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BMP ASSESSMENT MODEL FOR AGRICULTURAL NPS POLLUTION

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FINAL REPORT
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Executive Summary

California has a diverse and productive agricultural industry with about 289 commodities and one-ninth of the total U.S. farm cash receipts, totalling approximately $18 billion. This high productivity has not come about without some cost to the environment. Elevated concentrations of agrichemical residues, including nutrients and pesticides, have been detected in surface and ground waters in agricultural areas throughout the state. Agriculture has been implicated as a major contributor of nonpoint sources (NPS) of pollution. Best management practices (BMPs) are being promulgated to control NPS pollution.

BMPs promulagated for improving the efficiency of nitrogen use by crops and minimizing nitrate leaching losses to the environment include application of recommended rates of nitrogen fertilizers taking into account residual inorganic nitrogen in the soil, nitrate content in the irrigation water, mineralization of soil organic nitrogen, biological fixation of atmospheric nitrogen, and other inputs such as animal manures. Other nitrogen BMPS are timing of fertilizer applications, banding or incorporating nitrogen into soil, use of proper forms of fertilizers, improved in-farm water management to reduce leaching losses, capture and recirculation of surface runoff waters, and crop rotation to maximize residual soil nitrogen.

BMPs promulgated for salinity include maintaining salt balance in the root zone, providing leaching fraction to meet crop salt tolerances, monitoring soil and water salinities, evaluating quality characteristics of irrigation water for salinity, sodicity and specific toxic ions, selecting efficient salt leaching practices, planting seeds and seedlings in soil that are comparatively salt-free, improve irrigation application efficiency, and improve uniformity distribution of applied waters.

Water management in irrigated agriculture is a key practice in source control for nitrates and salinity. A wide array of BMPs are available for NPS pollution control. These BMPs have the potential of reducing NPS pollution but as the following paragraph notes, effective BMPs are site-specific. Moreover, the economic returns to growers implementing site-specific BMPs are not widely known.

BMPs could be assessed from field research experiments for instance, by comparing differing nitrogen fertilizer and irrigation water management practices, and evaluating nitrate leaching losses and economic returns. But a BMP for one set of crop, soil and climatic conditions may not be a BMP for another set of crop, soil and climatic conditions. Because there are hundreds of crops grown in California on many different types of soils under different climatic conditions and agronomic practices, it would be time consuming and costly to carry out such an evaluation.

This project instead approaches BMP assessment through simulation models. Such a BMP assessment model would need to have requisite characteristics to consider agronomic systems as a function of site-specific crops, soils, climate, irrigation, fertilization, and drainage. The simulation model should be field-calibrated and validated. It is this latter modeling approach which is the central focus of this project.

The initial phase of the investigation was to utilize a simulation model to assess nitrate leaching losses and economic returns of BMPs in a heavily fertilized crop, lettuce grown in the Salinas Valley. BMP practices studied were reduced water and/or fertilizer N applications. The second phase of this project was to assess salt balance and crop yield in a salt-affected valley. We examined the effects of deficit irrigation of alfalfa grown in the Imperial Valley relative to water savings for possible urban water use. We then examined the resulting impacts on crop yield, soil salinity and economic returns. A Study Team on Nitrates as well as a Study Team on Salinity were appointed to provide oversight and assistance to this project, particularly in the earlier stages.

After reviewing simulation models ranging from simpler conceptual mass balance to more complex and data-intensive research models for nitrates and salinity, we selected a model known as EPIC, Erosion/Productivity Impact Calculator, developed and tested by USDA-ARS mainly for crops grown in the midwest and southwest. The 1990 version of EPIC requires the following information and data:

(i) hydrology such as precipitation, irrigation, surface runoff, crop evapotranspiration, deep percolation, lateral subsurface flow, and soil water properties;

(ii) daily weather such as air temperature, solar radiation, wind velocity, relative humidity and precipitation;

(iii) crop growth parameters such as potential growth, leaf area index, water use, nutrient uptake (N, P), nutrient supply and demand, growth constraints, biomass, stresses on water, temperature and nutrient, aeration, root growth, water use and winter dormancy;

(iv) plant environmental control such as irrigation, drainage, fertilization, pesticides, and water application methods;

(v) nutrients such as nitrogen and phosphorus, soil organic matter, chemical and biological transformations, plant nutrient bioavailabilty and uptake;

(vi) salinity such as water and soil salinity, chemical weathering and mineral solubility, uniformity distribution of applied water, leaching efficiency, salt tolerance of crop plants;

(vii) tillage and erosion; and
(viii) economical evaluations.

The data base for nitrates and salinity was quite formidable because not all of the input data and model parameters were available for lettuce and alfalfa. The 1990 version of EPIC did not consider salinity and required development and integration of a salinity submodel.

Application of EPIC involved model calibration and validation with experimental field data. The validated model was then applied to a range of nitrogen and salinity scenarios. The EPIC-Nitrogen model was calibrated, validated and applied with 1990 nitrogen fertilization data on spring and summer plantings of lettuce in California's Salinas Valley, based on unpublished data from Professor Louise Jackson of UC-Davis. The newly developed EPIC-Salinity model was calibrated and validated with published data from the Grand Valley of Colorado, based on lysimeter studies directed by Dr. Gordon Kruse, USDA-ARS, Colorado. The validated salinity model was then applied to an ongoing deficit irrigation field study in California's Imperial Valley conducted by Dr. Frank Robinson and colleagues from UC Davis.

The model outputs from the physically-based EPIC model were then utilized to evaluate economic considerations. Production costs are considered such as irrigation, fertilization, weed control, pest control, land rent, amortization, tillage, and harvesting costs. Modeling economic agricultural management practices generally entails optimizing economic profits to determine optimal inputs to production. Typically, the set of management practices that provides the greatest profit to the farmer is considered to be the best one. However, this may not be the case when externalities such as off-the-farm water quality impacts are considered. These externality costs are not generally considered by farmers when they examine optimizing profits and determining the amounts of inputs to be applied in crop production. In this project, profit optimization was constrained by specified levels of nitrate leaching losses and salt balance. Uniformity of irrigation was a major consideration.

The principal results from the EPIC Nitrogen simulation model applied to lettuce production in the Salinas Valley included the finding that reducing the quantity of applied irrigation water is much more effective at decreasing nitrate leaching losses than reducing nitrogen fertilization rates. In lettuce production in the Salinas Valley, both fertilizer and irrigation water could be reduced by 50% from current practices with no reduction in yields. Since there is an interaction between applied water and nitrogen inputs, both have to be considered simultaneously. The optimal rates for spring and summer plantings of lettuce in the Salinas valley are 150 mm of irrigation and 84 kg N/ha fertilizer per planting. If such practices are implemented, nitrate leaching losses could be reduced by about 75%.

The principal results from the EPIC-Salinity model applied to deficit irrigation of alfalfa grown in the Imperial Valley included the following findings: at current water salinity levels of 850 mg/L TDS, the profit from optimum irrigation (1269 mm) is about $708/acre based on $130/ton alfalfa, $606/acre under minimum stress irrigation (1203 mm), $480/acre under short stress irrigation (991 mm) and $137/acre under long stress irrigation (821 mm); a decrease in water salinity to 425 mg/L results in a profit of $731/acre for optimum irrigation and an increase in water salinity to 1700 mg/L results in $627/acre. A single elimination of a 120 mm irrigation in the Imperial Valley is estimated to save about 74,400 acre-feet of water that could be used for urban use.

In summary, a successful attempt was made in applying the EPIC simulation model to evaluate a limited set of BMPs for nitrates in lettuce production in the Salinas Valley and deficit irrigation of alfalfa in the Imperial Valley. This model has considerable promise in application to other crops grown in California, and to assess more quantitatively BMP practices on nitrates and salinity noted previously. However, it will require a well-trained scientist or engineer to become familiar with EPIC and collect or synthesize input data and model coefficients.

ACKNOWLEDGMENTS

This project would not be complete without the generous sharing of field data from our colleagues to calibrate and validate the models used in this investigation. Louise Jackson, Department of Vegetable Crops, UC Davis , contributed unpublished data on nitrogen fertilization of lettuce fields in Salinas Valley, CA. Gordon Kruse, USDA-ARS, retired, Fort Collins, CO, provided published alfalfa lysimeter data from the Fruita Research Center, Grand Junction, CO. Frank Robinson, Department of Land, Air and Water Resources, retired, UC Davis, and Larry Teuber, Department of Agronomy and Range Science, UC Davis, contributed unpublished alfalfa irrigation data from the UC Desert Research and Extension Center, Imperial Valley, CA. We also acknowledge the economic data base made available to us by Karen Klonsky, Cooperative Extension, Department of Agricultural Economics, UC Davis.

We are indebted to the members of the Study Teams on Nitrates and Salinity for their valuable contributions during the early phases of this project. We acknowledge the guidance given by and the patience of SWRCB Program Managers Dr. Manuchehr Alemi and Mr. Walt Shannon.

INTRODUCTION

Surface and ground water pollution from agricultural non-point sources (NPS) of pollution is a growing problem. Agricultural practices and technologies to reduce agricultural NPS pollution are being recommended. However, methods of assessing the effectiveness of the recommended best management practices (BMPs) are quite limited.

The overall aim of this project is to assess the effectiveness of proposed BMPs for the agricultural NPS pollutants nitrates and salinity. One approach to addressing this objective is to utilize NPS pollution physical models that have requisite characteristics to evaluate potentials for the reduction and control of pollutants through BMPs, and economic models to evaluate the cost effectiveness of the recommended BMPs.

OBJECTIVES

The objectives of this project were addressed by the following tasks:

(1). Appoint Study Teams on Nitrate Modeling and Salinity Modeling to serve as resource persons, provide input to the work plan, and serve as peer reviewers.

(2). Review existing physical and economic models for direct application and/or extensions needed to meet the project objectives.

(3). Review existing literature on nitrate and salinity leaching losses to serve as case studies for model parameters, input and output data, and model calibration and validation.

(4). Formulate physical and economic models to assess BMPs to reduce and control nitrate and salinity in agricultural drainage.

(5). Conduct sensitivity analyses and model calibration, and revise model as needed.

(6). Validate the model.

(7) Review the applicability of the models to areas sensitive to the leaching of nitrates and salts.

(8). Prepare and submit progress reports, and draft and final reports.

STUDY TEAMS

Study Teams on Nitrate and Salinity Modeling were appointed in consultation with the SWRCB Program Manager. The members comprised of representatives from various state/federal agencies and university to serve as resource persons, provide inputs to the workplan, and serve as peer reviewers. The Study Teams were active in the early stages of this project and contributed valuable suggestions. After the modeling activities were initiated, no further meetings with them were held; mainly due to budget constraints for providing travel expenses. However, individual contacts with some were maintained throughout the duration of the project.

The Nitrate Study Team consisted of:

Jacque Franco, CA Dept. of Food and Agriculture, Sacramento.
James Thorup, Chevron Chemical, San Ramon.
Stuart Pettygrove, Cooperative Extension, UC Davis.
Kurt Schulbach, Cooperative Extension, Monterey County.
Curtis Lynn, Cooperative Extension, Tulare County
Richard Howitt, Dept. of Agricultural Economics, UC Davis.
Rudy Schnagl, Regional Water Quality Control Board, Sacramento.
David Smith, USDA Soil Conservation Service, Davis.
Walter Bunter, USDA Soil Conservation Service, Davis.

The Salinity Study Team consisted of:

Dennis Westcot, Regional Water Quality Control Board, Sacramento.
James Oster, Cooperative Extension, UC Riverside.
Dan Munk, Cooperative Extension, Fresno County.
Keith Knapp, Dept. of Soils and Environmental Sciences, UC Riverside.
Gregory Smith, Dept. of Water Resources, Sacramento.
Frank Robinson, Dept. of Land, Air and Water Resources, El Centro.
Kit Paris, USDA Soil Conservation Service, Davis.
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CHAPTER I. BEST MANAGEMENT PRACTICES

1.1. Potential BMPs for Nitrogen Management

Table 1.1. summarizes potential BMPs to improve the efficiency of nitrogen use in crop production and prevent excessive losses of nitrogen to the off-site environment.

TABLE 1.1.

Practice	Effects
Fertilizer amount:	
Application of recommended rate of N for each crop	Reduces excessive concentrations of soil nitrate
Inclusion of nutrient credits for:	
Residual inorganic N in soil	Reduces fertilizer N required for optimal crop yield
Inorganic N in irrigation water	Reduces fertilizer N required for optimal crop yield
Mineralization of soil organic N	Reduces fertilizer N required for optimal crop yield
Biologically fixed N	Reduces fertilizer N required for optimal crop yield
Animal Manures	Reduces fertilizer N required for optimal crop yield
Crop tissue nitrate analysis	Matches temporal crop N requirements to increase efficiency of N use via mid-season feedback for fertilizer timing and amount
Fertilizer timing:	
No application of N during periods of low crop N requirement and high leaching potential	Increases crop N use efficiency, reduces leaching of nitrate leaching. Timing depends on crop and climate
Split application	Increase efficiency of fertilizer N use by applying when crop need is greatest
Minimal or no late season N applications	Reduces excessive concentrations of soil nitrate
Fertilization method:	
Banding/incorporation	Reduces loss of N in runoff compared to broadcast application

TABLE 1.1 (continued)

Practice	**Effects**
Fertigation	Increases efficiency of crop use of N; can vary application rate to coincide with crop growth rate
Fertilizer form:	
Ammonia-based forms	Reduces leaching potential in the short-term than nitrate forms
Slow release fertilizers	Matches N release rate more closely with growing season crop requirement
Nitrification inhibitors	Reduced rate of nitrate formation results in less N leaching potential
Organic N:	
Storage of manure for spring application	Reduces nitrate leaching
Application of manure at rates to meet crop N requirements and not for manure disposal	Avoids excessive soil nitrate and salinity buildup
Irrigation management:	
Improved on-farm water management	Reduces nitrate leaching and surface runoff losses
Collection and reuse of nitrate in tailwater	Reduces nitrate loading of surface waters
Agronomic management:	
Use of deep-rooted crops	Extracts nitrate more efficiently from deeper soil depths
Rotation of deep-rooted, high N uptake crops after shallow-rooted high N requiring crops	Extracts residual nitrate from deeper soil depths
Cover crops	Adsorbs residual nitrate during winter season
Residue management:	
Management of residues so nitrate is not released before or during rainy season	Reduces nitrate leaching losses and increases N availability to crops

1.2. Potential BMPs for Salinity Management

Table 1.2. summarizes potential BMPs to minimize deleterious impacts of salinity on crop yield and salt loading to off-site environment.

TABLE 1.2.

Practice	Effects
Evaluate salt balance in crop root zone	Consider sources and sinks for better water and salinity management strategies
Management of saline soils	Control soil salinity in crop root zone to achieve acceptable crop yield; but in so doing, discharge of salt load to off-site environment is unavoidable
Measure initial soil salinity status	Gives information on distribution of soluble salts in the crop root zone and presence of salt-producing minerals such as gypsum; use this knowledge to select leaching and drainage practices
Select most efficient leaching practice	Use the least amount of water to desalinize soils in the crop root zone, e.g., unsaturated flow, cyclic leaching, changing quality of leaching waters, soil and water amendment
Assess drainability of soils	Allows for adequate drainage and salinity control in the crop root zone, e.g., underdrainage, deep plowing, shallow water table management
Monitor soil salinity periodically	Useful for crop selection and water management strategies such as leaching, drainage, drainwater reuse
Seed and seedling placement	Plant in areas of beds where surface salt is not likely to accumulate for seed germination and early plant growth
Planting salt tolerant plants	Allows for areas of elevated soil salinity and/or high salt irrigation waters to be planted; also for drain water reuse

TABLE 1.2. (continued)

Practice	**Effects**
Management of saline waters	Utilize waters to the fullest extent possible to minimize salt loading to off-site environment
Assess leaching fraction	Evaluate water salinity for use on specific crops, and soil and climatic conditions, guided by crop salt tolerance data and leaching fraction estimation
Assess irrigation water quality	Provide appraisal on suitability of given water for crop production
Salinity appraisal	Affects availability of water to crops; crops vary in their salt tolerance
Sodicity/salinity appraisal	Affects water infiltration rates into soils and soil permeability; may affect irrigation practice, leaching and drainage
Specific toxic ions appraisal	Affects crop sensitive to boron, sodium, chloride; may restrict certain crops and use of sprinkler application method
Diagnosing salt problems:	
Visual indications	May provide indication of salt problem but in most probability not the extent of salt damage or the contributing causes of salinity; needs to be followed up with more definitive diagnosis and measurements
Salinity measurements	Will give spatial and temporal distribution of salinity; use soil saturation extracts, salinity probe and/or EM device.
Assess potential causes of salinity	Evaluate irrigation water salinity, adequacy of leaching and drainage, and primary sources of salinity to ameliorate the salt problem
Assess other related problems	Evaluate crusting of surface soils, slow water penetration, specific ion toxicity, etc., to take corrective action

1.3. Potential BMPs for On-Farm Water Management

Since leaching losses of both nitrates and salts from croplands are strongly influenced by on-farm water management , Table 1.3. summarizes practices that would enable efficient water use and minimize subsurface drainage.

TABLE 1.3.

