Irrigation Water Supplied by Stream Water Level Control

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ABSTRACT

STREAM water levels in Mitchell Creek near Tarboro, North Carolina, were satisfactorily controlled for drought and flooding conditions by a water-inflatable dam (Fabridam). The reported 4-year period covers normal rainfall years in 1982 and 1985 (405 and 473 mm of rain for the corn-growing season and 80 and 82 mm of irrigation used, respectively); a dry year in 1983 (349 mm of rain and 175 mm of irrigation used); and a high rainfall year in 1984 (659 mm of rain during the corn-growing season and only 2 mm of irrigation used). By controlling the stream water level, runoff and drainage were redistributed, and adequate water was stored in the soil profile and shallow aquifer (2 to 7 m below the surface) to furnish irrigation water for eight center pivot systems, four volume gun hose reel systems, and one controlled-drainage/subirrigation system, irrigating 327 ha. Before the stream water level was controlled, only two center pivot systems and two volume guns, irrigating 79 ha, were able to operate and then only part time. Corn yields (4-year average) in fields with stream water level control were 27% more for nonsprinkler-irrigated fields and 71% more in sprinkler-irrigated fields than in fields without stream water level control. These increased yields would pay for the Fabridam in 15 years, pay the cost of irrigation, and without tax break consideration give an annual return for management of $100/ha.

INTRODUCTION

Water for irrigation is not always plentiful; and in some areas, groundwater levels are declining about 2 to 3 m/yr (U.S. Water Resources Council, 1978). For instance, a water shortage developed in the High Plains of Texas and in Nebraska after a few years of intensive irrigation.

Water resources may even become critical in the Southeast. In some areas of the Southeast, groundwater levels have dropped because withdrawals from aquifers have exceeded recharge (Padgett, 1984). In North Carolina, the piezometric water levels in the Yorktown, Castle Hayne, and Cretacens Aquifers have dropped 3 m, 24 m, and 30 m, respectively since 1965; and in South Carolina, the Black Creek and Middendorf Aquifers have dropped 9 m since 1965 (U.S. Geological Survey, 1985). The overall water budget (Padgett, 1984) showed that in North Carolina "for every 100 m of rainfall, 70 m^3 are lost to evapotranspiration and 24 m^3 are lost to direct runoff." This leaves 6 m^3 of usable water of which 3 m^3 is used by industry, 2.5 m^3 is used by agriculture, and 0.5 m^3 is used for domestic purposes. Thus, the Southeast may fully utilize its water resources, and new supplies may not be available for agriculture. Yet, stream flows to the Atlantic Ocean and Gulf of Mexico are estimated to be about 4.2 billion m^3 per day (U.S. Water Resources Council, 1978).

From this information two things are apparent: (a) agriculture must compete with industry and domestic users for water, and (b) a promising way to increase our water resources is by conserving some of the 24% (4.2 billion m^3 per day) lost in runoff and flowing into the ocean.

About 5 million ha of sandy loam and organic soils with seasonal high water tables that must be drained are found in the Atlantic Coastal Plains (Wenberg and Gerald, 1982). Approximately 15 to 25 million ha of farmland in the humid region of the United States is artificially drained, yet average crop yields during some years may be decreased from 15 to 30% due to deficient soil-water conditions in these same soils. Improved water management is receiving greater emphasis by farmers in the Coastal Plains areas along the Atlantic and Gulf coasts. Lack of complete water management is considered to be the single greatest barrier to producing sustained profitable yields in these areas.

One approach to reducing the demands on the deep groundwater wells for irrigation is to increase the use of shallow groundwater (less than 8 m from the surface) resources which are recharged annually by rainfall. The research project discussed here has identified a promising means of accomplishing this. Water can be conserved by watershed-scale controlled drainage practices without sacrificing the original drainage and flood control objectives of PL83-566 projects. Continued research and implementation of similar projects in other areas will result in significant savings in water and more efficient use of our resources.

The objective of this paper is to evaluate the effect of stream water level control (SWLC) by a water inflatable dam (Fabridam) on increasing the local water supply for agriculture by storing water in the shallow (less than 8 m) aquifer for irrigation use, thus conserving deep aquifer water supplies.

