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Flood Control Benefits of Aquatic Plant Control in Florida's Flatwoods Citrus Groves

ERIC M. THUNBERG AND C. N. PEARSON, JR.[1]

ABSTRACT

Development of new citrus production in Florida has been expanding into the low lying flatwoods areas in the Southern and Southwestern portions of the state. Citrus production is made possible in these areas only by extensive drainage control. This paper reports the findings of a simulation analysis to calculate the gross benefits of aquatic plant management in maintaining properly functioning drainage control. Benefits are measured as the avoided lost income from flood damaged citrus trees under varying aquatic plant control levels. Estimated annual gross flood control benefits were found to range between $66.73 and $86.75 per tree.

Key words: economic benefits, flood control, citrus trees, drainage canals, simulation model.

INTRODUCTION

Concern over the possibility of freezing temperatures in what prior to the mid-1980's had been traditional citrus production regions in Florida, has resulted in a southward movement in citrus industry expansion. The greatest amount of new grove development has been in the Southern and Southwestern portion of the state into what is called flatwoods production areas. The flatwoods production areas are characterized by poor natural drainage and sandy soils of somewhat acidic quality. The sandy topsoil layer is normally underlain by an impervious hardpan which maintains the groundwater level at less than 18 inches below the soil surface. Without drainage control seven out of every ten acres in the flatwoods area would be submerged during some portion of the year. In years of above

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[1] Assistant Professor and Research Assistant Food and Resource Economics Department, University of Florida, Gainesville, Florida, 32611. Received for publication October 12, 1992, and in revised form April 9, 1993.

average rainfall up to nineteen of twenty acres would be submerged for an extended period of time during the summer wet season (Heaney and Huber, 1982). Under these natural conditions citrus trees cannot be successfully cultivated due to their low tolerance to the effects of standing water in the rooting zone (Ford, 1968).

Flooding has two effects on citrus trees. First, when the soil profile is saturated, a state of anaerobiosis occurs in which no free oxygen is available for feeder root functions and normal plant transpiration is impeded (Young, 1951). The second effect is caused by prolonged exposure to naturally occurring microorganisms (genus *Desulphovibrio* and *Clostridium*) present in groundwater. These microorganisms produce sulfides and nitrites which are toxic to citrus feeder roots at concentrations as low as 0.1 ppm (Ford, 1965; Ford and Calvert, 1968). If a sufficient proportion of feeder roots is lost the tree will eventually die and will have to be replaced. The existing substrate and temperature found in South Florida provide ideal conditions for sulfide and nitrite producing microorganisms. Furthermore, the acidic quality of the flatwoods soils enhances the toxic effect of sulfides and nitrites on citrus feeder roots (Ford, 1964).

Citrus production in flatwoods areas is made possible by drainage and creating raised beds for planting citrus trees (Young, 1951). A representation of bedded citrus trees is shown in Figure 1. The raised beds are normally 24 inches in height and allow for improved drainage of the rooting zone which typically extends to 36 inches below the crown of the bed (Calvert, Koo, and Ford, 1967). By connecting these parallel furrows to drainage canals, runoff from a rain event can be removed. Obreza and Admire (1985) recommend that pumping capacity of a drainage control system be sufficient to lower the water table between 4.5 and 6 vertical soil inches in a 24 hour period.

The Aquatic Plant Problem

There are 137 different species of aquatic plants present in Florida waters (Schardt and Nall, 1988). Of these, 27 are exotic. Florida's warm climate, nutrient rich waters, and absence of natural control agents create ideal conditions for the rapid growth and spread of aquatic plants in drainage control systems (Stephens et al., 1963). Having the same effect as a decrease in channel cross sectional area, aquatic plants cause the hydraulic capability of the water control system to be reduced through a phenomenon known as Manning's coefficient of hydraulic roughness (Chow, 1959). The coefficient of roughness provides a measure of the effect of canal obstructions on the ability to carry water. Much like rust or dirt clogging small water pipes, the effect of aquatic plant infestations is especially noticeable in medium and small canals (canals with cross sectional areas of less than 2000 and 200 square feet respectively). In studies of drainage canals in agricultural areas, aquatic plants have been found to impede water flow by as much as 95 percent (Stephens et al., 1963).

