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ANALYSIS OF THE RELATION BETWEEN DISCHARGE FROM THE APOPKA SPRING AND LAKE AND GROUND-WATER LEVELS

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Analysis of the relation between discharge from the Apopka Spring and lake and ground-water levels

(This picture of the Apopka Spring pool is from Florida Geological Survey Bulletin 31, 1977.)

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Executive Summary

This report presents an analysis of the relation between discharge from the Apopka Spring and lake and ground–water levels. The objective of this analysis was to develop predictive equations that can be used by the St. Johns River Water Management District (SJRWMD) in models to assess impacts of proposed water-resources development and land-use changes. Measurements of discharge from Apopka Spring, which were made by Karst Environmental Services, Inc. from 1997 to 2003, were used in the analysis.

Three multivariate models that were developed all appear to be capable of giving estimates of discharge from the Lake Apopka spring that will probably be accurate within 2 or 3 ft^3/s most of the time. The most precise model has a standard error of regression of 1.94 ft^3/s.

It may be possible to determine which model is the most appropriate in the future after more discharge measurements have been made. In the meantime, it is suggested that an average of discharges predicted by all three of the multivariate models will furnish the best estimate of spring discharge.

Flow velocities in the spring orifice vary substantially during the one-minute measurement intervals. This short-period variation, together with possible longer-period flow variations over a period of several hours associated with lake seiche effects, may or may not be a source of measurement error. A continuous record of velocity at selected points within the spring orifice for a day or longer could provide data for understanding effects of short and long period variations in flow velocity on the accuracy of the measurements.

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Introduction

The St. Johns River Water Management District's (SJRWMD) Minimum Flows and Levels (MFLs) Program, implemented pursuant to Section 373.042, *Florida Statues*, 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 the consumptive use permitting (CUP) program.

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 that prevent significant harm and above which water is available for reasonable beneficial use. However, when use of water resources shifts the hydrologic conditions below those defined by the MFLs, significant ecological harm occurs. As it applies to wetland and aquatic communities, significant harm is a function of changes in the frequencies and durations of water level and/or flow events, causing impairment or destruction of ecological structures and 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, including Apopka Spring. As a part of the MFLs determination for Apopka Spring, SJRWMD requested statistical and graphical analyses to present a summary and assessment of the historical period of record of instantaneous Apopka Spring discharge measurements, Lake Apopka water levels, and Floridan aquifer potentiometric levels (head). The purpose of this assessment is to determine whether daily spring discharge can be predicted by using the measured difference between aquifer head and lake level data. The evaluation was to include recommendations regarding additional data collection and analyses needs to reduce data gaps and increase scientific knowledge. This report describes the development of ratings for estimating spring discharge from lake and ground water level data.

Method of analysis

Spring discharge (Q) should be related to the head difference between the aquifer and the spring water surface (lake level). Ground-water flow models such as the USGS MODFLOW (McDonald,M.G., and Harbaugh, A.W. 1988) make use of head difference to compute spring discharge. In other applications, water level in wells near springs have been used to estimate spring discharge from rating curves. An example of this relation is the procedure used by USGS to compute daily discharge from Silver Springs near Ocala from water-level measurements made in a nearby well.

A variety of models relating spring discharge to head difference, water levels measured in a well near the spring, and lake levels were examined to determine which combination of variables results in a predictive model with low prediction error and unbiased pattern of residuals. Charles Tibbals has suggested that use of time lags in water levels might be appropriate to account for factors such as aquifer elasticity and storage (Tibbals written communication May 1, 2003). Use of averages in well water levels and lake levels was also investigated. In developing models, the emphasis was to limit the number of terms in the model as much as possible. That is, terms were not added if only a slight decrease in regression error was noted.

The following types of models for estimating Q were evaluated

1. Single-variable models using well water levels, lake water levels, and head difference as the independent variable

2. Multivariate models using head differences, lake water level, and well water level as independent variables

3. Multivariate models including selected lags of lake and well water levels

4. Multivariate models including means of lake water level and well water level for selected periods

Data used in these analyses were furnished by SJRWMD, and were summarized and presented graphically using Microsoft Excel 2000 worksheets (Blattner, Ulrich, Cook, and Dyck 1999). Regression models were developed using the JMP statistical software package (SAS Institute, Inc, 2002), according to principles described by Afifi and Clark (1996).

The well water-level data used in these models are daily mean values from Floridan aquifer well L-0199, less than one mile from the spring. The lake level data used are daily mean values from the Lake Apopka water-level gage near Oakland.

The spring discharge data are from measurements made within the submerged orifice of Lake Apopka Spring with electromagnetic flow velocity instruments. There have been 31 measurements of discharge within the orifice since May 1971. The earliest measurements (8 measurements) were made between 1971 and 1992 by the U.S. Geological Survey (USGS). Beginning in 1997, 23 measurements have been made by Karst Environmental Services, Inc. (KES).

The measurement techniques used by USGS and KES were substantially different, particularly with respect to the number of velocity-measurement stations within the measurement cross-section: USGS used 11 or fewer stations (generally 5 or less) and KES used 22 to 52 stations (generally more than 30). Other differences included depth of the measuring cross-section: USGS measurements were made at a depth of about 45 ft below the lake surface, and KES measurements were slightly deeper, at about 51-54 ft below the lake surface. The USGS measurements were primarily a pioneering effort directed towards reconnaissance and development of an accurate measurement technique. Therefore, they were not consistent in technique from measurement to measurement.

The USGS measurements ranged from 28.4 ft^3/s to 70.4 ft^3/s, with a mean of 48.2 ft^3/s. The KES measurements ranged from 21.0 ft^3/s to 36.5 ft^3/s, with a mean of 27.6 ft^3/s. Although the two sets of measurements represent different time periods, at least some of the differences in magnitudes of measured discharge are probably the result of the differences in measurement technique, chiefly the difference in number of velocity-measurement stations. The KES measurement data show that there is considerable variation in velocity within the measurement section: during the March 19, 2003, measurement, velocities ranged from more than 0.8 ft/s near the right side of the section to less than 0.2 ft/s near the left side (Figure1). Thus, the KES discharge determinations are probably more accurate than those made by USGS, because of the relatively large number of stations used in the measurements.

A plot of measured discharge as a function of head difference indicates a difference in the USGS and KES data for many measurements (Figure 2). Four of the 8 measurements plot considerably above the trend line established using the KES data, and only 2 measurements are close to the KES trend line. Because of the differences in the measuring techniques, and because the KES data and the USGS data seem to define different trend lines with respect to head, only the KES data are used in the subsequent analyses.

Figure 1. Velocity distribution in the measuring section
(Illustration is from the KES report "Results of Discharge Measurements of Apopka Spring, Lake County, Florida; March 19, 2003)

