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EFFECTS OF MEASUREMENT FREQUENCY ON WATER-LEVEL SUMMARY STATISTICS

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Abstract: Wetland scientists and managers recognize the need to characterize hydrology for understanding wetland ecosystems. Hydrologic data, however, are not routinely collected in wetlands, in part because of a lack of knowledge about how to effectively measure hydrologic attributes and how frequently to measure water levels. To determine how measurement interval affects interpretation of water-level data, we analyzed data from seven wetlands in Oregon and Pennsylvania. We created subsets of daily data for each wetland, with measurement intervals of 2 to 28 days, then compared those subsets to the daily data for annual water-level summary statistics, monthly mean water levels, and occurrence/duration of threshold conditions (e.g., water in the root zone). Our primary goal was to determine if sampling at low frequencies can provide representative water-level data and accurate perceptions of the occurrence of water levels above thresholds. For annual water-level distributions, small data sets from 28-day measurement intervals provided summary data (e.g., median, quartiles, range) comparable to the 1-day reference data. For measurement intervals of seven days or less, average errors in estimates of stage (minimum, 25th, 50th, and 75th percentiles) were $\leq$ 0.03 m; for a 28-day interval, average errors were $<$0.05 m. Errors in estimates of maximum stage were considerably larger (0.11 m and 0.21 m for 7- and 28-day intervals, respectively) but can be circumvented using crest gauges. Errors in estimates of monthly mean stage varied greatly with measurement frequency (1–4% error for 7-day intervals, 5–15% error using one measurement per month), among wetlands and from month to month. Water-level durations above threshold values were problematic; for measurement intervals of 2 days and longer, 14-day exceedances of water in the root zone were frequently missed or spurious exceedance periods were identified. Overall, results show that sampling at monthly intervals, supplemented with crest gauges, provides a representative description of annual water-level distributions for use in classifying and comparing wetlands. More frequent sampling is required to characterize water levels for shorter (e.g., monthly) time periods and to reliably identify exceedance periods for water above threshold levels. More generally, the results remind us that the frequency and duration of sampling in hydrologic studies must be designed to ensure that data will support planned analyses.

Key Words: freshwater wetlands, measurement interval, water-level summary statistics, monthly mean water level, 14-day exceedance, sampling design

INTRODUCTION

The importance of hydrologic conditions to the structure and function of wetlands has long been recognized (e.g., Carter et al. 1979, LaBaugh 1986), but hydrology remains a component of wetland ecosystems that has not been extensively investigated. Mitsch and Gosselink (1993) recently reiterated this concern, observing that although hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes, it frequently is omitted in studies of these systems. They further noted that several of the needs for hydrologic information identified 20 years ago by Carter et al. (1979) are still valid, including the need for ''. . . improving, refining, and perhaps simplifying existing techniques for hydrologic measurements . . .;'' and for ''. . . making accurate measurements . . . and estimating the errors inherent in measurement techniques.'' Keddy et al. (1993) and Richter et al. (1996) have similarly noted the need for ecologically meaningful and measurable hydrologic indicators to support effective management of wetland resources.

Although measuring water levels is relatively straightforward, design of an effective and efficient sampling strategy can be difficult. In addition to identifying the specific types of data needed, designs must balance the need for information and the costs of obtaining it. Some types of research (e.g., determination of hydrologic budgets, separation of hydrographs and characterization of ground-water systems) require frequent, precise water-level measurements, often at several or many points within a wetland. Because of the intensive nature of such studies, data collection is usually limited to one or a few wetlands. In contrast, to address landscape-level issues such as wetland characterization, hydrogeomorphic (HGM) classification of wetlands (e.g., Cole et al. 1997, Shaffer et al. 1999), and regional assessments of wetland condition (Turner et al. 1995), large numbers of wetlands must be sampled. Because of budget and staffing constraints, sampling of individual wetlands in landscape-level studies is often limited to infrequent measurement of water levels. For these studies, good sampling design requires optimizing the tradeoff between the number of sites and the frequency of measurement.

An ideal design would use the longest measurement interval (i.e., would take the fewest measurements per site) that provides a data set with the precision and accuracy required to meet study goals. The difficulty, of course, lies in defining the measurement interval for such minimum data sets because we do not know whether infrequent sampling provides representative data for different types of analyses. In water-level and other time-series data, significant serial correlation usually exists (e.g., Matalas and Langbein 1962, Quimpo and Yang 1970, Loftis et al. 1991), so measurements taken at short intervals can generate redundant data and inflate project costs, whereas measurements taken at long intervals can miss important information and lead to equivocal or unreliable interpretation of results (Quimpo and Yang 1970). One approach that has been used to estimate sampling needs has been analyses of autocorrelation and information content (e.g., Matalas and Langbein 1962, Quimpo and Yang 1970, Loftis et al. 1991, Whitfield 1998), but these kinds of analyses have limitations. They provide a good approach for determining measurement intervals for estimates of means and variance but not for other types of analyses such as occurrence/duration of water levels above a threshold value. The analyses also require existing data from a site having water-level dynamics comparable to those expected in the sites for which the monitoring study is being designed.

In this paper, we evaluate effects of measurement interval on the reliability of several types of hydrologic data. The analyses stem from our recent and ongoing efforts to characterize the hydrology of wetlands in Pennsylvania and Oregon, USA, especially efforts to support HGM-based classifications (Cole et al. 1997, Shaffer et al. 1999). We realized that our large data sets provided an opportunity to examine the sensitivity of hydrologic variables to a critical aspect of study design—measurement interval. We used data for a subset of wetlands for which we had the most complete data and that represent the diverse hydrologic regimes found in our two study regions. We evaluated effects of measurement interval on several variables that have been used to characterize and compare the hydrology of wetlands, including descriptive statistics for stage (e.g., annual minimum, median, maximum, and range), monthly mean water levels, and duration of water levels above thresholds (e.g., water in the root zone). The specific goal of our analyses was to determine whether sampling at infrequent time intervals (up to 28 days) provides representative data for describing water levels and for accurately determining the persistence of water above thresholds. Because the required precision and accuracy of data depend on specific needs of the investigator, we focused on characterizing the magnitude of errors at different measurement intervals rather than assessing whether data met a specific criterion for precision and accuracy. Similarly, for threshold conditions, we focused on how duration of water levels above a threshold might be perceived (or mis-perceived) as the measurement interval changed, rather than on whether any specific duration was correctly identified in a particular data set.