Practice	Effects
Irrigation system evaluations	Improve application efficiency and better uniformity of application
Irrigation scheduling using real time weather data and other guidelines	Aids in proper timing of irrigation
Evaluating crop ET, fallow ET	Assesses vegetated and fallow surface water losses
Monitoring soil water status	Provides information on available soil water from irrigation and rainfall
Monitoring water flows and duration of application	Gives estimate of amount of applied water and minimizes deep percolation and runoff losses
Selection of proper irrigation method for site specific conditions	Improves water application
Surface irrigation methods:	
Land grading, slope modification	Produces more uniform slope and water intake
Shorten furrow length	Improves uniformity coefficient
Tail water recovery system	Increases water use efficiency
Cut-back irrigation for furrow, border, and basin irrigations	Controls advance/recession times for better uniformity
Surge flow irrigation	Improves uniformity distribution
Furrow compaction to reduce infiltration rates	Improves uniformity distribution
Sprinkler irrigation methods:	
Proper water pressure, sprinkler head and nozzle	Improves areal uniformity, prevent runoff losses
Proper layout/spacing, accounting for wind effects	Improves areal uniformity

TABLE 1.3. (continued)

Practice	**Effects**
Drip/trickle irrigation methods:	
Proper design, filtration system and water pressure	Improve uniformity and operating life of the system
Water treatment to prevent plugging by mineral deposits, and microbial debris	Aids in precise applications of water
Proper irrigation scheduling and operation	Increase water use efficiency and uniformity distribution
Checking variability of emitter discharge from wear and manufacturing variability	Decreases nonuniformity
Practice flushing of lines	Reduced plugging and increases system operation life
Subsurface irrigation methods:	
Monitoring shallow water table for draining excess water and/or crop water supply	Important for drainage impacted lands
Proper design, spacing and depth	Improves application and uniformity distribution
Subsurface drainage systems	Prevents waterlogging and associated salt buildup
Proper design, spacing and depth	Considers soil, crop and depth of water table; minimize draining of poorer quality water from deeper depths in water table
Drainwater reuse for salt-tolerant crops, trees, halophytes	Increases overall water usage; keeps it out of receiving waters

CHAPTER II. BMP ASSESSMENT MODELS FOR AGRICULTURAL NONPOINT SOURCE POLLUTION

2.1. Introduction

Subsurface agricultural drainage water containing salts, trace elements, and nitrates is known to contaminate surface and ground water quality in the Central Valley. Best Management Practices (BMPs) have been suggested in the Water Quality Control Plan for the San Joaquin River Basin as a means of controlling agricultural nonpoint source (NPS) pollution.

In this study, conceptual models are used to evaluate the potential for reduction and control of pollutants through BMPs. Economic models are used to evaluate the cost effectiveness of the BMPs. This work focuses on nitrates and salinity. Nitrates are assessed in this initial effort because conceptual nitrogen models are available, and extensive studies have been previously conducted on the relationship between nitrogen fertilization, crop yields, nitrate leaching losses, and economics. Salinity is included because of the impact of high total dissolved solids found in agricultural drainage waters on beneficial uses of water. Furthermore, the levels of trace elements, such as boron and selenium, have been directly related to the levels of salinity in shallow ground waters and in agricultural drainage waters on the west-side of the San Joaquin Valley.

The overall objective of this project is to assess the effectiveness of the proposed BMPs for control of agricultural NPS pollutants.

2.2. Agronomic Models

There are recent and excellent reviews of agronomic modeling and modeling concepts by Addiscott et al. (1991); Wagenet and Huston (1989); and Tanji (1981, 1982). The reader is referred to these for a detailed discussion of modeling concepts.

In brief, models are extended hypotheses which offer a representation of reality of the system of interest. Alternatively, models may be classed as a set of assumptions, the viability and applicability of which determines how well the model functionally represents the system. Models based on the best mathematical description of physical-chemical-biological systems are termed 'mechanistic'. They are 'deterministic' in nature since each set of conditions gives one unique outcome. Those models which rely on statistical probability are termed 'probabilistic'. They are 'stochastic' in nature since the exact outcome of any one set of events is not always the same. Models may also be classed according to their intended application, such as research or management. Management models commonly use simplifying assumptions so that they are 'functional' in nature, rather than mechanistic.

One example of a functional model is the 'capacity' model for unsaturated water flow in soils (Burns, 1974). It assumes that vertical water flow occurs when field capacity (FC) is exceeded, thereafter cascading to deeper soil layers in a manner analogous to a tiered water fountain. The corresponding mechanistic model uses a 'rate' approach involving analytical or numerical solution of the soil hydraulic conductivity (K)-water content (Q)-hydraulic head (H) relationship using appropriate differential equations (Richards, 1965). Conceptual models, such as the Hydrosalinity model of Tanji (1977) and nitrogen model of Tanji et al. (1979) are relatively comprehensive, but are designed for simplicity. Such models are often lumped-parameter, steady-state, and time- and space-averaged in nature. They have the advantage of low input data requirements, but they may not be able to evaluate complex interactions in agricultural systems, such as the effects of individual rates and timing of irrigation and fertilizer applications on nitrate leaching.

There are also screening models such as NLEAP (Shaffer, et al., 1991) which are designed to evaluate the pollution potential of a given site, but have very little, if any, predictive capacity.

There are dozens of single- or limited-application or stand-alone models in the literature that are not comprehensive enough in scope to be considered for utilization in the assessment of agricultural BMPs. The most promising models are comprehensive in nature, allowing for the assessment of complex interactions in agricultural systems. LeachM (Wagenet and Huston, 1989) is an excellent comprehensive mechanistic research model that has been widely applied to solute transport in soils—particularly for pesticides, salinity, and nitrate. EPIC (Sharpley and Williams, 1990) and its precursors CREAMS and GLEAMS (Leonard et al.. 1987) are relatively comprehensive, but are more of hybrid applied research or management types of models. Many of their routines are simplified for example, the water routing program of EPIC is a modified capacity model, not the more sophisticated K-Q-H finite difference mechanistic model used in LeachM. For this project, the agronomic model EPIC was selected for this project because it had much of the requisite characteristics. A description of EPIC is found in Chapter IV.

2.3 Economic Models

Modeling economic agricultural management practices generally entails optimizing economic profits to determine optimal inputs to production. Generally, the management practice that provides the greatest profits to the farmer is the best one. However, when externalities are taken into consideration this may not always be the case. In certain agricultural regions in California, farming practices have contributed to negative externalities such as nitrates and salts in the surface and ground waters. These contaminants can be a problem if the water is to be used as drinking water, or with salts, if the water is to be used again in agriculture. Society is obviously affected by contaminated water because it now must pay for the costs of cleaning the water which has been contaminated by agricultural practices. These are the costs that farmers generally do not take into consideration when optimizing profits and determining amounts of inputs to be applied in crop production.

The approach taken in profit maximization is to incorporate the nitrate and salt leaching into the farm's optimization problem. When permissible levels of nitrate and salinity leaching are targeted by regional water quality control boards, and these leachates can be estimated, the general approach is to constrain the optimization program to specific leaching levels. As profit is a function of water and nitrogen applied, so is the production of nitrates. Salt leaching is a function of applied water and its concentration of salts. Therefore, the constrained profit optimization model which is based on a specified level of nitrate or salt leaching, can be solved to determine optimal quantities of water and nitrogen applications.

An agronomic model is used to estimate crop production and nitrate and salinity leaching beyond the crop root zone on a daily basis. A crop production function for the season is needed to estimate yields. The estimation of yields, along with the product's market price determines the total revenue. Seasonal crop yield is a function of variable inputs such as applied water and nitrogen and the salinity concentration of the water applied. Estimating crop production and associated nitrate and salinity production as a function of the variable inputs is needed to assess the economic and environmental differences among alternative management practices. The literature is extensive in the area of estimating crop production and less so, at least in the economic literature, with nitrate and salinity production. Several recent studies have extended earlier research on crop production responses by investigating specifications based on theoretical aspects of agronomic systems. The specifications commonly examined are quadratic, von Liebig, and Mitscherlich-Baule. The latter two are nonlinear, plateau response curves whereas the quadratic has a descending portion. Grimm, Paris, and Williams (1987), and Ackello-Ogutu, Paris, and Williams (1985) compare the von-Liebig response curve to other commonly used functions. They conclude that the von-Liebig response curve fits well and is theoretically accurate in its assumption of the complementary nature of nutrient inputs. Frank, Beattie, and Embleton (1990) and Hexem, Sposito, and Heady (1976) compare the use of Mitscherlich-Baule and polynomial specifications. The Mitscherlich function is similar to the von-Liebig in its plateau nature but additionally allows for input substitutability. For the range of data they studied, the plateau response functions fit slightly better than the polynomial specifications.

In this study, because irrigation application uniformity is taken into account, over-application of water and nitrogen inputs may occur in a portion of the field. Over application of water may result in an actual yield decline due to the leaching of nutrients. Because of this, a yield response curve which includes the descending portion, such as a polynomial function, is necessary. Since the existing literature suggests that the test statistics for a quadratic function are as good as other polynomial specifications studied, it will be used in this study for estimating yield responses as a function of water and nitrogen inputs.

2.4. References

Ackello-Ogutu, C., Q. Paris, and W. Williams. 1985. Testing a von Liebig crop response function against polynomial specification. American Journal of Economics 67: 873-880.

Addiscot, T. M., A. P. Whitmore, and D. S. Powlson. 1991. Farming, fertilizers, and the nitrate problem. CAB International, Oxon, U.K.

Burns, I.G. 1974. A model for predicting the redistribution of salts applied to fallow soils after excess rainfall or evaporation. Journal. of Soil Science : 165-178.

Frank, M., B. Beattie, and M. Embleton. 1990. A comparison of alternative crop response models. American Journal of Agricultural Economics 73: 597-603.

Grim, S., Q. Paris, and W. Williams. 1987. A von Liebig model for water and nitrogen crop response. Western Journal of Agricultural Economics 12:182-192.

Hexem, R., V. Sposito, and E. Heady. 1976. Application of a two-variable Mitscherlich function in the analysis of yield-water-fertilizer relationship for corn. Water Resources Research 12(1): 6-10.

Leonard, R.A., W.G. Knisel, and D.A. Stills. 1987. Transactions. American Society of Agricultural Engineers 30:1403-1418

Richards, L. A. 1965. Physical conditions of water in soil. pg 318-333, *In* C. A. Black (ed.) Methods of soil analysis, Part 1, American Society of Agronomy, Madison, WI.

Shaffer, M. J., A. D. Halvorson, and F. J. Pierce. 1991. Nitrate Leaching and Economic Analysis Package (NLEAP): Model description and application. p. 285-322. *In* R. F. Follett, D. R. Keeney, and R. M. Cruse (ed.), Managing nitrogen for groundwater quality and farm profitability. Soil Science Society of America, Madison, WI.

Tanji, K.K. 1977. A conceptual hydrosalinity model for predicting salt load in irrigation return flows. Pages 49-70, IN Proceedings of the International Salinity Conference, H. Dregne, Editor, Texas Tech University, Lubbock, TX, 16-20 August 1976.

Tanji, K.K., F.E. Broadbent, M.Mehran and M. Fried. 1979. An extended version of a conceptual model for evaluating annual nitrogen leaching losses from croplands. Journal Environmental Quality 8: 114-120.

Tanji, K.K. 1981. Approaches and philosophy of modeling. Chapter 2, pages 20-41, IN Modeling of Wastewater Renovation: Land Treatment, I.K. Iskandar, Editor, John Wiley & Sons, NY.

Tanji, K.K. 1982. Modeling of the soil nitrogen cycle. Chapter 19, pages 721-772, IN Nitrogen in Agricultural Soils, F.J. Stevenson, Editor, Agronomy Monograph No. 22, American Society of Agronomy, Madison, WI..

Wagenet, R.J., and J.L. Huston. 1989. LEACHM. A finite difference model for simulating water, salt, and pesticide movement in the plant root zone. Version 2.0. Continuum, Vol. 2. NY State Resources Institute, Cornell University, Ithaca, NY

CHAPTER III. CONCEPTUAL APPROACH TO BMP ASSESSMENT

3.1. Simultaneous Environmental and Economic Optimization

The agronomic model EPIC is used to simulate the interaction among weather, hydrology, erosion, plant nutrients, plant growth, soil, tillage and other management factors. It simulates the sequential daily physical processes through a frequency distribution of weather events for a given set of farm management practices and technology.

The production functions of crop yield and nitrate/salinity leaching built into EPIC are calculated on a daily basis. At the end of the cropping period, EPIC summarizes the total yield, the total nitrate and salinity leached beyond the root zone, and the total amount of nitrogen fertilizer and water applied. EPIC is used to generate these data for different amounts of water and fertilizer applied and alternative management practices. These data are used to estimate seasonal production functions of crop yield and nitrate or salinity leached for different levels of water applied, water salinity, and nitrogen fertilizer applied. The estimated production and leaching relationships are then used to find economically optimal water and nitrogen fertilizer application for a given management practice and leaching constraint.

The range of water and nitrogen inputs used varies for each of the study sites and crops modeled. A "baseline" usage of these inputs, gathered from farm advisors and county crop reports, is used as a starting point for determining the range of these inputs to model.

For each management practice 121 yield and nitrate/salinity leaching data points are generated from 11 different levels of water applied and 11 different levels of nitrogen fertilizer applied. Approximately 75% of the water and nitrogen inputs are applied below the "baseline" amounts and the remainder is above the "baseline." Most of the data are below the "baseline" amount because, given a particular management practice, conserving nitrogen and water use is the means to achieve maximum profits with a binding nitrate or salinity leaching constraint; more data in this region usually means that a better fitting response curve is estimated.

For nitrate leaching, a second degree polynomial function with water (W) and nitrogen (N) input variables is used to estimate crop production (Y):

$$Y = b_0 + b_1*W + b_2*N + b_3*(W*N) + b_4*W^2 + b_5*N^2 \qquad (3.1)$$

This function was chosen because it incorporates the declining portion of crop yield with over-application of water and nitrogen application (an important issue in nonuniform irrigation), and the literature suggests that it predicts crop yield relatively well (Hexem, Sposito, and Heady, 1976, and Frank, Beattie, and Embleton, 1990). For the range of inputs used, nitrate leaching increases as more nitrogen and water is applied. The interaction of these two inputs is also very important to leaching. The function to estimate production of nitrates leached (A) with water and nitrogen variables is a first degree polynomial:

$$A = a_1 + a_2*W + a_3*N + a_4*(W*N) \qquad (3.2)$$

Statistical testing indicates that the above specification does not give significantly different results from a second degree polynomial specification.

For salinity leaching, a second degree polynomial function with water (W) and water salinity (WS) as variables is used to estimate crop production (Y):

$$Y = b_0 + b_1*W + b_2*WS + b_3*(W*WS) + b_4*W^2 + b_5*WS^2 \qquad (3.3)$$

The function to estimate production of salts leached (S) with water and water salinity variables is a first degree polynomial:

$$S = a_1 + a_2*W + a_3*WS + a_4*(W*WS) \qquad (3.4)$$

The parameters of these functions are estimated for each management practice for a given crop and location, assuming perfect irrigation application uniformity. The parameter estimates are then used to determine a new set of yield and leaching data based on different water application uniformities (a Christiansen Uniformity Coefficient, CUC, is used). The field is separated into uniformity quartiles, with each section receiving different applied water levels depending upon the degree of application uniformity. The conditional mean of water applied in each quartile is based on a normal distribution of input application with the standard deviation determined by the CUC. For each quartile, the amount of irrigation applied depends on this conditional mean and the targeted level of field-wide water application. Yield and leaching estimates for each quartile are averaged over the four quartiles to give a field-wide prediction of crop and leachate production. This new set of production data based on water application uniformities is regressed over the water, water salinity, and nitrogen input variables for parameter estimates on each level of CUC and each type of management practice.

The economic optimization routine for the two regions concerned with nitrate leaching takes the parameter estimates for the production functions and maximizes profits by choosing quantities of nitrogen and water application. The optimization problem is expressed as:

$$\text{MAX} \quad P*Y(N,W) - Pw*W - Pn*N \quad \text{subject to } A(N,W) = K, \qquad (3.5)$$

where P is output price, Pw and Pn are input prices of water and nitrogen, respectively, and K is the nitrate leaching constraint. Y(N,W) and A(N,W) are the crop yield and nitrate leaching production functions, respectively.

The optimal quantities of water and nitrogen application determined from this method is then used to calculate the farm-level profits. From this information, profit comparisons between management scenarios and irrigation application uniformities can be illustrated for different levels of the nitrate leaching constraint.

For salinity leaching, the economic optimization routine maximizes profits by choosing quantities of water application. The optimization problem is expressed as:

$$\text{MAX} \quad P*Y(W,WS) - Pw*W \qquad \text{subject to } S(W,WS) = L, \tag{3.6}$$

where P is output price, Pw is the input prices of water and L is the salt leaching constraint. Y(W,WS) and S(W,WS) are the crop yield and salt leaching production functions, respectively.

The optimal quantity of water application determined from this method is then used to calculate the farm-level profits. From this information, profit comparisons between management scenarios and irrigation application uniformities can be illustrated for different levels of the salinity leaching constraint.

