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# MEASUREMENT OF WETLAND HYDROPERIOD USING HARMONIC ANALYSIS

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*Abstract:* The pattern of water-level fluctuations in a wetland is its hydroperiod. Characterization of this pattern cannot be accomplished by measuring a single parameter, but some means of measuring hydroperiod is needed so that comparisons can be made both between wetlands and within a single wetland over time. Harmonic analysis can be used to characterize hydroperiod quantitatively by obtaining the amplitude and timing of the dominant periodic component in a time series of water levels. The utility of this method is demonstrated by investigating the link between water management in South Florida and nesting failure by wood storks in the Everglades wetland. With the quantitative measures of hydroperiod derived by harmonic analysis, I am able to demonstrate statistically the relationships between water management and hydroperiod in the Everglades and between hydroperiod and the probability of nesting failure. The simplicity and directness by which these results are achieved suggests the potential for harmonic analysis of hydroperiod as a general tool for wetland science.

*Key Words:* wetland, hydroperiod, harmonic analysis, hydrology, Everglades, wood stork, water management, wetland function

## INTRODUCTION

Hydroperiod is frequently cited as an all-purpose link between wetland function and hydrology (Brinson 1993, Mitsch and Gosselink 1993). The case can be made for the influence of other hydrogeomorphic characteristics, such as a wetland's position in the landscape (Brinson 1993). However, hydroperiod is well-ensconced in the vernacular of wetland science, and it will continue to serve in its present omnibus role for the foreseeable future. Problems arise from the fact that hydroperiod is difficult to measure in a way that captures its full nature. These problems will become more acute as wetland science is applied increasingly to the practical tasks of conserving, restoring, and creating wetlands, where it is necessary to make clear connections between hydrology and function and set quantitative hydrologic objectives for remediation or creation projects.

Of all definitions of hydroperiod, Brinson's (1993) description of it as an amorphous "wetness index" probably best characterizes current usage. Other, more exact definitions are inconsistent with each other and with the way hydroperiod is measured. Hydroperiod is referred to as "the pulsing water-flow regime . . . [that is] the key to wetland function and structure" (Odum et al. 1995) and as "the seasonal pattern of the water level of a wetland" and "a hydrologic signature of each wetland type" (Mitsch and Gosselink 1993). It is treated as if it can be determined from hydrologic measurements, but is hydroperiod a *flow* or a *level*? Apparently it is neither. When measured, hydroperiod is often defined to be the length of *time* that the wetland surface is inundated (e.g., Rowe and Dunson 1995, David 1996). An exception is the recent paper by Long and Nestler (1996) in which they use harmonic analysis and other measures to investigate subtle changes in hydroperiod. Measuring hydroperiod only by the length of time of inundation does not capture all of the qualities evoked by "seasonal pattern" or "water-flow regime." Is there a better way to measure hydroperiod?

In this paper, I explore the utility of harmonic analysis as a technique for measuring hydroperiod. For this purpose, hydroperiod is taken to be the seasonal pattern of water-level fluctuations. Any measurement of hydroperiod must include four types of information, each corresponding to a distinct attribute of the seasonal pattern. These are 1) the average water level for the period, 2) the intensity or amplitude of fluctuation, 3) the cyclic period(s) embedded in the fluctuations, and 4) the timing of fluctuations with respect to other processes, such as primary production or reproductive cycles, for example.

Harmonic analysis represents a series of data as the mean of the data plus the sum of a finite number of time-varying, sinusoidal functions. Each sinusoid, or harmonic component, corresponds to a distinct period

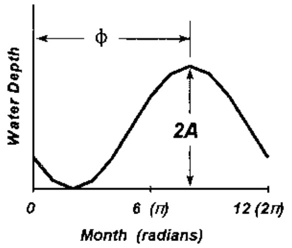

Figure 1. Amplitude, A, and phase angle, ϕ, are shown for the annual harmonic component of water depth. Phase angle can take on any value between 0 and $2\pi$ ($\approx$ 6.283) radians corresponding to range in time of 0 to 12 months.