MATERIALS AND METHODS

The stream water level control study was located on a

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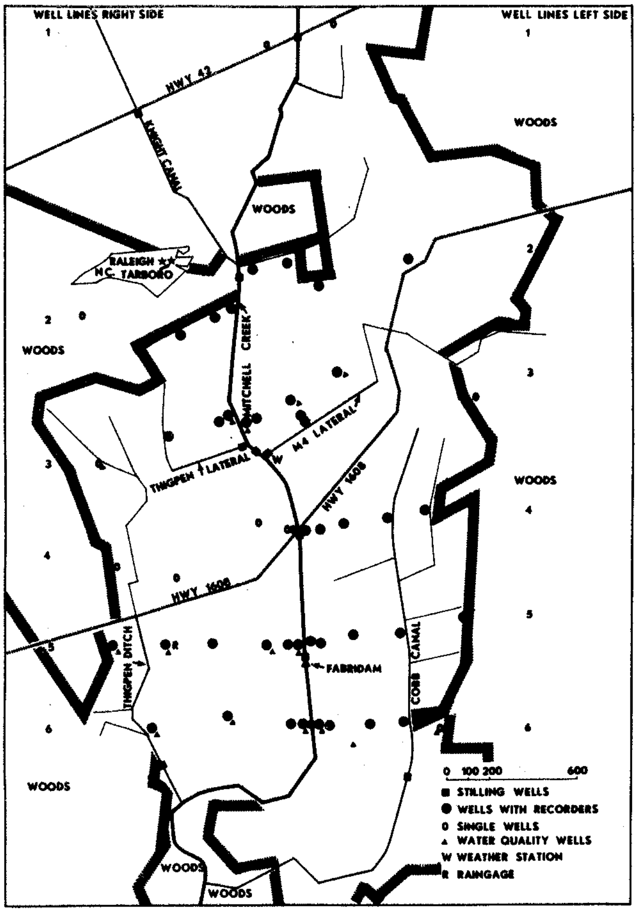

Fig. 1—Project sketch showing stream channel system and observation well locations on Mitchell Creek (scale in meters).

3.5-km section of Mitchell Creek in Edgecombe and Pitt counties, North Carolina (Fig. 1). The area, approximately 800-ha in size, was flat to gently rolling with no more than 1.5 m difference in elevation. The soil series, Altavista, Augusta, Cape Fear, Conetoe, Portsmouth, Roanoke, State, Tarboro, and Wahee, were closely mapped by the Soil Conservation Service. These soils were poorly to somewhat excessively drained, formed in sandy fluvial and marine sediments. The area was underlain by a coarse aquifer from approximately 2 to 8 m deep. A layer of blue, impermeable clay was below the coarse sand.

Six lines of water table observation wells (65 in all) were installed to monitor the water levels on each side of the creek (Fig. 1). Well locations ranged from 10 to 1000 m from the channel in lines perpendicular to the creek. More complete details of the study area were given by Doty et al. (1984a,b, 1986).

The study area was operated as the planned ditch drainage system for the first two years, 1980 and 1981. Volume of irrigation water pumped, stream flow, stream and groundwater levels, and crop yields were recorded. During the winter of 1981 and 1982, a water inflatable fabric dam (Fabridam) was installed on Mitchell Creek. Operation of the dam to provide stream water level control (SWLC) began April 2, 1982. Further description of the Fabridam was given by Doty et al. (1984). The control elevation settings of the stream water level above mean sea level (MSL) are shown in Table 1.

The actual amount of irrigation water pumped from Mitchell Creek was measured by flow meters placed on each farm irrigation unit. The actual area irrigated was determined by the area covered by each unit. The estimated potential water stored and pumped from Mitchell Creek for irrigation and the area irrigated was calculated based on a simulation model of numerical solutions to the Boussinesq equation developed by Badr (1983).