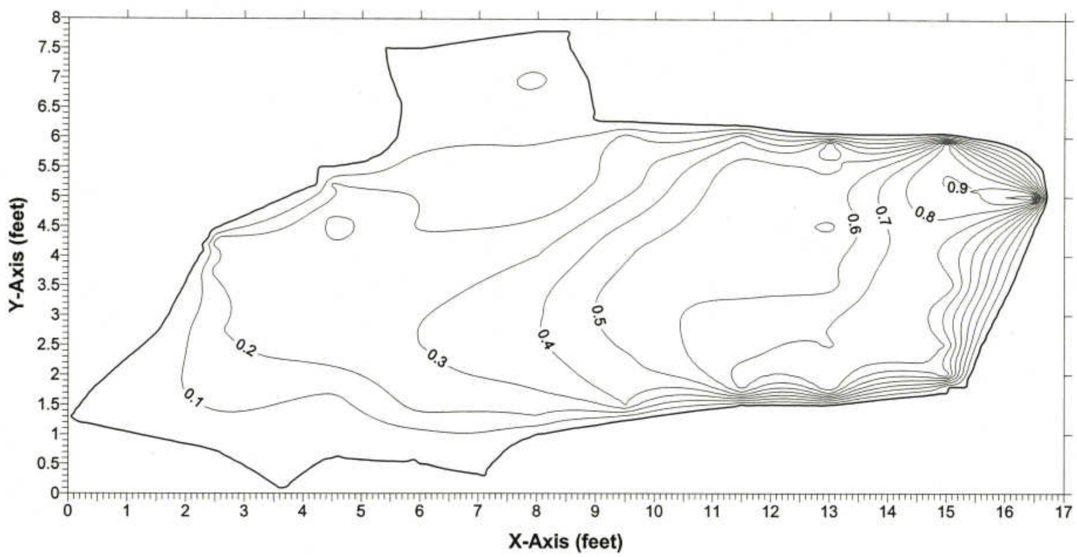
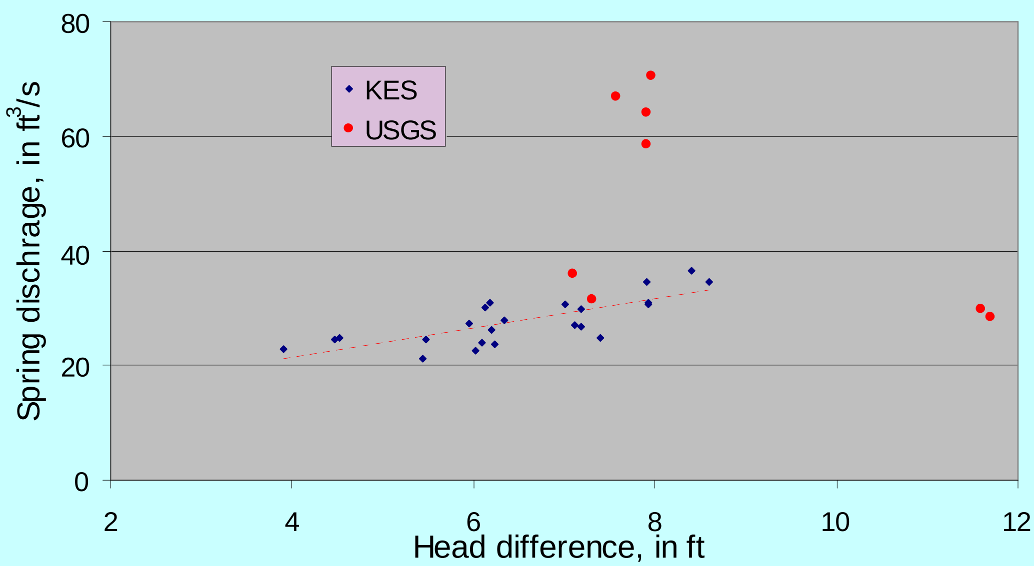


Figure 2. Relation between spring discharge and head difference.
(Head difference is the difference between lake level and water level in well L-0199. Both USGS and KES measurements are plotted. The trend line (----) is for KES data only.).



Results and discussion

Single-variable models

Single-variable models were of the form:

$$Q_i = A + B[X_i],$$

where Q_i is the spring discharge, X_i is one of several independent variables related to ground or lake water levels, and A and B are determined by least-squares regression. Lagged and average water levels were considered, as well as water levels on the same day as the measured discharge. In all, a total of six single-variable models were evaluated, each considering a selection of lag or average periods. For example, Q was evaluated for lags in lake or well water level ranging from 0 (no lag) to 180 days. Models using average water level for selected periods ranging from 0 to 180 days were also evaluated.

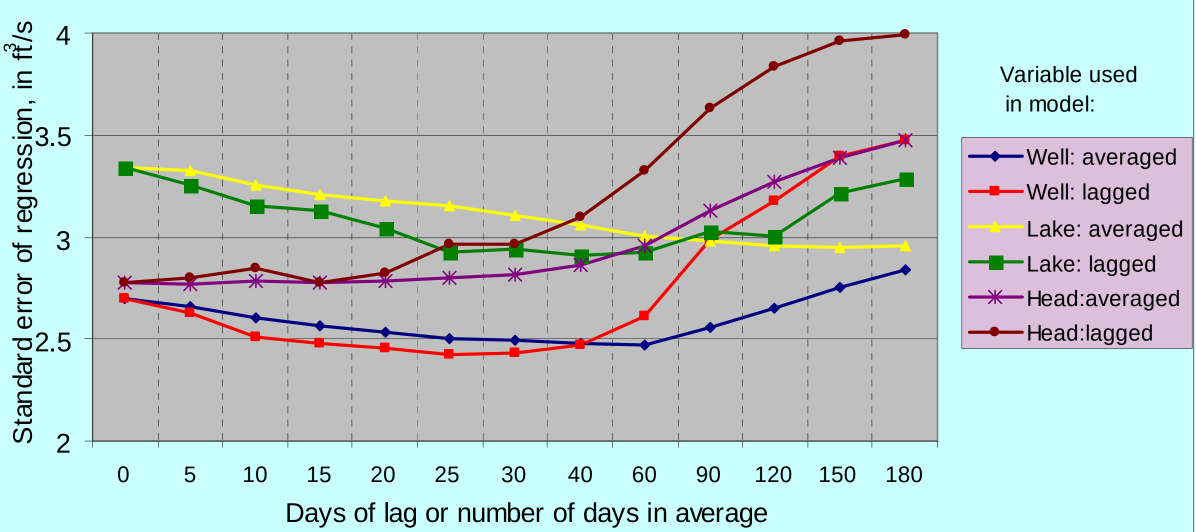
The summary of the standard errors of the regressions (Figure 3) indicates that the lowest errors are provided by using lagged well water levels (red line in Figure 3) as the independent variable. The lowest error occurs with a lag of 25 days and results in the following relation:

$$Q_i = 1.428[W_{i-25}] - 75.136, \qquad \text{(eq. 1)}$$

where Q_i is the spring discharge on day “i” (ft^3/s), and W_{i-25} is the well water level 25 days prior to the discharge measurement. The R^2 (coefficient of determination) for this relation is 0.67, indicating that the variation in W_{i-25} explains 67 percent of the variation in measured discharge. The standard error of regression is 2.42 ft^3/s.

Figure 3. Regression errors for six different single-variable models

($Q = f(W_i)$, $Q = f(L_i)$, and $Q = f(H_i)$, where Q is spring discharge, W is well water level, L is lake water, H is head difference, and "$_i$" is the number of days in the average or the lag interval



<u>Multivariate models using head differences</u>

The form of the models using water levels and head differences is

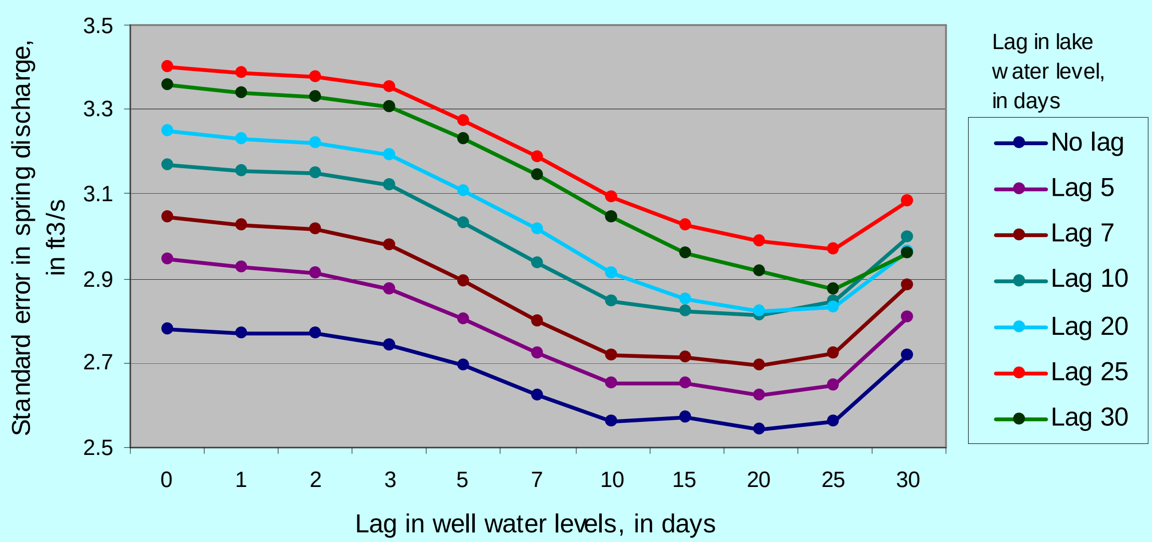
$$Q_{(i)} = A + B\,[W_{(i-n)} - L_{(i-m)}] \qquad \text{(eq. 2)}$$

where Q_i is the discharge of day "i", $W_{(i-n)}$ is the ground-water level n days before day i, $L_{(I-m)}$ is the lake water level m days before day i, and A and B are constants determined by least-squares regression.

