UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

WATER BALANCE FOR
CRATER LAKE, OREGON

OPEN-FILE REPORT 92-505

1992

U. S. DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Water balance for Crater Lake, Oregon

by

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OPEN-FILE REPORT 92-505

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1992

ABSTRACT

A water balance for Crater Lake, Oregon, is calculated using measured lake levels and precipitation data measured at Park Headquarters and at a gage on the North Rim. Total water supply to the lake from precipitation and inflow from the crater walls is found to be 224 cm/y over the area of the lake. The ratio between water supply to the lake and precipitation at Park Headquarters is calculated as 1.325. Using leakage determined by Phillips (1968) and Redmond (1990), evaporation from the lake is approximately 85 cm/y. Calculations show that water balances with precipitation data only from Park Headquarters are unable to accurately define the water-level variation, whereas the addition of yearly precipitation data from the North Rim reduces the average absolute deviation between calculated and modeled water levels by one half.

Daily precipitation and water-level data are modeled assuming that precipitation is stored on the rim as snow during fall and winter and released uniformly during the spring and early summer. Daily data do not accurately define the water balance, but they suggest that direct precipitation on the lake is about 10 % higher than that measured at Park Headquarters and that about 17 % of the water supply is from inflow from the rim.

INTRODUCTION

The water balance of Crater Lake, Oregon, is fundamental to understanding the fluxes of dissolved constituents in the lake and to calculating the amounts of dissolved constituents added by the inflow of thermal water (e.g. Nathenson, 1990; Collier and others, 1991). Phillips (1968), Simpson (1970), and Redmond (1990) have carried out water balances using differing methodologies. Phillips and Simpson obtained similar results, but Redmond obtained a substantially higher value for water supply to the lake than the earlier investigators. The purpose of this paper is to perform another analysis to determine if there are best values for the water balance.

Crater Lake offers unique opportunities for the analysis of water balance because of its relatively simple hydrology. The lake receives most of its precipitation directly, because it comprises 78 % of its drainage area. The lake has no surface outlet, and water is lost by evaporation and subsurface leakage. The lake level has been recorded daily to high precision (0.01 feet = 0.3 cm) since 1961. Precipitation has been measured daily at Park Headquarters (Figure 1) since 1931, except for interruptions during World War II (Redmond, 1990). Since 1964, precipitation has also been measured yearly on July 1 with a storage gage on the North Rim of the lake (Figure 1). Phillips's (1968) analysis necessarily focused on the early data, some of which are of uncertain quality, and he only had available two years of daily lake-level data. Redmond (1990) and this study have 27 years of data through 1988 for yearly balances and 22 years of complete daily data for water level and precipitation.

In the next section, the water balance is discussed based on yearly precipitation and lake-level data. It is shown that precipitation data at Park Headquarters are inadequate to accurately calculate the lake level variation based on the water balance. Using precipitation data from the gage on the North Rim in combination with that from Park Headquarters, it is shown that lake level variation can be more accurately modeled. In the following section, daily data are analyzed. Although there is a great quantity of daily data, it is shown that they are inadequate to accurately define the water balance. Given the water balance from yearly data, the daily data are used to calculate the ratio of precipitation on the lake to that measured at Park Headquarters.

WATER BALANCE USING YEARLY DATA

The yearly water balance is comprised of 1) water supply from precipitation q_p and inflow from the crater walls q_i and 2) water loss from leakage q_o and evaporation q_e. The change in volume of the lake is the change in lake level Δ for one year times the area of the lake A and may be expressed as:

$$A\,\Delta = q_p + q_i - q_o - q_e \,. \qquad (1)$$

Dividing by the lake area, each term may be expressed as a volume per unit area d, and the water balance may be written as:

$$\Delta = d_p + d_i - d_o - d_e \,. \qquad (2)$$

The inflow from the crater walls mostly flows in the spring and early summer when snow accumulated in the fall and winter melts. Over the period of a year, it seems reasonable to assume that the inflow should be proportional to the precipitation p measured at Park Headquarters. The water supply from precipitation should also be proportional to the precipitation at Park Headquarters, and the total water supply can expressed as a function of precipitation as:

$$d_p + d_i = ß\, p. \qquad (3)$$

Although Phillips (1968) found a suggestive relationship between leakage and lake level, Redmond (1990) could not verify the relation. As a first approximation, the leakage is assumed proportional to the long-term average precipitation p_o that keeps the lake level unchanged. Evaporation is likely to vary from year to year depending on temperature, wind, and humidity, but evaporation will also be assumed to be proportional to the long-term average precipitation p_o. If evaporation is a small fraction of total water loss, the yearly variation will have a small effect on the water balance. Over a period of many years when the average change in water level Δ is zero, the water supply will be ß p_o and so will the water loss. Thus equation (2) may be rewritten as:

$$\Delta = ß\, p - ß\, p_o. \qquad (4)$$

Equation (4) may be rearranged to:

$$p = p_o + \Delta/ß. \qquad (5)$$

Redmond (1990) used least-squares correlation based on equation (4) with precipitation as the independent variable and ß p_o as a single parameter and obtained the results given in Table 1 along with those of Phillips (1968) and Simpson (1970). For the three studies, the long-term average water supply ranges from 208 to 247 cm/y and the coefficient ß from 1.2 to 1.457. The range constitutes about 20 % for both quantities. Although not an unreasonable range for a water supply calculation, the range results in nearly a factor of two range in evaporation derived by differencing leakage from long-term water supply (Table 1).

There are three questions that are useful in understanding the differences between the three studies: 1) What is the effect of water year on the results? 2) Is precipitation the appropriate independent variable for the least squares correlation? 3) Are the differences between the results statistically significant? Each of these questions can be addressed by analysis of the data set for the 1962-1988 time period. Figure 2 shows the average daily precipitation for all years with complete data. The average water level was calculated by setting the water level at zero on September 30 and thus is at an arbitrary datum. Phillips (1968), Simpson (1970) and Redmond (1990) used Oct 1 - Sep 30 as their water year.* The storage precipitation gage is measured on July 1 for a water year of July 1 to June 30. Because these data are needed to improve the measure of precipitation, the significance of of changing the water year on the water balance must be determined. Only a small amount of precipitation occurs between July 1 and Sep 30 (Figure 2), and there should be little difference in precipitation for water years starting on July 1 or October 1. The water level on July 1 is nearly the highest level for the year while that on Oct 1 is nearly the lowest level for the year (Figure 2). Thus the July-1 start date tends to emphasize the level after most of the precipitation for the year has taken place, and the October-1 start date emphasizes the level after the level has dropped from the summer evaporation period. Most of the snow melt is completed by July 1 according to the data in Figure 4 of Redmond (1990), and the major inflow should be about the same for the two starting dates.

Water balances performed for the two starting dates show that the difference is not statistically significant. Figure 3 shows the yearly precipitation (top) and water-level data (bottom) for the Oct 1 - Sep 30 water year for the period 1961-1988 used by Redmond (1990). Although there are quite large excursions of water level during this period, there is no systematic evolution of water level. Figure 4 reproduces the correlation of Redmond (1990). Years with high precipitation appear to have an especially variable relationship between change in water level and precipitation. Results for the correlation in Figure 4 as well as for the July 1 - June 30 water year are given in Table 2. The slope ß that I calculate for the same data set used by Redmond (1990) is slightly different (Tables 1 and 2). The long-term average precipitation that keeps the lake level unchanged is identical for the two starting dates for water years. The differences for the parameter values are not statistically significant (Table 2) although the range is similar to that between Phillips and Redmond's values (Table 1). Thus it appears that these data without some additional constraint cannot distinguish between these results.

Even though the values for ß and ß p_o are different for the two starting dates for water years, the value of p_o is identical. This suggests that nearly all of the uncertainty is in ß, and one should consider using equation (5) as a basis for correlation. Another reason for using water-level change as the independent variable is that normal least squares minimizes the difference between the y-variable and the least-squares line in order to establish the best slope and intercept. Although precipitation is the source of water-level change, the variable with uncertainty is precipitation not water level. Water levels are known to 0.3 cm which is generally a small fraction of the change in water level. Although

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* The convention for water year is that the period Oct 1, 1987 to Sep 30, 1988 is known as the 1988 water year.

precipitation is measured to a similar number of significant figures, the gage at Park Headquarters is being used to represent precipitation over a 68 km^2 water shed. This is necessarily a noisy measurement. Table 2 gives the results for redoing the correlations with change in water level as the independent variable, and Figure 5 shows the correlation for the Oct 1 - Sep 30 water year. The standard error for p_o is 2 cm (Table 2), and this confirms that it is a well-determined quantity. The fractional uncertainties in ß and 1/ß are similar for both choices of independent variable, and there is no improvement in the uncertainty of this quantity by changing the independent variable. The values of ß are higher than the previous correlation resulting in increased total water supply estimates. Differences between values for the two starting dates for water years are far from statistical significance.

Based on the close determination of p_o, it is useful to show the effect of ß on calculated water level. The water level z_{i+1} in year i+1 is calculated from the water level z_i and precipitation p_i in year i from the relation:

$$z_{i+1} = z_i + ß\,(p_i - p_o), \qquad (6)$$

where precipitation for water year 1962 (October 1, 1961 to September 30, 1962) is used to predict the water level on October 1, 1962. Figure 6 shows calculated water-level histories for values of ß of 1.2 and 1.5 spanning the likely range from the results in Table 2. Although one curve agrees with measured water levels better in some years, the other curve agrees better in other years. Both model calculations have substantial mismatches in the periods 1972-77 and 1984-85. The available range of ß does not seem to be able to adequately model the actual variation in lake level. The basic determinant of the match is the average precipitation p_o rather than the slope ß.

In order to improve the prediction of lake level it is necessary to develop a more representative measure of precipitation. Fortunately, yearly precipitation measurements made at the North Rim make that possible. It has long been known that there is a substantial gradient of precipitation across Crater Lake, and adding a second data set makes it possible to more adequately sample this variation. It is also possible that some storms are not regionally extensive and will preferentially effect one site over the other. If there is experimental variability in measurements from one precipitation gage, adding a second gage provides the opportunity to better sample the true value in a given year. Figure 7 shows the North Rim measurement plotted against the Park Headquarters value for the period 1964-88. The two measures are closely correlated, and the slope relating the two is 0.718. The average precipitation for Park Headquarters during this period is 168.6 cm, and the predicted precipitation for Park Headquarters is 168.5 cm using the best slope and the average for the North Rim of 121.0 cm. Thus it seems reasonable to use the precipitation from the North Rim gage times 1.392 = 1/0.718 as another measure of precipitation on the lake. The scatter of the two data sets in Figure 7 indicates that a single measure of precipitation represents precipitation over the entire lake with an uncertainty of about ± 10 cm.

