A SIMULATION MODEL OF WATER DEPTH IN MANGROVE BASIN FORESTS[1]

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ABSTRACT. The construction and validation of a model simulating the water depth within mangrove basin forests is described. Rainfall, water table, water depth and tide data collected from a red mangrove basin forest on Marco Island, FL, was used to estimate model parameters. These included the basin spillover height, evapotranspiration-infiltration rate and the functional relationship of water depth change to rainfall, tide and basin spillover. The model was constructed with LOTUS 123 and calibrated from staff gauge water depth records. The model proved accurate and adaptable. Water depths from the model and staff gauge were correlated highly (r = 0.98). Data from an adjacent black mangrove forest featuring complex wet-dry cycling were used to modify the model. After calibration, the model provided an accurate record of water depths at the site (r = 0.89). This model will provide water depths used in a model of *Aedes taeniorhynchus* population dynamics.

INTRODUCTION

Aedes taeniorhynchus (Wiedemann), the black salt marsh mosquito, presents 2 problems for mosquito control efforts in south Florida. Firstly, large populations of adult females often migrate several miles from remote larval habitat (Provost 1951, 1952), exposing urban areas to severe mosquito outbreaks (Harden and Chubb 1960). Secondly, *Ae. taeniorhynchus* is subject to large annual variations in population (Ritchie 1984) that make efficient planning by mosquito control personnel difficult. Clearly, the ability to understand and predict short- and long-term mosquito abundance is a key to effective control of *Ae. taeniorhynchus* in south Florida.

To satisfy these goals, a model simulating the population dynamics of *Ae. taeniorhynchus* in mangrove has been developed.[2] A hydrological model serves as a integral component of this model. The hydrological model provides estimates of the water depth in a mangrove basin forest used to estimate the amount of larval and oviposition habitat, the timing of egg hatch and, in part, larval survival rates (Focks et al. 1988, Haile and Weidhaas 1977). This paper reports on the development and validation of the hydrology model. The simulation model of *Ae. taeniorhynchus*[2] population dynamics will be reported in a later paper. Additionally, the accuracy and utility of water table wells and staff gauges to collect hydrological data in mangrove basin forests will be examined. Copies of the hydrology model will be available from the author upon request.

MATERIALS AND METHODS

Study sites: Two sites (located on Marco Island, FL) were monitored from April 1985 to August 1987 to provide data for construction and validation of the hydrology model. The sites were chosen owing to their accessibility, prolific *Ae. taeniorhynchus* production and ecological and hydrological diversity.

The first site, Dogwood Ct. (named for an adjacent road), is a 0.7-ha red mangrove (*Rhizophora mangle* L.) basin forest of diverse topography. Lower elevations (1.5–2.8 ft NGVD (National Geodetic Vertical Datum)) are dominated by undulating hummocks created by the prop roots of red mangrove trees. This area grades into a gently sloping area (2.8–3.4 ft NGVD) of mixed red and black (*Avicennia germinans* L.) mangroves. This zone is connected to the highest area of the basin forest, the tropical hammock. The hammock zone is dominated by rubber vine (*Rhabdadenia biflora* (Jacq.) Muell.-Arg.), golden leather fern (*Acrostichum aureum* L.), sable palm (*Sabal palmetto* (Walt.) Lodd. ex Schultes), sea grape (*Coccoloba uvifera* L.), southern fox grape (*Vitis munsoniana* Simpson) and poison ivy (*Toxicodendron radicans* (L.)). The tropical hammock encircles the mangrove, forming a berm separating the basin forest from an adjacent bay (Barfield Bay) and from an adjacent mangrove forest (the April Ct. study site).

The second study site, April Ct. (also named for a nearby road), is a 0.4-ha mangrove basin forest. Lower elevations (2.0–2.7 ft NGVD) are dominated by black mangroves mixed with scattered stands of red mangrove. Higher elevations (2.7–3.0 ft NGVD) feature a thin growth of *Batis maritima* L. April Ct. is topographically simple;

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[1] This work was supported by a grant from the Collier Mosquito Control District, P. O. Box 7069, Naples, FL 33941.

[2] Ritchie, S. A. 1988. A simulation model of the population dynamics of the black salt marsh mosquito (*Aedes taeniorhynchus*) in a Florida mangrove forest. Ph.D. dissertation, University of Florida, Gainesville, FL, 266 pp.

it features a gentle sloping contour and an elevational range 50% smaller than the Dogwood Ct. site.

The 2 sites differ hydrologically. Maximum depth (measured at the lowest elevation and excluding floodings by extreme storm tides) was 1.6 ft (0.49 m) for Dogwood Ct. but only 0.75 ft (0.23 m) for April Ct. Thus, April Ct. dries both more quickly and more frequently than Dogwood Ct. Both sites were usually dry from late winter to late spring before becoming fully inundated by summer rains. Tidal flooding patterns also were dissimilar. A high berm (min. elevation 2.9 ft NGVD) protects Dogwood Ct. from tidal inundation except during unusual storm events; flooding was almost exclusively due to rain. April Ct. has a low (ca. 2.7 ft NGVD) berm that allowed tidal flooding several times each year. Mosquito production was more frequent and reached larger populations at Dogwood.