of oscillation and is parameterized by an amplitude and a phase angle (see Figure 1). Applied to hydroperiod, harmonic analysis is used to obtain the amplitude and phase angle (i.e., the timing of the dominant harmonic component that determines the overall pattern of the water-level fluctuations). The annual harmonic component will usually correspond to the dominant period in non-tidal wetlands, as in the example discussed below. By separately analyzing the record of water level in successive years, the pattern occurring within each year is described by the mean water level, the amplitude, and the phase angle of the annual harmonic component. Using these parameters as measures of hydroperiod, one can then apply statistical techniques to investigate sources of variation in hydroperiod and its consequences.

Here, I illustrate this application of harmonic analysis with data from the Florida Everglades. The history of the Everglades in this century is one of uninterrupted decline in ecosystem function. Decimation of wading bird populations is perhaps the most visible sign of this decline. For example, between 5,000 to 8,000 wood storks (*Mycteria americana* L.) annually nested in the southern Everglades during the period 1931 to 1946. These numbers declined to an estimated 2,650 birds in the period 1974 to 1981 and again to 750 birds for the period 1982 to 1989 (Ogden 1994). The same period saw the construction of massive water-control works for flood control and water supply in South Florida. It is hypothesized that water-management activities have changed the hydroperiod in the wetland feeding grounds used by wood storks, and this has adversely affected the timing of nesting and reproductive success (Kushlan 1987, Walters et al. 1992, Ogden 1994).

Using the results of harmonic analysis to characterize hydroperiod in the southern Everglades, I am able to test two assertions related to this hypothesis. First, hydroperiod is affected by water-management activities, and second, successful nesting by wood storks is directly related to hydroperiod in the wetland feeding grounds. If both of these assertions are true, then there exists at least the possibility that changes in water management can be made that favor successful nesting.

## HARMONIC ANALYSIS

Harmonic analysis is a method for decomposing a data series into purely periodic (i.e., sinusoidal) components. A series of $2N$ evenly spaced values, $y_j$, can be exactly described by its mean $\bar{y}$ and $N$ harmonic components such that

$$y_j = \bar{y} + \sum_{k=1}^{N} A_k \cos\left(\frac{2\pi j}{2N} - \phi_k\right). \qquad (1)$$

The $k$th harmonic component is parameterized by its amplitude, $A_k$, and phase angle, $\phi_k$ (Figure 1). For the case of $2N$ values in the series, $\phi_N$ is identically equal to zero. Therefore, decomposition of the data completely determines the mean, $N$ harmonic amplitudes, and $N-1$ phase angles. Decomposition of the data also distributes the total variance in the data, $S_y^2$, among the harmonic components. The variance of the $k$th harmonic component is given by

$$S_k^2 = \frac{A_k^2}{2}, \qquad (2)$$

and the sum of the variances of all the components is equal to the total variance in the data.

The amplitude and phase angle for a series of data $y_j$ containing $2N$ values can be computed directly by the following procedure (Davis 1986). First, coefficients $\alpha_k$ and $\beta_k$, corresponding to the $k$th harmonic component are calculated using:

$$\beta_k = \frac{1}{N} \sum_{j=0}^{2N-1} y_j \sin\left(\frac{2\pi jk}{2N}\right) \qquad (3)$$

$$\alpha_k = \frac{1}{N} \sum_{j=0}^{2N-1} y_j \cos\left(\frac{2\pi jk}{2N}\right) \qquad (4)$$

Then, the amplitude and phase angle are computed;

$$A_k = \sqrt{\alpha_k^2 + \beta_k^2} \qquad (5)$$

and

$$\phi_k = \arctan\left(\frac{\beta_k}{\alpha_k}\right) \qquad (6)$$

Equation 6 is satisfied by two angular values in the interval $0 < \phi_k < 2\pi$. To determine which of the two angles is the phase angle, $\alpha_k$ and $\beta_k$ are interpreted as the x and y coordinates of a point on the unit circle, and the phase angle is measured from the positive direction of the x axis.