METHODS

Data Sets

We collected water-level data used in these analyses in seven freshwater palustrine wetlands, four in the Portland, Oregon metropolitan area (OR-1 to OR-4) (Magee et al. 1993), and three in central Pennsylvania (PA-1 to PA-3) (Cole and Brooks 2000). The sites had a wide range of conditions in terms of short-term and annual water-level variability and duration of inundation (Figure 1, Table 1) and were diverse in terms of size, hydrogeomorphic class (Cole et al. 1997, Gwin

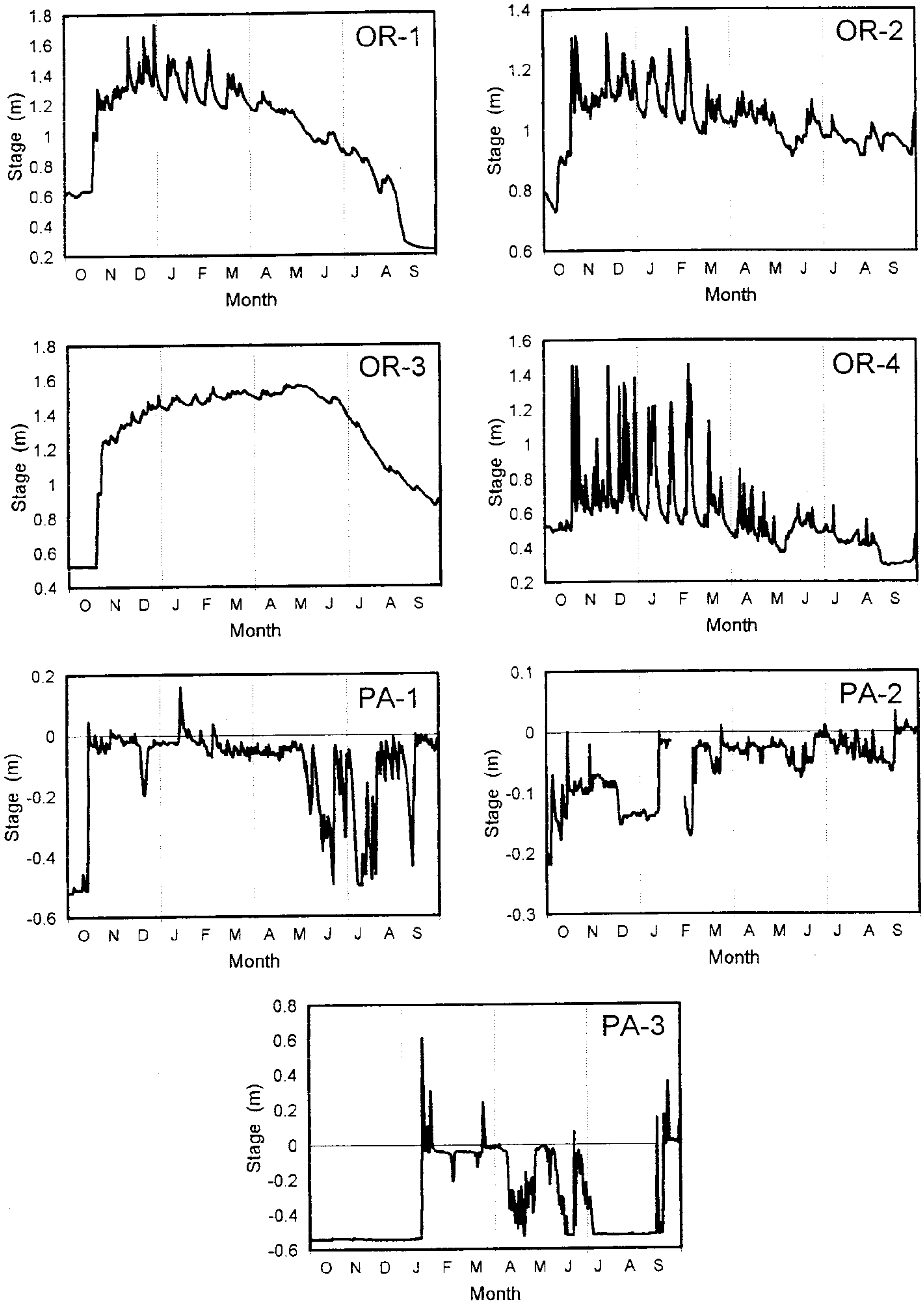

Figure 1. Hydrographs of study wetlands with daily stage data for water year 1995 (10/01/94 to 09/30/95) for Oregon wetlands, water year 1996 (10/01/95 to 09/30/96) for Pennsylvania wetlands.

et al. 1999), Cowardin class (Cowardin et al. 1979), land-use setting, and disturbance regime (Table 2).

We instrumented the Oregon wetlands with float-pulley, water-level monitors and captured data with electronic encoders and data loggers (SA101 encoder, DL86 logger, ACRO Systems, Inc., Silver Springs, NV [now High Sierra Electronics, Grass Valley, CA]). The gauges had an operating range of approximately 2.5 m (ca 1 m below to 1.5 m above ground level), with resolution of approximately 0.003 m and accuracy of 0.01 m. Water levels were referenced to the lowest ground surface in each wetland. Pennsylvania wetlands were instrumented with WL40 monitoring systems (Remote Data Systems, Wilmington, NC), which are self-contained units with a rigid capacitative sensor, placed in a 7.6 cm slotted PVC pipe with a wa-

Table 1. Summary of hydrologic conditions in study wetlands (1-day measurement intervals) in Pennsylvania and Oregon. Water levels in Oregon wetlands were referenced to the lowest ground surface in each wetland, in Pennsylvania wetlands to the ground level at the location of the gauge.

Attribute	OR-1	OR-2	OR-3	OR-4	PA-1	PA-2	PA-3
water year[a]	1995	1995	1995	1995	1996	1996	1996
n	365	365	365	365	366	354	366
stage (m)							
maximum	1.74	1.34	1.57	1.46	0.16	0.03	0.61
median	1.16	1.03	1.44	0.53	−0.05	−0.04	−0.51
minimum	0.22	0.73	0.52	0.29	−0.52	−0.22	−0.54
range in water level (m)							
maximum–minimum	1.52	0.61	1.06	1.17	0.68	0.25	1.15
90th–10th percentile	0.93	0.23	0.63	0.43	0.39	0.13	0.53
75th–25th percentile	0.50	0.12	0.37	0.19	0.10	0.07	0.50
84-day average stage (m)							
maximum	1.37	1.13	1.53	0.80	−0.02	−0.02	−0.02
minimum	0.53	0.96	1.06	0.39	−0.23	−0.11	−0.54
range	0.84	0.17	0.47	0.41	0.21	0.09	0.53
% data points above threshold							
surface (>0 m)	100	100	100	100	7	8	8
root zone (>−0.3 m)	100	100	100	100	86	100	41

[a] October 1, 1994 to September 30, 1995 for Oregon wetlands; October 1, 1995 to September 30, 1996 for Pennsylvania wetlands.

terproof data storage unit located above the sensor. The gauges had an operating range of 1.02 m (ca 0.5 m above and below ground level), with resolution of 0.005 m and accuracy of 0.01 m. Water levels were referenced to the ground level at each gauge. Installation and operation of gauges for the Pennsylvania wetlands are described in detail by Cole and Brooks (2000).