Collection and analysis of hydrological data: The daily high water table (ft NGVD), high tide (ft NGVD) and rainfall (in) were recorded at the sites from April 1985 to September 1987. A Steven's® recording water table well was placed on a hillside within 2 m of each basin forest. A Steven's® recording tide gauge was placed in Barfield Bay ca. 1 km away from the study sites. Daily rainfall was recorded ca. 100 m from the 2 sites.

Unfortunately, the wells frequently produced readings conflicting with observations of basin water depth. Therefore, water depth readings were collected and compared with well readings in an attempt to validate well data. Water depth was measured with a Steven's® staff gauge installed at the lowest spot in each basin. Well data was converted to water depth by subtracting the elevation at the staff gauge (1.5 and 2.0 ft NGVD at Dogwood Ct. and April Ct., respectively). Paired staff gauge and well estimates of water depth (75 at Dogwood Ct., 62 at April Ct.) were collected from May 24 to Aug. 26, 1987. The validity of the well to measure water depth was examined by regressing the 2 data sets against each other.

Spreadsheet model of Dogwood Ct. water depth: A simulation model of the Dogwood Ct. basin water depth was constructed from the hydrological data. An electronic spreadsheet, similar to the model developed by Hancock and Heaney (1987) and Rowan et al. (1988) was designed from the following generalized relationship: CHANGE IN WATER DEPTH = INPUT − OUTPUT.

Input includes positive changes in water depth due to rain and tide. Output includes negative changes in water depth due to evapotranspiration-infiltration (ETI) and spillover. The functional relationships between water depth change and each parameter were estimated by regression analysis. Parameters were calibrated by comparing the model output to staff gauge data. Equations are based on measurements in feet excepting rainfall, which is in inches.

Calibration was done graphically and quantitatively. Graphical calibration involved adjusting model parameters to match plots of model-estimated and observed water depth (see Figs. 3 and 4). Quantitative calibration involved adjusting parameters to minimize the residual of predicted water depth and observed water depth. Data analysis and model construction were conducted with the Lotus 1–2–3 spreadsheet on an IBM AT personal computer.

Estimation of hydrological parameters at Dogwood Ct.: Staff gauge data were used to estimate the ETI and the impact of rain on water depth. The mean change in water depth on days with no rain provided an estimate of ETI. Change in water depth due to rainfall was estimated by regressing change in water depth against rainfall; only days with rain > 0.10 in and an after rainfall water depth < 0.5 ft of the basin spillover height (see definition in next paragraph) were used. The impact of tide on Dogwood Ct. water depths was estimated by well and tide records and by observations of flooding tides. Balling and Resh (1983) determined that pond inundation height was related significantly to the production of salt marsh *Aedes* in California salt marshes. This parameter is hereby termed the basin spillover height since it defines the elevation at which spillover into and out of the basin occurs. Spillover into the basin occurs when the tidal height exceeds the basin spillover height. Spillover out of the basin occurs after extreme flooding by rain and/or tide and represents run-off out of the basin as the height of water in the basin reaches equilibrium with the basin spillover height. The basin spillover height was determined by observing the water depth during flooding tides and spillover events.

A complex interaction between water table and tides was observed when the Dogwood Ct. basin was dry. Well records indicated that, when dry, the Dogwood Ct. water table oscillated with a periodicity similar to the tide. This relationship was estimated by regressing daily high tide and well readings collected when the basin was dry and no major rainfall (> 0.2 in (0.50 cm) per day) occurred.

Spillover rates at the Dogwood Ct. basin were estimated from the well and tide records. Tidal spillover into the basin occurred when a high tide exceeded the basin spillover height. This was verified by tide data recorded during tidal floodings at Dogwood Ct. A function to provide estimates of spillover out of the basin following a flooding tide and/or heavy rain was developed by fitting a curve of predicted water depths to well and staff gauge data collected during spillover events.

Model construction, calibration and validation: The model consists of a series of columns representing data and calculations and rows representing consecutive days. Columns A–C are dates (by day, week and month, respectively), col. D is 24-h rainfall (in inches), and col. E is daily high tide in ft NGVD. Columns F–L are model calculation columns (in ft). Columns F and G calculate ETI, columns H and I calculate water depth change due to rain, column J calculates changes due to tidal flooding and spillover, and columns K and L calculate the predicted water depth (depth of water, in ft, at the staff gauge site) for a dry or flooded basin, respectively.

Model construction consisted of inputting data and parameters equations, initialization and calculation of water depth changes. Daily data and equations were inputted into their respective columns; initial construction was limited to 1987 data because all water depth measurements were taken at this time. The predicted water depth was calculated by adding the estimated water depth change to the previous day's water depth. A known water depth was used to initialize the model. This value was placed in column L (the predicted water depth) in the first row above the inputted data. Model construction was initialized with the first staff gauge record (0.38 ft (11 cm), taken on May 24, 1987). Later runs were initialized using model output (January 1, 1986) and an observed water depth during a flooding tide (January 1, 1987). Calculation of water depths for dates after initialization involved copying the parameter equation columns (col. E–L) at the first data row to the remaining data rows.