Figure 8 shows both data sets and Table 3 gives the correlation parameters. The North Rim gage was not installed until the 1964 water year, and two points on Figure 8 have only Headquarters data. Because there are two measures of precipitation, change in water level is used as the independent variable. The standard errors are somewhat smaller with the combined data set, but the results are not significantly different from using Headquarters data alone (Table 3). However, when the average of the two measures is used to model lake level, the improved correlation is striking (compare Figures 6 and 9). The average absolute deviation of the modeled water level from the measured water level is reduced from 25 cm for Headquarters data alone to 13 cm for the combined data set. Although the correlation of precipitation with change in water level is not notably improved, the addition of a second measure of precipitation has dramatically improved the modeled water-level variation.

Having obtained a water balance for the 1962-1988 time period, one would like to use the 1931-1962 data tabulated by Phillips (1968) to model water levels as did Redmond (1990). The earlier data are of significantly lower quality as water levels were only measured sporadically, at varying locations, and with varying reference levels. In addition, there are no precipitation data in the Park during World War II. The importance of the data from the North Rim gage for obtaining a good match during the 1962-1988 time period shows that the match just using data from the Park Headquarters gage will not be very good, as Redmond (1990) found. This problem does not invalidate Redmond's conclusion that the first order dependence of water level can be explained by the variation in precipitation with time. Instead of calculating water level, a more appropriate comparison is to use the earlier data to calculate the water balance parameters and then compare them to see if the difference is statistically significant. Several years during the 1931-1962 time period have no water-level measurements, and the water balance parameters have been calculated in two ways. In the first, only water-level changes for years with data are included. In the second, the precipitation and water-level change are averaged over the multi-year period with missing water-level data to generate values for intervening years. The results are given Table 4. The slope ß is very similar for the two calculations and to the value obtained for the 1962-1988 period. The precipitation p_o is 167 cm/y for the first method and 164 cm/y for the second method compared to 169 cm/y for the 1962-1988 time period. The differences are not statistically significant indicating that there has been no change in the water balance between the two time periods. The 2 and 5 cm/y differences in precipitation p_o may simply reflect measurement uncertainty although it seems likely that differences in measurement technique between the two time periods may bring some bias to the earlier measurements.

WATER BALANCE USING DAILY DATA

With the availability of many years of daily precipitation and water-level data, a water balance during the entire year should be possible. The purpose of this section is to develop a water balance using daily data and to use averages of several year's data to obtain appropriate values for parameters needed in the balance. Values obtained will be compared to those obtained using the yearly water balance. The basic notion that must be added to the yearly water balance is that precipitation on the rim is stored as snow during the winter and then released in the spring and early summer.

The instantaneous water balance may be written as:

$$\frac{dz}{dt} = d_{ws} - ß\, p_o \,, \tag{7}$$

where dz/dt is the rate of change of water level with time, d_{ws} is the water supply from precipitation and inflow, and $\beta\, p_o$ is the assumed constant leakage and evaporation. Although evaporation is not constant through the year, the first order variation in the water balance is assumed to be from varying water supply rather than from varying evaporation. Based on the data in Figure 4 from Redmond (1990), a reasonable model for the water supply from snow melt is that snow accumulates from November 1 to April 1. From April 1 to July 15, the snow melts at a uniform rate. Defining α as the fraction of the total water supply $\beta\, p$ that falls as direct precipitation during the period of snow accumulation, this can be expressed as:

$$d_{ws} = \begin{cases} \beta\, p & \text{Oct 1} = 0 \le t \le t_1 = \text{Nov 1} \\ \alpha\, \beta\, p & \text{Nov 1} = t_1 \le t \le t_2 = \text{Apr 1} \\ \beta\, p + \dfrac{1}{t_3 - t_2} \displaystyle\int_{t_1}^{t_2} \beta\, (1 - \alpha)\, p\, dt & \text{Apr 1} = t_2 \le t \le t_3 = \text{Jul 15} \\ \beta\, p\, . & \text{Jul 15} = t_3 \le t \le t_4 = \text{Sep 30} \end{cases} \qquad (8)$$

Many quantities could be used to match, but I will use the cumulative water supply from the start of the year. Rearranging equation (7), the cumulative water supply may be expressed as:

$$WS/\beta = \frac{1}{\beta} \int_0^t d_{ws}\, dt = \frac{1}{\beta} (z - z_o) + p_o\, t\, , \qquad (9)$$

where the dependence on β is isolated by placing it on the left hand side of equation (9). From equation (8), the same quantity can be expressed as:

$$WS/\beta = \begin{cases} \displaystyle\int_0^t p\, dt & 0 \le t \le t_1 \\ \displaystyle\int_0^{t_1} p\, dt + \int_{t_1}^{t} \alpha\, p\, dt & t_1 \le t \le t_2 \\ \displaystyle\int_0^{t_1} p\, dt + \left[\alpha + \frac{1 - \alpha}{t_3 - t_2} (t - t_2) \right] \int_{t_1}^{t_2} p\, dt + \int_{t_2}^{t} p\, dt & t_2 \le t \le t_3 \\ \displaystyle\int_0^t p\, dt\, . & t_3 \le t \le t_4 \end{cases} \qquad (10)$$

Thus the calculation of WS/β from equation (9) depends on β but not α and from equation (10) depends on α but not β. The integrals in equation (10) are converted into sums for discrete daily data.

Our objective is to choose ß and α such that the cumulative water supply calculated using equations (9) and (10) are the same at every day of the year. Rather than match individual years, average years grouped by amounts of yearly precipitation (low, medium, and high) are used. Figure 2 shows the average precipitation and water level for all years with complete data. Figures 10, 11, and 12 show precipitation and average water level for years with low- (<150 cm/y), medium- (>150 & < 180 cm/y), and high-precipitation (>180 cm/y). The low precipitation case maintains an approximately constant level through June and then decreases for the rest of the year because of low precipitation. The medium- and high-precipitation cases have increasing water levels through the fall and winter, relatively constant levels in the spring, and decreasing levels in the summer.

The first matching scheme assumes that the value for ß determined from the yearly water balance should hold through the year, and the average absolute deviation is minimized between water supply calculated from equations (9) and (10) in order to determine α. Based on the comparison of Park Headquarters and North Rim precipitation made above, it is clear that there is significant variability in the precipitation measured at Park Headquarters that is unrelated to the water balance. In order to make a consistent calculation for finding α, daily precipitation is adjusted so that the total precipitation for the year is what is calculated from equation (5) with ß = 1.325 and p_o = 169.2 cm/y. This adjustment factor $ß_a$ is introduced into equation (10) when calculating the water supply from precipitation data. The maximum adjustment is 5 %. This assumption is relaxed below.

Figure 13 shows the two calculated water supplies for the medium precipitation case for α =1.0, and Figure 14 shows the water supplies for α such that the average absolute deviation of the two calculations is minimized. As one would expect, the calculation for α =1.0 in Figure 13 shows a substantial excess in water supply calculated from precipitation that grows in the winter, becomes approximately constant during the late spring, and decreases to zero during the summer. The results in Figure 14 for α = 0.84 show that the two calculations for water supply match reasonably well throughout the year. The average absolute deviation has been reduced from 7.6 cm to 1.7 cm (Table 5). The simple model of storage and then uniform release explains the first order variation in water supply. Although one would like to improve the model, the use of a constant adjustment factor for precipitation makes it difficult to assess relative contributions of additional details. The next step would be to include nonconstant release of the snow melt and nonconstant evaporation. Since these two effects overlap for a significant part of the year, defining which effect is dominant would require more consistent daily-precipitation data than are available. There is a suggestion in the difference plot in Figure 14 that the rate of snow melt may be higher in the the late spring than the early summer and that the rate of evaporation may be higher in summer (larger ß in equation (9)) than winter.

Figures 15, 16, and 17 show the results for low, high, and average precipitation. The average absolute deviations are substantially reduced by the model from values calculated using α =1.0 (Table 5). The values of α obtained range from 0.81 to 0.90. The quantity ß α is a measure of the fraction of precipitation falling directly on the lake compared to that measured at Park Headquarters. The lake appears to receive about 10% more precipitation than that at Park Headquarters, though the range is from 7% to 19% (Table 5). Phillips (1968, p. E15) estimates that precipitation on the lake is 7% greater than at Park Headquarters. The appearance of the difference curves in Figures 15, 16, and 17 tends to confirm the notion that the rate of snow melt may be higher in the the late spring than the early summer and that the rate of evaporation may be higher in summer than winter, but uncertainties in precipitation amounts make this a weak conclusion. The matches with adjusted precipitation are compatible with the yearly water balance but do not lend any support to those values because they are used in the adjustment process.

Another method for matching the two calculations of water supply is to search parameter space for values of ß and α that minimize the average absolute deviation between the curves. Table 6 gives the results of such a search for the four cases. The search was conducted to the number of significant figures given for the two parameters, and no adjustment was made to the precipitation data. Values of α only range from 0.81 to 0.86. Values of ß range from 1.2 to 1.5 and span the entire range of reasonable values based on the yearly water supply. Average absolute deviations (Table 6) are similar for each case to the values given in Table 5. Although daily precipitation and water-level data are numerous, uncertainty in the precipitation data limit the ability of the data to determine the best value of ß. Visual comparisons provide no obvious rationale for choosing one match versus another. For example, Figure 18 shows the calculated water supplies for unadjusted precipitation for the high-precipitation case. Comparing Figures 16 and 18, neither is visually superior to the other in modeling the calculated water supply. Thus both the yearly and daily water balances are unable to fix ß with precipitation data only from Park Headquarters. The values for the average-precipitation case are quite similar to the values for the adjusted precipitation calculation (Tables 5 and 6). This agreement can be interpreted as showing that one needs the larger number of years in the average-precipitation case to get a good determination of ß and α. Alternatively, one could contend that that the agreement is fortuitous, because the adjustment factor $ß_a$ is so close to one.

CONCLUSIONS AND DISCUSSION

Finding the best values for the water balance for Crater Lake is far more illusive than one would expect from the great quantity of data available. With only precipitation data from Park Headquarters and data on lake levels, one cannot do better than than show that the coefficient ß (the ratio of lake-level change to the amount of precipitation above the long-term average) lies between about 1.2 and 1.5. The addition of precipitation data from the North Rim gage yields a better result because of the improved ability to model water-level variations. The formal limits of one standard error are that ß lies between 1.26 and 1.39 with a mean value of 1.325. The long-term average precipitation needed to keep lake level constant is well determined at 169 ± 2 cm. Phillips (1968) estimated that his water balance was accurate to 5 % over the long term and 10 % in a single year. Based on the statistical analysis in this paper, his estimate is correct. Averaging precipitation from Park Headquarters with adjusted values from the North Rim gage results in significantly improved model of lake level variation from precipitation data.