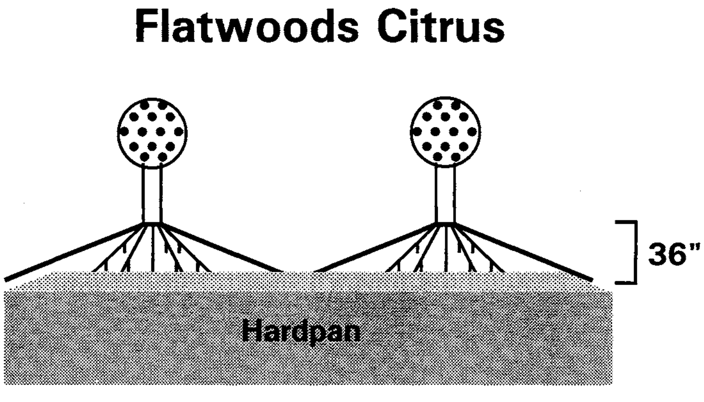

Figure 1. Cross-sectional diagram of a bedded citrus grove.

The inability to remove water from a citrus grove may result in significant tree loss depending upon the amount of rainfall and amount of time tree roots remain saturated. This paper reports the findings of a simulation model used to calculate the flood control benefits of aquatic plant control in flatwoods citrus groves. In this study all benefit figures reported are gross benefits due to the lack of data on aquatic plant control costs in Florida citrus drainage canals.

METHODS

The flood control benefit of aquatic plant control in a citrus grove is defined as being the amount of lost income that is avoided in the presence of an aquatic plant control program as compared to a no-control baseline (United States Water Resource Council, 1983). Lost income is defined as being the sum of the cost of replacing a citrus tree, and the amount of foregone income until the new tree reaches a level of production equivalent to that of the replaced tree. The amount of lost income avoided is computed by calculating the arithmetic difference between the amount of lost income under with and without aquatic plant control conditions. These calculations were made possible by constructing a simulation model linking a groundwater budget to tree root distribution relationships and a tree replacement cost budget. The components of the simulation model are described below.

Simulation Model

The simulation model used in this study is a modified version of a simulation model used to estimate residential flood control benefits of aquatic plant control (Thunberg, Pearson, and Milon, 1992). Space limits a detailed discussion of the model, however, documentation of the model and a copy of the spreadsheet program are available from the authors upon request. The simulation model consists of three components a water budget, a root loss - tree damage relationship, and an expected lost income avoided calculation.

Water Budget. The water budget uses a set of mathematical equations (Izuno, 1987) describing groundwater movement, canal system pumping capacity, and the level of obstructions in a canal to calculate the depth of the water table. For a specific amount of rainfall, water pumping capacity, and aquatic plant infestation, the depth of the groundwater is computed on a real-time basis. The latter is particularly important due to the fact that levels of sulfides and nitrites have been shown to be present at levels lethal to citrus feeder roots within 48 hours of groundwater saturation (Ford, 1968).

A sample water budget is shown in Figure 2. The rainfall events considered in the model are shown along the X-axis, while soil depth is shown along the Y-axis. The water budget is calculated assuming zero aquatic plants are present and a water pumping capacity of six vertical soil inches per 24 hour period. Figure 2 demonstrates the effect of time on groundwater depth. For a three year flood, the groundwater level lies six inches below the soil surface after a 24 hour period. When evaluated at 48 hours after the end of the rainfall event, the groundwater is 16 inches below the soil surface. For rainfall events equivalent to a 25 year flood or greater the groundwater is completely saturated even after 72 hours of pumping water out of the drainage system.