A set of regression analyses was completed for the following values of n and m: 0,1,2,3,5,7,10,15,20,25,and 30 days. Thus a total of 121 relations were evaluated, each with a different number of days used to lag lake and well water values.

The results of the regression analyses are summarized by plotting the standard errors of the regression relations for selected lags (Figure 4). The principal conclusions that can be drawn from this plot are that using lags in lake water level do not result in lower predictive errors for any lag in well water level, and that the lowest errors result from lags in well water levels in the 10 to 25 day range. The lowest error among the models evaluated is with a lag of 20 days in well water level and a 0-day lag in lake water level (Figure 4). This model results in a relation with a standard error of regression of 2.54 ft3/s that explains about 63% ($R^2 = 0.63$) of the variation in spring discharge.

Figure 4. Relation between error in estimated spring discharge and lags in lake and well water levels



Subsequent addition of other terms into the model (eq. 2) indicated that inclusion of a lagged lake water level improved the model significantly, resulting in the following model with the lowest regression error:

$$Q_i = -56.719 + 1.825[W_{i-25} - L_i] + 1.013[L_{(i-25)}] \qquad \text{(eq. 3)}$$

Thus, the "best" model evaluated is with a lag of 25 days in lake and well water level, and results in a relation with a standard error of regression of 2.16 ft^3/s that explains about 73 % ($R^2 = 0.73$) of the variation in spring discharge.

The stability and the robustness of the model in eq.3 was tested by selecting 5 random sets of 20 discharge measurements from the 23 measurements used to develop eq. 3. The constants in eq. 3, the R^2 , and regression error were then re-determined by least-squares regression for each of the 5 sets. Comparison of the results for the subsets with those for the full set of measurements indicates that the R^2 and regression errors do not vary markedly among the regressions, and that the constants in the regression have the same sign and similar magnitudes in all regressions (Table 1). This similarity in results among the subsets and the general agreement with the full set indicates that the model given in eq. 3 is probably robust and not greatly dependent on the set of discharge data used.

Table 1. Characteristics of models developed with subsets of the full set of discharge measurements: head difference model

$Q_i = A + B[W_{i-25} - L_i] + C[L_{i-25}]$, where L_i is lake water level, W_i is well water level, and L_{i-25} is lake water level on day (i-25). The subsets each use 20 randomly-selected discharge measurements from the 23-measurement set.

						Regression constants		
Subset	Dates dropped			R^2	Error	A	B	C
1	12-17-97	02-18-98	09-18-01	0.67	2.28	-50.014	1.739	1.019
2	01-17-01	06-19-01	12-19-02	0.73	2.22	-67.005	1.891	1.260
3	11-13-97	08-24-98	01-25-99	0.72	2.31	-51.542	1.912	1.025
4	05-04-99	10-09-99	12-19-02	0.76	2.09	-65.238	1.617	1.266
5	07-18-97	02-18-98	04-29-98	0.70	2.07	-59.410	1.717	1.166
Full set	None dropped			0.73	2.16	-56.719	1.825	1.013

Multivariate models using lagged lake and well water levels

The form of the models using water levels and head differences is

$$Q_i = A + B[L_i] + C[W_i]+D[L_{i-n}] \qquad \text{(eq. 4)}$$

where Q_i is the discharge of day "i", L_i is the lake level on day 'i', W_i is the well water level on day "i", $L_{(i-m)}$ is the lake water level m days before day "i", and A,B, C and D are constants determined by least-squares regression.

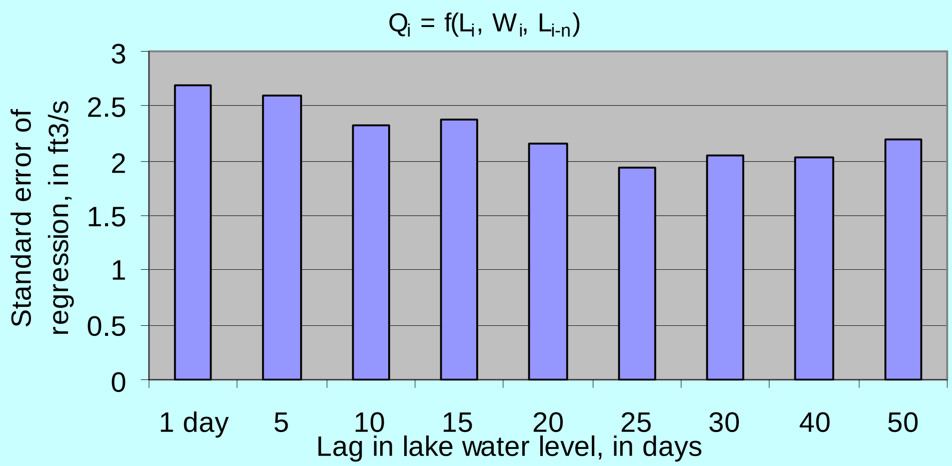
Experimentation with an additional term in eq. 4, a lagged well water level analogous to the lagged lake-level term, indicated that the inclusion of a lagged well-water term added little improvement to the model for any selected lag. Because simpler models are likely to be more robust and less specific to the data used to calibrate them, a lagged well water level term was not included.

A set of regressions was done for the following values of n: 1, 5, 10, 15, 20, 25, 30, 40, and 50 days. The results of the regression analyses are summarized by plotting the standard errors of the regression relations for selected lags (Figure 5). The lowest regression error results from lags of 25 days in lake water levels and the following relation:

$$Q_i = -48.195 - 5.360[L_i] + 1.707[W_i] + 4.650[L_{i-25}] \qquad \text{(eq. 5)}$$

The R^2 for this model is 0.79, and the standard error of regression is 1.94 ft^3/s.

Figure 5. Regression errors for models using lake and well water levels



The stability and the robustness of the model in eq. 5 was tested by selecting 5 random sets of 20 discharge measurements from the 23 measurements used to develop eq. 5. Comparison of the regression results for the subsets with those for the full set of measurements indicates that the R^2 and regression errors do not vary markedly among the regressions, and that the constants in the regression have the same sign and similar magnitudes in all regressions (Table 2). This similarity in results among the subsets and the general agreement with the full set indicates that the model given in eq. 5 is probably robust and not greatly dependent on the set of discharge data used.

Table 2. Characteristics of models developed with subsets of the full set of discharge measurements: lake and well water-level models

$Q_i = A + B[L_i] + C[W_i]+D[L_{i-25}]$, where L_i is lake water level, W_i is well water level, and L_{i-25} is lake water level on day (i-25). The subsets each use 20 randomly-selected discharge measurements from the 23-measurement set.