3.2. Minimizing Agricultural Nonpoint Source Impacts of Nitrate

California has a diverse and productive agricultural industry with about 289 commodities and one-ninth of the total U. S. farm cash receipts. This has not come without some environmental cost. Elevated concentrations of nitrate and other constituents have been detected in surface- and ground-waters in agricultural areas throughout the state. Agriculture has been implicated as a major non-point source of nitrate pollution because of the large amounts of nitrogen fertilizers and irrigation water used in intensive farming systems. Assessment of management practices to decrease nitrate leaching from agricultural sources is particularly needed in intensive vegetable production systems which utilize high inputs of water and nitrogen fertilizer.

How do we minimize nitrate leaching losses from agricultural sources? Implementation of so-called 'best management practices' (BMPs) has been suggested as a method to control agricultural non-point source (NPS) pollution. What are these BMPs? What criteria are used to determine whether one management practice is better than another? Section 208 of the Federal Clean Water Act of 1977 contains a legal definition of BMPs. In brief, agricultural BMPs minimize NPS pollution, while remaining economically viable for the producer. We could determine BMPs from research field experiments by comparing different irrigation and nitrogen fertilizer management practices and assessing their nitrate leaching potentials and economic returns. But a BMP for one set of crop, soil, and climatic conditions may not be a BMP for different set of crop, soil, and climatic conditions. Though field studies like these could supply the needed information for BMP assessment, there are hundreds of crops in California, grown on different soil types under different climatic conditions and agronomic practices. Such an effort would be time-consuming and costly. An approach to assessment of management practices is to model agronomic systems as a function of crops, soils, climate, irrigation, fertilization, and drainage. Figure 3.1. is a system flowchart depicting the required scope of such a comprehensive agronomic model. A number of soil nitrogen models have been developed (Tanji, 1982), ranging from input-intensive research models to simpler management models. Other large scale models for both nitrogen and salinity, similar in scope to that depicted in Fig. 3.1, have been used for both research and management purposes (Wagenet and Hutson 1989).

Economic studies on farm management practices to reduce nitrate leaching have not been as extensive as those studies on salinity. Johnson, Adams, and Perry (1991) examine the use of a crop growth simulation model and economic optimization to evaluate on-farm costs of reducing nitrate ground water contamination in Oregon. Results indicate that better timing and reduced application rates of nitrogen and water reduce nitrate drainage with relatively little loss in profits. Mentonelli, Boggess, and Jones (1991) developed a fertilizer response model that can be used to evaluate different fertilization strategies according to economic, agronomic, and environmental considerations. The model focuses attention on fertilizer management in the form of timing, rate, placement, and form as a means to maintain yield while reducing fertilizer application and therefore leaching in the form of nitrates.

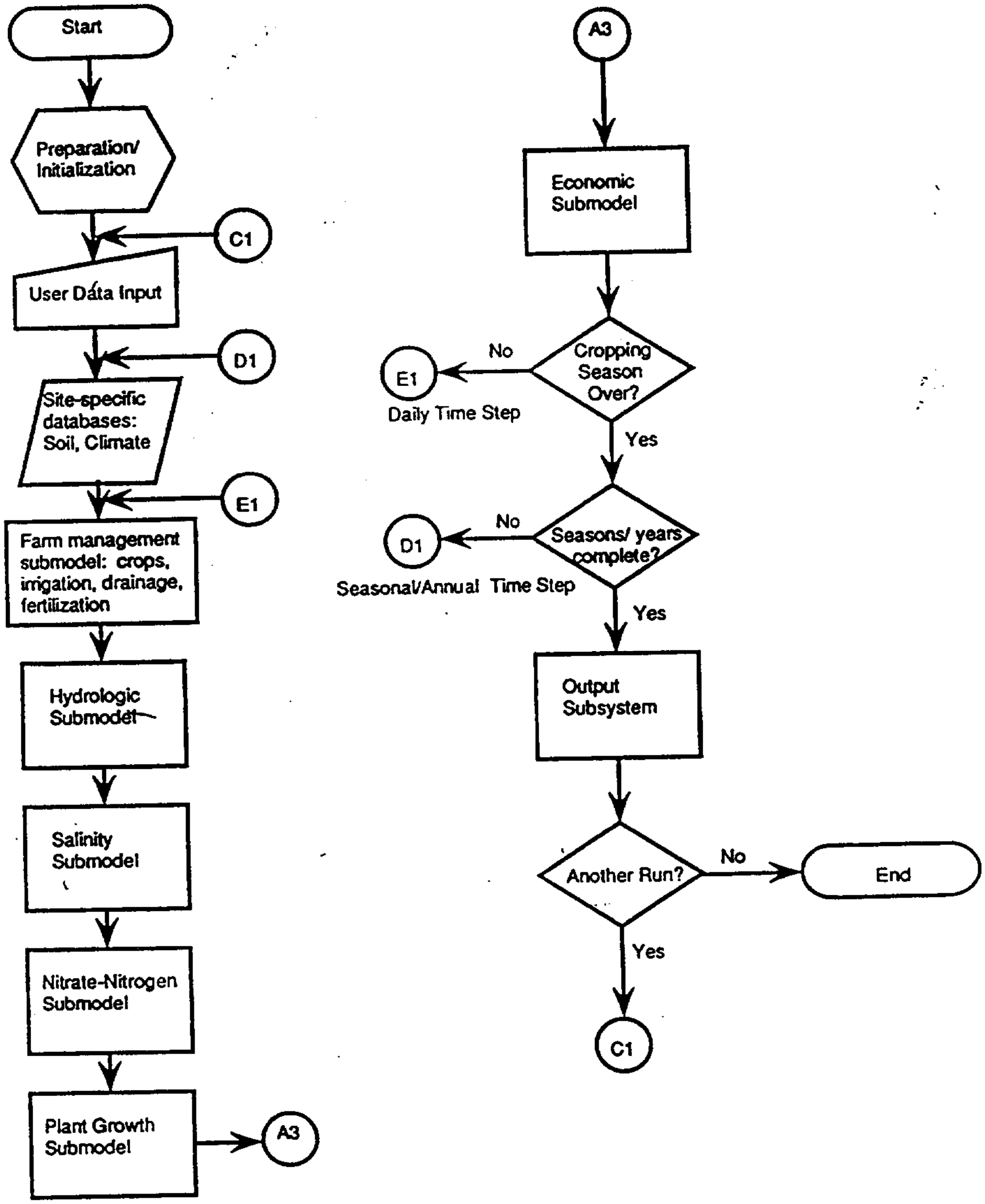


Figure 3.1. System flowchart of comprehensive agronomic model

3.3. Minimizing Agricultural Nonpoint Source Impacts of Salinity

There have been extensive economic studies on agricultural management practices in California to reduce salinity leaching into the ground water. Salt leaching is necessary for crops to flush excessive salts from the soils, but leaching raises the level and accumulation of salts in the ground water . Elevated levels of salts in the ground water can negatively affect yield as the ground water level rises into the root zone or is used for irrigation. The economic implications of managing agriculture differently to alleviate this problem has been studied primarily in the San Joaquin Valley and Imperial Valley. These studies find that yield decreases as soil salinity increases. Dinar, Rhoades, Nash, and Waggener (1991) studied several crops over a four year period in the San Joaquin and Imperial Valleys to estimate production functions describing yield, water quantity and quality, soil salinity and drainage volume. The coefficients estimated from their study are used to examine the effects of input water quality and quantity on yield, soil salinity, and drainage. Dinar and Knapp (1986) looked at alfalfa and cotton and salinity production functions to determine optimal water applications for the different crops, initial salinity, and water prices. Dinar, Knapp, and Rhoades (1986) estimated dynamic yield and salinity production functions for cotton with varying irrigation quantities and qualities. For cotton, seasonal applied water quantities are significantly affected by initial salinity levels and drainage disposal costs (Knapp and Dinar, 1988). As initial soil salinity increases, applied water quantity increases and the number of irrigations decrease. Drainage disposal costs affect applied water quantity negatively. Knapp (1991) formulated a dynamic optimization model for irrigation management and investment in an individual field over time. The model takes into consideration soil salinity as a limiting factor in crop production and the disposal costs of drainage flow. Bresler, Yaron, and Segev (1983) model optimal salt concentration of irrigation water when various water qualities are available for citrus. The improvement of drainage systems in western San Joaquin Valley farms is studied by Wichelns, Howitt, Horner, and Nelson (1990). They find that higher profits and the reduction of salt leaching justify the adoption of improved drainage systems.

The improvement of water application uniformity also has been studied as an economically feasible means of reducing salt leaching. Feinerman, Knapp, and Letey (1984) looked at the effects of salinity in irrigation water and application uniformity on yields, optimal water application, and profits for corn. Knapp (1984) examined the profit maximizing choice of water quantities given the choice of crop, water quality and the dynamics of salt accumulation over time. Dinar, Letey, and Knapp (1985) analyzed salinity, type of drainage, and uniformity of irrigation water in determining optimal water application and profitability. They found that the type of drainage system affects optimal values of applied water, profits, and drainage volume. Knapp (1991) modeled spatial variability in water application and soil salinity and finds that nonuniform irrigation infiltration and soil salinity have a significant impact on optimal water applications. In all these studies, a decrease in uniformity increases the optimal water application volume.

3.4. References

Ackello-Ogutu, C., Q, Paris, W. Williams. 1985. "Testing a von Liebig Crop Response Function Against Polynomial Specification," *American Journal of Agricultural Economics*, v.67, 873-880.

Braden, J., R. Larson, E. Herricks. 1991."Impact Targets Versus Discharge Standards in Agricultural Pollution Management," *American Journal of Agricultural Economics*. 388-397.

Bresler, E., D. Yaron, A. Segev. 1983. "Evaluation of Irrigation Water Quality for a Spatially Variable Field," *Water Resources Research*. v.19, 1613-1621.

Dinar, A., D. Zilberman. 1991. "Effects of Input Quality and Environmental Conditions on Selection of Irrigation Technologies," The Economics and Management of Water and Drainage in Agriculture. Kluver Academic Publishers, Boston, MA.

Dinar, A., J. Letey, K. Knapp. 1985. "Economic Evaluation of Salinity, Drainage and Nonuniformity of Infiltrated Irrigation Water," *Agricultural Water Management*, v.10, 221-223.

Dinar, A., J.D. Rhoades, P. Nash, B.L. Waggener. 1991. "Production Functions Relating Crop Yield, Water Quality and Quantity, Soil Salinity and Drainage Volume," *Agricultural Water Management*. v.19, 51-66.

Dinar, A., K. Knapp, J. Rhoades. 1986. "Production Function for Cotton with Dated Irrigation Quantities and Qualities," *Water Resources Bulletin*, v.22, no.11, 1519-1525.

Dinar, A., K. Knapp. 1986. "A Dynamic Analysis of Optimal Water Use Under Saline Conditions," *Western Journal of Agricultural Economics*. v. 11, 58-66.

Feinerman, E., K. Knapp, J. Letey. 1984. "Salinity and Uniformity of Water Infiltration as Factors in Yield and Economically Optimal Water Application," *Soil Science of America Journal.* v.48, 477-481.

Frank, M., B. Beattie, M. Embleton,. 1990. "A Comparison of Alternative Crop Response Models," *American Journal of Agricultural Economics,* v.73, 597-603 .

Grimm, S., Q. Paris, W. Williams 1987. "A von Liebig Model for Water and Nitrogen Crop Response," *Western Journal of Agricultural Economics,* v.12, 182-192.

Hexem, R., V. Sposito, E. Heady 1976. "Application of a Two-Variable Mitscherlich Function in the Analysis of Yield-Water-Fertilizer Relationships for Corn," *Water Resources Research,* v.12, no.1, 6-10.

Johnson, S., R. Adams, G. Perry. 1991. "The On-Farm Costs of Reducing Groundwater Pollution," *American Journal of Agricultural Economics.* 1063-1073.

Knapp, K. 1991a. "Irrigation Management and Investment Under Saline, Limited Drainage Conditions: 1, Model Formulation," working paper, University of California, Riverside.

Knapp, K. 1991b. "Irrigation Management and Investment Under Saline, Limited Drainage Conditions: 2, Characterization of Optimal Decision Rules," working paper, University of California, Riverside.

Knapp, K. 1984. "Steady-State Solutions to Soil Salinity Optimization Problems," *American Journal of Agricultural Economics,*" 279-285.

Knapp, K., A. Dinar. 1988. "Production with Optimum Irrigation Management Under Saline Conditions," *Engineering Costs and Production Economics,* v.14, 41-46.

Mentonelli, N, Boggess, Jones. 1991. "Integrating Economic and Environmental Considerations Into the Fertilization Decision Process." Selected paper, 1991 Annual Meetings of the American Agricultural Economics Association.

Wichelns, D., R. Howitt, G. Horner, D. Nelson 1990. "Economic Effects of Long-Term Restrictions on Drainage Water Disposal," *Applied Agricultural Research,* v.5, 48-55.

CHAPTER IV DESCRIPTION OF BMP ASSESSMENT MODEL EPIC

4.1. Introduction

Following a survey of nitrate and salinity models, we decided to use an existing model known as EPIC(Sharpley and Williams, 1990). This Erosion /Productivity Impact Calculator (EPIC) formulated by USDA-ARS scientists and engineers had requisite characteristics to assess BMPs. EPIC evaluates agronomic management practices as a function of crops, soils, climate, irrigation, fertilization, and drainage. EPIC meets the level of sophistication required to evaluate BMPs and the scope of required input data are readily to reasonably attainable. Some data, however, were difficult to obtain and had to be estimated. It was necessary to modify and extend EPIC's soil nitrogen subroutine to fit our chosen scenario, lettuce production in the Salinas Valley. Moreover, since EPIC did not contain any subroutine for salinity considerations, additional model formulations were needed. This section describes the 1990 version of EPIC, while changes or additions to EPIC are found in the model applications for nitrates and salinity.

EPIC was originally developed in order to assess the effect of erosion on long-term soil productivity. EPIC has the physically based components for simulating erosion, plant growth and related processes. EPIC also has the economic components for assessing the cost of erosion and for determining management strategies. The management strategies may involve decisions on drainage, irrigation, water yield, wind and water erosion control, weather, fertilizer and lime applications, pest control, planting date, tillage and crop residue.

EPIC can simultaneously and realistically simulate the processes for short and long periods. Though EPIC assumes homogeneity in 1 ha of area it can account for the vertical variations in the soil properties. EPIC is applicable to a wide range of soils, climate and crops.

In the following sections, the major components of EPIC will be described briefly. The details can be obtained from Sharpley and Williams (1990). The major components of EPIC consists of hydrology, weather, erosion, nutrients, soil temperature, plant growth, tillage, plant environmental control, and economics.

4.2. Model Components

4.2.1. *Hydrology*

Hydrology component of EPIC describes modeling of surface runoff, percolation, lateral subsurface flow, evapotranspiration, snow melt and water table dynamics.

Surface Runoff: Runoff volume is estimated by using a modification of Soil Conservation Service curve number technique. The required data for this technique is available. This technique can relate the runoff to soil type, land use and management practices. Hence, this method is computationally efficient and widely used. Daily surface runoff is computed as a function of daily rainfall and retention parameter which is, in turn, a function of soil type, land slope, land use and management, and soil water content.

Percolation is simulated by using a storage routing technique. Percolation occurs when the soil water content exceeds the field capacity. Percolation is computed as a function of initial soil water content, field capacity, and travel time which is, in turn, a function of soil porosity, field capacity and saturated hydraulic conductivity.

Lateral subsurface flow is calculated as a function of initial soil water content, field capacity and the lateral flow travel time which is, in turn, a function of clay content of the soil and soil strength factor.

Evapotranspiration : Depending upon the availability of input data the model offers two options to simulate potential evaporation: Priestly -Taylor and Penman methods. The Penman method requires data on solar radiation, air temperature, wind speed and relative humidity. On the other hand, the Priestly-Taylor method does not require wind speed and relative humidity data. The model computes evaporation from soils and plants separately. Actual soil water evaporation is estimated as an exponential function of soil depth and water content. Plant water evaporation is simulated as a linear function of potential evaporation and leaf area index. The potential evaporation is computed as a function of slope of the saturation vapor pressure curve, net solar radiation, soil heat flux, latent heat of vaporization, saturation vapor pressure, and vapor pressure at mean air temperature.

Snow melt occurs when the snow is present and the maximum temperature is greater than zero. The snow melt rate is a linear function of maximum temperature and water content of snow before melting occurs.

Water table dynamics is simulated by the model as a linear function of rainfall, surface runoff, and potential evaporation. The model drives the water table up and down, depending upon the rainfall, surface runoff and evaporation, and between input values of maximum and minimum depths from the surface.

4.2.2. *Weather*

Weather generator in the EPIC model can generate the daily weather data with the same statistical characteristics as the actual weather at any location. This part of the EPIC was developed for the cases when there is no sufficient weather data and/or for long term simulations of 50-100 years. The generated weather compartments are daily values of precipitation, maximum and minimum temperature, solar radiation, wind speed, and wind direction. The parameters governing the generation of the weather variables have been determined for many locations in the USA. The weather generated part of the EPIC was independently tested and evaluated at 134 stations located in the USA. It was concluded by Nicks et al. (1990) that the model was adequate for weather generating task required by the EPIC.

In the following subsections the weather generator part of EPIC will be discussed very briefly. The details can be obtained from Sharpley and Williams (1990).