The effect of aquatic plants on the ability to lower the groundwater level is shown in Figure 3. The water budget shown in Figure 3 is calculated after 72 hours for each rainfall event for two different levels of aquatic plant infestation. For comparative purposes, zero infestation and 95 percent infestation levels are shown. Under heavy aquatic plant levels, within 72 hours the groundwater level can be brought down only 4.5 inches below the soil surface for a three year flood as compared to 21.5 inches when aquatic plants are not present. Up to a 25 year event there is a substantial difference in groundwater management capability between the zero and 95 percent canal infestation scenarios. For flood events greater than or equal to a 25 year event the drainage system cannot remove sufficient quantities of water to affect groundwater levels regardless of aquatic plant infestation levels.

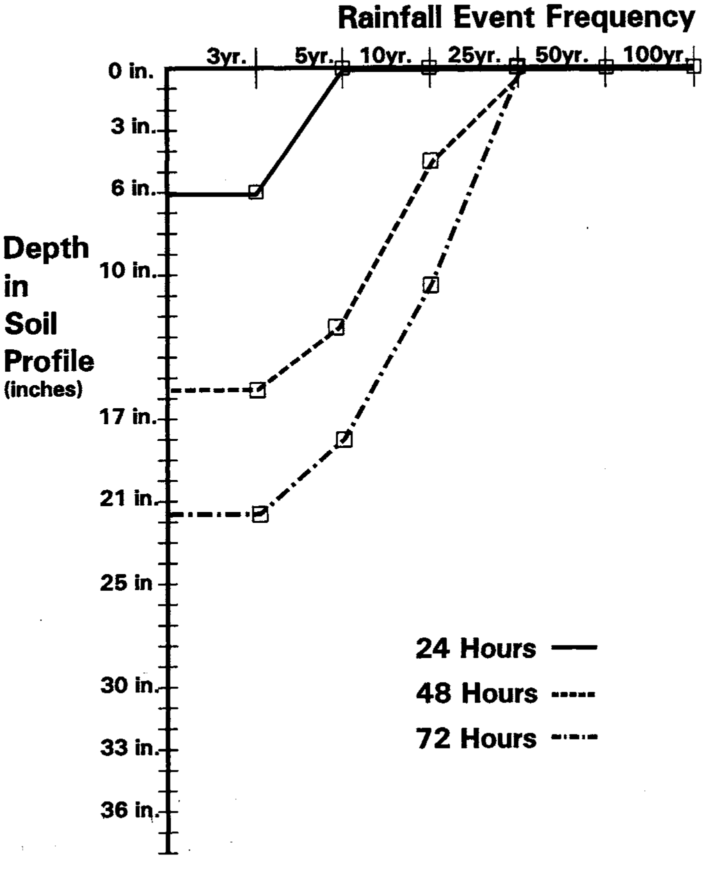

Figure 2. Water budget evaluated at 24, 48, and 72 hour post-flood intervals.

