CHARACTERIZING CYCLIC WATER-LEVEL FLUCTUATIONS IN IRRIGATION CANALS

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ABSTRACT: A technique is demonstrated for characterizing water-level fluctuations in irrigation canals using amplitude spectral estimates obtained with a fast Fourier transform. The technique, which is often used to analyze mechanical vibrations and electrical signals, is used with hourly water-stage data to calculate dominant frequencies, amplitudes, and peaking times of water-level fluctuations in eight irrigation canals in Utah and Washington. The results of this analysis indicate that water-level fluctuations dominated by a daily cycle are statistically significant and that the time of peak water level occurred between 4 and 10 a.m. in all the canals studied. Amplitudes of water-level fluctuations in six of the eight canals that were unlined and unregulated are found to depend on canal (reach) length. Low frequency fluctuations with periods ranging from three to 10 days existed in the canals, but are statistically significant only in the spring and fall. Observations are presented about the causes and possible measures for controlling water level fluctuations in the study canals.

INTRODUCTION

Day-to-day operation of irrigation canals is complicated by water-level fluctuations caused by variable demand, changes in control settings (i.e., turning headgates on, off, or changing check-gate settings), evaporation, seepage, and/or runoff and drainage that enters the canal from upslope lands. Irrigation districts often reduce water-level fluctuations by limiting the flexibility the water user has in starting, stopping, and regulating deliveries. Such practices, however, normally reduce the efficiency of on-farm water use (Clemmens and Dedrick 1984). Management strategies and/or canal modifications that limit water-level fluctuations and allow more flexible delivery are needed to facilitate improvements in on-farm water-use efficiency. Smaller water-level fluctuations can also increase the amount of water that can be conveyed in existing canals and reduce the size of new canals by decreasing freeboard requirements. Being able to characterize irrigation canal water-level fluctuations is a prerequisite to identifying their cause and to developing and evaluating measures for their control. The objectives of this study were to: (1) Demonstrate a method for characterizing water-level fluctuations that occur in irrigation canals; and (2) illustrate the resulting information and how it might be used.

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ANALYSIS OF WATER-LEVEL FLUCTUATIONS

In traditional hydrologic analysis, various statistical methods are used to characterize stream-flow (water-level) fluctuations for risk analysis and planning of hydraulic works. These methods include frequency analyses and probability density functions. Frequency analyses have been used to obtain the probability of the occurrence of a particular water level (Linsley et al. 1958). Probability density functions, also known as flow-duration studies, are used in the sizing of hydroelectric plants and storage reservoirs for streamflow regulation. Because these analyses are usually limited to the characterization of mean daily flows, the highest frequency that can be identified with them is not more than one cycle per day (*Water Measurement* 1967). On the other hand, frequency domain analysis, a technique that is used to analyze mechanical vibrations and electrical signals, can be used to study frequencies well above and below one cycle per day.

In the present study, frequency domain analysis is used to analyze season-long records of hourly water levels observed in eight irrigation canals, thus enabling the identification of fluctuations with frequencies as high as four cycles per day. Power spectra, formally, the Fourier transform of the autocovariance (Bendat and Piersol 1971), describe the distribution of water-level variance as a function of frequency. For a discretely sampled time series, $x(n)$, the discrete Fourier coefficients are given by:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-i(2\pi/N)nk} \qquad k = 0, 1, 2, 3 \ldots N-1 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $X(k)$ is the Fourier coefficient at radian frequency $2\pi k/N$, N is the record length, and $i = \sqrt{-1}$.

The power of the kth frequency is $|X(k)|^2$ and the power spectral density at frequency k is $|X(k)|^2/N$. Fast Fourier transform (FFT) algorithms make it unnecessary to calculate the autocovariance prior to obtaining power spectral estimates, and substantially reduce the amount of computation needed to compute the Fourier coefficients (Bendat and Piersol 1971).

If no further smoothing is performed, the estimates of power spectral density given by Eq. 1 are called periodograms, and are chi-square–distributed with two degrees of freedom (Bendat and Piersol 1971). Increasing the number of degrees of freedom, either by merging neighboring spectral estimates (i.e., frequency merging), or ensemble averaging the individual estimates from several realizations of the process, or both, leads to increasingly stable estimates of power spectral density.