Precipitation model is a first-order Markovian chain model developed by Nicks (1974). The input for the model requires monthly probabilities of receiving precipitation. On any given day the input must include information as to whether the previous day was dry or wet. A random number between (0-1) is generated and compared with appropriate wet-dry probabilities. If the random number is less than or equal to the wet-dry probability, then precipitation occurs on that day. When precipitation occurs, the amount is generated from a skewed normal daily precipitation distribution which is, in turn, a function of the standard deviation, skew coefficient and mean daily rainfall. If the standard deviation and skew coefficient are not available, then the daily rainfall is simulated by using a modified exponential function. Once the wet-dry state of the first day is established, the process can be repeated for the next day and so on throughout the simulation period.

Maximum and minimum temperature and solar radiation are generated from a multivariate normal distribution developed by Richardson (1981). The temperature model requires monthly means of maximum and minimum temperatures and their standard deviations as inputs. If these are not available, then the long-term observed monthly extreme maximum and minimum temperatures are used. The model estimates standard deviation as 0.25 of the difference between the extreme and mean value of the temperature for each month. The solar radiation model requires only the monthly means of daily solar radiation as input. For rainy days, the mean maximum temperature and solar radiation are adjusted by setting the wet day values less than the dry day values. For the adjustment of the mean maximum temperature, the fraction (0.5-0.9) of the difference between maximum and minimum temperatures on dry days is set as mean maximum temperature on wet days. For the adjustment of the solar radiation, the fraction (about 0.5) of the radiation on dry days is set as the radiation on wet days.

Wind part of EPIC was developed by Richardson and Wright (1984). Average daily wind velocity generated from a two-parameter gamma distribution and daily wind direction are considered as variables in this part. Wind direction expressed as radians from north in a clockwise direction is generated from a cumulative probability distribution of wind direction. "The Climatic Atlas of the United States" provides the base data (monthly percentages of wind from each 16 locations, average annual wind velocity and standard deviation of hourly wind) for generating daily wind velocity and direction.

Relative humidity model generates daily average relative humidity from the monthly average relative humidity by using a triangular distribution. Relative humidity is also adjusted for wet and dry days. This adjustment is performed by assuming that the relative humidity on dry days is a fraction of that on wet days.

4.2.3. *Erosion*

The model simulates erosion caused by rainfall/runoff, by irrigation, and by wind. The details of these can be obtained from Sharpley and Williams (1990). Here, we will briefly describe these process.

Rainfall/runoff erosion can be simulated by the model by employing several erosion methods, depending on the importance of the driving force of the erosion. These methods include the USLE (Wischmeier and Smith, 1978), the MUSLE (Williams, 1975) and Onstand-Foster modification of the USLE. The USLE depends strictly on the rainfall as an indicator of erosive energy. On the other hand, the MUSLE uses only runoff variables to simulate erosion and sediment yield. The Onstand-Foster equation contains the properties of the USLE and MUSLE energy factors. The USLE estimates only the annual sediment yield while the MUSLE can predict sediment yield from a single storm as well. The parameters that are involved in these erosion models are: (a) soil erodibility factor which depends on soil type, soil cover and organic carbon of the soil; (b) crop management factor which depends on soil cover; (c) steepness factor which depends on land surface slope and the slope length; (d) erosion control practice factor; (e) coarse fragment; (f) rainfall energy (for the USLE) and runoff volume (for the MUSLE).
Irrigation -induced erosion in furrows is estimated by the MUSLE model (Williams, 1975). The volume of runoff is estimated as the product of the irrigation volume applied and irrigation runoff ratio. The peak runoff rate is estimated for each furrow by using the Manning's equation and assuming that the flow depth is 0.75 of the ridge height and that the furrow is triangular. In the case of surface irrigation (without furrows) the peak runoff is assumed to be 0.00189 m^3/sec per m of the field width.

Wind erosion was simulated by EPIC using the modified Manhattan, KS, equation (Cole et. al., 1982). Soil loss from a wind erosion is computed as a function of soil erodibility index (calculated by using a soil textural triangle), the climatic factor (calculated as a function of annual wind speed, average monthly precipitation, evaporation, and temperature), soil ridge roughness factor (function of row height and row interval), field length along the prevailing wind direction (function of field dimensions, field orientation and wind direction), and the quantity of vegetative cover (calculated as a function of standing live biomass, standing dead residue, and flat crop residue).

4.2.4. *Nutrients*

The nutrient part of EPIC was tested against observed data obtained from field experiments throughout the USA. The results indicated that EPIC was capable of making long-term simulations of soil nitrate (N) and phosphorus (P) cycling, plant uptake and yield, fertilizer requirements and residue incorporation. Transformations of N and P between labile and more stable pools were satisfactorily simulated over long period of time by Sharpley et al. (1990).

Nutrients in EPIC include N and P transport by soil water, organic N and P transport by sediment, denitrification and minerilization of N, immobilization of N and P, and mineral P cycling. The details of these processes can be obtained from Sharpley and Williams (1990). The brief explanation of these processes are as follows.

Nitrate transport by soil water is modeled by EPIC by considering the surface layer separately. The total flow leaving the surface layer consists of surface runoff, lateral subsurface flow and percolation. On the other hand, the model considers that the flow in the other soil layers consists of lateral subsurface flow and percolation. In order to start calculations, initial mass (weight) of nitrate in the soil layer should be known. The amount of nitrate lost from the soil layer due to the water flow leaving that soil layer is computed as a function of initial amount of nitrate in that soil layer, volume of water flow leaving that soil layer, and the porosity and wilting point water content of that soil layer. The total concentration of the nitrate in that soil layer can be found by dividing the calculated nitrate mass by the water flow volume. The amount of nitrate leached from an upper layer to the bottom layer due to the percolation, and the amount of nitrate lost due to surface runoff and lateral subsurface flow are computed as a product of total nitrate concentration and the component of each flow volume.

Nitrate movement from bottom to upper layers due to soil water evaporation is also modeled by EPIC. Soil evaporation occurs from bottom to upper layers by mass flow. Hence, the amount of nitrate moved up to an any soil layer will be calculated as a sum of the product of the nitrate concentration and soil water evaporation volume in the contributing soil layers.

Organic N transport by sediment is estimated by employing the modified loading function developed by Williams and Hann (1978). The function is a linear function of sediment yield, concentration of organic N in top soil layer, and enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that in the soil. Enrichment ratios are logarithmically related to sediment concentration as described by Menzel (1980).

Denitrification , as one of the microbial processes, is a function of temperature and water content. Denitrification rate is estimated as a function of amount of nitrate, nitrate cycling temperature, and organic carbon. When the soil moisture content is less than 0.9, the denitrification rate is assumed to be zero. When the soil temperature is less than or equal to zero soil temperature, the function is set to zero.

Minerilization : The model considers two sources of minerilization-- fresh organic N pool and stable organic N pool. Fresh organic N pool is associated with crop residue and microbial biomass. Stable organic N pool is associated with the soil humus. Minerilization from a fresh organic N pool is estimated as a product of the amount of fresh organic N , and decay rate constant for the fresh organic N which is a function of carbon/nitrogen and carbon/phosphorus ratio factor, residue corporation factor, and soil water content at field capacity. The stable organic N pool is divided into two as active and stable pools. Only the active pool of organic N is subjected to minerilization and this is estimated as a product of pool fraction (function of a number years of cultivation) and total organic N. The humus minerilization is estimated as a function of humus rate constant, soil water content, settled bulk density, and current bulk density as affected by tillage. The schematic representation of N pools and flow considered by EPIC is illustrated in Figure 4.1.

Immobilization determines the decomposition rate which has an important effect on erosion. The daily amount of immobilization is computed by subtracting the amount of N contained in the crop residue from the amount of N assimilated by the microorganisms. Immobilization depends strongly on N or P availability in the soil.

Soluble P loss in surface runoff is simulated by partitioning into the solution and sediment phases as described by Leonard and Wauchope (Knisel, 1980). Soluble P in a runoff is estimated as a function of runoff volume, and concentration of P in sediment and water.

Estimation of P transport by sediment is similar to that of N transport by sediment which was described above. Similarly, minerilization and immobilization models of P developed by Jones et al. (1984) are similar in structure to those of N models described above. Minerilization from the fresh organic P pool is estimated as a function of fresh organic P in crop residue and decay rate constant for P. Minerilization of organic P associated with humus is estimated as a function of such parameters as organic P content of soil layer, soil water content, soil temperature, bulk density, and humus rate constant.

Mineral P cycling model was developed by Jones et. al. (1984). Mineral P is transferred among three pools: labile, active mineral and stable mineral. Fertilizer P is labile but it can easily be transferred to the active mineral pool. Flow between the labile and active mineral pools is governed by an equilibrium equation, which is a function of soil temperature, P sorption coefficient, soil water content, amount of active mineral pool, and amount of labile P. The P sorption coefficient, which is a fraction of fertilizer P remaining in the labile pool after the initial rapid phase of P sorption is completed, is a function of chemical and physical soil properties such as $CaCO_3$ concentration, and base saturation as determined by ammonium acetate. The model assumes that at equilibrium, the stable P pool is four times as large as the active mineral P pool. The schematic representation of P pools and flows considered by EPIC is illustrated in Figure 4.2.

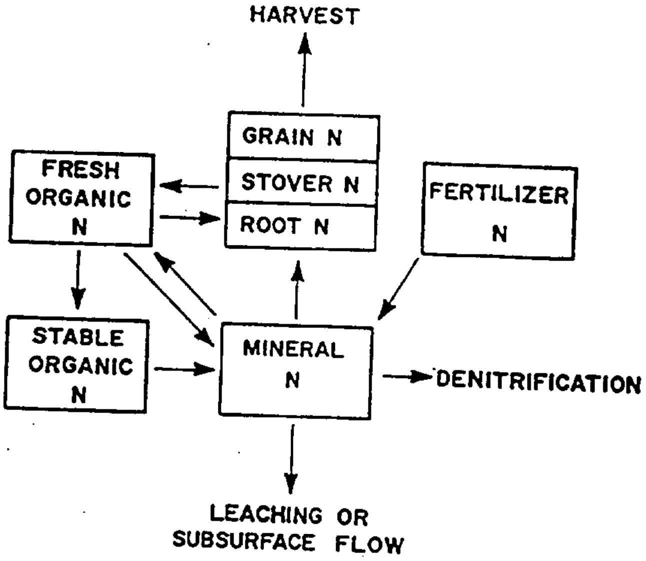


Figure 4.1. Nitrogen pools and flows in the nutrient submodel of EPIC

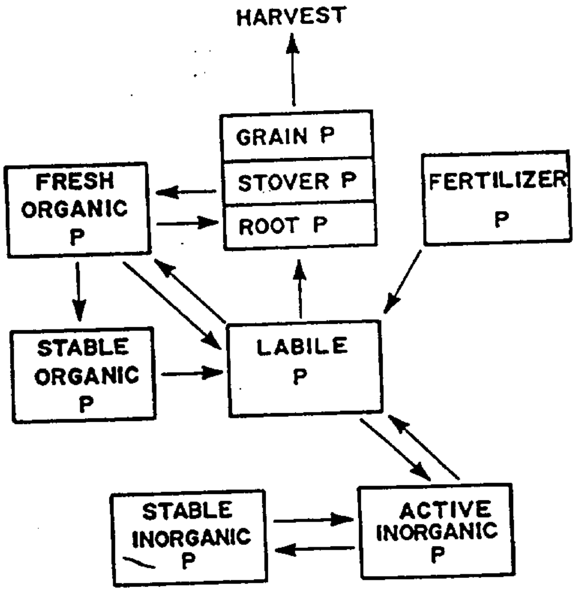


Figure 4.2. Phosphorus pools and flows in the nutrient submodel of EPIC

4.2.5. *Soil Temperature*

Daily average soil temperature at the center of each soil layer is simulated by EPIC for use in nutrient cycling and hydrology simulation. Given the previous day's temperature, the model can estimate the current day's soil temperature as a function of soil surface temperature, soil depth, and a lag coefficient. The model assumes that temperature stays constant at dumping depth, which is a function of soil bulk density and water content. Soil temperature is dependent on air temperature, precipitation, and previous soil temperature. Depending on number of wet days, number of days, and number of dry days the soil temperature is adjusted in order to account for soil surface temperature on wet and dry days. If the soil surface is not bare, the surface temperature is affected by the surface cover. The model makes necessary adjustments in order to account for non-bare surfaces as well.

4.2.6. *Plant Growth*

EPIC uses a single model for simulating all the crops by taking into account all the growth parameters of each crop. EPIC is capable of simulating growth for both annual (grow from planting date to harvest date), and perennial crops (maintain their root system throughout the year). Phenological development of the crop is based on daily heat unit accumulation which is a function of maximum and minimum temperatures, and crop specific base-temperature at or below which no growth occurs.

The crop growth part of EPIC contains subdivisions for potential growth, water use, nutrient uptake, and growth constraints. The details of these can be obtained from Sharpley and Williams (1990). The brief descriptions of these parts are given below.

<u>*Potential growth*</u>: Potential increase in a biomass is computed as a function of photosynthetic active radiation, which is a function of solar radiation and leaf area index (LAI), and increase in day light, which is a function of time of the year and the latitude. LAI is computed as a function of heat units, crop stress and crop development stages. The model simulates the partitioning of biomass to the root system. Hence, it is capable of simulating the potential daily change in the root weight. Rooting depth is simulated as a linear function of heat units and root zone depth.

Crop height is computed as a product of the maximum height of the crop and the square root of heat unit factor.

Crop yield is estimated by taking the product of harvest index, which is a function of heat unit factor, and the above-ground biomass.

<u>*Water use*</u> : Potential water use is estimated as a fraction of the potential evaporation. The fraction is 1/3 of LAI. Potential water use from the soil surface to any root depth is estimated as a

function of potential evaporation, soil depth, root zone depth, and water use distribution parameter. The higher the value of the parameter, the higher the water use near the surface. The model can also overcome water deficiency problem by allowing plants to use more water from other soil layers. The total compensation can be accomplished by taking the difference between total water use rate at the bottom of a layer and the sum of water use above the layer.

Nutrient uptake part of the crop growth model can simulate N demand and supply, N fixation, and P uptake. Crop use of nitrogen is estimated by taking the difference between the crop N content and ideal N content for that day. The nitrogen demand is estimated as a function of optimal N concentration of the crop, accumulated biomass, and actual N uptake. The optimal N concentration of the crop is a function of crop parameters expressing N concentration and heat unit index, which is the fraction of the growing season. The actual N uptake is a function of potential water use, amount of nitrate in the soil and soil water content. The model is capable of adjusting the N uptake during extreme conditions. The model ensures that actual N uptake can not exceed plant demand when mass flow estimates are too large. The model also provides, despite the availability of NO_3, for increased N supply when mean flow rates are too low.

N fixation is estimated by EPIC as a linear fraction of daily plant N uptake for legumes. The fraction of uptake is estimated as a linear function of soil NO_3 content factor, soil water content factor, and plant growth stage factor. The soil NO_3 content factor is a function of the weight of NO_3 in the root zone and the root depth. The soil water content factor depends on water contents at 0.3m of soil, at wilting point, and at field capacity. The plant growth stage factor is a function of heat unit index.

Phosphorus uptake is simulated by the model as it was in the N uptake part of the model. P demand rate is a function of optimal P concentration, actual P uptake rate, and accumulated biomass. Soil supply of P is estimated as a function of labile P factor for uptake, root weight in the soil layer, total root weight on the day, and P demand rate for the plant.

Growth Constraints Due to the constraints imposed by the plant environment, the potential crop growth and yield are not generally achieved at the desired level. The stresses occur mostly due to the lack of water, lack of nutrients, maximum and minimum temperatures, aeration, and aluminum toxicity. EPIC can estimate the stresses imposing constraints on biomass accumulation, root growth, and yield.

The biomass constrained is estimated by considering the minimum value among the stress factors of water, nutrients, temperature, and aeration. The water stress factor is computed as a function of water use and plant water evaporation rate. The nutrient stress factor is based on the ratio of accumulated plant N and P to the optimal values of N and P. The N and P stress factors are computed as a function of crop N and P uptake rate, optimal N and P concentrations of the crop, and accumulated biomass. The plant temperature stress factor is estimated as a function of soil surface temperature, base temperature for the crop, and optimal temperature for the crop. The aeration stress may occur when soil water content approaches saturation. The water content of the top 1 m of soil is considered in estimating the degree of the aeration stress.

The root growth constraint is estimated as the minimum of the soil strength, temperature, and aluminum toxicity stresses. These stresses are determined from the soil properties. The parameters of the soil strength factor are bulk density, soil texture and soil water content. Cold soil temperature may limit growth rate, especially when subsoil layers warm slowly in the spring. Aluminum (Al) toxicity can limit root growth in some acid soil layers. The Al toxicity stress is a function of Al saturation.

Crop yield may be reduced through water stress-induced reduction in the harvest index which is affected by the water stress. Another stress on the yield is winter dormancy. The day length growth constraint is used by EPIC to simulate a winter dormant period for fall planted crops. If a crop becomes a dormant in winter, the heat unit summation is set to zero by EPIC in order to provide for rapid new growth when temperatures increase in the spring. The model does not allow the plant to grow during the dormant period.