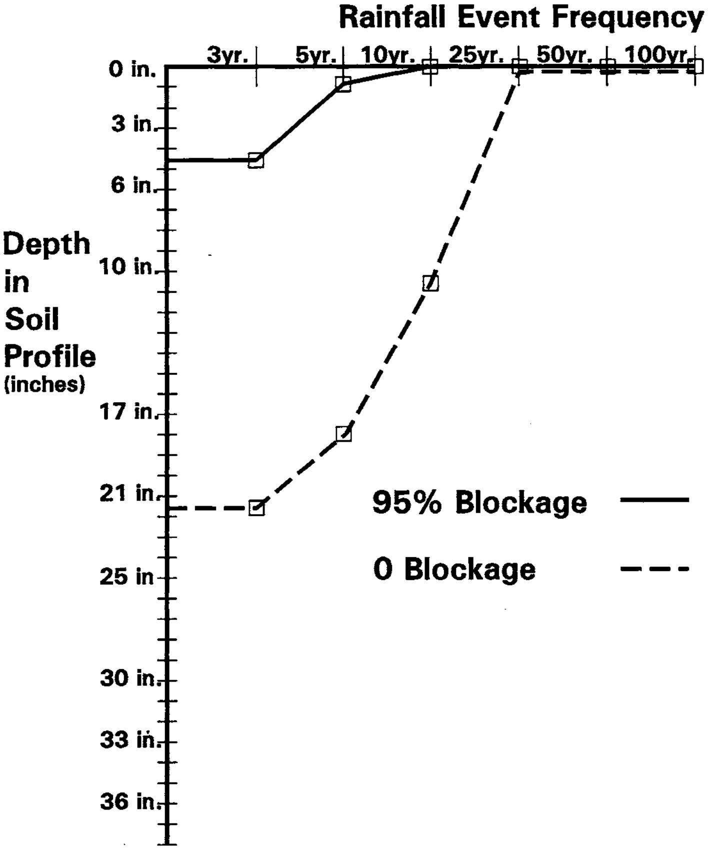

Figure 3. Water budget evaluated at 72 hours post-flood under conditions of zero and 95 percent canal blockage.

Root Loss - Tree Damage Relationship. The root distribution of citrus trees grown in poorly drained areas is quite different from that of the well drained soils of the upland ridge areas of the state (Reitz and Long, 1955). In poorly drained soils, the majority of the root mass is concentrated in the upper 18 inches of the soil profile. Thus, effective groundwater management hinges on maintaining groundwater levels at or under 18 inches below the soil surface. The effect of aquatic plants on the ability to lower groundwater levels was shown in Figure 3. In Figure 4 this effect is combined with a cumulative root mass distribution curve to show the percentage of the tree's root system that remains under anaerobic conditions after a 72 hour period for different flood events.

In Figure 4 each marker on the cumulative root distribution curve represents the depth of the groundwater and the percentage of the root mass lying above the groundwater. The latter represents the portion of the root mass that is not susceptible to the toxic effects caused by anaerobic conditions. The numbers associated with each marker indi-

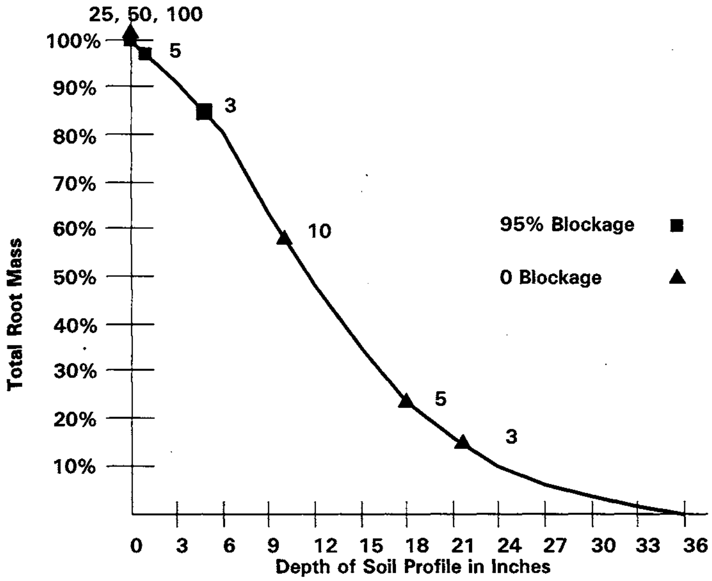

Figure 4. Graphical representation of a citrus tree cumulative root distribution curve.