The water balance based on daily data indicates that precipitation on the lake is about 10 % higher (186 cm) than that measured at Park Headquarters (using $ß\,\alpha \approx 1.1$ from Table 5). For ß = 1.325, $ß - ß\,\alpha \approx 0.225$ or about 17 % of the water supply is from inflow from the crater walls. Given that the crater rim is 22 % of the lake's drainage basin and assuming that maybe 1/3 of the snow evaporates during melting on the rim, average precipitation on the rim would be about 10 % higher (205 cm) than that on the lake and about 21 % higher than that at Park Headquarters. Given that precipitation at the gage on the North Rim (121 cm) is only 72 % of that at Park Headquarters, the precipitation on the south rim at higher elevations must be significantly greater than that at the lower elevation of Park Headquarters.

The division of water loss into leakage and evaporation is problematic. On the regional map for average annual lake evaporation of Kohler and others' (1959), Crater Lake is located between the 81 and 86 cm/y contours. Meyers (1962, p. 95) interpolated an evaporation rate of 83 cm/y for Crater Lake for a total evaporation of 4.42×10^7 m^3/y over the area of the lake. Phillips (1968) calculated the evaporation rate by subtracting the leakage from the total water supply. He measured the leakage of 149 cm/y by looking at changes in water levels for Crater Lake during cold periods when there was no precipitation and assuming that evaporation would be minimal. Using this study's value for water supply of 224 cm/y, Phillips' estimate of leakage results in an evaporation rate of 75 cm/y. Redmond (1990) calculated leakage of 127 cm/y from two periods when the lake was frozen. Using this study's value for water supply, Redmond's estimate of leakage results in an evaporation rate of 97 cm/y. Neither of these figures for leakage are particularly satisfying as they are based on short periods of data. However, the major discrepancy in evaporation rates in Table 1 was because of Redmond's high value for total water supply of 247 cm/y. Accepting this study's value for total water supply, the estimates of evaporation now range from 75 to 97 cm/y, and the estimates bracket the estimated rate of Meyers (1962). For purposes of calculation, a rate of 85 cm/y seems reasonable, recognizing that this rate is uncertain by ± 10 %.

ACKNOWLEDGEMENTS

Data for the storage precipitation gage were supplied by R. L. Kraus of the Medford office of the U.S. Geological Survey. In recent years, the gage has been maintained by R. Edmund, M. A. Gentile, J. G. House, R. L. Kraus, J. L. Moffet, and M. J. Warwick. The long-term records for Crater Lake exist because it was selected as a Hydrologic Benchmark station in 1963. Reviews by Gary Gallino and Michael Sorey were helpful.

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Table 1. Parameter values for yearly water balances for Crater Lake, Oregon. Precipitation p_o is value at Park Headquarters that will result in no change in level for Crater Lake, coefficient ß is ratio of level change to precipitation greater than p_o, supply is total water supply to the lake divided by the area of lake. Water loss from the lake is made up of leakage and evaporation, both expressed as volume divided by total lake area.

Reference	Water Year	Precip. p_o cm/y	Coef. ß	Supply ß p_o cm/y	Leakage cm/y	Evaporation cm/y
Meyers (1962)						83.2
Phillips (1968)	Oct 1 - Sep 30	164.6	1.26	208	149	59
Simpson (1970)	Oct 1 - Sep 30	173	1.2	208	139	69
Redmond (1990)	Oct 1 - Sep 30	169.2	1.457	246.5	127	120
This study	July 1 - June 30	169.2	1.325	224.2		

Table 2. Parameter values for yearly water balances for Crater Lake, Oregon, obtained by various correlations of yearly change in water level with precipitation data for the 1962-1988 time period. Uncertainties are standard errors. P-values are from t test (two tailed).

Water Year	Precip. p_o cm/y	Coef. ß	Supply ß p_o cm/y	1/ß
	Precipitation as independent variable			
July 1 - June 30	169.2	1.256 ± 0.092	212.5 ± 15.7	
Oct 1 - Sep 30	169.1	1.454 ± 0.090	246.0 ± 15.3	
P-values		<0.2	<0.2	
	Water level as independent variable			
July 1 - June 30	169.0 ± 2.4	1.424	240.7	0.703 ± 0.051
Oct 1 - Sep 30	169.0 ± 1.9	1.592	269.1	0.628 ± 0.039
P-values	<1			<0.5

Table 3. Parameter values for yearly water balances for Crater Lake, Oregon, obtained by correlations of yearly change in water level with precipitation data for the 1962-1988 time period. Uncertainties are standard errors. P-values are from t test (two tailed). Average absolute deviation is the sum of the absolute values of the difference between measured and calculated water level divided by the number of years.

Precipitation Data	Precip. p_o cm/y	Coef. ß	Supply ß p_o cm/y	1/ß	Avg. Absolute Dev. (cm)
Water level as independent variable - July 1 to June 30 Water Year					
Headquarters	169.0 ± 2.4	1.424	240.7	0.703 ± 0.051	25.3
Headquarters & North Rim	169.2 ± 1.7	1.325	224.2	0.755 ± 0.036	12.5
P-values	<1			<0.5	

Table 4. Parameter values for yearly water balances for Crater Lake, Oregon, obtained by correlations of yearly change in water level with precipitation data for the 1962-1988 and 1931-1962 time periods. Water-level change as independent variable. Uncertainties are standard errors. P-values are from t test (two tailed) comparing each result for 1931-1962 time period to 1962-1988 time period.

Time Period	Precip. p_o cm/y	Coef. ß	Supply ß p_o cm/y	1/ß
1962-1988	169.2 ± 1.7	1.325	224.2	0.755 ± 0.036
Water-level changes for years with data.				
1931-1962	166.6 ± 3.7	1.310	218.2	0.763 ± 0.091
P-values	<0.5			<1
Water-level changes for years with missing data obtained by averaging.				
1931-1962	164.4 ± 3.1	1.309	215.2	0.764 ± 0.083
P-values	<0.2			<1

Table 5. Parameter values for water balances for Crater Lake, Oregon, using daily data. Each case is an average of several year's data. Measured precipitation is adjusted using coefficient $ß_a$ to satisfy long-term water balance at the end of the year. Average absolute deviation is difference between calculated water supplies based on equations (9) and (10). Water supply for α = 1.0 assumes no precipitation is accumulated as snow on crater walls. Other values of α based on minimizing average absolute deviation.

Case	Precip. p cm/y	Coef. $ß_a$	Coef. α	Avg. abs. dev. (cm)	ß α
		For ß = 1.325 and p_o = 169.2 cm/y			
Low	130.9	0.972	1.00	4.25	
	"	"	0.90	1.69	1.19
Medium	162.8	0.985	1.00	7.62	
	"	"	0.84	1.71	1.11
High	200.3	1.049	1.00	11.73	
	"	"	0.81	2.26	1.07
Average	164.3	1.004	1.00	7.65	
	"	"	0.84	1.58	1.11

Table 6. Parameter values for water balances for Crater Lake, Oregon, using daily data. Each case is an average of several year's data. Average absolute deviation is difference between calculated water supplies based on equations (8) and (9). Values of ß and α obtained by minimizing average absolute deviation.

Case	Precip. p cm/y	Coef. ß	Coef. α	Avg. abs. dev. (cm)	ß α
Low	130.9	1.35	0.86	0.95	1.16
Medium	162.8	1.20	0.85	1.81	1.02
High	200.3	1.51	0.81	2.47	1.22
Average	164.3	1.37	0.83	1.63	1.14

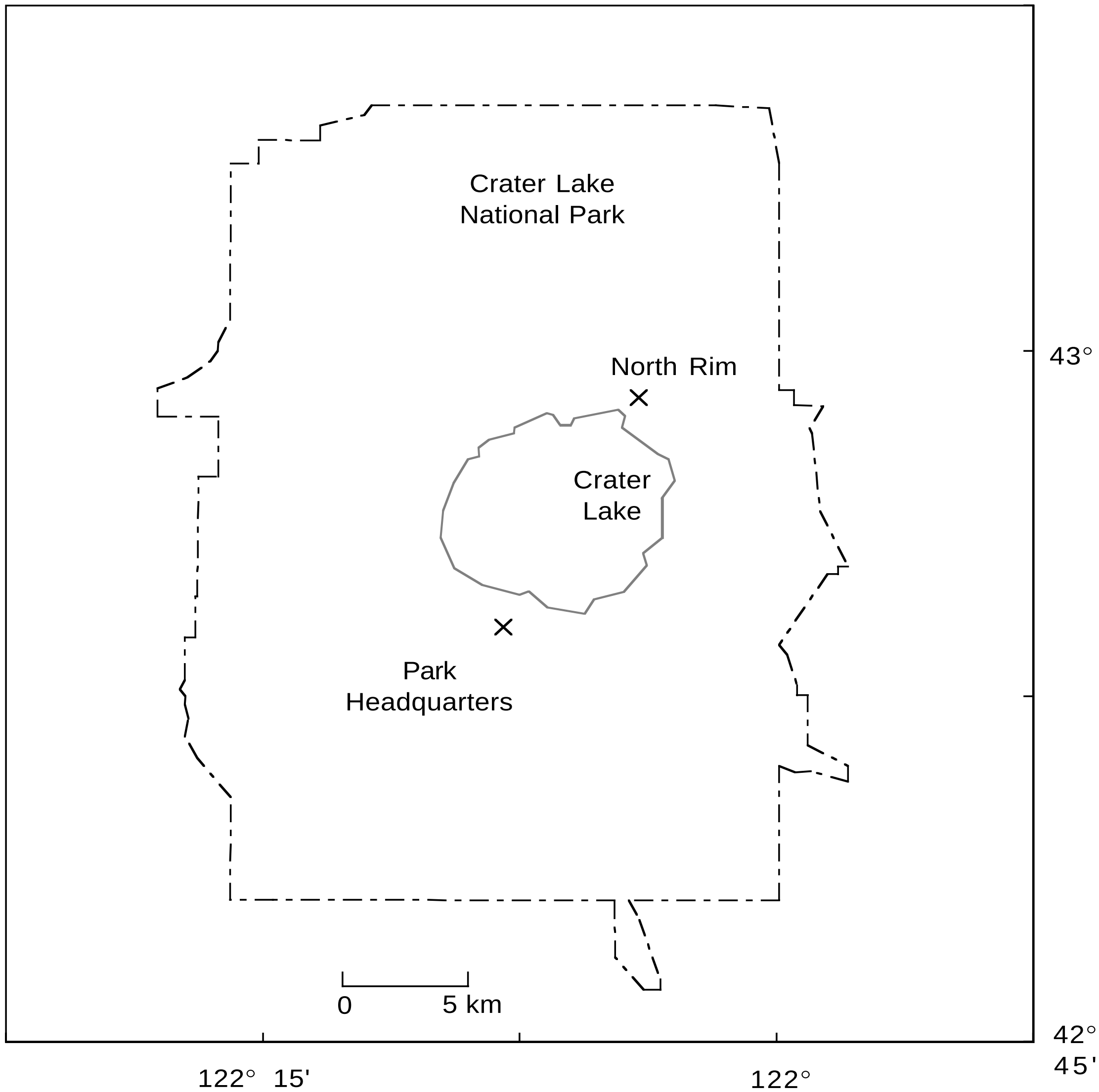

Figure 1. Map of Crater Lake National Park showing locations of precipitation gages at Park Headquarters and at the North Rim.