4.2.7. *Tillage*

The tillage component of EPIC mixes nutrients and crop residues within the plow depth, simulates changes in bulk density, converts standing residue to flat residue, and simulates ridge height and surface roughness. The amount of material in a soil layer after mixing can be computed as a function of the mixing efficiency of the tillage operation, and amount of the material in the soil layer in the plow depth before mixing. The change in the bulk density in the soil layer after tillage is estimated as a function of bulk density in a soil layer before tillage, and bulk density of the soil when it is completely settled after tillage. The conversion of standing residue to flat is a function of standing residue before tillage, plow depth, and mixing efficiency of the tillage operator.

4.2.8. *Plant Environmental Control*

EPIC provides mechanisms for applying irrigation water, fertilizer, lime, and pesticides, and/or for simulating a drainage system.

EPIC provides options to irrigate dryland or irrigated lands with sprinkler or furrow irrigation. The applications may be user specified or automatic. In order to trigger an automatic irrigation plant- water stress level, maximum volume application per growing season, and minimum time interval between applications should be specified by the user. The automatic irrigation volume is computed as a function of root zone field capacity, root zone water content before irrigation, and runoff ratio.

EPIC provides two options for applying fertilizer -- user specified or automatic. In the case of user-specified, the user shall supply the dates and rates of N and P. In the automatic case, the user shall specify plant stress level to trigger N fertilizer application, the maximum N application per growing season, and the minimum number of days between applications.

EPIC simulates the use of lime to neutralize toxic levels of Al and/or to raise soil pH to near optimal values. Soils with variable charge clays are usually limed only to reduce Al saturation to acceptable levels. Al saturation is estimated for each soil layer as a function of base saturation calculated from cation exchange capacity, organic carbon content, and soil pH. For highly weathered soils, the lime required to neutralize toxic Al in the plow layer is estimated as a linear function of Al saturation, effective cation exchange capacity, and soil bulk density.

EPIC considers three pests-insects, weeds, and plant disease. Crop yield is adjusted by multiplying the daily simulated yield by the pest factors. Pesticides are applied on user-specified dates.

Furrow diking, which is a practice of building small dikes across furrows to conserve water for crop production, reduces runoff, and consequently aids in erosion control. EPIC allows the construction of dikes for any ridge spacing and at any interval down the furrows. When runoff destroys the dikes the model EPIC rebuilds them automatically. The model also considers the changes that might occur in storage volume of dikes as a result of settling caused by rainstorms.

4.2.9. *Economics*

The economic component of EPIC consists of a crop budget and accounting subsystem. Costs of producing and marketing the crops are computed by the model. The model divides the costs into two groups: (1) The group which is independent of yield; and (2) The group which is dependent of yield. The costs which are assumed to be independent of yield include tillage and preharvest machine operation costs. The costs which are yield-dependent include seed and amendment costs.

Tillage and preharvest machine costs are calculated outside of EPIC and inputted as one variable into the tillage file. Seed costs, which are product of seeding rate and cost per kg, and crop prices are entered into the crop parameter file of EPIC for each crop code. Amendment costs which include elemental N and P, irrigation water, and lime costs, are also inputted into the EPIC crop parameter file for each crop code..

Total cost per hectare is computed as the sum of costs for machinery operations, seed, and amendments. Market value per hectare is computed by the model as the product of crop yield and net crop price which is the market price minus the harvest, hauling, and other yield-dependent processing costs.

Depending upon the cost figures entered into the appropriate EPIC input files, the model computes annual cost and returns by crop. The model can capture the annual distributions of profits and costs. Hence, EPIC budget information is quite useful not only for profit but also for risk analysis. Therefore, risk analyses capability of EPIC greatly enhances the analytical value of EPIC for economic studies.

4.3. Concluding Remarks

EPIC has been successfully applied to several problems by several researchers. The model's weather generator portion was tested against observed data and it was concluded by Nicks et al (1990) that the model results were in a good agreement with the observed data. Sharpley et al (1990) realistically simulated transformations of N and P between labile and more stable pools over a long period of time. They also concluded form the comparison of observed and simulated model results that EPIC was capable of making long term simulations of N and P cycling, plant uptake and yield, fertilizer requirements, and residue incorporation. Steiner et. al (1990) applied EPIC to estimate wheat and sorghum growth in dryland. The comparison of observed and simulated results indicated that EPIC satisfactorily simulated mean growing season evapotranspiration, annual runoff, crop yield, and growing season soil water depletion (Steiner et al 1990). Williams and Renard (1985) showed that EPIC performed well in predicting crop yield and runoff in humid regions. Cooler et al (1990) concluded from a study in Idaho that EPIC satisfactorily simulated forage yield, runoff, soil water, erosion and evapotranspiration from a sagebrush range site. Smith et al (1990) concluded from their study on assessing the performance of EPIC in simulating total N, organic P, organic C, and pH that EPIC compared favorable with observed data. Kiniry et al (1990) concluded from their study that EPIC gave satisfactory simulations of corn, rice, sunflower, soybeans, and barley yield in a wide range of environments.

From these research studies, it can be concluded that EPIC, as a research tool, is useful in developing and validating model components, performing sensitivity analysis, and designing field experiments.

4.4. References

Cole, G.W., Lyles, L., and Hagen, L.J., 1982. "A simulation model of daily wind erosion soil loss". *1982 ASAE winter meeting*, paper no.82-2575.

Cooley, K.R., Robertson, D.C., Springer, E.P., Williams, J.R., and Hanson, C.L., 1990. "Evaluation of EPIC using a sagebrush range site". *In Sharpley, A.N., and Williams J.R. : EPIC-Erosion/Productivity Impact Calculator, I. Model Documentation.*, U.S. Dept. of Agric. Technical Bulletin, no.1768, pp:235.

Jones, C.A., Cole, C.V., Sharpley, A.N., and Williams, J.R., 1984. "A simplified soil and plant phosphorus model, I. Documentation". *Soil Sci. Soc. Am. J.*, 48(4), pp:800-805.

Kiniry, J.R., Spanel, D.A., Williams, J.R., and Jones, C.A., 1990. "Demonstration and validation of crop grain yield simulation by EPIC". *In Sharpley, A.N., and Williams J.R. : EPIC-Erosion/Productivity Impact Calculator, I. Model Documentation.*, U.S. Dept. of Agric. Technical Bulletin, no.1768, pp:235.

Knisel, W.G., 1980. "CREAMS, A field scale model for chemicals, runoff, and erosion from agricultural management system". *U.S. Dept. Agric. Conserv. Res.* Report, No.26, pp:643.

Menzel, R, G., 1980. "Enrichment ratios for water quality modeling". *In W.G. Knisel, ed.: CREAMS, A field scale model for chemicals, runoff, and erosion from agricultural management system.* U.S. Dept. Agric. Conserv. Res. Report, No.26, pp:643.

Nicks, A.D., 1974. "Stochastic generation of the occurrence pattern, and the location of the maximum amount of daily rainfall". *In Proc. Symp. Statistical Hydrology,* 1971, Tucson, AZ., U.S. Dept. Agric. Misc. Publ. No.1275, pp:154-171.

Nicks, A.D., Richardson, C.W., and Williams, J.R., 1990. "Evaluation of the EPIC model weather generator". *In Sharpley, A.N., and Williams J.R. : EPIC-Erosion/Productivity Impact Calculator, I. Model Documentation.*, U.S. Dept. of Agric. Technical Bulletin, no.1768, pp:235.

Richardson, C.W., 1981. "Stochastic simulation of daily precipitation, temperature and solar radiation". *Water Resources Research,* 17(1):182-190.

Richardson, C.W., and Wright, D.A., 1984. "WGEN: A model for generating daily weather variables". *U.S. Dept. Agric., Agric. Res. Ser.*, ARS-8, pp:83.

Sharpley, A.N., Jones, C.A., Gray, C., and Cole, C.V., 1984. "A simplified soil and plant phosphorus model: II. Prediction of labile, organic, and sorbed phosphorus". *Soil Sci. Soc. Am. J.* 48:800-805.

Sharpley, A.N., and Williams J.R., 1990. "EPIC-Erosion/Productivity Impact Calculator, I. Model Documentation". *U.S. Dept. of Agric. Technical Bulletin*, no.1768, pp:235.

Sharpley, A.N., Jones, C.A., and Williams, J.R., 1990. "The nutrient component of EPIC". *In Sharpley, A.N., and Williams J.R. : EPIC-Erosion/Productivity Impact Calculator, I. Model Documentation.*, U.S. Dept. of Agric. Technical Bulletin, no.1768, pp:235.

Smith, S.J., Sharpley A.N., and Nicks, A.D., 1990. "Evaluation of EPIC nutrient projections using soil profiles for virgin and cultivated lands of the same soil series". *In Sharpley, A.N., and Williams J.R. : EPIC-Erosion/Productivity Impact Calculator, I. Model Documentation.*, U.S. Dept. of Agric. Technical Bulletin, no.1768, pp:235.

Steiner, J.L., Williams, J.R., and Jones, D.R., 1990. "Evaluation of EPIC using a dryland wheat-sorghum-follow crop rotation". *In Sharpley, A.N., and Williams J.R. : EPIC-Erosion/Productivity Impact Calculator, I. Model Documentation.*, U.S. Dept. of Agric. Technical Bulletin, no.1768, pp:235.

Williams, J.R., 1975. "Sediment yield prediction with universal equation using runoff energy factor". *U.S. Dept. Agric., Agric. Res. Ser.*, ARS-S-40.

Williams, J.R., and Hann, R.W., 1978. "Optimal operation of large agricultural watersheds with water quality constraints". *Texas Water Resources Institute, Texas A&M Univ.*, Technical Report, No.96, pp:152.

Williams, J.R., and Renard, K.G., 1985. "Assessments of soil erosion and crop productivity with process models, (EPIC)". *In : R.F. Follett and B.A. Stewart, eds., Soil Erosion and Crop Productivity, Amer.* Soc. of Agron., Madison, WI., pp:67-103.

Wischmeier, W.H., and Smith, D.D., 1978. "Predicting rainfall erosion losses, a guide to conservation planning". *U.S. Dept. Agric.*, Agric. Handb., No.537, pp:58.

CHAPTER V. NITRATE LEACHING MODEL APPLIED TO LETTUCE PRODUCTION

This section consolidates accomplishments under Tasks 2, 3, 4, 5, and. 6 relative to nitrate leaching physical model and presents Tasks 3, 4, 5, and 6 on economic analyses.

5.1. Abstract

Nitrate pollution of ground waters and surface waters is a growing problem in California. A 1988 State Water Resources Control Board (SWRCB) survey of 38,000 wells found 9% exceeded the maximum concentration limit of 10 mg/L NO_3-N, an increase of about 3 times in the last 30 years. Over half the nitrate contamination originates from agricultural non-point source (NPS) pollution. Best management practices (BMPs) have been suggested as a means of minimizing agricultural NPS pollution, while maintaining economic viability for the grower.

The Salinas Valley experiences large-scale NO_3 contamination of ground water because of input-intensive vegetable production systems. Crisphead lettuce is the major crop grown in this region, accounting for about half of total US production. This study used agronomic and economic modeling of nitrate leached, yield, and profit as a function of crop, soil, climate, irrigation, fertilization, and other management inputs to assess BMPs in the Salinas Valley.

Economically optimal irrigation and N fertilization inputs were obtained for a number of management scenarios, including non-uniform irrigation application. Irrigation volume, timing, and distribution uniformity were most important. The amount and timing of fertilizer nitrogen applications were the next most important variables to manage for cost-effective control of agricultural NPS nitrate pollution. Most nitrate leaching was associated with irrigation rather than rain. Simulation of double-cropped lettuce showed: (1) For the same total water applied, six irrigations per crop increased profits by more than 70% over four irrigations per crop at a nitrate leaching constraint of 60 kg NO_3-N/ha/yr, which coincided with the economic optima for each irrigation treatment; (2) Maximum profits were obtained with no fall pre-irrigation and half the usual spring pre-irrigation using an irrigation target of 50% of the field watered to evapotranspiration plus a 15% leaching fraction (ET+LF) at an irrigation system distribution uniformity of 0.84; (3) Economic optimums were at about 50% the standard 450 mm irrigation water applied per crop and 67% the 200 kg /ha fertilizer N applied per crop. Use of these BMPs would reduce nitrate leaching by about 50 % and increase profits by about 20 %; and (4) The nature of the irrigation water input-N fertilizer input-profit relationship suggests that the perceived risk of substantial yield and profit losses associated with under-fertilization and under-watering provides the only logical rationale for grower over-application of these inputs.

5..2. Introduction

Nitrogen (N) application to cool-season vegetables (e.g. lettuce, celery and cole crops) often exceeds crop demand, resulting in nitrate ($N0_3^-$-N) losses via leaching and denitrification (Lorenz and Maynard, 1988; Feigin et al., 1982; Lund, 1979). In California and Arizona, recommendations for lettuce range from 112-225 kg N ha^{-1}, yet an additional 25-150 kg N ha^{-1} is typically applied (USDA, 1991; Doerge et al., 1991; Lund et al., 1978; Raushkolb and Mikkelson, 1978; Whitaker et al., 1974). Growers may over-apply fertilizer to avoid perceived risk of low yield and low quality of these high cash value crops.

In California, $N0_3^-$ contamination of ground water is a severe problem in the central coast region of California where more than 200,000 acres of vegetable crops are produced. This is the nation's largest production area for cool-season vegetable crops (lettuce, celery and cole crops). In Monterey County, 48 percent of the wells in the upper unconfined aquifer exceed the 10 mg/L $N0_{3-}$-N public health drinking water standard (MCWCFCD, 1988). Production of lettuce in Monterey County is unparalleled worldwide, accounting for over 50 percent of the fresh lettuce supply in the United States with a value of $330 million per year. This section focuses on lettuce because it is the prominent Monterey County crop in terms of acreage, economics, and environment.

Crop-soil models can provide valuable information about optimization of plant growth while minimizing water and N inputs. They overcome the need for extensive N and water application experiments, and modeling with on-farm data as a basis makes results pertinent to grower's decisions. For example, such models allow assessment of optimal N fertilizer levels by making hypothetical simulations of crop productivity while progressively increasing fertilizer inputs and identifying the input level at which plant productivity ceases to increase. The same can be done for water inputs. Evaluation of inputs in relation to crop productivity on different soil types is also possible. The EPIC (Erosion-Productivity Impact Calculator) model (Sharpley and Williams, 1990) contains submodels for assessing plant growth, effects of weather, drainage, soil $N0_3^-$ concentrations, leaching of $N0_3^-$, and microbial transformations of N. The model has been used primarily to assess grain crops, but has been upgraded in this study to include crop growth parameters for head lettuce. Growers are interested primarily in maximizing profits, although environmental sustainability may also be an important secondary consideration, particularly for family-owned farm enterprises. Regulators are primarily interested in minimizing agricultural NPS pollution, although cost-effectiveness is an important secondary consideration. That combination of management practices which achieves a specified reduction in $N0_3^-$ leaching with the least economic cost is the optimal site-specific BMP for $N0_3^-$.

The objective of this study is to a determine site-specific BMP for lettuce grown in the Salinas Valley, as an example. The methodology employed, however, could be applied to virtually any agronomic system, provided adequate data inputs are available. The general approach taken is to use agronomic modeling of input management-crop response interactions with subsequent economic optimization of these factors.

5..3. Materials and Methods

A custom-modified version of EPIC (Sharpley and Williams, 1990) was used to model agronomic systems. The model was calibrated using field data (Warden et al., 1992). Irrigation water and nitrogen management inputs were optimized for economic profit by appropriate economic linear optimization routines (House et al., 1992).

5.3.1. Model Calibration

The 11-hectare study site was located near Salinas, California on a Mocho silty clay loam (Fine-loamy, mixed thermic Fluventic Haploxeroll). Field data from this site was used for model calibration (L. E. Jackson, unpublished data). Head lettuce was double-cropped (average yield of 3.28 T ha^{-1} crop^{-1}). Spring and summer iceberg lettuce crops were planted May 2 and July 30, respectively, and were harvested on July 16 and October 10, respectively. Residual NO_3-N in the soil profile was 200 kg/ha following a summer 1989 celery crop. Nitrogen fertilizer was incorporated at a 50 mm depth on June 5 and August 28 at 82 kg N/ha, and was applied with irrigation water on October 5 at 22 kg/ha. Spring and summer lettuce crops received 205 and 285 mm of irrigation water, respectively. The crops were virtually free of 'corky root' disease, a prevalent problem in the Salinas Valley, so uptake of nitrogen and water were near optimal.

Daily weather data was input into EPIC from the CIMIS (California Irrigation Management Information System) database, averaging 1990 values for the Watsonville and Salinas stations. Where field values were no available, USDA-Soil Conservation Service SOILS 5 database information was used. EPIC crop growth parameters for lettuce were synthesized from the literature and data from studies in the Salinas Valley. Lettuce biomass and total soil inorganic N were the primary variables used for calibration.

5.3.2. Conditions of Simulation

The case study was based on the field data used for model calibration with some modifications. Irrigation and fertilization rates were based on data in "Sample Cost to Produce Lettuce in Monterey County - 1986" by J. W. Huffman, Kurt Schulbach, and E. A. Yeary. The maximum rate of N fertilization was 168 kg/ha per crop, close to the rate of 178 kg N/ha reported by Lorenz and Maynard(1988) for a head lettuce crop. The maximum rate of irrigation water was 300 mm per crop. We assumed use of 2 acre-feet/acre of water per lettuce crop at 50% application efficiency or 1 surface foot of effective applied irrigation water. Average measured irrigation efficiencies were 58% in another study ("Season Long Crop Water Use and Irrigation Efficiency Evaluation" 1988, by Kurt Schulbach).

