rating relationships for the period 10-1-2002 through 9-30-2005 indicates overall good agreement between the two relationships (Figure 33). The mean discharge for the period is 623 ft ft^3/s based on the rating developed with measurements made only at the 3900 ft station, and 614 ft ft^3/s (after normalizing calculated discharge to the 3900 ft station) based on the rating developed with measurements made only at locations greater than 20,000 ft downstream from the spring pool. This is less than a 2 % difference between the two relationships with respect to mean discharge for the period, and indicates that the normalization factor of 0.90 provides generally good estimates of discharge at the 3900 ft station given discharge at the mouth of the Silver River.

However, individual daily discharges calculated from the two relationships occasionally differ by much greater amounts. For example, for September 7, 2004, the calculated daily discharges are 294 ft ft^3/s based on the relationship developed from the 3900 ft station measurements, and 435 ft ft^3/s (normalized to the 3900 ft station) based on the relationship developed from the greater than 20,000 ft station measurements. This is a difference of nearly 40 **%**.

Figure 33. Comparison of discharges calculated with two different relations using head difference as the independent variable

(Q3900 is from the relation developed using only measurements made at 3900 ft downstream from spring pool; Q20000 is from relation developed using only measurements made more than 20,000 ft downstream, after normalizing calculated discharge to the 3900 ft location. Head_CE76 is the head difference between well CE76 and spring pool).



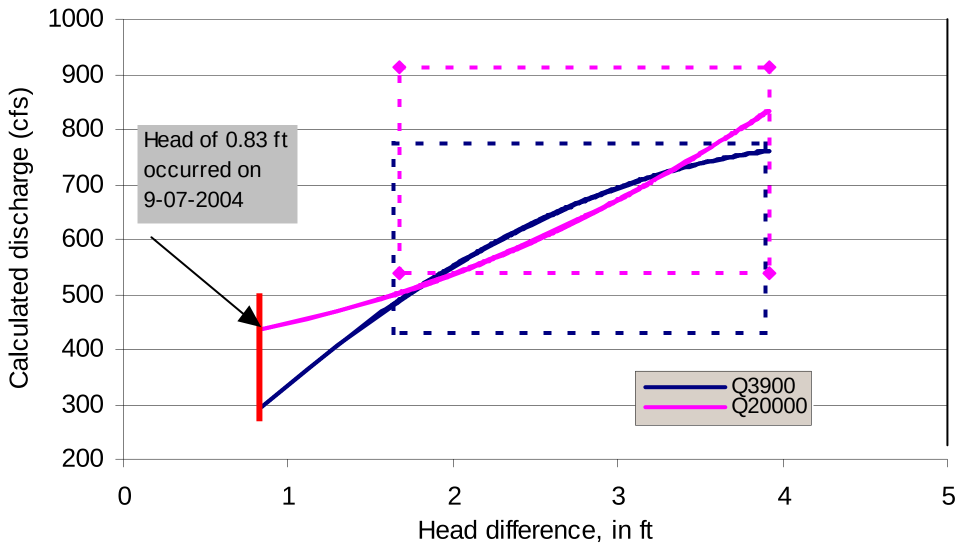
This large difference in discharges calculated for September 7, 2004 results from use of the rating relationships with independent variable (head difference) values that are outside the range of values used to develop the relationship. Both of the rating relationships (figure 34) match generally well (5 **%** or less difference) within the head difference range over which measurements used to develop the relationships were made (see boxes in Figure 34). However, both ratings must be extrapolated by about 0.8 ft for calculation of discharge at the head difference of 0.83 ft that occurred on September 7, 2004. The two ratings diverge rapidly at head difference less than about 1.7 ft, and this divergence results in large differences between discharges calculated using both relationships for these low head difference conditions.

The relatively large differences in the these two relationships at some head-difference conditions is at least partially due to the small number of measurements used to develop the relationships. For the period October 1, 2002 through September 30, 2005, there were only 12 measurements at locations greater than 20,000 ft downstream from the spring pool, and only 14 measurements at the 3900 ft station. Details of the regressions are given in Appendix C.

This comparison is a good example of the inaccuracies in calculated discharge that may occur when independent values (i.e., well water level or head difference) are outside the range of values used to develop the relationships.

Figure 34. Comparison of two regression ratings of discharge as a function of head difference for 10-1-2002 through 9-30-2005

(Q3900 is from the relation developed using only measurements made at 3900 ft downstream from spring pool; Q20000 is from relation developed using only measurements made more than 20,000 ft downstream, after normalizing calculated discharge to the 3900 ft location. The boxes represent the range of head and discharge data in developing the relations.



Use of Other Water-level Data for Recomputing the Historical Discharge Record for Silver Springs

The position of a well with respect to the potentiometric field surrounding the spring vents could influence the sensitivity of the relationship of spring discharge to well water level. A possibility for further study is to investigate use of water-level data from other nearby wells as an alternative to the Sharps Ferry well for recomputing spring discharge.

Only two wells (other than the Sharps Ferry Well) near Silver Springs have daily water-level data for several years that might be used for estimating historical daily spring discharge. These are CE47 and ROMP119. The location and period of record for these wells are summarized in Table 7.

Table 7. Location and period of record for wells CE47 and ROMP119

Well name	**Latitude**	**Longitude**	**Distance from spring**	**Period of record**
CE47	29 11 36	082 01 56	2 miles southeast	Jan. 1969 – current
ROMP119	29 01 33	082 14 09	17 miles southwest	Dec 1983 – June 2004
Sharks Ferry	29 11 15	081 59 25	3 miles east-southeast	Oct 1932 – Sept 2002

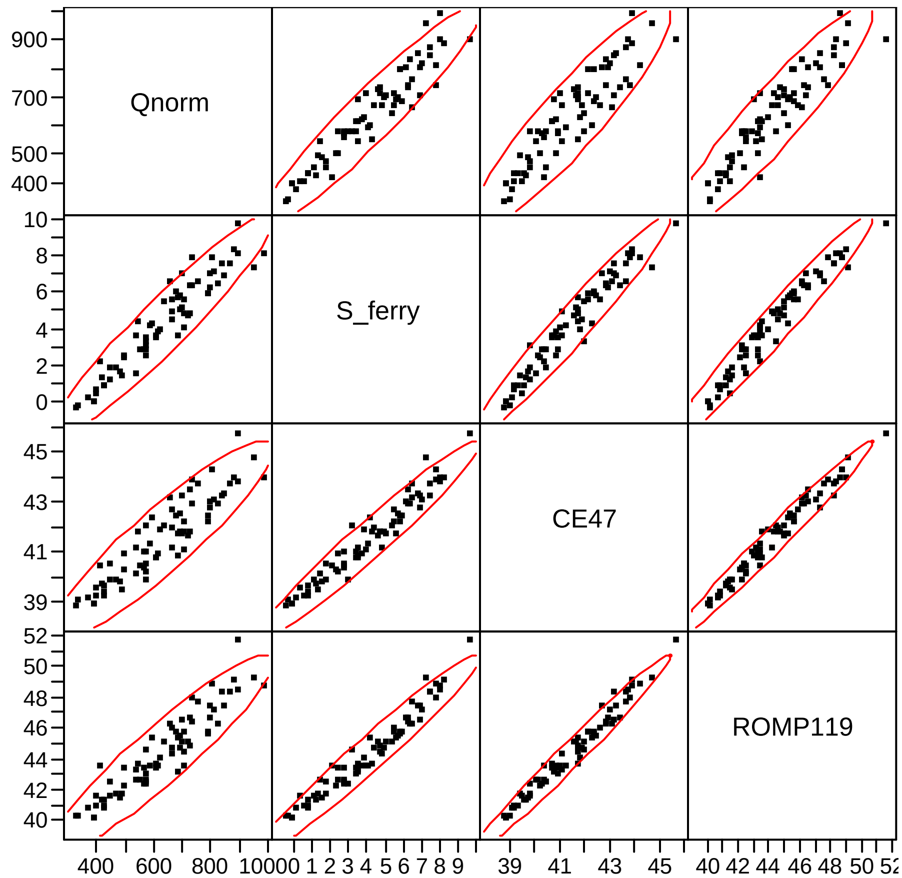
Water levels in the three wells are highly correlated (Figure 35), and spring discharge (Qnorm) is highly correlated with water levels in all three wells. The best correlation between spring discharge and well water level is for the Sharps Ferry well (period of record), suggesting that this well is the best choice for use in calculating historical spring discharge. Further exploratory work would be required to confirm this.

Figure 35. Correlation between normalized spring discharge and water level in wells near Silver Springs for the period of concurrent record (January 1983 through September 2002)

(Qnorm is measured discharge in the Silver River, normalized to the station 3900 ft downstream from spring pool. S_ferry, CE47, and ROMP119 are wells near Silver Springs that have water-level data for the period 1983 through 2002. Axes units are discharge, in ft^3/s for Qnorm, and water level, in ft, for the wells.

Correlations

	Qnorm	S_ferry	CE47	ROMP119
Qnorm	1.0000	0.9511	0.9158	0.9312
S_ferry	0.9511	1.0000	0.9711	0.9748
CE47	0.9158	0.9711	1.0000	0.9854
ROMP119	0.9312	0.9748	0.9854	1.0000



Summary and Conclusions

From 1933 to 2005 there have been more than 300 measurements of discharge in the Silver River. Locations of these measurements have ranged from about 300 ft downstream from the spring pool to just upstream from the confluence of the Silver River and Ocklawaha River, about 5.7 miles downstream from the spring pool.

Methods developed in a previous project (German, 2006)were used to normalize discharge measurements at any location to equivalent discharge at the mouth of the Silver River, about 5.7 mi downstream from the spring pool.

Relationships between normalized measured discharges and water levels in nearby wells were developed and used to calculate daily discharges from records of daily water levels. Similar relationships were developed using head differences between water levels in nearby wells and the spring pool.

Comparison of USGS original daily spring discharges with recomputed discharges indicates that the original USGS values are generally higher than the recomputed values. These differences are relatively small (less than 2 **%**) prior to 1960, and probably are caused by slight differences in the rating relationships used to calculate discharges from water levels. Differences in USGS reported discharges and the re-computed discharges are greater after 1960 and probably are the result of the normalization of the discharge-measurement data evaluated to develop the relationships to re-compute the daily discharge values.

Comparisons of discharges computed from well water levels (Qpw) with discharges computed from head differences (Qph) indicate that during periods of backwater there may be significant differences (more than 20 **%**) between the two calculated values. The backwater events are relatively infrequent, however, so the mean difference in Qph and Qpw over a long time period is probably insignificant compared with errors in making discharge measurements used to construct the relationships between discharge and water level or head. However, use of the head-difference relationship, rather than the well water-level relationship, is recommended, because the head-difference relationship provides a more accurate estimate of discharge, especially during times when head is changing rapidly.

There is generally a diurnal cycle in well water level and head difference due to barometric pressure changes. These head difference fluctuations generally span about 0.05 ft or less, apart from the day-to-day trend in head difference and result in a diurnal fluctuation in calculated spring discharge that is probably less than 10 ft^3/s. Of course, much greater changes in head difference and calculated discharge can occur during the day due to changes in water levels both in the Floridan aquifer and in the surface water system in response to hydrologic events such as rainfall and water releases from the Moss Bluff dam.

The re-computation of daily discharge from January 2003 through September 30, 2005 was done using both hourly and daily head values, to determine whether there is a significant difference in calculated discharge from the two procedures. During most days, the difference was 0.01 ft^3/s or less. Based on this comparison, there would seem to be no significant errors in daily mean discharges calculated using daily mean head or well water level, as was the practice before 2003.

A second set of well water levels vs. discharge ratings and head differences vs. discharge ratings was developed to eliminate possible effects of inaccuracies in the distance-normalization of measured discharges on the rating relationships, and to provide another set of re-calculated discharges for comparison with the first set. The second set of ratings was developed using only measurements at single selected locations. Actual measured discharges were used rather than normalized discharges. The second set of regressions generally produced annual mean discharges that differed from the original (first) set by less than 15 ft^3/s . The first set of ratings was developed used measurements from multiple locations that were all normalized to the 3900-ft station.

Discharges calculated from a rating relationship developed from measurement data for the mouth of the Silver River for the period 10-1-2002 through 9-30-2005 were compared with discharges for the same period that were calculated from a rating relationship developed from measurement data from the 3900 ft station. There is overall good agreement between the calculated discharges from the two relationships. The mean discharge for the period is 623 ft^3/s based on the rating developed from measurements made only at the 3900 ft station, and is 614 ft^3/s (after normalizing calculated discharge to the 3900 ft station) with the rating developed with measurements only made at locations greater than 20,000 ft downstream from the spring pool. This is less than a 2 **%** difference between the two relationships with respect to mean discharge for the period, and indicates that the normalization factor of 0.90 provides generally good estimates of discharge at the 3900 ft station given discharge at the mouth of the Silver River. However, individual daily discharges calculated from the two relationships occasionally differ by much greater amounts. For example, on September 7, 2004, the calculated discharges are 294 ft3/s based on the relationship developed from the 3900 ft station measurements, and 435 ft3/s (normalized to 3900 ft station) based on the relationship developed from the greater than 20,000 ft measurements. This large difference results from the use of the rating relationships developed with a small number of discharge measurements (14 or fewer) and with independent variable (head difference) values that are outside the range used to develop the rating relationship.

The position of a well with respect to the potentiometric field surrounding the spring vents could influence the sensitivity of the relationship of spring discharge to well water level. It is recommended that water-level data from other nearby wells be evaluated for use in recomputing historical spring discharge. Water levels in three wells near Silver Springs are highly correlated and spring discharge is highly correlated with water levels in all three wells. The best correlation between spring discharge and well water level is for the Sharps Ferry well, suggesting that this well is the best choice for use in calculating historical spring discharge. Further exploratory work would be required to confirm this.

References

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Enfeld, Mestas-Nunez, and Trimble, “The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S.”, Geophysical Research Letters, Vol. 28, No. 10, Pages 2077-2080, May 15, 2001

German 2006, Assessment of spring discharge measurement data for priority springs in the St. Johns River Water Management District, Pub. No.: SJ2006-SP9 http://www.sjrwmd.com/technicalreports/spubs1.html#2006

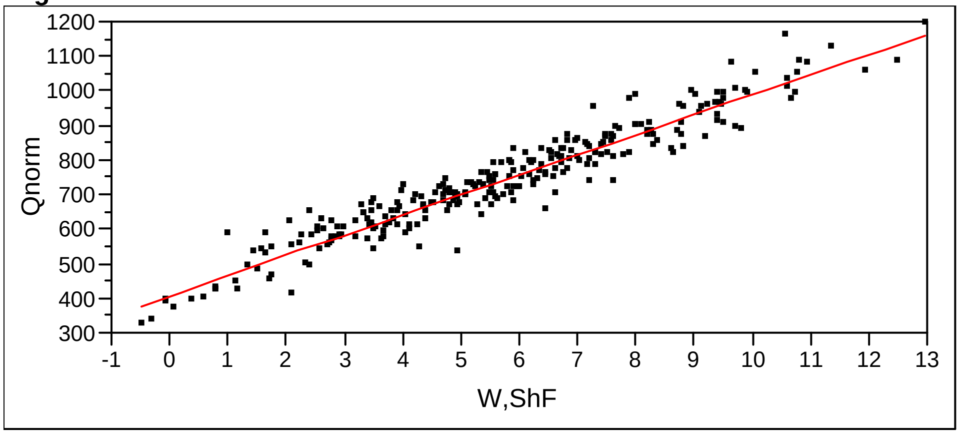
SAS Institute Inc. 2002. JMP Version 5 Statistics and Graphics Guide: SAS Institute Inc.,707 p.

Appendix A – Details of Regression Analyses: All Locations

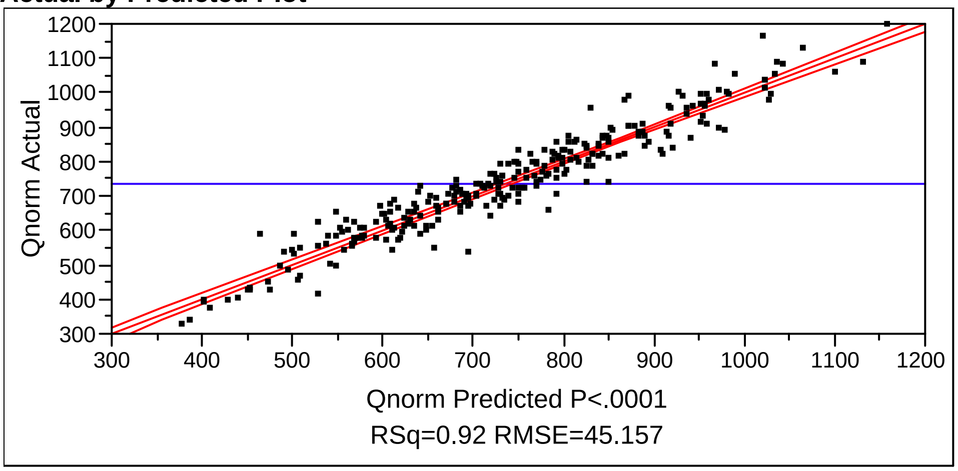
Response Q_{norm} : 1933 through 2002

Independent variable: Water level in Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



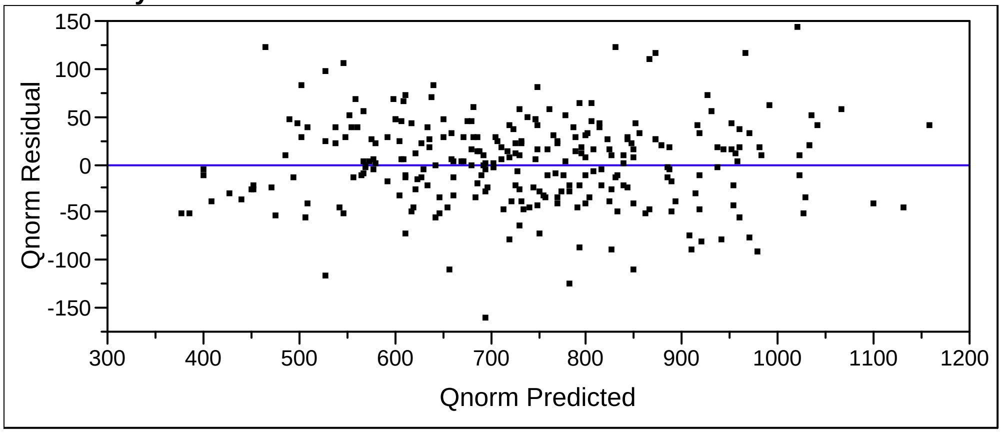
Summary of Fit

RSquare	0.921277
RSquare Adj	0.920689
Root Mean Square Error	45.15737
Mean of Response	735.3422
Observations (or Sum Wgts)	271

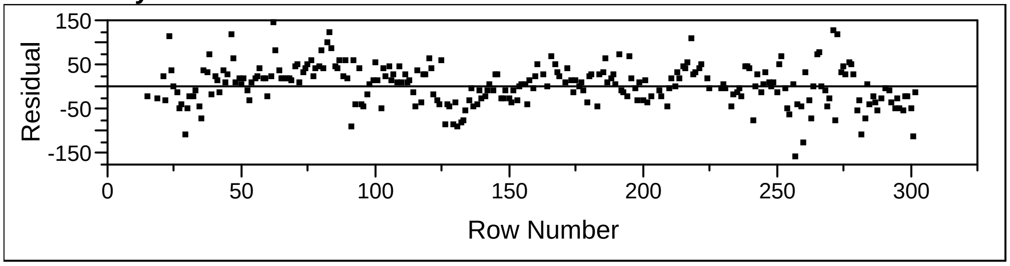
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	407.63456	6.686918	60.96	<.0001
W,ShF	58.141743	1.04091	55.86	<.0001
(W,ShF-5.64281)*(W,ShF-5.64281)	-0.053742	0.306611	-0.18	0.8610

Residual by Predicted Plot

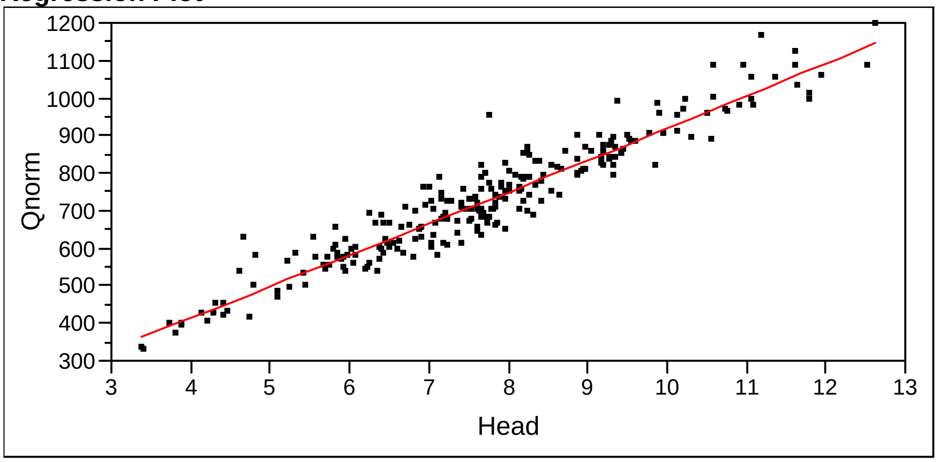


Residual by Row Plot

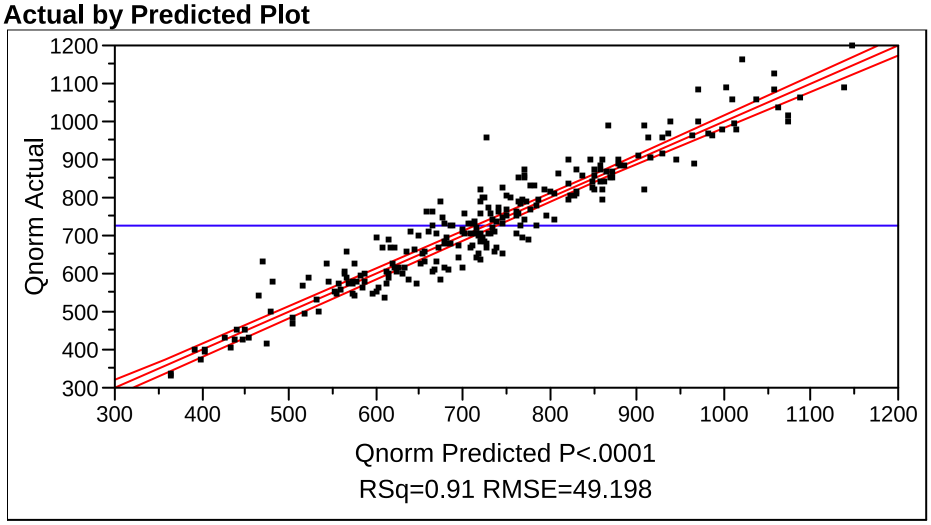


Response Q_{norm} : 1933 through 2002
Independent variable: Head difference between spring pool and Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