The model was calibrated and validated by comparing predicted and actual water depths. Qualitative comparisons involved plotting estimated and actual water depths. Quantitative comparisons consisted of calculation of the mean model residual (difference between model estimated and actual water depth); actual and absolute residuals were calculated. Model calibration involved adjusting model equating until a minimal mean residual was obtained for both initialization dates. The model was considered valid if the graphical output mimicked actual water depths and if the mean absolute residual was ≤0.10 ft (3.5 cm). Further validation involved calculating the correlation coefficient between model output and known water depths.

Model performance was improved by the addition of 2 new parameters. Examination of the calibration plot indicated that the rate of water depth change due to ETI and rainfall were not constant over the range of water depth; both appeared to increase as the water depth declined. Functions to account for these observations were developed incorporating the previous water depth (water depth at the staff) in the regression analysis of ETI and water depth change due to rain. For ETI, the mean ETI and water depth for 8 rainless periods (total of 43 days) during the summer of 1987 were regressed. ETI was expressed as a proportion of the estimated mean summer ETI (ca. 0.04 ft (1.2 cm) per day in summer). By using an indexed value, the function can be used to correct the mean ETI as it changes seasonally. Rainfall regressions simply involved regressing the change in water depth against rainfall and the previous day's water depth. These functions were incorporated into the basic model, and the model was calibrated and validated as described earlier. The model producing the best validation results was used to generate output from data collected from April 1985 to December 1986.

Modification using the April Ct. data set: Model modification involved substituting the hydrology parameters from April Ct. for those for Dogwood Ct. Regression analysis was used to estimate hydrological parameters from staff gauge data collected from May to August 1987. The parameter values were input into the model, and model calibration and validation proceeded as described earlier. Hydrologic data collected from April 1985 to August 1987 were used in subsequent model runs.

RESULTS

Analysis of well data: Both water table wells provided an unsatisfactory record of the basin water depth. Although a positive correlation ($r = 0.85$) was found between paired water table well and staff gauge readings at Dogwood Ct. (Fig. 1); the r^2 value (0.71) indicates that the well does not adequately measure the water depth. The April Ct. well also failed to record water depths accurately; the correlation coefficients and r^2s of paired well and staff gauge readings were 0.64 and 0.41, respectively. The discrepancy is most notable when the basin is flooded by the tide (Fig. 2), suggesting that the

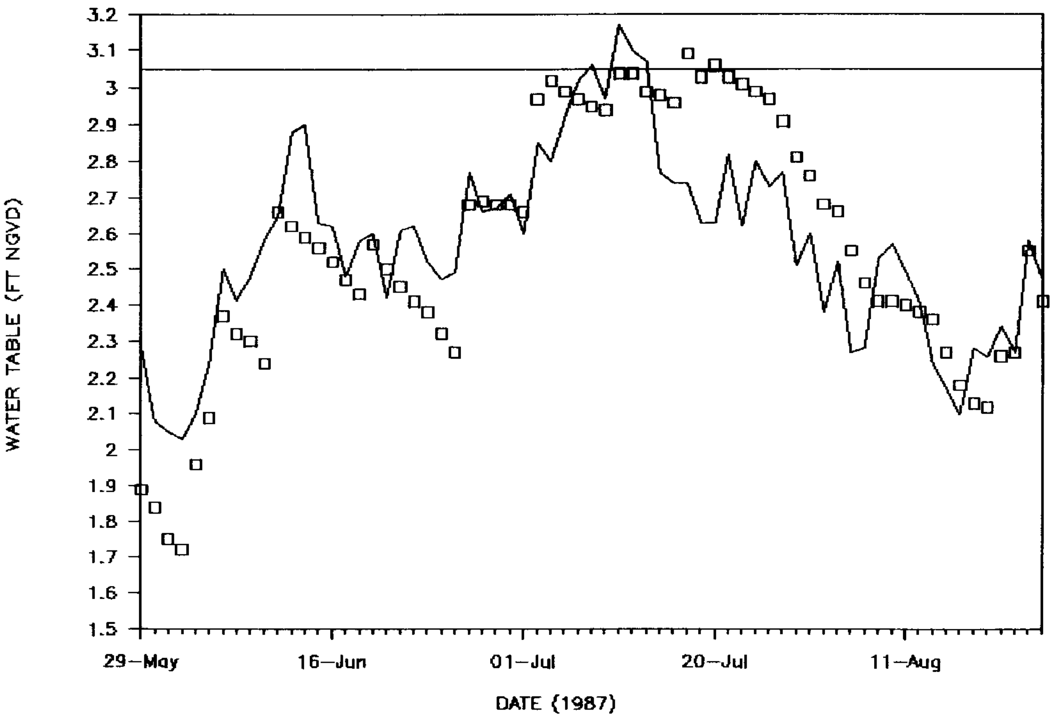

Fig. 1. Recorded water tables at Dogwood Ct. mangrove basin forest. Squares represent staff gauge readings and the line is daily high water table from recording water table well. Straight line at 3.05 ft NGVD represents the basin spillover elevation.

