Figure 1:
A schematic display of the crop-water-soil-drainage system.

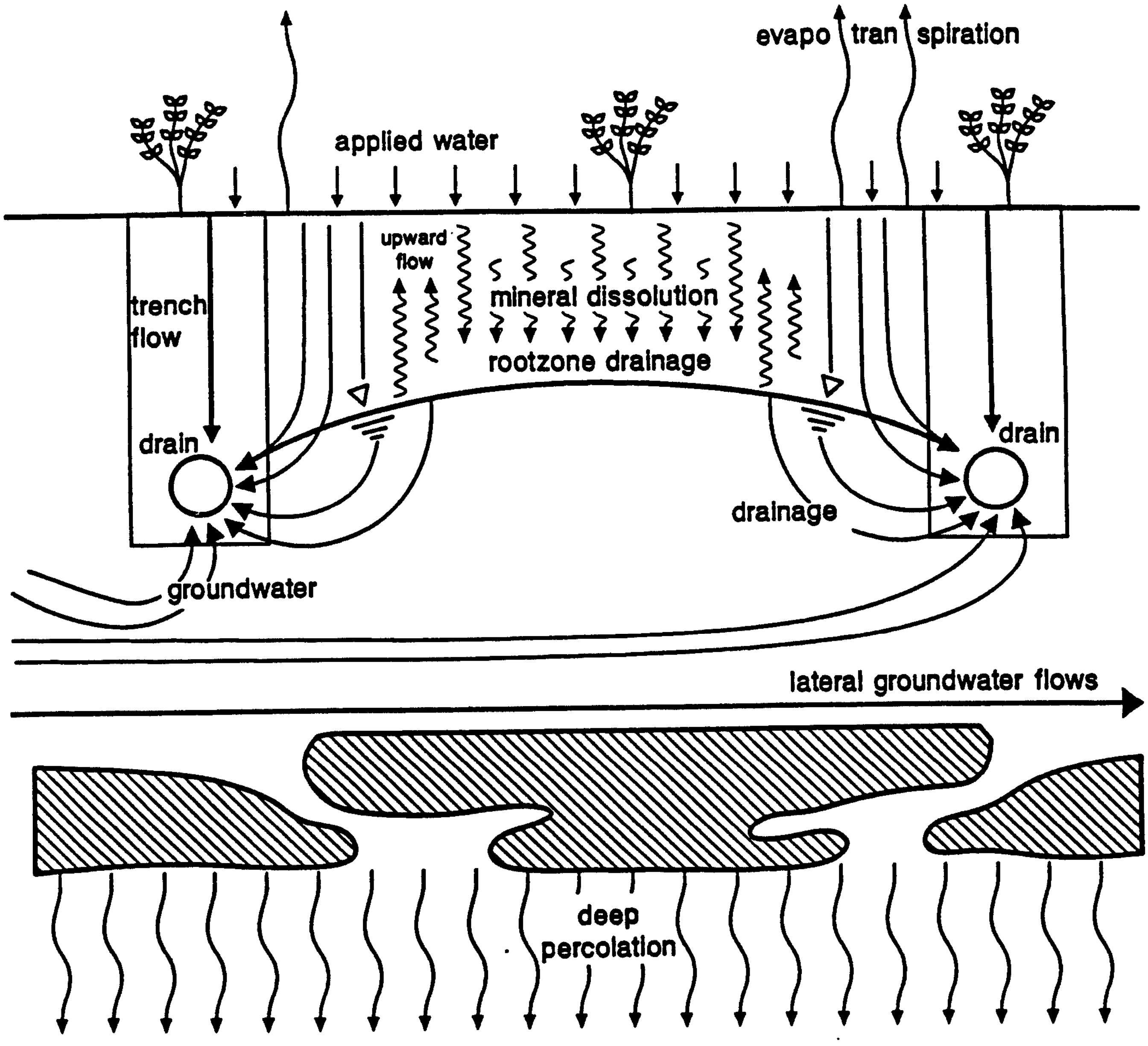


Figure 2:
Areas with drainage problems in the San Joaquin Valley, California.

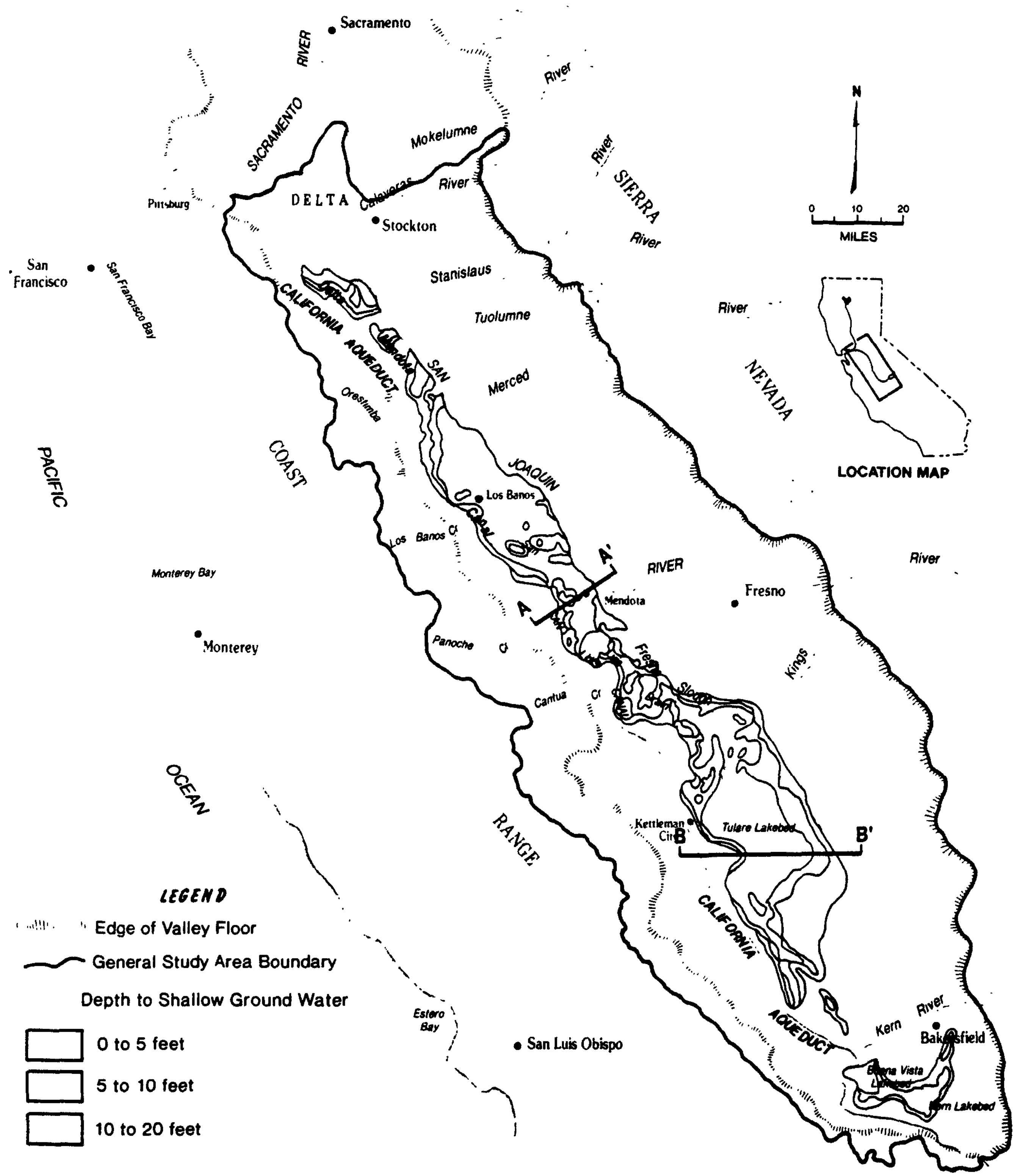
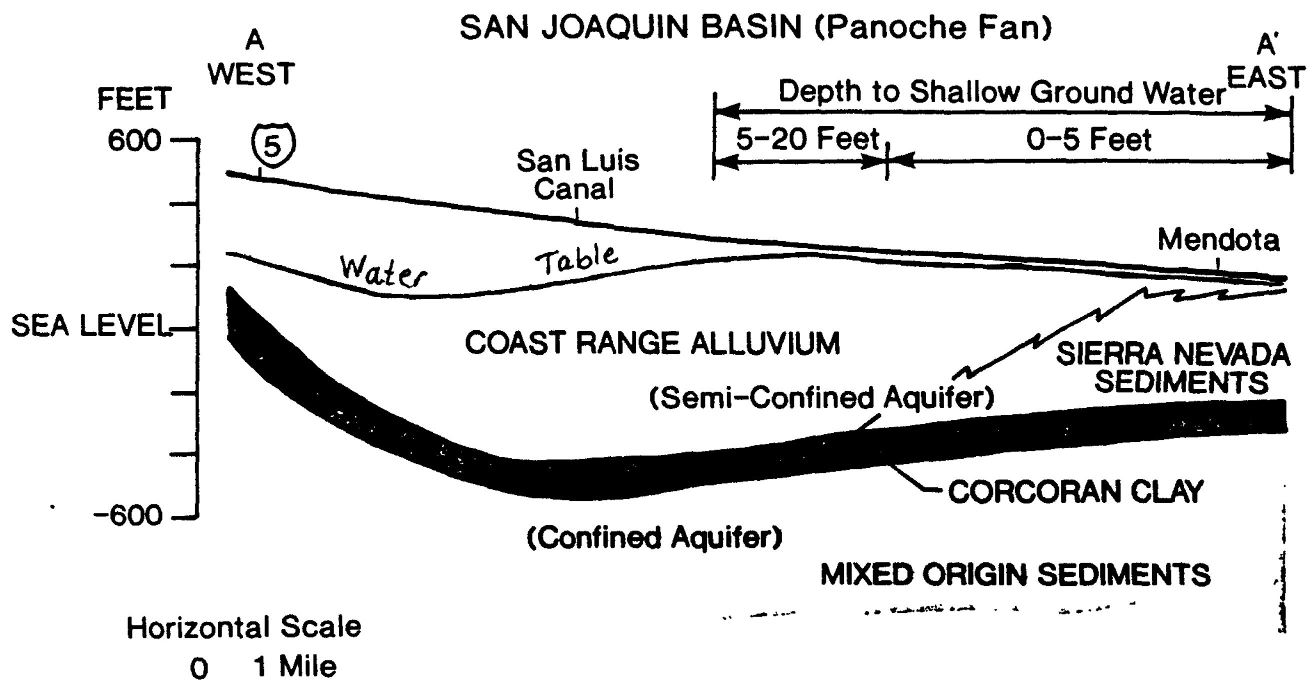
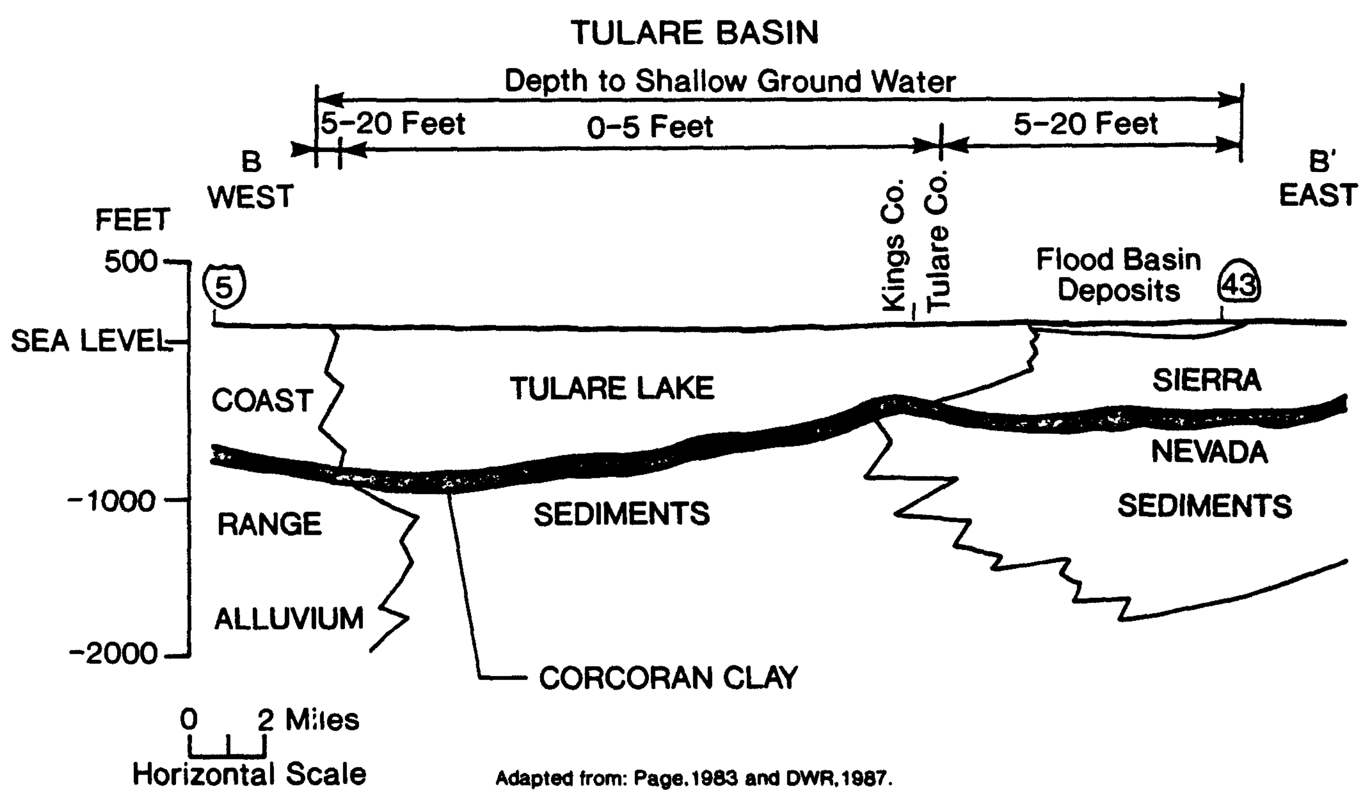


Figure 3:
Generalized Geohydrological cross-sections in the San Joaquin and Tulare basins (locations shown in Figure 2).



Adapted from: Belitz, 1988 and DWR, 1987.



Adapted from: Page, 1983 and DWR, 1987.