						Regression constants			
Subset	Dates dropped			R^2	Error	A	B	C	D
1	01-25-99	06-16-99	12-19-02	0.80	2.01	-53.910	-5.760	1.562	5.295
2	09-17-97	03-20-98	01-17-01	0.74	1.95	-38.740	-5.087	1.647	4.296
3	04-29-98	05-04-99	10-09-99	0.79	1.84	-51.829	-6.185	1.777	5.461
4	09-18-01	09-19-02	12-19-02	0.77	2.01	-53.688	-5.621	1.544	5.175
5	02-18-98	12-20-01	06-20-02	0.75	2.02	-43.806	-5.409	1.723	4.615
Full set	None dropped			0.79	1.94	-48.195	-5.360	1.707	4.650

Multivariate models using mean lake and well water levels

The form of the models using water levels and head differences is

$$Q_i = A + B[L_i] + C[W_i] + D[ML_m] \qquad \text{(eq. 6)}$$

where Q_i is spring discharge, L_i is lake level, and W_i is well water level on day "i", ML_m is the mean lake level for the m days preceding day "i", and A, B, C, and D are constants determined by least-squares regression. Thus, this form is the same as in eq. 4 except that the last term represents a mean lake water level rather than a lagged lake water level.

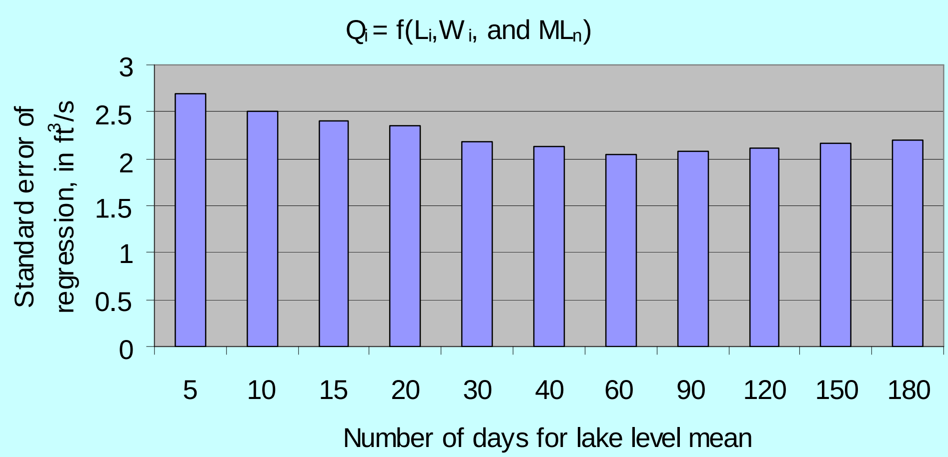
Experimentation with an additional term in eq. 6, a mean well water level analogous to the mean lake-level term, indicated that the inclusion of a mean well-water term added little improvement to the model for any selected averaging period. Because simpler models are likely to be more robust and less specific to the data used to calibrate them, a lagged well water-level term was not included.

A set of regressions was done for the following values of n: 5, 10, 15, 20, 30, 40, 60, 90, 120, 150, and 180 days. The results of the regression analyses are summarized by plotting the standard errors of the regression relations for selected lags (Figure 6). The lowest regression error results from means of 60 days for lake water levels:

$$Q_i = -51.528 - 5.601[L_i] + 1.798[W_i] + 4.840[ML_{60}] \qquad \text{(eq. 7)}$$

The R^2 for this model is 0.76, and the standard error of regression is 2.05 ft^3/s.

Figure 6. Regression errors for models using mean lake levels



Regression analyses were also done in which the 23 observations were not weighted equally. Rather, each observation was given a weight that was inversely proportional to the standard deviation of the lake water levels in the 60-day means. This weighting procedure was done to determine if a more uniform set of residuals would result. The pattern of residuals using the weighted regression was nearly identical with the pattern for the regression using equal weight for each observation.

Comparison of the regression results for 5 random subsets with those for the full set of measurements indicates that the R^2 and regression errors do not vary markedly among the regressions, and that the constants in the regression have the same sign and similar magnitudes in all regressions (Table 3). This similarity in results among the subsets and the general agreement with the full set indicates that the model given in eq. 7 is probably robust and not greatly dependent on the set of discharge data used.

Table 3. Characteristics of models developed with subsets of the full set of discharge measurements: mean lake level models

$Q_i = A + B[L_i] + C[W_i]+D[ML_{60}]$, where L_i is lake water level, W_i is well water level, and ML_{60} is average lake water level for 60 days preceding day (i). The subsets each use 20 randomly-selected discharge measurements from the 23-measurement set.

						Regression constants			
Subset	Dates dropped			R^2	Error	A	B	C	D
1	03-19-03	01-17-01	12-19-02	0.80	1.94	-54.706	-5.693	1.825	4.952
2	11-13-97	04-25-98	09-17-27	0.78	2.06	-39.649	-6.824	2.151	5.496
3	02-18-98	08-24-98	03-19-03	0.77	1.96	-48.360	-5.272	1.916	4.335
4	07-18-97	10-09-99	06-20-02	0.82	1.78	-72.940	-4.199	1.535	4.055
5	11-13-97	12-17-97	09-18-01	0.73	2.19	-42.481	-5.651	1.894	4.646
Full set	None dropped			0.76	2.05	-51.528	-5.601	1.798	4.840

Comparison of fit among the multivariate models

Hydrographs of predicted and measured discharge were plotted for each of the 3 multivariate models. Predicted discharge is plotted for models calibrated with each of the 5 random subsets of measurements, as well as for models calibrated with the full set of measurements. These plots indicate that the random subsets of data resulted in models that closely followed the pattern of discharge predicted by the full set of measurements, with differences between any one of the 5 subsets and the full model being generally less than 1 ft^3/s (Figures 7-9). The least variation among the sets of models was for the head-difference models (Figure 7) , and the greatest variation among the models was for the lagged water-level models (Figure 8).

A difference among the discharges predicted by the 3 models is particularly noticeable for a period of several weeks beginning January 18, 2001. On this day there is a relatively large increase in the discharge predicted by the lagged water-level model (eq. 5) and the mean water-level model (eq. 7). This increase is relatively small for the head-difference model (eq. 3). The increased in predicted discharge is due to an abrupt change in lake level (and thus head difference) that occurred on that date (Figure 10). No measurements were made during the period of greatest predicted increase, however, so the accuracy of the predictions during this period of rapid head change is not known.

Figure 7. Discharge calculated from head-difference models, June 1997 - March 2003
Blue line: Model developed using all 23 discharge measurements (eq. 3); Red lines: Five models developed using random subsets of 20 discharge measurements; Green dots: discharge measurements

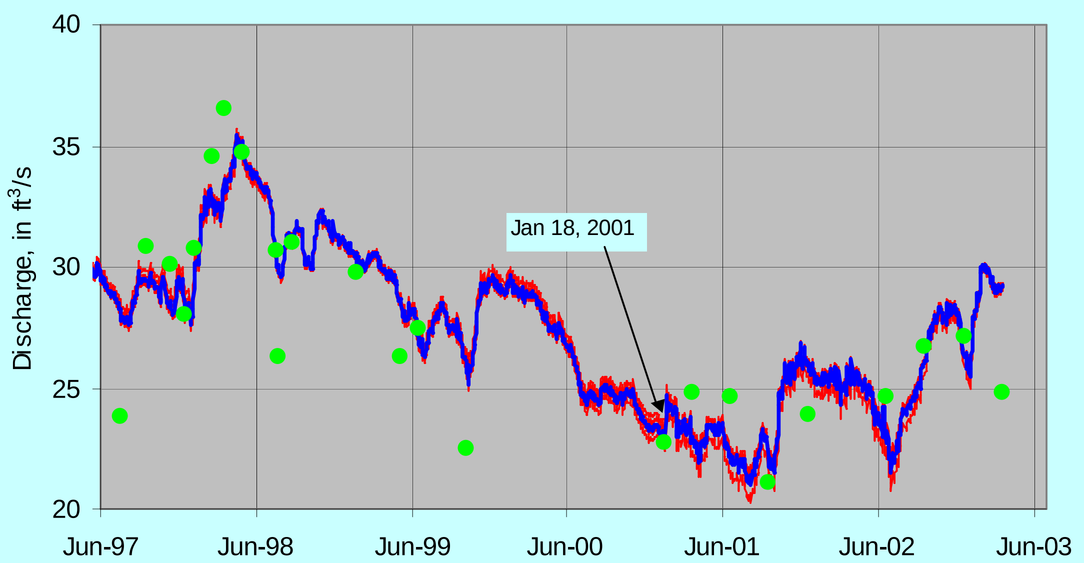


Figure 8. Discharge calculated from lagged lake and well water level, June 1997 - March 2003
Blue line: Model developed using all 23 discharge measurements (eq. 5); Red lines: Five models developed using random subsets of 20 discharge measurements; Green dots: discharge measurements