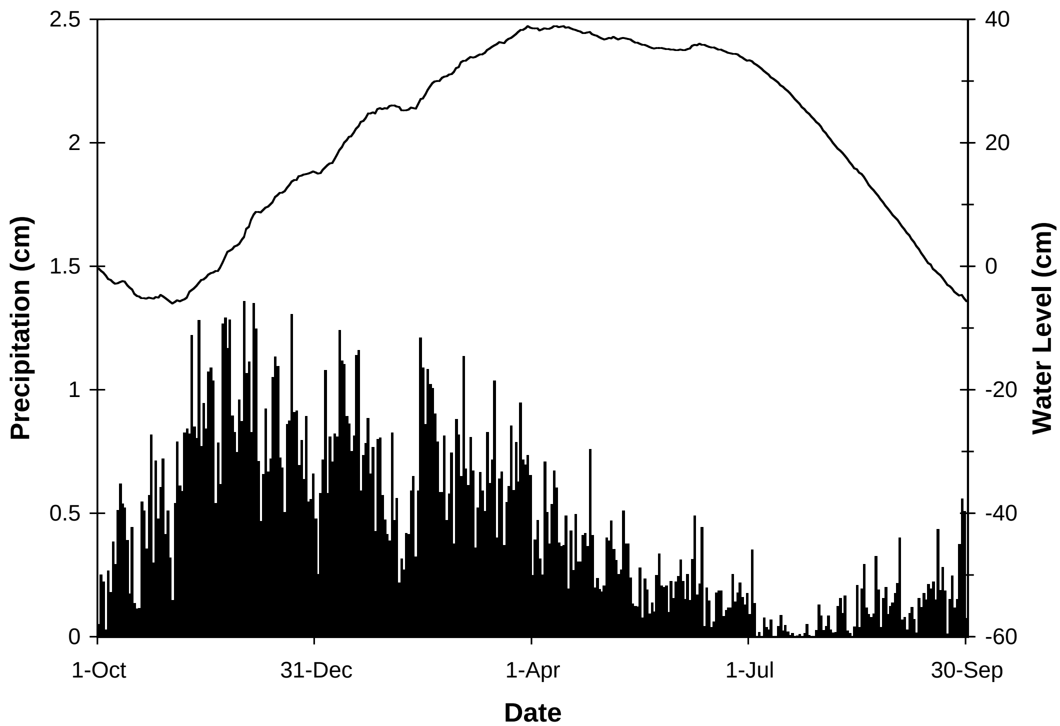

Figure 2. Water level for Crater Lake and daily precipitation at Park Headquarters averaged over years with complete records (Water years 1962-64, 1966-72, 1975-77, 1979-85, 1988-89). Water-level data from U.S. Geological Survey (1970, 1976, 1972 - 1979, 1981a & b, 1983), Alexander and others (1987, 1988, 1989), Hubbard and others (1983, 1984, 1986, 1989, 1990). Precipitation data from National Oceanic and Atmospheric Administration (1961-89).

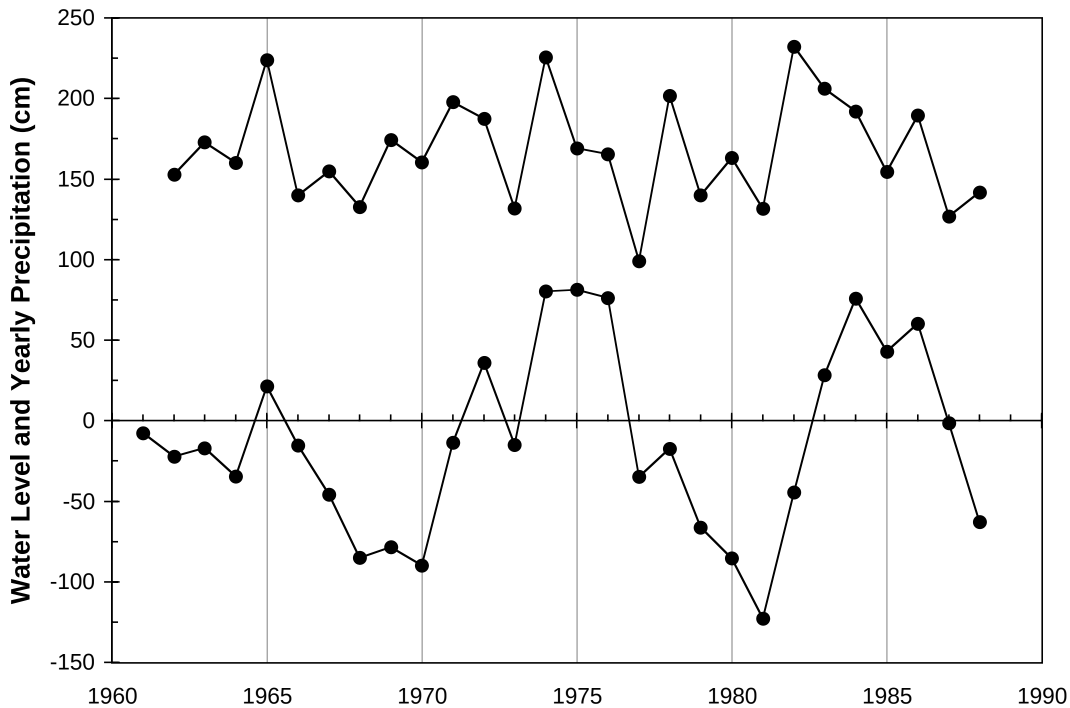

Figure 3. Water level for Crater Lake (above 1882.14 m elevation) and yearly precipitation at Park Headquarters. Water year is Oct 1 to Sep 30.

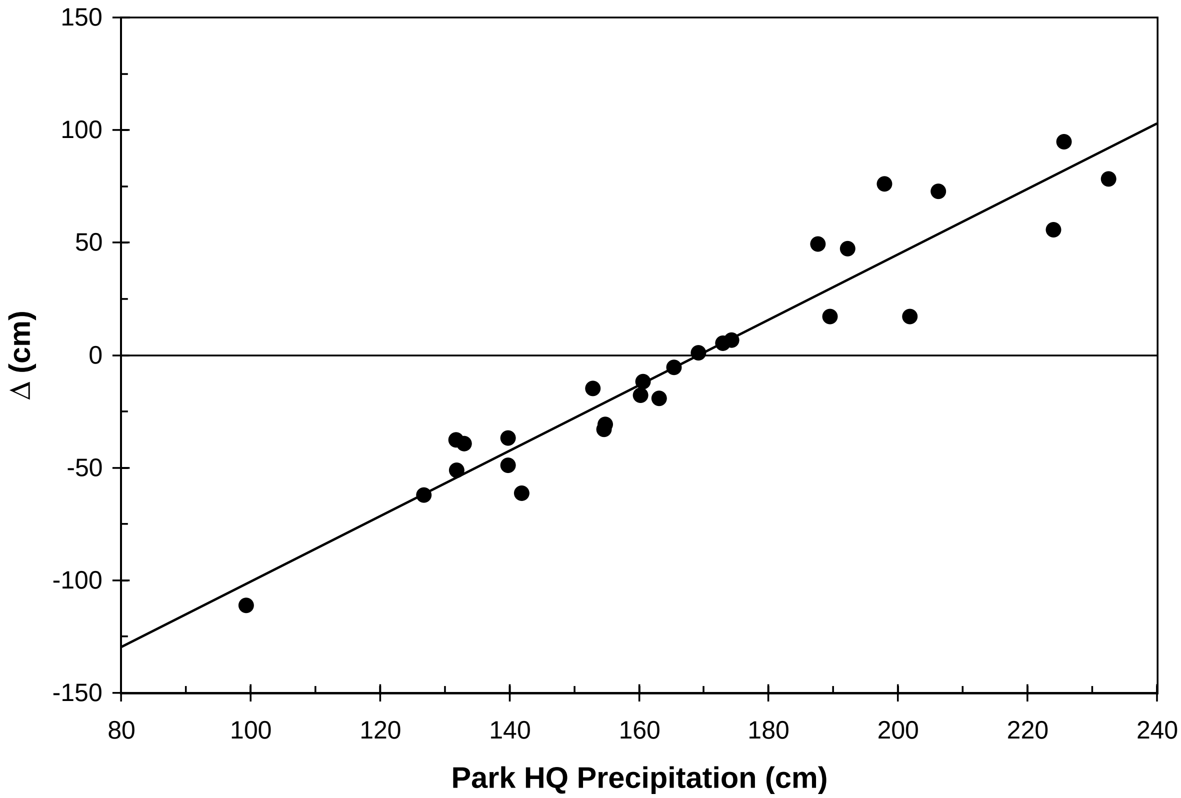

Figure 4. Change in level Δ from Oct 1 to Oct 1 versus precipitation for period 1962-1988. Correlation line uses precipitation as independent variable.