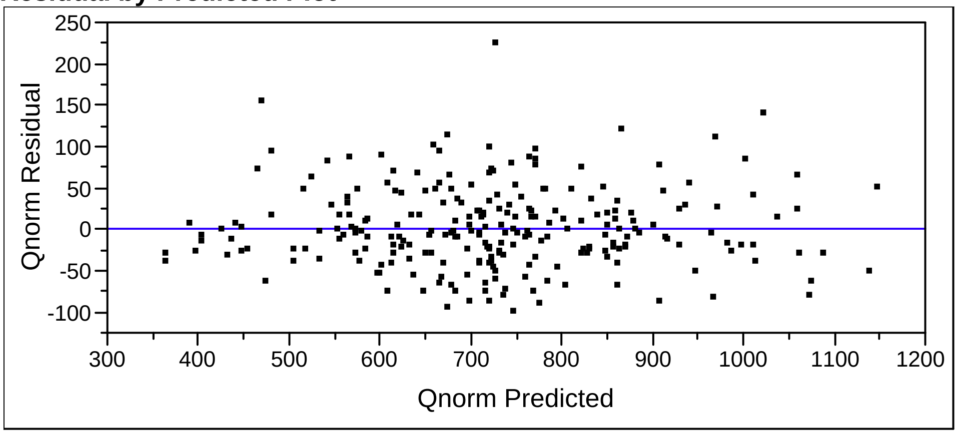
Summary of Fit

RSquare	0.907782
RSquare Adj	0.907026
Root Mean Square Error	49.1985
Mean of Response	724.8542
Observations (or Sum Wgts)	247

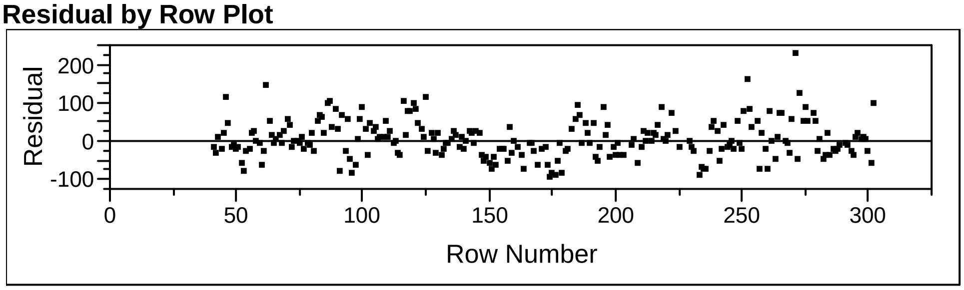
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	72.00723	13.70312	5.25	<.0001
Head	84.611753	1.736975	48.71	<.0001
(Head-7.70499)*(Head-7.70499)	0.2785946	0.670199	0.42	0.6780

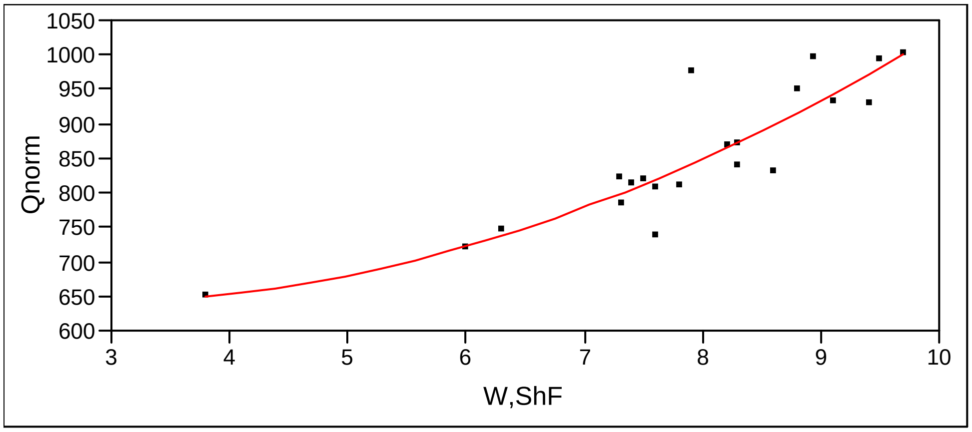
Residual by Predicted Plot



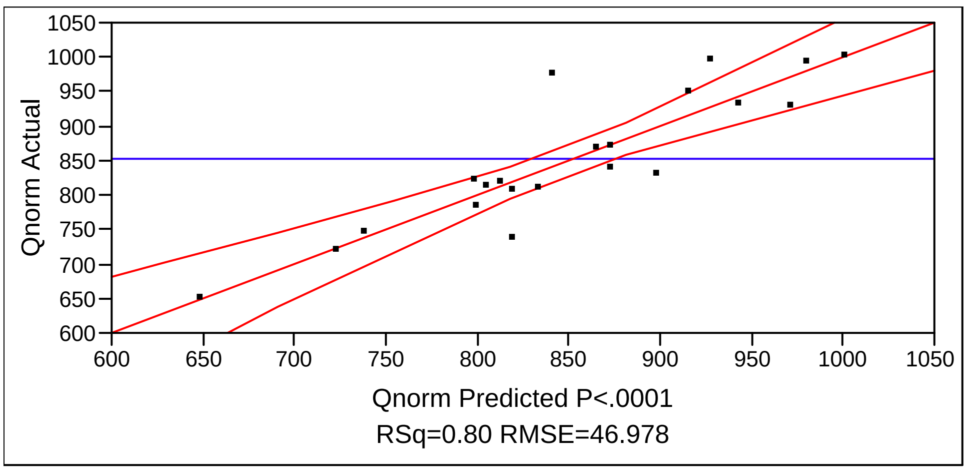
Residual by Row Plot



Response Q_{norm} : 1933 through 1946
Independent variable: Water level in Sharps Ferry well (w,ShF)
Regression Plot



Actual by Predicted Plot



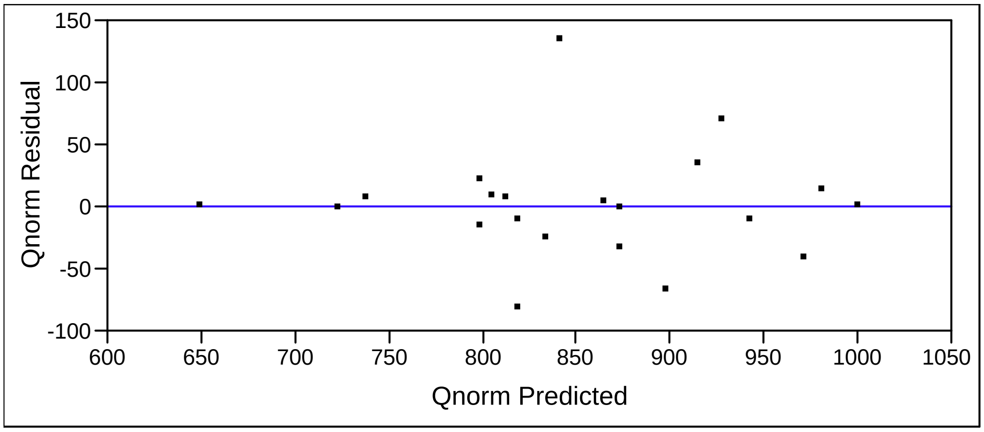
Summary of Fit

RSquare	0.797869
RSquare Adj	0.775411
Root Mean Square Error	46.97839
Mean of Response	851.3882
Observations (or Sum Wgts)	21

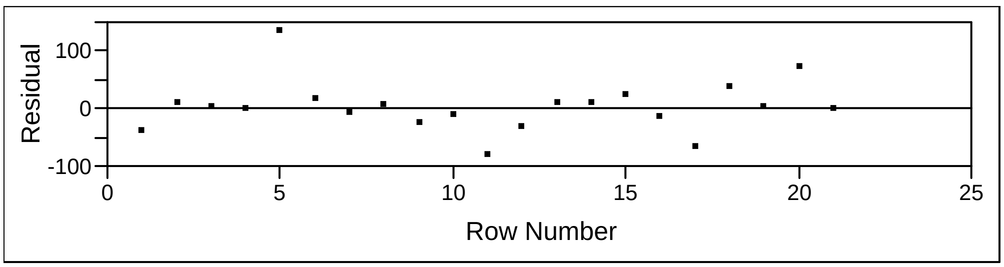
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	245.27488	82.77822	2.96	0.0083
W,ShF	75.424103	9.902093	7.62	<.0001
(W,ShF-7.87381)*(W,ShF-7.87381)	7.0305679	3.722016	1.89	0.0751

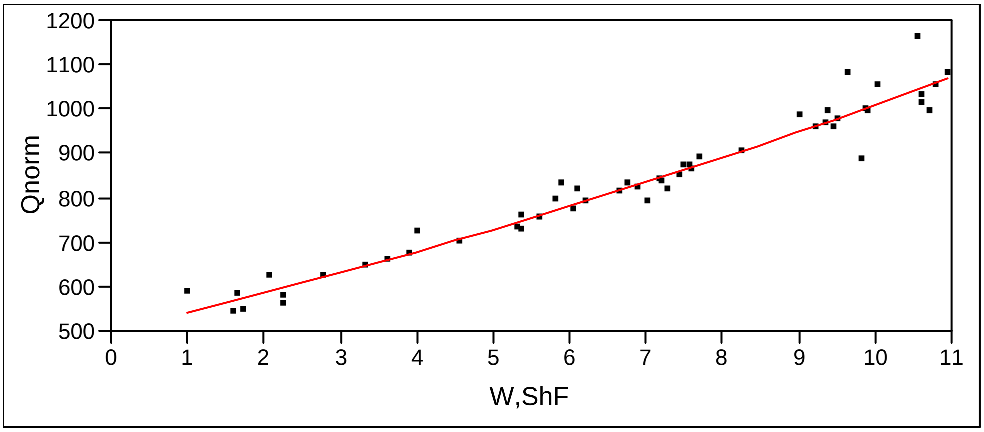
Residual by Predicted Plot



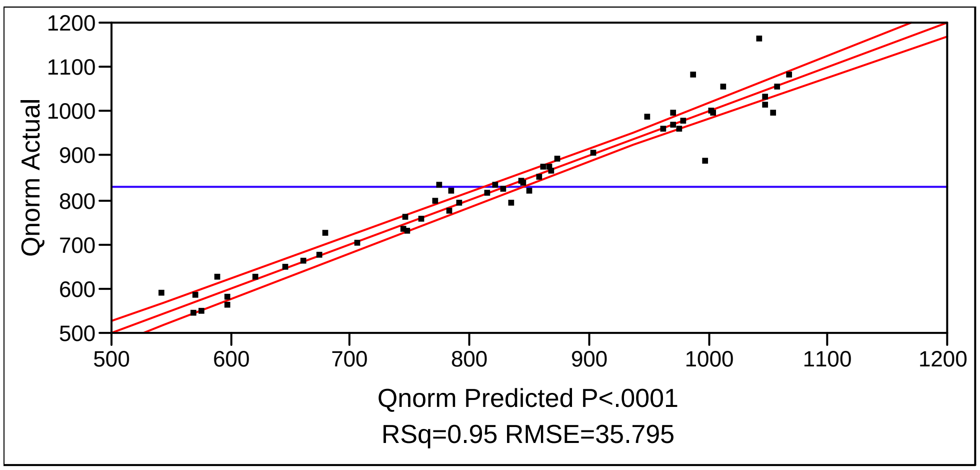
Residual by Row Plot



Response Q_{norm} : 1947 through 1959
Independent variable: Water level in Sharps Ferry well (w,ShF)
Regression Plot



Actual by Predicted Plot



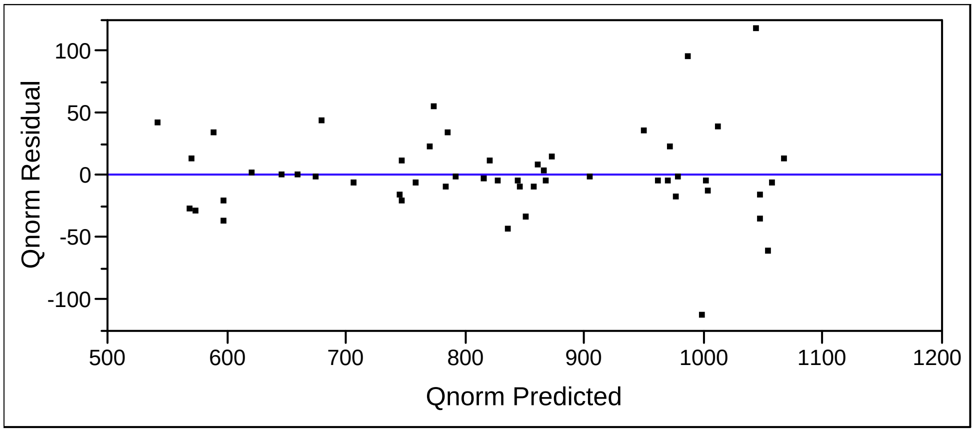
Summary of Fit

RSquare	0.951433
RSquare Adj	0.949451
Root Mean Square Error	35.79492
Mean of Response	829.311
Observations (or Sum Wgts)	52

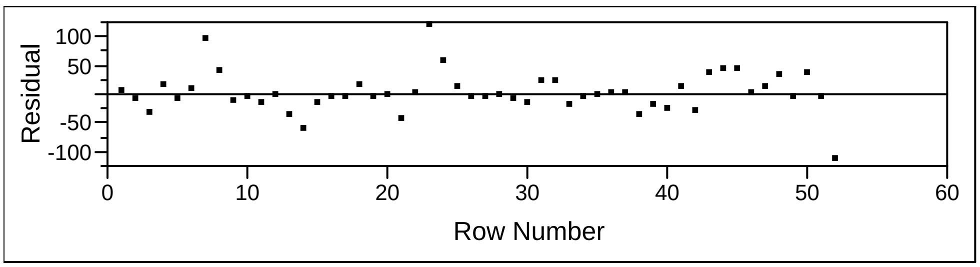
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	452.45967	15.80242	28.63	<.0001
W,ShF	54.522245	1.840264	29.63	<.0001
(W,ShF-6.7475)*(W,ShF-6.7475)	1.0846289	0.624251	1.74	0.0886

Residual by Predicted Plot

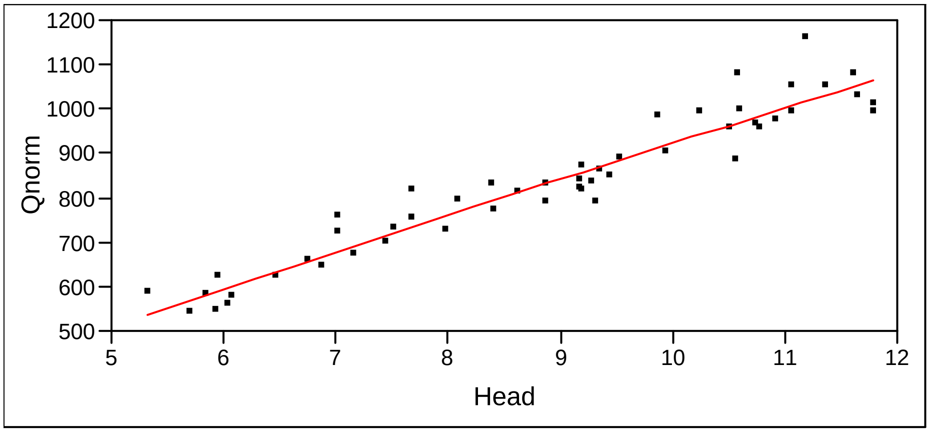


Residual by Row Plot

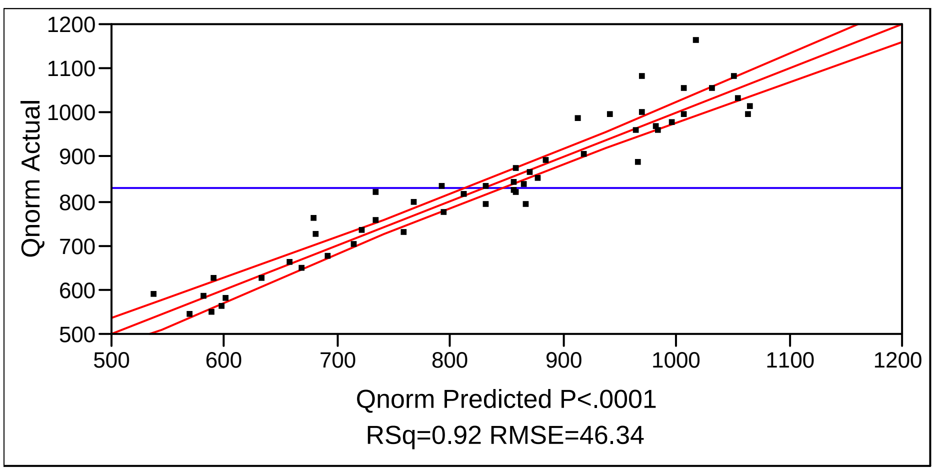


Response Q_{norm} : 1947 through 1959
Independent variable: Head difference between spring pool and Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



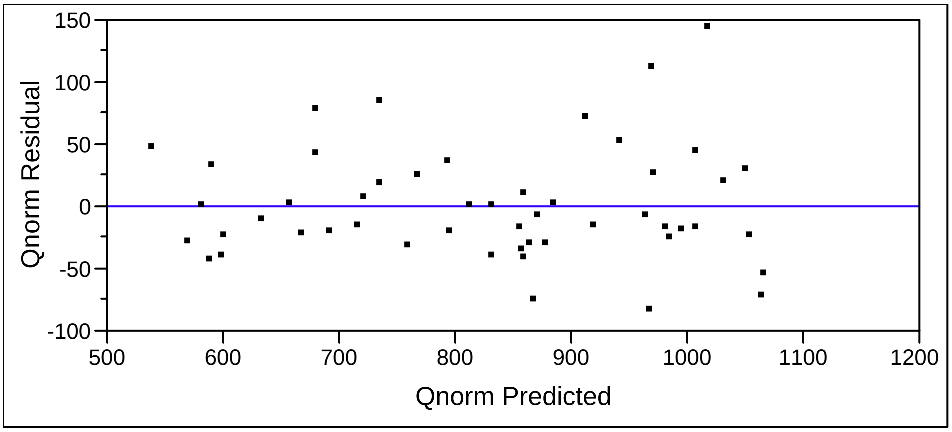
Summary of Fit

RSquare	0.920167
RSquare Adj	0.916841
Root Mean Square Error	46.34036
Mean of Response	828.5478
Observations (or Sum Wgts)	51

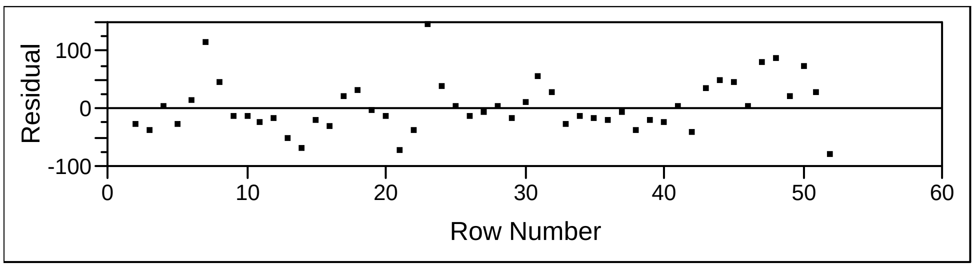
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	111.60933	33.97109	3.29	0.0019
Head	81.202026	3.528338	23.01	<.0001
(Head-8.84961)*(Head-8.84961)	-0.473962	2.010747	-0.24	0.8147

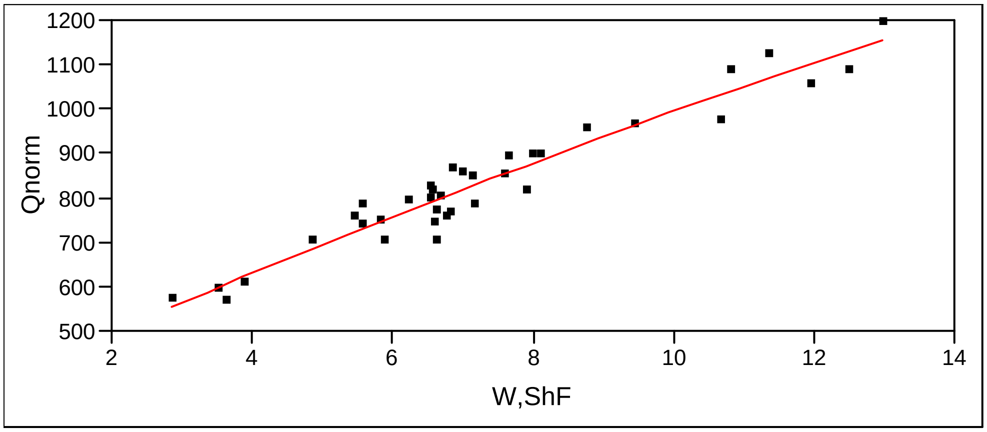
Residual by Predicted Plot



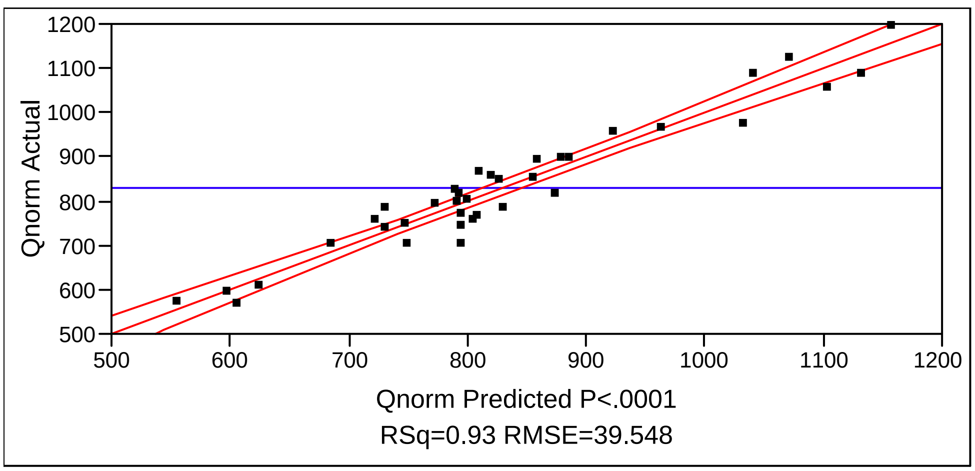
Residual by Row Plot



Response Q_{norm} : 1960 through 1969
Independent variable: Water level in Sharps Ferry well (w,ShF)
Regression Plot