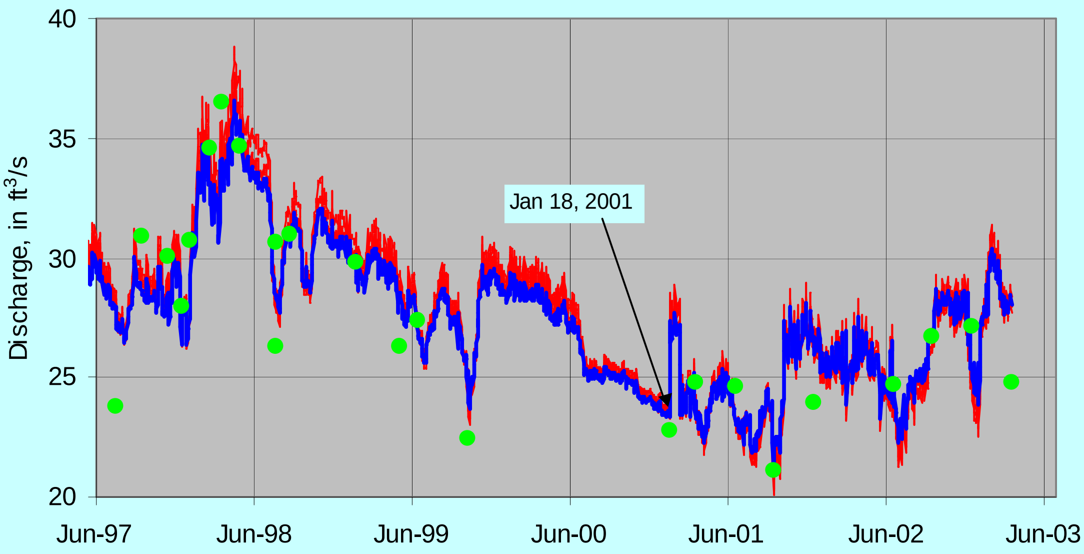


Figure 9. Discharge calculated from mean lake and well water level, June 1997 - March 2003
Blue line: Model developed using all 23 discharge measurements (eq. 7); Red lines: Five models developed using random subsets of 20 discharge measurements; Green dots: discharge measurements

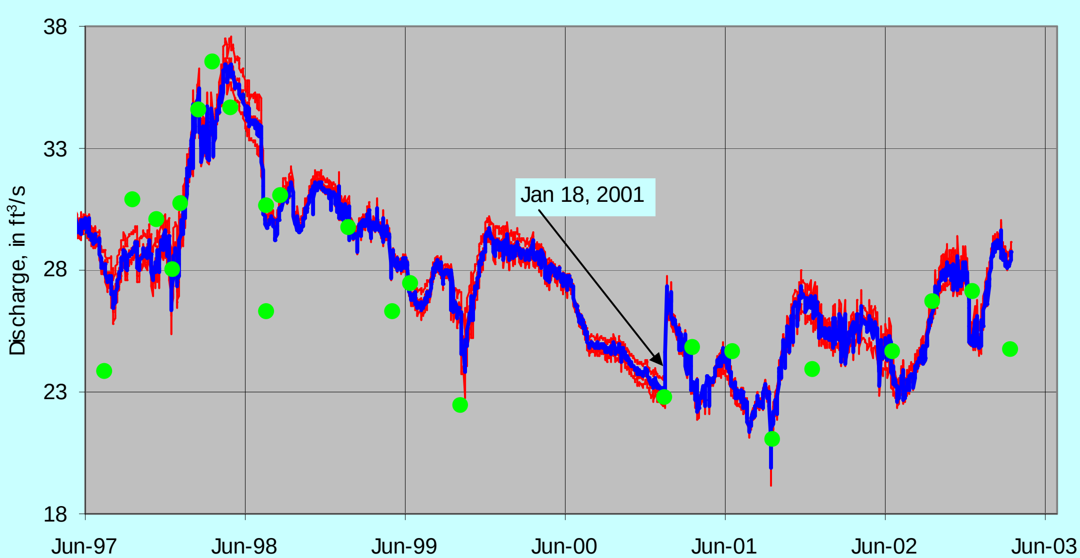
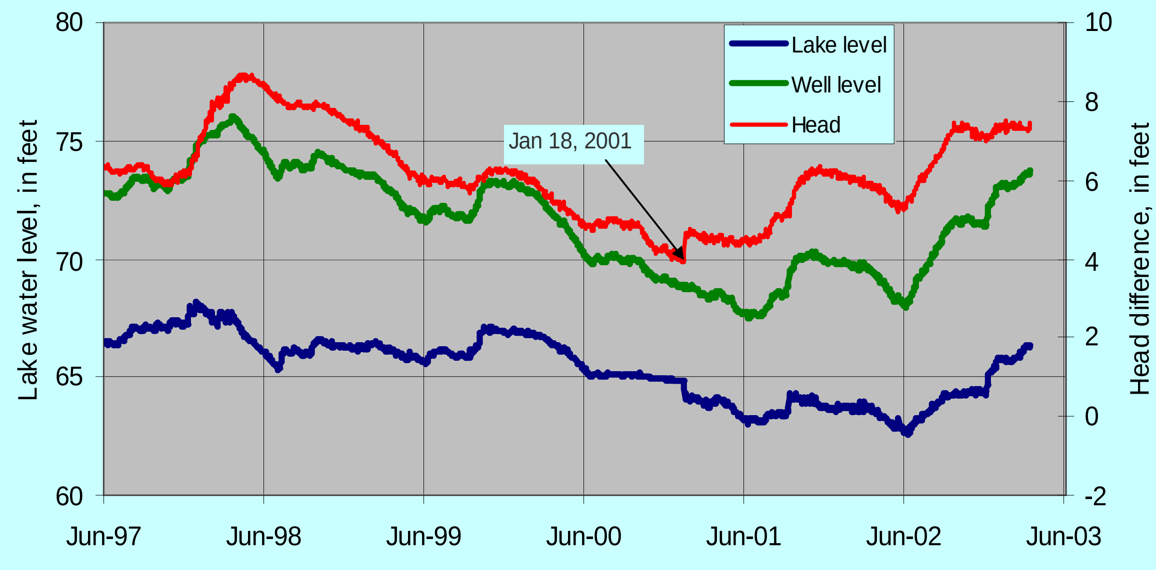


Figure 10. Lake water level, well water level, and head difference, June 1997 - March 2003



Plots of the relation between predicted and measured discharge indicate that the distribution of points around the trend line appears generally to indicate a good fit throughout the range of discharge for all models (Figures 11-13).