The amplitude of the data at any particular frequency is proportional to the square root of the power spectral level at that frequency. The constant of proportionality depends on the details of the normalization used to form the power spectrum.

PROCEDURES

Dominant frequencies, amplitudes, and peaking times were determined and used to characterize water-level fluctuations in irrigation canals—five in Utah and three in Washington. Water-level data for six of the canals (five in Utah and one in Washington) were previously obtained using standard

TABLE 1. Canals Studied to Identify Fluctuation Characteristics

Canal (1)	Section length (miles) (2)	Type (3)	Capacity		Control	Mile to closest upstream spillway (7)	Recorder	Delivery	Length of record analyzed (10)
			Begin (4)	End (5)	Section (6)		Type[a] (8)	Schedule[b] (9)	
Roza Prosser, WA	23	Earth and concrete lined	600	200	Drop	none	A	1	August, September 1986
SVID Prosser, WA	20	Earth and Rock	750	150	Drop	none	A	2	August, 1986
Benton Prosser, WA	4	Earth	100	68	Channel	none	B	2	1985, 1986
WestA USGS (10117510) Tremonton, UT	22	Earth	800	150	Channel	none	C	4	1979–1981
WestB USGS (10117530) Tremonton, UT	22	Earth and Rock	800	150	Channel	1/4 mile	C	4	1979–1980
Hammond Corinne, UT	25	Earth	150	30	Drop	5 miles	B	3	1979–1980
Corinne Corinne, UT	20	Earth	350	100	Check	10 miles	B	3	1979–1980
Central Corinne, UT	13	Earth	100	35	Check	1/2 mile	B	3	1979–1980

[a] Type of Water-Level Recorder; A. Campbell CR7 Data Logger with Analog and Digital Filtering; B. Stevens Type-F Recorder in Stilling Well; C. Stevens Digital Recorder in Stilling Well.

[b] Delivery Schedule: 1. Locked On and Off by Management, Changes Allowed Five Times per Week with 24-Hour Notice; 2. Same as 1, Changes Allowed Only Three Times per Week with 24-Hour Notice; 3. Deliveries Scheduled and Rotated in Canal Sections; 4. 90% of Discharge to Major Laterals by Management, Remainder Scheduled with Water Users Having Control.

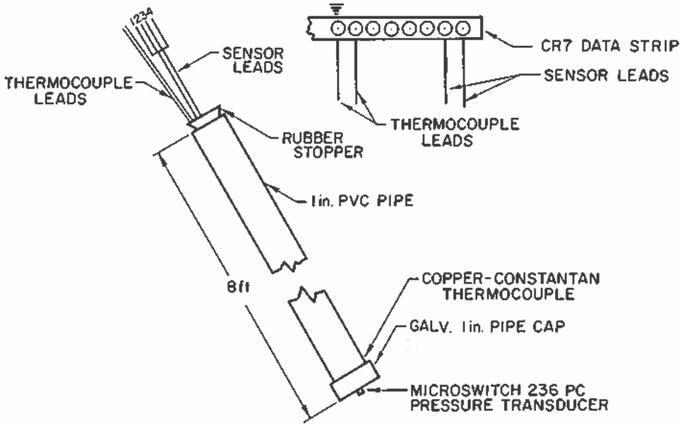

FIG. 1. Water-Level Sensor Developed for Study

stilling wells (*Water Measurement* 1967) with either Stevens type-F or digital recorders (see Table 1). Because hourly data were not available for the Roza and SVID canals in Washington (see Table 1), a water-level sensor with a temperature-compensated pressure transducer (see Fig. 1) was developed specifically for the present study to digitally measure water stages and temperatures in these canals to within 0.5%. Power spectral analysis of water-level data was used to identify the fluctuation characteristics. Reaches were selected on the basis of the availability of hourly water-level records and absence of automatic controls. The canals studied and the length of records analyzed are described in Table 1.