Figure 4:
Effect on regional net incom of different levels of drainage tax (steady state model)

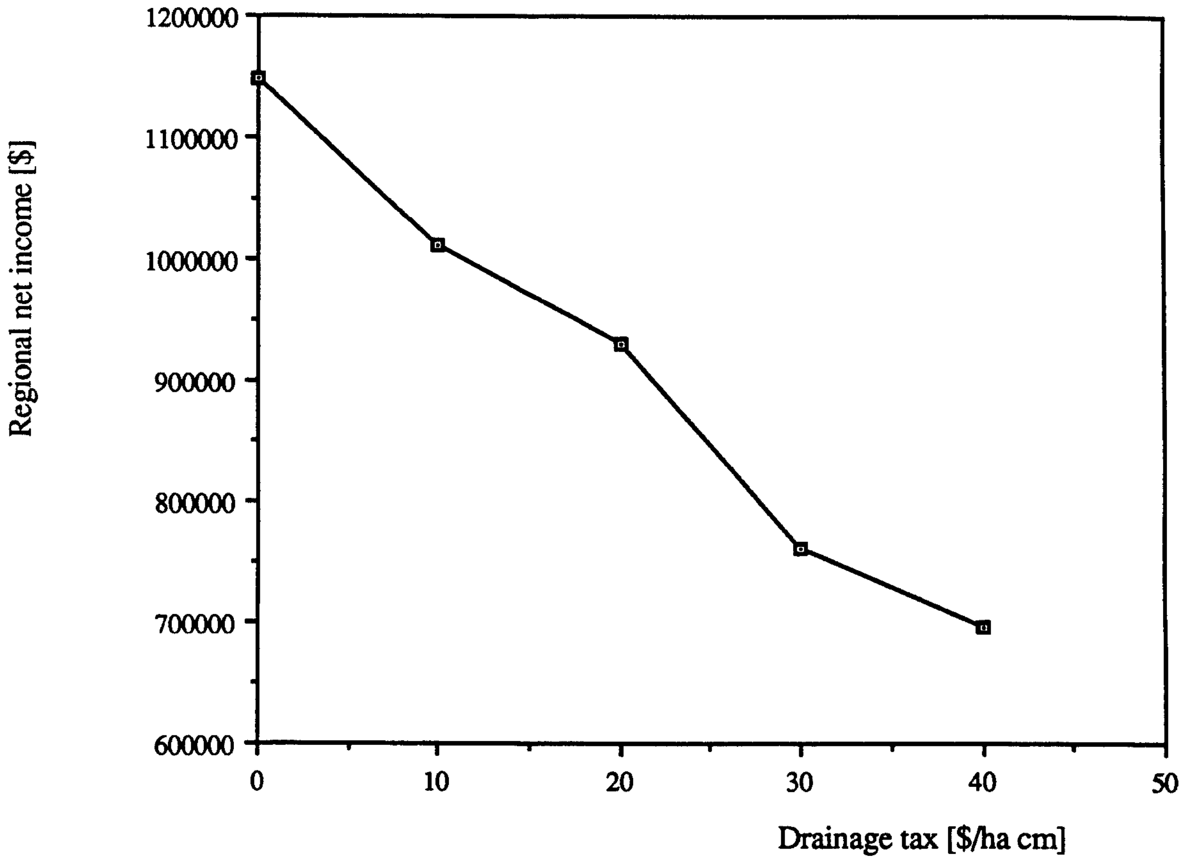


Figure 5:
Effect on regional net income of different levels of water prices (steady state model)

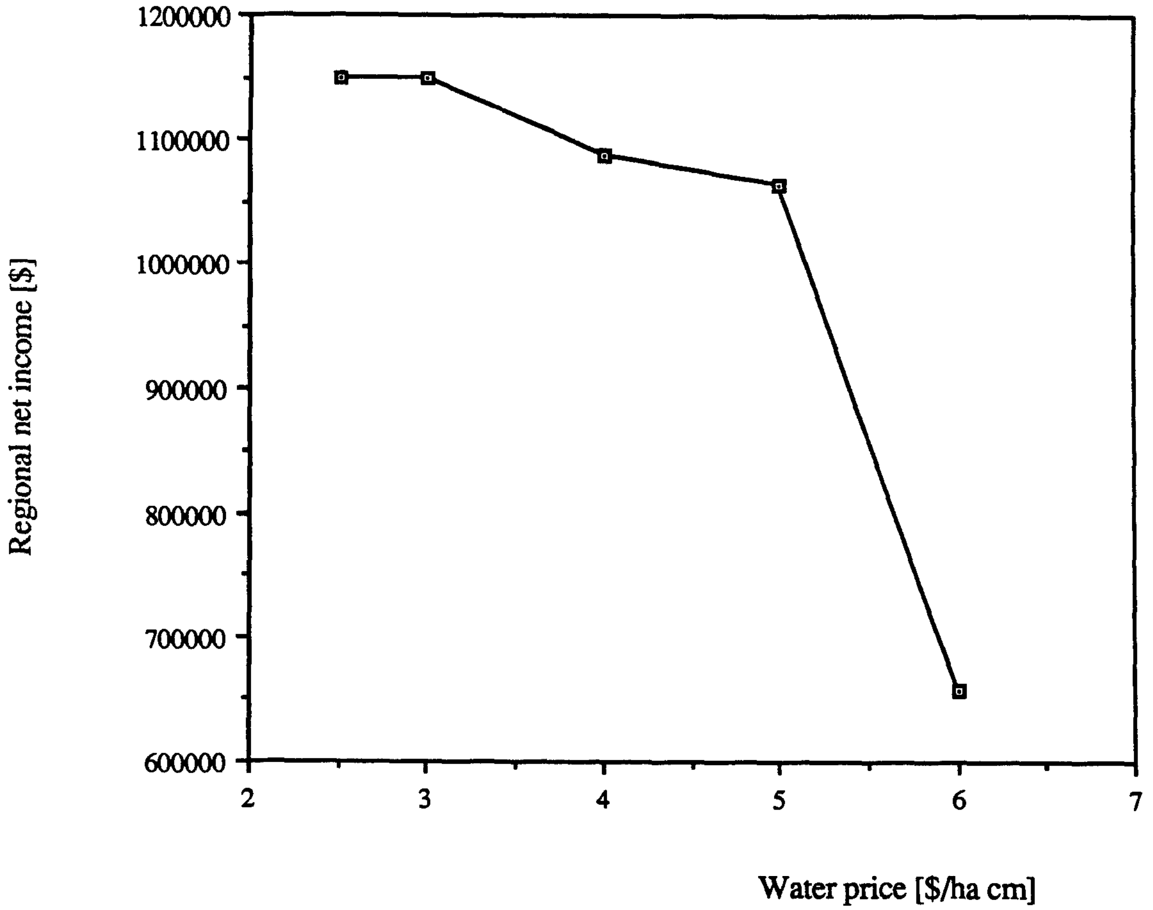


Figure 6:
Effect on drainage quolity and volume of different levels of drainage tax (steady state model)

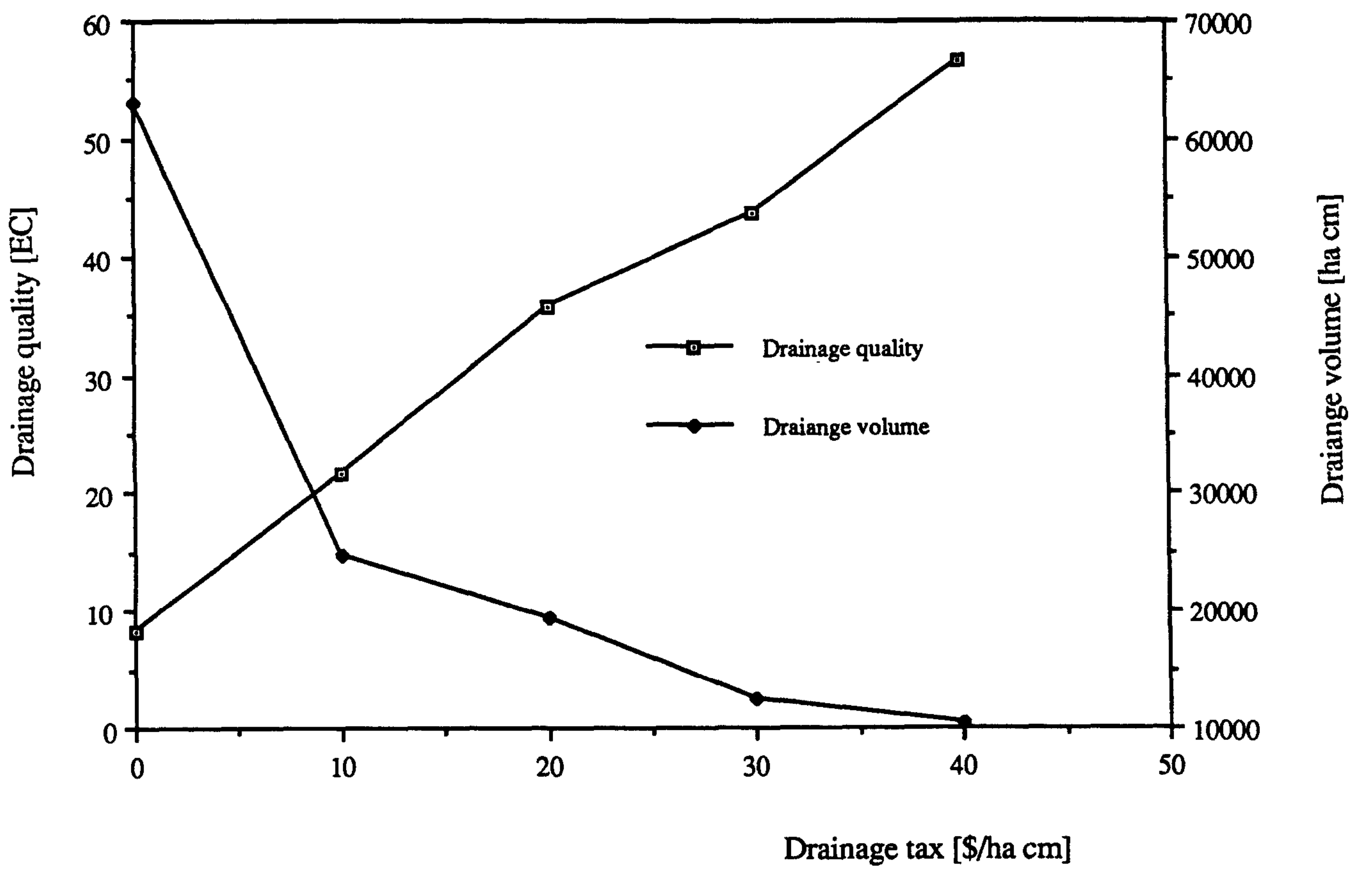


Figure 7:
Effect on drainage quality and volume of different levels of water prices (steady state model)

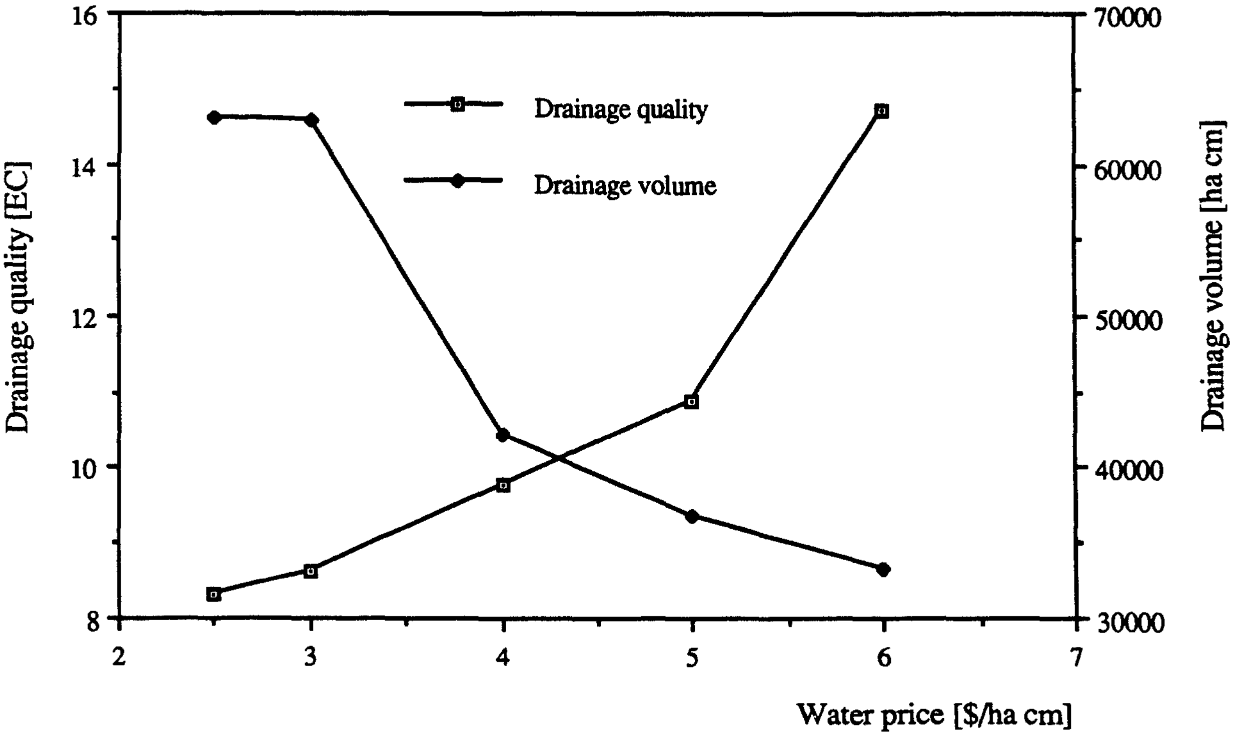


Figure 8:
Effect on net regional income of different surface water quota (dynamic model)

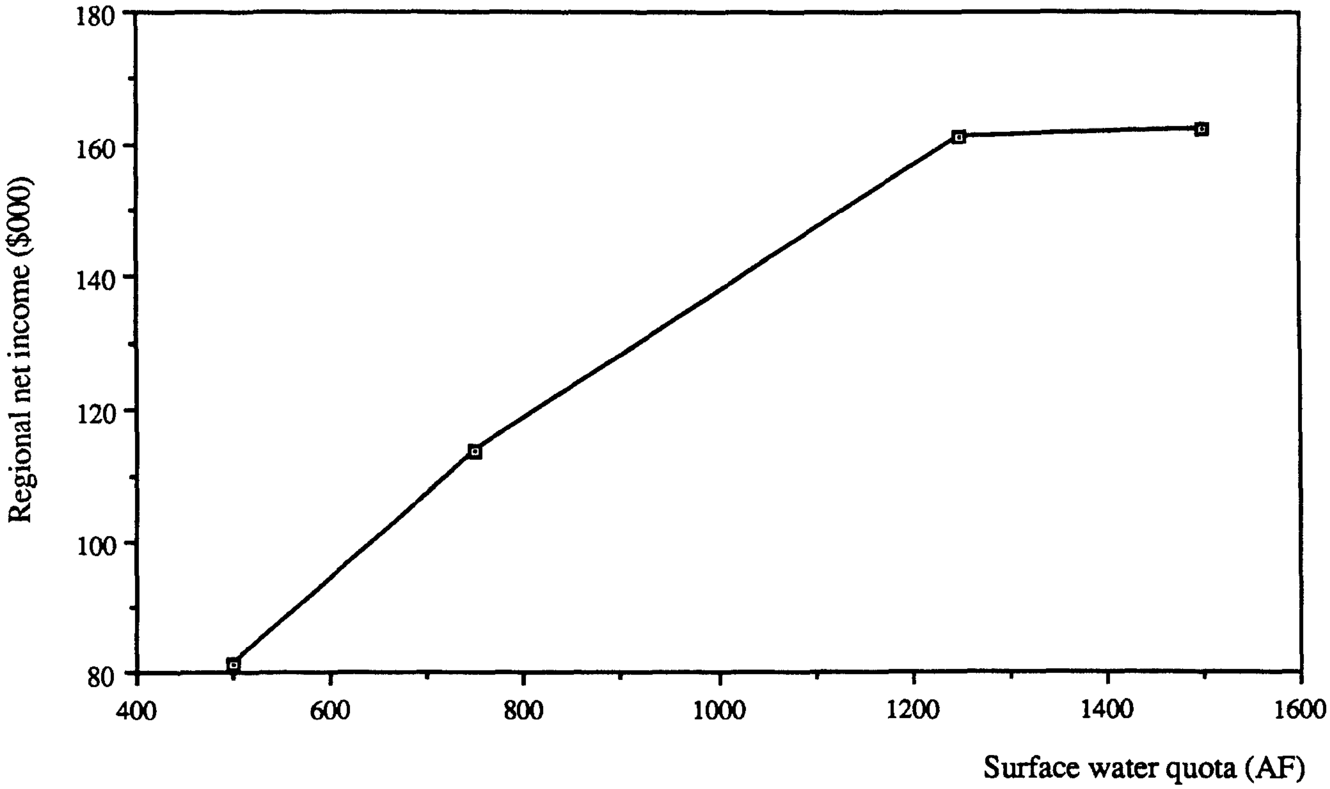


Figure 9:
Effect on regional net income of different
levels of drainage permits (dynamic model)