Actual by Predicted Plot



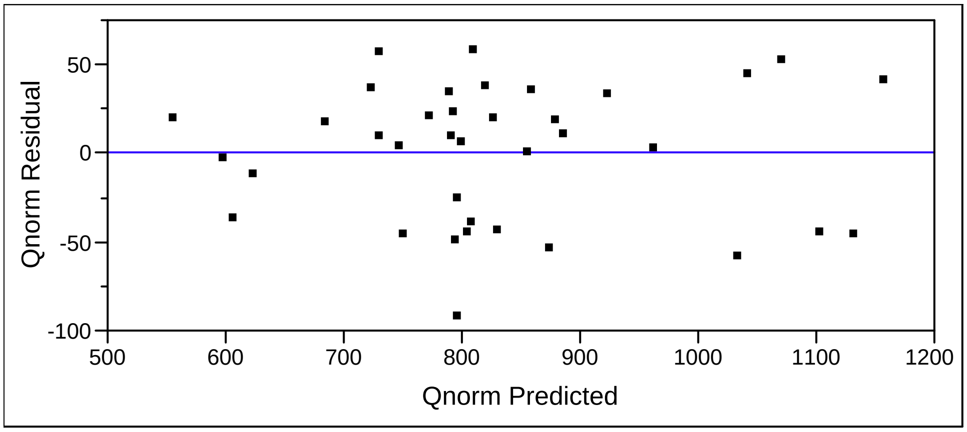
Summary of Fit

RSquare	0.934076
RSquare Adj	0.930198
Root Mean Square Error	39.5479
Mean of Response	829.8996
Observations (or Sum Wgts)	37

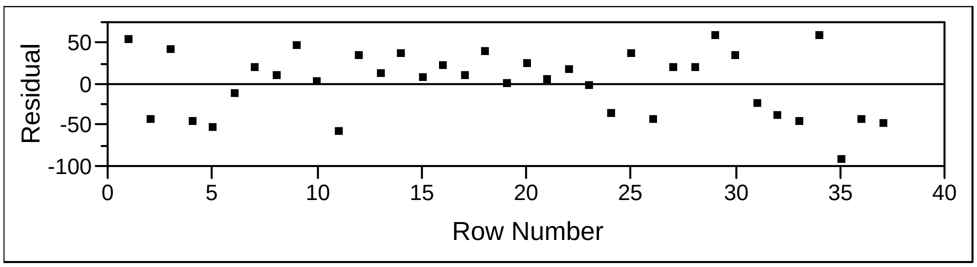
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	395.2569	21.24083	18.61	<.0001
W,ShF	60.416542	3.024129	19.98	<.0001
(W,ShF-7.26054)*(W,ShF-7.26054)	-0.694815	0.86593	-0.80	0.4279

Residual by Predicted Plot

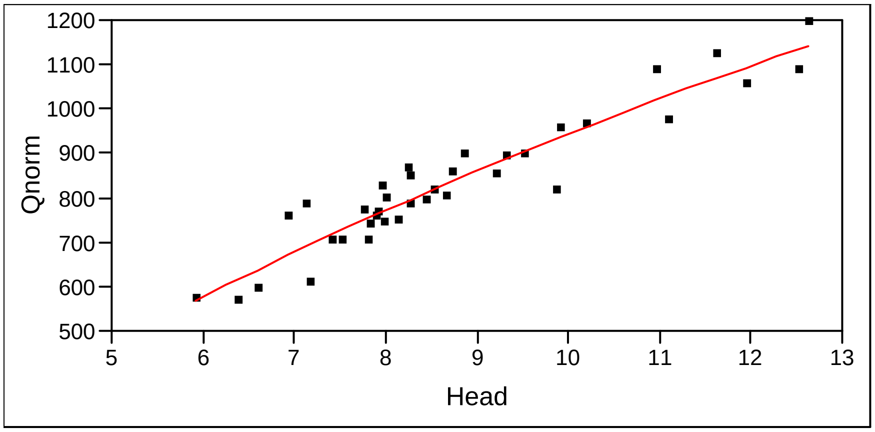


Residual by Row Plot

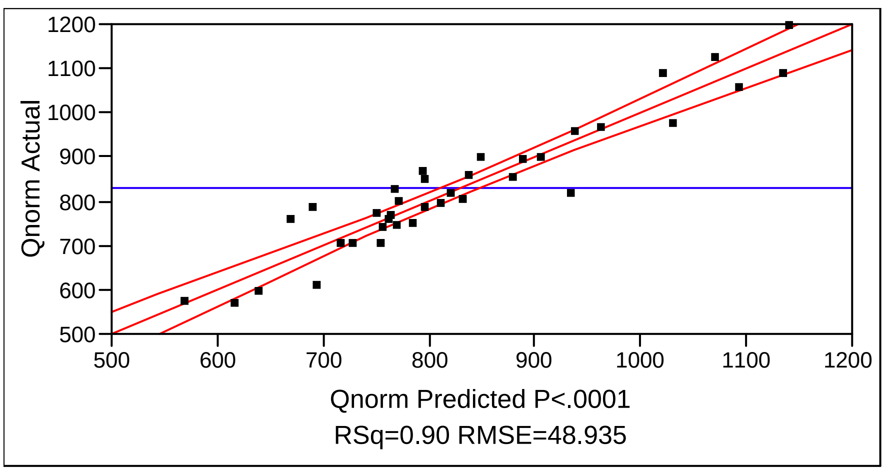


Response Q_{norm} : 1960 through 1969
Independent variable: Head difference between spring pool and Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



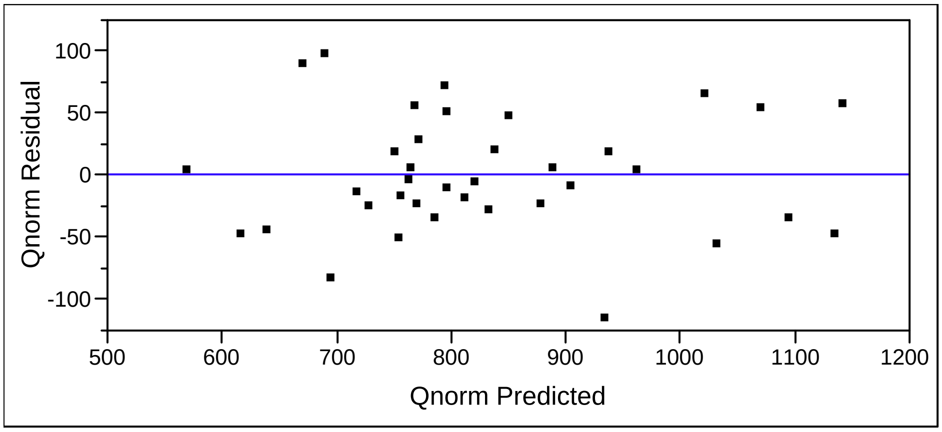
Summary of Fit

RSquare	0.899068
RSquare Adj	0.893131
Root Mean Square Error	48.93469
Mean of Response	829.8996
Observations (or Sum Wgts)	37

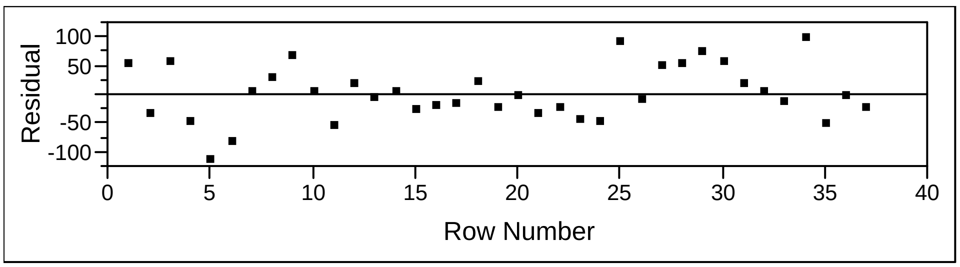
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	68.068708	48.69462	1.40	0.1712
Head	88.071402	5.911463	14.90	<.0001
(Head-8.73135)*(Head-8.73135)	-2.621655	2.543203	-1.03	0.3099

Residual by Predicted Plot

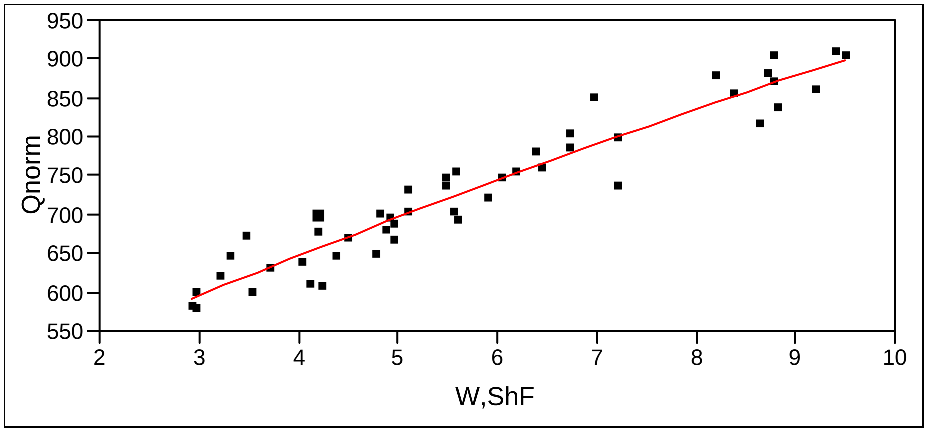


Residual by Row Plot

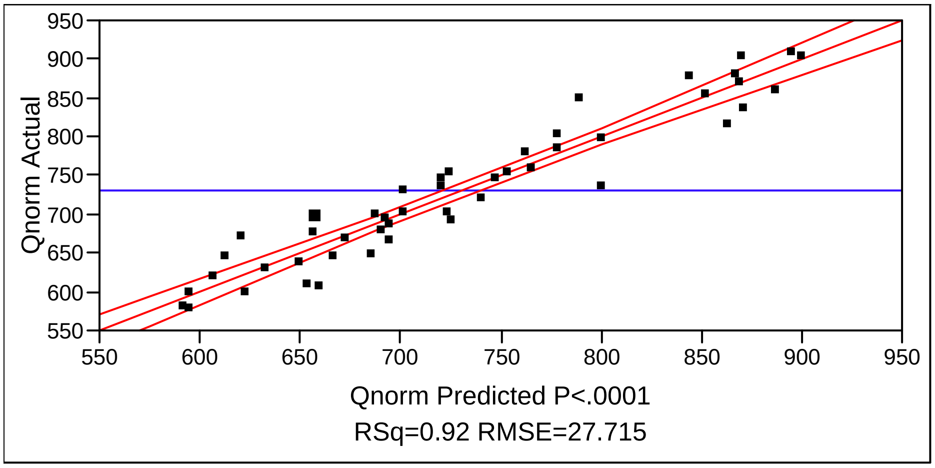


Response Q_{norm} : 1970 through 1975
Independent variable: Water level in Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



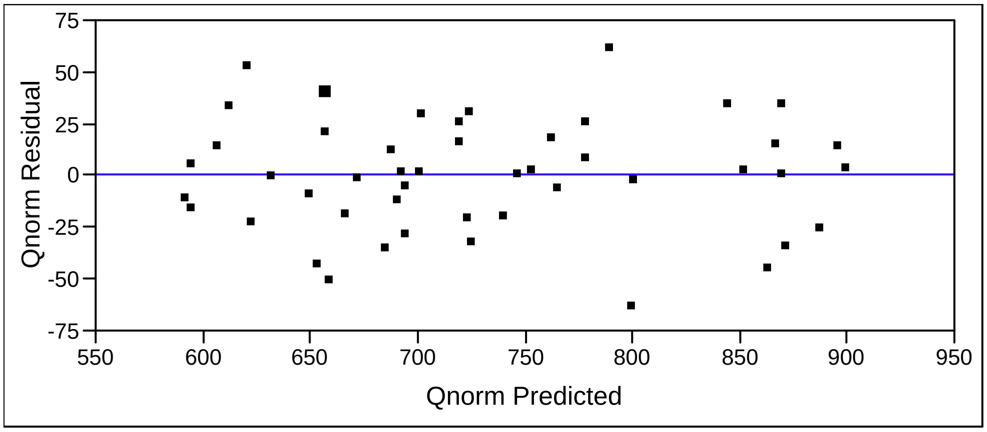
Summary of Fit

RSquare	0.918567
RSquare Adj	0.914948
Root Mean Square Error	27.71501
Mean of Response	730.1388
Observations (or Sum Wgts)	48

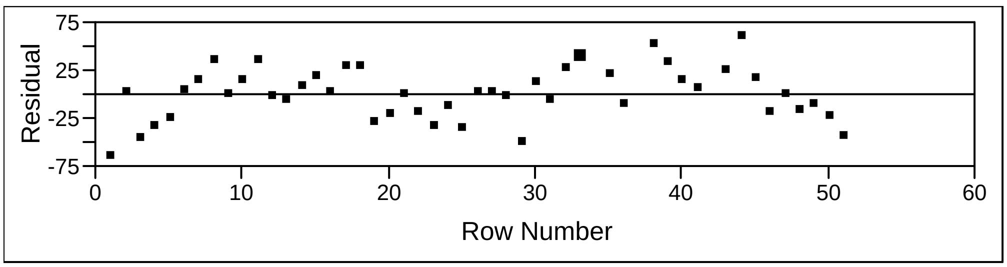
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	459.1104	12.71379	36.11	<.0001
W,ShF	47.45683	2.290439	20.72	<.0001
(W,ShF-5.77151)*(W,ShF-5.77151)	-0.774471	1.142272	-0.68	0.5012

Residual by Predicted Plot

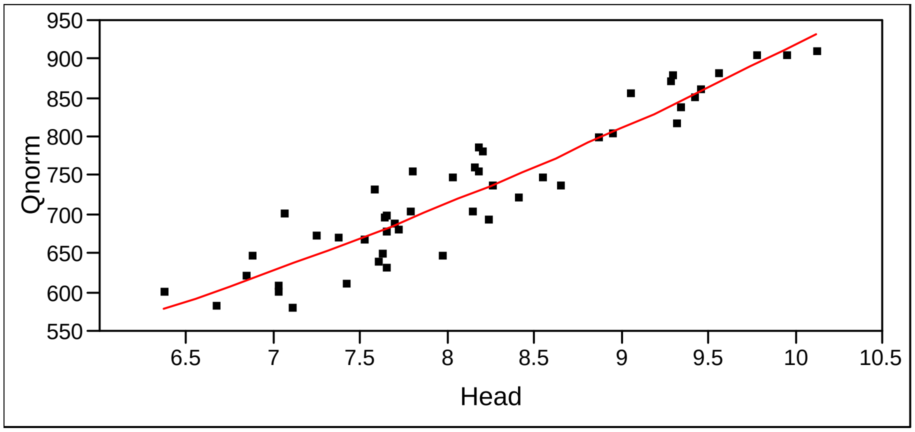


Residual by Row Plot

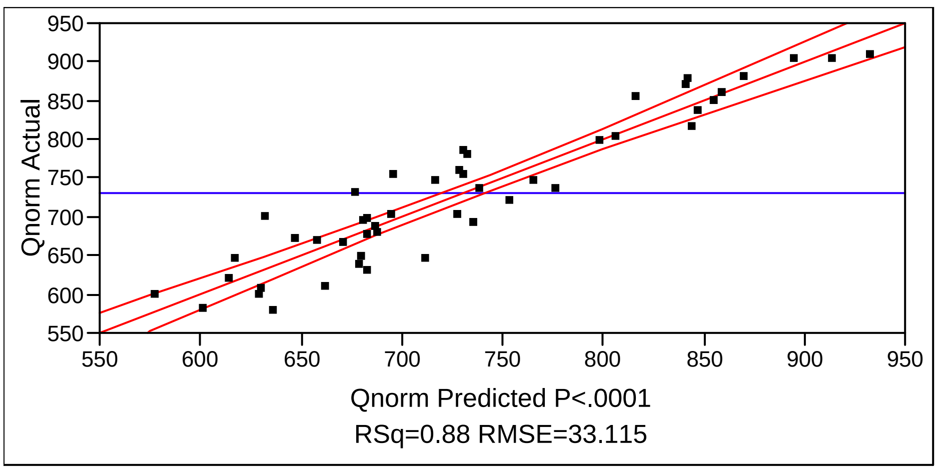


Response Q_{norm} : 1970 through 1975
Independent variable: Head difference between spring pool and Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



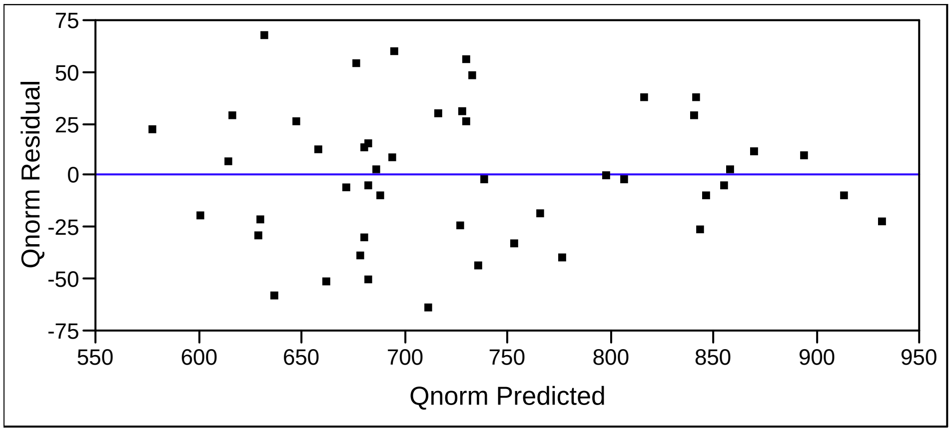
Summary of Fit

RSquare	0.88374
RSquare Adj	0.878573
Root Mean Square Error	33.11547
Mean of Response	730.1388
Observations (or Sum Wgts)	48

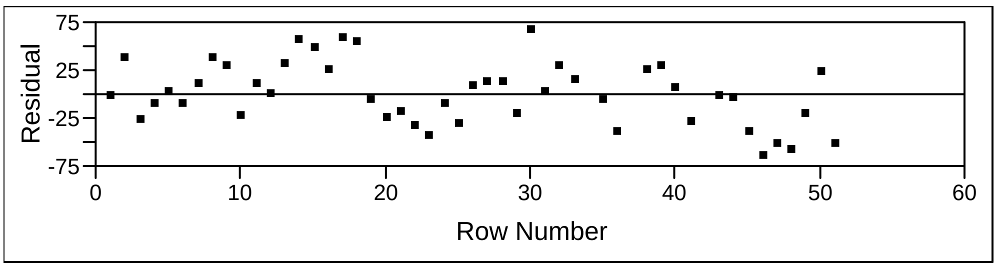
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-33.06161	43.23625	-0.76	0.4485
Head	93.359585	5.441228	17.16	<.0001
(Head-8.12797)*(Head-8.12797)	5.0751224	5.252007	0.97	0.3390

Residual by Predicted Plot

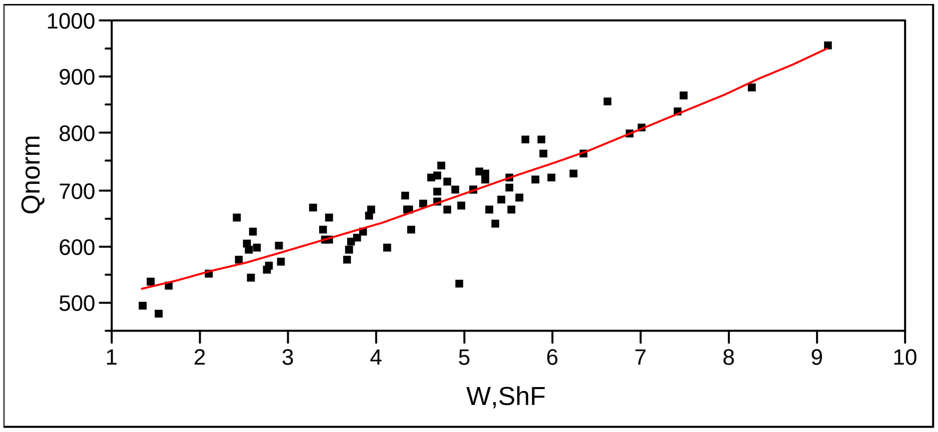


Residual by Row Plot

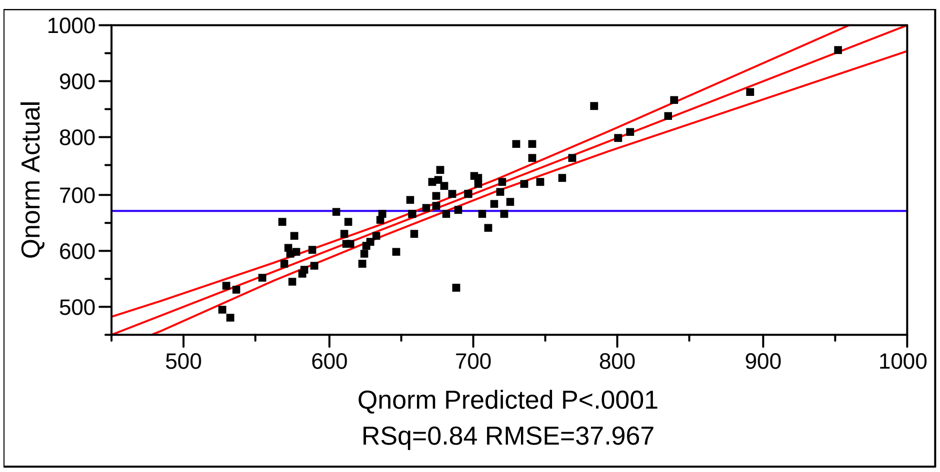


Response Q_{norm} : 1976 through 1995
Independent variable: Water level in Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



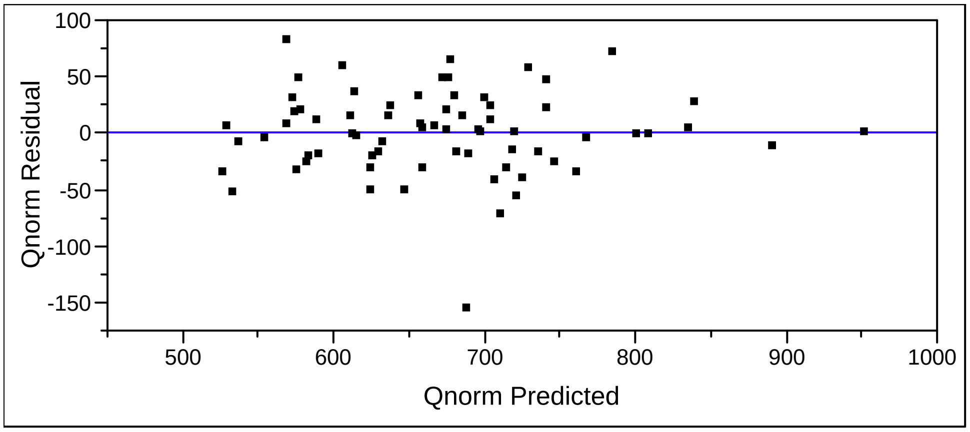
Summary of Fit

RSquare	0.840975
RSquare Adj	0.836228
Root Mean Square Error	37.96711
Mean of Response	669.319
Observations (or Sum Wgts)	70