Data Analysis

We designed data analyses to examine several types of water-level descriptors that have been used to characterize wetland hydrology. Because water levels vary on a continuous time frame, any set of discrete measurements provides an estimate of the true distribution of water levels. Our goal was to determine how the reliability of those estimates is affected by the frequency of measurement and the number of data points, with a focus on determining whether infrequent measurement can provide representative data for wetland classification and for regional assessments. We analyzed data for one year because one annual cycle is probably the minimum monitoring period likely to be used for characterizing wetland hydrology. We used daily data as our reference data set, based on preliminary analyses showing close correspondence between daily data and raw three-hour data sets. In those analyses, except for a few values of maximum stage, estimates of water-level distributions (e.g., minimum, median, 25th and 75th percentiles) from the daily data set were always within 0.02 m of the corresponding value for 3-hour data, and most (>90%) values were within 0.01 m. From raw data, we took the instantaneous stage at midnight for daily values; we used data collected during water year 1995 (10/01/94 to 09/30/95) for Oregon sites and water year 1996 (10/01/95 to 09/30/96) for Pennsylvania wetlands. The 1-day data sets were then used to create a series of data subsets for measurement intervals of 2, 4, 7, 14, and 28 days. For each measurement interval, we generated all subsets of data that might have been collected during the year (e.g., for the 4-day measurement interval we created four data sets—one with data for days 1, 5, 9 . . .; a second for days 2, 6, 10 . . .; a third for days 3, 7, 11 . . .; and a fourth for days 4, 8, 12 . . .). This procedure resulted in a total of 56 data sets for each wetland, with the number of sample points in each data set inversely related to the measurement interval. The 1-day data set had 365 data points for the Oregon wetlands and 366 for the Pennsylvania wetlands (1996 was a leap year). Data sets for the 2-day interval had 182 or 183 data points; those for a 4-day interval had 91 or 92 data points, etc.; the smallest data sets (28-day interval) had 13 or 14 data points.

Annual Water-Level Distributions. For each wetland and data set, we determined seven percentiles of the water-level distribution, including the minimum (0th percentile), median (50th percentile), and maximum

Table 2. Characteristics of study wetlands. In descriptions of disturbance, ''wetland'' describes conditions within the wetland and ''landscape'' describes conditions in the surrounding landscape.

Site ID	Area (ha)	HGM Regional (Sub)Class[a]	Cowardin Class[b]	Land Use (Local)	Disturbance
OR-1	1.0	riverine	PEM	agriculture	wetland—moderate, some grazing landscape—moderate, pasture/row crops
OR-2	1.8	in-stream depression	PEM/PUB	undisturbed	wetland—severe, excavated pond landscape—moderate, but urbanizing
OR-3	0.1	depression	PUB	industrial	wetland—severe, fill, hydrologic modification landscape—severe, industrial, transportation corridor
OR-4	0.9	depression in riverine setting	PUB/PEM/PSS	commercial	wetland—severe, excavated pond landscape—severe, urbanized, hydrologic modification
PA-1	2.0	slope	PEM/PSS	agriculture and residential	wetland—moderate, road and farm runoff landscape—moderate, pasture and some urbanization
PA-2	0.2	riparian depression	PEM	undisturbed	wetland—pristine landscape—pristine, forested
PA-3	0.3	headwater floodplain	PSS/PEM	agriculture and residential	wetland—severe, sedimentation landscape—severe, agriculture, hydrologic modification

[a] HGM classes for Oregon wetlands defined by Gwin et al. (1999), for Pennsylvania wetlands by Cole et al. (1997).

[b] Classes as defined by Cowardin et al. (1979); PEM—palustrine emergent wetland, PSS—palustrine scrub-shrub wetland, and PUB—palustrine unconsolidated bottom.

(100th percentile), along with 10th, 25th, 75th, and 90th percentiles. We recognized the potential for large errors in estimates of minimum and maximum water levels in the reduced data sets and included 10th and 90th percentiles in analyses so we could characterize a larger portion of the water-level distribution than that between 25th and 75th percentiles. Out-of-range values (e.g., well was dry or water overtopped gauge) occurred at some sites and were recorded as the minimum or maximum reading for the gauge and included in analyses. For each percentile, we calculated means for all data sets and for each measurement interval. We also identified extreme (highest and lowest) values for each percentile for each site and measurement interval.

We computed errors in stage data as the absolute value of the difference in stage between the 1-day data set and the data set being evaluated:

$$\text{error}_{p,w,i} = |\text{stage}_{p,w,i} - \text{stage}_{p,w,1}| \qquad (1)$$

where p, w, and i identify the percentile of the data distribution, wetland, and measurement interval, and 1 refers to the 1-day data set. To facilitate overall comparison of data (i.e., across percentiles and among measurement intervals), we calculated the mean error in stage for each percentile and measurement interval, using data for each wetland (eqn. 2), and for all wetlands (eqn. 3):

$$\text{mean\_error}_{p,w,i} = \sum_{i=1}^{m} \text{error}_{p,w,i}/\text{m} \qquad (2)$$

$$\text{mean\_error}_{p,i} = \sum_{w=1}^{n} \sum_{i=1}^{m} \text{error}_{p,w,i}/(\text{m}*\text{n}) \qquad (3)$$

where ''m'' is the number of data sets for the measurement interval, and ''n'' is the number of wetlands.

Because total range in stage varied widely among wetlands (0.25 to 1.52 m), we also computed errors as a percentage of the total range in stage (maximum − minimum) of the 1-day data set for each wetland to facilitate comparison of data among wetlands. Percent error was computed as:

$$\text{pct\_error}_{p,w,i} = 100*\text{error}_{p,w,i}/\text{range}_{w,1} \qquad (4)$$

We calculated mean percent error for each wetland and for all wetlands using an approach identical to that for mean error in equations 2 and 3, except by using ''pct_error'' rather than ''error.'' Finally, to provide an estimate of the worst-case magnitude of errors for each measurement interval, for each percentile and measurement interval we calculated the mean of the largest percent error for each wetland:

$$\text{max\_pcterr}_{p,i} = \sum_{w=1}^{n} (\text{max\_pcterr}_{p,w,i})/\text{n} \qquad (5)$$

where $\text{max\_pcterr}_{p,w,i}$ is the value of the largest percent error, for a given percentile and measurement interval, for each wetland.

We also calculated and compared several measures of the annual range in water level for each measurement interval. We calculated total (maximum minus minimum) and interquartile (75th minus 25th percentile) ranges and also estimated seasonal range by calculating moving 84-day averages of stage for each data set, identifying the highest and lowest 84-day values, and computing the difference between them as the seasonal range in water level. The 84-day moving average is adapted from the 90-day average suggested by Richter et al. (1996) and was used here because we believe it describes typical wet and dry season conditions better than maximum and minimum values that are defined by extreme conditions. We used 84 days in lieu of 90 days because 84 days is an exact multiple of all of our measurement intervals and thus allows direct comparison of data for a common time period.