A question that can arise is whether fluctuations in the data show any periodicity or whether they are

Table 1. ANOVA for testing the significance of a harmonic component.

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Squares | F Test |
|---|---|---|---|---|
| Harmonic Component | $SS_M$ | 2 | $MS_M$ | $\frac{MS_M}{MS_R} = \frac{(n-3)}{2}\frac{r^2}{(1-r^2)}$ |
| Residual | $SS_R$ | n−3 | $MS_R$ | |
| Total | $SS_T$ | n−1 | | |

n = number of data values.
$r^2$ is the proportion of the total variance in the data explained by the harmonic component.

purely random in nature. This is equivalent to the question of the significance of the harmonic components. One approach to testing for periodicity in the data is through analysis of variance (ANOVA). The annual harmonic component is cast in the role of a "model." The hypothesis underlying the test is that the model accounts for a significant portion of the total variance in the data. Two degrees of freedom are allocated to the model, one each for the amplitude and phase angle that parameterize the harmonic component (Table 1). The proportion of the total variance explained by the model is equal to $r^2$ and can be calculated directly from the total variance in the data and the amplitude of the harmonic component being tested:

$$r^2 = \frac{S_k^2}{S_y^2} = \frac{A_k^2}{2S_y^2} \tag{7}$$

The relationship between the test statistic $MS_M/MS_R$ and $r^2$ shown in Table 1 follows directly from this and the fact that the proportion of the total variance contributed by the residuals is $(1 - r^2)$.

Tests by Schuster and Fisher (Fisher 1950) for the significance of a harmonic component take a slightly different approach, and they are described briefly here for comparison with the ANOVA test (Table 2). Schuster's test is applicable to testing the significance of an arbitrary harmonic component, and it is based on a comparison of the variance of the component with the variance expected if the total variance in the data is uniformly distributed among the harmonic components. The basis for Fisher's test is similar, but it is designed to test the significance of the harmonic component chosen because it has the largest amplitude. The null hypothesis in both of these tests is that the amplitude of the harmonic component is not larger than would be expected for data randomly chosen from a normal distribution. As with the ANOVA, the test statistics for these tests can be used to establish a critical value of $r^2$ for a given significance level. The tests of Schuster and Fisher are slightly more conservative than the ANOVA test, and this is reflected in higher critical values for $r^2$ (Table 2).

## STUDY SITE

The Everglades is an expansive freshwater wetland that occupies the center of the South Florida peninsula. At the beginning of this century, the Everglades ex-

Table 2. Comparison of tests of significance for a harmonic component.

| | | *Critical Value for $r^2$ | | |
|---|---|---|---|---|
| | | Significance Level | | |
| Method | Test Statistic | p = 0.05 | p = 0.01 | Distribution |
| ANOVA | $\frac{MS_M}{MS_R} = \frac{(n-3)r^2}{2(1-r^2)}$ | 0.486 | 0.641 | **F** dist. with $v_1 = 2$ and $v_2 = n-3$ |
| Schuster | $\frac{C_1^2}{C_m^2} = \frac{n}{2}r^2$ | 0.499 | 0.768 | $P\left[\frac{C_1^2}{C_m^2} > k\right] = e^{-k}$ |
| Fisher | $g = r^2$ | 0.616 | 0.722 | $P[g > g_c] \approx m(1 - g_c)^{m-1}; m = \frac{n}{2}$ |

* Critical values of $r^2$ are shown for the case of n = 12.