TABLE 1. CONTROL LEVEL SETTINGS FOR THE FABRIDAM 1982-1985

Setting above MSL, m	Date of setting (mo da yr)	Reason for change
10.28	4/2/82	Fabridam installed
11.28	5/28/82	To increase water supply after planting
11.55	7/6/82	To increase water supply to crops
10.40	10/7/82	Over winter stream water level
10.80	5/4/83	Begin water storage for growing season
11.50	5/17/83	To supply water for growing season
10.40	12/16/83	Over winter stream water level
10.80	2/21/84	Begin water storage for growing season
11.30	4/27/84	To increase water storage
11.70	5/28/84	To increase water supply after planting
11.10	5/30/84	To allow drainage after rain
11.70	6/6/84	To increase water storage
11.60	7/16/84	To allow drainage
11.40	7/17/84	To allow drainage
10.80	7/18/84	To allow drainage
11.70	8/6/84	To increase water supply to crops
11.40	8/10/84	To allow drainage
11.70	8/13/84	To increase water supply to crops
11.00	9/11/84	Hurricane Diana
11.30	9/17/84	Water supply and nitrate control over winter
11.60	6/19/85	To increase water storage
11.55	7/15/85	To reduce pressure in dam
11.65	7/25/85	To increase water storage
11.50	7/29/85	To allow drainage
11.25	8/01/85	To allow drainage
11.45	8/7/85	To increase water storage
11.55	8/14/85	To increase storage
11.25	8/20/85	To allow drainage and set for winter

The 800-ha area was divided into three treatment areas: (a) the stream water level control treatment area (with SWLC) which extended from the Fabridam to about 2,700 m upstream; and two treatment areas without SWLC, (b) below the Fabridam, and (c) above the control area, at distances greater than 3,005 m above the Fabridam. Comparisons of water storage and irrigation applications were before SWLC (1981) and after the Fabridam was installed (1983).

About 625 ha were in cultivation in the SWLC area above the Fabridam. The major crops in the area are corn, soybean, and peanuts. Small amounts of cotton and tobacco were also grown. Crops were sampled by hand for yield estimates from 3 × 2 m plots. Two plots were sampled from the crop near the water table observations wells.

RESULTS AND DISCUSSION

The rainfall by month for the 1980-1985 study period is shown in Table 2. The 30-year average rainfall for the area is 571 mm for the corn-growing season and 1,199 mm for the water year September through August. During this study, the growing season rainfall for 1981, 1982, and 1985 was close to but less than normal (452,

TABLE 2. RAINFALL ON THE MITCHELL CREEK WATERSHED FOR WATER YEAR–SEPTEMBER THROUGH AUGUST

Month	Water year					
	1980-81	1981-82	1982-83	1983-84	1984-85	30-yr avg.
	mm					
September	68	12	95	135	123	105
October	204	47	89	46	7	67
November	52	13	49	78	22	76
December	46	97	89	154	34	85
January	37	112	44	59	99	98
February	55	106	134	130	75	93
March	51	81	120	110	27	104
April	23	94	59	84	5	83
May	96	24	94	184	60	96
June	69	90	58	30	101	106
July	78	78	59	260	196	151
August	186	119	79	101	111	135
Total	965	873	969	1371	860	1199
Corn-growing season Apr-Aug Total	452	405	349	659	473	571

405, and 473 mm, respectively) (Table 2). 1983 was a dry year with only 349 mm of rain during the corn-growing season. 1984 was extremely wet with 659 mm of rain during the corn-growing season.

Rainfall for the last year before SWLC at the Fabridam, 1981 (452 mm), was greater for the April through August period than it was for the same period in 1983 (349 mm). However, there was more rainfall over winter (September-March) (620 mm) in 1983 than in 1981 (513 mm).

Effect of Stream Water Level Control on the Water Table

The water table was affected throughout the area above the Fabridam (about 625 ha). Controlling the stream water level reduced drainage to Mitchell Creek and stored water in the shallow aquifer and the soil profile. A cross-sectional view through the center of the area above the Fabridam (along well line #4, Fig. 1) is shown in Fig. 2. The water table elevation (WTE) on 16 December 81 shows how the water table was drawn down by the deep channels of Mitchell Creek. With SWLC, the water table was from 1 to 2 m closer to the surface on 1 August 1984 than it was in 1981. With the considerable amount of rain that occurred prior to 1 August 1984, the

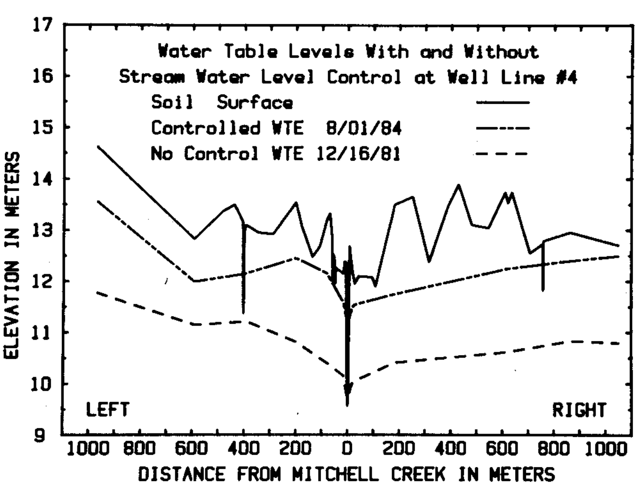

Fig. 2—Water table and soil surface elevations above mean sea level in relation to distance from Mitchell Creek before and after Fabridam installation at Well line 4.