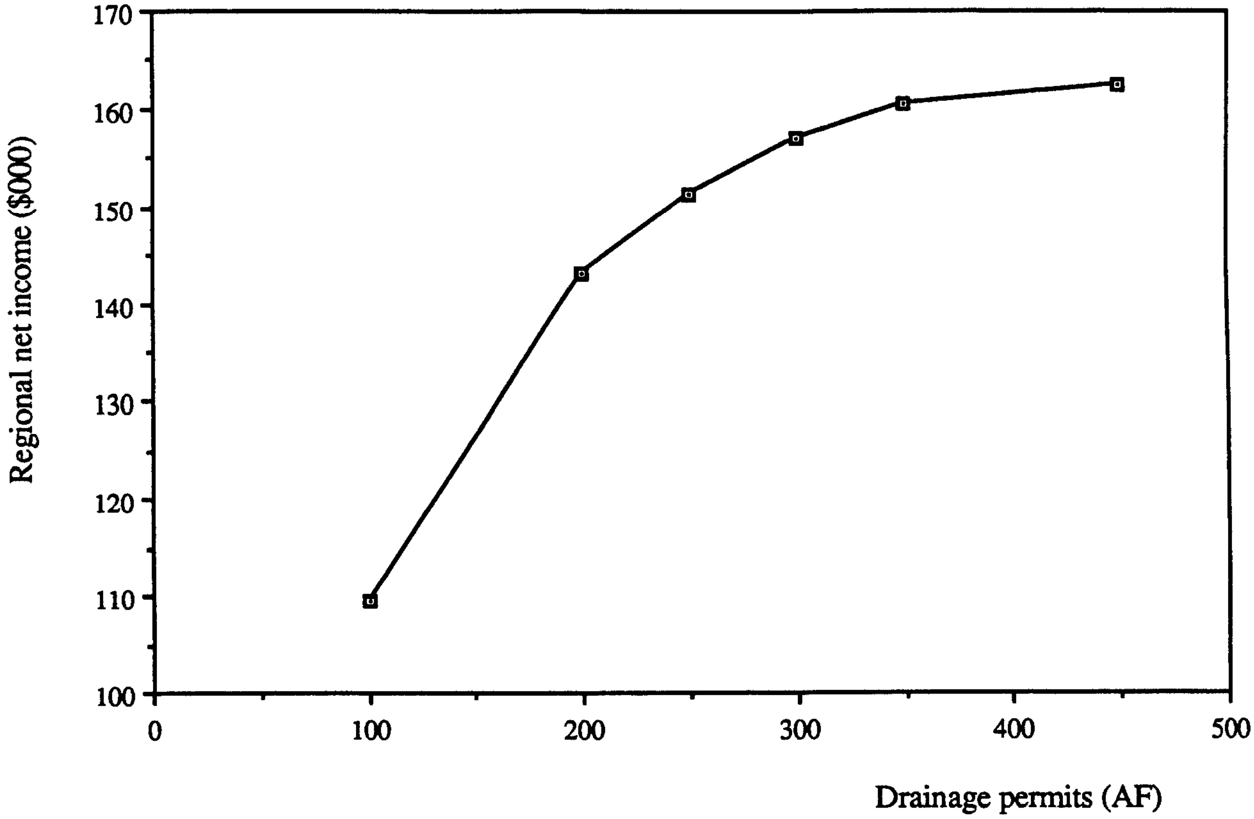


Figure 10:
Changes over time of discharged drainage as affected by water quota and drainage permits (dynamic model)

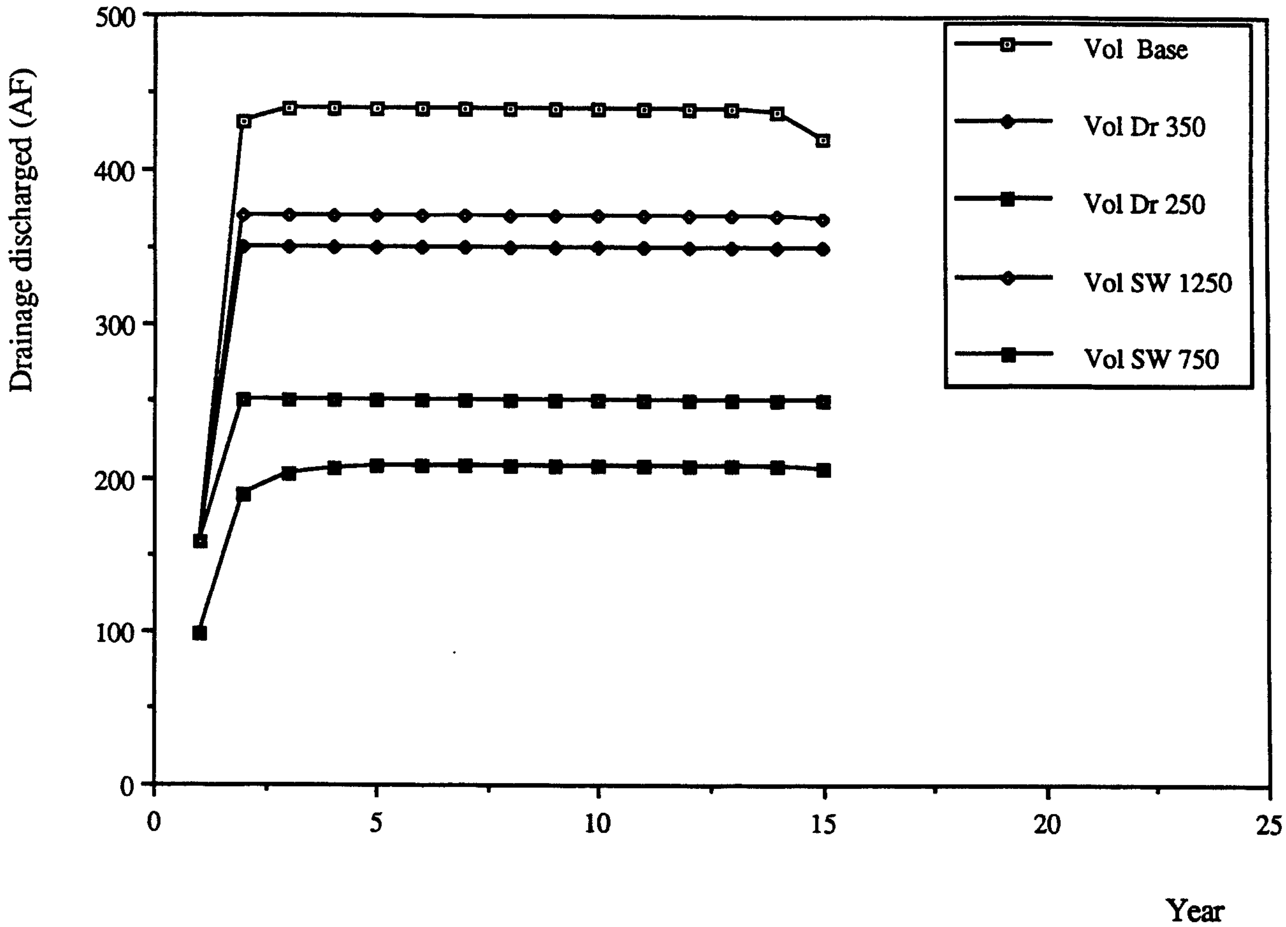


Figure 11:
Changes over time of initial soil salinity as affected by waer quota and drainage permits

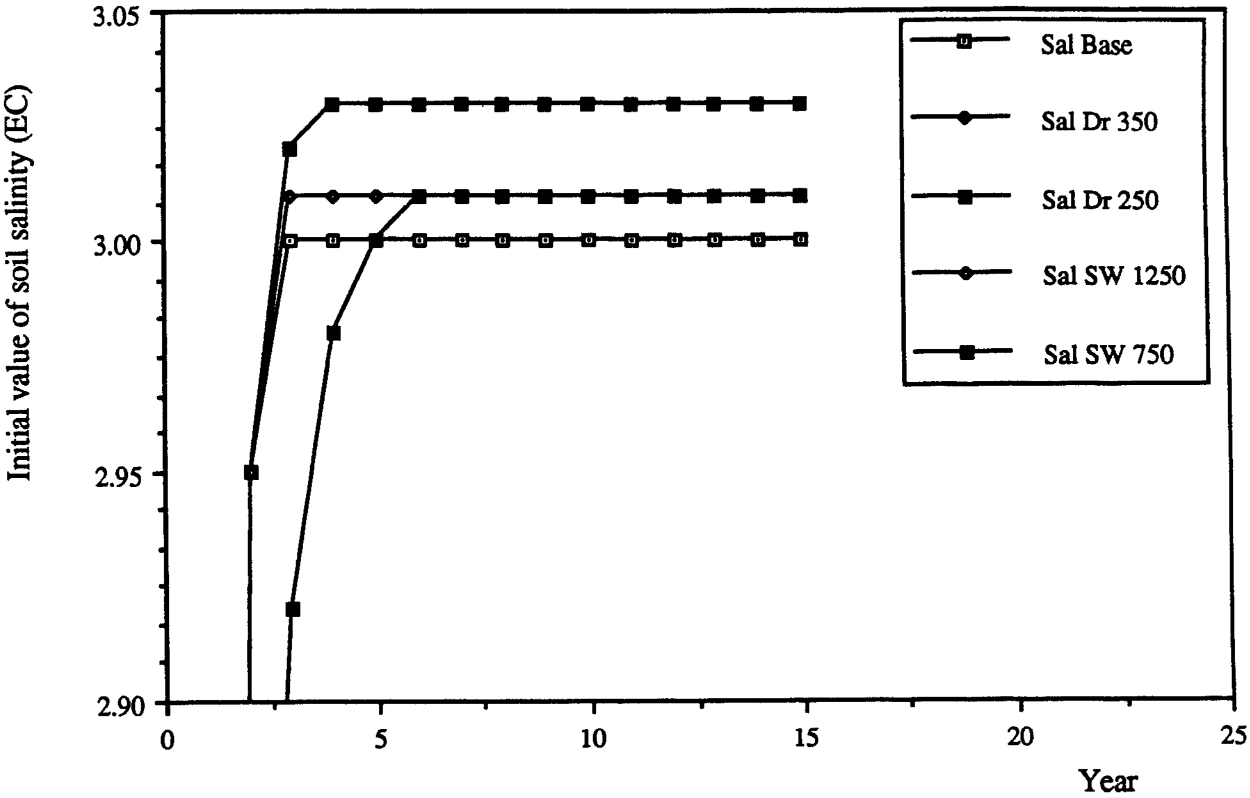
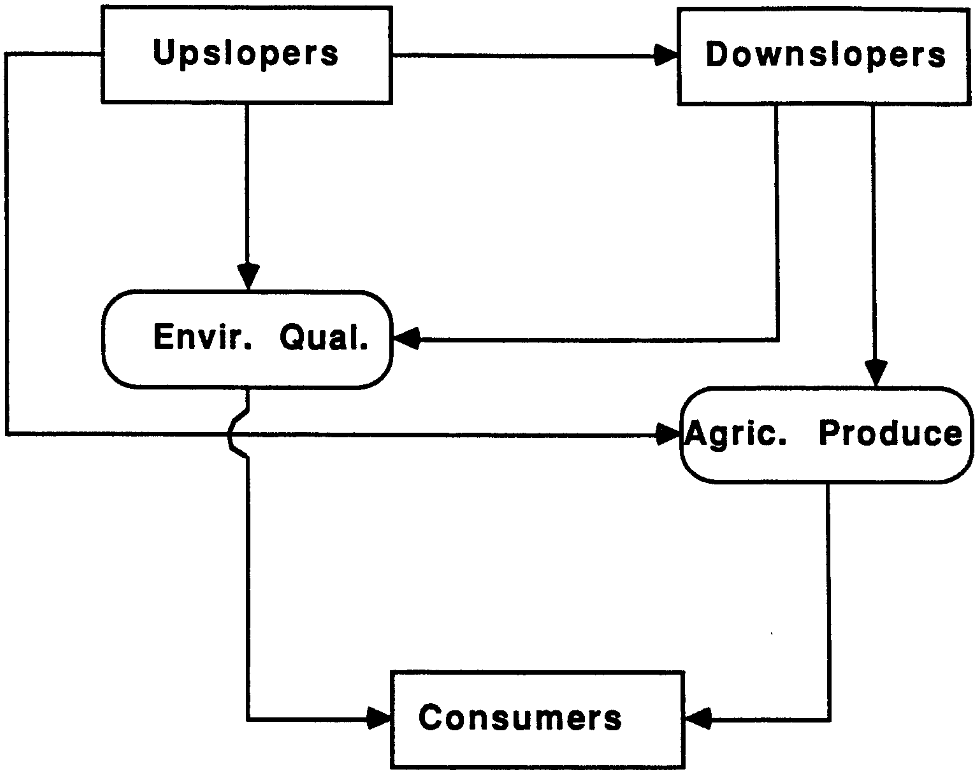


Figure 12:
The Framework for the Analysis-
The Game Parties and the System



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May 6, 1991

FLORIDA'S EXPERIENCE WITH MANAGING NONPOINT SOURCE PHOSPHORUS RUNOFF INTO LAKE OKEECHOBEE*

by

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*Paper prepared for presentation at the 1991 AERE workshop, "The Management of Nonpoint Source Pollution", Lexington, Kentucky, June 6-7, 1991.

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FLORIDA'S EXPERIENCE WITH MANAGING NONPOINT SOURCE PHOSPHORUS RUNOFF INTO LAKE OKEECHOBEE

W.G. Boggess, E.G. Flaig and C.M. Fonyo[1]

Lake Okeechobee is the second largest freshwater lake contained in the contiguous United States with a surface area of 730 square miles and a drainage area of more than 4600 square miles (SWIM, 1989). Located in south central Florida (Figure 1), the Lake is the direct water supply for five municipalities, provides backup supply for the lower east coast of Florida, and provides ecological, recreational and irrigation benefits to many Users.z Lake Okeechobee is a shallow (i.e. average depth of 9 feet), highly productive, eutrophic lake which is in danger of becoming hypereutrophic due to excessive nutrient inputs, primarily phosphorus from agricultural activities.

The threat posed by phosphorus runoff to the Lake was first documented in a series of studies in the 1970s (Joyner, 1971, Davis and Marshall, 1975, and Federico, et. al., 1981). The latter study examined the trophic status of the Lake using a modified Vollenweider model which identified phosphorus as the limiting nutrient. The studies also determined that the Taylor Creek/Nubbin Slough (TC/NS) and Lower Kissimmee River (LKR) drainage basins (Figure 1) contributed 30% and 20% respectively of the phosphorus loads to Okeechobee, and 5% and 31% respectively, of the water inflows. Direct rainfall accounted for 39% of the water and 17% of the phosphorus.

Concurrent with Joyner's early study, the Governor called together a Conference on Water Management in South Florida in September, 1971. One of the conclusions of the conference was that the condition of Lake

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[2] In 1985-86 the combined recreational and commercial fishing industries generated $28.4 million in expenditures and sales (Bell, 1987). Bell also estimated that the lake's recreational user value was $8.3 million annually, or converting this to an asset value, the Lake Okeechobee fishery resource was valued at nearly $100 million. The lake also provides irrigation water for the sugarcane industry which is estimated to provide 18,000 jobs and to generate $1.3 billion annually of economic activity in the state (Mulkey and Clouser, 1988).

Okeechobee, the heart of both water quantity and quality in south Florida, should be improved (Special Project, 1976). The Governor's Conference was followed by a public hearing in 1972 sponsored by the Central and Southern Florida Flood Control District (renamed and rechartered as the South Florida Water Management District (SFWMD) in 1972)[3]. The results of this hearing, coupled with widespread public and governmental agency concern over the condition of Lake Okeechobee, prompted the Florida Legislature to establish and fund the Special Project to Prevent the Eutrophication of Lake Okeechobee in 1973. The final report published in 1976 identified the primary sources of phosphorus as high density dairy pastures and faulty dairy waste control systems. The report prioritized the TC/NS and LKR basins for implementation of phosphorus management plans.

More recent figures for the entire Lake Okeechobee Watershed confirm that agriculture is the dominant source of phosphorus entering the watershed (Fonyo, et. al., 1991). The largest sources of net phosphorus imports to the basin are improved dairy and beef cattle pastures (45.9% of the total), followed by sugar mills (14.9%), dairy barns (14.3%), sugarcane fields (13.5%), and truck crops (6.9%) (Table 1). Table 2 summarizes phosphorus imports into the Lake Okeechobee Watershed by material. Fertilizer constitutes 73.2% of the total, and dairy feeds account for 15.9%. Together, fertilizers and feed account for 93.5% of the annual imports of phosphorus and agricultural production is responsible for 98 % of the net phosphorus imports to the watershed.

The purpose of this paper is to describe and then examine what can be learned from Florida's 15 years of experience with trying to control phosphorus runoff from agricultural lands into Lake Okeechobee. Specific objectives are: (1) to provide a brief description of the natural system, (2) provide an overview and chronology of phosphorus management/control programs; (3) outline and describe the evolution of monitoring programs and

[3] The 1972 Florida Water Resources Act (Florida Statutes, Chapter 373) assigned the management of water rights to the State, and created a system of five water management districts in the state based on hydrologic boundaries. The Act was based on the Model Water Code developed by Maloney et. al. (1972). The districts are governed by a board of directors appointed by the Governor and have their own property taxing authority. The districts are charged with managing and protecting water resources. Although the districts have a great deal of autonomy in dealing with water resource issues, they are subject to legislative mandates (e.g. SWIM Act) and to various state agencies with ultimate responsibility for water resource issues such as Florida Department of Environmental Regulation.

analysis; (4) outline the evolution of phosphorus control technologies and incentives for adoption, (5) examine the costs and impacts of the various programs; and (6) derive lessons and implications for other similar problems.

Background

One hundred years ago, south Florida fresh water circulated in a slow, rain-driven cycle (40-65 inches per year) of meandering rivers and streams, shallow lakes, and wetlands including unique saw grass marshes. Starting at a chain of lakes south of Orlando, water flowed into the Kissimmee River. The Kissimmee meandered 110 miles south into Lake Okeechobee. During wet seasons, water spilled over the lake's low southern rim, and flowed south across the Everglades saw grass in a 50-mile wide sheet moving at a rate of approximately one hundred feet per day toward Florida Bay.