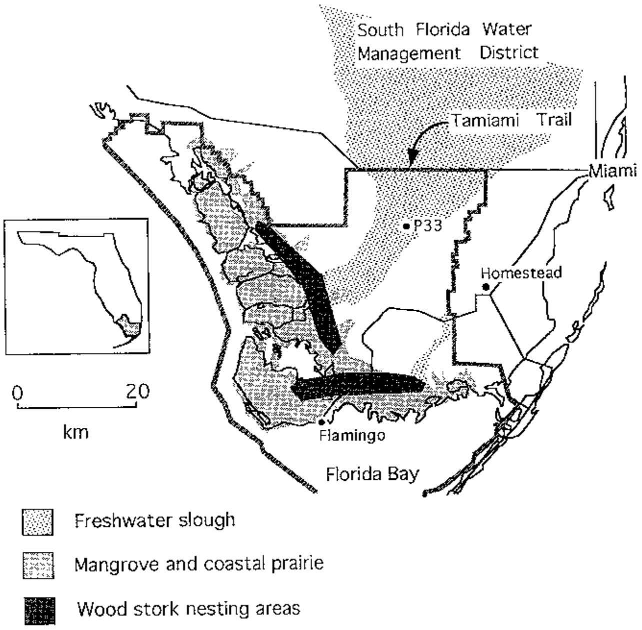

Figure 2. Long-term records of water level at P33 in the Everglades National Park are used to illustrate harmonic analysis of wetland hydroperiod. Water level is affected by management of surface flows into the Park across Tamiami Trail. Water level also influences the timing and reproductive success of wood storks nesting around the southwestern end of Shark Slough, the larger of the two freshwater sloughs in the Park.

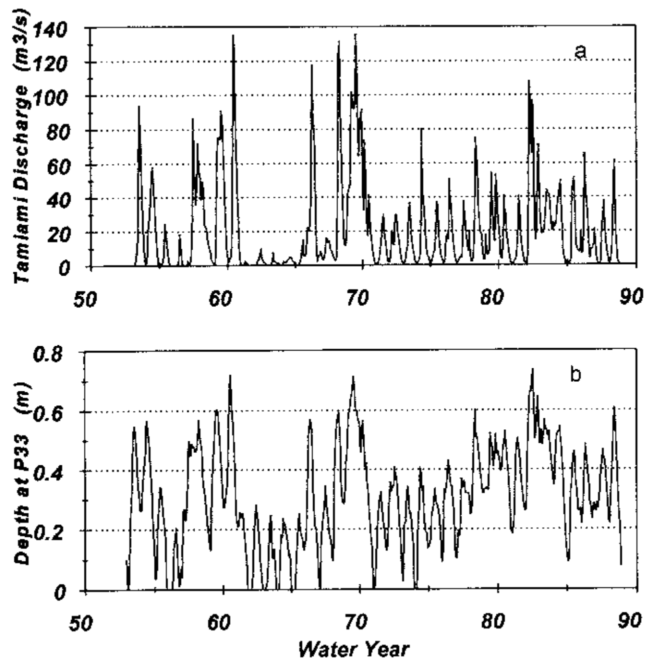

Figure 3. Monthly average discharge into the Park across Tamiami Trail (a) and water depth at P33 (b) for the water years 1953 to 1988. A water year is defined as the period April to March to coincide with the annual wet-dry cycle.

tended south from Lake Okeechobee to mangrove estuaries at the southern tip of Florida. Approximately two thirds of this area either has been drained for agriculture and urban development or is actively managed by the South Florida Water Management District for flood control and water supply. The remaining undisturbed portion of the Everglades is contained mostly within the boundaries of Everglades National Park. Shark Slough is the major feature of the wetlands in the Park. This is a permanently flooded "channel" 5 to 10 km wide with an all but imperceptible slope. Water entering Shark Slough across the northern boundary of the Park slowly flows south and southwest, discharging into the mangrove estuarine areas along the coast of the Gulf of Mexico (Figure 2).

All of the surface water discharging into Everglades National Park across Tamiami Trail passes through flow-control structures. This study makes use of the total monthly discharge through these structures and monthly average water depth at station P33 for the period 1953 to 1988 (Figure 3). During this period, the amount of water discharged annually into the Park has varied drastically with changing water-management practices. Completion of the major water-control works in South Florida was accomplished in the early 1960s, at which time discharge into the Park was virtually eliminated for a period of 4 years. This brought to the fore the conflict between water-management objectives north of Tamiami Trail and the water needs of the Everglades ecosystem to the south. A schedule of minimum monthly flows into the Park was established in 1970 to address this conflict, and refinements in water management have continued to the present, generally for the purpose of enhancing the amount and timing of water deliveries to the Park.