In describing analyses, we have focused on measurement interval, but in actual analyses, the number of data points was likely more important than measurement interval in affecting reliability of data. For a given measurement interval, the number of data points is proportional to the duration of monitoring, so a potential benefit of increasing the duration of monitoring is to increase the number of data points, perhaps decreasing errors in estimates of water-level descriptors. To evaluate this possibility, we analyzed data for the four Oregon wetlands for three years (calendar year 1994–1996) in the same manner described above for water-year 1995 data. Errors in estimates of percentiles of water-level distribution in the 1995 and three-year data were then compared.

Monthly Mean Water Level. Monthly mean water level is used to describe temporal variability. Using procedures analogous to those described above for the annual data set, we created subsets of monthly data for each wetland and characterized uncertainties in estimates of monthly mean water level for each wetland. We used 1-day data as the reference condition and estimated mean water levels for 2-day, 4-day, and 7-day measurement intervals for each month; we also estimated means for data sets with two measurements per month (e.g., 1st and 16th, 2nd and 17th, etc.) and for one daily value per month. For one measurement per month, we looked at data for all days of the month and also at data just for the 15th day of the month (Novitzki 1979). The rationale for sampling on the 15th is that it samples the midpoint (for that month) of any trend of changing water level (e.g., drawdown during spring and summer). In contrast, a sample taken at the start of the month, for instance, would overestimate the monthly mean during a prolonged period of falling water levels or would underestimate the mean in a period of rising water. To describe errors in the reduced data sets, we calculated the root mean square error (RMSE) of differences between estimates of mean stage for each data set and the mean stage defined by the 1-day reference data. We summarized data for each measurement interval and month.

Threshold Water Levels. Along with distributions of water levels, we determined the occurrence and duration of water levels above specific thresholds. Threshold data are used in wetland delineation and can also be important for understanding distributions of vegetation and development of redoximorphic features of soils (e.g., Environmental Laboratory 1987, National Research Council 1995). Frequencies of water level above threshold levels also have been shown to vary between naturally occurring wetlands and mitigation wetlands and among HGM classes, suggesting that threshold data can be useful for classifying and comparing different kinds of wetlands (Cole et al. 1997, Shaffer et al. 1999).

To evaluate how measurement interval affects the perceived occurrence and duration of water above a threshold level, we analyzed occurrence of water above two thresholds—inundation (stage > 0 m) and water in the root zone (> -0.30 m). For each data set, we determined the proportion of data points with water levels above each threshold. We also identified each period when water was in/above the root zone for 14 or more consecutive days (16 days for a 4-day interval). To identify 14-day occurrences, we counted only the time between consecutive measurement dates (e.g., for a 7-day measurement interval, the water level must be > -0.30 m on three consecutive dates). Our goal in this analysis was to assess how perceptions of exceedance periods might change with measurement interval, so we evaluated all apparent exceedance periods for the year, rather than limiting consideration to data for the growing season as would be done in an analysis for purposes of delineation. We conducted these analyses only for two Pennsylvania wetlands because water was present in the root zone throughout the year in the other five wetlands. We summarized results to describe overall comparability of exceedance periods defined for the 1-day data and for longer measurement intervals.

We compared the occurrence of 14-day exceedance periods defined by other data sets to conditions in the 1-day reference data and characterized results for each data set as

1. ‘‘similar’’ = same number of exceedance periods, with comparable start and end dates;
2. ‘‘omission’’ = at least one 14-day exceedance pe-

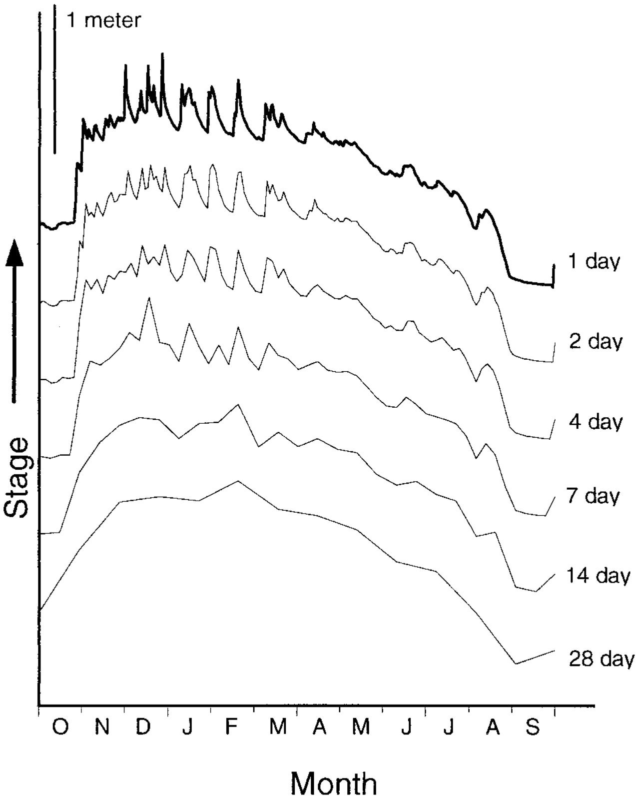

Figure 2. Hydrographs of water levels in wetland OR-1 for the period October 1, 1994 to September 30, 1995 for measurement intervals of 1 to 28 days. Data are offset along the Y-axis for presentation purposes; actual stage (1-day data) varied from 0.22 to 1.74 meters.

riod occurred in the 1-day data set, but not in the data set being evaluated;

3. "spurious exceedance" = a 14-day exceedance period was identified in the data set being evaluated, but not in the 1-day data;
4. "extension" = an exceedance period was identified in both the 1-day data and in the data set being evaluated, but lasted longer, by more than 14 days, in the data being evaluated; or
5. "merger" = two or more discrete exceedance periods identified in the 1-day data were merged into a single, longer exceedance period in the data set being evaluated.

RESULTS

Hydrographs from site OR-1 for measurement intervals of 1 to 28 days (Figure 2) provide an example of how perceptions of changes in water level can be affected by measurement interval. The hydrograph for 1-day data shows both a well-defined annual pattern in stage and extensive short-term variability in water levels associated with storm events. For measurement intervals longer than one day, the annual pattern in stage remains well-defined, even in data for a 28-day interval. Detail about short-term change, however, decreases as the measurement interval is increased. The choppy hydrographs for 4- and 7-day intervals suggest that considerable short-term variability in stage is occurring, but hydrographs convey essentially no information about the frequency, magnitude, or duration of those changes. Hydrographs for 14- and 28-day intervals give no information about the occurrence of short-term changes in water level.