Modification of the natural freshwater system in south Florida began in the late 1800s as investors began developing the area. Over the next 100 years, a series of development, drainage, flood protection, and water supply programs resulted in the construction of 1400 miles of canals and levees. The most important project was the federally funded, massive flood-control and water supply project known as The Central and Southern Florida Flood Control Project which was authorized by Congress in 1948. Major modifications included: (1) the channelization of the Kissimmee river into a 52 mile-long, 300 foot-wide, 60-foot deep canal known as C-38; (2) construction of the 25 foot-high, Herbert Hoover Dike encircling Lake Okeechobee and providing control over all inflows to and outflows from the Lake; and (3) creation of three water conservation areas south of Lake Okeechobee to store excess flood waters and to provide supplemental water supply. A series of canals, control structures and pumping stations are currently used to control freshwater movement south of Lake Okeechobee.

Agriculture first began to develop around Lake Okeechobee in the 1920s. Originally agriculture was limited by poor drainage and poor soils. Identification of micronutrient deficiencies in the Everglades Agricultural Area (EAA) led to a significant increase in production in the 1930s. Establishment of the sugar program in the 1960s led to a dramatic increase in sugarcane and winter vegetable acreage. It was during this period that water quality problems first began to develop south of the Lake.

Agriculture north of the Lake consists primarily of dairy and beef cow/calf operations with limited acreage of citrus and vegetable production. Dairying, the most important agricultural industry, first began to develop in Okeechobee County in the early 1950s. Originally the south Florida dairy industry had been concentrated around Miami, but urban development after World War II forced them to move. The south Florida dairy industry is now centered in Okeechobee County just north of Lake Okeechobee.

As a result of Central and South Florida Flood Control Project, the major components of the natural drainage system can be controlled somewhat independently. Given this degree of independence and the differential nature of the water quality problems, current concerns overwater quality in central and south Florida have manifested themselves as three separate efforts: (1) the Kissimmee River Restoration Project which aims to "restore" the natural meandering flow of the river through oxbows and wetlands (Loftin, et. al., 1990); (2) the Lake Okeechobee SWIM* plan which is designed to control nutrient loads in order to protect the lake's vital water supply, recreational, and ecological benefits; and (3) the Everglades SWIM plan designed to address concerns about the quantity, temporal distribution and quality of water released from the Everglades Agricultural Area (EAA) south through the Water Conservation Areas (WCAs) into the Everglades National Park (Everglades SWIM, 1990).

The latter concern has been the subject of litigation. In October 1988, the U.S. Attorney's office in Miami sued the SFWMD and the Florida Department of Environmental Regulation (FDER), charging that state and federal water-quality regulations had been violated by allowing agricultural runoff from the EAA to damage Loxahatchee Refuge and the Everglades National Park. The lawsuit has been contested with considerable fervor. District and United States scientists have met on several occasions to resolve issues of fact. In January 1991, recently elected Governor Chiles negotiated a 60 day stay in order to conduct an Everglades Summit to resolve the lawsuit. Numerous sessions have been conducted and the state legislature recently passed additional

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[4] In 1987 the legislature passed the Surface Water Improvement and Management (SWIM) Act (Chapter 373.451-373.4595 Florida Statutes). The act dictates that the five water management districts in Florida design and implement SWIM plans for priority water bodies. The act also established a trust fund to provide financial support through FDER.

legislation to help resolve the issues. The case is scheduled for trial in September, 1991. In the interim, the District has begun implementation of the Everglades SWIM plan.

The remainder of the paper focuses on efforts aimed primarily at controlling nutrient loads to Lake Okeechobee which have culminated in the Lake Okeechobee SWIM Plan.

Phosphorus Management/Control Programs

Based on the 1976 recommendations of the Special Project to Prevent the Eutrophication of Lake Okeechobee, initial nutrient control efforts focused on reducing phosphorus runoff from dairies in the TC/NS basins (Albers, et. al., 1991). The first program was a state funded project called the Taylor Creek Headwaters Program (TCHP) which began in 1978 with the objective to fence cows from waterways and determine the impact on stream water quality. The project was limited in scope, confined to the headwaters of Taylor Creek.

In 1981, federal funds were obtained under the Rural Clean Waters Program (RCWP) to address water quality concerns in the entire TC/NS basin. The goal of the TC/NS RCWP was to reduce phosphorus concentrations in water flowing into Lake Okeechobee from the basin by 50% by 1992 (NWQEP, 1989). The objectives were to implement BMPs and evaluate the impact on basin water quality. The state-funded TCHP project was combined with the RCWP program to provide additional funds for the implementation of BMPs. The SFWMD was given the responsibility for monitoring water quality to determine the efficacy of BMPs for phosphorus reduction beginning in 1978 and continuing to date (Flaig and Ritter, 1989).

The Lower Kissimmee River RCWP was initiated in 1987 to reduce agricultural nonpoint source pollution in the LKR basin. The objective was to implement BMPs for each dairy to reduce loadings from animal waste and fertilizer. The goal was to reduce phosphorus loads to the Lake by 43%. The specific phosphorus load reduction goal and the design of the BMPs for the dairies were ultimately based on the provisions of the Dairy Rule and SWIM Act.

In August, 1985, the Governor directed the secretary of FDER to direct a study of the conditions affecting Lake Okeechobee and to make recommendations for its protection and improvement. FDER formed the Lake Okeechobee Technical Advisory Committee (LOTAC I) which concluded that the phosphorus concentrations in the lake doubled between 1973 and 1984 and that the lake was losing its ability to assimilate phosphorus (LOTAC, 1986). LOTAC I produced a number of recommendations including that detailed agricultural BMPs should be planned and implemented in the TC/NS and LKR basins which would prohibit discharge of barn wash water and retain the runoff from high cow density areas for the 25-year, 24-hour storm. LOTAC I also recommended that a set of research and demonstration projects totaling approximately $8 million be conducted to examine fertilization practices, dairy ration formulation, chemical and biological treatment of barn wash water, and basic biogeochemical behavior of phosphorus in soil and water.

In August, 1986 the Governor issued executive order 86-150 directing the secretary of FDER to implement the recommendations of LOTAC I with regulations to be in place by May, 1987. The Florida Department of Agriculture and Consumer Services (DACS) was directed to complete a cost share program patterned after the TCHP by October, 1986. FDER, working with SFWMD, SCS, and dairy representatives drafted the "Dairy Rule" (F.A.C. 17-6.330 through 17-6.337) which became effective June, 1987. The rule specified that the dairies in the TC/NS and LKR basins had to implement specified technologies to prevent the discharge of barn wash water and to retain the runoff from high intensity areas for the 25-year, 24-hour storm. A total of 49 dairies (approximately 45,000 cows) came under the jurisdiction of the Dairy Rule. DACS secured funds from the legislature to cost share the construction.

The dairy industry requested, and were granted, a buyout program for dairies that chose not to comply with the dairy rule. Dairymen were offered a payment of $602 per cow (approximately half of the money was provided by SFWMD and half by the State) in return for a deed restriction prohibiting the property from being used for a dairy or any other concentrated animal feeding operation. The dairymen retained ownership of the cows and the property. A total of 17 dairies signed contracts for the buyout which will eliminate 12,721 cows from the basin.

The 1987 SWIM Act directed the SFWMD to protect the water quality of Lake Okeechobee and specified that the long term annual phosphorus load should be reduced to 397 tons (Chapter 373.451-373.4595, Florida Statutes). The SFWMD was required to develop a plan to meet this reduction by July, 1992. The

SFWMD developed an interim plan (SWIM, 1989) consisting of research and regulatory initiatives. The regulatory component of the SWIM plan is to be accomplished primarily by the implementation of phosphorus performance standards A performance standard of 0.18 mg per liter average annual, total phosphorus concentration was adopted for inflows to the lake. The standard was calculated by dividing the 397 ton target loading by the long-term water inflow to the lake. The 0.18 performance standard is applied to tributary discharges but not to runoff from individual properties. For dairies, the allowable discharge concentration for total phosphorus was set at 1.2 mg per liter based on calculations that the assimilative capacity of streams and wetlands would result in the 0.18 standard being met at the lake inflow structure. However, the dairies were exempted from permitting and enforcement under the SWIM plan since they were currently under the jurisdiction of the FDER Dairy Rule. For improved pasture land uses, which include dairy heifer and beef cow-calf operations, the standard is 0.35 mg per liter. Other land uses are required to remain at their historical levels, with the exception that land uses currently below the 0.18 standard are permitted to come up to the standard. All land uses other than dairy are currently subject to permitting and enforcement under the SWIM plan (Rule 40E-61, F. A.C.).

Monitoring Activities

The monitoring program in the Okeechobee basin has three basic purposes: (1) to determine the effects of alternative land management practices on downstream water quality; (2) to evaluate the trends in water quality over time; and (3) to monitor compliance with runoff concentration standards. The water quality monitoring program for the TC/NS and LKR basins has evolved over time due to changes in land management and agency requirements. Over the last 17 years the program has expanded from simple collection of water samples at major structures to a complex network that includes automated water samplers and *in situ* water quality monitoring devices.

Water quality monitoring first began in TC/NS in 1973 as part of an Agricultural Research Service (ARS) study to identify the impacts of drainage on open charnel water quality (Allen et. al., 1976). In 1978, the SFWMD took responsibility for evaluating the water quality impacts of BMPs employed under the TCHP and expanded the ARS monitoring network to include surface water sampling sites throughout the TC/NS basin (Flaig and Ritter, 1989). The objective was to collect data for identifying trends and quantifying, where possible, changes in surface water quality that occurred due to changes in land use and/or implementation of BMPs.

In 1986, the network was modified to monitor discharge water quality for each dairy to provide a higher degree of resolution for identifying trouble spots, and to monitor specific site performance of BMPs under the Dairy Rule (Flaig and Ritter, 1989). The monitoring sites included automated sampling stations on the dairies and tributaries to provide information for estimating loads, verifying and calibrating water quality models, and developing a more complete water quality record. The additional information provided state and federal agencies responsible for administering cost sharing under the TCHP, RCWP, and Dairy Rule programs with a means of determining the effectiveness of the cost share funds. Expanded networks were essentially complete within LKR by fall, 1987 and within the TC/NS by summer, 1988 (Flaig and Ritter, 1989).

The monitoring program was modified again in 1989 to support the regulatory aspects of the "Works of the District" rule formulated under the interim Lake Okeechobee SWIM plan (Flaig and Ritter, 1989). The objectives of the program are to evaluate the efficacy of BMPs, to provide background information for a surveillance monitoring program, and to provide on-going checks on compliance with the runoff concentration standards. The District also provides runoff water quality data for each dairy to FDER to assist their evaluation of the Dairy Rule.

Under the "Works of the District" rule a total phosphorus concentration standard was selected over a phosphorus load standard due to ease of implementation and greater correlation to changing land use management (Flaig and Ritter, 1989). A load standard requires precise field measurements for calculation of discharge at each site. Accurate flow measurements are difficult to obtain for streams with a low gradient, poor access, and poor stream measurement sections. In addition, nutrient loads from storm runoff are very sensitive to hydrologic variation and long term monthly or annual phosphorus loads would depend upon rainfall patterns and seasonal influences which would complicate enforcement.

The concentration standard has been converted into a regulatory criteria to provide a workable, attainable standard requiring minimal data collection (Flaig and Ritter, 1989). The components of the off-site performance standard are: (1) a total phosphorus concentration standard not to be exceeded on an average annual basis; and (2) a maximum total phosphorus concentration not to be exceeded when fewer than six samples have been collected. These values are baaed on the 50% probability that the annual off-site phosphorus concentration limitation will be exceeded. The first criteria defines an average annual standard by which to evaluate long term behavior. The second criteria provides a means to identify a serious problem with a limited record of water quality samples. These criteria have been formulated into an administrative rule for permitting and enforcement (Rule 40E-61, F.A.C.).

Monitoring Data Collected

Monitoring activities in the TC/NS and LKR basins consist of surface water sampling, rainfall measurement, stream stage and ground water stage measurement (Flaig and Ritter, 1988). Surface water grab samples are collected weekly at all dairies and tributaries in both TC/NS and LKR. Samples are analyzed for nitrogen and phosphorus species and physical parameters: pH, dissolved oxygen, conductivity, turbidity, and color. Similar samples are collected and analyzed for quality assurance and quality control. In addition, the dairies are required under the Dairy Rule to sample phosphorus concentrations in groundwater on a quarterly basis.

The costs of the monitoring program area major concern in the implementation of the program. Water sample collection and analysis for total phosphorus range from $50 to $95 per sample. The cost increases where sample sites are difficult to reach, which is common with dairy discharge locations. Assuming two discharge locations, weekly sampling, and a cost of $50 per sample, monitoring costs would exceed $5000 per year for a dairy. The SFWMD is responsible for monitoring surface water discharges. The dairies are required by FDER monitor ground water quality on a quarterly basis.

Phosphorus Management Technologies and Incentives

To be technically effective, phosphorus control practices have to physically change phosphorus flows through the system (Figure 2). Phosphorus flows can be impacted in four general zones in the system: (1) phosphorus material imports (source reduction); (2) onsite treatment/storage; (3) phosphorus product exports (export enhancement); and (4) offsite treatment/storage. Control practices that operate in zones (1) and (3) may be classified as phosphorus use management practices, whereas those operating in zones (2) and (4) are phosphorus waste management practices. Practices operating in all four zones have been proposed and studied as options for controlling phosphorus runoff into Lake Okeechobee. However, to date, only source reduction and onsite treatment/storage technologies have been implemented.

Dairies in the Lake Okeechobee basin are currently implementing the third generation of phosphorus management BMPs with a possible fourth generation on the horizon. The various phases of BMP implementation tended to overlap and dovetail together making it difficult to quantify precisely the efficacy of the various stages of BMP implementation. A brief, chronological discussion of the four generations of technologies and incentives follows.

In the early 1970s the State and SCS encouraged the development of lagoon systems to capture milking barn wash water and to direct the effluent into seepage fields. The second generation of BMPs was associated with the TCHP program and consisted of pasture improvement and waterway protection to eliminate the direct loading of wastes (i.e. onsite storage). The TCHP program, initiated in 1978, was a small scale trial program limited to the headwaters of Taylor Creek which accounted for only 1 % of the water, but 12% of the phosphorus entering Lake Okeechobee via S191 (Albers et. al., 1991). The program was voluntary, with the state providing 100% cost sharing.

The TC/NS RCWP program was approved and funded in 1981. The primary goal of the TC/NS RCWP was to extend the scope of the TCHP by contracting with all twenty-four of the dairies in the drainage basin to implement pasture and waste management BMPs to reduce nutrient runoff (beef cow/calf farms that had been extensively drained and lands within a quarter mile of waterways were also targeted). Specific BMPs implemented included: fencing cattle from waterways, establishing vegetative filter strips along waterways, providing cattle crossings over streams and ditches, providing shade structures for cattle away from streams and waterways, and recycling barn wash water (RCWP, 1990). The program was voluntary, with 75% federal cost sharing. The TCHP program was combined with the TC/NS RCWP in 1981 and the state funds were used to leverage the federal cost sharing.

The LKR RCWP began in 1987. Originally it was envisioned as an extension of the TC/NS RCWP with the primary focus being to improve pasture and nutrient management on dairy and beef cow/calf farms via voluntary participation with federal cost sharing. However, in 1987 the state passed both the Dairy Rule and the SWIM Act which mandated implementation of technology standards by 1991 and performance standards by 1992. Faced with these new regulations, dairymen shifted their focus from low cost, pasture and nutrient management BMPs (second generation) towards more mechanical capture and removal methods (third generation) that would satisfy the technology standard specified in the dairy rule (RCWP, 1990). Thus, the incentive structure under the LKR RCWP has evolved from voluntary, with federal cost sharing into a technology based standard, with primarily state cost sharing.

The dairy rule represents the third generation of BMPs. Passed in June, 1987, the dairy rule specifies that all dairies were required to submit construction permit applications along with BMP designs by June, 1989. Within 18 months of construction permit issuance, the BMP construction must be completed and an operating permit obtained from FDER. In order to satisfy the technology standard, the dairy rule designs were required to: (1) collect all wastewater and runoff from barns and high intensity areas for a 25-year, 24-hour storm; (2) dispose of nutrients by approved methods, particularly land application by irrigation (3) fence cattle from waterways; and (4) monitor water quality discharges to insure system adequacy. The dairy rule technologies formalize the earlier focus on onsite storage enhancement and expand the focus to include nutrient recycling and source reduction. In addition, pilot onsite treatment options (chemical and biological) have been evaluated as have been options for exporting dairy wastes as a soil amendment.