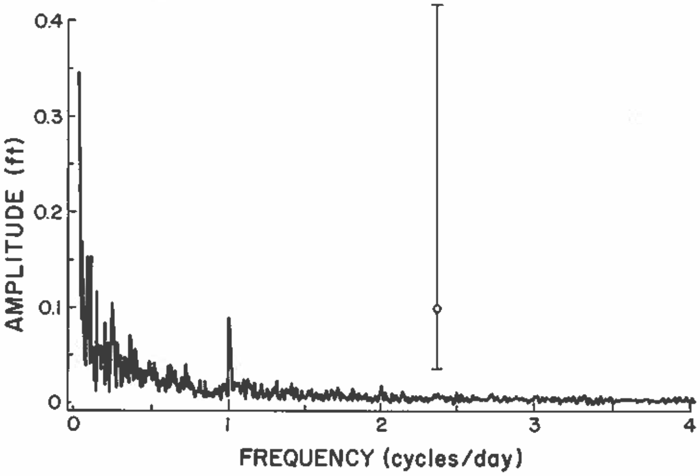

FIG. 2. Water-Level Amplitude versus Frequency from Periodogram Estimates for WestA Canal near Tremonton, Utah, 1980 (Two Degrees of Freedom; Bar Indicates 95% Confidence Interval)

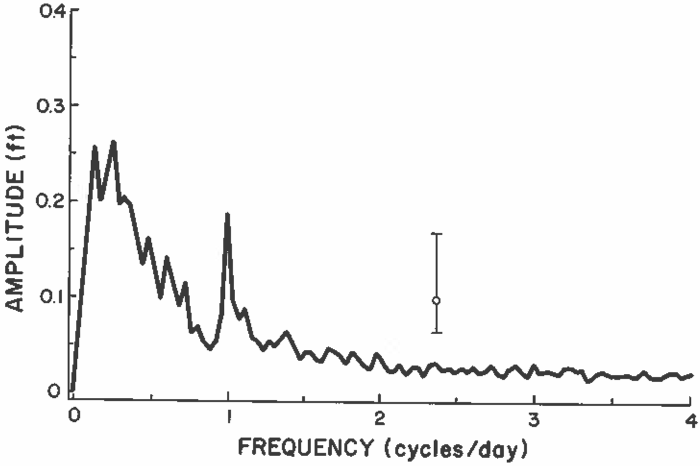

FIG. 3. Water-Level Amplitude versus Frequency from Smoothed Power Spectral Estimates for the WestA Canal near Tremonton, Utah, 1980 (Five Frequencies Merged; 10 Degrees of Freedom; Bar Indicates 95% Confidence Interval)

Estimates of water-level amplitude as a function of frequency obtained from periodograms via an FFT routine (Rice 1983) for the WestA Canal are shown in Fig. 2. To increase statistical stability, periodogram estimates from neighboring frequencies were merged (summed) to produce smoothed power spectral estimates with two additional degrees of freedom for each frequency merged. Fig. 3 displays smoothed amplitude spectral estimates (every five frequency bands have been merged) for the WestA canal data. Comparison of the 95% confidence intervals in Figs. 2 and 3 readily demonstrates the additional statistical stability that is derived from frequency merging.

RESULTS AND ANALYSIS

Two annual canal records, WestA and Hammond canals (Figs. 4 and 5) were selected as examples of the data analysis of the eight canals studied. The WestA and Hammond canals are part of the Bear River Canal system near Tremonton, Utah. Water delivery in the system is on a weekly, scheduled rotation system that provides delivery according to a continuous flow rate of one cfs per 70 acres (1 $m^3/s/1{,}000$ ha), but allows larger flow rates for shorter time periods. The schedule is on the honor system and the gates are set to the maximum flow allowable. The water users, at their pleasure, can open and close their gates to control the flow of water during their turn.

The WestA and Hammond canals exhibit great changes in water levels at the beginning of the season before the irrigation district is able to accurately anticipate demands and while the canal carries more water than necessary to meet demand (Figs. 4 and 5). After mid-May (Julian calendar day 135), the mean water levels stabilize, but continue to show short-term variations. Water levels for this latter period range from 3.8–4.7 ft (1.2–1.4 m) in the WestA Canal and from 1.3–2.0 ft (0.4–0.6 m) in the Hammond Canal.