## METHODS

### Characterization of Hydroperiod

The subtropical climate of South Florida is characterized by distinct wet and dry seasons during the year, and this is reflected as a strong seasonal fluctuation in the water levels and flows in the Everglades. The period May to October is the wet season during which water levels and surface flows increase, and the period November to April is the dry season during which water levels and flows decrease (Figure 3). For each year, the hydroperiod was characterized using Equations 3 through 6 to calculate a mean and an amplitude and phase angle for the first (annual) harmonic component of water-level fluctuations. Fluctuations in surface-water discharge were also characterized in this way. The discharge and water-depth data were analyzed on the basis of a "water year," defined as the

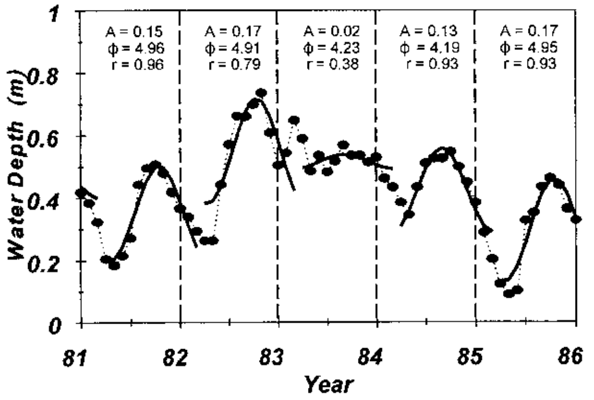

Figure 4. A subset of water depth data at P33 is shown with the annual harmonic components superimposed by water year. High water levels in spring 1983 caused a departure from the usual peaked seasonal cycle for that year. As a result, the annual harmonic component accounts for little of the total intra-annual variation in water year 1983. This is reflected in a low value for the correlation coefficient, *r*.

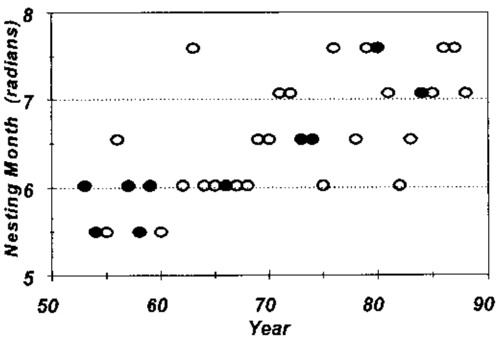

Figure 5. Wood stork nesting behavior during the period 1953 to 1988 is characterized by the month (measured in radians) in which nesting was initiated and a rating of the season as "successful" (closed circles) or "failed" (open circles). Note that no nesting occurred for years 1961 and 1977. Initiation of nesting is measured relative to January 1 of the calendar year in which the dry-down that "signals" the start of nesting occurred. See Figure 1 for the correspondence between month and radians.

period April to March of the following calendar year, coinciding with the annual wet-dry cycle. (Note that this definition differs from the more usual October to September period.) Thus, each 12-month period of data generally included a single peak bounded by minima at the beginning of the wet period and the end of the dry period. Subsequently, the phase angles were adjusted so that zero radians corresponds to January, the start of the calendar year.

Harmonic analysis can produce spurious results when water-level fluctuations do not show a distinctive peak. For example, this occurred at P33 in 1983 (Figure 4). If the harmonic component is obscured by other sources of variation, then does the phase angle measure the timing of the "true" annual harmonic component or does it merely record the location of the datum with the largest random departure from the mean? To overcome this problem, I used the significance test based on ANOVA (Table 2) to distinguish between years that displayed a distinctive peak in water levels and years that did not. The criterion used was that the correlation coefficient between the data and annual harmonic component must exceed 0.697 ($r^2 > 0.486$ for n = 12, i.e., 1 datum per month), which is significant at the $\alpha = 0.05$ level. This level of significance is acceptable because the test is not being used inferentially, rather it is used to screen parameters for subsequent analysis. The ANOVA test is preferred over the other tests summarized in Table 2 because it addresses the question of whether the data display a distinctive peak directly without regard to how the peak may have arisen. The more conservative tests by Fisher and Schuster test whether a particular harmonic component could have arisen purely by chance.