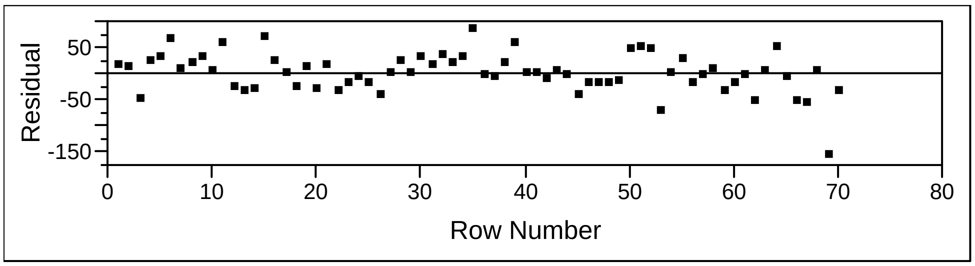
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	433.91832	13.31257	32.59	<.0001
W,ShF	51.306677	2.85085	18.00	<.0001
(W,ShF-4.47029)*(W,ShF-4.47029)	2.2927294	1.238038	1.85	0.0684

Residual by Predicted Plot

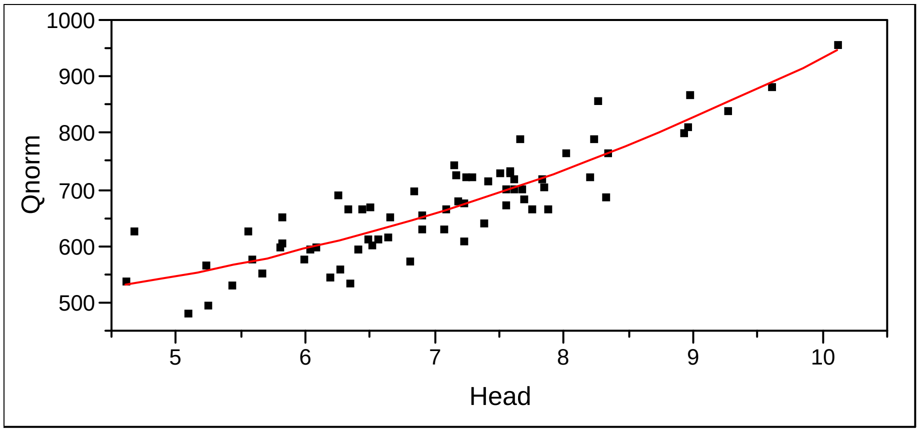


Residual by Row Plot

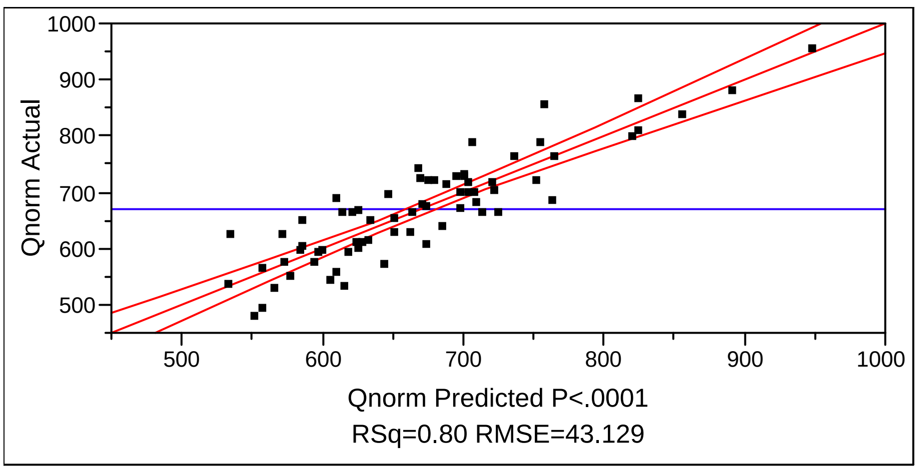


Response Q_{norm} : 1976 through 1995
Independent variable: Head difference between spring pool and Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



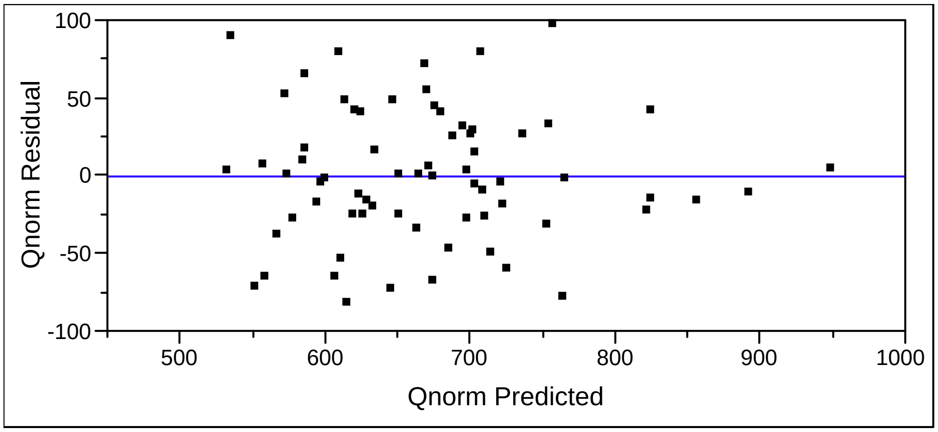
Summary of Fit

RSquare	0.797851
RSquare Adj	0.791725
Root Mean Square Error	43.12869
Mean of Response	669.394
Observations (or Sum Wgts)	69

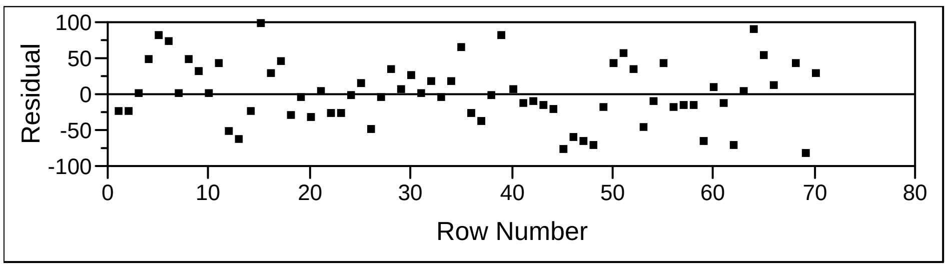
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	163.15723	32.38266	5.04	<.0001
Head	70.606396	4.593739	15.37	<.0001
(Head-7.03333)*(Head-7.03333)	7.3759427	2.871693	2.57	0.0125

Residual by Predicted Plot

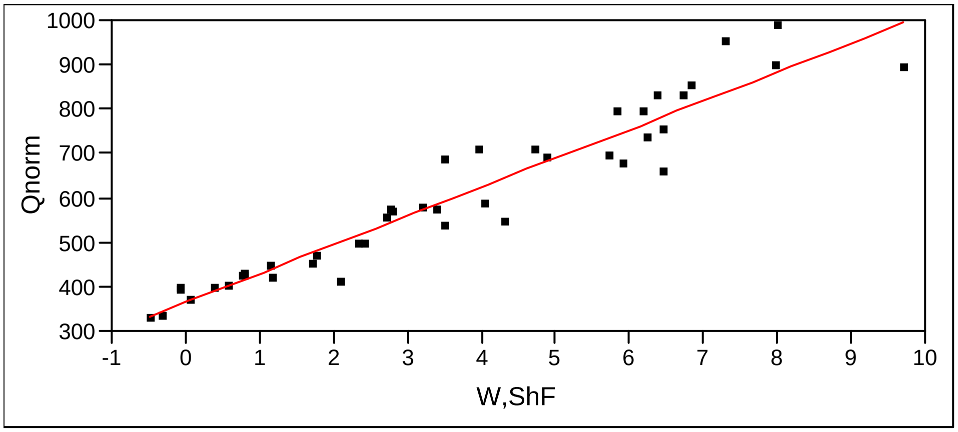


Residual by Row Plot

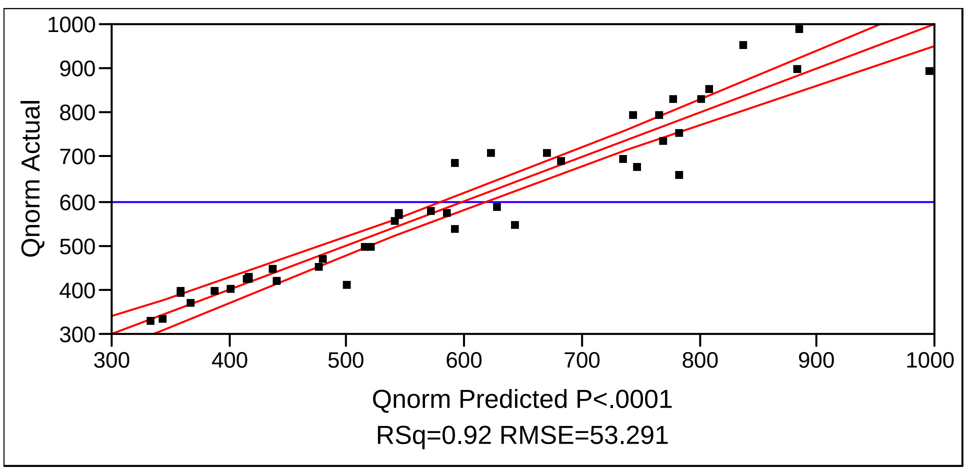


Response Q_{norm} : 1996 through 2002
Independent variable: Water level in Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



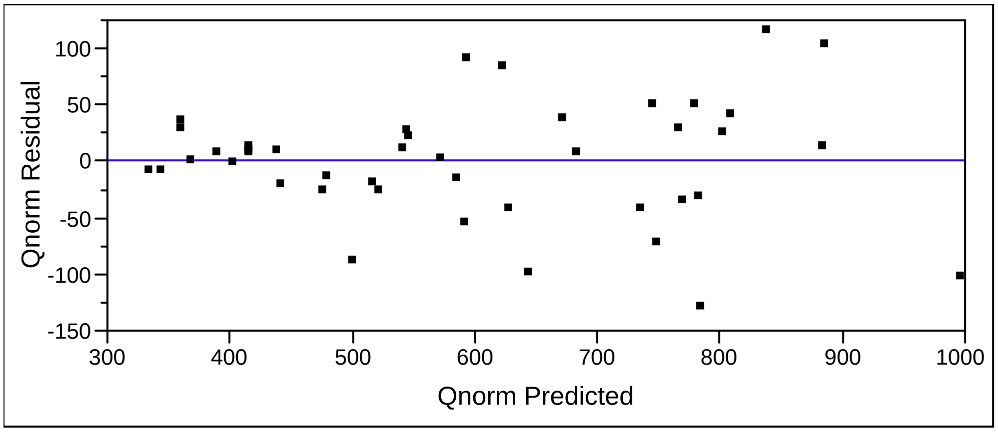
Summary of Fit

RSquare	0.919531
RSquare Adj	0.915508
Root Mean Square Error	53.29118
Mean of Response	596.9567
Observations (or Sum Wgts)	43

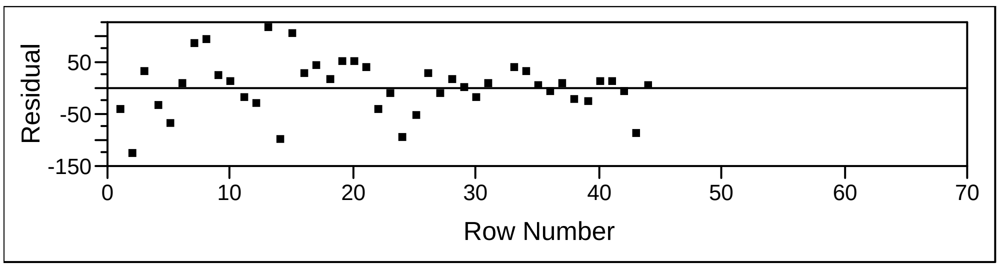
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	363.66825	14.68462	24.77	<.0001
W,ShF	64.980511	3.138964	20.70	<.0001
(W,ShF-3.59047)*(W,ShF-3.59047)	-0.003057	1.16666	0.00	0.9979

Residual by Predicted Plot

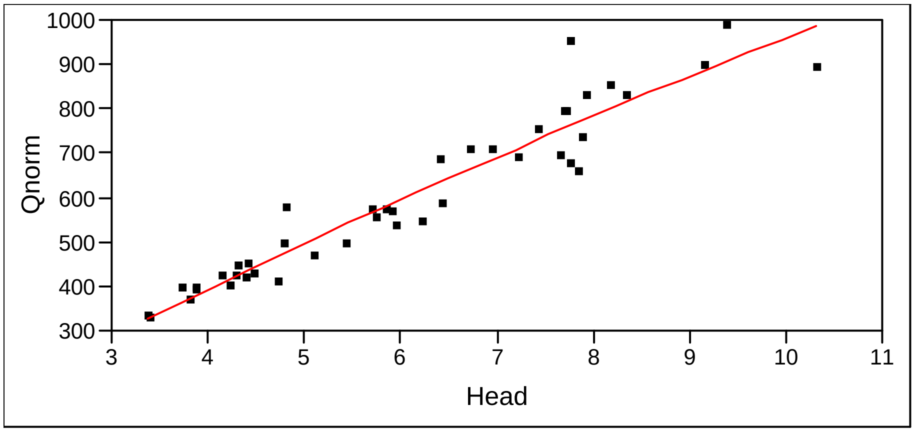


Residual by Row Plot

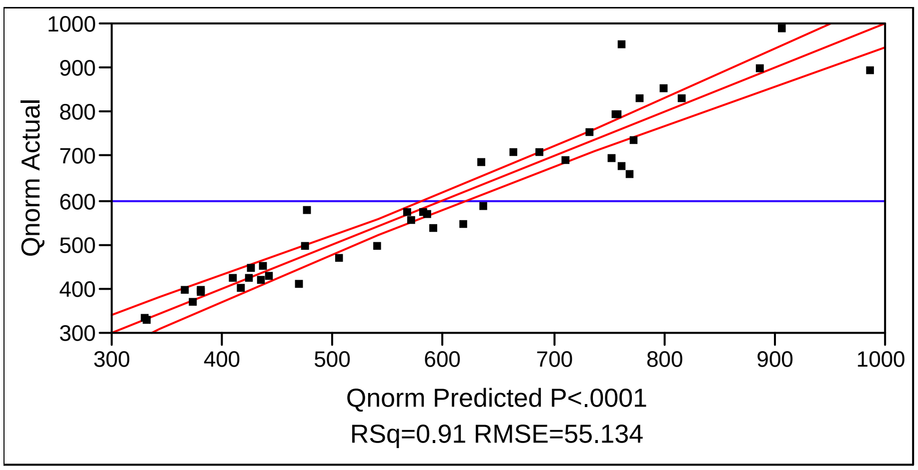


Response Q_{norm} : 1996 through 2002
Independent variable: Head difference between spring pool and Sharps Ferry well (w,ShF)

Regression Plot



Actual by Predicted Plot



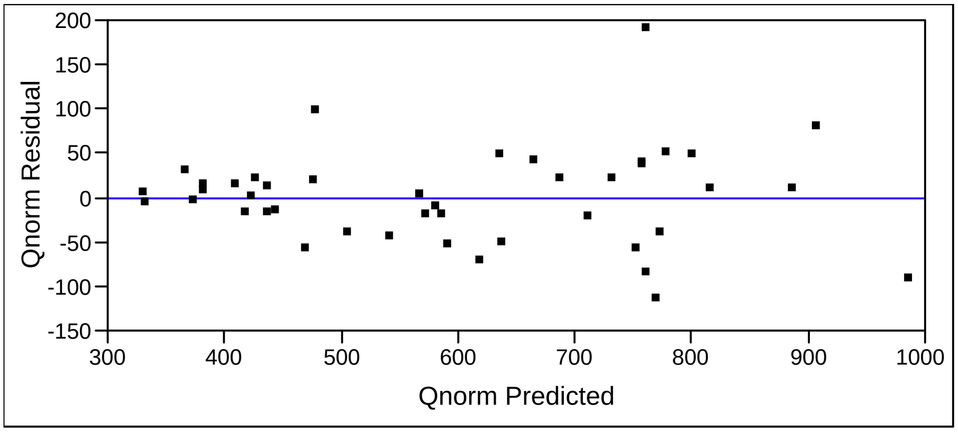
Summary of Fit

RSquare	0.91387
RSquare Adj	0.909564
Root Mean Square Error	55.13377
Mean of Response	596.9567
Observations (or Sum Wgts)	43

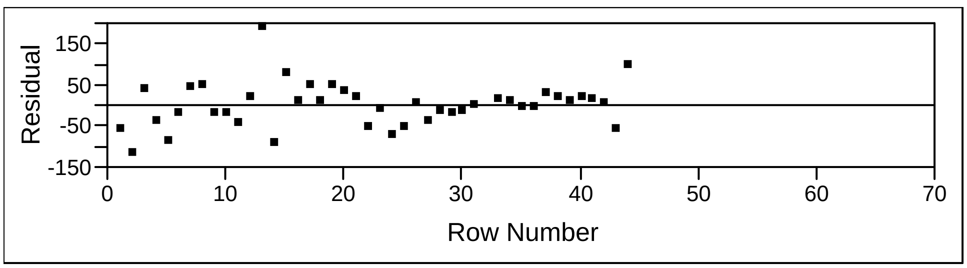
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11.823875	29.6283	0.40	0.6920
Head	97.172546	4.886952	19.88	<.0001
(Head-6.07512)*(Head-6.07512)	-1.609179	2.608016	-0.62	0.5407

Residual by Predicted Plot

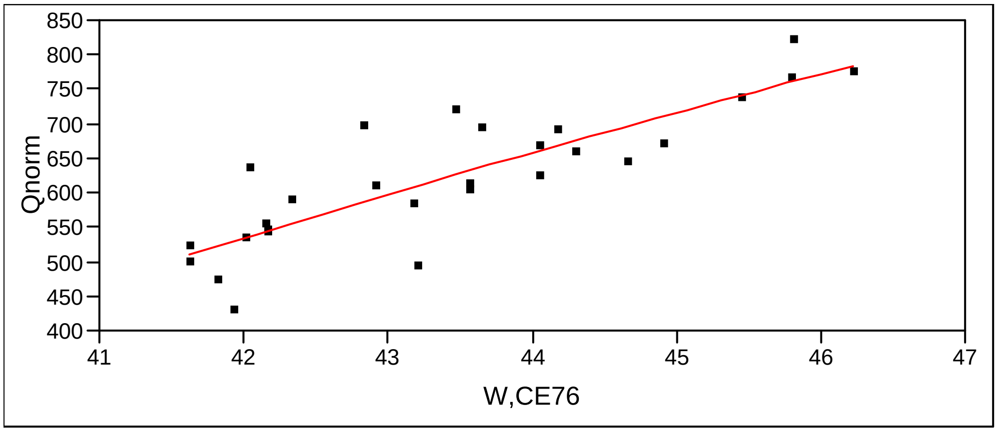


Residual by Row Plot

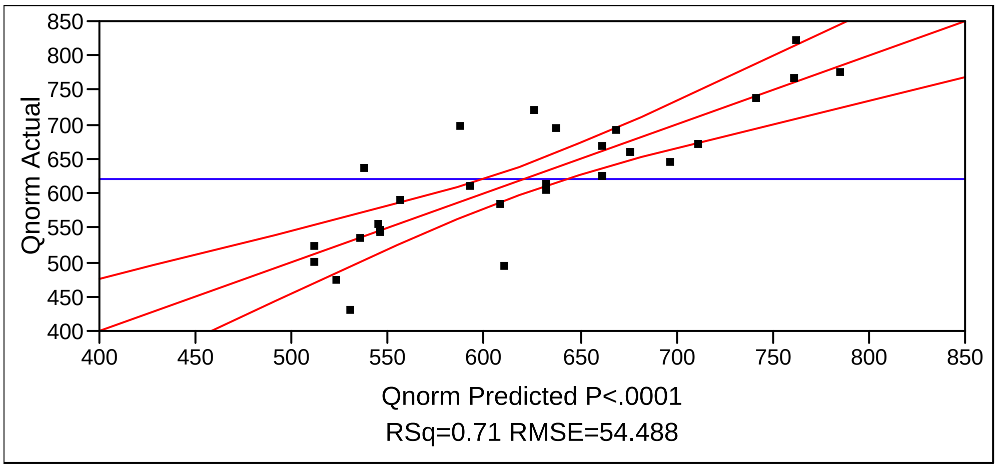


Response Q_{norm} : 2003 through 2005
Independent variable: Water level in CE76 well (w,CE76)

Regression Plot



Actual by Predicted Plot



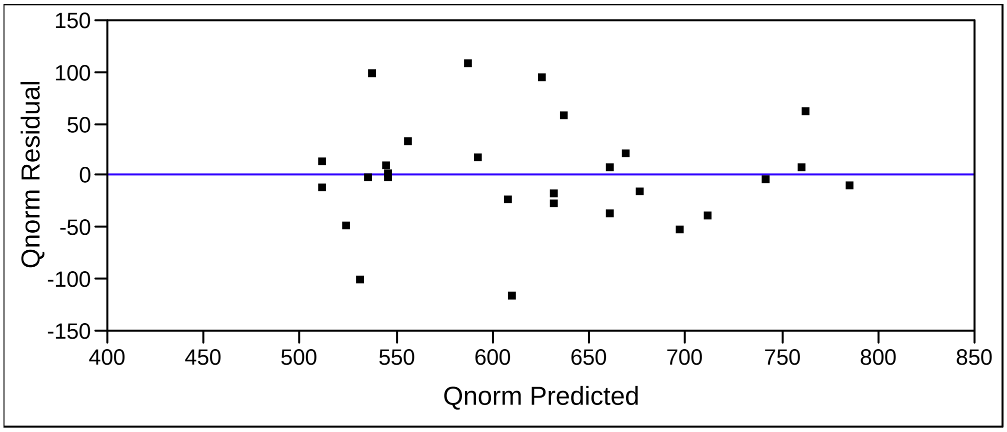
Summary of Fit

RSquare	0.711746
RSquare Adj	0.688685
Root Mean Square Error	54.48836
Mean of Response	620.6815
Observations (or Sum Wgts)	28