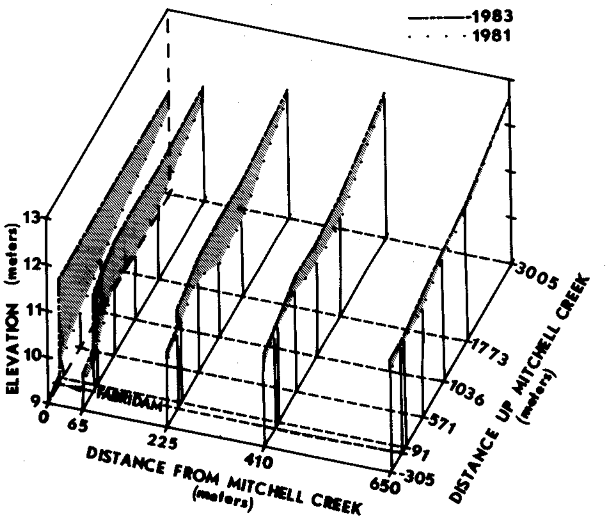

Fig. 3—Soil-water storage for 1981 (before installation of Fabridam) and 1983 (after installation) in relation to distance from Mitchell Creek, above and below the dam.

water table was still draining toward Mitchell Creek. SWLC controls drainage and stores water underground in the shallow aquifer within the watershed.

This storage of water was depicted for an area on the right side of Mitchell Creek looking upstream from 305 m below the Fabridam and 650 m on the east side of the creek to 3005 m upstream from the Fabridam (Fig. 3). The shaded area is the soil water storage increase in 1983 over that in 1981 for 30 June. Below the Fabridam, 0 to −305 m, there was little difference in storage, indicating that rainfall for the 2 years were similar. Rainfall for the month of June was 69 and 58 mm for 1981 and 1983, respectively. Above the Fabridam, there was considerably more water in Mitchell Creek in 1983 than in 1981. At 65 and 225 m away from the Creek, there was more storage in 1983 than in 1981. At 410 m from the creek, this storage began to subside, and at 650 m away from the creek, storage in 1983 was similar to that in 1981.

The stored water in the shallow aquifer flows to the channel and can be pumped from the creek. Sufficient amounts of irrigation water was available for pumping from Mitchell Creek to sustain production during the droughty months of July and August. This is depicted in Fig. 4. Notice that the water level in the stream was raised to a maximum about 20 May 1983, and the water level in the soil profile and shallow aquifer was held in that position until about 15 July when pumping of irrigation water reached a high rate. From 15 July through 30 August, water was withdrawn and used for irrigation. In 1981, farmers were only able to use two center pivot systems and two volume guns. With these four systems in operation, farmers were unable to pump continuously and pumping had to stop over night so the flow from upstream could refill Mitchell Creek. After the Fabridam was installed, eight center pivot systems, four volume guns, and one controlled-drainage/subirrigation system were able to pump water as needed for irrigation (Table 3).

The difference in the amount of irrigation water pumped from Mitchell Creek with no SWLC in 1981 and with SWLC in 1983 is shown by month and seasonal total in Fig. 5. Considerably more water was pumped for

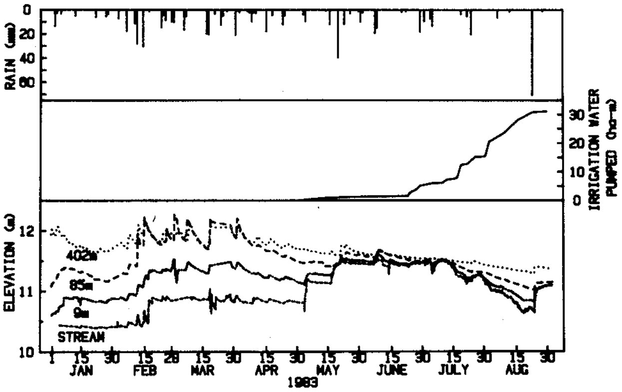

Fig. 4—Relationship with time of rainfall, irrigation water pumped, and water table elevations at various distances from Mitchell Creek in 1983.