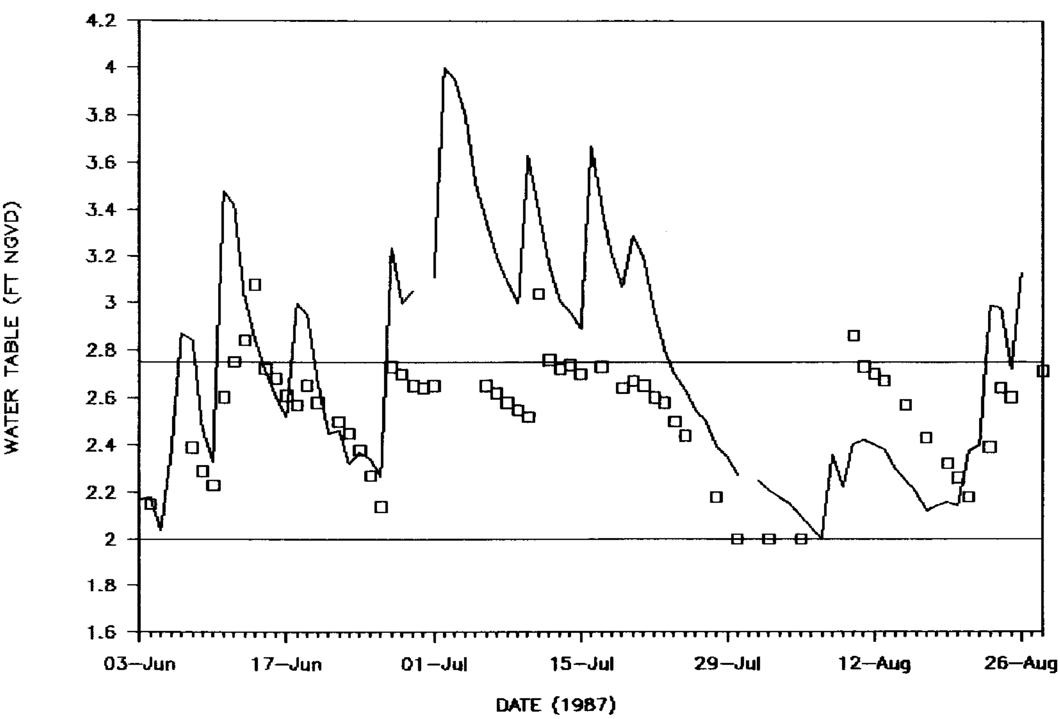

Fig. 2. Recorded water tables at the April Ct. mangrove basin forest. Squares represent staff gauge readings; the line is the daily high water table from the recording water table well. Straight lines at 2.75 and 2.00 ft NGVD represent the basin spillover and drydown elevations, respectively.

tide can flood the basin with little impact on the underlying water table.

Estimation of hydrological parameters: ETI was estimated by the mean change in water depth on rainless days; the mean ± SD daily change in water depth for rainless days was −0.036 ± 0.024 ft (−1.1 ± 0.7 cm). Because winter evapotranspiration rates in south Florida are ca. 50% of summer values (Smajstrla et al. 1984), the following sine function was used to estimate ETI rate at Dogwood Ct.:

$$\text{ETI} = -(0.03 + 0.01(\text{SIN}(2\text{PI}(\text{WEEK-15})/52))) \quad (1)$$

where WEEK is the week of the year.

It was speculated that ETI loss would decrease proportionally as the water depth dropped below the soil surface. Once open water is unavailable, soil water may become more tightly bound as the soil dries, reducing ETI rates. Thus, ETI is corrected by the following function when the basin is dry:

$$\text{CETI} = \text{ETI} \times (1 + \text{PREVIOUS WATER DEPTH})^3 \quad (2).$$

The relationship of rainfall to change in water depth was also estimated from the summer staff gauge data. Significant regressions were obtained for rain and rain × rain^2 vs. water depth change ($P < 0.01$, $r^2 = 0.733$ and 0.743, respectively). Since the quadratic model does not increase r^2 significantly, it was not used in the model. For the linear model,

$$\text{WATER DEPTH CHANGE} = -0.072 + (0.215 \times \text{RAIN}) \quad (3);$$

rain is measured in inches. The equation suggests that light rains [< 0.07 in (0.18 cm)] did not increase water depth.

The interaction of tide and water depths at Dogwood Ct. is dynamic; tides serve to flood the basin and to support the water depth during dry periods. Observations of flooding tides indicate that the Dogwood Ct. basin spillover height is 3.1 ft (94 cm) NGVD; this corresponds to a water depth of 1.6 ft (49 cm) at the staff gauge site. The basin requires a tide in excess of 3.2 ft (97.5 cm) NGVD for complete inundation. A significant regression was found between daily high tide and daily high water depth when the Dogwood Ct. basin was dry. Regression analysis indicated that the response of the water depth to high tide involved a time lag. The respective r^2 for high tides 3, 2, 1 and 0 days before the well reading was 0.32, 0.54, 0.72 and 0.66. For calculation convenience, the "0 day" regression formula,

$$\text{WATER DEPTH} = -0.66 + (0.2 \times \text{TIDE}) \quad (4)$$

is used in the model.