Figure 11. Relation of predicted to measured discharge from head-difference model (eq. 3)

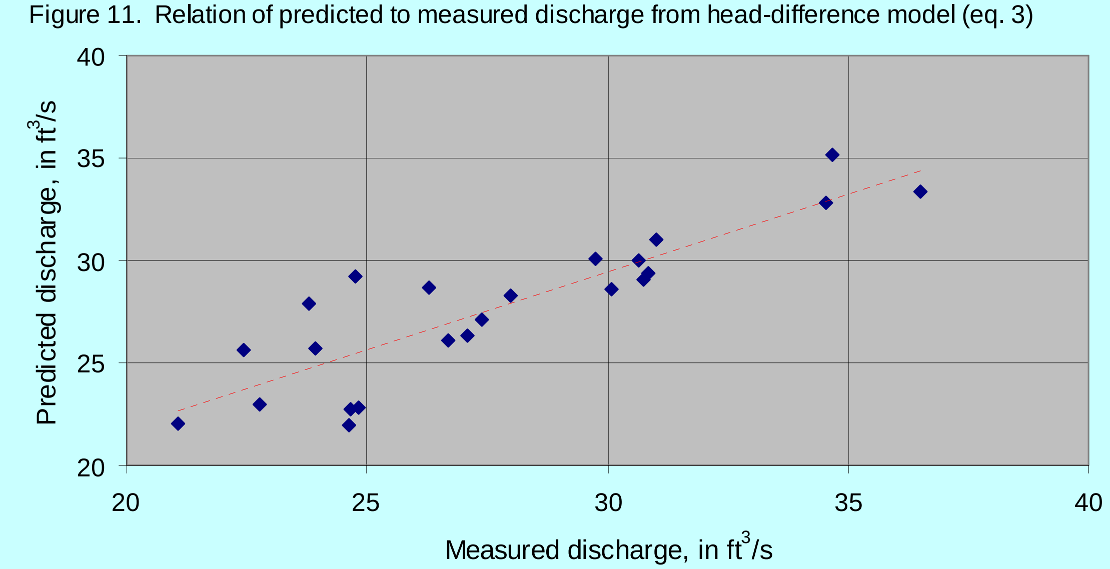


Figure 12. Relation of predicted to measured discharge from lagged water-level model (eq. 5)

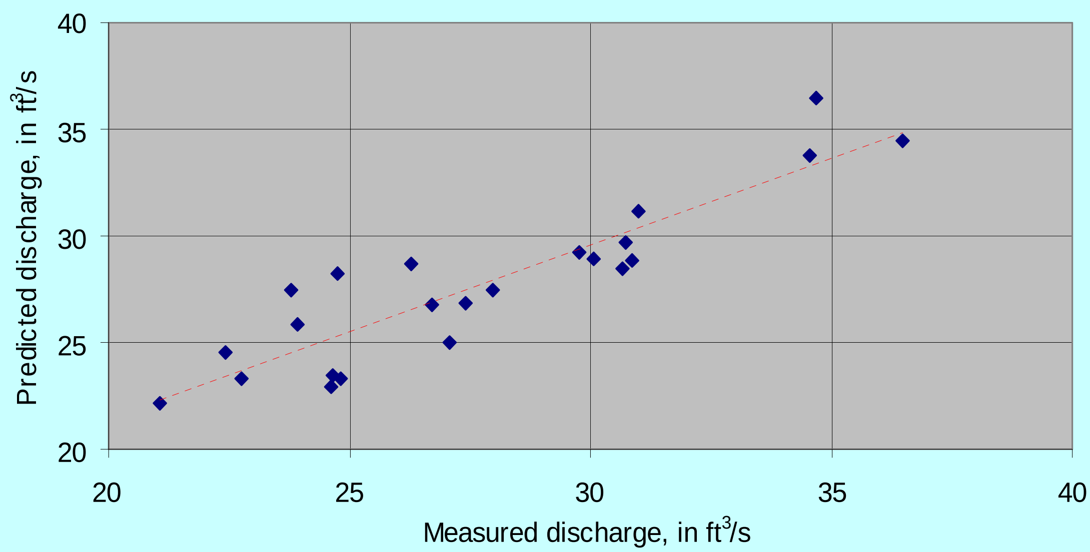
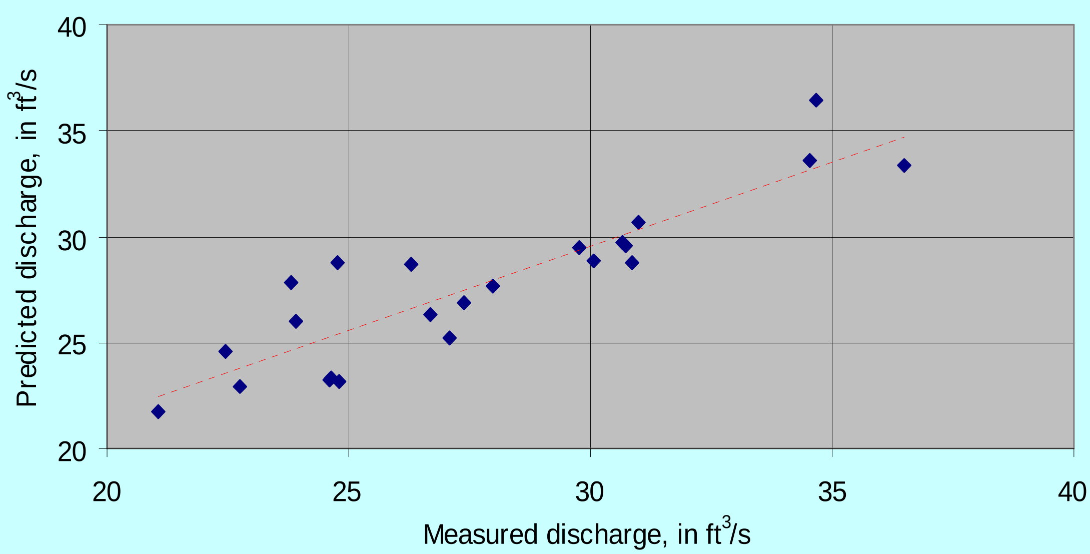


Figure 13. Relation of predicted to measured discharge from mean water-level model (eq. 7)



The pattern of residual variation indicates that there is no apparent relation between residual magnitudes and predicted discharges for any of the 3 models (Figures 14-16). The residual plots indicate the accuracy of the models in predicting discharge, and indicate that discharge prediction errors will probably be less than 5 ft^3/s, and often will be within 2 ft^3/s using any of the 3 models.

Figure 14. Relation of residuals to predicted discharge from head-difference model (eq. 3)

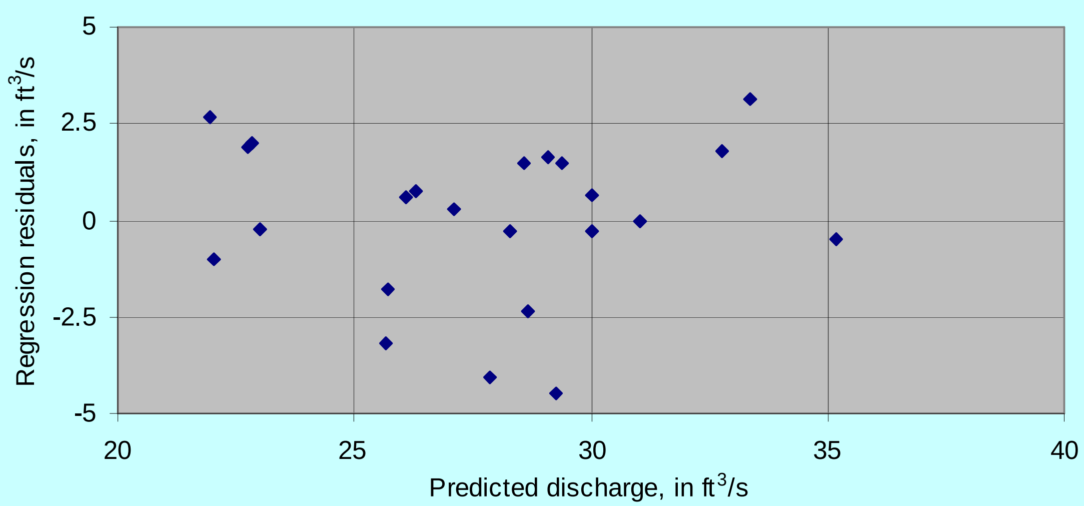


Figure 15. Relation of residuals to predicted discharge from lagged water level model (eq. 5)