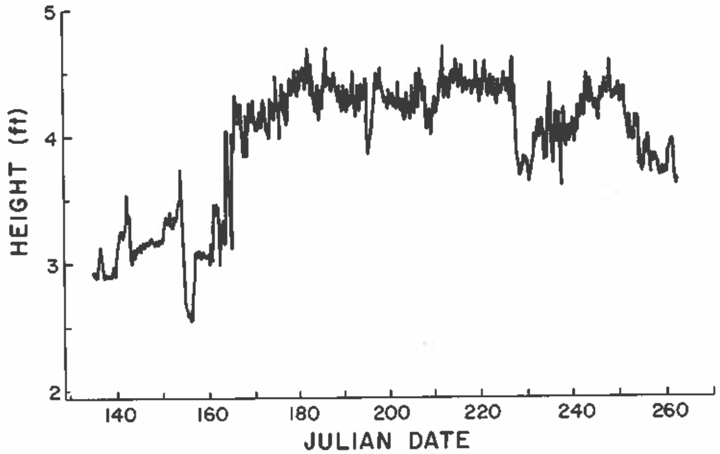

FIG. 4. Canal Gage Height Records, WestA Canal above Salt Creek near Tremonton, Utah (No. 10117510), Beginning May 15, 1980

Dominant Frequencies

The dominant frequencies of water-level fluctuations for each canal were obtained by taking the gage height data and computing smoothed spectral estimates for each of the records using the FFT analysis. Ensembles of records were averaged to produce smoothed spectral estimates with additional degrees of freedom. Spectral estimates show some significant low frequency fluctuations, which are the result of very long trends (monthly or seasonal). No attempt was made to filter the data to remove these long-term trends.

The WestA Canal has flows of 800 cfs (23 m^3/s) at its head and 150 cfs

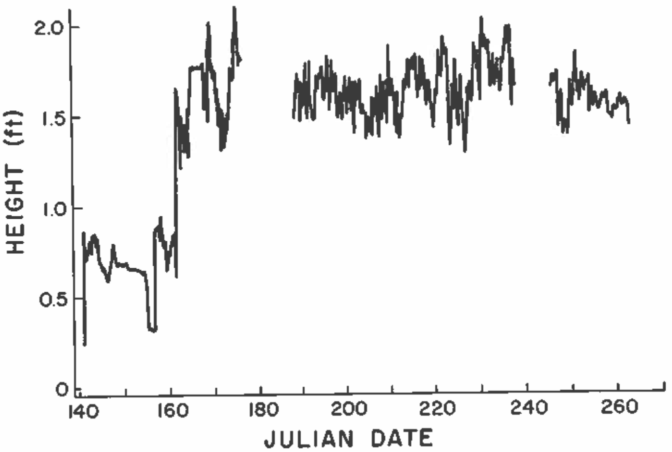

FIG. 5. Canal Gage Height Records, Hammond West Branch Canal near Corinne, Utah (No. 5 of Highway 83), Beginning May 21, 1980

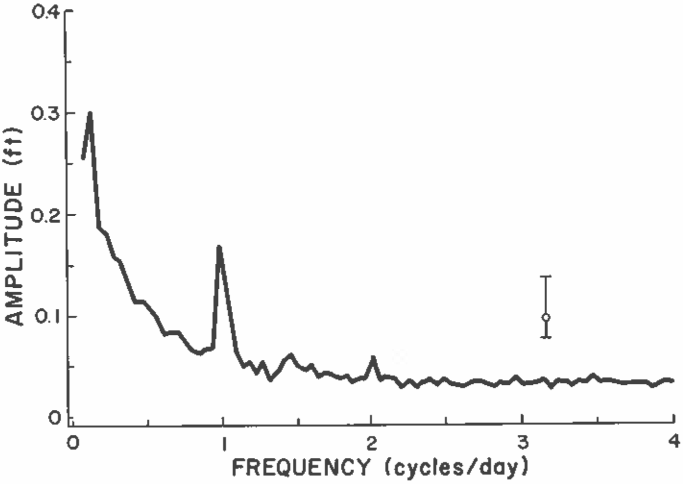

FIG. 6. Amplitude versus Frequency for WestA Canal (24 Degrees of Freedom; Bar Indicates 95% Confidence Interval)