Data collected during 1985 was used to correct the rate of water depth change to account for spillover out of the Dogwood Ct. basin. On June 27, 1985, 7.25 in (18.4 cm) of rain fell on the Dogwood Ct. basin, raising the water depth to 3.74 ft (114 cm) NGVD, a depth 0.64 ft (20 cm) above the basin spillover height. Model output was calibrated to this data to obtain a function to estimate water depth changes from rains that result in basin spillover (CORRECTED CHANGE). The function initially calculates the change in water depth due to rain (Eq. 2). Subsequently, the portion exceeding the basin spillover height is multiplied by 0.10, thereby simulating how spillover damps extreme rises in the water depth. A similar procedure was used to estimate rain-induced increases for water depths at or above the basin spillover height. In this case, rainfall was multiplied by 0.05.

The rate of basin spillover was estimated from well records of two spillover events (the above mentioned storm and Tropical Storm Bob). On July 22–23, 1985, Tropical Storm Bob produced 11.6 in (29.5 cm) of rain and a tide of 3.94 ft (120 cm) NGVD at Dogwood Ct., pushing the Dogwood Ct. water depth to 4.4 ft (134 cm) NGVD. Both storms produced a sudden increase in water depth that declined rapidly due to spillover. The estimated spillover rate derived from these data is

$$\text{CORRECTED CHANGE} = -(0.02 \times \text{WATER DEPTH}^2) \quad (5)$$

where water depth is the depth, in ft, at the staff gauge.

Model construction, calibration and validation: Calculations used in the basic model employ conditional statements to select the appropriate calculation. Conditional statements were nested, creating several options within a single calculation. For example, calculation of water depth change due to rain employs different calculations depending upon 3 conditions (is the basin dry, partially flooded or flooded with spillover?).

Incorporating the previous water depth into ETI and change due to rain (CHANGE) functions improved model performance. Water depth elevation had a significant relation to ETI and change due to rain. The regression of the mean water depth against the average summer ETI index was significant ($P < 0.01$, $r^2 = 0.83$); ETI (indexed) = 1.72 − 0.71 (MEAN WATER DEPTH), where mean water depth refers to the mean value for the rainless period from which the ETI index was calculated. Incorporation of the previous day's water depth in the regression of water depth change against 24 h rainfall increased the r^2 from 0.73 to 0.80. The resulting equation was

$$\text{WATER DEPTH CHANGE} = 0.028 + (0.198 \times \text{RAIN}) - (0.082 \times \text{PREVIOUS WATER DEPTH}) \quad (6).$$

These equations were incorporated into the model and modified by calibration using 1987 staff data. Model performance was improved somewhat by these functions; the mean actual residual decreased from −0.028 to −0.001 ft (−0.85 to −0.03 cm), the mean absolute residual improved from 0.071 to 0.055 ft (2.16 to 1.67 cm), and the correlation between staff gauge data and model output changed from 0.968 to 0.979.

The model derives final water depth output from 2 concurrent models. DRY (dry model) describes changes in water depth, as influenced by tide, for a dry basin; WET (wet model) describes changes in water depth for a flooded or dry basin without incorporating tidal influence on a dry basin.

The DRY model varies depending on whether the basin is flooded. Under dry conditions, DRY calculates the water depth according to the equation WATER DEPTH = −0.66 + (2 × TIDE). CORRECTED CHANGE is added to this amount to account for any change due to rainfall. Since under flooded conditions the output from DRY might be greater than the output from WET (and therefore erroneously selected as the water depth by FINAL), DRY is set at −5, a value invariably less than WET. FINAL model (FINAL) chooses the best water depth estimate from the model (WET or DRY) that has the highest water depth value. This value is set to ft NGVD by adding the staff elevation (1.5 ft (45.7 cm) NGVD) to it.

Modification of the model using the April Ct. data set: Hydrological parameters unique to the April Ct. study site were estimated and successfully implemented into the hydrology model. Values of parameters estimated from staff data or observation include the basin spillover height (2.75 ft (83.8 cm) NGVD) and ETI rate (0.07 ft (2.1 cm) per day in the summer). Values of other parameters (water depth change due to rain, spillover, seasonal change of ETI and tide) were estimated by the model calibration procedures used for Dogwood Ct.