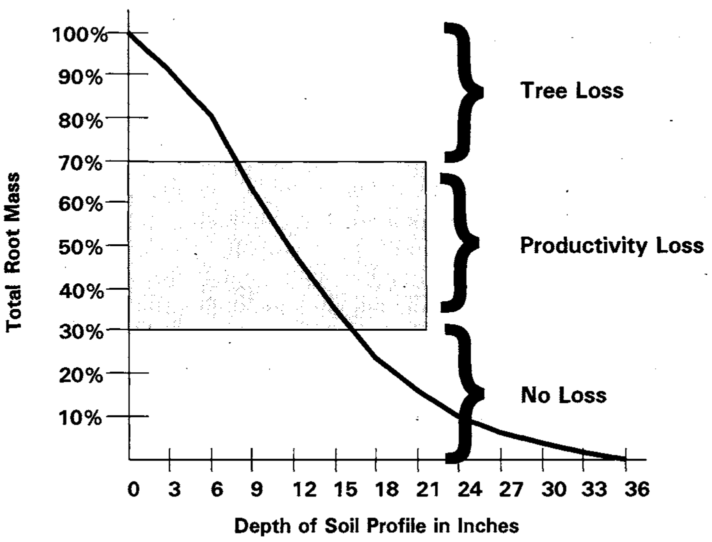

Figure 5. Graphical representation of a citrus tree root loss - tree damage relationship.

cate the flood event. For example, consider the three year flood event under 95 percent and zero percent blockage. For the 95 percent blockage case, in excess of 85 percent of the tree's root mass is still subject to groundwater saturation after 72 hours post-flood. By contrast, for an unobstructed canal less than 20 percent of the root mass is saturated. In Figure 4 it is shown that regardless of the level of canal obstruction, 100 percent of the tree's root mass is saturated after 72 hours post-flood for a 25 year event or greater. This suggests that for larger floods, mitigation of damages is likely to be a function of canal system design, whereas, for smaller floods, aquatic plant control may be an important factor in reducing flood damages in citrus groves.

The physiological effects of prolonged root exposure to anaerobic conditions depends upon the amount and duration of exposure. Unfortunately very little information is available to develop a quantitative relationship between root loss and tree damage. However, what is known is that there are three possibilities, 1) a small percentage of total root mass is killed but the tree is neither killed nor suffers any appreciable fruit loss, 2) a moderate proportion of feeder roots are killed and the tree suffers a short run decline in productivity, but the tree does not die, and 3) sufficient root mass is killed and the tree eventually dies or suffers such a decline in productivity as to render the tree unprofitable to maintain (Abbitt, 1977; Savage, 1961). Figure 5 illustrates these possibilities using a cumulative root distribution curve.

In order to make the simulation model operational it was necessary to make two simplifying assumptions. First, since insufficient data exists to quantify short term productivity losses due to root damage caused by flooding, these income losses were omitted from the model. The second simplifying assumption is that the tree will need to be replaced (due to death or economic replacement criteria) if the root loss reaches a critical cutoff point. For comparative purposes a cutoff of 80 percent root loss (shown in Figure 5) was selected. Both of these assumptions are likely to result in underestimates of the value of aquatic plant control. However, due to a lack of empirical data that might otherwise have been used, it was deemed preferable to err on the conservative side.

Computing the Cost of Replacing a Citrus Tree. Using a spreadsheet based model Muraro, Abbitt and Spreen (1978) computed the economic cost of replacing an unproductive citrus tree as a function of the cost of planting, abnormal maintenance associated with early tree growth, and lost income due to foregone fruit sales. After updating the tree planting and abnormal maintenance costs to current levels, and making adjustments based on revised citrus production data by age of tree (Florida Citrus Mutual, 1991), the Muraro, Abbit and Spreen spreadsheet was used to compute the tree replacement cost for this study. Table 1 shows these calculations.

Table 1 shows the flow of income and maintenance costs over a 25 year period for a mature, fully productive citrus tree, as compared to that of the income, replacement, and maintenance costs for a tree that must be replaced. Using an interest rate of 10 percent, and discounting these flows to present value terms, results in a net present value of $148.79 for a mature tree as compared to $25.85 for a replaced tree. Using these values the present value of lost income avoided by not having to replace a citrus tree is $119.94.