($4.3\ m^3/s$) at the recorder. Eighty-four percent of the outflow from the canal is through district managed laterals, 16% through user-controlled turnouts. Flow records indicate both district laterals and user turnouts have a relatively constant flow when open, but the turnouts can be opened or shut according to the delivery schedule. Smoothed amplitude spectral estimates for the WestA Canal (Fig. 6) indicate significant fluctuations with a frequency of one cycle per day. These district laterals are rarely regulated daily and probably would not contribute to one cycle per day fluctuations (see Table 1). User turnouts probably contribute only minimally to the cyclic fluctuations, since they affect only 16% of the outflow.

The smoothed amplitude spectral estimate for the Hammond Canal (Fig. 7) shows significant peaks at 1.00, 0.67, and 0.20 cycles per day (periods of 1.00, 1.50, and 5.00 days, respectively). The capacity at the upstream end of the Hammond canal is 180 cfs ($5\ m^3/s$) and 30 cfs ($1\ m^3/s$) at the recorder, located in a pool formed by a check. The water is distributed through water-user-controlled turnouts. Water-user demand could contribute to the fluctuations observed in this canal. The cyclic fluctuation period of five days could be caused by water users' preference (i.e., irrigators would rather irrigate during the week and turn off on the weekend).

The only frequency with significant fluctuations for all eight canals studied was one cycle per day. This is illustrated in Fig. 8, which presents the smoothed amplitude spectral estimates for all the ensembles of data used in this study. The differences in management strategies and user freedom reduce the possibility that these fluctuations are caused by demand or management changes.

To get additional insight into the characteristics of these canal fluctuations, seasonal water levels were analyzed. Available spring, summer and fall data were each ensemble averaged. Fig. 9 shows the smoothed amplitude spectral estimates of the seasonal data. One cycle per day fluctuations were significant in all seasons at a 95% confidence interval. Both spring and fall data

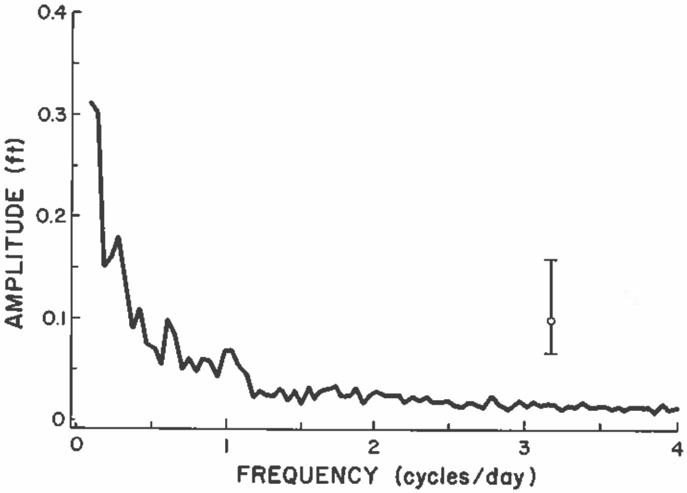

FIG. 7. Amplitude versus Frequency, Hammond Canal (12 Degrees of Freedom; Bar Indicates 95% Confidence Interval)

had significant fluctuations at lower frequencies at an 80% confidence interval. These fluctuations are probably the result of canal managers making gate adjustments during the spring and fall in response to weekly variations in irrigator demand due primarily to changes in weather. These low frequency fluctuations are not present during the peak of the season because the flow demanded by irrigators is nearly constant and equal to, or only slightly less than, the design flow for the canal. As a result, fewer and smaller gate adjustments are normally made during the peak of the season.