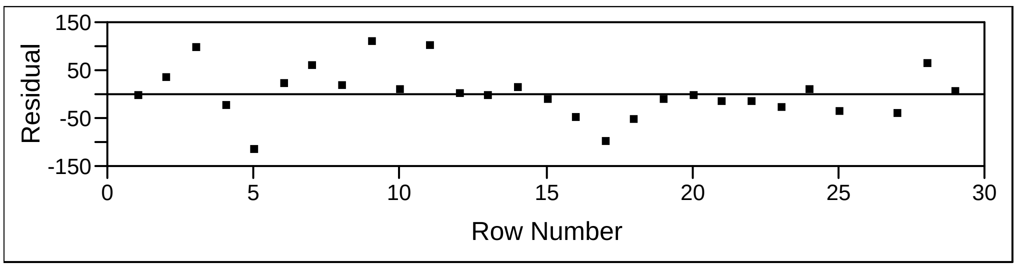
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2009.002	365.1429	-5.50	<.0001
W,CE76	60.616645	8.513431	7.12	<.0001
(W,CE76-43.4161)*(W,CE76-43.4161)	-1.125626	5.851267	-0.19	0.8490

Residual by Predicted Plot

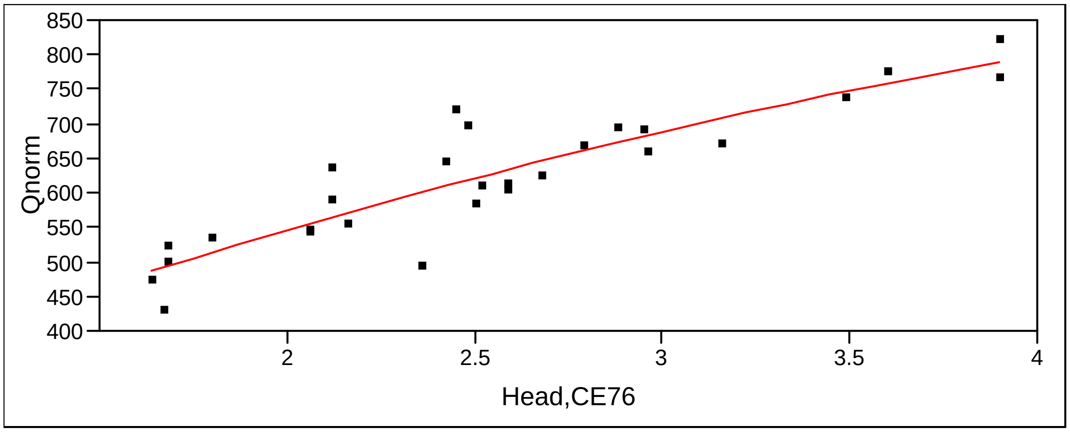


Residual by Row Plot

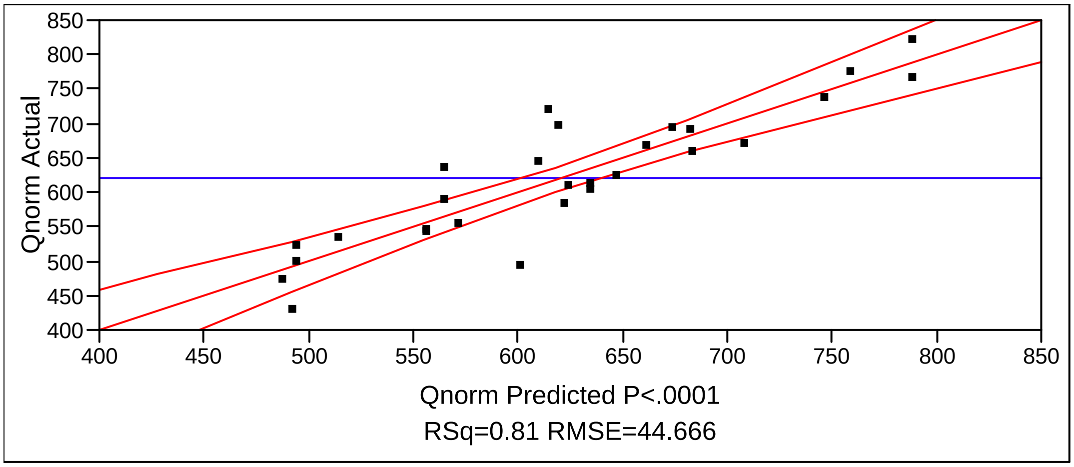


Response Q_{norm} : 2003 through 2005
Independent variable: Head difference between spring pool and CE76 well (w,CE76)

Regression Plot



Actual by Predicted Plot



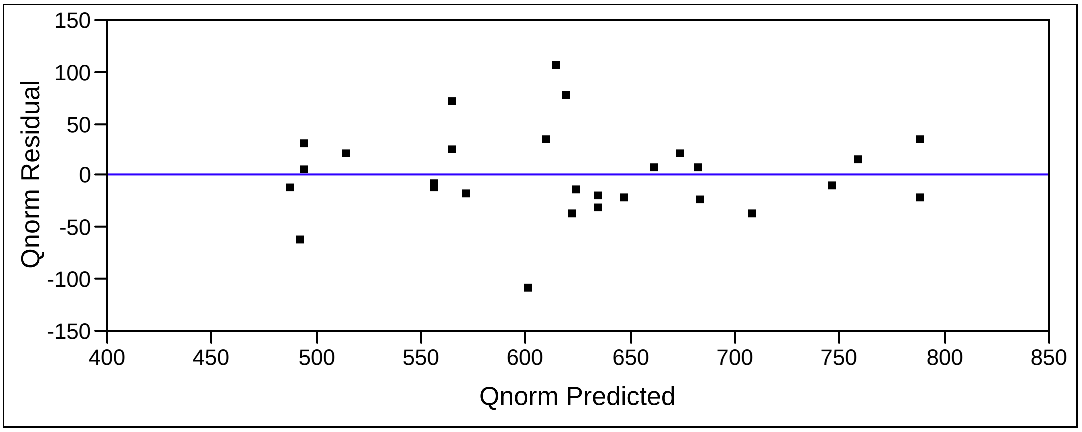
Summary of Fit

RSquare	0.806305
RSquare Adj	0.790809
Root Mean Square Error	44.66583
Mean of Response	620.6815
Observations (or Sum Wgts)	28

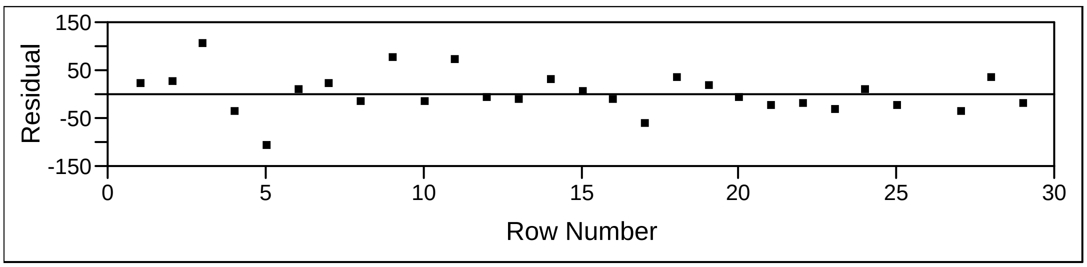
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	268.92475	35.95746	7.48	<.0001
Head,CE76	140.91572	14.73201	9.57	<.0001
(Head,CE76-2.54321)*(Head,CE76-2.54321)	-16.45428	18.21526	-0.90	0.3750

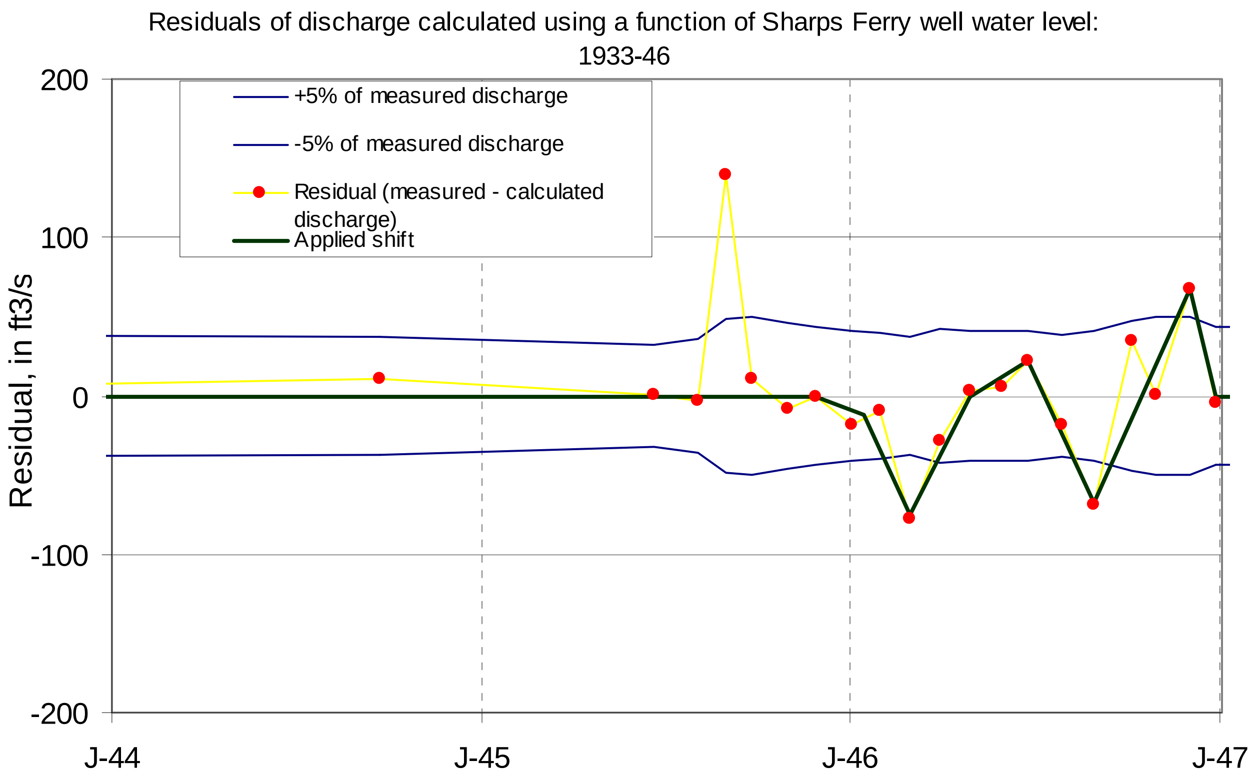
Residual by Predicted Plot

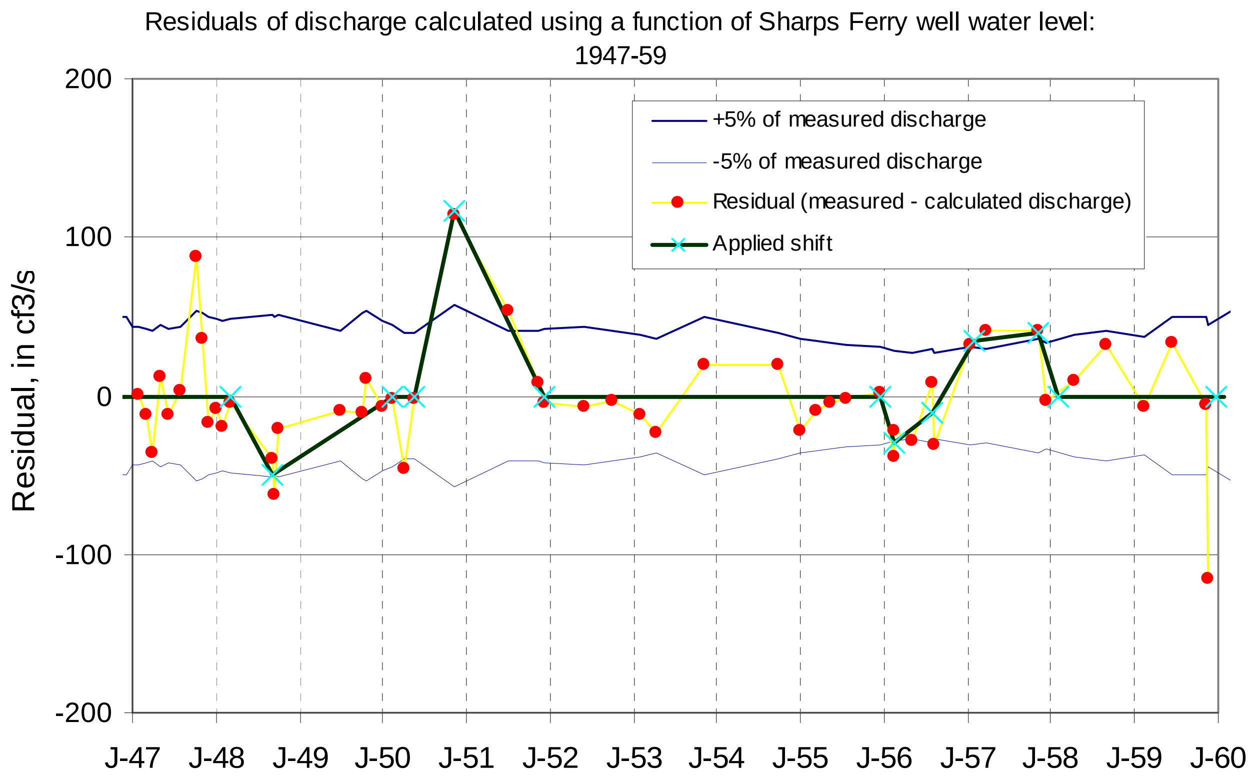


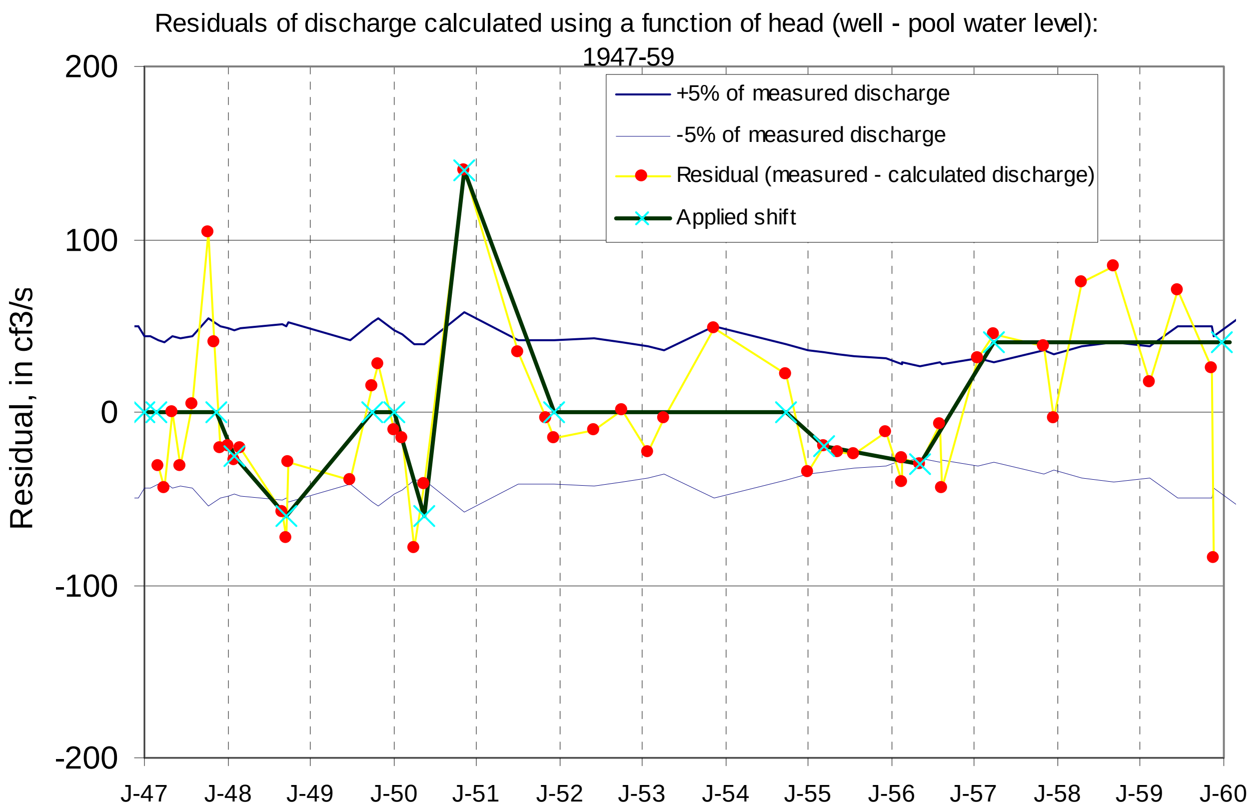
Residual by Row Plot

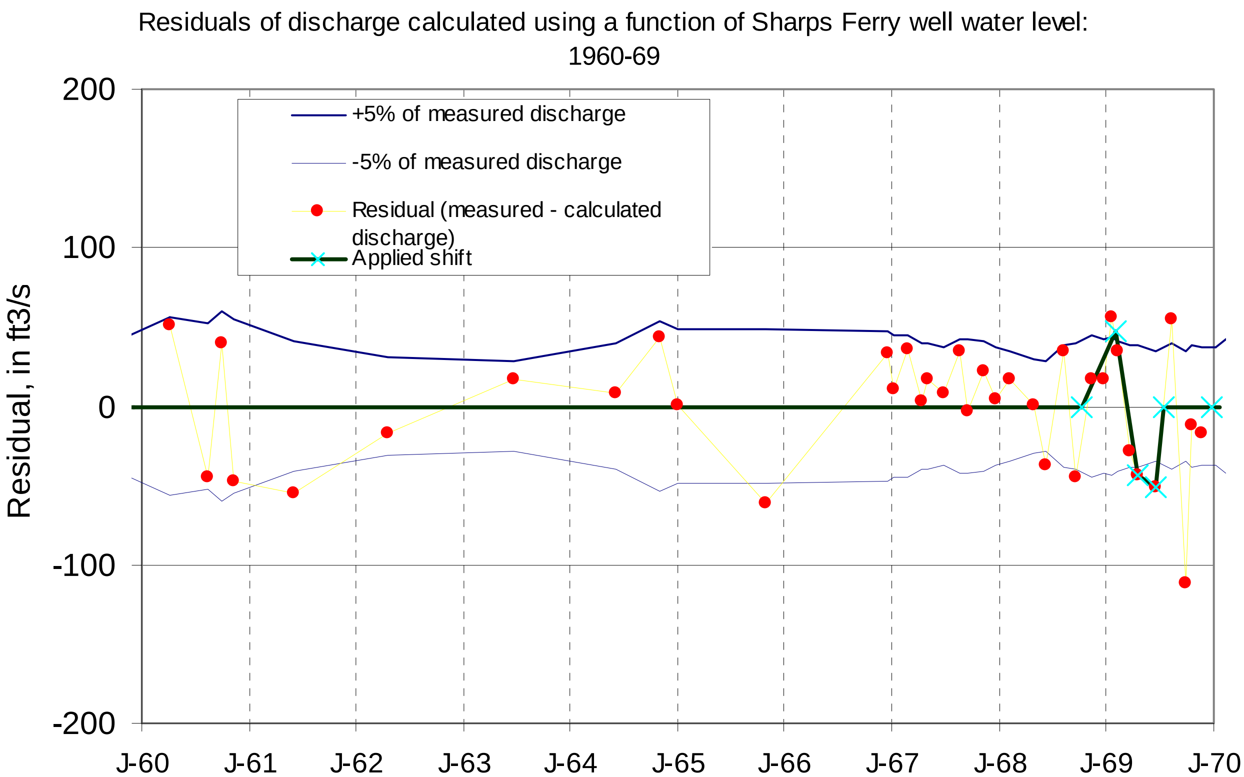


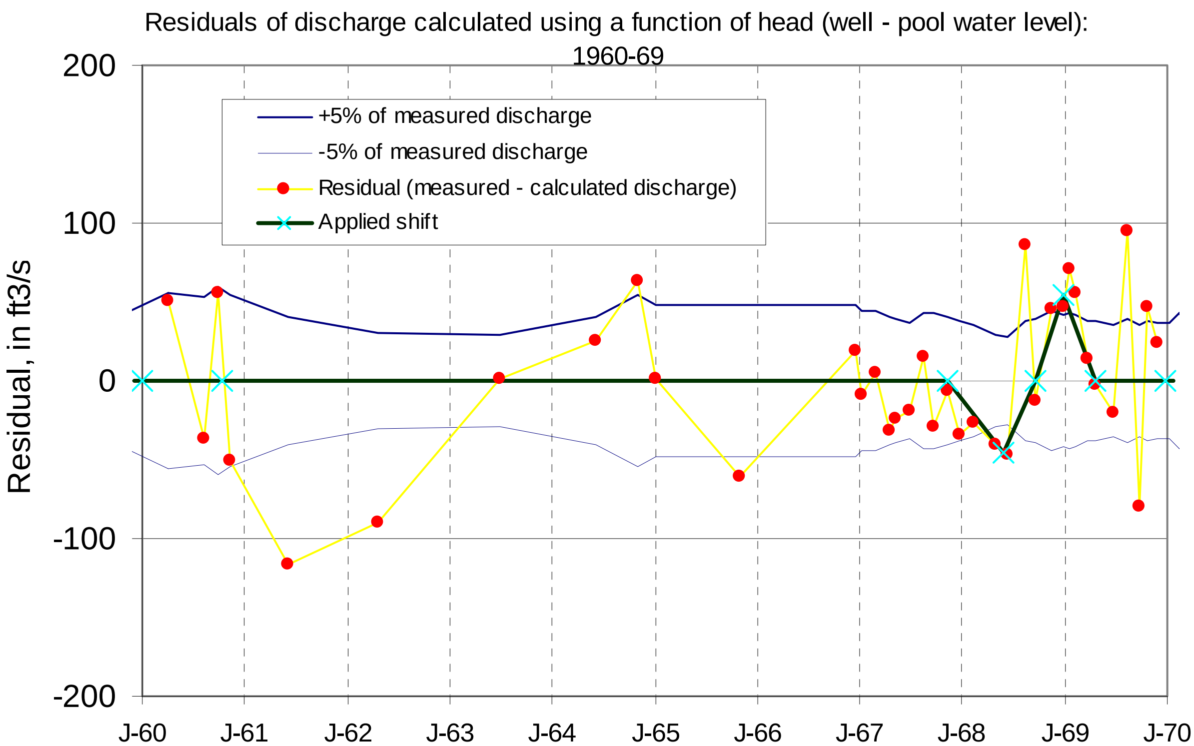
Appendix B – Residual and Shift Plots

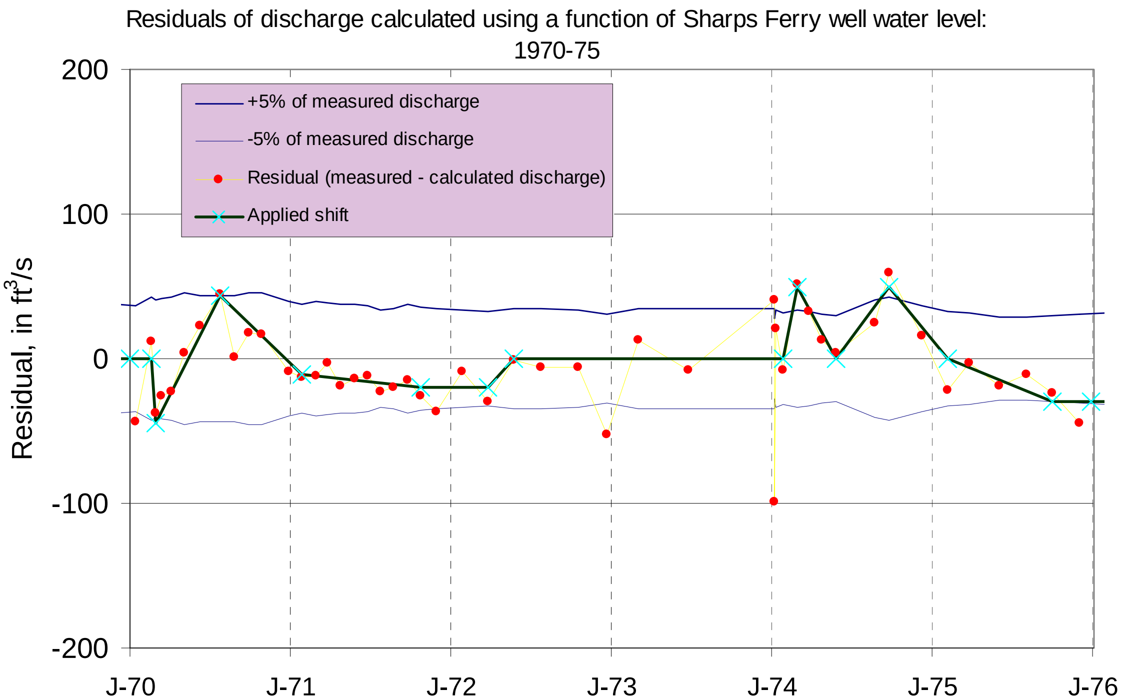

Residuals of discharge calculated using a function of Sharps Ferry well water level:
1933-46
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
Residual, in ft3/s
200
100
0
-100
-200
J-44
J-45
J-46
J-47