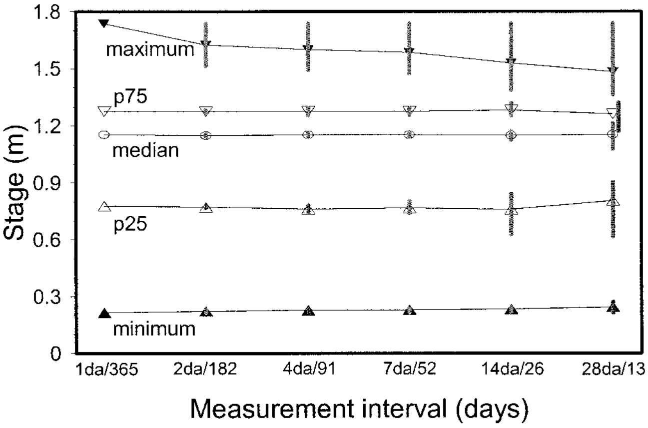

Figure 3. Summary of stage data for wetland OR-1 for the period October 1, 1994 to September 30, 1995 showing average and range (vertical bars) in stage, for measurement intervals of 1 to 28 days, for quartiles of stage distribution. Labels on the X-axis indicate measurement interval (days) and the number of sample points in each data set.

Annual Water-Level Distributions

We summarized data for OR-1 (Figure 3) to show how measurement frequency affects means and ranges of estimates of the annual stage distribution. For four of the percentiles shown (minimum, median, 25th, and 75th percentiles), mean stage values for measurement intervals of 2 to 28 days were consistently close ($\pm$0.03 m) to the 1-day (reference) values. Variability in estimates of stage in individual data sets was also small; for intervals of 7 days or less, all estimates of stage were within 0.035 m of the 1-day value ($\leq$ 2.5% of range in stage), and for intervals of 14 and 28 days ($n = 26$ or 13, respectively), all estimates were within 11% of the 1-day value and most were much closer.

Errors in estimates of maximum stage were considerably larger than for other points on the water-level distribution for OR-1. Average estimates of maximum stage decreased monotonically, from the reference value of 1.74 m (1-day data) to 1.48 m in 28-day data. The average error in estimates of maximum stage increased from 0.11 m (2-day data) to 0.25 m (28-day

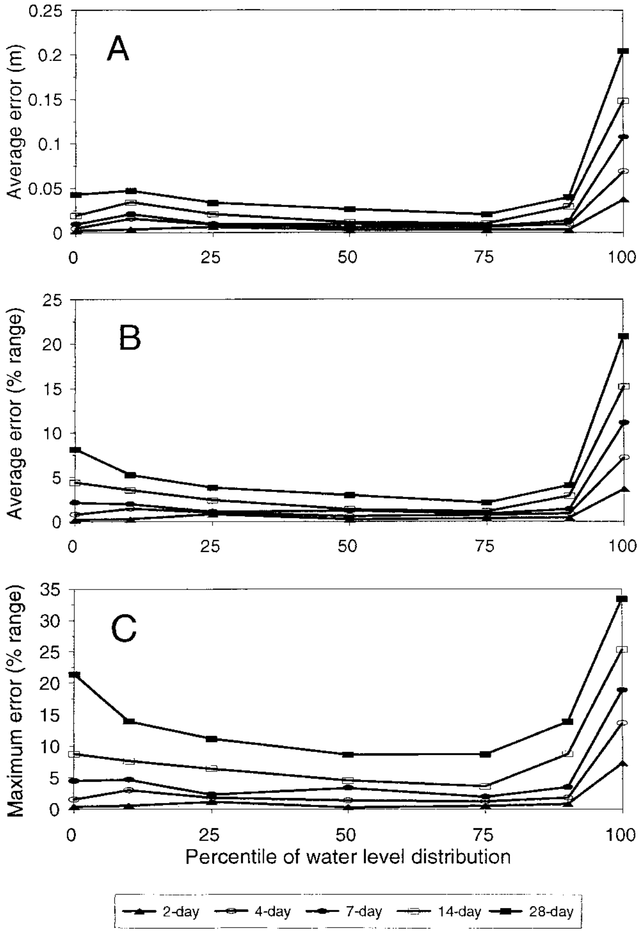

Figure 4. Average and maximum errors in estimates of stage for all wetlands and measurement intervals showing (A) the mean of the absolute value of errors between estimated values and reference values (in m); (B) the mean of the absolute value of errors between estimated values and reference values, expressed as a percentage of the range in total stage at each site; and (C) the mean of the absolute value of the largest error, as a percentage of the total range in stage in each wetland, for each wetland and measurement interval.

data). Worst case errors in estimates of maximum stage were as large as 0.37 m, a value of about 25% of the total range in stage for OR-1. The relatively large errors reflect the fact that maximum stage is single-valued and occurred during a short-lived storm event in which water levels were substantially higher than during non-storm conditions. The potential for a similar situation exists with minimum stage, although in this and probably many other wetlands, errors in estimates of minimum stage are small because it is the final datum in a gradual recession of water levels.

Combining data for all wetlands, data sets, and measurement intervals, we found that average errors in estimates of water level were generally small (Figure 4a). With the exception of maximum water levels, average errors were <0.02 m and <0.05 m for 7- and 28-day intervals, respectively. The size of errors increased monotonically with measurement interval, but even the smallest data sets (13 data points) generally provide representative estimates of the stage distribution. For the diverse data from the seven wetlands considered in our analyses, errors were small across all percentiles except maximum water level, for which the average deviation from true maximum stage varied from 0.04 m (2-day data) to 0.21 m (28-day data).

Errors expressed as a percentage of the total range in stage (Figure 4b) are consistent with data in Figure 4a, showing small errors in most estimates of stage distribution. For data between the 10th and 90th percentiles of distributions, the average error in stage was ≤2% of the range for a 7-day measurement interval and ≤ 5% of range for data collected at 28-day intervals. Errors for minimum stage are somewhat larger (8% for 28-day interval), whereas errors for maximum stage are considerably larger, ranging from 4% (2-day data) to 21% (28-day data). Despite the very diverse dynamics and ranges of water levels in the seven wetlands considered here, there was, in general, little difference in the size of errors among the seven wetlands. For example, the overall average error for 28-day data in estimated water levels for the 10th, 25th, 50th, 75th, and 90th percentiles of distributions varied from 2.3% in PA-3 to 5.5% in PA-1. Differences in estimates of maximum stage between wetlands were much more pronounced. The mean error in estimates of maximum water level was only 1% for OR-3 (a site with water levels controlled by ground water and very little short-term variability in stage) but was 31% in OR-4 (a site with many large storm peaks) and 45% in PA-3 (a site at which the 1-day maximum stage was more than 0.5 m higher than all but a few other daily stage levels). Worst-case errors in stage estimates (i.e., the averages of maximum errors for each of the seven wetlands) (Figure 4c) were larger than average errors by about a factor of two. With the exception of maximum stage, averages of maximum errors were ≤ 5% for measurement intervals of seven days or less and ≤ 15% for the 10th to 90th percentiles of stage, even for a 28-day interval.