Calculation of Expected Lost Income Avoided. The benefit criterion used for this study is the expected value of avoided lost income attributable to a given level of aquatic plant control when compared to a no control baseline condition. Mathematically this calculation may be stated as:

$$\sum_{i=1}^{N} P_i D(X_i) - \sum_{i=1}^{N} P_i D^*(X_i)$$

where:

i = flood event i
N = the maximum flood event
D = a damage function associated with the no-plant control case
D^* = a damage function associated with the with-plant control case
X_1 = the amount of lost income associated with event i
P_i = the probability that flood event i will occur.

TABLE 1. CALCULATION OF CITRUS TREE REPLACEMENT COST

	Productive Tree (10 years old)		Replaced Tree	
Year	Income[a]	Maintenance	Income	Maintenance
1	22.88	5	0.0	21
2	22.88	5	0.0	13
3	22.88	5	5.76	11
4	22.88	5	5.76	7
5	21.28	5	5.76	5
6	21.28	5	10.24	5
7	21.28	5	10.24	5
8	21.28	5	10.24	5
9	21.28	5	10.24	5
10	21.28	5	22.88	5
11	21.28	5	22.88	5
12	21.28	5	22.88	5
13	21.28	5	22.88	5
14	21.28	5	22.88	5
15	21.28	5	21.28	5
16	21.28	5	21.28	5
17	21.28	5	21.28	5
18	21.28	5	21.28	5
19	21.28	5	21.28	5
20	21.28	5	21.28	5
21	21.28	5	21.28	5
22	21.28	5	21.28	5
23	21.28	5	21.28	5
24	21.28	5	21.28	5
25	21.28	5	21.28	5
Net Present Value = $148.79			Net Present Value = $28.85	

[a]Assumes an output price of $6.40/box for valencia oranges and .9, 1.5, 1.7, 3.575, and 3.125 boxes per tree for 3-5, 6-8, 4/9, 10-14, and 15-24 year old trees respectively (Florida Citrus Mutual, 1991).

Equation 1 is specified as a discrete function because only a limited number of rain events are considered in the model. The probability of each flood event is calculated on the basis of the event's frequency over a 100 year period. Thus, the probability that a 100 year flood will occur in any given year is given by its reciprocal, 1/100 or .01. In the simulation model, single discrete events equivalent to 100, 50, 25, 10, 5 and 3 year flood events were considered. Converting these event frequencies into probabilities and applying the appropriate damage functions yields an estimate of the expected average annual lost income avoided.

Within the simulation model, calculation of equation one is accomplished in four steps. First, given a specified pumping capacity, canal blockage level, and rainfall event, the water budget computes the height of the groundwater in the soil profile at a specified time after the rain has ended. The rainfall associated with each flood event is assumed to take place over a 24 hour period (Anonymous, 1987). Specification of flood events in this manner is an abstraction from the many different ways in which rain events may occur. However, the defining characteristic of a flood event is the height of the resulting flood water and not necessarily the actual amount of rain that falls. The 24 hour rainfall event is based on hydraulic engineering estimates of the amount of rain that would result in a specified flood event. The water budget is evaluated 72 hours after the rain event has ended.

The second step in the simulation is to determine the amount of root loss that may have occurred. This step involves linking the water budget to a root distribution curve. In this manner an estimate of the percentage of the root mass that remains under anaerobic conditions is determined. As described earlier, if a sufficient percentage of the root mass remains under these conditions for a prolonged period, the tree will die. Since nitrites and sulfides have been shown to be present in the soil profile at levels toxic to citrus feeder roots within 48 hours of groundwater saturation (Ford and Calvert, 1968; Ford, 1968), it was assumed that all feeder roots that remained under anaerobic conditions for an additional 24 hours (a total of 72 hours from the end of the rainfall event) would be killed. Further, if after 72 hours at least 80 percent of the root mass remains under anaerobic conditions, the tree is assumed to be sufficiently damaged as to warrant replacement.