Data for initial soil conditions are given in Table 5.1. Residual nitrate was assumed to be 60 kg/ha NO_3-N in the soil profile. Nitrogen fertilizer was incorporated at a 50 mm depth on June 5 and August 28 at 168 and 128 kg/ha, and was applied with irrigation water on October 5 at 40 kg/ha. Each crop was furrow irrigated in equal amounts six times during the growing season at 10-14 day intervals. Rates of irrigation and fertilization were decreased from 100% to 0% of maximum at 10% increments for model simulations. Economic modeling involved calculating profit as the difference of revenue from lettuce yield and marginal costs of applied water and fertilizer.

TABLE 5.1. EPIC SOIL DATA FOR MOCHO SILT LOAM.

	Soil Layer Depth (m)			
	0-0.15	0.15-0.45	0.45-0.75	0.75-1.05
Porosity (m/m)	0.472	0.396	0.434	0.472
Field Capacity SW (m/m)	0.252	0.227	0.179	0.228
Wilting Point SW (m/m)	0.118	0.093	0.074	0.109
Soil Water (m/m)	0.152	0.126	0.100	0.139
Sat'd. Conductivity (mm/h)	8.75	1.50	11.34	10.86
Bulk Density (Ton/m^3)	1.40	1.60	1.50	1.40
Sand (%)	14.8	17.8	22.8	20.3
Silt (%)	63.0	63.5	64.5	64.8
Clay (%)	22.2	18.7	12.7	14.9
pH	7.3	7.5	7.4	7.3
CEC (cmol/kg)	24.9	22.8	20.3	23.1
Nitrate (g/Ton)	8.0	1.0	4.0	6.0
Active Org. N (g/Ton)	152.0	86.0	26.0	26.0
Stable Org. N (g/Ton)	814.0	457.0	380.0	394.0
Organic C (%)	0.88	0.62	0.37	0.43
Crop Residue (Ton/ha)	12.0	8.0	0.00	0.00

5.4. Results and Discussions

Figure 5.1 and Table 5.2 give the results of model calibration. Figure 5.1 plots the total mass of nitrates in g/m^2 in the root zone for a whole year. The results from EPIC compare favorably with measured data though modeled estimates of total soil nitrates were slightly out of phase with observations. Table 5.2 shows a comparison of simulated and measured total biomass of lettuce at harvest for the spring and summer plantings. The simulated results are remarkably close to observations. The primary model parameters in the calibration procedure were saturated hydraulic conductivity, and active organic N. The secondary model parameters in the calibration procedure were crop residue, soil bulk density, and soil clay content.

Simulations were carried out for the 1990 case study at 100% rates of irrigation water and N fertilization. Figure 5.2A depicts seasonal nitrate storage, plant uptake and N leached. Figure 5.2B gives simulation on labile soil organic matter and humus organic matter. The difference between these two is soil N mineralization. Figure 5.2C presents rainfall events , evapotranspiration and deep percolation losses. Figure 5.2D shows simulated biomass of the roots of lettuce and the total biomass for the spring and summer crops. Event-dependent interactions can be inferred from these simulated data. For instance, nitrate leaching was primarily associated with deep percolations from irrigation during the growing seasons. And mineralization of soil organic matter increased substantially after incorporation of the residues from harvesting the lettuce crop.

Figure 5.3 shows the effects of nitrate leaching losses as a function of irrigation water applied. Figure 5.4 shows the effects of nitrate leaching losses as a function of N fertilizer applied. These two figures may be used to assess turning points (break points). For instance, leaching of nitrate was most effectively reduced up to 50% of the 'normal' quantity of applied irrigation water and at 65% of the applied fertilizer N. Below these break point values, the rate of reduction in nitrate leaching per reduction in either irrigation or fertilization rate become smaller and zero at 10-15% of the maximum rates. Reducing the quantity of irrigation water appears to be more effective at reducing leaching losses than reducing the applied N fertilizer.

Figure 5.5 shows the interactive effects of irrigation and nitrogen fertilization on lettuce yield. This figure takes the baseline management practice of 6 irrigations per crop and assumes a perfectly uniform irrigation application. As the figure indicates, both nitrogen fertilizer and irrigation water could be reduced up to 50% of 'normal' with relatively little reduction in yield. Decreases in water and nitrogen beyond 50% results in rapid decreases in crop yield.

Figure 5.6 illustrates the interactive effects of irrigation and nitrogen fertilization on nitrate leaching beyond the crop root zone. This figure shows that irrigation is a primary variable to manage if nitrate leaching is to be minimized. Since applied irrigation water and nitrogen fertilization interact, however, it is important to manage both of these variables together. If one reduces nitrogen without reducing irrigation water, the crop uptake efficiency is reduced because nitrate is swept past the roots in the irrigation waters. If irrigation water is reduced, more nitrogen is available in the rootzone for plant uptake.

Figure 5.7 relates relative profit to percent of water and nitrogen applied. As seen by the peak in the graph, relative profit is maximum at a 50% reduction in water and nitrogen application. The shape of the graph portrays some interesting characteristics. For water and nitrogen input applications less than 50%, profits decline at an increasing rate. For applications greater than 50% profits slightly decrease. This observation indicates that management practices of over-application of fertilizer and water entails less risk than deficit application of these inputs. With high cash crops such as lettuce, it is not surprising that water and nitrogen inputs are over-applied since this lessens the risk of obtaining sub-optimal crop yield and quality.

Figure 5.8 illustrates the effects of irrigation uniformity on relative yield, and nitrate leached for irrigation application targets of 50% and 90%. The field is divided into uniformity quartiles. Each graph illustrates the effects on each quartile and on a field wide average. The lowest quartile represents the quarter of the field at the end of the irrigation run or the one receiving the least water if the field is not perfectly uniform. The highest quarter is the section receiving the most water. The irrigation targets represent what fraction of the field receives the adequate or targeted irrigation volume. A 50% target means half the field or the first two quarters receive at least this amount. A 100% target means the entire field receives at least this amount of water. As the field becomes less uniform, over-watering is more prevalent because to meet the required irrigation target, more water must be applied.

Figure 5.8a - 5.8b show the effect of Christiansen Uniformity Coefficient (CUC) on relative yield. On average, yield declines as the uniformity of water application decreases but it does so differently depending on the targeted irrigation amount. With a 90% target, yield does not start to decrease until the uniformity is 0.70 and with a 50% target, it starts to decline at 0.90 CUC. The reason for this can be explained by observing the irrigation effects on the field quartiles. Over-watering affects yield negatively because it leaches out important crop nutrients in the soil such as nitrogen fertilizer. With a 50% target, only the lowest quartile is significantly affected by CUC. The lowest quartile does not receive enough water to restore crop growth as the CUC declines. In this way, non-uniformity for a 50% irrigation target affects yield negatively because of deficit watering. With a 90% irrigation target, the lowest quartile is targeted to receive the adequate water supply. The rest of the field is therefore over-watered. This can be seen when the uniformity falls below 0.70 CUC. At this point the upper quartiles receive too much water and crop yield in this area of the field declines.

Figures 5.8c -5.8d illustrate the effects of CUC on relative nitrate leaching. Depending on the targeted irrigation level, the results are quite different. For a 50% irrigation target, the average nitrate leached declines slightly as the irrigation uniformity decreases. With a 90% irrigation target, nitrate leaching increases with a decrease in CUC. The results seem counter-intuitive for the 50% target, but they are not when the relationships are described in quartiles. With a 50% target, the lower half of the field's decrease in leaching with declining CUC outweighs the upper half of the field's increase in leaching. The decrease in leaching is especially noted in the lowest quartile. This quartile receives substantially less water as CUC falls. Less water application means less nitrates are leached beyond the crop root zone. With a 90% irrigation target, the upper three-quarters of the field are receiving too much water and nitrate leaching increases as the irrigation uniformity declines. The lowest quartile's nitrate leaching does not change because it is targeted to receive the adequate water volume for a levels of CUC. This means that on average, nitrate leaching increases with decreases in CUC.

Overall, Figure 5.8 has some interesting results concerning irrigation uniformity from a field quartile perspective. At the higher ends of irrigation uniformity, crop yield is relatively unaffected, yet nitrate leaching differs depending on the irrigation coverage target. It increases for higher targets such as 90% and decreases for lower targets such as 50% of the field.

The effects of levels of nitrate leached beyond the crop root zone for different management practices on relative water and nitrogen applied, relative yield, and relative profit is portrayed in figure 5.9. The levels of nitrate leached correspond to nitrate leaching constraints set in the economic optimization subroutine. The baseline management practice modeled for this figure is irrigating six times per crop at a Christiansen Uniformity Coefficient of 0.80 and a 50% irrigation coverage target. The alternative practices modeled are: (1) eliminating pre-irrigation for the spring crop and applying half the volume of pre-irrigation normally applied for the summer crop; and (2) applying nitrogen fertilizer a week before harvest for greening of the lettuce.

Figure 5.9a indicates that as the nitrate leaching constraint is tightened, the relative water applied decreases at an increasing rate. For each permissible level of leaching, the alternative pre-irrigation strategy uses relatively less water than the other two management practices. The baseline and greening practices indicate relatively little differences in the amount of water applied.

Figure 5.9b shows that as the leaching constraint is tightened, the relative nitrogen applied decreases at a somewhat constant rate. The alternative pre-irrigation strategy uses relatively less nitrogen than the other two practices for each permissible level of nitrate leached.

Figure 5.9c indicates the relative effect on crop yield with different permissible levels of nitrate leaching. As indicated by the concave nature of the curves, tightening the leaching constraint from approximately 90 kg/ha, yield declines at an increasing rate. Not considered in EPIC-N model is salinity, which would be an additional constraint. The baseline practice is inferior throughout, and the end of season greening practice dominates in the increasing yield response range. This is probably because end of season application of fertilizer in the spring crop positively affects the summer crop germination and growth. In other words, even though it greens-up the spring lettuce it does not affect its yield, yet the residuals are carried over to the next crop. Nitrate leaching constraints beyond what would be called a realistic level (above approximately 90 kg/ha would be sub-optimal for a farmer to practice). The alternative to pre-irrigation strategies is dominant.

Figure 5.9d illustrates a concave relationship of the effect of nitrate leaching levels on relative profit. Tightening leaching from 80 kg/ha, profits decline at an increasing rate. The alternative to pre-irrigation strategy dominates throughout. With a 10% decline of profit from the maximum, nitrate leaching decreases from approximately 80-50 kg/ha. Beyond 50 kg/ha, profits decline rapidly and the three management scenarios converge. However, from the grower's perspective, the optimum rate (when nitrate leaching is held to approximately 80 kg/ha for maximizing the relative profit) does not necessarily provide adequate protection of ground water quality.

Overall, Figure 5.9 shows that nitrate leaching can be substantially decreased with little loss in farm profits. This is because crop yield does not decrease dramatically with reductions in water and fertilizer application. This means less water and nitrogen input costs and relatively little reduction in crop yield, profits do not greatly decline with large cuts in permissible nitrate leached. This alternative to pre-irrigation strategy is the dominating practice and is shown to use less water and nitrogen and obtains higher profits that the other two scenarios modeled.

5.5. Conclusions

Standard output for a double-cropped lettuce simulation shows the interaction between different agronomic components. Note that most of the nitrate leaching is associated with irrigation events rather than rain. Yield was not reduced until input levels dropped below 50% of the maximum irrigation and fertilization rates. Use of half the maximum rate of these inputs would result in about a 75% reduction in nitrate leaching.

Irrigation volume, timing, and distribution uniformity were the most important management variables for the cost-effective control of agricultural NPS nitrate pollution. The amount and timing of fertilizer nitrogen application were the next most important variable to manage under irrigated agronomic systems.

The model suggests that optimal rates for lettuce production at this site are 150 mm of applied irrigation water and 84 kg N/ha fertilizer for each of the spring and summer plantings. Implementation of these optimal rates would reduce nitrate leaching losses by about 75%.

5.6. References

Adriano, D. C., F. H. Takatori, P. F. Pratt, and O. A. Lorenz. 1972. "Soil Nitrogen Balance in Selected Row-Crop Sites in Southern California." *Journal of Environmental Quality* 1:279-283.

Bakker, M. J., J. H. G. Slangen, and W. Glas. 1984. "Comparative Investigation into the Effect of Fertigation and of Broadcast Fertilization on the Yield and Nitrate Content of Lettuce (*Lactuca sativa* L.)." *Netherlands Journal of Agricultural Science* 32:330-333.

Bar-Yosef, B., and B. Sagiv. 1982. "Trickle Irrigation and Fertilization of Iceberg Lettuce." In: Scaife, A.(Ed.), *Plant Nutrition 1982: Proceedings of the 9th International Plant Nutrition Colloquium*, Warwick University, England, August 22-27, 1982. Slough UK Commonwealth Agricultural Bureaux, pp. 33-38.

Bauder, J. W., and B. R. Montgomery. 1980. "N-Source and Irrigation Effects on Nitrate Leaching." *Agronomy Journal* 72:593-596.

Doerge, T. A., R. L. Roth, and B. R. Gardner. 1991. *Nitrogen Fertilizer Management in Arizona.* College of Agriculture, University of Arizona, Tucson, Arizona, 87 pages.

Feigin, A., J. Letey, and W. M. Jarrell. 1982a. "Celery Response to Type, Amount, and Method of N-Fertilizer Application Under Drip Irrigation." *Agronomy Journal* 74:971-977.

Feigin, A., J. Letey, and W. M. Jarrell. 1982b. "Nitrogen Utilization Efficiency by Drip Irrigated Celery Receiving Preplant or Water Applied N Fertilizer." *Agronomy Journal* 74:978-983.

House, B. W., B. T. Warden, G. E. Helfand, and D. M. Larson. 1992. Economic and environmental aspects of non-uniform agricultural irrigation. Proc. Am. Agric. Econ. Assoc., Baltimore, MD, Aug, 1992. (selected paper).

Huston, J. L., and R. J. Wagenet. 1989. LEACHM: Leaching Estimation and Chemistry Model. CONTINUUM Water Resources Institute, Vol. 2. Cornell Univ., Ithaca, NY.

Jackson, L. E. and L. J. Stivers. "Lettuce Root Distribution Under Four Management Systems." *Biological Agriculture and Horticulture.* In press.

Letey, J., and A. Dinar. 1986. "Simulated Crop-Water Production Functions for Several Crops When Irrigated with Saline Waters." *Hilgardia* 54:1-32.

Letey, J., J. W. Biggar, L. H. Stolzy, and R. S. Ayers. 1978. "Effect of Water Management on Nitrate Leaching." In: *Proceedings of the National Conference on Management of Nitrogen in Irrigated Agriculture*, P. F. Pratt, Ed., Department of Soil and Environmental Sciences, University of California, Riverside, pp. 231-249.

Letey, J., J. W. Blair, D. Devitt, L. J. Lund, and P. Nash. 1977. "Nitrate-Nitrogen in Effluent from Agricultural Tile Drains in California." *Hilgardia* 45:289-319.

Letey, J., J. W. Blair, D. Devitt, L. J. Lund, and P. Nash. 1979. "Nitrate-Nitrogen in Effluent from Specific Tile-Drained Fields." In: *Nitrate in Effluents from Irrigated Lands*, Pratt, P.F., ed., Final Report, NSF-RANN.University of California, Riverside, pp.247-296.

Letey, J., W. M. Jarrell, N. Valoras, and R. Beverly. 1983. "Fertilizer Application and Irrigation Management of Broccoli Production and Fertilizer Use Efficiency." *Agronomy Journal* 75:502-507.

Lorenz, O. A., and D. N. Maynard. 1988. Knott's handbook for vegetable growers. John Wiley & Sons, Inc., New York, NY 456 pp.

Lorenz, O. A., and J. V. Hubbard. 1943. "Results of Lettuce Fertilizer Experiments and Soil Nitrification Studies in Salinas Valley." Division of Truck Crops, University of California, Davis. Photocopy.

Lund, L. J. 1979. "Nitrate Leaching and Nitrogen Balances for Selected Fields in the Santa Maria Valley." In: *Nitrate in Effluents from Irrigated Lands*, Pratt, P.F., Ed., Final Report, NSF-RANN. University of California, Riverside., pp. 355-415.

Lund, L. J., J. C. Ryden, R. J. Miller, A. E. Laag, and W. E. Bendixen.1978. "Nitrogen Balances for the Santa Maria Valley." In: *Proceedings of the National Conference on Management of Nitrogen in Irrigated Agriculture*, Pratt, P.F., Ed., Department of Soil and Environmental Sciences; University of California, Riverside, pp. 395-413.

Rauschkolb, R. S., and D. S. Mikkelsen. 1978. *Survey of Fertilizer Use in California*. Bulletin 1887 Univ. of California Cooperative Extension, Berkeley, California.

Shaffer, M. J., A. D. Halvorson, and F. J. Pierce. 1991. Nitrate Leaching and Economic Analysis Package (NLEAP): Model description and application. p. 285-322. *In* R. F. Follett, D. R. Keeney, and R. M. Cruse (ed.), Managing nitrogen for groundwater quality and farm profitability. Soil Science Society of America, Madison, WI.