Errors in estimates of the range in stage vary sharply among the three variables considered (Figure 5). For total range in stage, errors in estimates increased substantially with measurement interval; for 7 and 28-day intervals, average estimates of range were only 87% and 71% of the true range defined by the 1-day data. The underestimates of total range were expected, as they reflect the underestimates of maximum stage in many data sets. Errors in estimates of interquartile range were all ≤2%; for seasonal range, errors were ≤2% in 2- to 14-day data and <8% in 28-day data.

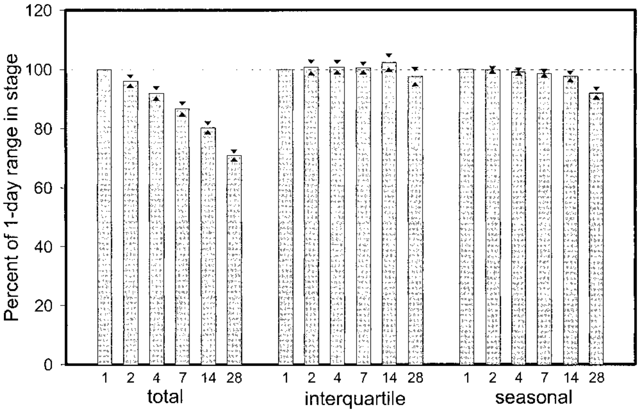

Figure 5. Average range in stage for all wetlands and data sets for each measurement interval, expressed as the percent of range in the 1-day data sets. Data are shown for total range (maximum minus minimum), interquartile range (25th to 75th percentiles), and seasonal range (84-day maximum minus 84-day minimum). Symbols indicate ± one standard error of mean.

Comparison of data for one- and three-year periods for the Oregon wetlands shows that, along with other benefits of extending the duration of monitoring, it also helps reduce errors in estimates of water-level distributions. In the three-year data sets, errors for average and worst-case estimates of stage (for minimum, median, 10th, 25th, 75th, and 90th percentiles) and for measurement intervals of 2 to 28 days were reduced by 55–65% compared to errors based on one year of data, confirming the importance of sample size in the analysis. Errors in estimates of maximum stage, however, were reduced by $\leq$ 10% in the larger data sets, reflecting the low probability of capturing a single extreme value with infrequent measurements, regardless of the duration of monitoring.

Monthly Mean Water Levels

Uncertainties in estimates of monthly mean stage varied widely with measurement interval, among sites, and from month to month at individual sites. Not surprisingly, errors in estimates of monthly stage increased as measurement interval increased, with RMSE changing from an average of less than 0.01 m (2-day interval) to 0.09 m for measurements taken only once a month (Table 3). Expressed as a percentage of total range in stage for each site, mean errors were less than 1% of range at all sites for a 2-day interval, increased to 1–4% of range for 7-day measurements, and to 5–15% of range for once-a-month measurements. Errors varied by a factor of about three among wetlands and were smallest (as a percentage of range) for OR-3, a ground-water site with very little short-term variability in water levels. The largest errors occurred in data for OR-4 and the three Pennsylvania wetlands, all of which had substantial short-term variability in water levels. Figure 6 shows an example of monthly data for PA-1; for this wetland, errors varied by an order of magnitude from month to month. Errors were large in October (RMSE for 7-day data = 0.054 m) and in June and July, months with fluctuating water levels, but were low (RMSE for 7-day data $\leq$0.01 m) during winter and early spring (November to April) when the seasonal water table was stable at the ground surface. For once-a-month sampling, errors for a sample taken on the 15th day of the month were only slightly smaller than for a sample taken on a random day of the month.

Threshold Water Levels

The proportion of time that water levels exceeded thresholds varied greatly among sites (Tables 1 and 4).

Table 3. Root mean square error (RMSE) of estimates of monthly mean water level from estimates made using 2-, 4-, and 7-day measurement intervals and estimates made using one or two measurements per month. Mean water levels for 1-day data were used as the reference value in computing errors. For one measurement per month, data are included for two sets of analyses, one for measurements taken on all possible sample dates, and a second for measurements taken only on the 15th day of each month. RMSE values are in meters; values in parentheses express RMSE as a percent of the total range in stage for each site.

Site	2-Day Interval	4-Day Interval	7-Day Interval	Twice per Month	Once per Month	
					All Days	15th Only
OR-1	0.006 (0.4)	0.012 (0.8)	0.018 (1.2)	0.049 (3.2)	0.084 (5.5)	0.090
OR-2	0.002 (0.3)	0.010 (1.6)	0.017 (2.7)	0.040 (6.6)	0.062 (10.2)	0.051
OR-3	0.002 (0.2)	0.003 (0.3)	0.014 (1.3)	0.030 (2.9)	0.055 (5.2)	0.027
OR-4	0.011 (0.9)	0.036 (3.1)	0.047 (4.1)	0.118 (10.1)	0.164 (14.1)	0.156
PA-1	0.004 (0.5)	0.010 (1.4)	0.026 (3.8)	0.056 (8.2)	0.100 (14.7)	0.097
PA-2	0.002 (0.6)	0.005 (2.1)	0.009 (3.7)	0.028 (11.0)	0.032 (13.0)	0.030
PA-3	0.007 (0.6)	0.031 (2.7)	0.049 (4.3)	0.075 (6.5)	0.153 (13.3)	0.123
mean—all sites	0.005 (0.5)	0.015 (1.7)	0.025 (3.0)	0.056 (6.9)	0.093 (10.9)	0.082

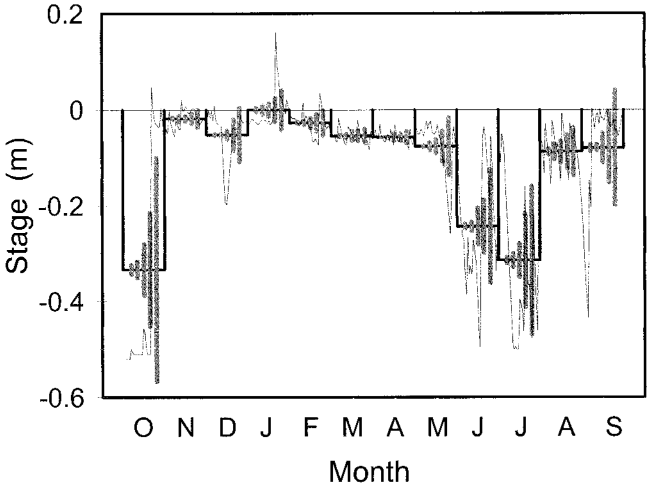

Figure 6. Effects of measurement interval on uncertainty in estimates of monthly mean water levels for PA-1. Daily stage (solid line) and monthly mean stage from 1-day data (bars) are shown; error bars (± 1 root mean square error (RMSE)) show increasing values of RMSE for estimates of monthly mean stage determined for measurement intervals of (left to right) 2 days, 4 days, 7 days, 2 measurements per month, and 1 measurement per month.