Typical dairy rule designs call for constructing perimeter ditches around the hams and high intensity areas[5] to collect all of the runoff from a 25-year, 24-hour storm. The runoff is processed through a two-stage lagoon system and then applied, via center pivot irrigation systems, to forage production sprayfields. The sprayfields have to be sized to insure that annual application rates of phosphorus don't exceed the forage crop's uptake, generally 60 pounds per acre per year. In addition, the dairies must have sufficient land available for land spreading of solids collected.

The State initially planned to provide 75% cost sharing of construction costs under the dairy rule. However, escalating construction costs from an initial cost share estimate of $250,000 to over $1,000,000 per dairy, resulted in a revised sliding scale for cost sharing. DACS currently provides cost sharing ranging from $233 to $433 per cow depending upon the size of the dairy, with the smaller dairies receiving the higher rate (Conner, 1989). This sliding scale reflects the significant construction cost economies of scale enjoyed by large dairies (i.e. 1500 cows) relative to small dairies (i.e. 350 cows) (Giesy, 1987). The net result is that cost sharing under the dairy rule ranges from 30% to 75%.

The companion dairy buyout program provides an alternative economic incentive-based option to the technology baaed standard. A fixed payment of $602 per cow is offered (based on political "fairness" or equity concerns).[6] Thus, there is no "market" or competitive bidding for the easements. However, one would hypothesize that smaller, less efficient and/or dairies with particular location or drainage problems would be more apt to accept the buyout option. One-third (17) of the dairies have opted for the buyout. Fifteen of the seventeen dairies were relatively small with an average herd size of just over 650 cows versus an 1025 cow average for the thirty-two dairies that chose to comply. In addition, one operator decided to close two large

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[5] High intensity areas are defined as areas of concentrated animal density generally associated with milking barns, feedlots, holding pens travel lanes and contiguous milk herd pasture where the permanent vegetative cover is equal to or less than 80 percent.

[6] The $602 figure reflects an approximate 75% cost share of an estimated cost of $800 per cow to move a dairy 500 miles.

dairies (2900 cows) because he had inadequate land available for spreading of wastes. Dairymen had knowledge of the specific phosphorus concentrations in runoff from their lands prior to the final buyout deadline.

A fourth generation of BMP implementation looms on the horizon. Under the interim Lake Okeechobee SWIM plan, phosphorus concentration performance standards have been specified for the dairies and other land uses in the basin. The performance standards are not currently being permitted or enforced on the dairies, but the option exists. A few dairies, perhaps in anticipation of enforcement of the performance standards have chosen to go to total confinement or semi-confinement dairy systems which reflects the fourth generation of technologies.

The evolution of phosphorus control practices reflects a trend toward increasing collection and treatment of dairy wastes. The percentage of the dairy wastes being collected steadily increases from approximately 25% under the first generation of BMPs, to 65% under low-tech dairy rule designs, to 85% under the high-tech dairy rule designs, to essentially 100% under total confinement. In addition, the level and type of treatment of the wastes also increases from first generation simple lagoon/drain field to two-stage lagoon with controlled land application to potentially fourth generation chemical or biological treatment. The net effect has been a steady conversion of a primarily nonpoint source to a point source.

Uncertainty due to lack of information about the extent and mechanics of the phosphorus runoff problem and about the efficacy of alternative control technologies led to a cautious, evolutionary application of control technologies. The evolution of incentives for participation reflected the same uncertainties. Economic and "fairness" (equity) concerns dominated early programs. Whereas, efficacy and the certainty of effect have dominated more recent programs. As a result, incentives have slowly evolved from purely voluntary with 100% cost sharing, through voluntary with steadily decreasing cost sharing, to regulatory technology based standards with partial cost sharing, to the potential threat of performance based standards.

With the exception of the dairy buyout and cost sharing, economic incentives have not been employed. In the early stages of the problem, concerns over equity and in finding a "fair" solution limited the use of economic incentives to cost sharing. In the later stages, economic incentives were generally considered to be too uncertain in their effectiveness and strict technology and performance standards were imposed instead.

Three additional types of economic incentives would appear to be feasible options. One would be to convert the dairy buyout or easement program from a fixed amount to a market or bid system that would reflect the differential costs of compliance and values of the dairying property right across dairies of different sizes, locations, and management capabilities. This approach would combine the desirable efficiency aspects of economic incentives with the high certainty of efficacy sought by environmentalists.

Secondly, since over 90% of the phosphorus entering the basin is accounted for in fertilizers and feeds (Table 2), an inputs tax would be relatively easy to implement and administer. However, an inputs tax provides only indirect incentives to control emissions and thus as a sole approach would probably not be an effective means of achieving the rather stringent water quality goals dictated in the SWIM plan. It does provide a relatively cheap program to implement and administer, and it would provide a source of funds for companion cost sharing or abatement programs.

An emissions tax would provide more direct incentives for dairymen to control runoff. However, as discussed in the water quality monitoring section, runoff loads are very difficult to quantify and thus concentration standards and monitoring protocols have been developed for implementing the performance standards. Emissions taxes or tradeable emission permits could conceptually be based on the same concentration measurements (Segerson, 1988).

Summary of Costs and Impacts

Formal cost effectiveness calculations for the various programs or for the implementation of specific BMPs are complicated by several factors. First, the various programs and expenditures have been intertwined making it difficult to separate overall expenditures by program. Second, it is difficult to quantify the impact of specific changes in land use due to lags in effects, variations in rainfall, and overlapping practices. Third, many of the programs for which expenditures have been made are still in process - many of the dairies that accepted the buyout have yet to close and construction is still underway for many of the remaining dairies. It will take another year or two for all of the practices to be implemented and several years before the impacts can be measured. However, it is possible to trace out the history, source and magnitude of expenditures to date and to examine overall changes in water quality trends.

Program Costs

Nearly $33 million has been spent over the past ten years on programs to control phosphorus runoff from agricultural lands north of Lake Okeechobee (Table 3). Various government sources have provided approximately three-quarters of the total with farmers providing the balance. Expenditures for research, permitting, monitoring and enforcement are not included in the government total. Likewise expenditures for roofed structures and for operation and maintenance of the BMPs are not included in the farmers' total.

The State provided $15.55 million (63%) of the $24.6 million government total, the SFWMD provided $5.95 million (25%), and the federal government $3.14 million (12%). However, the federal government provided 82% of the government funding for the RCWP.

The breakdown of expenditures between the RCWP and the Dairy Rule are rather arbitrary since the two programs overlapped beginning in 1987. A total of $2.13 million was spent by the government and $435,277 by farmers under the TC/NS RCWP prior to the Dairy Rule. An additional $4.55 million has been expended under the auspices of the TC/NS-LKR RCWP since 1986. Much of this was spent in the LKR on practices required by the Dairy Rule which go far beyond the original RCWP goals pasture and nutrient management. This shift in emphasis is reflected in the difference in the average cost of BMPs installed in the two basins. In TC/NS, 27,897 acres were served by BMPs at a total cost of $1.72 million or $61 per acre. In the LKR, 6,926 acres were served by BMPs at a total cost of $3.16 million or $456 per acre (RCWP, 1990).

The dairy rule and dairy buyout programs have been funded without federal support. The state government provided the majority of the finding, although the SFWMD provided nearly half (49%) of the dairy buyout cost share (Table 3). Construction costs for the Dairy Rule plans range from $418 to $1086 per cow with an average cost of $659 per cow. Two dairies elected to construct total confinement barns at an approximate cost of $1200 per cow. Total government cost share has averaged $401 per cow under the dairy rule and $602 per cow under the dairy buyout.

Inpacts - Monitoring Data Analysis

The ecological health of Lake Okeechobee has been related to the total phosphorus (TP) concentration in the pelagic zone of the Lake (Federico, et. al. 1981). Where the concentration is below 50 mg/m^3 the Lake is considered healthy. Since the early 1970s the concentration appears to have risen steadily (Figure 3). In recent years the concentration has fluctuated dramatically from year to year. The in-lake phosphorus concentration shows little correlation with phosphorus loading (Figure 3). The poor correlation is due in part to fluctuating Lake stage and resuspension of bottom sediments which is common in shallow lakes. Although the long term health of the Lake is linked to the load, there is little year-to-year correlation between load and in-lake concentration.

There is also no clear pattern in the time series of annual loads for the tributaries TC/NS (S191) and LKR (S65E, S154) (Figure 4)[7]. The calculated loads at the basin scale are very sensitive to runoff volume. In particular, storm events following long antecedent dry periods tend to produce large TP flushes. In this region where tropical storms and long dry seasons are typical, there is rarely an average year. Consequently it is difficult to relate changes in phosphorus load to changes in land management. Experience has shown that the TP concentration in runoff is a function of cow density and proximity to open water runoff concentrations from lagoons range from 20 to 40 mg/l, while runoff from intensive pastures range from 2 to 5 mg/1 and unimproved pasture runs less than 1 mg/l.

[7] T tests were performed comparing the mean loadings during the period 1973-1979 with the mean loadings during the period 1980-1989. The means loadings from TC/NS were 43 tons lower during the 80s (113.5 tons) than during the 70s (156.9 tons). However, the coefficient of variation was 0.44 and the difference was significant at only a 15% confidence level. Changes in loadings from S154 and S65E were not significant at levels less than 25%. Interestingly, average total loadings from all basins other than S191, S154 and S65E were essentially unchanged from the 1970s (304.7 tons) to the 1980s (298.8 tons) if the impact of the IAP is ignored. The IAP was initiated in 1979 and has been credited with reducing average TP loadings to the Lake by 10 tons per year (SWIM, 1989).

The long term trend in total phosphorus concentration in tributary runoff is a useful metric for evaluating land use change. The time series of TP concentration for runoff from TC/NS (S191) for the period 1973-1991 is presented in Figure 5. There are three distinct periods in the data. During the mid-1970s, cow numbers were increasing and water quality was steadily decreasing. This period corresponded with the Special Project Report in 1976 documenting that phosphorus was the limiting factor in the Lake and identifying the dairies as the primary source. During the late 1970s and early 1980s the "dairy phosphorus problem" began to receive a lot of attention resulting in the TCHP in 1978 and the TC/NS RCWP in 1981. Trend runoff concentrations of TP at S191 were essentially unchanged during this period. Under the RCWP, BMPs began to be implemented in the TC/NS basin beginning in 1983 and the result has been a significant downward trend during the 1980s. A similar trend is evident in the runoff concentration data from the Taylor Creek Headwaters area (Figure 6).

Median TP concentrations in runoff from TC/NS peaked at approximately 1.1 mg/l around 1980, since then they have declined by about 50% to between 0.5 and 0.6 mg/l. A similar decline in absolute terms is needed to reach the 0.18 mg/1 standard that has been established by the SFWMD. Most of the decline to date can be attributed to second generation BMPs installed under the TC/NS RCWP. It is too early to assess whether the combined effects of the Dairy Rule and the buyout will be sufficient to reach the target concentration at S191. At present, only six of the sixteen dairies in the basin that chose to comply with the Dairy Rule have fully implemented the Dairy Rule technologies and several of the ten dairies that accepted the buyout have not yet closed.

The long term trends in TP concentration from the LKR (S65E, S154) tell a different story (Figures 7 and 8). Runoff TP concentrations have been increasing steadily since 1975. In S154 (i.e. a small subbasin in the LKR) the increase has been significant and TP concentrations now are similar to those observed at S191. Concentrations at S65E, which represents the majority of the drainage from the LKR, are much lower with seasonal medians of less than 0.1 mg/l although peak concentrations have reached 0.5 mg/l. These concentrations reflect the greater volume of runoff passing through S65E and the lower density of dairy cows in the basin.

The increasing trends in TP concentration in runoff from the LKR can be attributed to several factors. First, cow numbers have continued to increase in the basin particularly in S154, during the 1980s. Second, it wasn't until 1987 that BMPs began to be installed under the LKR RCWP. By that time the Dairy Rule had been passed and the majority of the dairymen waited until their dairy rule designs were approved before they began to implement BMPs. The result is that a higher percentage of the dairies in the LKR have completed construction of their dairy rule designs (9 out of 12) compared to only 6 out of 16 in the TC/NS. Seven dairies in the LKR accepted the buyout.

Monitoring data from the individual dairies indicate that phosphorus concentrations in runoff increase during and shortly after construction of the dairy rule facilities. Thus, the short run impact of the dairy rule has been to increase phosphorus concentrations slightly. These effects are reflected in the overall runoff concentrations at stations TCHW 18, S65E, and S154 from late 1989 to 1991. Careful examination of Figures 6, 7, and 8 reveals that peak concentrations have tended to persist for longer periods of time during the construction phase and that the apparent trend is increasing slightly.

Overall, the results from the monitoring program indicate that the BMPs have improved water quality, particularly in the TC/NS basin. It is clear that water quality can be improved by practices that enhance soil storage, reduce P imports, and reduce availability of P to surface water discharge. However, runoff concentrations at many of the tributaries still exceed the 0.18 standard. More time is needed before the impact of the dairy rule and dairy buyout programs can be assessed.

Implications

One of the most obvious implications of the Lake Okeechobee experience is that programs designed to solve complex, nonpoint pollution problems are going to be evolutionary in terms of their complexity, rather than revolutionary. The political process of dealing with the uncertainty and lack of information about the problem and alternative solutions, equity concerns (including property right / takings issues), and administrative inflexibility once programs are put in place, all but guarantee a cautious, step-by-step approach. In the case of Lake Okeechobee, key components of the nonpoint programs have evolved in complexity over time including technologies, monitoring programs, and incentive mechanisms.

The evolution of technologies is in effect converting a primarily nonpoint source into a point source. Likewise, monitoring programs have evolved in purpose and design from an initial focus on problem assessment, to measuring efficacy of practices, and finally to providing a basis for implementing and determining compliance with performance standards. Finally, incentive mechanisms have evolved from purely voluntary with full cost sharing, to voluntary with partial cost sharing, to implied regulatory threats, to a technology based standard with cost sharing, to finally a performance based standard with no cost sharing. However, the threat of potential regulation throughout the process stimulated high levels of "voluntary" participation.

The second major implication is that communication and cooperation are essential if complex nonpoint problems are to be solved. Participation in the program by the dairies was greatly assisted by clear documentation that phosphorus loads affected the health of the Lake, and that dairies were the primary source of the problem. Likewise, although the SFWMD is often perceived as the "bad guys", the presence of monitoring and regulator staff in Okeechobee County greatly improves communication and understanding, particularly since the requirements of the landowners have continued to evolve over time. Finally, the TC/NS - LKR RCWP has experienced an unusual degree of cooperation between federal, state, district, and county governments as well as with the dairymen, which has been critical to the success of the program.

The third major implication is that traditional textbook economic incentives (emission taxes) have not been utilized in the Lake Okeechobee programs and may not be viable alternatives for many nonpoint source problems due to the uncertainty of effect, political aversion, administrative inflexibility, and monitoring (measurement) problems (Anderson, et. a1., 1990, Baumol and Oates, 1988). A broader concept of economic efficiency that accounts for the reality of deferential political and administrative costs associated with alternative incentive mechanisms needs to be encouraged. Economic incentives have and can continue to play a role in the Lake Okeechobee situation, however. Input taxes can be used to raise revenues to offset the costs of abatement, cost sharing can be provided, property right easements can be purchased, and marketable permit systems may be feasible in some circumstances.

The fourth major implication is that before emissions can be taxed or emission permits traded, emissions must be measurable. For many nonpoint source pollutants this is not technically or economically feasible. Measuring nonpoint source loadings is particularly difficult and expensive. However, the SFWMD has developed procedures to economically monitor nonpoint concentrations which are being used as the basis for assessing compliance with performance standards. Concentration measurements may also provide a feasible basis for implementing a marketable permit system or, if the political constraints can be resolved, an emissions tax.

The fifth major implication is that the combination of incentives, timely research and demonstration projects, and flexibility to respond has resulted in cost effective results. The formulation of performance standards in the Lake Okeechobee SWIM plan and the potential threat of enforcement is a critical factor in stimulating the development of a market for composting dairy wastes as a soil amendment and in the reduction in phosphorus content of dairy feed rations. Unfortunately, the performance standards are coming on the heels of a technology standard which has already limited the flexibility of the dairies to respond.

The power of the market was also exhibited indirectly in the Lake Okeechobee dairy buyout as the higher cost and/or dairies with higher discharge concentrations were selectively attracted to the program. The efficiency of the program would have been enhanced if a competitive bidding system had been employed.