Amplitudes

Amplitudes associated with dominant frequencies for each canal were determined from amplitude spectra, as previously described. Examination of

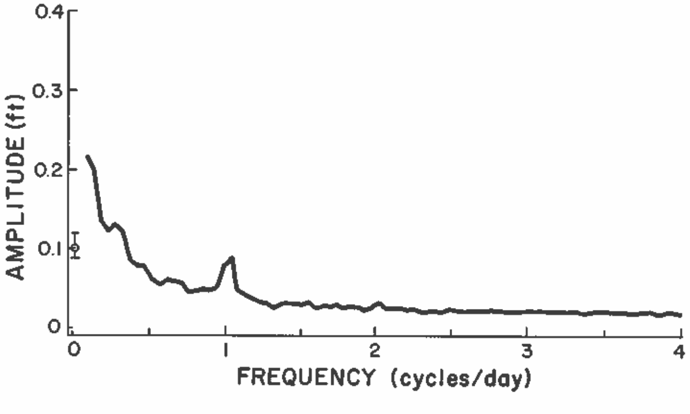

FIG. 8. Amplitude versus Frequency for All Canals Studied (88 Degrees of Freedom; Bar Indicates 95% Confidence Interval)

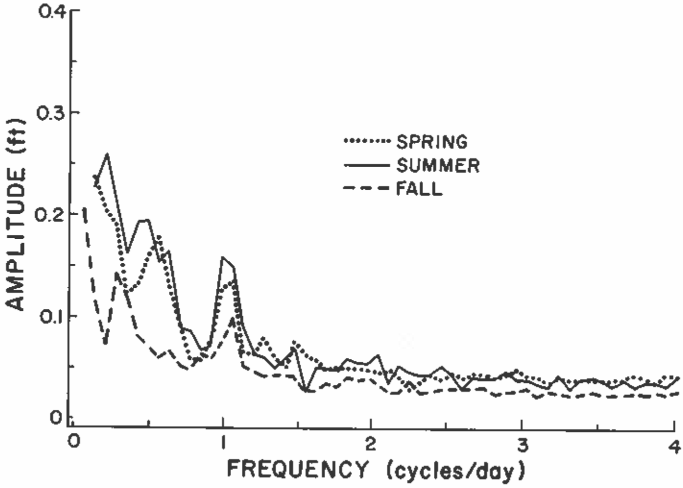

FIG. 9. Amplitude versus Frequency for Spring, Summer, and Fall, Using All Records Available (Spring, 16 Degrees of Freedom; Summer, 12 Degrees of Freedom; Fall, 12 Degrees of Freedom)

the amplitudes from all eight canals indicates that periods of one, three, five and 10 days are dominant. As can be observed from Fig. 10, only the one-day period is present in all the canals. The three- and five-day periods could be caused by the weekly demand cycles (i.e., users not irrigating on weekends). The one cycle per day amplitudes in Fig. 10 are arranged in descending order of water distribution per mile.