If for a given, canal pumping capacity, level of blockage, and rainfall amount less than 80 percent of the root mass remains under anaerobic conditions after a 72 hour period, it is assumed that the tree will not need to be replaced, hence, no losses occur. The present value of lost income associated with replacing a flood damaged citrus tree was estimated to be $119.24. To calculate the expected value of this loss, the present value of lost income must be multiplied by the probability that the specific rainfall event will occur.

Step three yields the expected present value of lost income for a given level of pumping capacity, rainfall, and canal blockage. In step four the simulation systematically varies rainfall and aquatic plant infestation levels to compute the expected present value of lost income for each combination of rainfall and plant blockage levels. Once these estimates are derived the benefits of aquatic plant control are computed by subtracting the estimated lost income associated with a baseline condition from that of incrementally greater aquatic plant control levels. The difference between the base and any given higher level of aquatic plant control is a measure of the benefit (lost income avoided) of the higher level of plant control relative to the base.

RESULTS AND DISCUSSION

For simulation purposes six different flood events and ten different canal blockage levels were selected. The results of the analysis are reported in Table 2. Column one of Table 2 shows the estimated lost income associated with

TABLE 2. ANNUAL PER TREE BENEFITS OF AQUATIC PLANT CONTROL FOR FLORIDA FLATWOODS CITRUS TREES.

Canal Blockage (%)	Expected Present Value of Lost Income ($)	Expected Present Value of Benefits ($)
90	88.00	0.0
80	88.00	0.0
70	88.00	41.71
60	46.29	41.71
50	46.29	41.71
40	46.29	41.71
30	46.29	41.71
20	21.17	66.73
10	21.27	66.73
0	21.27	66.73

each level of canal obstruction. For example, the expected present value of lost income due to flooding for a canal that is only 10 percent efficient is $88.00 as compared to $21.27 for a canal that is 80 percent efficient[2]. The second column of Table 2 presents the economic benefits with each level of canal efficiency as compared to the base; in this case 10 percent efficiency. For example, an aquatic plant control program that maintained canals at 80 percent efficiency or better, results in annual flood control benefits of $66.73 per tree.

The results reported in Table 2 can be used in two ways. First, the benefits for any given aquatic plant control program can be read directly from the table. For example, an aquatic plant control program that had a target control level of 50 percent canal efficiency would yield annual benefits of $41.71 per tree. Assuming an average of 116 trees per acre (Muraro and Holcomb, 1992), aquatic plant control benefits would be $4,838.36 per acre.

The second way in which Table 2 can be used is in computing the marginal benefits associated with a change in an existing aquatic plant control program. The benefits of increased aquatic plant control, from 70 to 80 percent efficiency for example, can be calculated by subtracting the benefits of the new higher control level ($66.73) from that of the current program ($41.71) resulting in marginal benefits of $25.02 per tree. As long as the per tree cost of the increased level of aquatic plant control is less than $25.02 then the new control program is economically justified. Note, however, that the marginal benefit of target control levels greater than 80 percent efficiency is zero. This means that efforts to increase canal efficiency beyond 80 percent would yield no added benefits and would not be justified on an economic basis.

The results reported in Table 2 rest on three important assumptions; the time at which the water budget is evaluated (72 hours), the canal system pumping capacity (six inches per 24 hour period), and the percentage of root loss required to kill a tree (80 percent). In order to test how robust the simulation results would be with respect to each of these assumptions, a sensitivity analysis was conducted, the results of which, are reported in Table 3.

Sensitivity Analysis

The expected present value of aquatic plant control benefits are shown in the columns of Table 3 for three different canal pumping capacity levels and for three different time periods for evaluating the water budget. Sensitivity analyses using root loss levels of 70 and 75 percent were also conducted. However, the gross benefit measures were similar to that reported in Table 2 and are not reported. These results are available from the authors upon request.