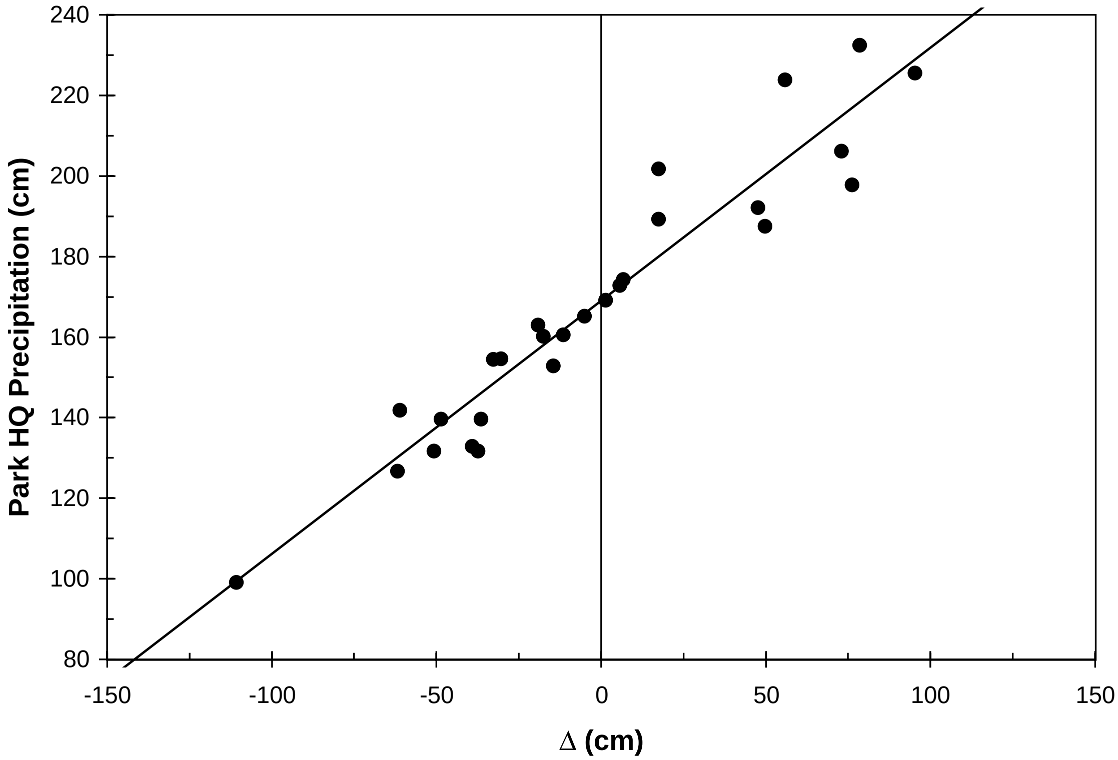

Figure 5. Precipitation versus change in level Δ from Oct 1 to Oct 1 for period 1962-1988. Correlation line uses change in level as independent variable.

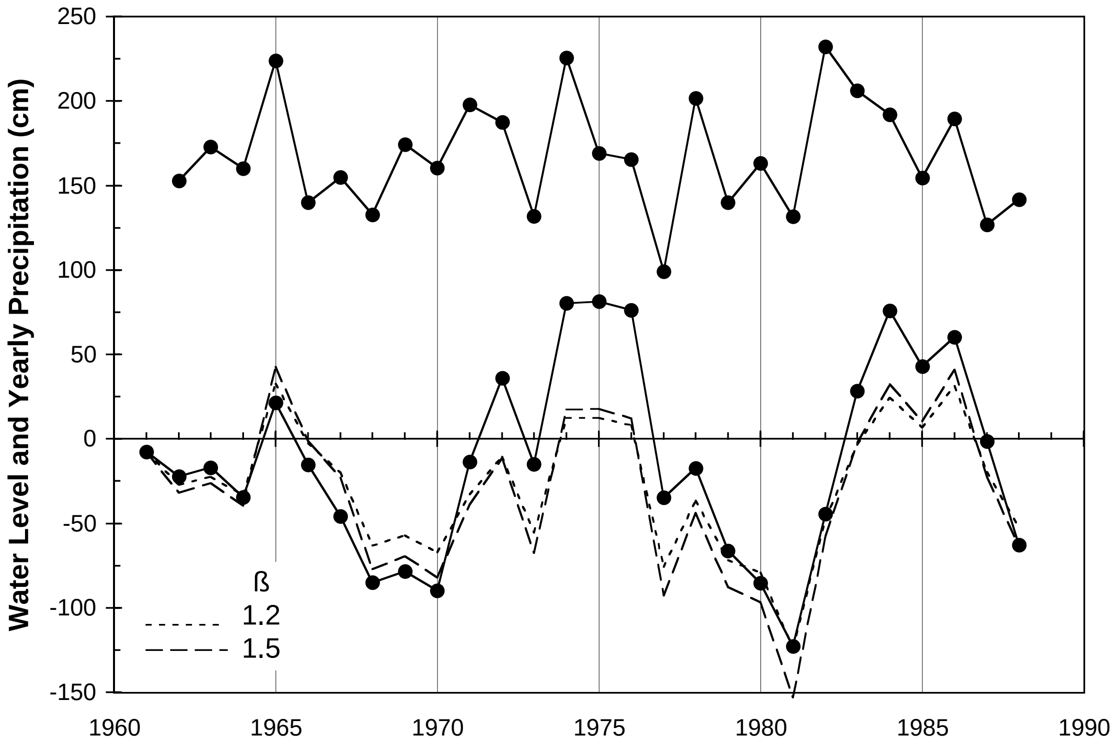

Figure 6. Water level for Crater Lake (above 1882.14 m elevation) and precipitation at Park Headquarters. Water year is Oct 1 to Sep 30. Water levels shown by broken lines calculated using equation (6) from measured precipitation values.

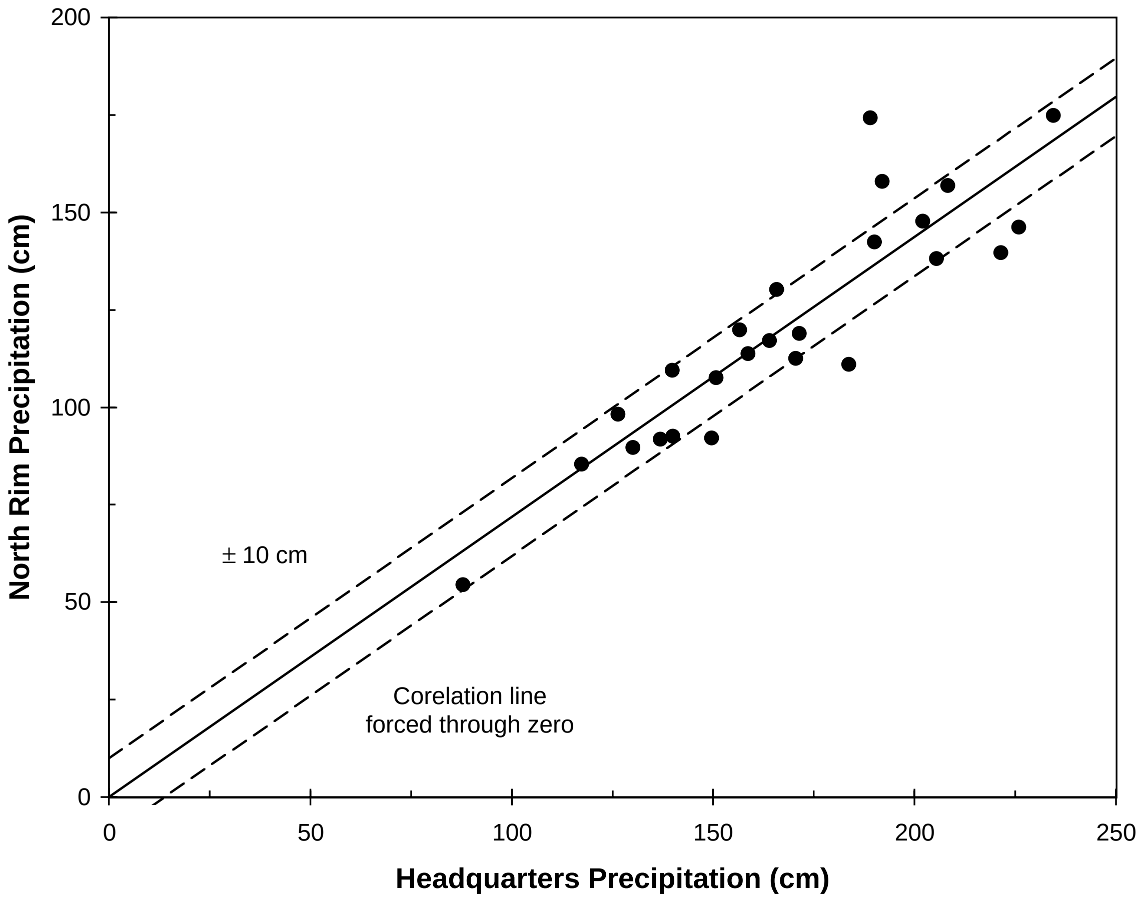

Figure 7. Precipitation at North Rim gage versus that at Park Headquarters for July 1 - Jun 30 water year for 1964-88 time period. Correlation line calculated assuming that line passes though 0. Precipitation data for North Rim gage from National Oceanic and Atmospheric Administration (1966-77) and unpublished records of U.S. Geological Survey.

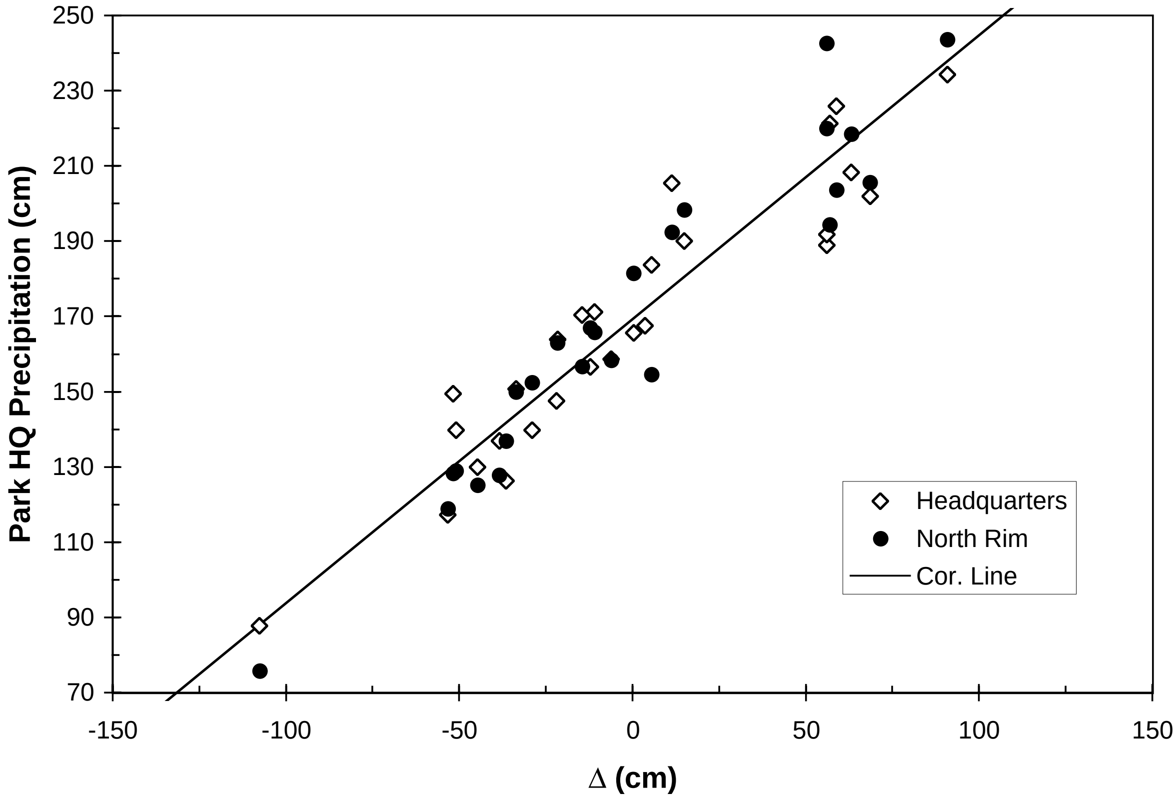

Figure 8. Precipitation at Park Headquarters (1962-88) and calculated from the measurement at the North Rim (1964-88) versus change in level Δ from July 1 to July 1. Correlation line uses change in level as independent variable.