Linear correlation of the amplitudes versus the outflow per mile of canal

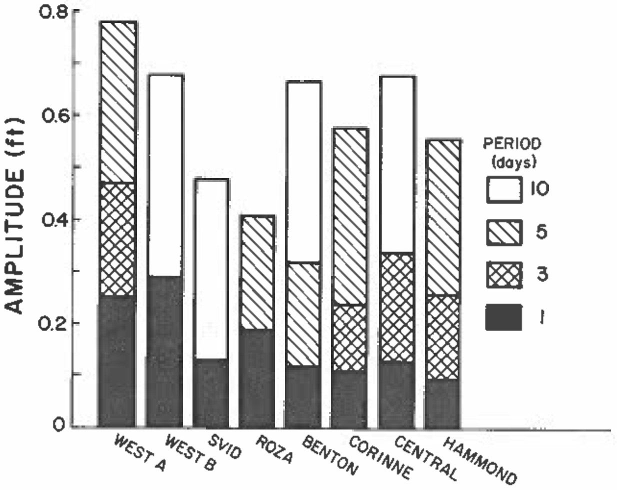

FIG. 10. Amplitude of Dominant Frequencies Identified in Study

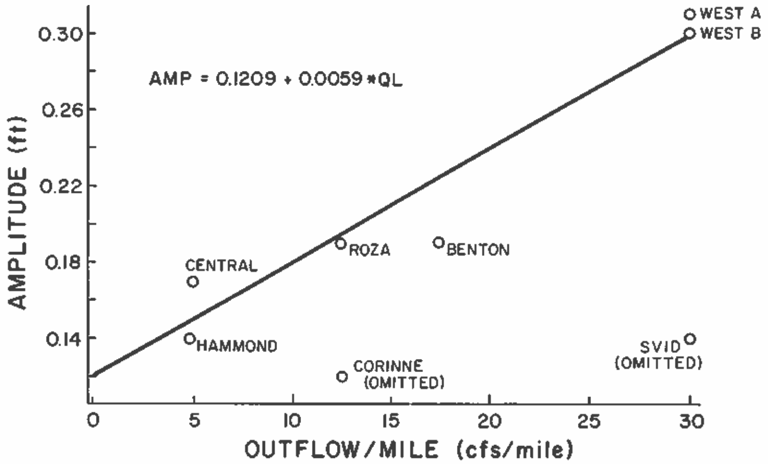

FIG. 11. Amplitude of Daily Fluctuations versus Outflow per Mile of Canal: Corinne and Roza Canals Not Included in Regression Analysis for Eq. 2

(Fig. 11) gives a coefficient of determination (r^2) of 0.93, using data from six of the eight canals. The correlation equation is:

$$AMP = 0.1209 + 0.0059Q_l \quad (2)$$

where AMP is the fluctuation amplitude at one cycle per day and Q_l is the outflow per mile of canal. The equation was derived using canals that are unlined throughout most of their length and have no automatic controls (i.e., no regulated spillways, water-level controllers, or reservoirs). The other two canals, SVID and Corinne, were not included in the analysis because of existing controls that dampened fluctuations (indicated on Fig. 11). The SVID Canal has a large check upstream of the recorder that acts as a regulating reservoir to dampen fluctuations. The Corinne Canal recorder is located in a spillway pool, which reduces the amplitude of the fluctuations there.

Daily Fluctuation Cycles

The hourly mean gage height for each record was obtained by using the entire record (spring, summer, and fall) and grouping the data according to the hour of day. Means and standard deviations were then obtained for each hourly group. Figs. 12 and 13 show plots of the mean gage height versus hour for the WestA and Hammond canals. These figures show a very definite daily peaking time for each record. The WestA Canal has an average daily peaking time of 7 a.m. for the entire year. The amplitude of its mean hourly gage height is not large (0.16 ft, or 4.8 cm), but for the study period it is consistent. The Hammond Canal peaks earlier in the day but it is not as consistent as the WestA Canal. The difference in mean hourly gage height for the two canals (Figs. 12 and 13) could be caused by different management systems. The WestA Canal distributes the water mainly through district laterals that do not introduce fluctuations into the canal, while the Hammond Canal is controlled more by the water users. The difference in use patterns between the canals could cause the differences in peaking times.