Model validation and simulation runs: The model provided valid estimates of water depths at the Dogwood Ct. and April Ct. sites. Plots of model output and staff gauge data (Figs. 3 and 4) indicate the model simulates realistically the water depth at both sites under a diverse set of hydrological conditions. Quantitatively, the Dogwood Ct. model performed better than the April Ct. model (Table 1), although the mean absolute residual was within the acceptance depth (0.10 ft (3.5 cm)) for both models. Although no staff data were available for other dates, observations suggest that the models estimated site water depths accurately. For 24 cases at Dogwood Ct., the model was within 0.1 and 0.2 ft 20% and 54% of the cases, respectively. At April Ct. the model was within 0.1 ft of the estimates' water depth in 16 of 17 (94%) cases. The only exception occurred during a flooding tide on July 22, 1985. Gauge records indicated that the high tide for the previous 4 days was 2.50 ft (76.2 cm) NGVD, a tide 0.2 ft (6.1 cm) below flood elevation at April Ct. A comparison of model output to water table well records (Figs. 5 and 6) indicate that the model provides valid water depth estimates under a variety of hydrological conditions. These conditions ranged from severe flooding due to hurricanes (1985) to drydown from winter drought (1986). The model accurately portrays complex scenarios such as the multiple tidal floodings associated with Hurricane Elena in late August 1985. Perhaps most significantly, the model accurately predicted the late spring drydown of the Dogwood Ct. in 1987 (Fig. 3). This drydown, albeit brief, drastically reduced a fish population introduced by a flooding tide in early January. As a result, a large brood of *Ae. taeniorhynchus* was able to survive until larvicide was applied.

The valid performance of the model using the April Ct. data set indicates that the model can be adapted to estimate water depths at different basins. The key parameters appear to be the basin spillover height and the elevation of the referenced staff gauge. The remaining parameters (water depth change due to range, spillover and ETI) can be estimated by calibration using staff data.

DISCUSSION

Several conclusions can be drawn from this study. First, recording water depth wells can only provide an accurate record of mangrove basin hydrology if placement is accurate. Well stations at elevations distinct from the basin bottom may record different water depth elevations and may miss perched water depths resulting from tidal flooding. However, this equipment does provide accurate data that is necessary for model construction. Nonetheless, the

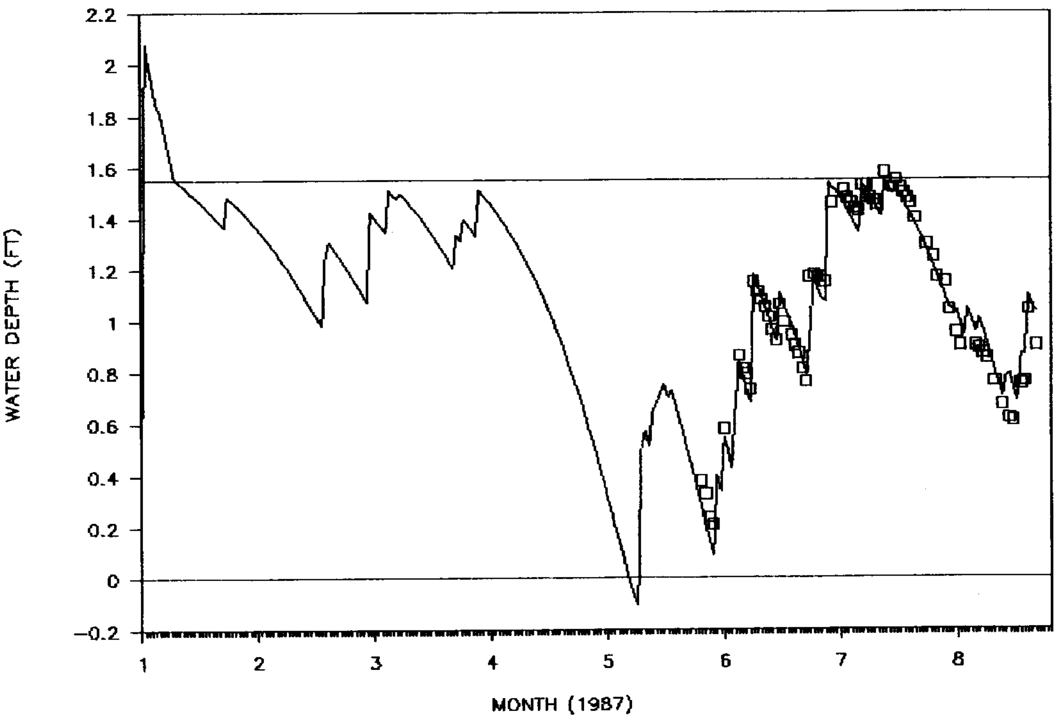

Fig. 3. Model-estimated (line) and staff gauge readings (squares) of Dogwood Ct. water depths used in model calibration; line at 1.55 ft represents the basin spillover height.