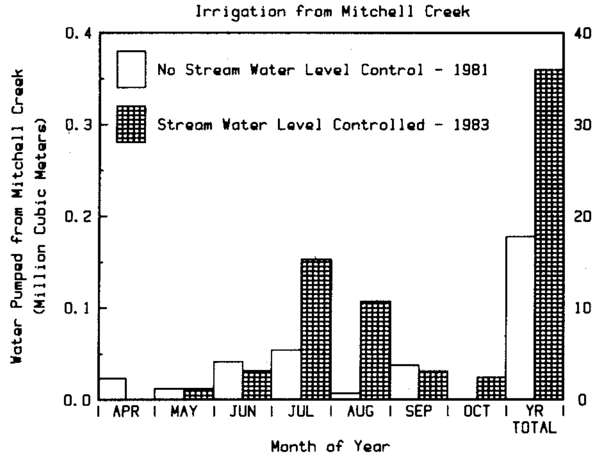

Fig. 5—Irrigation water pumped from Mitchell Creek before (1981) and after (1983) the Fabridam installation.

irrigation in 1983 with the additional units in operation. The total volume of water pumped in 1983 was 0.36 million m^3 as compared to only 0.18 million m^3 in 1981. In 1983, 175 mm of water were applied to about 210 ha (Table 3), while in 1980, only 122 mm of water was applied to 79 ha. This shows that water used for irrigation more than doubled in 1983 compared to 1980. In July 1983, 153,000 m^3 of water was pumped compared to 178,000 m^3 pumped the entire year in 1981.

Table 4 shows results of a modelling effort to determine maximum area for irrigation. The potential use of water stored in the soil profile by SWLC is shown for 1982 rainfall and ET conditions (Badr, 1983). These data do not include the effects of stream flow or channel storage. With no control, the model showed that a minimum of 0.035 cm/day of water flows into Mitchell Creek. This amount of water can be pumped every day at the rate of 2.5 cm/day which covers only 1.4% of the area each day. Assuming that crop use is 0.5 cm of water each day, a return to the same area every 5 days is needed to irrigate a crop without stress. Without SWLC, only 7% (1.4 × 5) of the area could be irrigated, which is about 44 ha. However, with a return frequency of 14 days, 20% (1.4 × 14) of the area could be irrigated.

With the stream water levels controlled by the Fabridam, the higher water table causes an increase in flow to the creek and approximately 0.10 cm/day of water was the minimum flow into the stream which could be pumped out covering 4% of the area at a 2.5 cm/day application rate. With a return frequency of 5 days 20% (4 × 5) of the area (about 125 ha) could be irrigated. With a 13-day return frequency, 52% (4 × 13) of the area (about 325 ha) could be irrigated. This substantiates field observations. Without SWLC, farmers were irrigating approximately 13% of the area (79 ha) in 1980. But at the present rate of irrigation in 1983, 1984, and 1985, 34, 46, and 52% (210, 225, and 327 ha), respectively, of the area was being irrigated (Table 2).

This analogy is used to explain how SWLC works. Consider the area above the Fabridam as a bucket. If this bucket has a hole in it (Mitchell Creek), and the water is flowing out of it, then there is very little water stored in the bucket to pump for irrigation when it is needed. But if this hold is plugged (by the Fabridam) and only a small amount of the water is allowed to seep out of the bucket (seepage through the soil to the lower elevation stream below the Fabridam), water is stored for irrigation. However, when the bucket becomes completely full, it will overflow the top (flow over the Fabridam), the plug must be pulled to allow water to be released. The Fabridam works like the plug in the bucket. SWLC raises the water level underground to form an underground lake for later use. This stored water would normally flow downstream and on to the ocean.