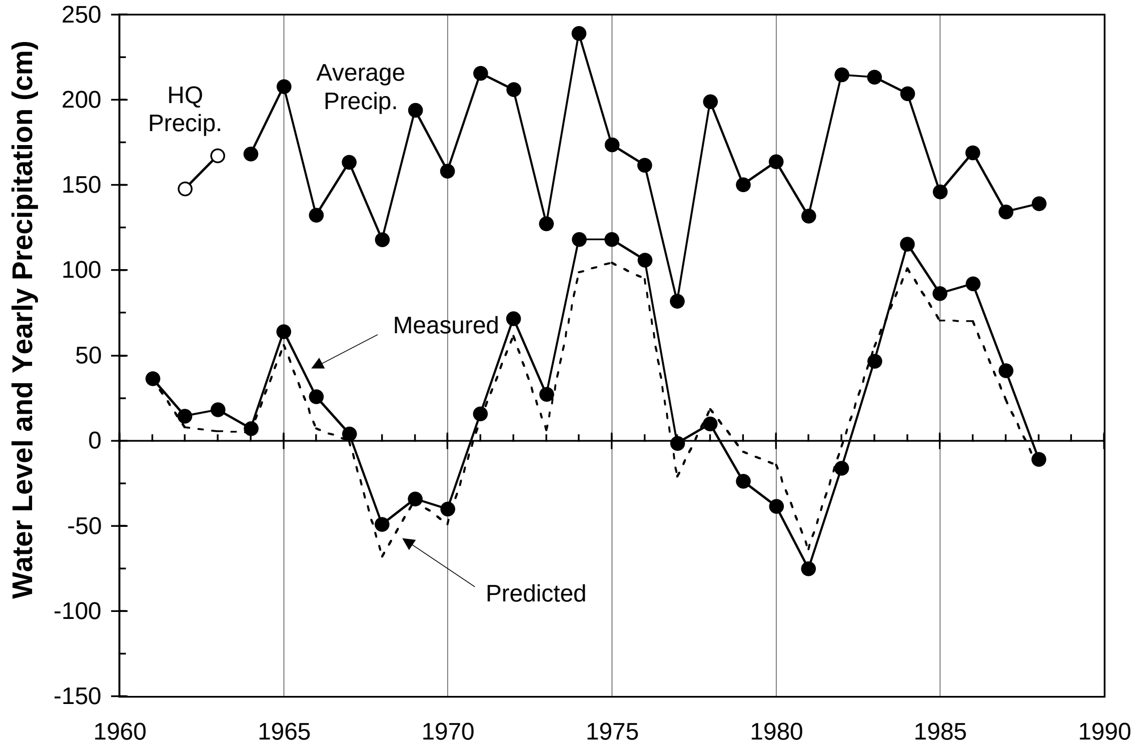

Figure 9. Water level for Crater Lake (above 1882.14 m elevation) and precipitation at Park Headquarters (1962-63) and average of values for Park Headquarters and North Rim adjusted to mimic Park Headquarters values (1964-88). Water year is July 1 to June 30. Water levels shown by broken line calculated using equation (6) from precipitation values shown.

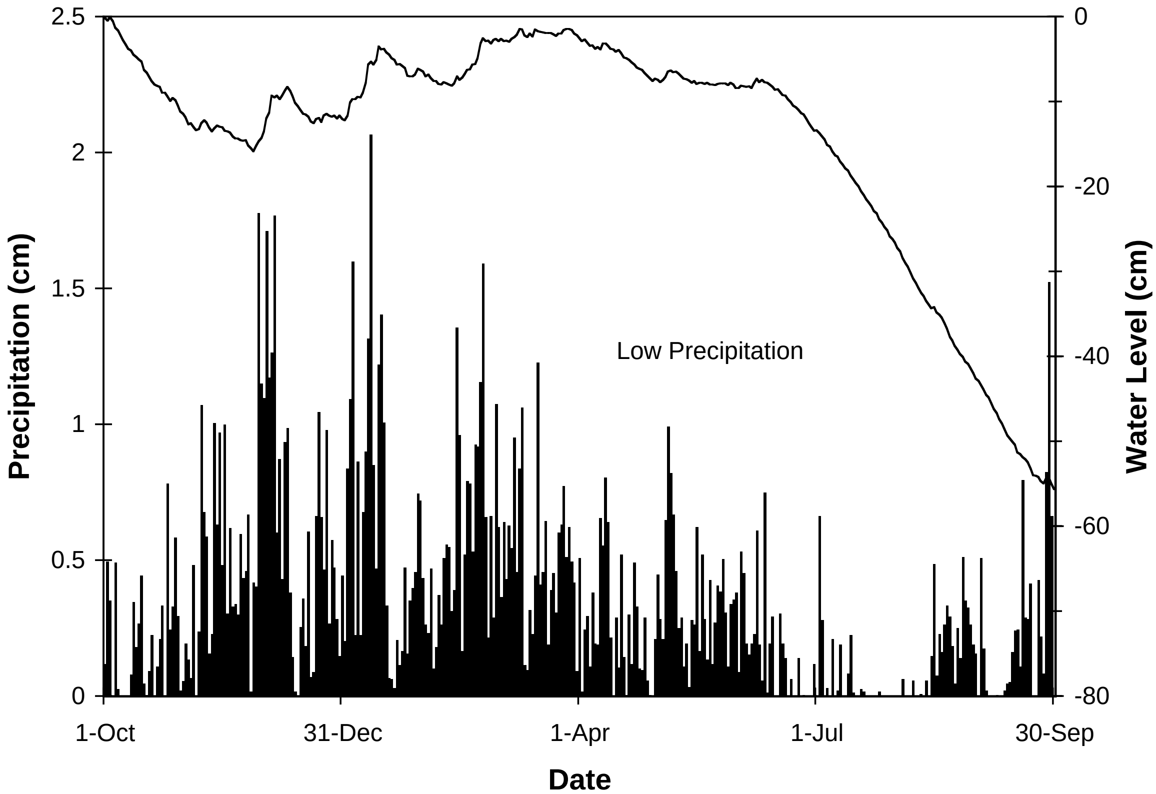

Figure 10. Water level for Crater Lake and daily precipitation at Park Headquarters averaged over years with low (< 150 cm/y) precipitation (Water years 1966, 68, 77, 79, 81, 88).

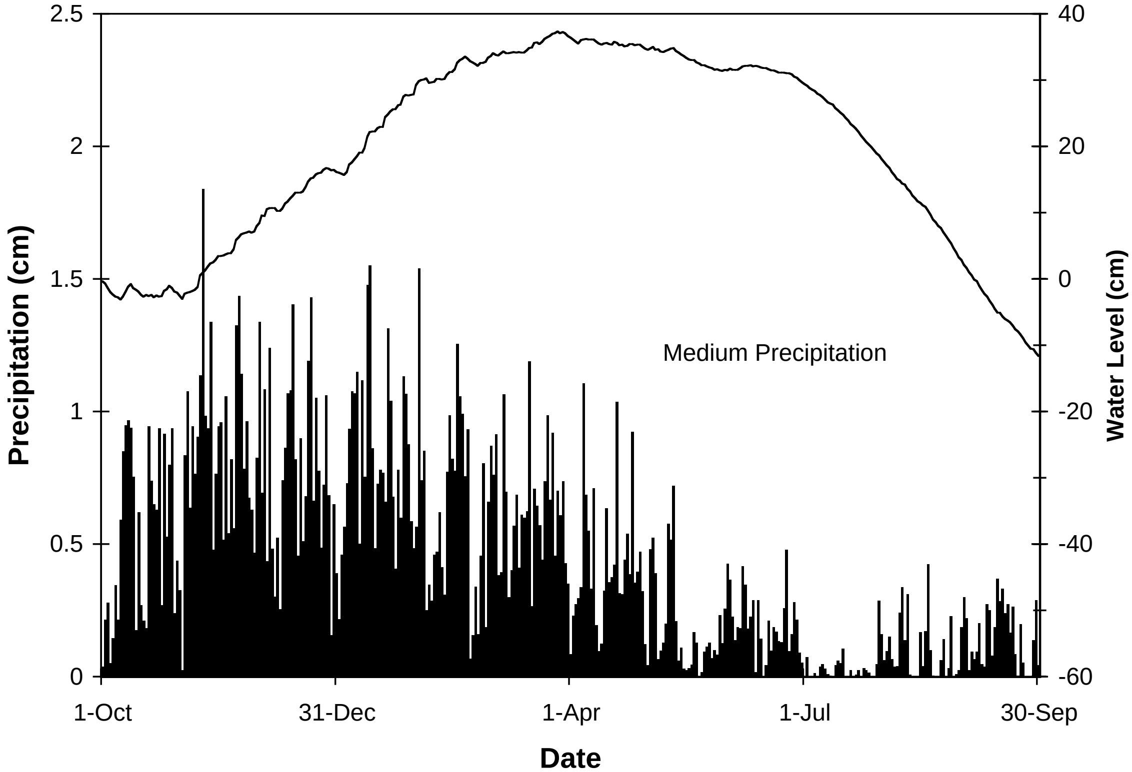

Figure 11. Water level for Crater Lake and precipitation at Park Headquarters averaged over years with medium (> 150 cm/y & < 180 cm/y) precipitation (Water years 1962, 63, 64, 67, 69, 70, 75, 76, 80, 85).