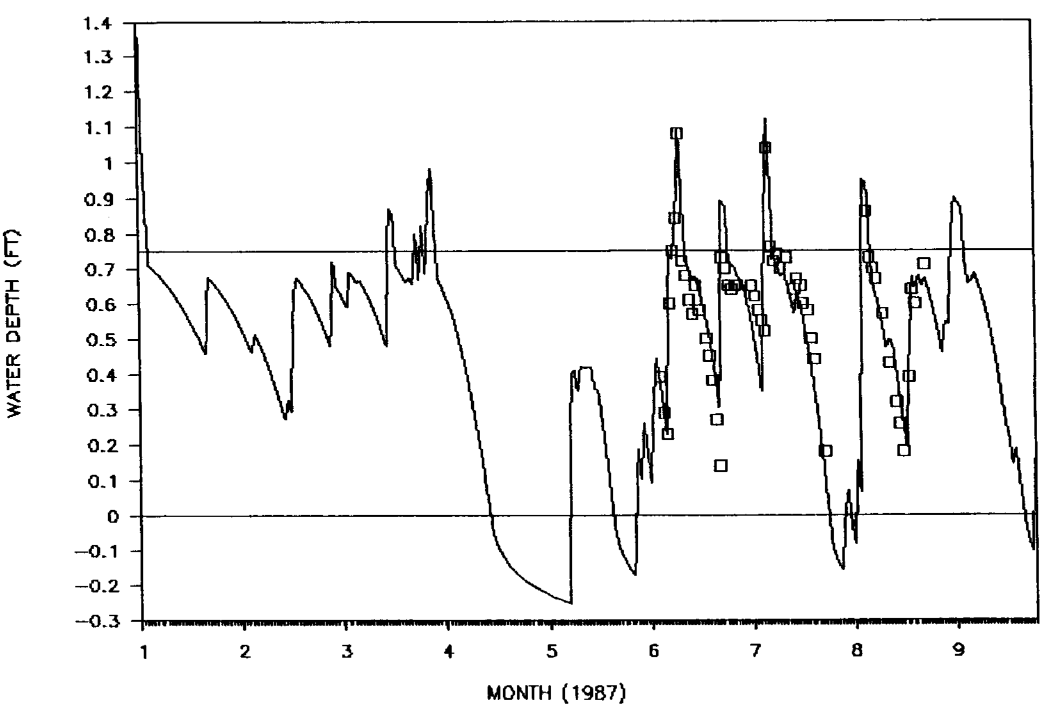

Fig. 4. Model-estimated (line) and staff gauge readings (squares) of April Ct. water depths used in model calibration; line at 0.75 ft represents the basin spillover height.

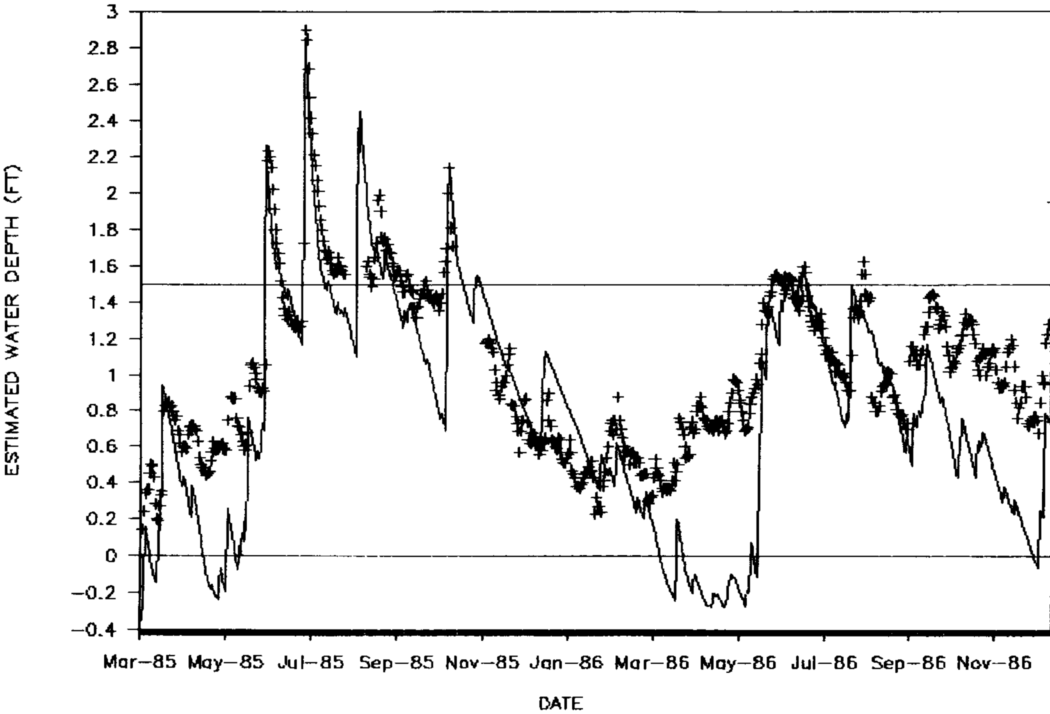

Fig. 5. Dogwood Ct. water depths estimated by the model (line) and by a recording water table well (crosses) for April 1985–December 1986. The large peaks in July, September and October 1985 are from Tropical Storm Bob and Hurricanes Elena and Juan, respectively.