The final implication is that nonpoint source problems are generally going to be addressed in a frost effectiveness context (Baumol and Oates, 1975) due to the difficulty of measuring benefits, uncertainty about key parameters of the problem, and the political preference for specifying specific targets (e.g. the SMIM Act's 397 ton target for Lake Okeechobee). However, cost effectiveness calculations are extremely complex in the case of most nonpoint source problems due to the evolutionary aspect of technologies and incentives, and the dynamics of the system including lags in effect and stochastic effects.

An accurate cost effectiveness assessment of the Lake Okeechobee nonpoint source programs is impossible at this point in time. However, preliminary results are consistent with two common characteristics of pollution control programs. First, the marginal cost of reducing emissions increases exponentially. Preliminary results from the TC/NS RCWP indicate that roughly a 45% reduction (0.5 mg/l) in seasonal median trend phosphorus concentrations was achieved at a cost of approximately $100 per cow. On the other hand, the Dairy Rule and buyout programs cost $400 and $602 per cow respectively, and the hope is that the median trend concentrations will fall another 0.4 mg/l. Second, increasing the reliability of nonpoint source regulations (i.e. a concentration standard which must be met ninety percent of the time rather than on average) would drive up costs dramatically as evidenced by the peak concentrations in the monitoring data.

Future Directions

Recently, the Chesapeake Bay Nonpoint Source Evaluation Report (1991) recommended that efforts to clean up the Bay: (1) take a mass balance approach, (2) employ a systematic planning framework, (3) target problem areas, (4) utilize a mix of regulatory and nonregulatory mechanisms, and (5) shift from using the term BMPs to Best Management Systems (BMSs) to reflect a more comprehensive, systems approach. The University of Florida is currently working with the SFWMD to assist them in developing a final SWIM plan for Lake Okeechobee that is consistent with the majority of the Chesapeake Bay Report recommendations.

A geographic information system (GIS) based, decision support system is being developed to assist District managers in evaluating alternative nonpoint source control plans. The system, dubbed LOADSS, takes a mass balance approach and provides a systematic planning framework for evaluating both pollution reduction and abatement practices. The GIS structure allows for spatial evaluation and targeting of phosphorus control practices. The purpose of LOADSS is to provide information on the cost effectiveness of alternative plans for achieving the 397 ton target. This information will be utilized along with evaluations of alternative incentive mechanisms to formulate the final Lake Okeechobee SWIM plan. The final plan will likely incorporate a combination of pollution reduction and abatement practices and a mix of incentive mechanisms.

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Table 1. Sources of annual net phosphorus imports to the Lake Okeechobee watershed.

Basin Activity	Annual Net P Import (tons/yr)	% Total Net P (%)
Nonpoint Source Activities		
Improved pasture	2736	45.8
Sugarcane	807	13.5
Truck Crops	412	6.9
Other agricultural	106	1.8
Urban	75	1.3
Total Nonpoint Sources	4136	69.3
Point Source Activities		
Dairy	850	14.2
Sugar mills/refineries	907	15.2
Sewage treatment plants	74	1.2
Total Point Sources	1831	30.7
Total All sources	5967	100.0

Source: Fonyo et. al. 1991.

Table 2. Summary of imports of phosphorus-containing materials to the Lake Okeechobee watershed.

Material	P Import (tons/yr)	% Total P
Fertilizer (P_2O_5)	5379	73.2
Feed supplements-beef	326	4.4
Feed-dairy	1168	15.9
Replacement heifers-dairy	16	0.2
Detergent-dairy	6	0.1
Sugarcane	304	3.1
Food and detergent-human consumption	145	2.0
Total Annual P Import	7344	100.0

Source: Fonyo et. al. 1991

Table 3. Costs of programs for controlling phosphorus runoff from agricultural lands north of Lake Okeechobee.

	Source of Funds ($)					
Programs	Federal	state	SFWMD	Total Government	Farmer	Total All Sources
RCWP No. 14	3,143,042	310,119	400,000	3,817,161	448,920	**4,302,081**[h]
Dairy Rule	-	**11,339,448**[i]	1,800,000[j]	13,139,448	**5,088,067**[k]	18,227,515
Dairy Buyout	-	3,904,368	3,751,456	7,655,824	**2,518,758**[l]	10,174,582
Total	3,143,042	15,553,935	5,951,456	24,612,433	8,055,745	32,704,178

Sources Rural Clean Water Project No. 14, Annual Progress Reports 1988, 1989 and 1990. Florida Department of Agriculture and Consumer Services.

[h]**$2,567,598** ($2, 132,321 government cost share and $435,277 farmer cost share can be apportioned to the TC/NS RCWP prior to the Dairy Rule.) The remaining $1,734,483 can be apportioned to the LKR RCWP - which has been implemented in conjunction with the Dairy Rule. (Figures are based on 1988, 1989 and 1990 RCWP No. 14 annual progress reports.)

[i]**Includes** $2,259,881 that was administered through the **RCWP.**

[j]**Does** not include research or monitoring costs.

[k]**Based** on estimated total construction costs for eligible items. Cost of ineligible items such as roofed structures are excluded as are operation and maintenance costs. Includes $553,002 of farmer cost share under the RCWP.

[l]**Estimate** based on 12,721 cows at $198 per cow (i.e. $800-602).

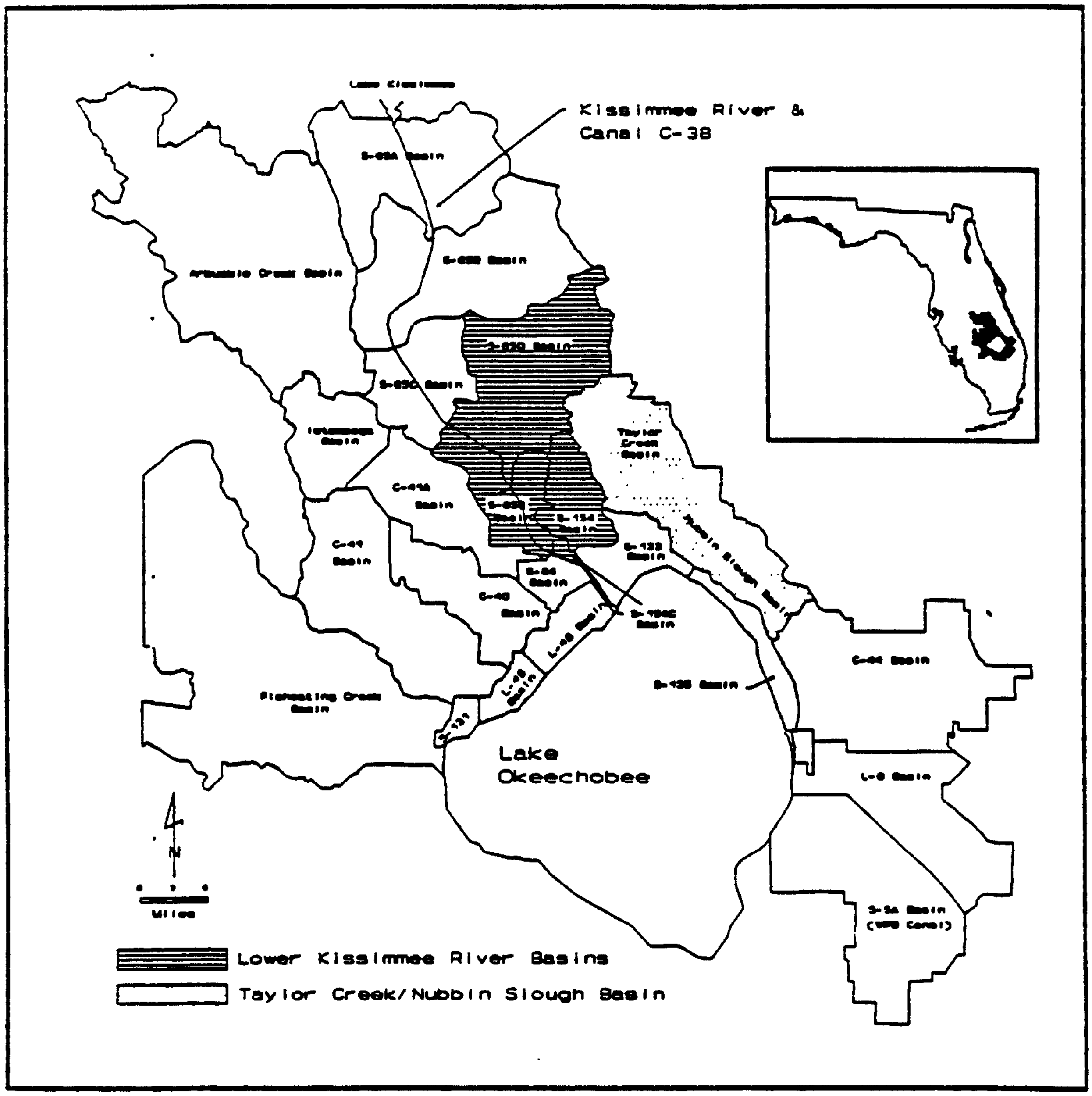

Figure 1. Location of Lake Okeechobee and the major drainage basins.

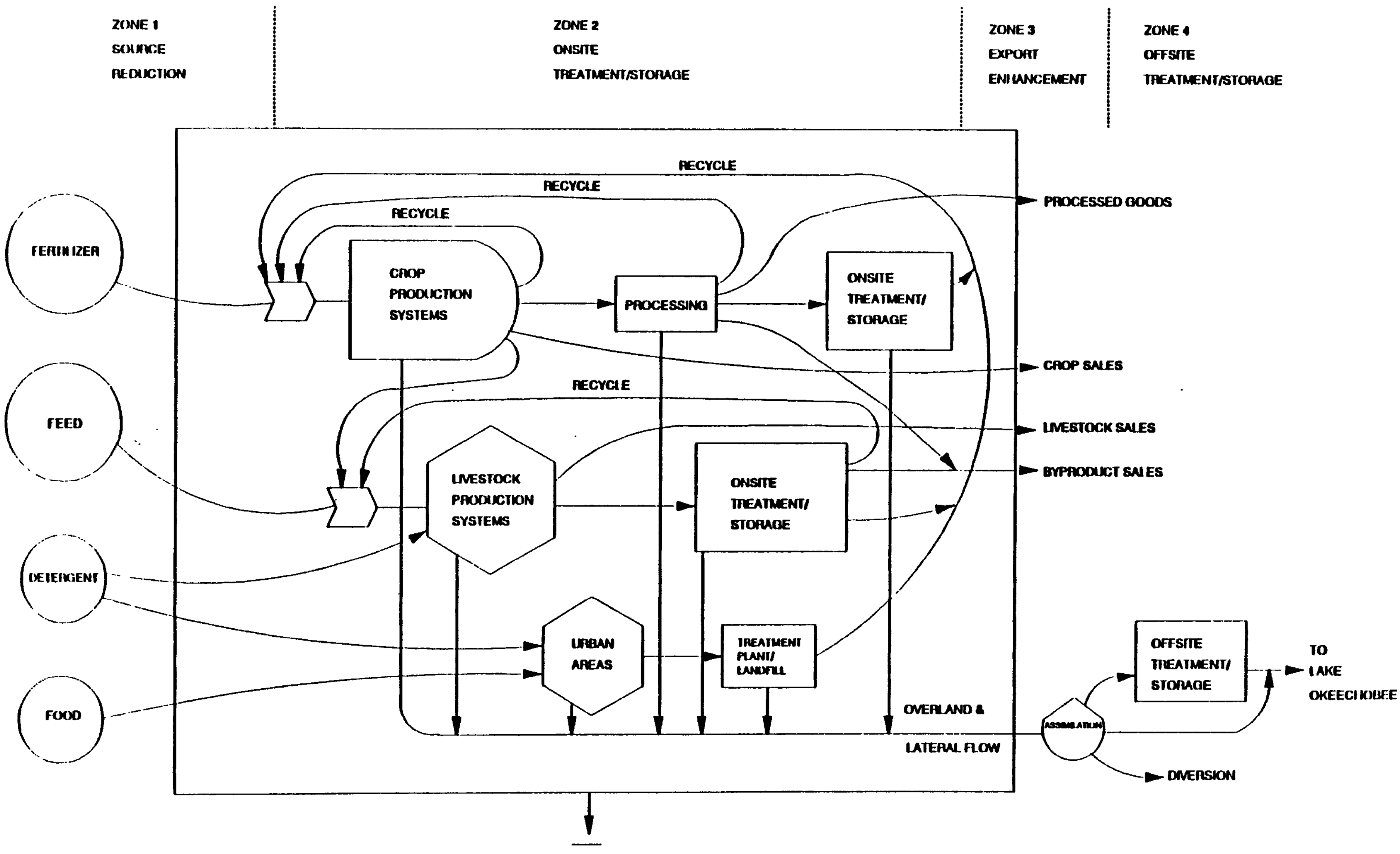

Figure 2. Phosphorus flow diagram for the Lake Okeechobee watershed.

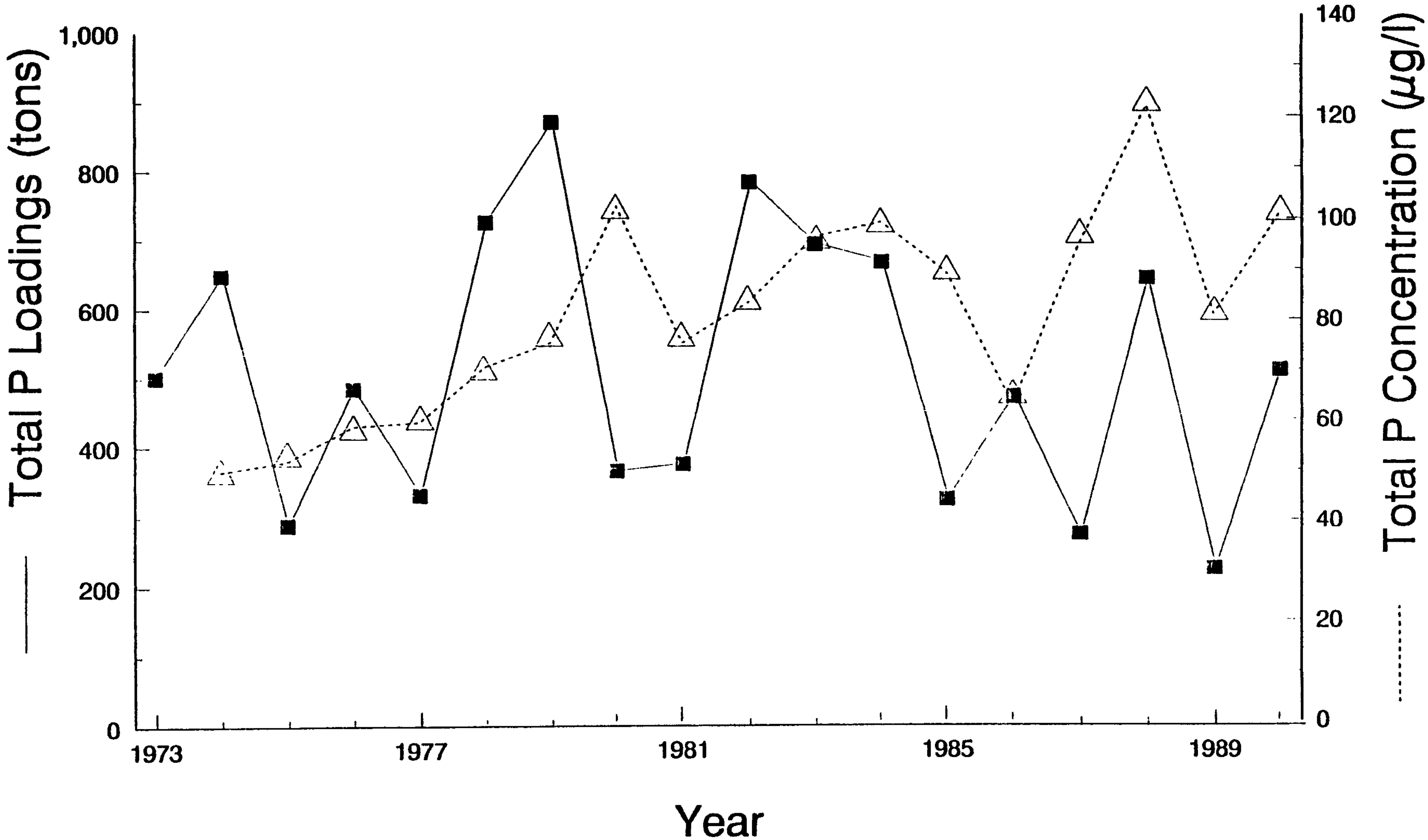

Figure 3. Total Phosphorus loads and in-lake TP concentrations for Lake Okeechobee (1973 - 1990).