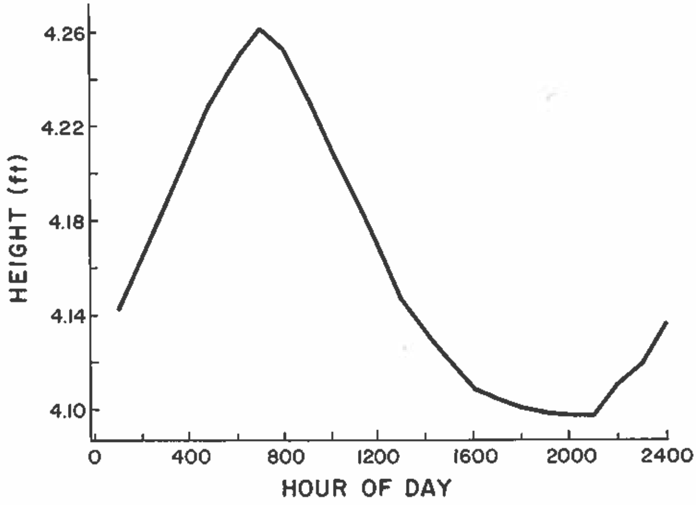

FIG. 12. Hourly Mean Gage Height, WestA Canal Near Tremonton, Utah, 1980

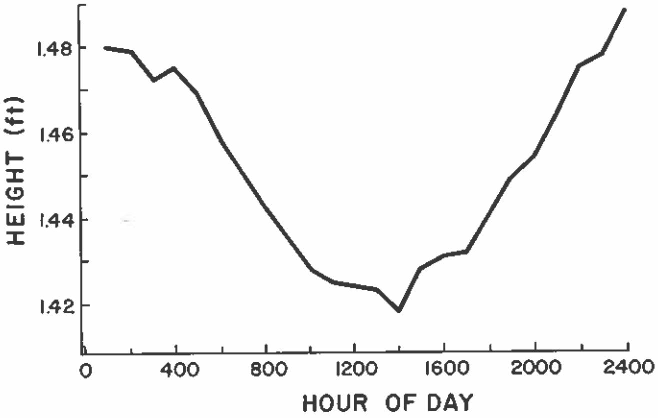

FIG. 13. Hourly Mean Gage Height, Hammond West Branch Canal Near Corinne, Utah, 1980

Peaking times (averaged over all the years analyzed) varied from canal to canal, ranging from 4 to 10 a.m. Because the fluctuations seem to follow a daily solar cycle, they may be caused by cyclic diurnal variations in evaporation and seepage from the canal. Diurnal changes in seepage occur when there are diurnal variations in canal water temperature large enough to cause significant changes in fluid viscosity and, hence, hydraulic conductivity. The daily fluctuations could also result from daily cycles in the rate at which runoff, and/or subsurface drainage from upslope irrigated lands, enters the canals.

CONCLUSIONS

Amplitude spectral estimates obtained with a fast Fourier transform were used to analyze hourly water-stage data from eight irrigation canals in Utah and Washington. Dominant frequencies, amplitudes, and peaking times of water level were calculated and used to characterize water-level fluctuations of the canals. The major results of this analysis and some general observations about causes of and measures for controlling water-level fluctuations in the study canals follow.

All eight irrigation canals had statistically significant one cycle per day fluctuations in water level, with peaks occurring between 4 and 10 a.m. This indicates that water-level fluctuations seem to follow a daily solar cycle and that they may be the result of diurnal variations in evaporation and seepage rates. They could also be the result of daily cycles in the rate at which runoff, and/or subsurface drainage from upslope irrigated lands, enters the canals.

Amplitudes of fluctuations in six of the eight canals that were unlined and unregulated were linearly related to canal outflow per mile. It therefore appears that the amplitude of water-level fluctuations may be reduced by shortening reach length in these canals. This could be done by installing checks, automated spillways, or re-regulating reservoirs.

Low frequency fluctuations with periods of 3–10 days existed in all canals, but were statistically significant only during the summer and fall. This is probably because crop-water-use rates change most rapidly during the spring and fall. Thus, it may be possible to control water-level fluctuations by scheduling water diversions into the canal from crop-water-use forecasts, especially during the spring and fall.

ACKNOWLEDGMENT

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APPENDIX. REFERENCES

Bendat, J., and Piersol, A. G. (1971). *Random data: Analysis and measurement procedures*. Wiley Interscience, New York, N.Y., 184–193.

Clemmens, A. J., and Dedrick, A. R. (1984). "Irrigation water delivery performance." *J. Irrig. Drain. Engrg.*, ASCE, 110(1), 1–13.

Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H. (1958). *Hydrology for engineers*. McGraw-Hill Book Company, New York, N.Y.

Mitchell, K. C. (1987). "Characterizing and modeling water level fluctuations in irrigation canals," thesis presented to Washington State University, at Pullman, Wash., in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Rice, J. R. (1983). *Numerical methods, software, and analysis: IMSL reference edition*. McGraw-Hill Book Company, New York, N.Y.

Water measurement manual. (1967). U.S. Department of the Interior, Bureau of Reclamation, U.S. Government Printing Office, Denver, Colo.