## Nesting Failure

Detailed observations on wading bird nesting habits in the Everglades date from the 1930s when the National Audubon Society began collecting data. This study makes use of the overall success or failure of the annual nesting effort by the wood stork as summarized by Ogden (1994) (Figure 5). These data are the most complete of all the major species of wading birds in the Everglades, and there is the added advantage that each year wood storks nest at the same locations in the headwaters of the mangrove estuaries (Figure 2). The initiation of nesting coincides with the drawdown of water levels towards the end of the dry season. Declining water levels concentrate prey fish in contracting pools within easy reach of the nesting sites. Hydroperiod is thought to influence nesting through this phenomenon.

## Data Analysis

The relationship between hydroperiod and managed surface-water discharge at Tamiami Trail was investigated by stepwise multiple regression analysis using the general linear model procedure in the SAS statistical package (Statistical Analysis Systems Institute, Inc. 1989). For purposes of comparison with harmonic parameters, failure and success of the nesting effort for a year (Figure 5) were coded as "0" and "1," respectively. The two years in which nesting did not occur were also coded as "0." The relationship between the probability of nesting failure and hydroperiod in the preceding year was investigated by stepwise multiple logistic regression, again using the routine available in the SAS statistical package.

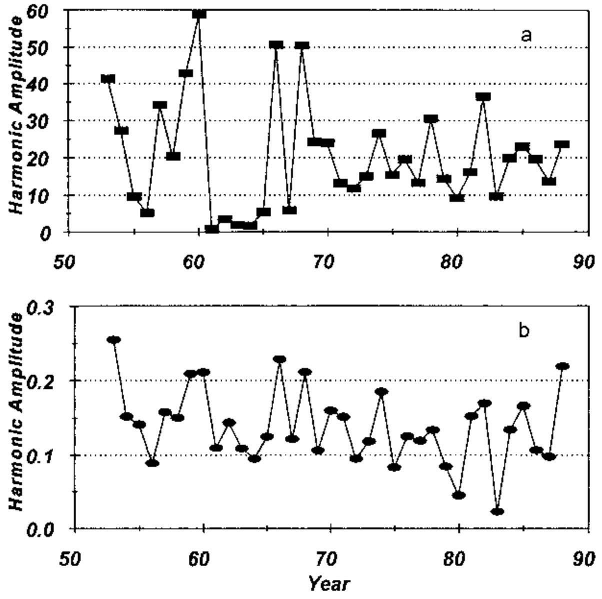

Figure 6. Amplitudes of the annual harmonic component are shown for discharge at Tamiami Trail (a) and water depth at P33 (b).

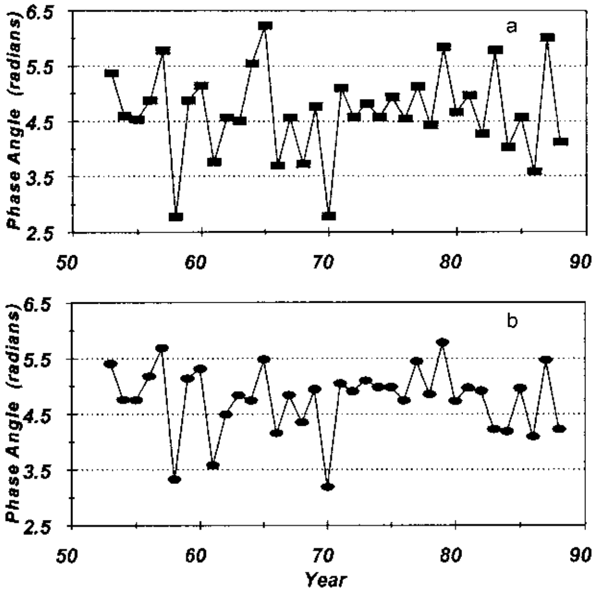

Figure 7. Phase angles of the annual harmonic component are shown for discharge at Tamiami Trail (a) and water depth at P33 (b).