Residuals of discharge calculated using a function of Sharps Ferry well water level: 1947-59
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
Residual, in cf3/s
200
100
0
-100
-200
J-47
J-48
J-49
J-50
J-51
J-52
J-53
J-54
J-55
J-56
J-57
J-58
J-59
J-60

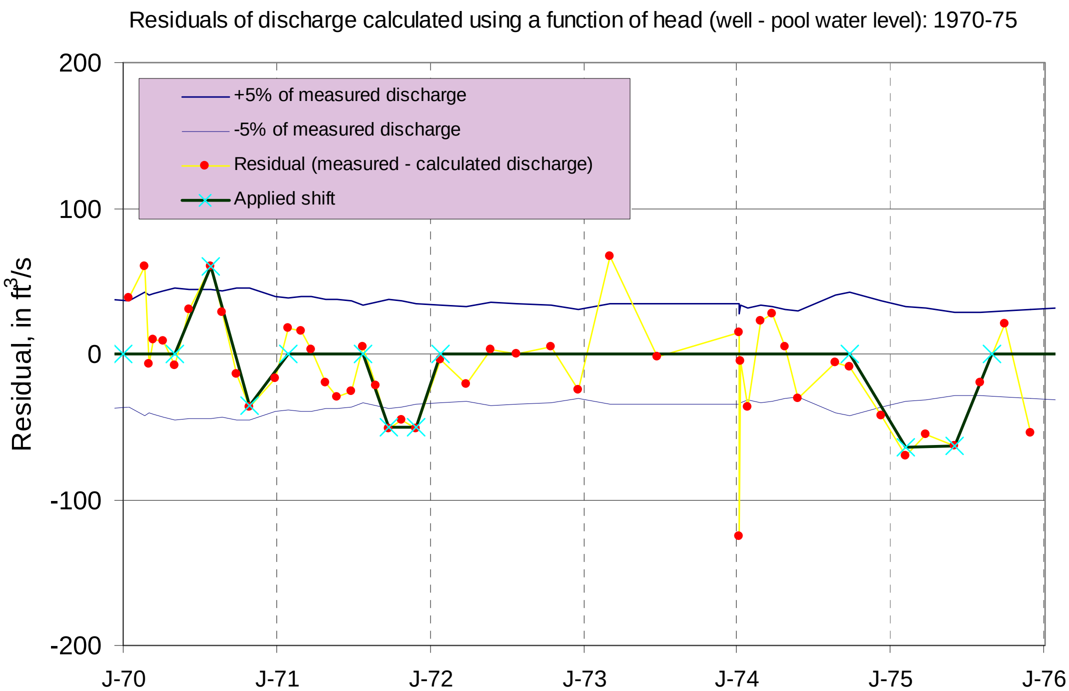

Residuals of discharge calculated using a function of head (well - pool water level): 1947-59
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
Residual, in cf3/s
200
100
0
-100
-200
J-47
J-48
J-49
J-50
J-51
J-52
J-53
J-54
J-55
J-56
J-57
J-58
J-59
J-60


Residuals of discharge calculated using a function of Sharps Ferry well water level: 1960-69
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
Residual, in ft3/s
200
100
0
-100
-200
J-60
J-61
J-62
J-63
J-64
J-65
J-66
J-67
J-68
J-69
J-70

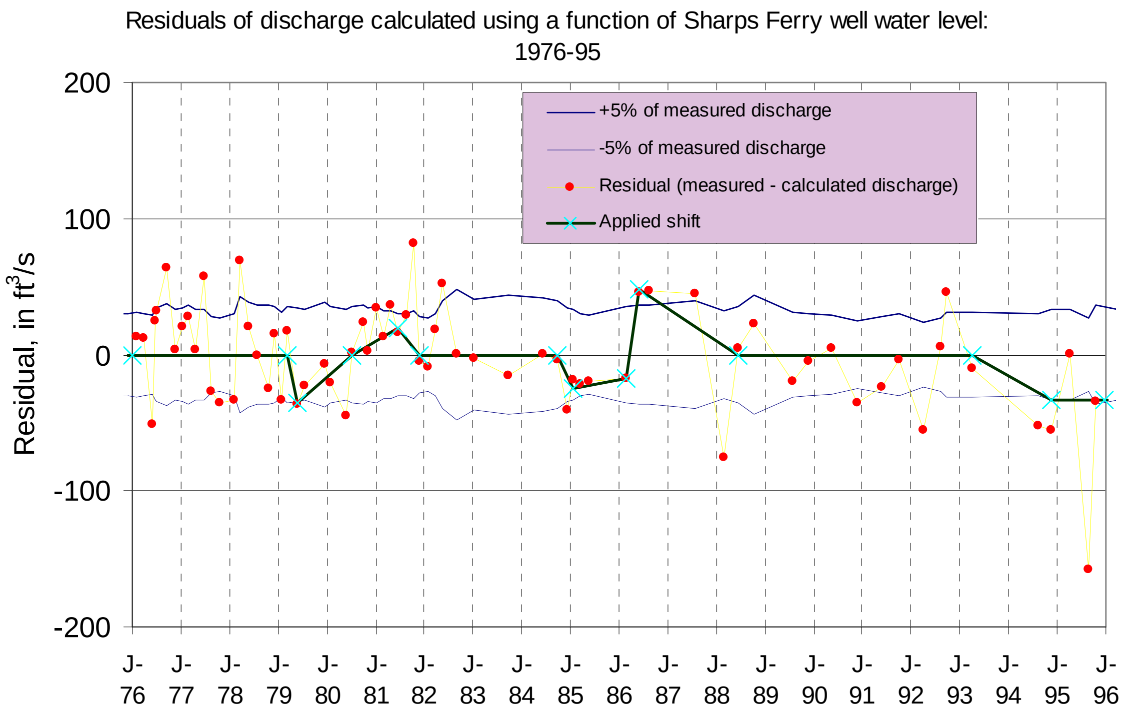

Residuals of discharge calculated using a function of head (well - pool water level): 1960-69
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
Residual, in ft3/s
200
100
0
-100
-200
J-60
J-61
J-62
J-63
J-64
J-65
J-66
J-67
J-68
J-69
J-70

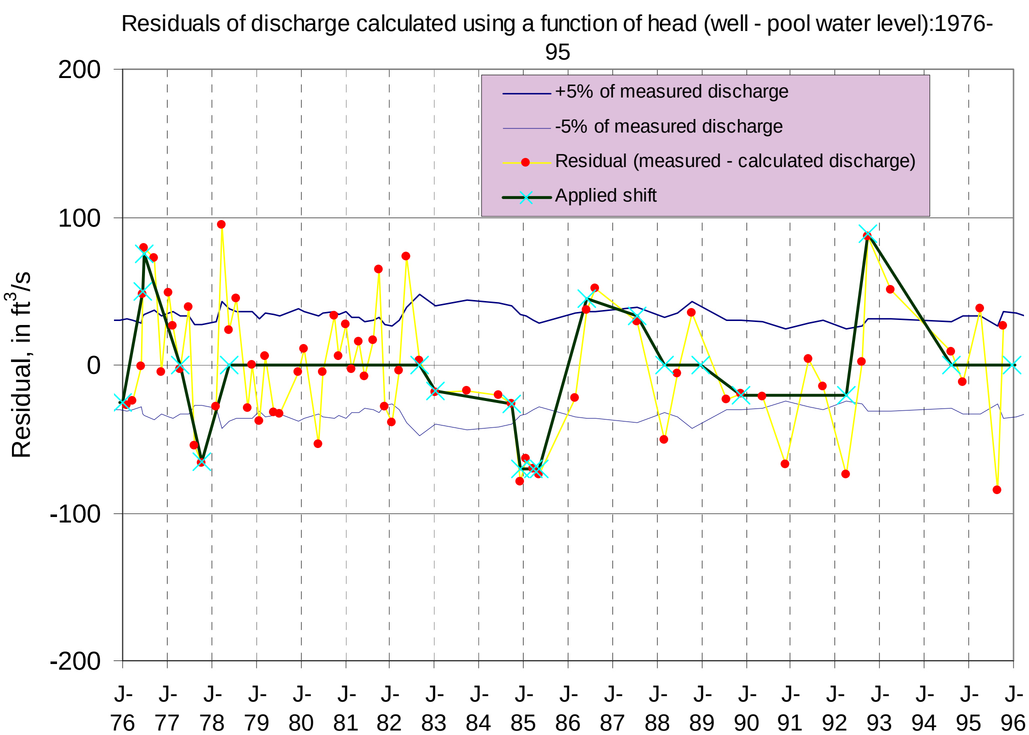


Residuals of discharge calculated using a function of Sharps Ferry well water level: 1970-75
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
Residual, in ft3/s
200
100
0
-100
-200
J-70
J-71
J-72
J-73
J-74
J-75
J-76

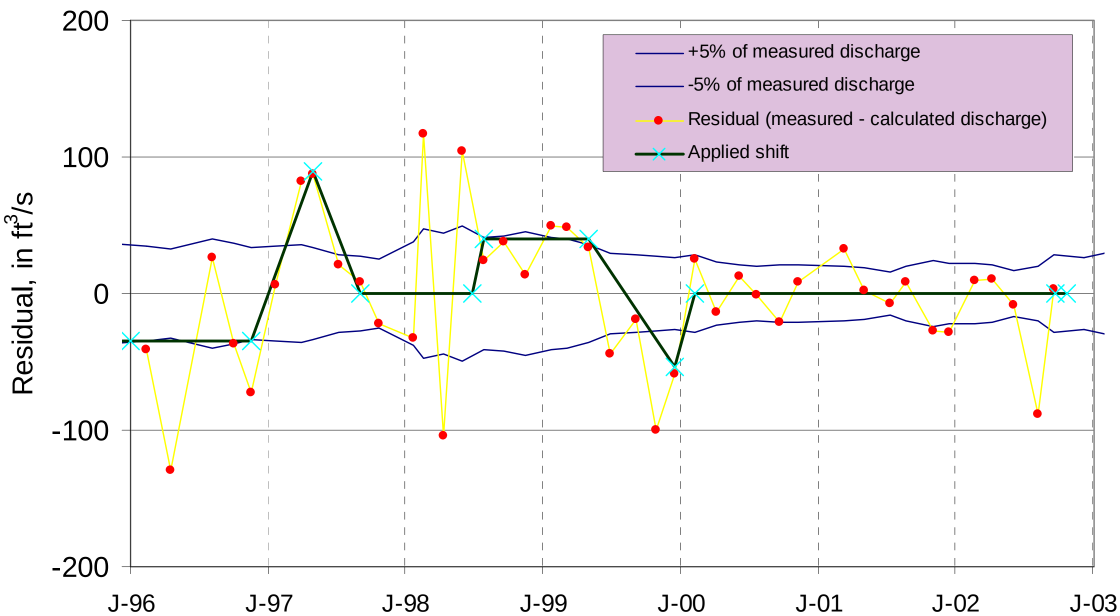


Residuals of discharge calculated using a function of head (well - pool water level): 1970-75
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
Residual, in ft3/s
200
100
0
-100
-200
J-70
J-71
J-72
J-73
J-74
J-75
J-76

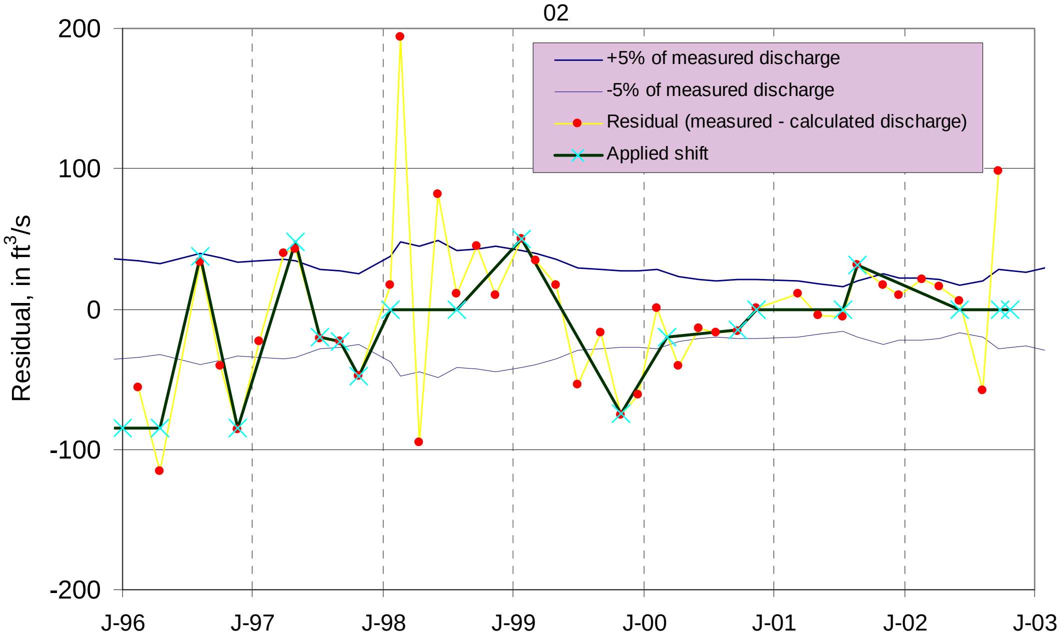

Residuals of discharge calculated using a function of Sharps Ferry well water level: 1976-95
200
100
0
-100
-200
Residual, in ft3/s
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
J-76
J-77
J-78
J-79
J-80
J-81
J-82
J-83
J-84
J-85
J-86
J-87
J-88
J-89
J-90
J-91
J-92
J-93
J-94
J-95
J-96

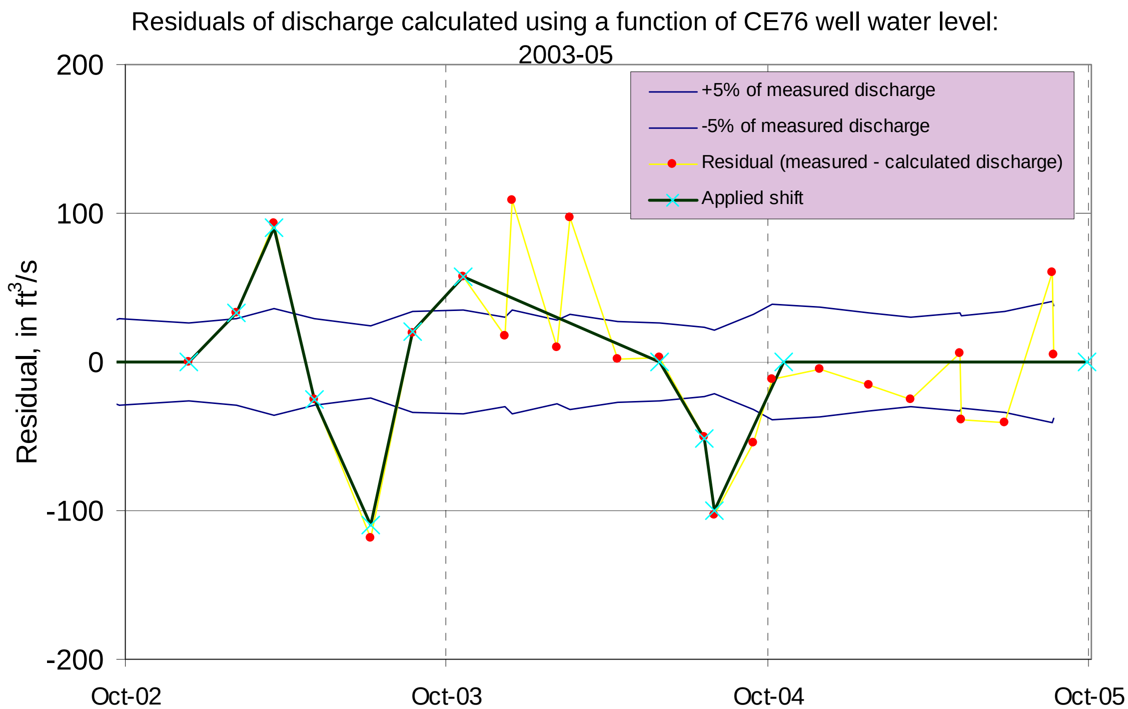

Residuals of discharge calculated using a function of head (well - pool water level):1976-95
200
100
0
-100
-200
Residual, in ft3/s
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift
J-76
J-77
J-78
J-79
J-80
J-81
J-82
J-83
J-84
J-85
J-86
J-87
J-88
J-89
J-90
J-91
J-92
J-93
J-94
J-95
J-96

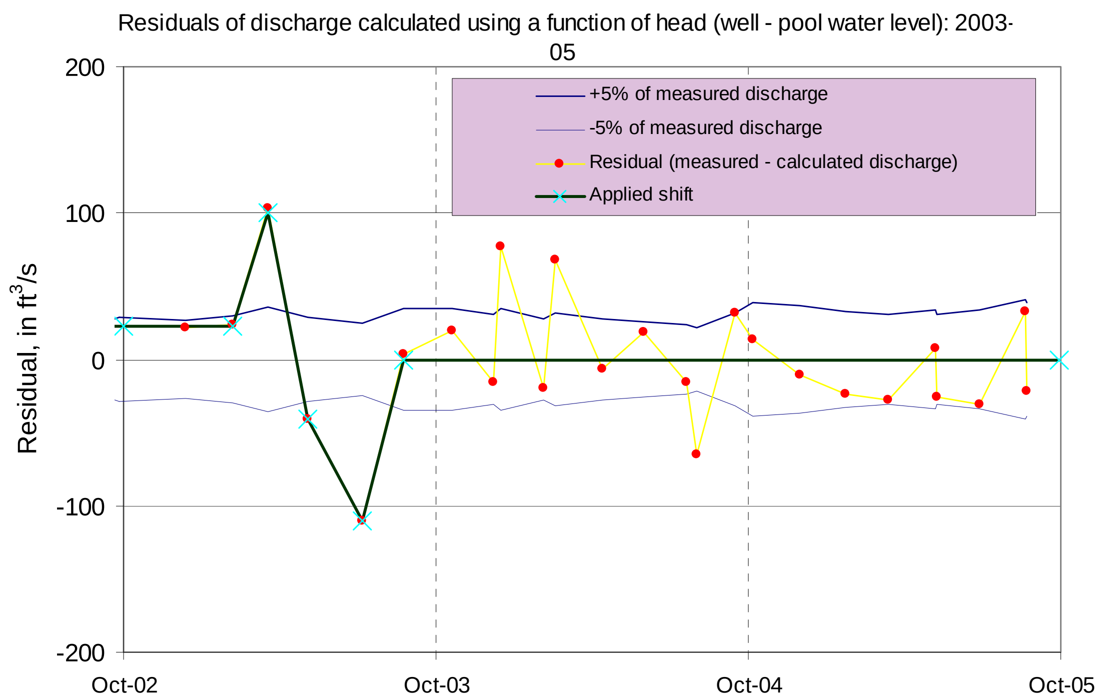
Residuals of discharge calculated using a function of Sharps Ferry well water level: 1996-2002



Residuals of discharge calculated using a function of head (well - pool water level): 1996-02

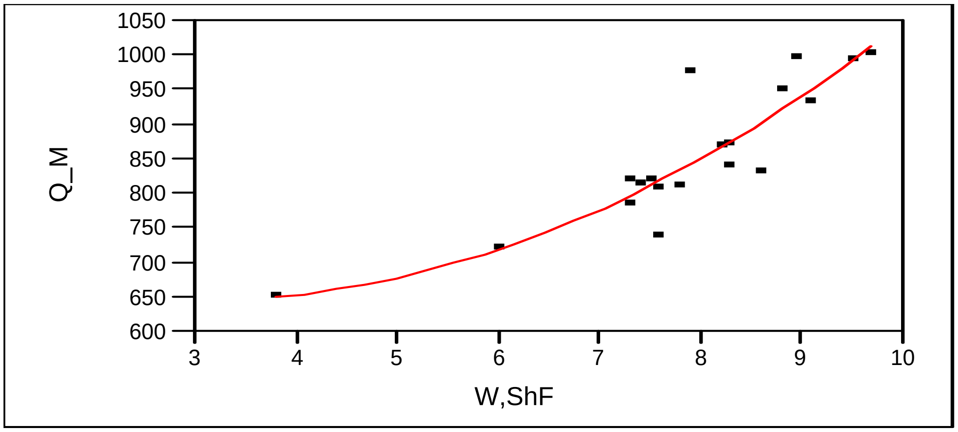



Residuals of discharge calculated using a function of CE76 well water level: 2003-05
Residual, in ft3/s
200
100
0
-100
-200
Oct-02
Oct-03
Oct-04
Oct-05
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift

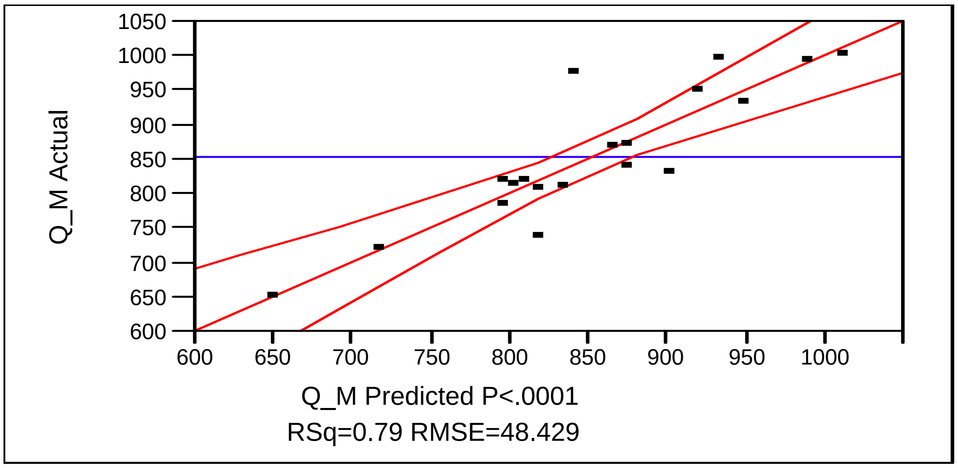

Residuals of discharge calculated using a function of head (well - pool water level): 2003-05
Residual, in ft3/s
200
100
0
-100
-200
Oct-02
Oct-03
Oct-04
Oct-05
+5% of measured discharge
-5% of measured discharge
Residual (measured - calculated discharge)
Applied shift

Appendix C – Details of Regression Analyses: Single Location Selections

Response Q_M:
1933 through 1946 at 3900 ft downstream from spring pool
Independent variable: Water level in Sharps Ferry well (W,ShF)
Regression Plot



Actual by Predicted Plot



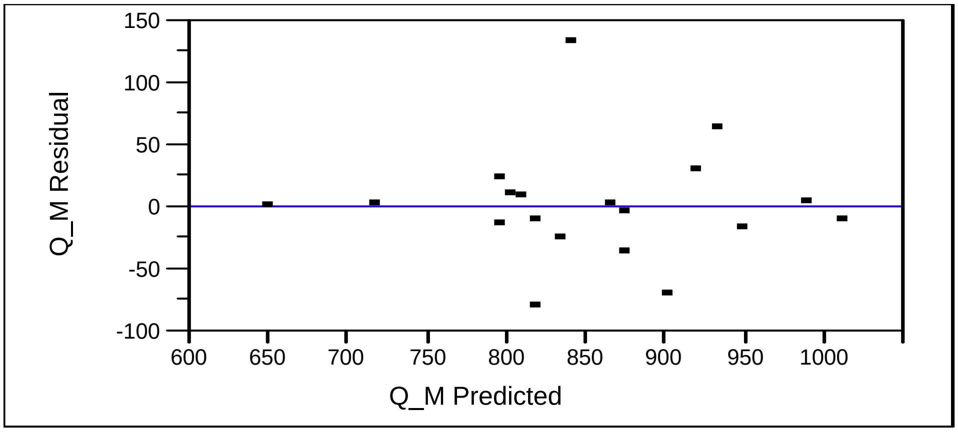
Summary of Fit

RSquare	0.790116
RSquare Adj	0.76388
Root Mean Square Error	48.42852
Mean of Response	852.7368
Observations (or Sum Wgts)	19

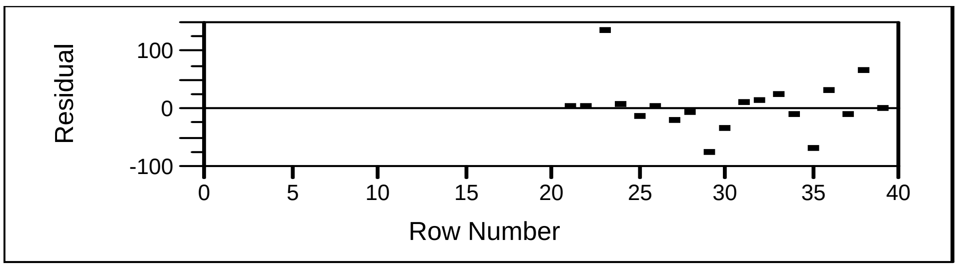
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	210.32621	95.84352	2.19	0.0433
W,ShF	79.835607	11.50123	6.94	<.0001
(W,ShF-7.87632)*(W,ShF-7.87632)	8.1389332	4.03184	2.02	0.0606

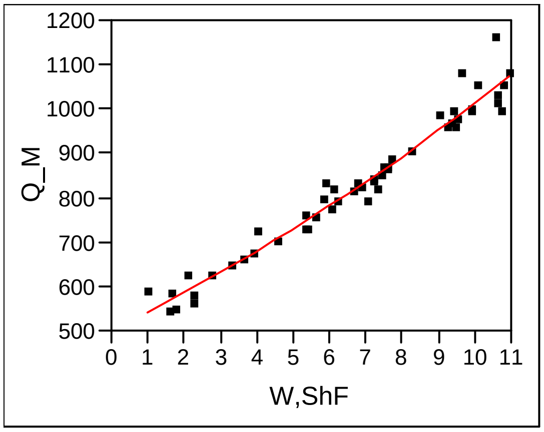
Residual by Predicted Plot



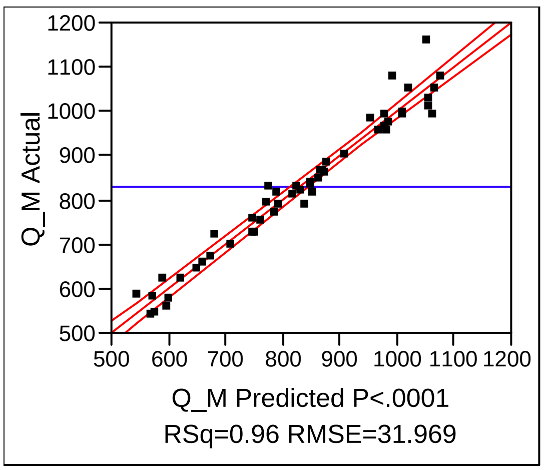
Residual by Row Plot



Response Q_M
1947 through 1959 at 3900 ft downstream from spring pool
Independent variable: Water level in Sharps Ferry well (W,ShF)
Regression Plot



Actual by Predicted Plot



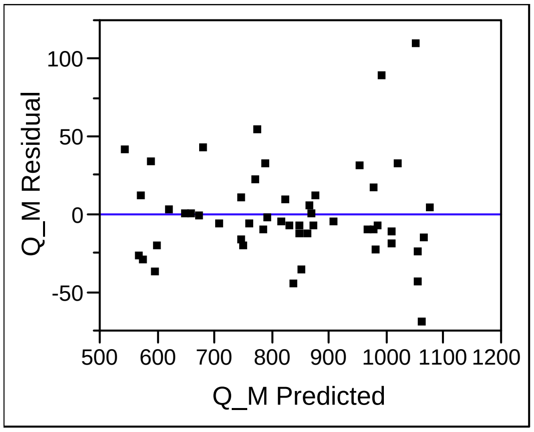
Summary of Fit

RSquare	0.961941
RSquare Adj	0.960355
Root Mean Square Error	31.96907
Mean of Response	828.0196
Observations (or Sum Wgts)	51

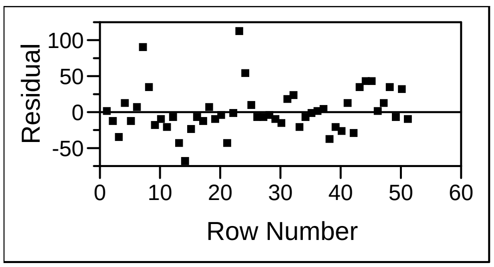
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	447.48769	13.93643	32.11	<.0001
W,ShF	55.375094	1.644346	33.68	<.0001
(W,ShF-6.68725)*(W,ShF-6.68725)	1.241378	0.559178	2.22	0.0312

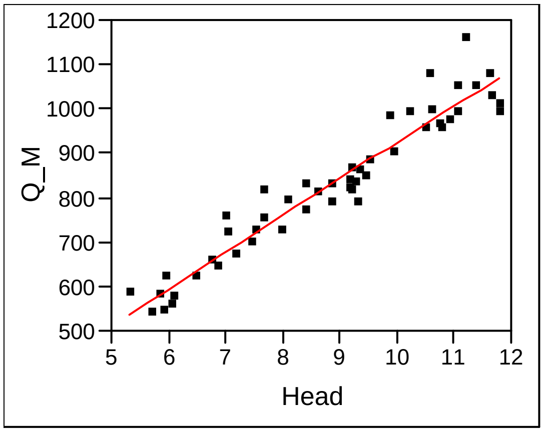
Residual by Predicted Plot



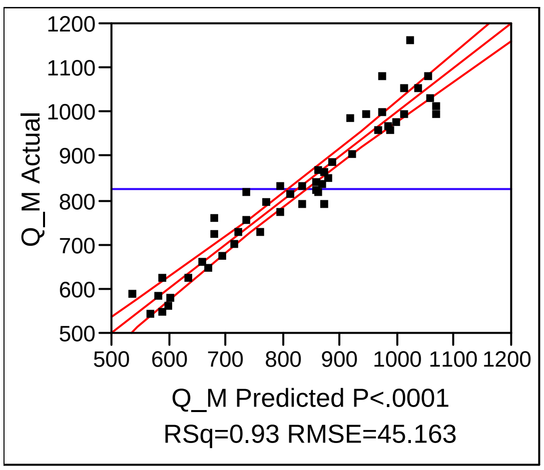
Residual by Row Plot



Response Q_M
1947 through 1959 at 3900 ft downstream from spring pool
Independent variable: Head difference between spring pool and Sharps Ferry well (W,ShF)
Regression Plot



Actual by Predicted Plot



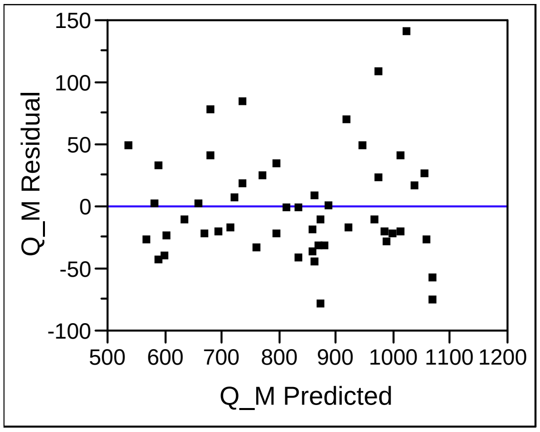
Summary of Fit

RSquare	0.925532
RSquare Adj	0.922363
Root Mean Square Error	45.16324
Mean of Response	827.22
Observations (or Sum Wgts)	50

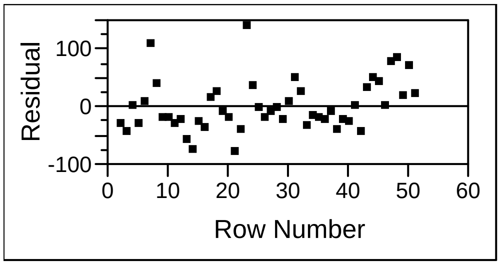
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	105.79913	32.79965	3.23	0.0023
Head	82.026906	3.442569	23.83	<.0001
(Head-8.8156)*(Head-8.8156)	-0.480342	1.959674	-0.25	0.8074

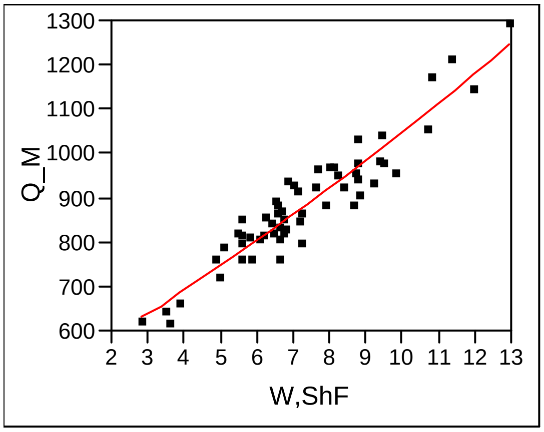
Residual by Predicted Plot



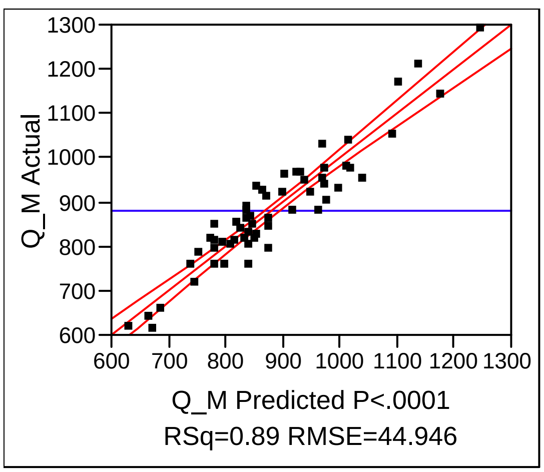
Residual by Row Plot



Response Q_M
1960 through 1971 at 13,200 ft downstream from spring pool
Independent variable: Water level in Sharps Ferry well (W,ShF)
Regression Plot



Actual by Predicted Plot



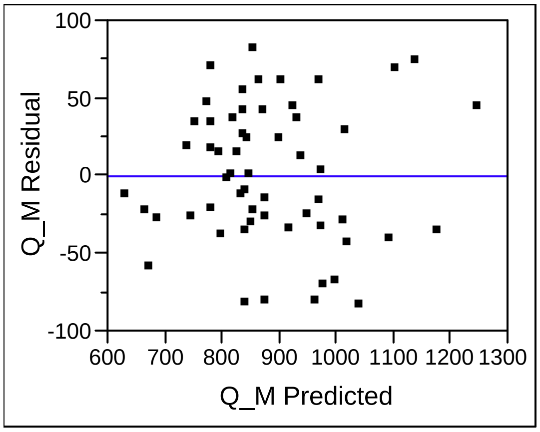
Summary of Fit

RSquare	0.887853
RSquare Adj	0.883775
Root Mean Square Error	44.94615
Mean of Response	881.6552
Observations (or Sum Wgts)	58

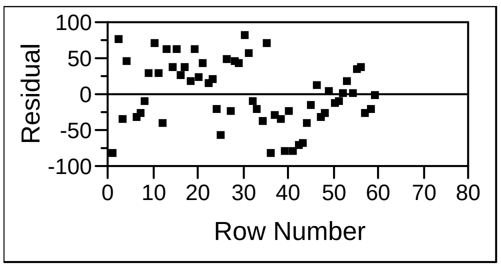
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	443.12517	22.03947	20.11	<.0001
W,ShF	59.847593	3.028655	19.76	<.0001
(W,ShF-7.27125)*(W,ShF-7.27125)	0.814665	0.977861	0.83	0.4084

Residual by Predicted Plot

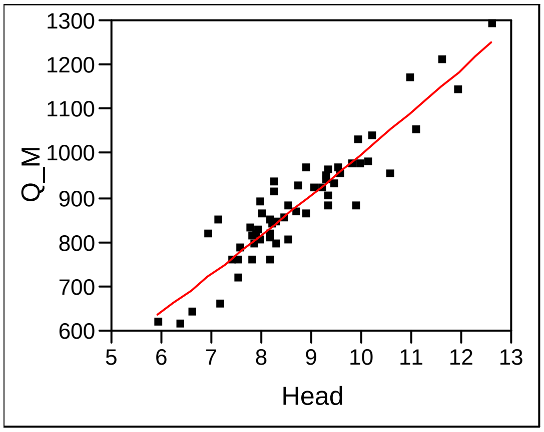


Residual by Row Plot

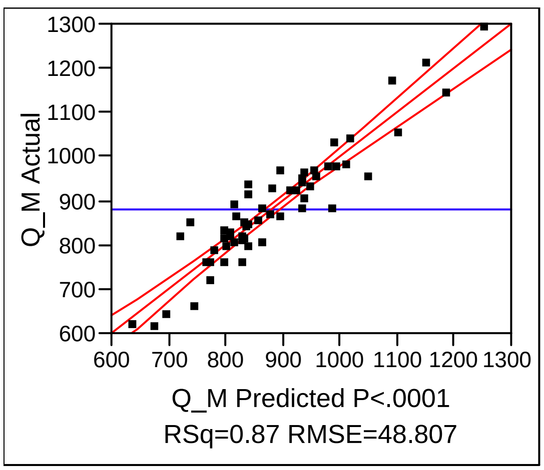


Response Q_M
1960 through 1971 at 13,200 ft downstream from spring pool
Independent variable: head difference between spring pool and Sharps Ferry well (W,ShF)

Regression Plot



Actual by Predicted Plot



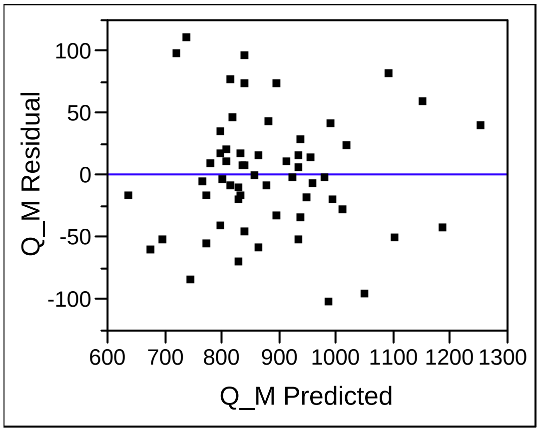
Summary of Fit

RSquare	0.867761
RSquare Adj	0.862952
Root Mean Square Error	48.80669
Mean of Response	881.6552
Observations (or Sum Wgts)	58

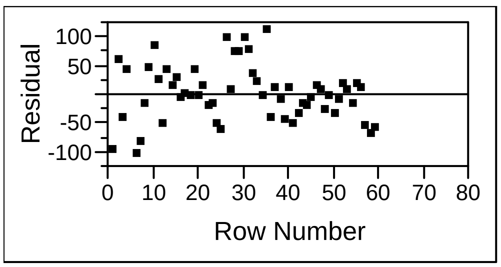
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	90.348214	45.03798	2.01	0.0498
Head	90.548889	5.304888	17.07	<.0001
(Head-8.71746)*(Head-8.71746)	1.1032297	2.497709	0.44	0.6604

Residual by Predicted Plot

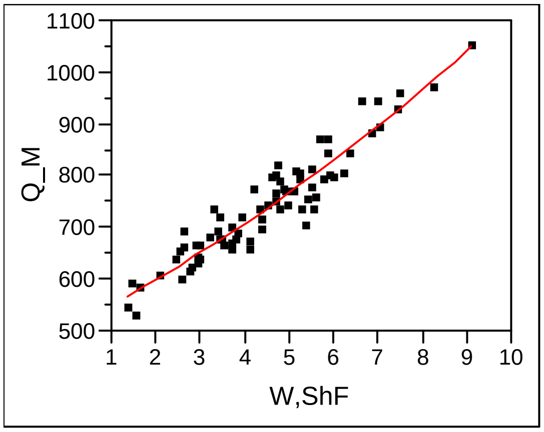


Residual by Row Plot

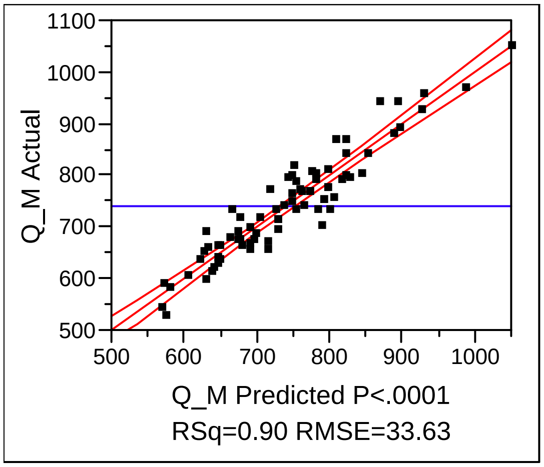


Response Q_M
1971 through 1995 at greater than 20,000 ft downstream from spring pool
Independent variable: Water level in Sharps Ferry well (W,ShF)

Regression Plot



Actual by Predicted Plot



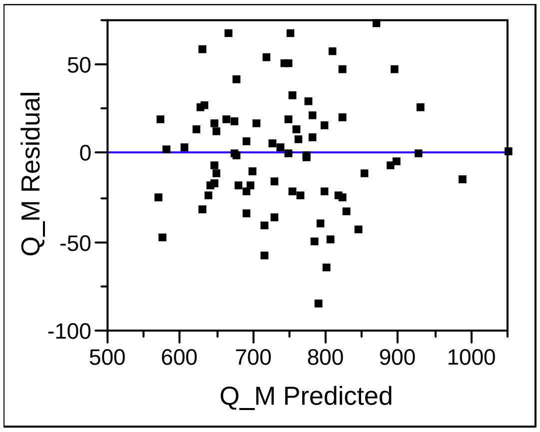
Summary of Fit

RSquare	0.896706
RSquare Adj	0.893837
Root Mean Square Error	33.63001
Mean of Response	740.04
Observations (or Sum Wgts)	75

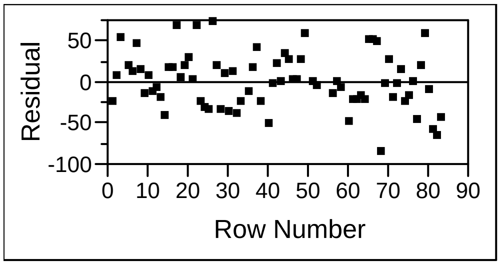
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	469.12087	11.5157	40.74	<.0001
W,ShF	59.312879	2.474379	23.97	<.0001
(W,ShF-4.4868)*(W,ShF-4.4868)	1.8534156	1.097103	1.69	0.0955

Residual by Predicted Plot

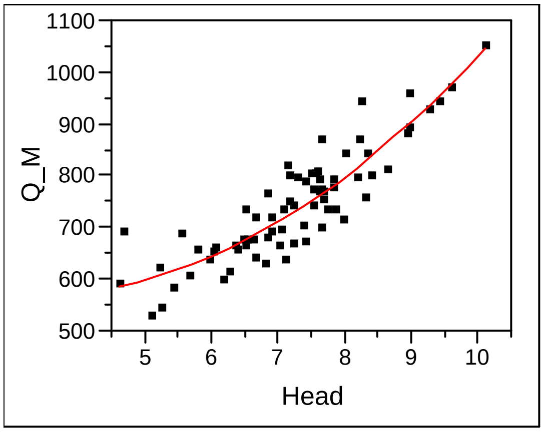


Residual by Row Plot

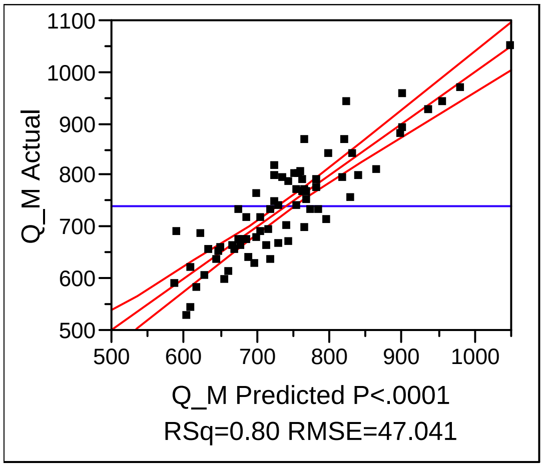


Response Q_M
1972 through 1995 at greater than 20,000 ft downstream from spring pool
Independent variable: Head difference between spring pool and Sharps Ferry well (W,ShF)