The results reported in Table 3 lead to a couple of interesting observations. First, assuming that there is no control program and if the groundwater budget is evaluated at 72 hours then added pumping capacity provides no increase in economic benefits. However, if the water budget is evaluated at 96 hours and canal efficiency is at least 20 percent, then increasing pumping capacity to eight vertical inches per 24 hour period yields average annual benefits of $41.71 per tree. Similarly, if the water budget is evaluated at 120 hours, investment in pumping capacity to seven inches results in the same level of benefits, provided a 20 percent canal efficiency is maintained. Additional benefits ranging between $2.51 and $17.51 per tree can be achieved if higher canal efficiency levels are maintained.

The preceding analysis indicates that investment in added pumping capacity may be a substitute for aquatic plant control expenditures. However, the relative benefits and costs of investing in increased pumping capacity would need to be weighed against that of an aquatic plant control program.

The second observation is that the most conservative combination of assumptions; 1) requiring 80 percent root loss before tree replacement, 2) evaluating the water budget at 120 hours post-flood, and 3) assuming a pumping capacity of eight vertical soil inches per 24 hour period, results in the highest estimated values of aquatic plant control program benefits. These assumptions do in fact result in the lowest levels of expected lost income, particularly at higher levels of aquatic plant control. However, the baseline damage estimate (a 10 percent canal efficiency) from which the benefit measures were computed was invariant with respect to changes in assumptions. Under these conservative assumptions, expected damages are lower at higher levels of aquatic plant control. Since the estimated base is the same across all combinations of assumptions, a smaller number subtracted from the same base will result in a larger difference, hence the larger benefit estimates.

The sensitivity analysis shows that the economic benefit of aquatic plant control in flatwoods citrus groves ranges between zero and $86.75 per tree depending upon the selected control level, pumping capacity, and time period selected for evaluating the water budget. If the maximum possible benefit is selected for each of these combinations, the range of economic benefits narrows to between $66.73 and $86.75 per tree. These findings indicate that the benefits of aquatic plant control in flatwoods citrus groves may

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[2] In this study canal efficiency is defined to be a measure of a canal's water carrying capacity relative to its original design specifications. A canal efficiency level of 70 percent means that the canal operates at 70 percent of its original specifications.

TABLE 3. SENSITIVITY ANALYSIS OF ECONOMIC BENEFITS OF AQUATIC PLANT CONTROL FOR CHANGES IN CANAL SYSTEM PUMPING CAPACITY AND DIFFERENT TIME PERIODS FOR EVALUATING THE GROUNDWATER BUDGET.

Canal Efficiency (percent)	Pumping Capacity = Six Vertical Inches			Pumping Capacity = Six Vertical Inches			Pumping Capacity = Eight Vertical Inches		
	Post-Flood Time for Evaluating the Groundwater Budget			Post-Flood Time for Evaluating the Groundwater Budget			Post-Flood Time for Evaluating the Groundwater Budget		
	72 Hours	96 Hours	120 Hours	72 Hours	96 Hours	120 Hours	72 Hours	96 Hours	120 Hours
10	base	base	base	base	base	base	base	base	base
20	0	0	0	0	0	41.71	0	41.71	41.71
30	0	41.71	41.71	41.71	41.71	41.71	41.71	41.71	41.71
40	41.71	41.71	41.71	41.71	41.71	66.73	41.71	41.71	66.73
50	41.71	41.71	66.73	41.71	66.73	66.73	41.71	66.73	66.73
60	41.73	66.73	66.73	41.71	66.73	79.24	66.73	66.73	79.24
70	41.71	66.73	79.24	66.73	66.73	79.24	66.73	79.24	84.24
80	66.73	66.73	79.24	66.73	79.24	84.24	66.73	79.24	84.24
90	66.73	66.73	79.24	66.73	79.24	84.24	79.24	84.24	86.75
100	66.73	66.73	84.24	79.24	84.24	86.75	79.24	84.24	86.75

be substantial and should be an integral part of an overall grove management program.

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