Sharpley, A. N., and J. R. Williams. 1990. EPIC--Erosion/Productivity Impact Calculator: 1. Model Documentation. USDA Tech. Bull. No. 1768. 235 pp.

State Water Resources Control Board. 1988. Nitrate in drinking water, report to the legislature. Rep. no. 88-11WQ, Div. of Water Quality, 148 p.

Tanji, K. K. 1982. Modeling of the soil nitrogen cycle. *In* F. J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22:721-772.

U.S. Environmental Protection Agency. 1989. Nonpoint source agenda for the future.

U.S. Environmental Protection Agency. 1990. National survey of pesticides in drinking water wells, phase 1 report, 98 p.

United States Department of Agriculture 1991. *Agricultural Chemical Usage 1990, Vegetable Summary*. National Agricultural Statistics Service, Economic Research Service Washington, D.C.

United States Department of Agriculture. 1978. *Growing Cauliflower and Broccoli.* Farmers' Bulletin No. 2239, USDA, Washington, D.C.

Warden, B. T., B. W. House, L. E. Jackson, and K. K. Tanji. 1992. Modeling the fate of nitrogen in the rootzone: management and research applications. p. 75-87, Proc. Calif. Plant and Soil Conf., Fresno, CA, 28-29 Jan., 1992.

Table 5.2 Model calibration: comparison of measured total lettuce biomass at harvest with model estimates.

	Spring crop	Summer crop
	g dw m^{-2}	
Measured	3.60 ± 0.57	2.96 ± 0.26
Modeled	3.61	2.92

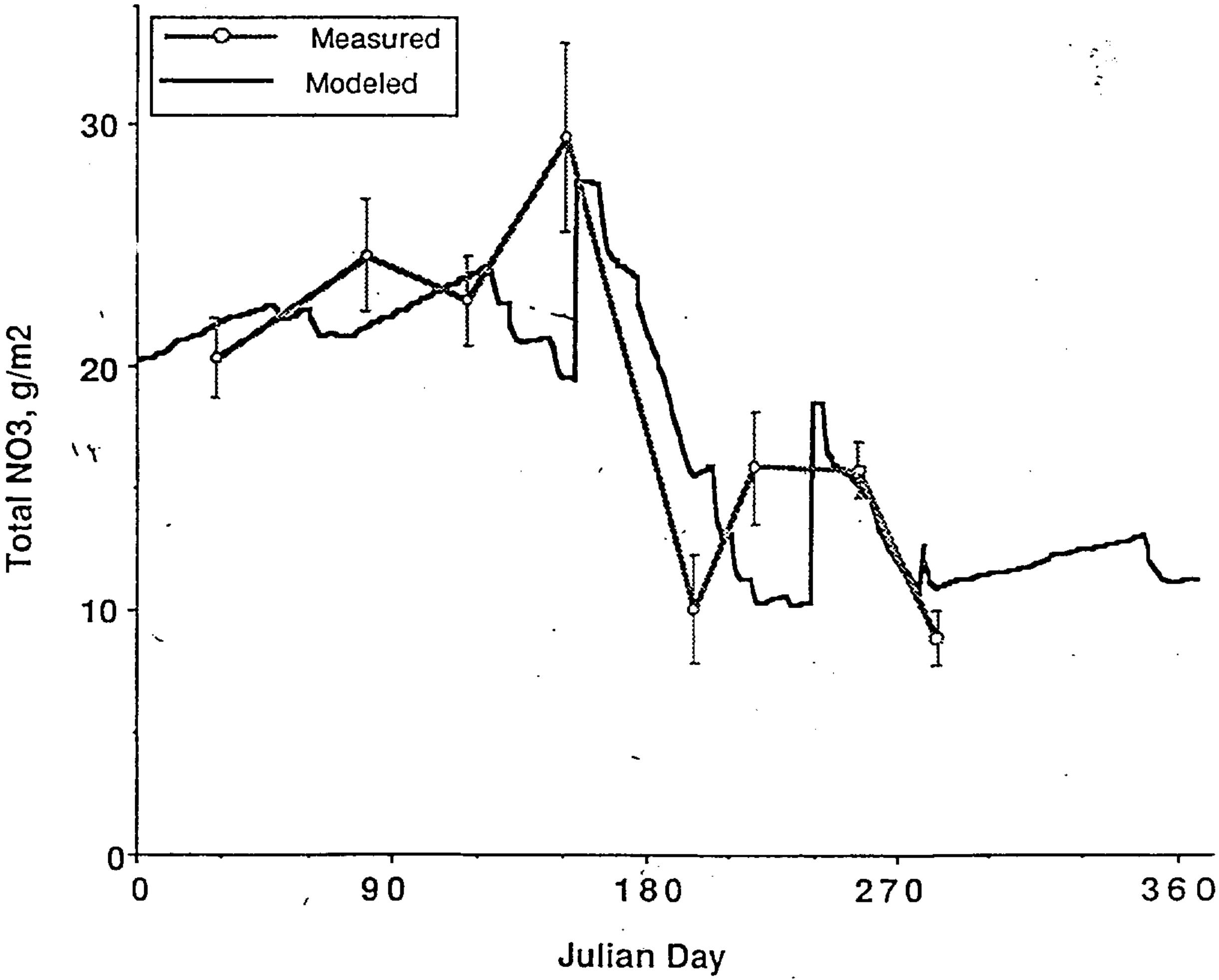


Figure 5.1 Model Calibration: comparison of measured total soil profile nitrate with model estimates.

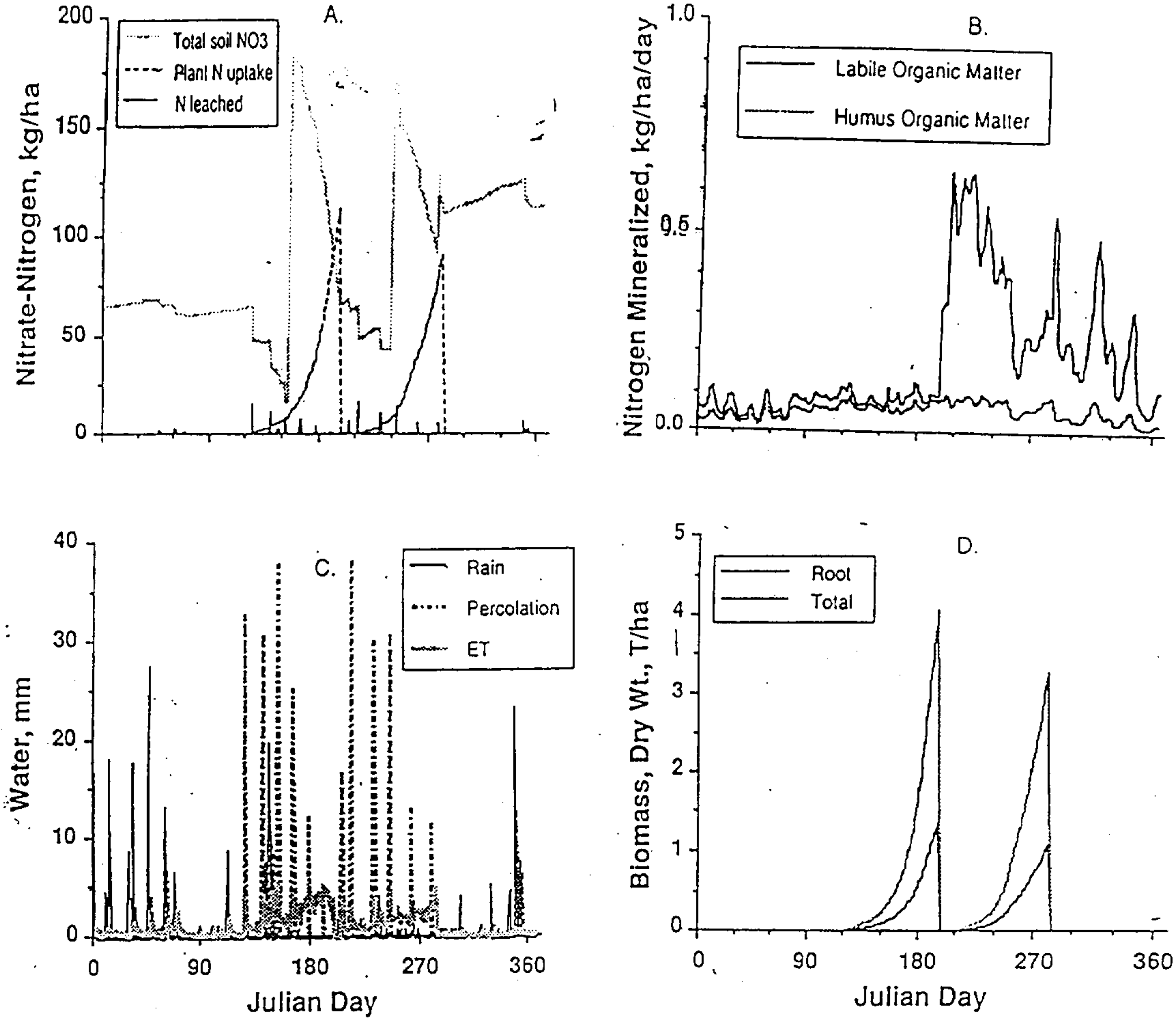


Figure 5.2 EPIC model output: A. nitrate sources and sinks; B. soil N mineralization; C. water sources and sinks; D. crop biomass.

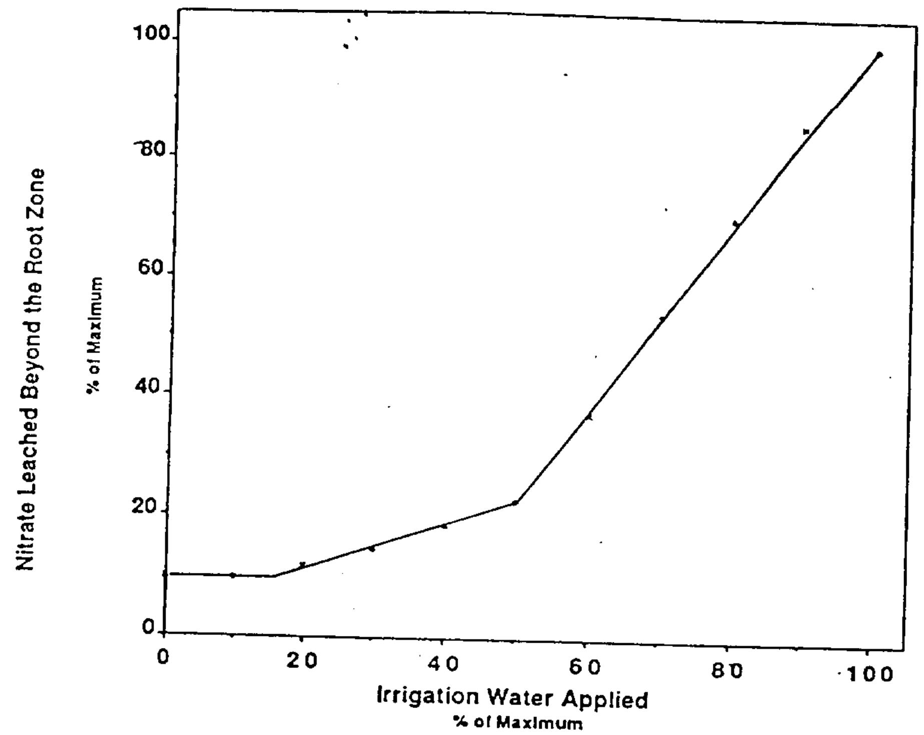


Figure 5.3 : Effect of quantity of irrigation water applied on nitrate leaching.

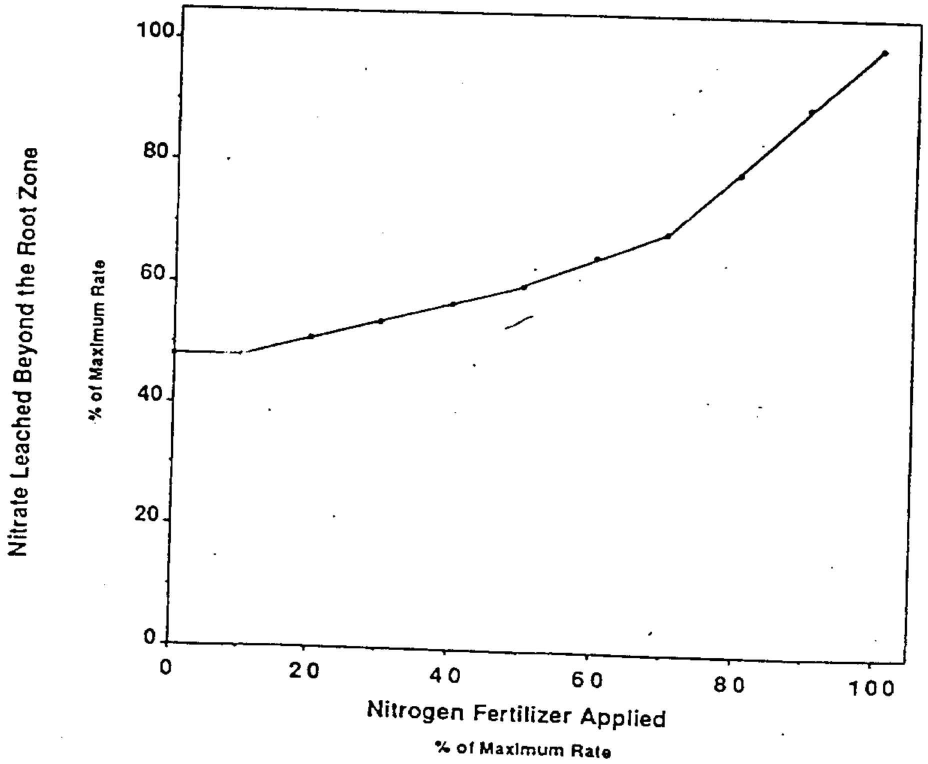


Figure 5.4 : Effect of nitrogen fertilizer rate on nitrate leaching.

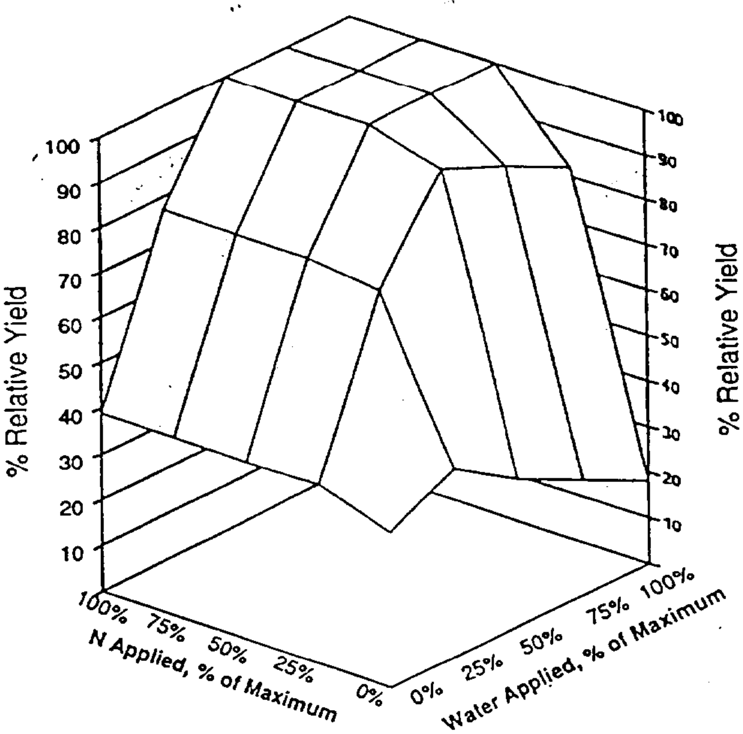


Figure 5.5 Interactive effects of irrigation and N fertilization on lettuce yield.

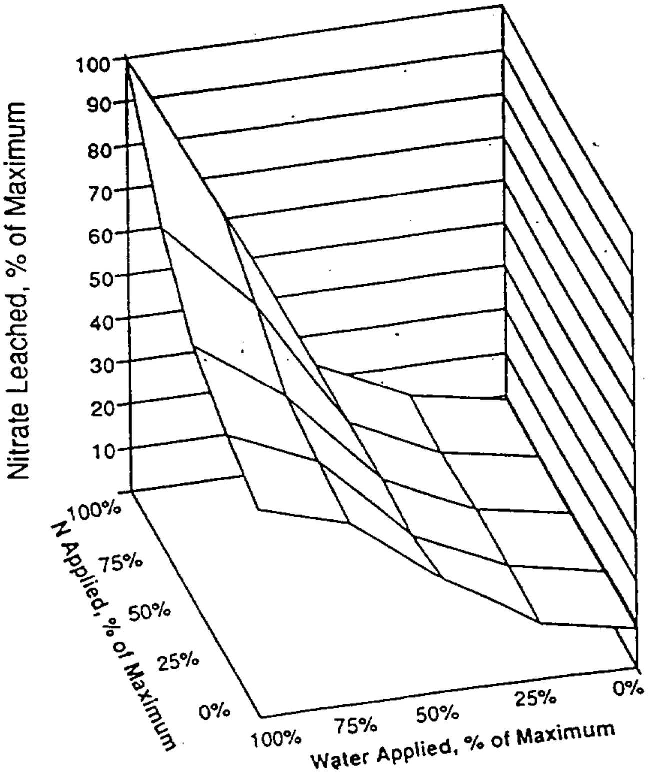


Figure 5.6 Interactive effects of irrigation and N fertilization on nitrate leaching beyond the root zone.