In 1983 the soil profile, 'our bucket', was stored full of water to the elevation of the Fabridam. As rainfall occurred, with the bucket full, excess water overflowed the Fabridam. As the water level in the stream rose, drainage to the stream was reduced and the water

TABLE 3. IRRIGATION WATER PUMPED AND HECTARES OF SURFACE WATERING, 1980-85

Year	No. System used*			Avg. yearly irrig. appl.	Area covered/ surface watering	Irrig. water pumped from Mitchell Creek
	CP	VG	CDSI			
				mm†	ha	m^3†
1980	2	2	–	122	79	96,234
1981	2	3	–	159	118	187,970
1982	5	3	–	80	142	114,280
1983	6	4	1	175	210	352,840
1984	6	3	1	2	285	6,530
1985	8	4	1	82	327	261,284

*CP = center pivot; VG = volume guns; CDSI = controlled-drainage/subirrigation system.

†Water applied to the 8-ha CDSI system was not measured and not used to calculate average irrigation application.

TABLE 4. POTENTIAL USE OF WATER STORED IN THE SOIL PROFILE BY STREAM WATER LEVEL CONTROL BASED ON 1982 RAINFALL*

Condition	Drainage to stream	Irrigation rate	Hectares irrigated: 325	125	44
			Return frequency		
	cm/day	cm/day	days	days	days
No control	0.035	2.5	36	14	5
Stream control	0.100	2.5	13	5	–

*Does not include stream flow or channel storage (Badr, 1983).

transferred to underground storage. The increase in stream water level elevation stopped the flow at 3005 m upstream of the Fabridam, and as the water level upstream rose, the drainage water was transferred to storage. In July and August the water level above the Fabridam dropped below the preset Fabridam surface (Fig. 4) as the water was being pumped out for irrigation. Water saved in the spring was used by the crops and pumped to irrigate other crops. In case of a period of heavy (80 mm) or extended rainfall, the Fabridam is automatically lowered (the plug is pulled from the bucket), and the stream water level is lowered, which drains the fields normally.

The stream flow below the Fabridam was not adversely affected by controlling the water level above the dam (Doty et al., 1986). During a 64-day period in 1983, little or no water flowed over the Fabridam because of a lack of rainfall and irrigation pumping. At 300 m downstream from the dam, the stream water level rose slightly during this period. High stream water levels above the dam and associated high field water tables caused increased groundwater seepage to the lower stream water level downstream, which maintained base flow downstream without flow over the Fabridam. Therefore, the water available for pumping from Mitchell Creek below the dam was about the same with or without the Fabridam.

All the land in the 625-ha area above the Fabridam does not need sprinkler irrigation. In fields with low elevations and the water table less than 1 m from the surface, water was supplied from the water table for most of the year. About 200 ha (rainfed, Table 5) of the 625-ha SWLC area received additional water from the subsurface because of the higher water table. For example, in Fig. 2, areas at 150 and 75 m from the creek on the left side and 100, 300, 700, and 1000 m on the right side did not need sprinkler irrigation in August 1984. However, as water was pumped from Mitchell Creek for irrigation in the summer of 1983, the water table at those points dropped and irrigation was probably needed. If a watershed is very flat and the water table can be controlled within 0.60 m to 1 m from the surface, no sprinkler irrigation would be needed.

Crop Yields

Crop yields were significantly increased with SWLC

TABLE 5. AVERAGE CROP YIELD FOR 1982-1985 ON WATER TABLE MANAGEMENT TREATMENTS

Water table management system	Corn	Soybean	Peanut
	------------ t/ha ------------		
Stream water level control			
Rainfed	7.75b*	2.10cd	3.76b
Sprinkler irrigated	10.45a	2.83b	5.61a
Below the Fabridam			
Rainfed	6.12c	2.02d	3.06b
Sprinkler irrigated	11.09a†	3.47a	5.55a
Above control area			
Rainfed	5.50c	1.99d	4.81a
Sprinkler irrigated	8.63b	2.49bc	—

*Subtreatments followed by the same letter within a column are not significantly different at the 95% probability level.
†This data for 1985 only.

TABLE 6. ANNUAL COST ANALYSIS OF THE FABRIDAM USED TO SUPPLY WATER FOR SPRINKLER IRRIGATION

	$/ha
Increase in return from corn yield	426*
(Less payment on dam (Principle + interest))	-132†
Total return to management for maintenance and irrigation	294
(Less cost of irrigation, Worm et al., 1982)	-182
(Less operation and maintenance of Fabridam)	- 12
Net return to management	100‡

*(Irrigation + SWLC) - No control 4.33 t/ha increase (avg. for 4 yr) x $98.40/t ($2.50/bu).
†248,700 x 0.13147 crf for 15 yr @ 10% interest (327 - 79 = 248 ha).
‡In addition, a 27% increase in corn yield was shown for about 200 ha of nonsurface irrigated land, and no tax break on the investment was considered.