Regression Plot



Actual by Predicted Plot



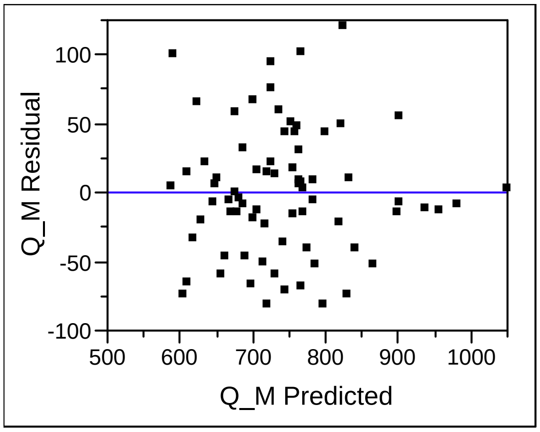
Summary of Fit

RSquare	0.800697
RSquare Adj	0.795083
Root Mean Square Error	47.04073
Mean of Response	740.1216
Observations (or Sum Wgts)	74

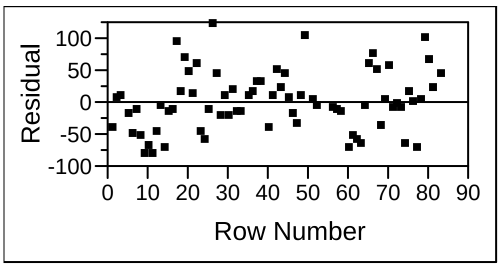
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	144.63488	35.80259	4.04	0.0001
Head	80.70123	4.866648	16.58	<.0001
(Head-7.22041)*(Head-7.22041)	10.12985	2.996449	3.38	0.0012

Residual by Predicted Plot

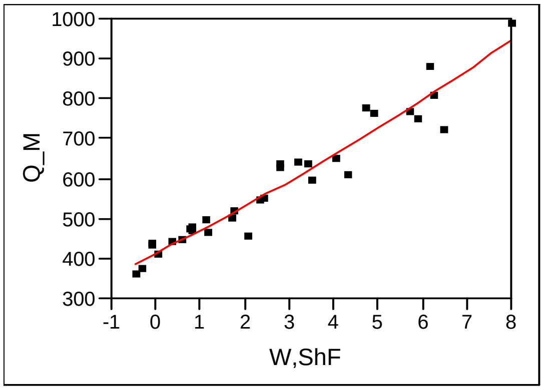


Residual by Row Plot

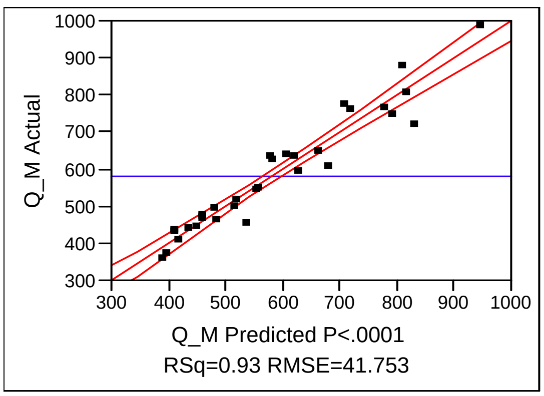


Response Q_M
1996 through 2002 at greater than 20,000 ft downstream from spring pool
Independent variable: Water level in Sharps Ferry well (W,ShF)

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.93369
RSquare Adj	0.929117
Root Mean Square Error	41.75277
Mean of Response	582.0313
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	711855.44	355928	204.1696
Error	29	50555.53	1743	Prob > F
C. Total	31	762410.97		<.0001

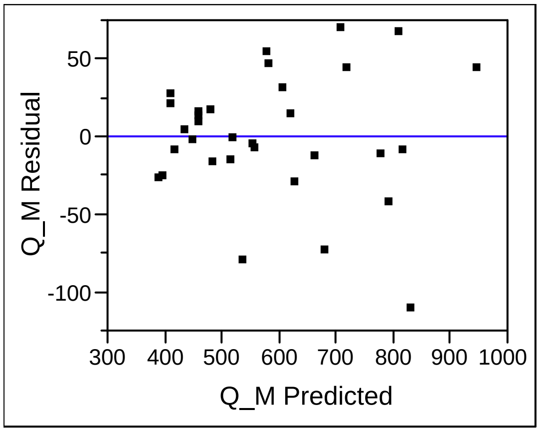
Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	27	50519.527	1871.09	103.9496
Pure Error	2	36.000	18.00	Prob > F
Total Error	29	50555.527		0.0096
				Max RSq
				1.0000

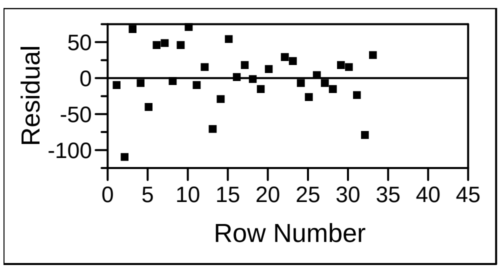
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	403.33258	11.88425	33.94	<.0001
W,ShF	63.051807	3.571348	17.65	<.0001
(W,ShF-2.71813)*(W,ShF-2.71813)	1.3742132	1.438075	0.96	0.3472

Residual by Predicted Plot

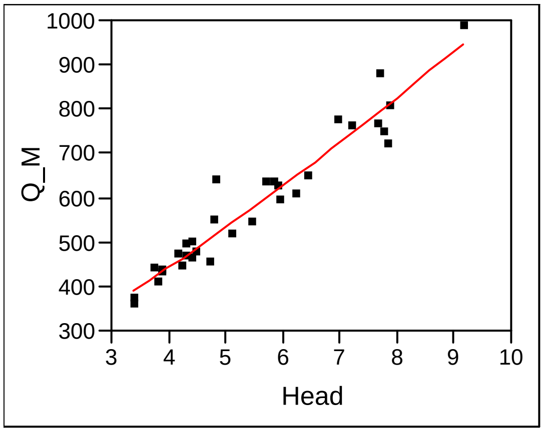


Residual by Row Plot

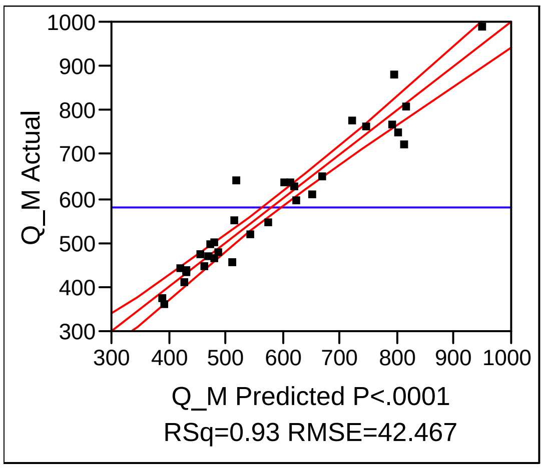


Response Q_M
1996 through 2002 at greater than 20,000 ft downstream from spring pool
Independent variable: Head difference between spring pool and Sharps Ferry well (W,ShF)

Regression Plot



Actual by Predicted Plot



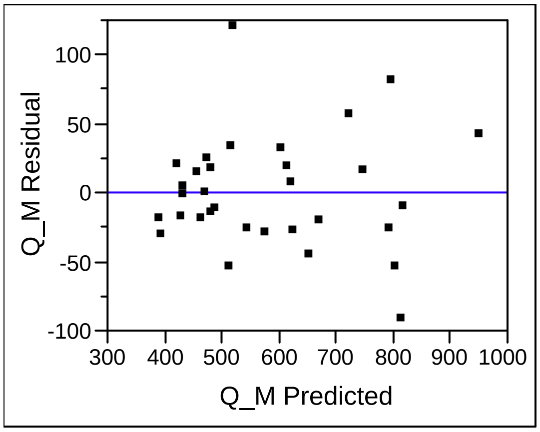
Summary of Fit

RSquare	0.931403
RSquare Adj	0.926672
Root Mean Square Error	42.46659
Mean of Response	582.0313
Observations (or Sum Wgts)	32

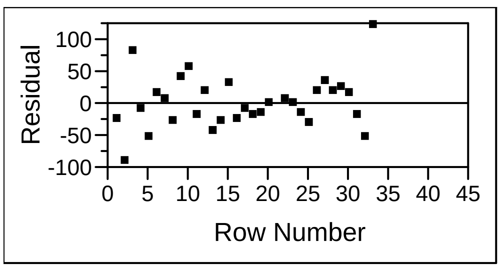
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	63.151709	28.66482	2.20	0.0357
Head	93.9279	5.667061	16.57	<.0001
(Head-5.47875)*(Head-5.47875)	1.7575746	3.309423	0.53	0.5994

Residual by Predicted Plot

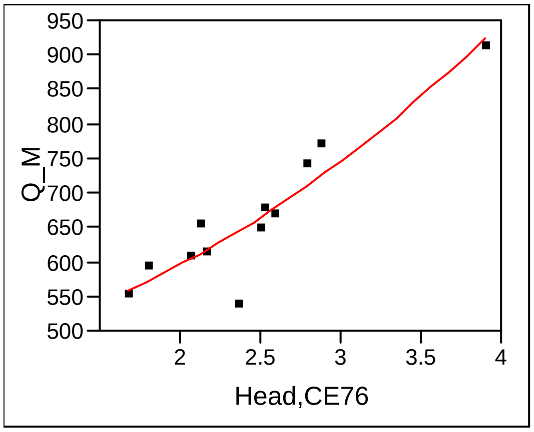


Residual by Row Plot

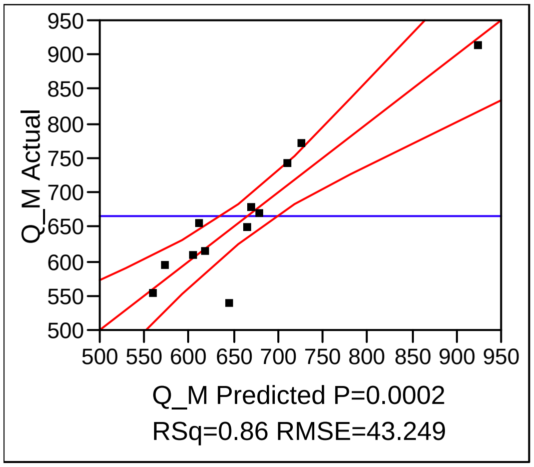


Response Q_M
2002 through 2005 at greater than 20,000 ft downstream from spring pool
Independent variable: Head difference between spring pool and well CE76

Regression Plot



Actual by Predicted Plot



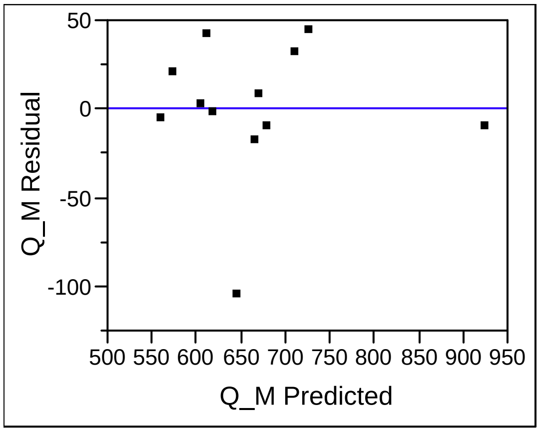
Summary of Fit

RSquare	0.858406
RSquare Adj	0.826941
Root Mean Square Error	43.24898
Mean of Response	664.5
Observations (or Sum Wgts)	12

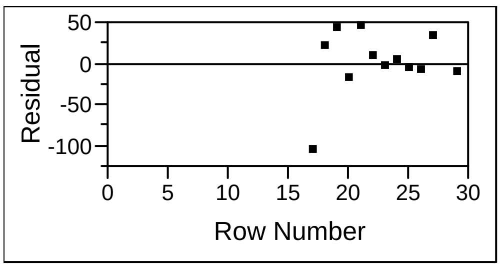
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	296.02457	65.00743	4.55	0.0014
Head,CE76	147.40834	28.13705	5.24	0.0005
(Head,CE76-2.44667)*(Head,CE76-2.44667)	24.693178	27.87776	0.89	0.3988

Residual by Predicted Plot

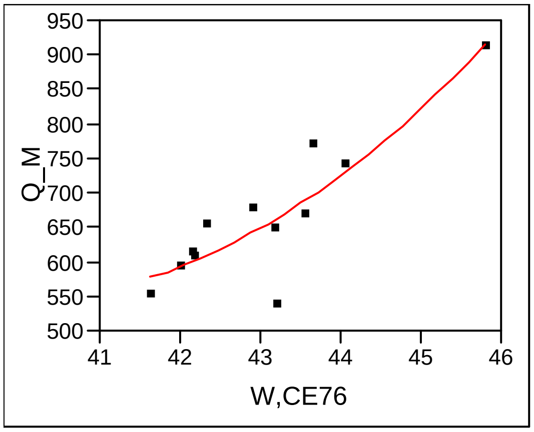


Residual by Row Plot

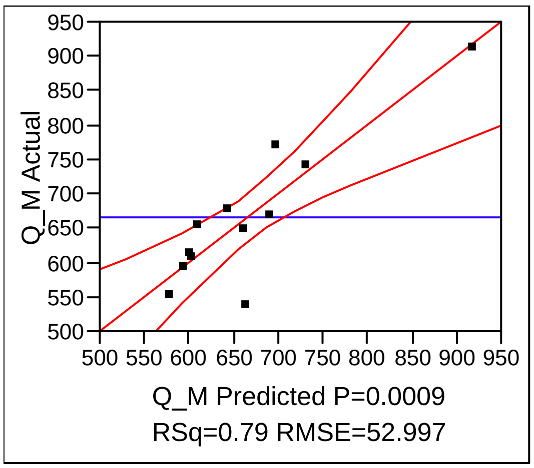


Response Q_M
2003 through 2005 at greater than 20,000 downstream from spring pool
Independent variable: Water level in well CE76

Regression Plot



Actual by Predicted Plot



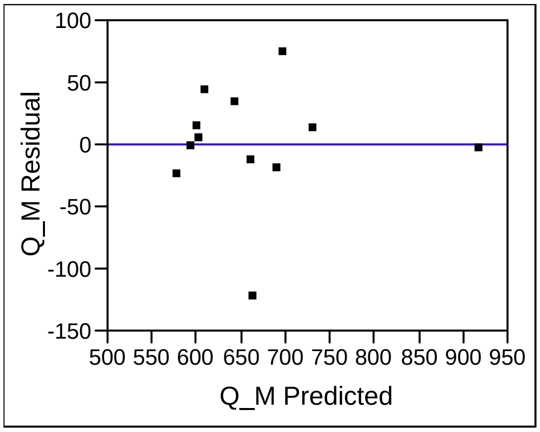
Summary of Fit

RSquare	0.787385
RSquare Adj	0.740138
Root Mean Square Error	52.99681
Mean of Response	664.5
Observations (or Sum Wgts)	12

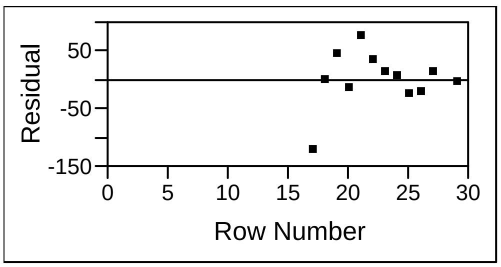
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2248.635	758.5073	-2.96	0.0158
W,CE76	67.375723	17.78313	3.79	0.0043
(W,CE76-43.0533)*(W,CE76-43.0533)	10.253374	9.746138	1.05	0.3202

Residual by Predicted Plot

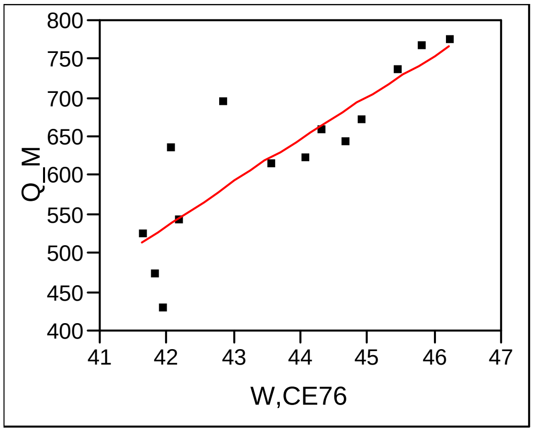


Residual by Row Plot

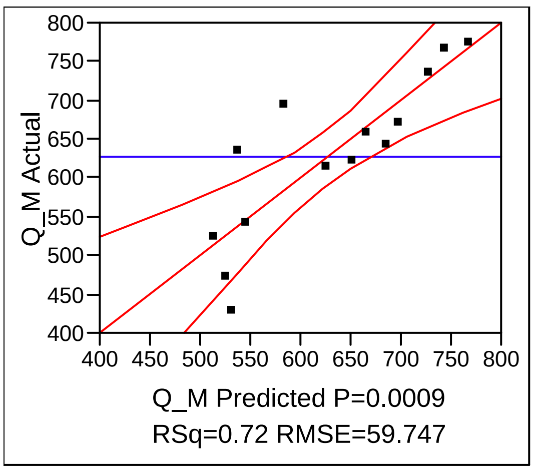


Response Q_M
2003 through 2005 at 3900 ft downstream from spring pool
Independent variable: Water level in well CE76

Regression Plot



Actual by Predicted Plot



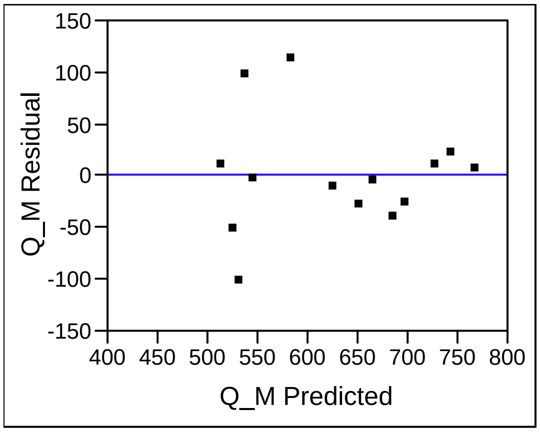
Summary of Fit

RSquare	0.722513
RSquare Adj	0.672061
Root Mean Square Error	59.74685
Mean of Response	627.1429
Observations (or Sum Wgts)	14

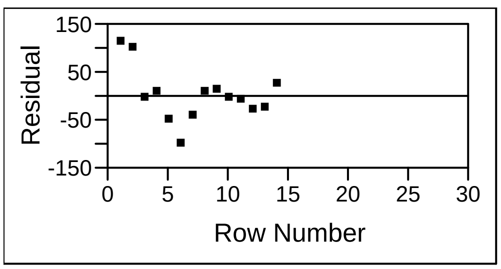
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1790.033	454.5922	-3.94	0.0023
W,CE76	55.398288	10.4752	5.29	0.0003
(W,CE76-43.6693)*(W,CE76-43.6693)	-0.847175	8.816037	-0.10	0.9252

Residual by Predicted Plot

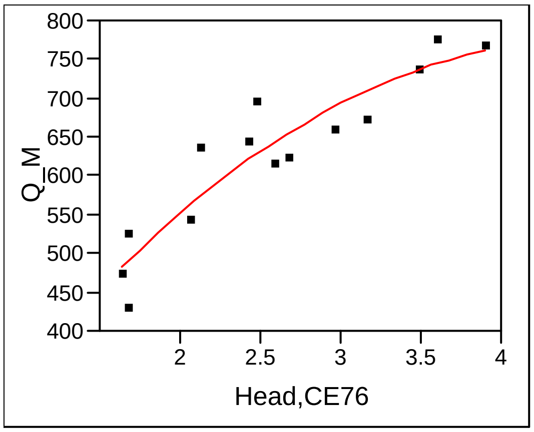


Residual by Row Plot

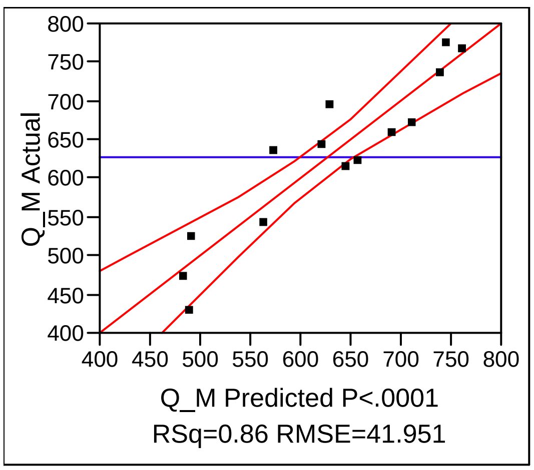


Response Q_M
2003 through 2005 at 3900 ft downstream from spring pool
Independent variable: Head difference between spring pool and well CE76

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.863197
RSquare Adj	0.838323
Root Mean Square Error	41.95098
Mean of Response	627.1429
Observations (or Sum Wgts)	14

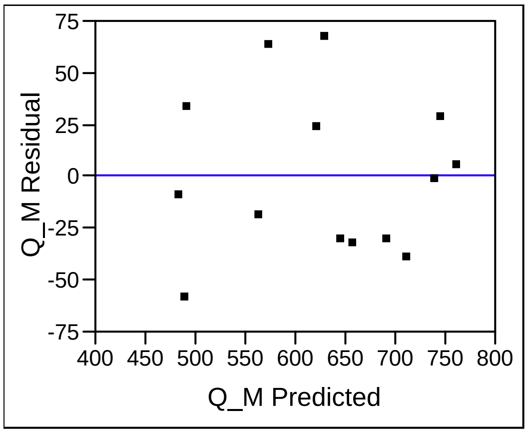
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	122148.98	61074.5	34.7037
Error	11	19358.74	1759.9	Prob > F
C. Total	13	141507.71		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	293.34824	42.41095	6.92	<.0001
Head,CE76	135.22246	16.2897	8.30	<.0001
(Head,CE76-2.60357)*(Head,CE76-2.60357)	-35.85062	23.60161	-1.52	0.1570

Residual by Predicted Plot



Residual by Row Plot