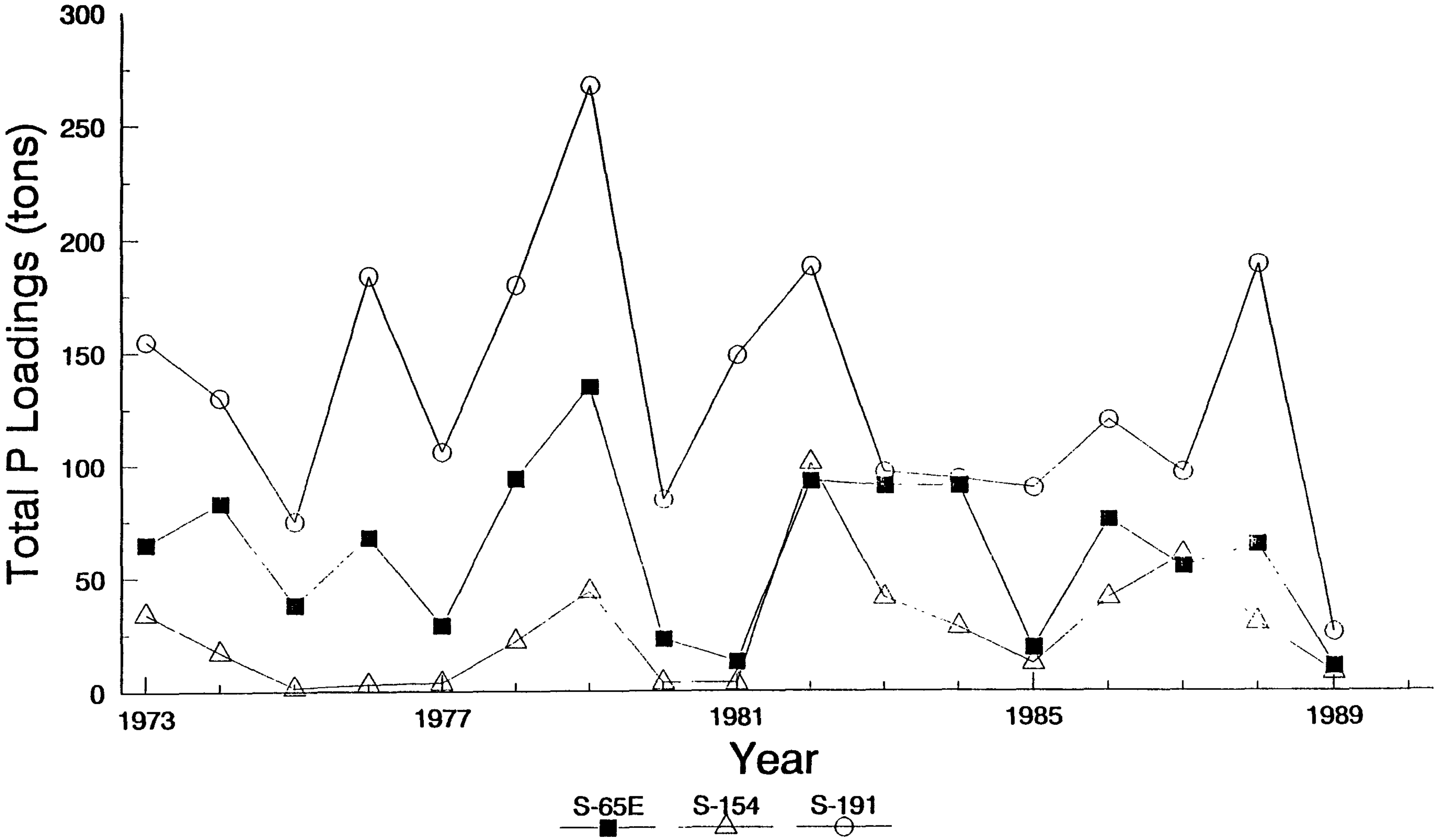

Figure 4. Total phosphorus loads to Lake Okeechobee from S-65E, S-154 and S-191 tributaries (1973 - 1989).

Analysis of Policy Options for the Control of Agricultural Pollution in California's San Joaquin River Basin

by

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ANALYSIS OF POLICY OPTIONS FOR THE CONTROL OF AGRICULTURAL POLLUTION IN CALIFORNIA'S SAN JOAQUIN RIVER BASIN

by

Marca Weinberg
Catherine Kling
James Wilen

California's San Joaquin Valley contains one of the nation's richest areas of agricultural production. The Valley is situated in the southern part of the State, between California's Coastal Range to the west and the Sierra Nevada Range to the east. The San Joaquin River drains the area, flowing northward and emptying into the San Francisco Bay. Parent materials for the region's westside soils are deep layers of marine sediments and hence these soils contain a significant amount of soluable salts and trace elements, including selenium, molybdenum, boron, arsenic, chromium and others. On the east side of the valley, relatively coarse alluvial soils have been deposited from the uplifted Sierra Nevada range. These soils are relatively free of the salts and trace elements that characterize the west slope soils.

The San Joaquin Valley would be an area of considerably lower agricultural productivity were it not for the large irrigation infrastructure that supports it. Water is supplied both through deep water wells and surface supplies delivered through large aquaducts that transport water throughout California. A patchwork of irrigation districts exists that facilitates allocation to members under contracts with the United States Bureau of Reclamation. Most of these contracts are 40 year contracts that specify fixed quantities to be delivered under fixed prices. Water prices are less than prices that would recover full costs of the delivery system andmay be less than variable costs.

While the soils of the Valley are rich, poor natural drainage hampers production in some areas. This problem is made acute by the presence shallow clay layers or lenses that are impervious to water. These clay lenses are particularly a problem in the valley trough where high water tables concentrate saline and trace elements in the root zones. To mitigate the harmful effects of salinity, farmers need to leach the salts through the soil profile by applying water in excess of plant needs to flush the soils. In upslope areas, leaching generates laterally moving groundwater with high concentrations of toxic elements, which then flows into the water tables of lower lying areas. In downslope areas over perched water tables, farmers have installed subsurface drainage systems to control water depth. These drain systems collect toxic drain waters which have historically been disposed in canals that empty into the San Joaquin River.

In 1983, the discovery of toxic levels of selenium in waterfowl in Kesterson Reservoir focused public attention on the San Joaquin Valley and the role of irrigated agriculture as the source of elements such as selenium, molybdenum, boron, and salts. As a result of the problems experienced at Kesterson, the State Water Resources Control Board adopted water quality standards for selenium and other elements in the San Joaquin River. These policies generated considerable research devoted to bio-physical modeling of agronomic and hydrological relationships as well as investigations of technological and engineering solutions. Unfortunately,insufficient attention has been given to the question of how to motivate changes in farming practices necessary to reduce drainage pollution and meet the standards.

This paper reports some investigations of several policy options available to address the agricultural pollution problem in the San Joaquin Valley. The study area is an interesting laboratory for investigating both point and non-point source pollution generated from agriculture. Leaching by upslope farmers generates polluted drain waters which flow subsurface into the perched water tables of lower lying farmlands. These interactions between upslope and downslope farmers, as well as lateral interactions between farmers in the same strata can be considered non-point source externalities. Mitigating activities undertaken by installing drain tiles creates a second-stage point source problem since pollutants at sump outfalls are, in principle, measurable. Thus conventional instruments such as effluent taxes as well as input taxes, subsidies, and technological requirements are all candidate policies.

The region modeled is a 68,000 acre area of diverse irrigated agriculture operating within a hydrological system of considerable complexity. This area includes lands with varied soil, elevation, and water table characteristics, nested within 9 water districts, each with its own water supply allocations and pricing policies. In the next section, we briefly describe the model and its principle features and assumptions. The following section describes some of the modelling results and the final section summarizes and offers some concluding thoughts.

II. MODEL STRUCTURE

In order to simulate regional response to various policy options, we developed an integrated economic/hydrological model and calibrated it to conditions representative of the San Joaquin Valley. The economic model predicts farmer decision making regarding crop choice, applied water, and irrigation technology/water management practices. The drainage area is divided up into physically homogeneous cells, each of which is similar with respect to soil type, drainage conditions, depth to impervious layer, and elevation above sea level. These cells are in turn divided into subcells corresponding to water district jurisdictions which vary in the characteristics of water contracts held. The model can be run as an integrated system encompassing the larger drainage area or as smaller subsystems to compare results under different economic, hydrologic, or institutional configurations.

The agricultural system simulated contains a variety of crops and agricultural practices. About half of the irrigated acreage is planted to cotton each year. Other primary crops include processing tomatoes, sugarbeets, melons, and wheat. Alfalfa hay and rice are important crops in some districts and a variety of vegetables and other specialty crops are also grown in the area. Cropping patterns vary by water district and are influenced by relative market conditions, rotational practice, drainage and soil conditions, etc.

Irrigation efficiency and the volume of drainage water generated vary by crop and with irrigation technology and management. Irrigation of salt-sensitive shallow rooted crops such as vegetables, melons, and small grains tends to be less efficient and hence generates more drain water than irrigation of long-season relatively salt tolerant crops. Irrigation system performance is an important factor in drainage generation and is included explicitly in the model. Irrigation efficiency enters the crop production functions and an irrigation technology cost function describes costs as a function of system performance.

The model describes joint production of two outputs, the primary crop yield and collected drain water. Water applied in excess of crop needs enters a drainage production function. The optimization component of the model selects crop acreage allocations, applied water, and irrigation efficiency subject to the technological relationships defining production, drain water generation, and irrigation technology costs. Resource and acreage limitations constrain the choices and policy instruments enter either as parameters that modify prices and costs or as constraints.

A. Crop Production Functions

Crop production functions in this analysis are developed (following Letey and Dinar) by combining von Liebig (plateau) functions with plant growth model results that predict relative yields as a function of root zone salinity. The procedure is as follows. First it is assumed that under non-saline conditions, yield achieves a maximum value (Y_{max}) for all values of applied water greater than ET_{max}, the minimum plant water requirement necessary to achieve Y_{max}:

$$(1) \qquad Y_{ns} = S(AW - AW_t) \qquad AW_t < AW < ET_{max}$$

$$= Y_{max} \qquad AW \geq ET_{max}$$

Where:

Y_{ns} is yield under nonsaline conditions

S represents the slope of the nonsaline production function

AW is applied water (acre-feet/acre)

AW_t is the minimum water application sufficient to generate positive yields (acre-feet/acre).

Under saline conditions, it is necessary to determine the yield decrement (YD) associated with various levels of water applications and salinity (EC). Since empirical data do not exist over a range of salinity and water applications, we generated data utilizing the physical plant growth model in Letey and Dinar. The model has performed well in comparisons with experimental data and consists of the equations:

for $AW_t < AW < ET_{max}$:

$$(2) \qquad \frac{100(YD)^2}{B \cdot S(AW - AW_t)} + YD \cdot C' - \frac{EC_i \cdot S \cdot AW}{2}$$

$$- .1EC_i \cdot S \cdot AW \cdot ln\left[\frac{YD}{AW \cdot S} + \left(1 - \frac{YD}{AW \cdot S}\right)e^{-5}\right] = 0$$

for AW $\geq ET_{max}$:

$$(3) \qquad C' + \left[\frac{100YD}{B \cdot Y_{max}}\right] - \left[1 - \frac{ET_{max}}{AW} + \frac{YD}{AW \cdot S}\right]^{-1}$$

$$\cdot \left[.5EC_i - .1EC_i \cdot \ln\left\{1 - \left[\frac{ET_{max}}{AW} - \frac{YD}{AW \cdot S}\right](1 - e^{-5})\right\}\right] = 0$$

where terms are as defined above, EC_i is an electrical conductivity measure of water salinity and C' is the value of salinity above which yield decrements begin to occur.

Equations (2) and (3) are in implicit form and describe yield response that would result from steady applications of water with a constant salinity level EC over time. Given values for maximum yields (Y_{max}), maximum and minimum crop water requirements $(ET_{max}$ and $AW_t)$, non-saline production function slopes (S), and Maas-Hoffman yield/salinity slopes (B), these equations can be solved for the yield decrement for a range of applied water and water salinity values. Input values were obtained from Letey and Dinar for cotton, wheat, tomatoes, sugarbeets, and alfalfa. Applied water was scaled by seasonal pan evaporation (E_p) calculated for the study area. The data generated were then used to fit crop production functions quadratic in applied water and salinity:

$$(4) \qquad RY_{s,a,c} = \alpha_{0,c} + \alpha_{1,c}(AW_{s,a,c}/E_{p,c}) + \alpha_{2,c}(AW_{s,a,c}/E_{p,c})^2 + \alpha_{3,c} \cdot EC_i + \alpha_{4,c} \cdot EC_i^2 + \alpha_{5,c}(AW_{s,a,c}/E_{p,c}) \cdot EC_i$$

Where:

s = 1,..,14 $\equiv$ cell index

a = 1,..,4 $\equiv$ subarea index

c = {alfalfa hay, cotton, melon, sugarbeets, tomatoes, wheat} $\equiv$ crop index

$RY_{s,a,c} \equiv$ relative yield (percent of maximum yield)

$AW_{s,a,c} \equiv$ water applied to crop c, in area a (af)

$EC_i \equiv$ soil salinity measure

$E_{p,c} \equiv$ seasonal pan evaporation (af/acre)

$\alpha_{i,c} \equiv$ estimated production coefficients, i = 0,...,5.

Fitted values and t-statistics for the production coefficients are presented in Table 1. A production function for melons is derived from observed data. Salinity variables are not included in the production function for melons because data describing electrical conductivity of applied water are not available.

Table 1. Fitted Crop Production Function Coefficients[a]

Crop:	α_0	α_1	α_2	α_3	α_4	α_5	R^2
Alfalfa Hay	-0.03	1.47	-0.13	0.02	0.00	-0.17	.9990
	(-5.11)	(159.00)	(-14.65)	(1.71)	(-0.40)	(-21.66)	
Cotton	-0.62	5.95	-5.46	-0.02	-0.01	0.03	.9999
	(-186.13)	(457.01)	(-293.63)	(-2.48)	(-2.96)	(4.26)	
Melons[b]	--	1.40	-0.49	..	--	--	--
Sugarbeets	-0.29	1.94	-0.11	0.02	0.00	-0.11	.9996
	(-71.63)	(159.87)	(-8.66)	(3.52)	(0.81)	(-18.38)	
Tomatoes	-1.19	3.26	-0.52	0.16	0.01	-0.43	.9982
	(-76.39)	(73.44)	(-13.92)	(7.97)	(0.50)	(-23.15)	
Wheat	-0.26	1.94	0.02	0.05	-0.01	-0.11	.9996
	(25.47)	(51.98)	(0.42)	(5.55)	(-1.38)	(-10.63)	

[a] t values are presented in parentheses, but no statistical properties are claimed because the data were generated using a simulation model of crop yields.

[b] Melon function parameters were derived rather than estimated so t values and R^2 can not be determined. Salinity (EC_i) coefficients were not derived for melons due to a lack of data.

For simulation purposes, these crop production functions were modified to allow for irrigation inefficiencies by assuming that the water available to the plant is applied water scaled by an irrigation efficiency (IE) parameter. Since the main means of reducing subsurface runoff is to improve irrigation efficiency, we model IE as a choice variable. Increasing irrigation efficiency imposes costs, and these are modeled by estimating an irrigation cost function described next, using available engineering and technical data.

B. Irrigation Cost Function

As discussed above, the key to reducing subsurface drain water is to improve irrigation efficiency and infiltration uniformity by adopting more efficient irrigation technologies or improving irrigation management. Infiltration uniformity is a function of irrigation technology, management, and the variation of soils throughout a field.

About 80% of the agricultural lands in the drainage problem area are currently irrigated with furrow or border strip systems that are operated at relatively low irrigation efficiencies. Variations in soil characteristics, the length of furrows, water delivery rates, and cultural practices influence the degree of infiltration uniformity observed in surface irrigated fields. Irrigators can improve irrigation efficiency and infiltration uniformity by reducing furrow lengths, compacting the furrows, and establishing a uniform grade throughout the field. Pressurized irrigation systems including sprinkler, surge, and low energy precision application systems will achieve greater efficiency and uniformity when field conditions are suitable and the systems are managed properly.