## RESULTS AND DISCUSSION

The impacts of changes in water-management practices on discharge into the Park are evident as changes in amplitude and phase angle of discharge at Tamiami Trail and water level at P33 (Figures 6 and 7). Notable are the sustained drop in amplitudes for discharge during the early 1960s following completion of the water control works and an apparent reduction in the variability of the phase angle during the 1970s when discharges to the Park were regulated by a prescribed monthly schedule of minimum water deliveries. Starting in the early 1980s, regulation of discharge has been less prescribed, and the effects of this change are reflected in more variation in the timing of periods of high discharge during the year. During the early 1960s, amplitudes for discharge at Tamiami Trail were at their extreme lowest, but amplitudes for water level at P33 remained near their average value. This attenuated effect of discharge on P33 water levels may reflect the influence of local precipitation, magnified by the flatness of the terrain, during the period of extremely low surface flow.

### Relationship Between Hydroperiod and Water Management

There is a direct relationship between the annual harmonic components of water level at P33 (i.e., hydroperiod) and managed surface-water discharge at Tamiami Trail as revealed in the results of the regression analysis (Table 3). The strongest relationships between hydroperiod and discharge occur between like harmonic parameters. For example, the amplitude of discharge fluctuation is the most important component in the model for hydroperiod amplitude as indicated by the F statistic computed from the Type III sum of

Table 3. Results of stepwise multiple regression analyses of hydroperiod on the annual harmonic parameters of managed discharge (amplitude $A_D$, phase angle $\phi_D$, and annual mean $M_D$) and Year. Results shown are for 34 years of data. F values are calculated from the Type III Sum of Squares.

a. Hydroperiod amplitude: $A = 0.098 + 0.0032*A_D - 0.000938*M_D$; model $r^2 = 0.676$.

| Source | F | Prob > F |
|---|---|---|
| intercept | 148.81 | 0.0001 |
| $A_D$ | 50.13 | 0.0001 |
| $M_D$ | 6.61 | 0.0152 |

b. Hydroperiod phase angle: $\phi = 0.827 + 0.00763*A_D + 0.727*\phi_D$; model $r^2 = 0.838$.

| Source | F | Prob > F |
|---|---|---|
| intercept | 21.97 | 0.0001 |
| $A_D$ | 8.14 | 0.0076 |
| $\phi_D$ | 210.75 | 0.0001 |

c. Hydroperiod yearly mean: $M = -0.0380 + 0.00590*M_D + 0.00305*\text{Year}$; model $r^2 = 0.797$.

| Source | F | Prob > F |
|---|---|---|
| intercept | 0.29 | 0.5951 |
| $M_D$ | 111.39 | 0.0001 |
| Year | 9.51 | 0.0043 |

Table 4. Stepwise logistic regression analysis of nesting failure on the P33 hydroperiod parameters (amplitude A, phase angle $\phi$, and annual mean M) and Year for 34 years of data. Final model is:

$$\ln\left(\frac{P[failure]}{P[success]}\right) = -1.7025 - 29.5*A + 0.101*Year$$

| Source | Wald Chi-Square | Prob > Chi-Square |
|---|---|---|
| intercept | 0.243 | 0.6222 |
| A | 5.52 | 0.0188 |
| Year | 4.21 | 0.0401 |

squares (Table 3a). These results are based on 34 years of data. Two years were excluded because water levels did not show a significant annual peak, as determined by the ANOVA test of significance.

Year appears in the model for yearly mean water levels (Table 3c). Otherwise, neither hydroperiod nor the harmonic parameters for managed discharge were correlated with Year, in spite of the changes in water management that occurred during the study period. These results only indicate the absence of a simple linear trend in the data. Other types of changes are suggested by the data (see Figures 6 and 7) as discussed above.