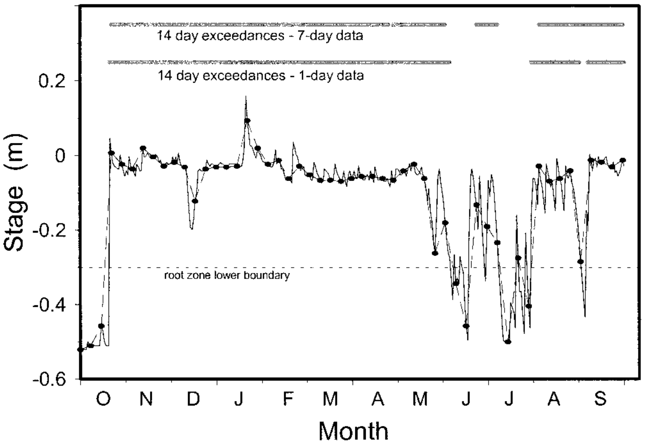

Figure 7. One-day (solid line) and 7-day (broken line with circles) stage for wetland PA-1 showing examples of perceived differences in the occurrence of periods of 14 or more days of water in/above the rooting zone. Bars at the top indicate periods of 14-day exceedance for the 1- and 7-day data sets.

The four Oregon wetlands all had standing water throughout the year, whereas Pennsylvania wetlands had water in the root zone for 41 to 100% of the year and standing water for 7 to 9% of the year. For measurement intervals of 2 to 14 days, estimates of the time water was in the root zone varied considerably among data sets (e.g., from 35 to 50% of the year in PA-3). Estimates of the extent of inundation also showed important variability; some data sets for PA-1 and PA-2 did not have any measurement points with standing water, but other data sets overestimated the true occurrence by nearly a factor of two (Table 4).

The apparent occurrence of 14-day exceedance periods for water in the root zone varied greatly with measurement interval. For PA-1 (Figure 7), both 1- and 7-day data sets identified a long period of persistent water in the root zone for about the first eight months of the year. For the balance of the year, the two data sets identified very different 14-day exceedance periods. The 1-day data had two exceedance periods, from days 303–336 and 340–365, but in 7-day data (for the example data set used here), these periods were merged into a single exceedance from days 308–364. The 7-day data also had water in the root zone on three consecutive measurement dates (days 266, 273, 280), which led to identification of this period as another 14-day exceedance, but there was no 14-day exceedance in 1-day data. Measurement dates can also affect perceived results. A different data set for a 7-day interval, started one day later than the example data just described, would have identified exceedance periods similar to those in 1-day data (i.e., it would have identified two separate exceedance periods between days 309–365 and would not have identified a 14-day period of high water around days 260–280).

A summary of data for apparent 14-day exceedances of water in the root zone (Figure 8) shows that with

Table 4. Percentage of water levels exceeding threshold levels for measurement intervals of 1 to 14 days. For intervals of 2 to 14 days, ranges of values for individual data sets are listed. Values listed for percentage of time water levels were above the base of the rooting zone (−0.3 m) include the percentage of time when standing water was present.

			PA-1		PA-2		PA-3	
Interval (Days)	# Data Sets	Data Points per Set	Root Zone	Standing Water	Root Zone	Standing Water	Root Zone	Standing Water
1	1	366	86	7	100	9	41	7
2	2	183	85–86	7	100	7–10	41	3–7
4	4	92	85–88	5–8	100	7–11	40–42	4–9
7	7	52	81–88	6–8	100	2–12	37–46	6–10
14	14	26	77–96	0–12	100	0–16	35–50	4–12

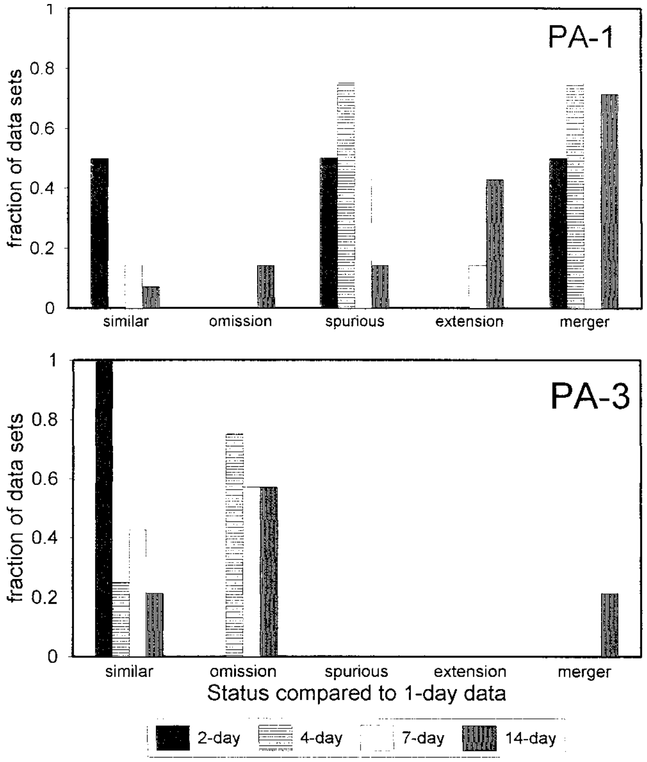

Figure 8. Histograms comparing the apparent occurrence of 14-day exceedances of water in the root zone in PA-1 and PA-3 for measurement intervals of 2 to 14 days compared to occurrences in the 1-day data. For PA-1, the sum of values for some measurement intervals is more than 1.0 because some individual data sets had both a merger of exceedance periods and a spurious 14-day exceedance. Status of each data set was characterized as ''similar'' = same number of exceedance periods, with comparable start and end dates; ''omission'' = at least one 14-day exceedance period occurred in the 1-day data set but not in the data set being evaluated; ''spurious exceedance'' = a 14-day exceedance period was identified in the data set being evaluated but not in the 1-day data; ''extension'' = an exceedance period was identified in both the 1-day data and in the data set being evaluated but lasted longer, by more than 14 days, in the data being evaluated; or ''merger'' = two or more discrete exceedance periods identified in the 1-day data were merged into a single, longer exceedance period in the data set being evaluated.

one exception (2-day data for PA-3), no more than half the data sets for any measurement interval for PA-1 or PA-3 had exceedance periods similar to those in the 1-day data. Inconsistencies were especially common in data for PA-1, for which only 3 of the total of 27 data sets had exceedance periods similar to those in the 1-day data. At this site, both merged periods and spurious exceedances were common, but exceedance periods sometimes also were extended or missed. For PA-3, most discrepancies between data for 1-day and longer intervals arose from a single exceedance in 1-day data that lasted 16 days. This exceedance was missed in many of the data sets with measurement intervals of 4 days or more.