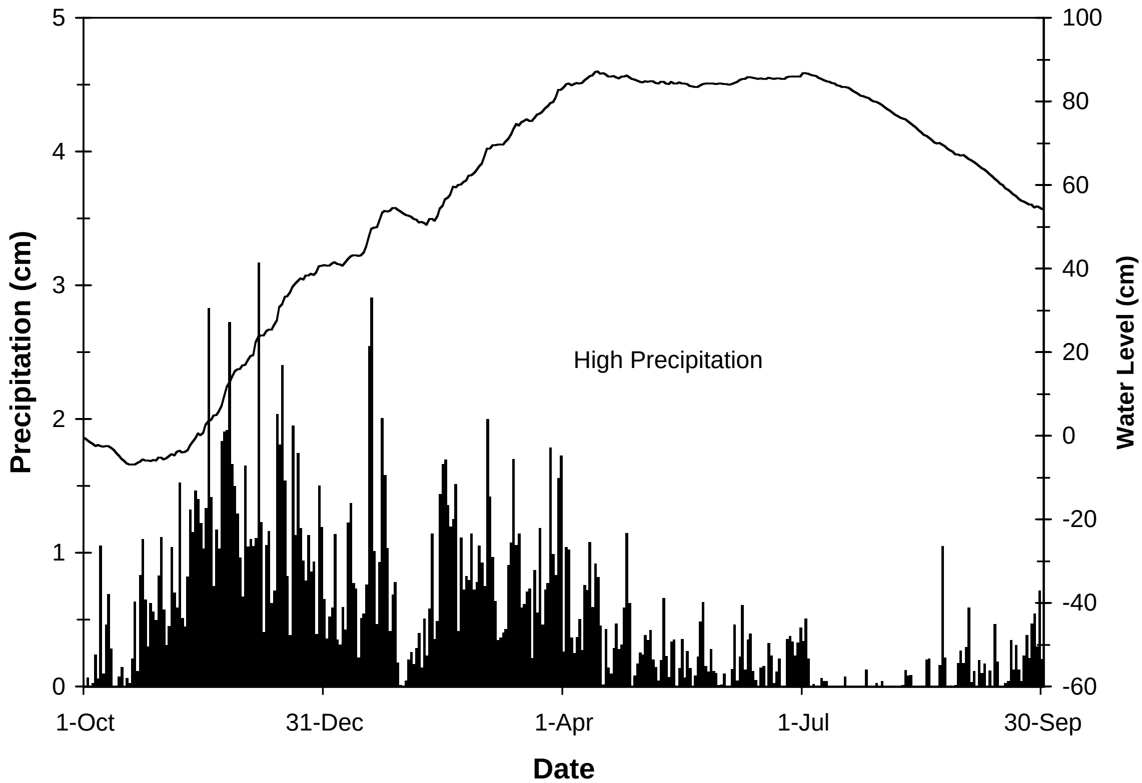

Figure 12. Water level for Crater Lake and precipitation at Park Headquarters averaged over years with high (> 180 cm/y) precipitation (Water years 1971, 72, 82, 83, 84, 89).

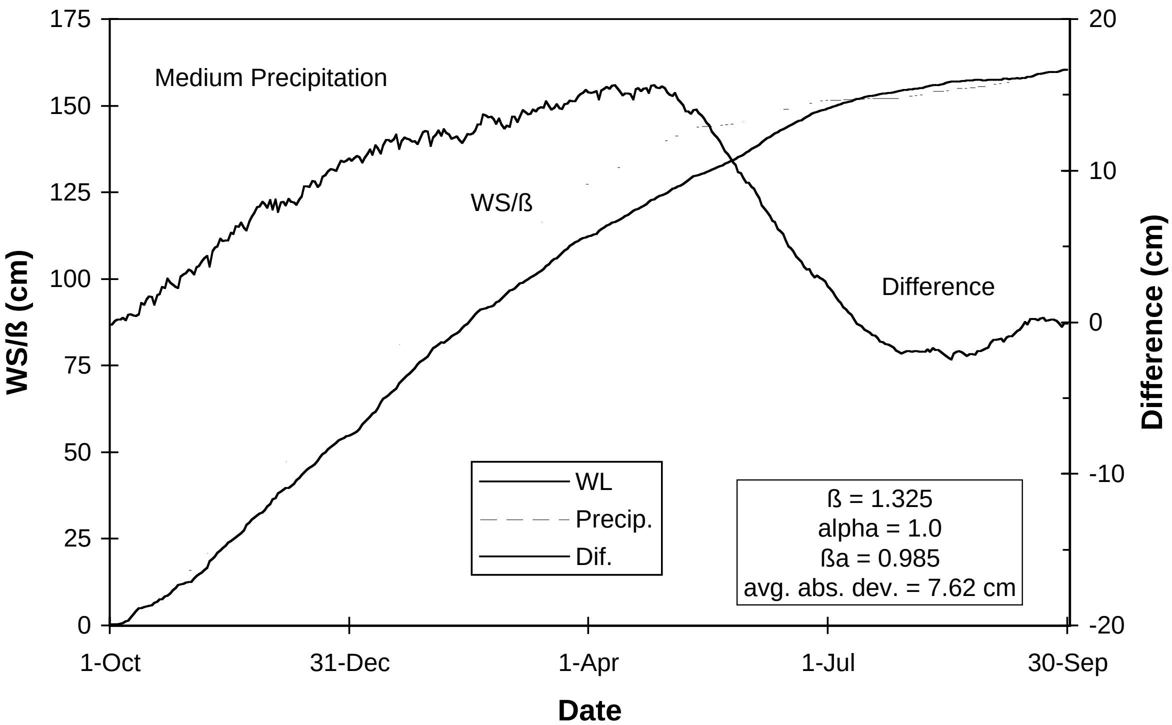

Figure 13. Cumulative water supply over coefficient ß calculated from water level by equation (9) and from precipitation by equation (10) for medium precipitation case. Calculation for $\alpha = 1$ assumes that there is no storage of precipitation as snow on crater walls. Precipitation adjusted by factor $ß_a$ so that total precipitation for year matches that from known water-level change using ß = 1.325 and p_o = 169.2 cm/y.

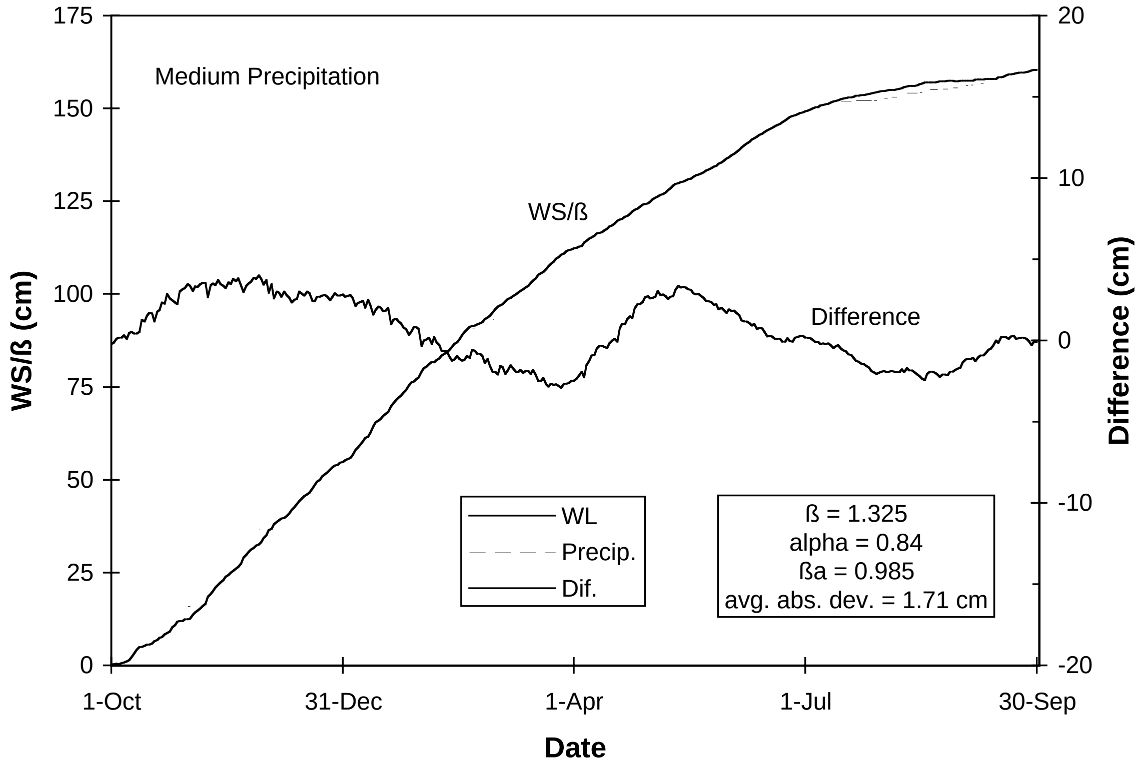

Figure 14. Cumulative water supply over coefficient ß calculated from water level by equation (9) and from precipitation by equation (10) for medium precipitation case. Value for α chosen based on minimizing average absolute deviation between two calculated water supply curves. Precipitation adjusted by factor $ß_a$ so that total precipitation for year matches that from known water-level change using ß = 1.325 and p_o = 169.2 cm/y.

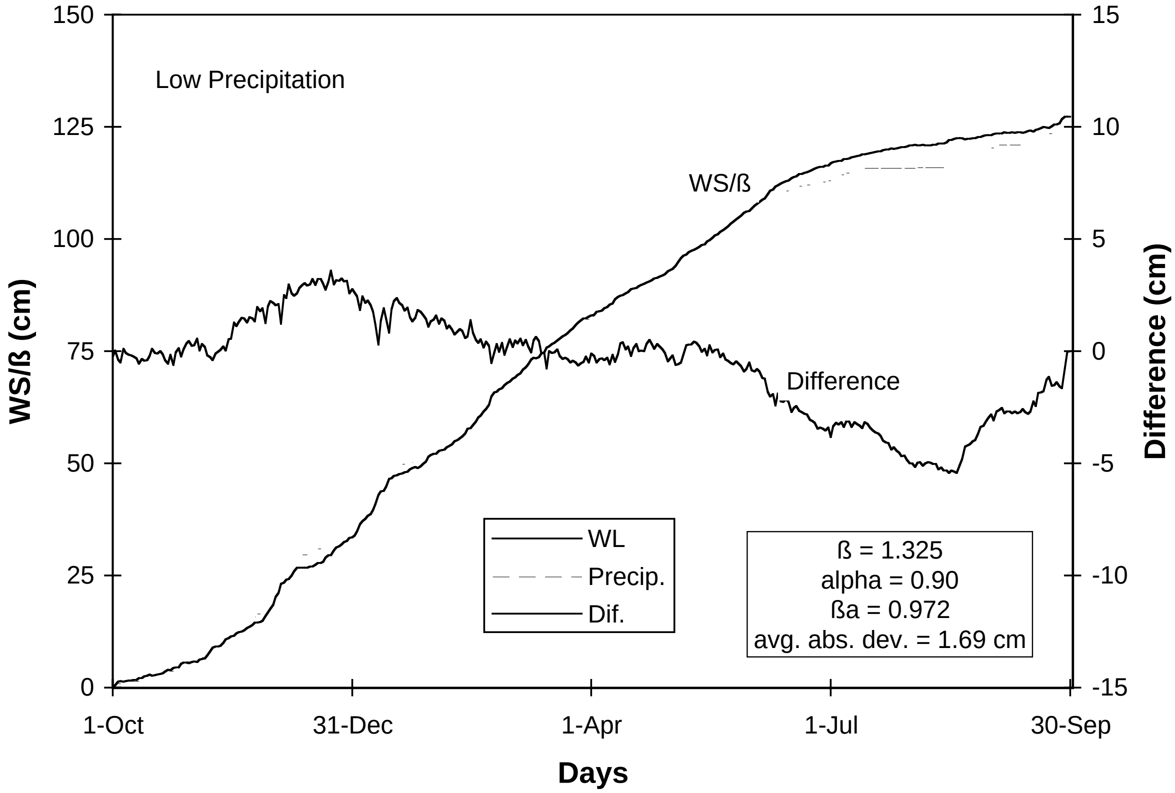

Figure 15. Cumulative water supply over coefficient ß calculated from water level by equation (9) and from precipitation by equation (10) for low precipitation case. Value for α chosen based on minimizing average absolute deviation between two calculated water supply curves. Precipitation adjusted by factor $ß_a$ so that total precipitation for year matches that from known water-level change using ß = 1.325 and p_o = 169.2 cm/y.