### Relationship Between Nesting Failure and Hydroperiod

A strong relationship exists between the probability of nesting failure and hydroperiod amplitude at P33 (Table 4); failure is more likely in years with lower hydroperiod amplitudes. The results shown here include the two years in which nesting did not occur by coding these years as "failed." Similar results were obtained when these years were excluded from the analysis. The probability of failure is also affected by Year (i.e., there is a higher probability of failure in later years independent of the effect of hydroperiod amplitude). However, nesting failure is most highly affected by hydroperiod amplitude, as indicated by the chi-square values reported in Table 4.

Two possible links between water level and nesting failure are recognized, and their relative importance is the subject of debate. Both involve the effectiveness with which declining water levels concentrate prey fish in residual wetland pools near the nesting areas. The first link involves the overall magnitude and rate of decline in water levels; prey fish are concentrated less effectively in years with smaller and less rapid declines in water levels. The results obtained above support the importance of this link. Hydroperiod amplitude is directly related to the magnitude of the decline in water levels during the dry period and thus also the rate of change. The second link involves the occurrence of rising water levels late in the drying period; reversals in the drawdown of water levels, due to rainfall for example, disperse prey fish at a time when the food requirements are high due to the presence of young in the nests. The phenomenon of water-level reversals is not measured by any of the hydroperiod parameters discussed in this paper. In a review of evidence for the relationship between reproductive success and wetland hydrology in the Everglades, Frederick and Spalding (1994) observe that only the significance of water-level reversals on nesting failure has been demonstrated statistically. If this is true, then the results obtained here are the first statistical evidence for a link between nesting failure and the overall magnitude and rate of decline of water levels during the dry period.

Much more is known about the causes of the decline in nesting by wading birds in the Park than has been presented here. However, a complete discussion of the topic falls outside the scope of this paper. The main objective of this paper is to illustrate the use of harmonic analysis as a means of measuring hydroperiod. Readers interested in the effects of water management on wading birds in the Everglades are directed to Walters et al. (1992) and Ogden (1994). Generally, a consensus is building that changes in hydroperiod are not the cause for the decline in wading bird nesting, but that other factors are implicated, such as reduced productivity in estuarine areas. The results presented above do not support the consensus view. Admittedly, the analysis leading to these results is limited, and there are more hydrologic and bird data that could be considered before drawing a firm conclusion. On the other hand, the application of harmonic parameters to measure hydroperiod leads directly to the use of objective, statistical tests of hypotheses, such as presented above. Different conclusions may have been reached in the studies that support the consensus view had they used these measurements of hydroperiod.

## CONCLUSIONS

Hydroperiod cannot be measured by a single parameter. The pattern of water-level fluctuations in a wetland has many aspects, and it requires the record of water level itself to capture them all. However, some means of summarizing hydroperiod is needed so that comparisons can be made both between wetlands and within a single wetland over time. The example from the Everglades illustrates this point and its relevance to management aimed at restoring breeding populations of wading birds there. If the hypothesized links between hydroperiod and nesting success and between water management and hydroperiod are true, then water management practices can be improved to encourage nesting success. These hypotheses can really only be tested through statistical analysis, and this requires a set of parameters that describe hydroperiod quantitatively. In other applications, the objectives may be to assess future impacts of development on wetland function and design mitigation of these impacts. Harmonic measurements of hydroperiod can be used to quantify impacts of development and specify performance criteria for mitigation schemes.

The harmonic parameters, mean, amplitude, and phase angle, are one way to measure wetland hydroperiod. Each parameter corresponds to a recognizable characteristic of the overall pattern of water-level fluctuations; therefore, they can be understood intuitively. The utility of the harmonic parameters has been illustrated through their application, here, in the Everglades and by Long and Nestler (1996) in a bottomland hardwood swamp in eastern Arkansas. Results were obtained simply and directly, and this suggests the potential for harmonic analysis of hydroperiod as a general tool for wetland science.

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