Water conservation and drainage reduction can be achieved through changes in irrigation practices but these changes will increase production costs. We compiled data from Davids and Gohring for eleven irrigation technologies and three management levels. These data include annualized capital, maintenance, and labor costs for selected technologies. These data were used to fit quadratic irrigation technology cost functions:

$$(5) \qquad ITC_{s,a,c} = \beta_{o,c} + \beta_{1,c} \cdot IE_{s,a,c} + \beta_{2,c} \cdot IE_{s,a,c}^{2}$$

where:

$ITC_{s,a,c} \equiv$ annualized irrigation technology and application cost ($/Acre)
$\beta_{i,c} \equiv$ estimated irrigation cost coefficients, i = 0, 1, 2.

using a full frontier quadratic programming approach (Aigner and Chu) to estimate the parameters. Crop-specific cost functions were estimated for alfalfa hay, melons, and wheat. A single function was estimated for row crops including cotton, sugarbeets, and tomatoes because these crops are irrigated similarly. Cost function coefficients are displayed in Table 2.

Table 2: Irrigation Cost Function Coefficients

Crop:	β_o	β_1	β_2
Alfalfa Hay	56.66	-110.92	227.69
Row Crops	118.77	-413.57	514.10
Melons	74.56	-287.20	403.67
Wheat	14.62	-73.60	208.80

C. Drainage Function

The exact relationship between applied water and collected drain water is not well understood, and is likely to be field specific and depend on soil properties, water quality, crop water requirements and root structure, seasonal timing of water applications, and the drain system design and spacing. Irrigation system choice and performance are also important in drainage production. Only water applied in excess of plant needs (on any portion of a field) contributes to drainage, and irrigation system parameters influence water application decisions (Feineman, Letey, and Vaux). A mass balance approach is used in this study to approximate water movement through the root zone.

The volume of collected drain water that is expected to result from irrigation and cropping pattern decisions is determined as a function of water applications and irrigation efficiency on overlying fields, soil properties, and water table conditions. This formulation is adapted form a similar one in the Westside Agricultural Drainage Economics Model (San Joaquin Valley Drainage Program 1989):

$$(6)\quad CDW_{s,a} = [\{[\Sigma_c(AW_{s,a,c}\cdot(1-RO_{s,a,c}-EL_{s,a,c}-IE_{s,a,c}) \cdot ACRES_{s,a,c}/L_{s,a}]\cdot[2(POROS_s-SPRET_s)]^{-1}\} + ELUNS_s - (ELGR_s - DRNDPTH_s)]\cdot DA_{s,a}\cdot KD_{s,a}$$

where:

$CDW_{s,a} \equiv$ collected drain water (acre-feet)

$RO_{s,a,c} \equiv$ surface runoff (% of AW)

$EL_{s,a,c} \equiv$ evaporation losses (% of AW)

$L_{s,a} \equiv$ total irrigable land in subarea a (acres)

$POROS_{s,a} \equiv$ soil porosity

$SPRETUN_{s,a} \equiv$ specific retention of the soil

$ELUNS_{s,a} \equiv$ elevation of (bottom of') unsaturated zone in soil profile (feet)

$ELGR_{s,a} \equiv$ elevation of ground surface (feet)

$DRNDPTH_{s,a} \equiv$ depth of drains (below ground surface elevation) (feet)

$KD_{s,a} \equiv$ drain efficiency (%)

Surface runoff and evaporation losses are calculated as seven percent of water applications. The first term in (6) is expected deep percolation per acre. This is divided by specific yield to convert the volume of expected deep percolation to an equivalent depth that is added to existing ground water table heights. The difference between average water table depth and drain depth is multiplied by area to calculate the volume of water that is available to enter a drainage system. This volume is scaled by drain efficiency to obtain an estimate of expected drain water volumes.

D. The Programming Model

The optimization problem is to choose crop land allocations $(ACRES_{s,a,c})$, irrigation efficiency $(IE_{s,a,c})$, water applications $(AW_{s,a,c})$, and water sales $(SW_{s,a})$ to maximize net returns to land and management (equation (7)) subject to the production, drainage, and irrigation cost functions (8) through (13). Upper or lower bounds on crop land allocations are imposed on some crops. Total water and land constraints reflect the limited availability of these resources.

Equations (8) through (13) define technological relationships for relative yield, actual yield, collected drain water, and irrigation technology in the complete description of the simulation model, presented below. The total use of land and water resources is constrained to the amounts of these resources available in each subarea (equations (15) and (16)). Upper bounds are placed on crop land allocated to sugarbeets and tomatoes to reflect the limited number of [Bcontracts available for these crops and the small number of processing facilities in the area (equation (17a)). Maximum levels are also specified for melon acreage. A lower bound on cropland allocated to wheat reflects the typical use of this crop in rotation with other crops in the area (equation (17b)).

Simulation Model

(7) Maximize $NRLM_{s,a} = \Sigma_c([(P_c - HC_c)\cdot Y_{s,a,c} - PC_c]\cdot ACRES_{s,a,c}$
$- [P_{w,s,a}\cdot AW_{s,a,c} - ITC_{s,a,c}]\cdot ACRES_{s,a,c})$
$- DC\cdot DA_{s,a} + PM_w\cdot SW_{s,a} - t_d CDW_{s,a}$

subject to:

(8) $RY_{s,a,c} = \alpha_{0,c} + \alpha_{1,c}(AW_{s,a,c}\cdot IE_{s,a,c}/E_{p,c})$
$+ \alpha_{2,c}(AW_{s,a,c}\cdot IE_{s,a,c}/E_{p,c})^2 + \alpha_{3,c}\cdot EC_i$
$+ \alpha_{4,c}\cdot EC_i^2 + \alpha_{5,c}(AW_{s,a,c}\cdot IE_{s,a,c}/E_{p,c})\cdot EC_i$

(9) $RY_{s,a,c} \leq 1.0$

(10) $Y_{s,a,c} = YMAX_{s,a,c}\cdot RY_{s,a,c}$

(11) $CDW_{s,a} = [\{[\Sigma_c(AW_{s,a,c}\cdot(1-RO_{s,a,c}-EL_{s,a,c}-IE_{s,a,c})$
$\cdot ACRES_{s,a,c}/L_{s,a}]\cdot[2(POROS_s-SPRET_s)]^{-1}\} + ELUNS_s$
$- (ELGR_s - DRNDPTH_s)]\cdot DA_{s,a}\cdot KD_{s,a}$

(12) $ITC_{s,a,c} = \beta_{o,c} + \beta_{1,c}\cdot IE_{s,a,c} + \beta_{2,c}\cdot IE_{s,a,c}{}^2$

(13) $\Sigma_c\ ACRES_{s,a,c} \leq L_{s,a}$

(14) $(\Sigma_c\ AW_{s,a,c}\cdot ACRES_{s,a,c}) + SW_{s,a} \leq W_{s,a}$

(15) a) $ACRES_{s,a,c} \leq A_{s,a,c}\cdot L_{s,a}$ (c= sugarbeets, tomatoes, melons)
b) $ACRES_{s,a,c} \geq A_{s,a,c}\cdot L_{s,a}$ (c = wheat)

(16) $CDW_{s,a} \leq DRNLIM_{s,a}$

(17) $\Sigma_{s,a}\ CDW_{s,a} \leq DRNLIM$

This specification pertains to any given cell (s) and subarea (a) combination. All variables in the model are described in this section. A complete description of notation is provided in Table 3.

Table 3: Alphabetical Guide to Simulation Model Notation

s = 1,..,12 ≡ **cell** index

a = **1,..,4** ≡ subarea index

c ={alfalfa, cotton, melons, sugarbeets, tomatoes, wheat} ≡ crop index

$\mathbf{ACRES_{s,a,c}}$ ≡ acres of crop c planted in area a (acres)

$\mathbf{AW_{s,a,c}}$ ≡ water applied to crop c, in area a (af)

$\mathbf{CDW_{s,a}}$ ≡ collected drain water (af)

$\mathbf{DA_{s,a}}$ ≡ drained acres (acres)

DC ≡ drain system costs ($/acre)

$\mathbf{DRNDPTH_{s,a}}$ ≡ depth of drains (below ground surface elevation) (feet)

DRNLIM ≡ maximum volume of drain water allowed (af/acre)

$E_{p,c}$ ≡ seasonal pan evaporation (af/acre)

ECi ≡ soil salinity measure

$\mathbf{EL_{s,a,c}}$ ≡ evaporation losses (% of AW)

$\mathbf{ELUNS_{s,a}}$ ≡ elevation of (bottom of) unsaturated zone in soil profile (feet)

$\mathbf{ELGR_{s,a}}$ ≡ elevation of ground surface (feet)

$\mathbf{HC_{c}}$ ≡ harvest costs ($/ton)

$\mathbf{IE_{s,a,c}}$ ≡ irrigation application efficiency

$\mathbf{ITC_{s,a,c}}$ ≡ annualized irrigation technology and application cost ($/acre)

$\mathbf{KD_{s,a}}$ ≡ drain efficiency (%)

$L_{s,a}$ ≡ total irrigable land in subarea a (acres)

P~&price of water in subarea a ($/af)

$\mathbf{P_{c}}$ ≡ crop output price ($/ton)

$\mathbf{PC_{c}}$ ≡ preharvest costs ($/acre)

$\mathbf{PM_{w}}$ ≡ market price of water ($/af)

$\mathbf{POROS_{s,a}}$ ≡ soil porosity

$\mathbf{RO_{s,a,c}}$ ≡ surface runoff (% of AW)

$\mathbf{RY_{s,a,c}}$ ≡ relative yield (percent of maximum yield)

$\mathbf{SPRETUN_{s,a}}$ ≡ specific retention of the soil

$\mathbf{SW_{s,a}}$ ≡ volume of water sold in water market (af)

$\mathbf{t_{d}}$ ≡ drain water tax ($/af)

$\mathbf{W_{a}}$ ≡ total volume of water available in area a (af)

$Y_{s,a,c}$ ≡ yield of crop c attained in area a (tons/acre)

$\mathbf{YMAX_{s,a,c}}$ ≡ maximum yield attainable (tons/acre)

$\alpha_{i,c}$ ≡ estimated production coefficients, i = 0,...,5

$\beta_{i,c}$ ≡ estimated irrigation cost coefficients, i = 0, 1, 2

Policy parameters are included in the objective function of the model to represent incentive-based policy tools. Taxes and subsidies on selected inputs and outputs are examined as policy tools to *motivate* improvements in irrigation practices and drainage reduction strategies. Resource constraints are imposed in the model to examine policies that *require* changes in irrigation and drainage practices. Examples include water supply restrictions, drainage discharge standards, irrigation technology requirements, and restrictions on crop land allocations.

The volume of drain water generated in a given cell and subarea can be constrained with equation (16) while a regional drainage constraint is modeled by limiting the volume generated by all cells and subareas (equation (17)). A district-level constraint on collected drain water can be imposed by selecting the pertinent cells and subareas.

The drainage discharge constraints are set to nonbinding levels and all of the incentive-based policy parameters, including the water market price, are set equal to zero for the base case analysis. The policy parameters and resource constraints are allowed to vary when examining policy alternatives in the following section.

III. SIMULATION RESULTS

This section examines the environmental and economic implications of policy selection. The analysis provides an aggregated summary of policy response for the drainage area as a whole. Comparisons of relative costs and benefits of several policies are made by holding the level of drainage constant across all policies. Drainage reduction goals of 10%, 20% and 30% are specified to compare policies. Policies examined include crop-specific water taxes, uniform water taxes, effluent and irrigation efficiency standards, and combinations of uniform water taxes and irrigation efficiency subsidies, in addition to effluent taxes and water markets.

A. Base Case Analysis

The area encompassed in this analysis approximates the drainage study area as defined by the State Water Resources Control Board (California, 1987). The model cells included represent 68,000 irrigable acres, 44,000 of which are drained. Cells that overlap the drainage study area designation but do not contain drained acres are not included. A total of sixteen subareas are modeled, and nine water districts are represented in this analysis. Results are averaged for all subareas and thus represent the regional average value predicted for most variables. Cropping patterns are presented as the percent of total irrigable acres in the region that are predicted to be devoted to each crop. The results of the base case analysis are presented in Table 4.

In the absence of any policy intervention the model predicts that 66 % of the acreage will be planted in cotton, 9% in tomatoes, 7% each in sugarbeets and wheat and 6% in melons. It is predicted that 5% of irrigable acreage will be left fallow. These results are reasonable approximations of historic practices in the region with the exception of the large amount of cotton acreage predicted by the model. Averages of actual values for crop acreage allocations, water applications and yields reported in the region are presented in Table 5. The large cotton acreage allocations predicted arise as a consequence of the omission of many crops typically planted in relatively small acreages. These crops combine to makeup approximately 14% of the cropped acreage in the region, acres that are devoted by the model to cotton instead.

Table 4. Results of Base Case Simulation

	Cotton	Melons	Sugar-beets	Tom.	Wheat
Acres (% total)	66%	6%	7%	9%	7%
Applied Water (feet)	3.33	1.90	4.67	3.27	2.38
Irrigation Efficiency (%)	73%	67%	74%	78%	68%
Irrig. tech & mngmt costs ($/acre)	91.94	62.84	97.27	108.28	62.73
Yield (tons/acre)	0.62	8.83	29.92	32.89	3.02
Marginal DW Product (aw) (cdw/ac)	0.15	0.19	0.15	0.11	0.20
Marginal DW Product (ie) (cdw/ac)	-2.45	-1.36	-3.62	-2.31	-1.79

Fallow Acres	5%
Collected drain water (af/acre)	0.45
Collected drain water (af/drained acre)	0.69
Net Revenues ($/acre)	339.40

Table 5. Average reported values for cropping patterns, water applications, and yields

	Acres* (% irrigable)	Applied Water"* (af/a)	Yields" (tons/a)
Cotton	48%	3.24	0.67
Melons	8%	2.07	8.90
Sugarbeets	6%	4.57	29.70
Tomatoes	8%	3.22	31.74
Wheat	9%	2.30	2.79
Model Crops	86%	na	na
Fallow	7%	na	na

Notes: Weighted average (1984-1988) from primary DSA districts.. Source: BOR crop reports
** Average (1986-1988) for Broadview WD only. Source: Wicheins (1989)

Predicted irrigation efficiency levels range from 67% on melons to 78% on tomatoes, with levels of 68%, 73% and 74% for wheat, cotton and sugarbeets, respectively. The environmental consequences of these agricultural production activities derive from .69 acre feet of collected drain water produced per drained acre. This figure matches closely with the estimate of.7 acre feet per acre in the tile drained areas of the drainage study area arrived at by the San Joaquin River Basin Technical Committee (California, 1987). Net returns to land and management from crop production are estimated to be $339 per acre.

B. Comparison of Policy Options

The importance of characterizing the regional implications of policy alternatives for achieving drainage reduction goals was noted at the outset of this section. This issue is addressed in this section by examining the cost of achieving a specified objective with a first-best policy as well as through comparison with results associated with policies that are less efficient. Drainage reduction objectives often, twenty and thirty percent are considered.

Ten Percent Drainage Reduction

Results indicate that a ten percent reduction in collected drain water could be achieved with small adjustments in agricultural production activities and with minimal consequences for the region. A drain tax of $100/af would motivate the necessary changes and assure that the drainage reduction objective is met at least cost, *given existing water supply institutions*. A drain water discharge standard imposed regionally and allocated among cells and subareas in an efficient manner would accomplish the same objective, as would an appropriately specified set of input taxes. The efficiency implications of these policies, as reflected in average crop returns, are identical, though the fiscal implications are not. Simulation results for the drain tax scenarios are presented in Table 6. Base case results are included in the table to facilitate comparisons. Results indicate a cost of less than $3/acre for meeting the drain water objective. A drain tax would cost farmers an additional $40/acre in tax payments, on average. The fiscal costs of the instrument swamp the costs of meeting the environmental objective, in this case.

The ten percent drainage reduction objective could also be achieved as a result of a water market in which water is sold at a price of $72.50/af. Predicted responses to this policy are included in the third column of Table 7. Crop returns under this instrument are essentially the same as those achieved as a result of a first-best policy choice; the efficiency cost of a water market is only $.07/acre. Net returns increase with the positive revenues received from water sales and are $22/acre higher than base levels.

Twenty Percent Drainage Reduction

A twenty percent reduction in collected drain water in the region involves more significant changes than the ten percent reduction, though the least cost solution to this problem involves a reduction in crop returns of only $6.50/acre. The first-best policies considered that yield this result include a drain tax of $132 per acre foot of collected drain water and an efficiently allocated drainage reduction standard. Simulation results are presented in Table 7.

Three policies that do not motivate a least cost solution are considered a water market in which water maybe sold between districts as well as outside the region, a uniform water tax and a crop-specific water tax. The latter is a policy that would fall between a first-best set of input taxes, i.e. a set that includes crop, cell and subarea-specific