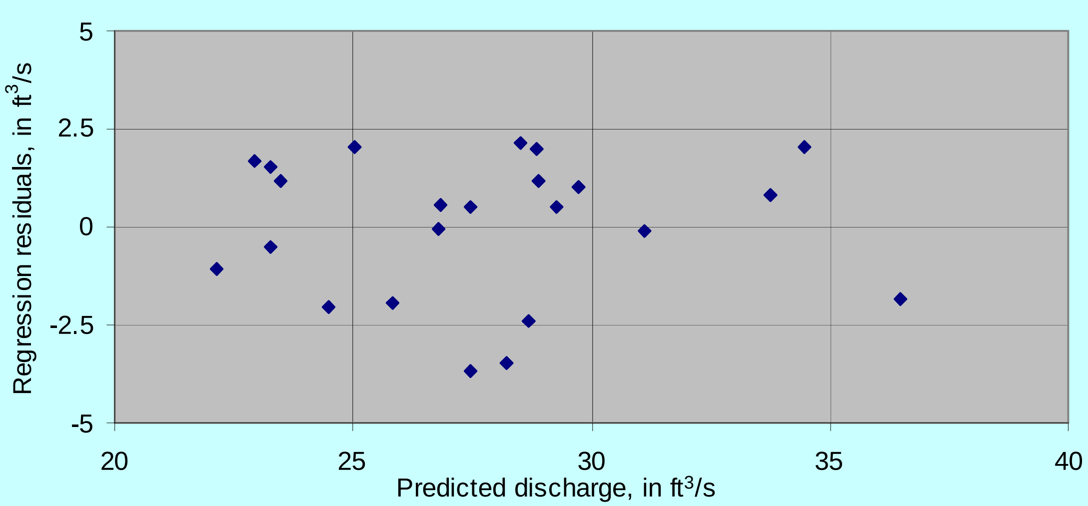
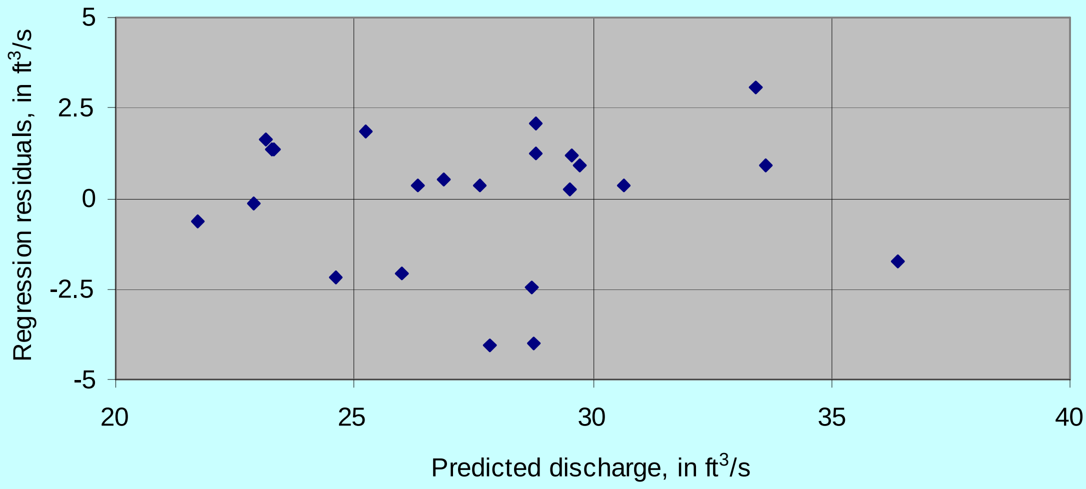


Figure 16. Relation of residuals to predicted discharge from mean water level model (eq. 7)



Recommendations for model usage

The 3 multivariate models (eq. 3, 5, and 7) discussed above all appear to be capable of giving estimates of discharge from Apopka Spring that will probably be accurate within 2 or 3 ft^3/s most of the time. The most precise model is the lagged water-level model (eq. 5), with a standard error of regression of 1.94 ft^3/s. The least precise model is the head-difference model (eq. 3), with a standard error of regression of 2.16 ft^3/s. The lagged water-level model (eq. 5) may be somewhat less robust with respect to data used to calibrate it, as indicated by a greater scatter in predicted discharges using models calibrated with random subsets of the measurements (Figure 8).

It may be possible to determine which model is the most appropriate in the future after more discharge measurements have been made. In the meantime, it is suggested that an average of discharges predicted by all three of the multivariate models (eq. 3, 5, and 7) will furnish the best estimate of spring discharge.

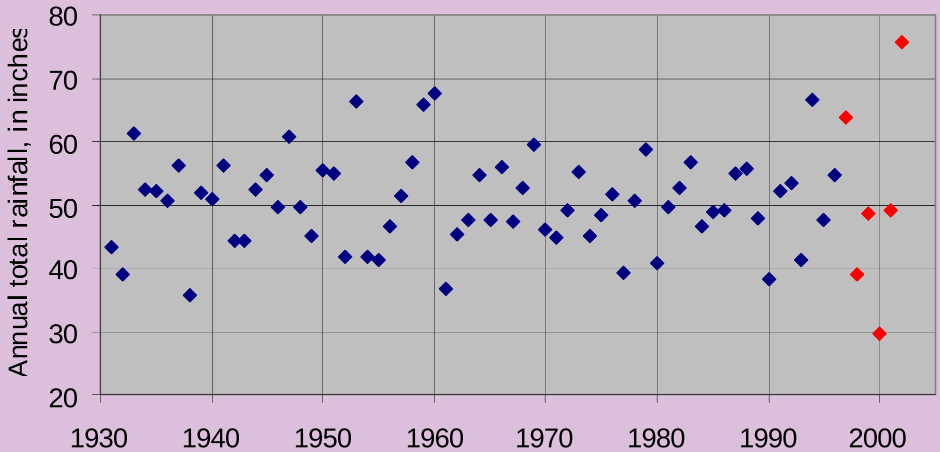
The range in discharges that were measured should be considered in assessing the accuracy of these models. The relatively good fit of the models at measured discharges greater than 31 ft^3/s (Figures 11-13) may be an artifact of the small number of measurements in that range (3 measurements). Additional measurements may indicate scatter in the upper part of the ratings is as great as the scatter that is observed at measured discharges less than 29 ft^3/s. Therefore, additional high-end discharge measurements may result in models with prediction accuracies that are somewhat less accurate than indicated by the models described here.

Hydrologic conditions during the period used for model calibration

The discharge data used in this model calibration were collected during the period July 1997 to March 2003. Annual rainfall totals for NOAA rainfall stations at Orlando and at Clermont were averaged and examined to determine if rainfall during the period of data collection was representative of the long-term range in rainfall conditions for the area. These data (Figures 17) indicate that the most extreme annual rainfall totals since 1931 occurred during the 1997-2002 period. The highest annual total (75.8 in.) occurred in 2002, and the lowest annual total (29.7 in.) occurred in 2000. The mean for the 1997-2002 period was 51.0 in. and the mean for the 1931-1996 period was 50.5 in. Therefore, the 1997-2002 period of data collection should be representative of long-term rainfall conditions, both in terms of mean rainfall and high and low annual totals.