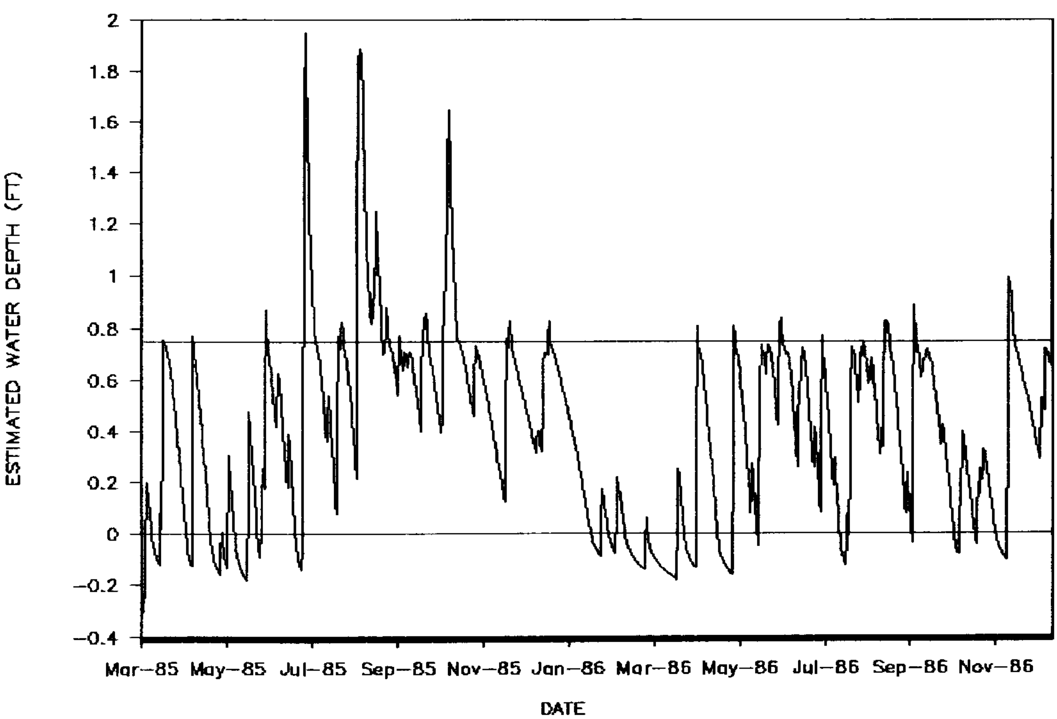

Fig. 6. Model-estimated water depths at April Ct. for April 1985–December 1986.

Table 1. Comparison of water depths (feet above staff elevation) estimated by the hydrology model and staff gauge at the Dogwood Ct. and April Ct. study sites. Data collected from May–August 1987.

	Study site			
	Dogwood Ct.		April Ct.	
	Model	Staff	Model	Staff
Mean	1.06	1.06	0.61	0.58
SD	0.34	0.35	0.21	0.20
Max.	1.54	1.58	1.12	1.08
Min.	0.09	0.21	0.10	0.14
Residuals				
Mean actual	−0.001		0.023	
Mean absolute	0.055		0.078	
Correlation, r	0.979		0.894	

data suggest that a simple staff gauge may provide an adequate and inexpensive alternative. Finally, basic hydrological data (rain and height of tide and water depth) can be used to construct a model that accurately mimics mangrove basin water depths.

The hydrology model has several valuable attributes. The model appears to be "self-correcting." The magnitude of error in the estimated water depths tend to diminish as the summer progresses and the basin fills; the basin spillover height therefore serves as a self-correcting feature of the model. The model can be updated at any time. Observed water depths can be input into the model, increasing its accuracy. The model can be easily modified to estimate the hydrology of different basins. Basin-specific parameters can be estimated from staff data or by calibrating an existing model to staff data.

The model has several applications to mosquito ecology and control. A model can be used to correct invalid well records by adjusting for limitations of the wells and by estimating values for missing data. The model can be used to generate water depths for input into system models (i.e., population dynamics of fish, mosquitoes, etc.) of the basin. This can include scenario testing to examine worst/best case scenarios of mosquito production. Scenario identification might lead to accurate long range forecasting of mosquito populations. Furthermore, hydrology models can be adapted to different mosquito-producing basins to predict mosquito populations over a larger area and at diverse basin types. Basin specific hydrology models might be used to predict water depths both of basins that are flooded frequently by tides and of basins that are flooded rarely by tides. The use of these coupled-system models could greatly aid our understanding of *Ae. taeniorhynchus* population dynamics. However, before such adventuresome model games are undertaken, the hydrological and entomological validity of both models must be examined. Other parameters, such as the relationship of ETI to soil moisture, should be examined. Additional and diverse basins must be targeted for modeling. Further detail, such as stage-cumulative pond area, would facilitate mosquito modeling (Rowan et al. 1988). Eventually, a collection of "off the shelf" models might be available to simulate the hydrology of a broad range of mosquito-producing habitats.

Even at this, the model may be too cumbersome for application in a remote census mosquito warning system. Such a system requires a network of models or a generalized model to provide hydrological input over a wide geographical area. Logistics may necessitate sacrificing realism for the sake of simplicity and computational efficiency. This could be accomplished by simplifying or eliminating noncritical parameters such as spillover rates.

ACKNOWLEDGMENTS

The author would like to acknowledge the following for their help. Technical assistance by Eric Johnson, Henry LaRose and the staff of the South Barfield Fire Station is appreciated. I am thankful for the editorial criticism by James Heaney, Howard Frank, Richard Brenner, Daniel Kline and Jon Allen. And finally, the financial support of the Collier Mosquito Control District is appreciated.

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