DISCUSSION

Our results, characterizing errors in estimates of annual water-level distributions for a diverse group of wetlands, show that data from infrequent measurements provide generally representative estimates of water-levels distributions. Except for maximum water level, estimates of variables derived from 28-day data were, on average, within 0.05 m and 5% of the values defined by daily measurements and were smaller for shorter measurement intervals. Large errors in estimates of maximum or minimum stage need not compromise the overall ability to collect reliable data using long measurement intervals because there are alternate approaches for measuring extreme values of stage. A variety of measuring devices exist to provide accurate determination of maximum and minimum levels, regardless of interval (e.g., Euliss and Mushet 1996, Richter 1997). The precision and accuracy required for water-level data can vary greatly with the intended uses of the data. For data uses requiring high precision and accuracy, or for applications describing short-term changes in water level (e.g., characterization of diurnal phenomena or storm-event changes), sampling at intervals less than one day is required. For data uses that require a general understanding of annual patterns in water level, such as for classifying and comparing water conditions in populations of wetlands (e.g., comparing wetlands in different hydrogeomorphic classes), our data suggest that measurements taken at intervals as long as one month (supplemented as needed by crest gauge data) can effectively characterize water levels.

For describing monthly water levels, the appropriateness of using long measurement intervals once again depends on planned uses of data. As measurement intervals increase, increasing errors in estimates of mean water level will at some point compromise the representativeness of data. For intervals of seven days or less, errors averaged <5% of water level range at all seven study wetlands, an error probably acceptable for data uses requiring a general understanding of the pattern of monthly changes in water level.

Variability in estimates of the time water levels exceeded a threshold led to inconsistent perceptions of annual site conditions; these seem to be explained by the frequency of water levels above the threshold. For water in the root zone in PA-3, for example, variability among data sets for the site was fairly large but did not change the perception that water levels were in the root zone for a substantial portion of the year and also below it for a significant part of the year. In cases where occurrence of a condition was less common (e.g., inundation at PA-1 or PA-2), perceptions from some data sets could be seriously misleading, as they either completely missed actual occurrences of inundation or substantially overestimated occurrence. These kinds of results (and by implication, analogous attempts to characterize any condition occuring for only a short period of time) demonstrate the difficulty of using infrequent measurements to try to identify or, in particular, to quantify an uncommon condition. Crest gauges are not an option for describing conditions such as the persistence of water above a threshold because they only document the occurrence of a condition, not when or for how long it occurred.

Long measurement intervals can also result in substantive errors in the identification of apparent exceedance periods when water is above a threshold level. In an analysis of the duration of inundation (water $>$ 0.0 m), we found spurious exceedance periods for PA-2 when water was in fact rarely above ground level. In our data set, water elevations were above 0.0 m for only 6 days during one 32-day period, but because high water happened to occur at 7-day intervals during this time, we had spurious identifications of 14-day high water. Because of the possibility of gross errors of this kind, we recommend that measurement intervals of less than one week be used for identification of water-level exceedances.

Our data show frequent errors in identification of exceedances of threshold water levels that are attributable not only to measurement interval, but also to the days measurements were taken. We did not assess whether these kinds of errors affected the status of PA-1 or PA-3 in meeting any specific criterion (e.g., water in the root zone for $\geq$14 consecutive days during the growing season) because our goal was not to assess these wetlands *per se*, but to use them as a case study to show how measurement interval affects perceived achievement of a criterion. For a 14-day period or any analogous regulatory criterion, our results suggest that determination of an exceedance of something like ''14 consecutive days'' cannot be determined reliably except by sampling with at least a daily measurement interval.

From the perspective of water conditions as a determinant of biogeochemical or ecological processes, our results suggest the problems of a regulatory definition based on exceedance for a specific time interval. In PA-1, for example, the wetland had water in the root zone for 19 of 20 days from day 261 to 280 but not for 14 consecutive days. If this were the only period when water happened to be in the root zone of this wetland, it would not meet a hydrology criterion of 14 consecutive days. The presence of water in the root zone for 19 of 20 days at the site, however, would be expected to significantly influence soil conditions and to exert competitive pressures on vegetation. For characterizing ecologically significant events, identification of exceedances using 2- or 4-day data sets is probably not only reasonable, but might be as good as or even better than a criterion for exceedance on 14 consecutive days. However data are to be used and interpreted, the differences we observed in perceived 14-day exceedances highlight the need to explicitly define study goals before designing field data collection to ensure that data are collected that can meet those needs.

We have noted the need for data collection to be linked to research and management needs and have focused on the suitability of data collected at infrequent intervals for characterizing a variety of water-level variables. While our analyses indicate that these data provide representative summaries of conditions for some applications, this approach does not generate data suitable for analyses requiring high precision and accuracy (e.g., ground-water gradient analyses of Hunt et al. 1999) or for characterizing phenomena occurring on short time scales (e.g., diurnal variability and separation of storm hydrographs). The converse is also true, however, that collection of high resolution data is not a realistic approach for all applications. Investigators with limited resources often cannot afford to install and maintain gauges, so they often have chosen not to do any kind of hydrologic sampling. Results here, together with results of recent analyses of data for populations of wetlands (e.g., Cole et al. 1997, Shaffer et al. 1999) show that data collected at biweekly to monthly intervals can be used effectively to characterize and classify wetlands and that this approach should be considered by those with limited resources.

Our approach in this manuscript has been to characterize the uncertainties in data for a number of types of water-level data analyses that result from increases in measurement interval. In general, we did not determine whether data met a specific error criterion ($<$X%) nor determine what measurement frequency is necessary to reduce uncertainty below a specific value. Rather, we tried to use our data as case studies to show how errors are related to measurement frequency and to identify types of analyses for which infrequent measurements do, or in some cases do not, seem to provide a reasonable approach for data collection. We recognize that every wetland is different and that all investigators must determine data quality objectives to suit their needs and have tried to provide examples of data that will help guide design decisions by others.

In most analyses, we used data for a one-year period because a year is probably the minimum period for which most hydrologic monitoring studies are likely to be designed. We recognize that some investigators may want or need to use data for a shorter period of time, such as a growing season. For some analyses (e.g, exceedance of threshold conditions), use of data for a shorter time period should not affect analyses, but in other cases, reductions in the number of data points will increase the uncertainties in summary data. In general, we recommend that monitoring be conducted for more than a year when possible. A longer sampling period will contribute to decreases in uncertainty of data; more importantly, sampling for an extended period of time provides insight into how wetland water levels respond to stochastic events affecting wetland hydrology, including extreme storm events and interannual variability in precipitation.

We hope our results encourage more extensive collection of hydrologic data in a wide range of wetland management and ecological studies, especially for work at landscape to regional scales. General characterization of hydrology by infrequent measurement of water levels does not require specialized equipment or expertise, is not costly or especially time-consuming, and provides data that can support a variety of analyses. The recognized importance of hydrologic data to support wetland research and management, weighed against the relatively low costs of infrequent measurements, argues for a broader incorporation of hydrologic data collection in future research and assessment projects. Our results also suggest that for studies of wetland populations and landscapes, instead of intensive sampling of one or a few sites, the option of less frequent sampling of a large number of wetlands should be seriously considered, as it ultimately may provide better overall characterization of the wetland resource.

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