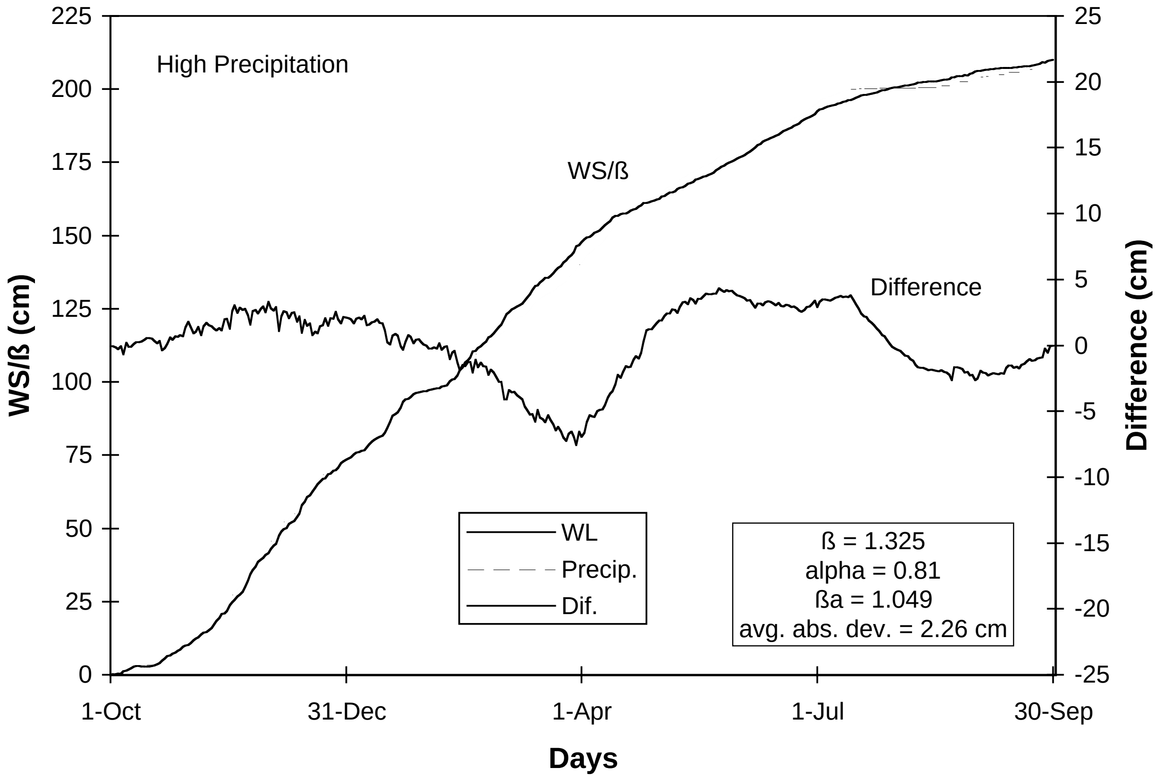

Figure 16. Cumulative water supply over coefficient ß calculated from water level by equation (9) and from precipitation by equation (10) for high precipitation case. Value for α chosen based on minimizing average absolute deviation between two calculated water supply curves. Precipitation adjusted by factor $ß_a$ so that total precipitation for year matches that from known water-level change using ß = 1.325 and p_o = 169.2 cm/y.

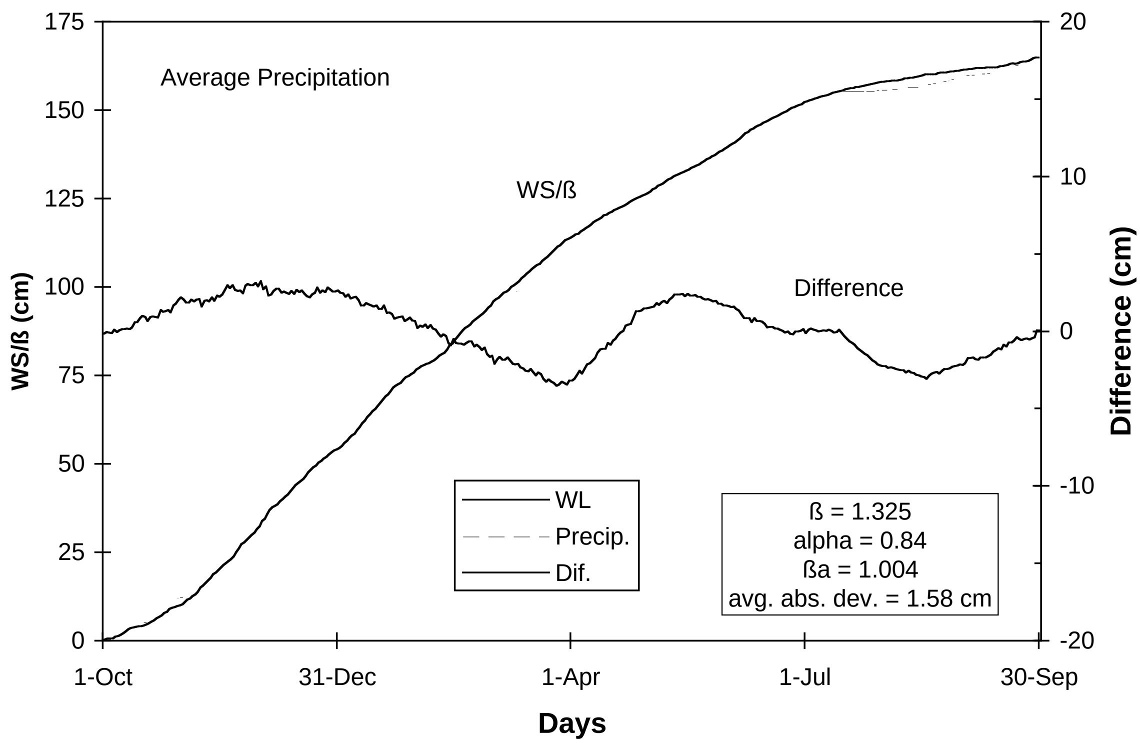

Figure 17. Cumulative water supply over coefficient ß calculated from water level by equation (9) and from precipitation by equation (10) for average precipitation case. Value for α chosen based on minimizing average absolute deviation between two calculated water supply curves. Precipitation adjusted by factor $ß_a$ so that total precipitation for year matches that from known water-level change using ß = 1.325 and p_o = 169.2 cm/y.

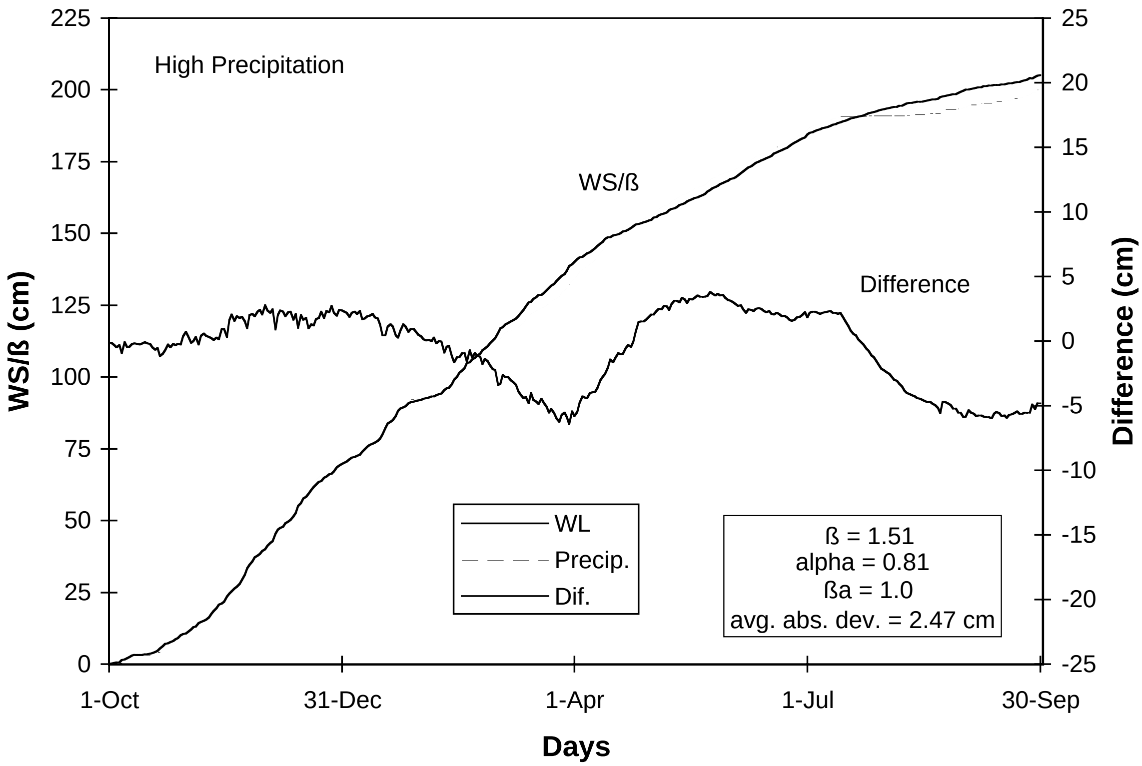

Figure 18. Cumulative water supply over coefficient ß calculated from water level by equation (9) and from precipitation by equation (10) for high precipitation case. Values for ß and α chosen based on minimizing average absolute deviation between two calculated water supply curves. p_o = 169.2 cm/y.