Figure 17. Annual rainfall totals for the Lake Apopka area

(Annual totals are the average for NOAA stations in Orlando and Clermont)



Discussion of measurement techniques

Details of a spring discharge measurement by KES, Inc. in July 1998, are given in Table 1. Velocities are in ft/s, area is in ft^2, and discharge is in ft^3/s. Low and high velocities refer to lowest and highest indicated velocities during a one-minute period, and the average velocity is the average for the one-minute period. This measurement is typical of all measurements made by KES, except that more measurement stations (up to 52 stations) were used in measurements made in 2002 and 2003. A Marsh McBirney electronic flow meter was used to make the measurements at points along a grid installed within the spring orifice using aluminum rods. The installation of the grid provided an accurate means of determining section areas and location of measuring stations. The number and positioning of measuring stations appears to be adequate due to the fact that no location accounted for more than about 7 percent of the total discharge.

T able 4. Details of Apopka Spring measurement made July 21, 1998
(Measurement was made by KES, Inc.)

Station	Low velocity	High velocity	Average velocity	Area	Discharge	% of total discharge
1	0.38	0.61	0.50	2.18	1.08	3.52
2	0.61	0.82	0.72	2.00	1.43	4.66
3	0.82	1.01	0.92	2.47	2.26	7.36
4	0.87	1.21	1.04	2.13	2.21	7.20
5	0.37	0.52	0.45	2.63	1.17	3.81
6	0.58	0.75	0.67	1.75	1.16	3.79
7	0.76	1.02	0.89	1.75	1.56	5.08
8	0.78	1.10	0.94	1.75	1.65	5.36
9	0.47	0.64	0.56	2.63	1.46	4.75
10	0.50	0.84	0.67	1.75	1.17	3.82
11	0.49	0.69	0.59	1.75	1.03	3.36
12	0.45	0.93	0.69	2.06	1.42	4.63
13	0.43	0.61	0.52	2.66	1.38	4.51
14	0.50	0.77	0.64	1.75	1.11	3.62
15	0.45	0.69	0.57	1.75	1.00	3.25
16	0.22	0.51	0.37	2.28	0.83	2.71
17	0.29	0.47	0.38	2.97	1.13	3.68
18	0.40	0.57	0.49	1.75	0.85	2.77
19	0.38	0.55	0.47	1.75	0.81	2.65
20	0.20	0.52	0.36	1.75	0.63	2.05
21	0.07	0.29	0.18	1.88	0.34	1.10
22	0.02	0.02	0.02	1.97	0.04	0.13
23	0.14	0.30	0.22	2.63	0.58	1.88
24	0.23	0.37	0.30	1.75	0.53	1.71
25	0.27	0.47	0.37	1.75	0.65	2.11
26	0.29	0.41	0.35	1.75	0.61	2.00
27	0.13	0.27	0.20	1.66	0.33	1.08
28	-0.09	-0.06	-0.08	2.50	-0.19	-0.61
29	0.01	0.16	0.09	2.80	0.24	0.78
30	0.03	0.32	0.18	1.75	0.31	1.00
31	0.13	0.28	0.21	1.75	0.36	1.17
32	0.14	0.37	0.26	1.97	0.50	1.64
33	0.07	0.21	0.14	4.13	0.58	1.88
34	0.04	0.19	0.12	1.97	0.23	0.74
35	0.05	0.25	0.15	1.69	0.25	0.83
				SUM:	30.69	100.00

The measurement technique used by KES appears to be capable of furnishing highly accurate measurements of spring discharge. The only recommendation that might be suggested regarding these measurements is that the variation in velocity in the measuring section should be studied to see if improvements to measurement accuracy are possible. Two types of velocity variation are likely. One type of variation is short-period (on the order of seconds or minutes) velocity fluctuations associated with turbulence. Another type of variation has a longer period, perhaps on the order of hours, and is associated with wind-induced variation in lake water level (i.e., seiche). Either of these two types of velocity variation could affect measurement accuracy.

The existence of short-period velocity variation seems likely because of the large range in velocities observed at most stations during the one-minute measuring intervals. For example, velocities ranged from 0.87 to 1.21 ft/s at station 4 during the July 1998, measurement. If the measuring interval is relatively long in comparison with the frequency of the velocity change, then the measurement is probably an accurate representation of the average flow. Otherwise, a longer velocity-measuring interval may be necessary for an accurate discharge measurement.

Long-period cyclic variation with a cycle-time longer than the time required to make the measurement could lead to errors, especially if the measurement was started during a peak or trough of the cycle. For example, if spring discharge cycled from 25 to 30 ft^3/s over a 2 or 3 hour period, the mean discharge for the day would be 27.5 ft^3/s (assuming no longer-term changes are occurring), but a measurement made during the peak of the cycle might be closer to 30 ft^3/s.

It is recommended that a continuous record of velocity be obtained at a selected station for a period of several hours, beginning before a discharge measurement and ending some time after the measurement has been completed. This continuous record will elucidate the importance of both short-period and long-term velocity changes, and will provide information necessary for developing procedures to enhance the accuracy of the measurements.

It is recommended that more discharge measurements be made, if possible, during high-discharge periods. The highest discharge measured is 36.5 ft^3/s, but only 3 measurements greater than 31 ft^3/s have been made. More measurements at high discharge might better define the high end of the discharge rating and might provide a more realistic assessment of accuracy of models used for discharge prediction.

Summary and conclusions

The major findings and conclusions from this investigation of the relation between discharge from Apopka Spring and lake and ground-water levels are:

(1) Measurements of discharge from Apopka Spring have been made by USGS (8 measurements from 1971 to 1992) and KES (23 measurements from 1997 to 2003). The measurements made by KES are probably the most accurate because of the greater number of velocity-measurement stations used. Thus, only the KES measurements were used in this analysis.

(2) The best single-variable model is:

$$Q_i = 1.428[W_{i-25}] – 75.136, \qquad \text{(eq. 1)}$$

where Q_i is the spring discharge on day “i” (ft^3/s), and W_{i-25} is the well water level lagged 25 days. The R^2 for this model is 0.67 and the standard error of regression is 2.42 ft^3/s.

(3) The best model as a function of water levels and head differences is:

$$Q_i = -56.719 + 1.825[W_{i-25} - L_i] + 1.013[L_{(i-25)}] \qquad \text{(eq. 3)}$$

where W_{i-25} is the well water level lagged 25 days, L_i is lake water level, and L_{i-25} is the lake water level lagged 25 days. The R^2 for this model is 0.73 and the standard error of regression is 2.16 ft^3/s.

(4) The best model as a function of lagged water levels is:

$$Q_i = -48.195 - 5.360[L_i] + 1.707[W_i] + 4.650[L_{i-25}] \qquad \text{(eq. 5)}$$

The R^2 for this model is 0.79, and the standard error of regression is 1.94 ft^3/s.

(5) The best model as a function of mean water levels is:

$$Q_i = -51.528 - 5.601[L_i] + 1.798[W_i] + 4.840[ML_{60}] \qquad \text{(eq. 7)}$$

The R^2 for this model is 0.76, and the standard error of regression is 2.05 ft^3/s.

(6) The magnitude of the residuals indicate the accuracy of the models in predicting discharge, and indicate that discharge prediction errors will probably be less than 5 ft^3/s, and often will be within 2 ft^3/s using any of the 3 multivariate models. These residuals result from the combination of error in the discharge measurement and error in fit of the predictive relation to measured discharge. Additional discharge measurements during high discharge conditions may indicate that model accuracies are somewhat less accurate than indicated by the present models.

(7) The KES procedure appears to be capable of furnishing highly accurate measurements of spring discharge.

(8) KES measurements indicate that flow velocities at most stations vary substantially during the one-minute measurement intervals. This short-period (seconds or minutes) variation, together with possible long-period (hours) variations, is likely a source of measurement error.

(9) A continuous record of velocity should be obtained at a selected velocity-measurement station for a period of several hours spanning the period before, during, and after a discharge measurement . This record will help to elucidate the effects of short and long period variations in flow velocity and will provide information necessary for developing procedures to enhance the accuracy of the measurements.

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