for sprinkler irrigated and nonirrigated conditions (Table 5). For the 4-year average, rainfed corn yields were 1.63 t/ha (7.75-6.12) (27%) more with SWLC than below the Fabridam with no control. The addition of sprinkler irrigation produced 4.33 t/ha (10.45-6.12) (71%) more corn yield than below the Fabridam under rainfed conditions. Peanut and soybean yields were increased but not significantly (Table 5). Crops below the Fabridam were irrigated by water stored above the Fabridam to supply a center pivot, while crops in the SWLC area were irrigated by volume gun. Also, soybeans in the SWLC area competed with peanuts for irrigation with the volume gun.

Cost Analysis

What is the value of this stored water? Madariaga and McConnell (1984) showed that "marginal value product" of irrigation water in crop production for the Mid-Atlantic States ranged from 0.06 to 0.26 $\$/m^3$ depending on the model used. In this study, the 4-year average showed that irrigation produced an additional profit of 0.14 $\$/m^3$ of water added even after the cost of the Fabridam (132 $/ha) (Table 6) was deducted.

The Fabridam cost $248,700. The annual payments for 15 years at 10% interest would be $132/ha per year based on the 248 ha irrigated (Table 6). The increase in corn yield was 4.33 t/ha (10.45-6.12), and at $98.40/t, the annual increase of income was $426/ha. Worm et al. (1982) found that it cost $182/ha/yr to operate a center pivot system including additional fertilizer for irrigation. Their figures may be high since they were pumping from a deep well. Over the 4-year period, the operation and maintenance ranged from $4,623 in 1983 to $2211 in 1985 for an average of $3030 per year and for the 248 ha, an average of $12/ha/yr. However, Table 5 shows a net return of $100/ha to management. This is a sizable return with the Fabridam paid off in 15 years. There were no considerations given for the tax break on the investment. In addition, a 1.63 t/ha (7.775-6.12) (27%) increase in corn yield was shown for about 200 ha of nonsurface irrigated land.

SUMMARY AND CONCLUSIONS

In the southern Coastal Plains, water levels in the deep aquifers have dropped as much as 30 m since 1965, while stream flows to the Atlantic Ocean and Gulf of Mexico are estimated to be about 4.2 billion m^3 per day. Agriculture must compete with industry and domestic users for water. If the deep groundwater supply continues to drop, as since 1965, a portion of the 4.2 billion m^3 per day now reaching the ocean must be conserved to meet projected water demands.

In the sandy soils of the southern Coastal Plains, SWLC has the possibility of redistributing the runoff and drainage water to supply water for irrigation. On Mitchell Creek in North Carolina, over a 4-year period, SWLC redistributed runoff and drainage in the watershed to allow adequate irrigation for crops, while still providing for flood control. In 1983, 352,840 m^3 (56 mm on the 625-ha watershed) of water was pumped from Mitchell Creek for irrigation. This is only 16% of the growing season rainfall. Doty et al. (1986) estimate that more than 10 times this amount was left in storage, which is less than 60% of the 969 mm water year rainfall. In 1980, before SWLC, water from Mitchell Creek supplied only 2 center pivots and 2 volume-guns, irrigating only 79 ha with 122 mm. This would be only 15 mm on the 625-ha area or 3% of the 1980 growing season rainfall. But, in 1985, SWLC stored water in the soil profile, and the shallow aquifer and Mitchell Creek supplied water for more than 8 center pivots, 4 volume guns, and 1 controlled-drainage/subirrigation system. At the 1983 application of 175 mm on the 1985 coverage area of 327 ha, the water pumped from Mitchell Creek would be 572, 250 m^3, which would be only 92 mm over the 625 ha or 19% of the 1985 growing season rainfall. SWLC increased the water available for pumping from Mitchell Creek from 3% of growing season rainfall in 1980 to 16% in 1983 and to an estimated 19% of growing season rainfall in 1985.

The cost analysis with SWLC indicates that the $248,700 Fabridam can be operated and maintained, paid for in 15 years, the cost of irrigation covered, and a profit of $100/ha shown. Irrigation produced an additional profit of 0.14 $\$/m^3$ of water added. Therefore, all future water resource projects should be planned with SWLC as one of the objectives.

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