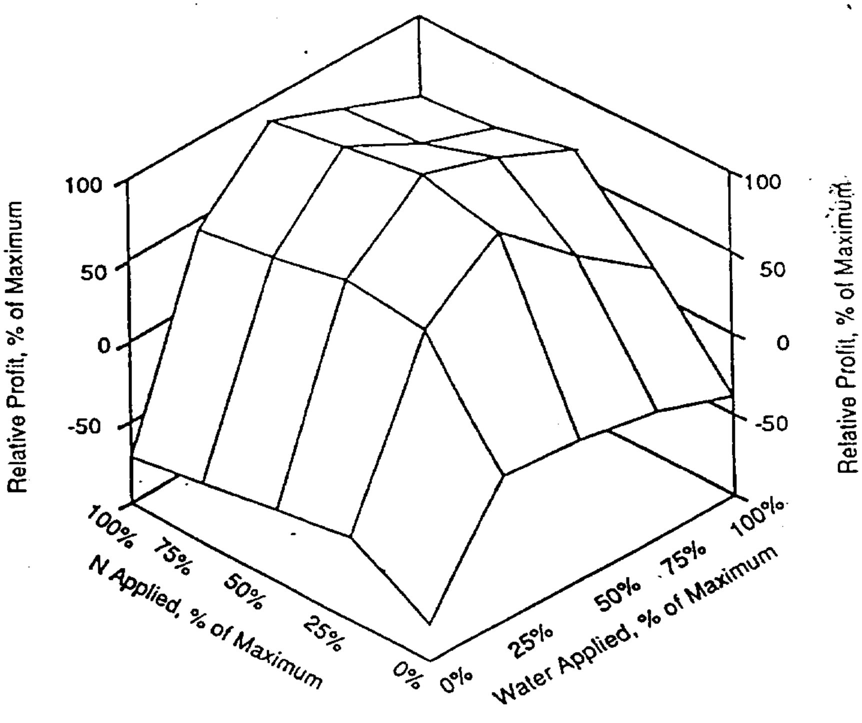


Figure 5.7 Interactive effects of irrigation and N fertilization on relative profit.

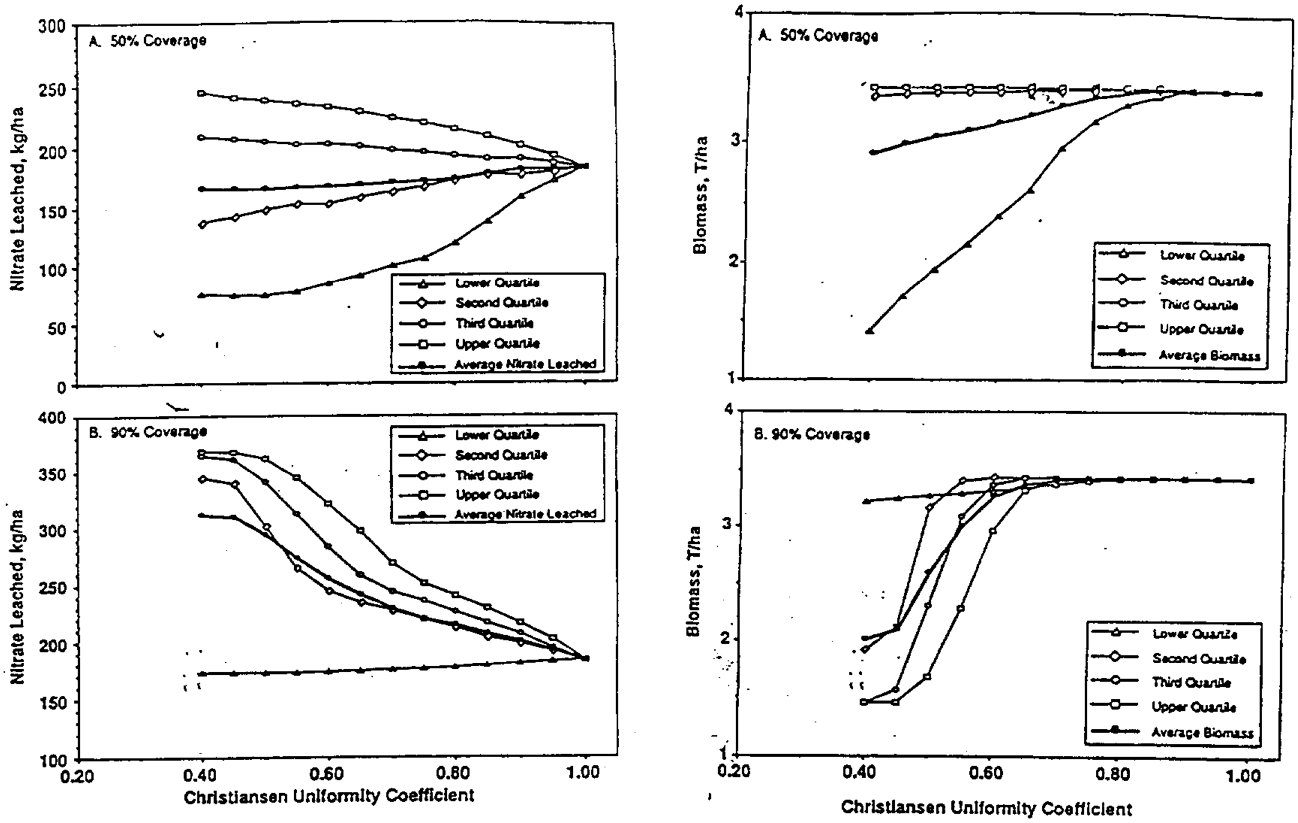


Figure 5.8. Effect of non-uniform water application on biomass accumulation: (a) 50% Coverage; (b) 90% Coverage; and on nitrate leaching: (a) 50% Coverage; (b) 90% Coverage

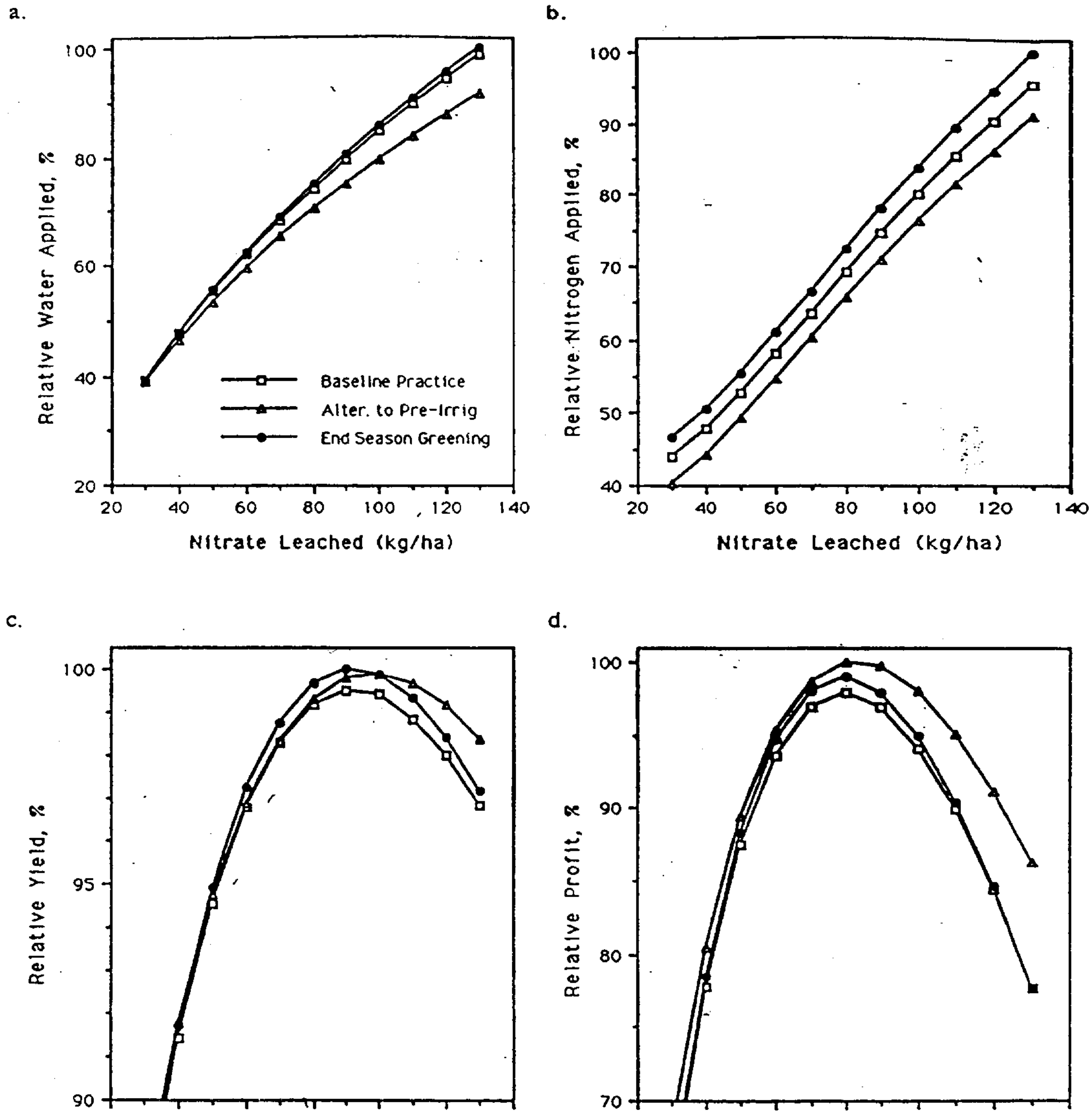


Figure 5.9. Effects of levels of nitrate leached beyond the crop root zone for different management practices on: (a) relative water applied; (b) relative nitrogen applied; (c) relative yield; (d) relative profit

CHAPTER VI. SALINITY MODEL APPLIED TO ALFALFA PRODUCTION

6.1. Introduction

Salinization due to imbalance between incoming and outgoing salts in irrigated lands is a continuing problem faced by irrigated agriculture. About 20 million ha of irrigated land in the world are affected by high salinity (Kovda, 1983). In California, nearly 1.8 million ha of irrigated cropland are affected by salt problems (Tanji,1990). In the west side of San Joaquin Valley in California, alone, about 0.31 million ha of irrigated land are affected by excessive salinity (San Joaquin Valley Drainage Program, 1990). California has a diverse and productive agricultural industry with about 289 commodities and one-ninth of the total U.S. farm cash receipts. However, in certain regions of California, farming practices have contributed to negative externalities such as nitrates and salts and other elements in surface and ground waters. Subsurface agricultural drainage water containing salts, trace elements and nitrates are known to affect surface and ground water quality in the Central Valley of California. These contaminants are problematic if the water is used as drinking water. High salt concentration also make such water problematic when it is used again in agriculture, and for other beneficial uses.

Management of salinity is important in both agricultural production and off-site impacts from agricultural drainage. Best Management Practices (BMP) have been suggested in the San Joaquin River Basin Plan as means of controlling non-point source pollution (NPS). The objective of this project is to assess the effectiveness of the proposed BMPs for control of agricultural NPS pollutants. In this study, a conceptual model, EPIC, is used to evaluate potentials for reduction and control of pollutants through BMPs. EPIC is able to model a comprehensive agronomic system. An agronomic system is modeled as a function of crops, soils, climate, irrigation, fertilization, and drainage. The details of EPIC can be obtained from Sharpely and Williams (1990).

Although EPIC has most of the components of an agronomic system, it does not have a salinity component. In this study, the salinity component was built into EPIC and incorporated with other parts of EPIC. Modeling of salinity involves three parts. The first part is to model salinity in the surface layer of an agricultural land. At the surface layer, the total water flow leaving the surface layer consists of surface runoff, lateral subsurface flow, and vertical deep percolation. The second part is to model salinity in other soil layers. In these other layers, the total water flow consists of lateral subsurface flow and downward percolation. The third part is to model the upward movement of salt due to surface soil water evaporation.

In addition to modeling salt movement in soil layers, the dissolution and precipitation of gypsum are also considered. Gypsum is one of the major contributors of dissolved mineral salts in waters from gypsiferous irrigated lands. In agricultural lands which contain gypsum, it has been observed that salinity in the soil and percolation increase beyond the expected limits from

ET concentration (Tanji, 1977). When gypsum interacts with water, it dissolves and increases the calcium and sulfate ions in the soil layers. During soil water evaporation, calcium and sulfate ions evapoconcentrate and may precipitate back to gypsum if the solubility product constant of gypsum is exceeded, consequently reducing the existing salt concentration in the soil layers. Modeling of gypsum was also built into EPIC in three parts and incorporated with other related components of EPIC. The first part is to model gypsum dissolution at the surface layer of a soil. The next part is to model gypsum dissolution in other soil layers. Finally, gypsum precipitation was modeled during soil water evaporation.

In the following subsections we present the details of these mathematical developments for salinity modeling.

6.2 Downward Salt Movement

The amount of soluble salt in runoff is estimated by considering the top 10 mm soil layer. The total amount of water leaving the layer is the sum of runoff, lateral subsurface flow and deep percolation. This can be expressed as

$$W = R + L + I \qquad (6.1)$$

where W represents the total amount of water lost from the first layer (mm), R is runoff (mm), L is lateral subsurface flow (mm) and I represents percolation (mm). The amount of salt associated with W is

$$S = W * C_S \qquad (6.2)$$

where S denotes salt mass lost with W from the first layer and C_S is the salt concentration in the first layer. At the end of the day, the mass of salt left in the layer is expressed as

$$SL = SL_O - S \qquad (6.3)$$

where SL represents the mass of the salt contained in the soil layer at the end of the day, and SL_O is the mass of the initial salt (at the beginning of the day) contained in the soil layer. The resultant salt concentration can be estimated by dividing the mass of salt by the water storage volume :

$$C_s' = C_s - C_s\left(\frac{W}{P_o - P_l}\right) \qquad (6.4)$$

where C_s' represents the concentration of salt at the end of a day, P_o is the soil porosity, and P_l is the wilting point water content (mm) for the soil layer. Equation (6.4) is a finite approximation for the following exponential equation (Sharpley and Williams, 1990).

$$C_s' = C_s * \exp\left(\frac{-W}{P_o - P_l}\right) \tag{6.5}$$

Thus, the mass of salt lost from the soil layer S can be calculated for any volume of water leaving the layer W by integrating equation (6.5). When this integration is performed, the following equation is obtained (Sharpley and Williams, 1990).

$$S = SL\left[1 - \exp\left(\frac{-W}{P_o - P_l}\right)\right] \tag{6.6}$$

Equation (6.6) gives the mass of salt lost from the soil layer due to the volume of water leaving the soil layer. The average concentration of salt for the day can be expressed as :

$$C_s = \frac{S}{W} \tag{6.7}$$

The masses of salt contained in runoff, lateral flow and percolation are estimated as the products of the corresponding volume of water and the concentration from equation (6.7). These can be expressed as :

$$R_s = C_s * R \tag{6.8}$$

$$L_s = C_s * L \tag{6.9}$$

$$I_s = C_s * I \tag{6.10}$$

where R_s represents the mass of salt in the runoff, L_s is the mass of salt in the lateral subsurface flow and I_s is the mass of salt in the percolation flow (salt that leaches from an upper to a lower layer). When salt leaching is computed for the other layers, except the first soil layer, surface runoff is not considered.

6.3. Upward Salt Movement

When water is evaporated from the soil, salt is moved upwards into the top soil layer by mass flow. The equation for estimating this salt transport is expressed as :

$$E_s = \sum_{l=2}^{n} EV_l * C_{s_l} \qquad (6.11)$$

where E_s represents the mass of salt moved from lower layers to the top layer by soil water evaporation, EV represents the amount of soil water evaporation. Subscript l refers to soil layers, and n represents the number of layers contributing to soil water evaporation.

Three subroutines were built into EPIC in order to model downward salt movement in the surface layer, in other soil layers except the surface layer, and upward salt movement due to soil water evaporation. In order to perform salinity simulation, initial salt distribution along the soil profile has to be known. These data can be obtained from the field.

6.4. Gypsum Dissolution

The time-dependent dissolution of gypsum is defined as (Kemper et. al., 1975) :

$$\frac{\partial C_g}{\partial t} = K(C_{gs} - C_g) \qquad (6.12)$$

where C_g represents the solution concentration at any time, C_{gs} is the solution concentration at gypsum saturation and K represents the gypsum dissolution coefficient.

Gypsum concentration at saturation C_{gs} is taken as 4% (g of gypsum/ g of soil) or 2.63 g/liter (Karajeh, 1991). Integrating equation (6.12) between t=0 when water enters the soil element and $t=t_c$ when water leaves the element will yield the following equation

$$-\ln\left(1 - \frac{C_g}{C_{gs}}\right) = Kt_c \qquad (6.13)$$

Keren and O'Connor (1982) conducted a gypsum dissolution study using soil samples amended with 2% and 4% gypsum under different flow velocities. From their study, they concluded that the right hand side of equation (6.13) can be expressed as :

$$Kt_c = \alpha\, t_c^{0.5} + \beta \qquad (6.14)$$

where α and β are coefficients of the linear function. Kemper et. al., (1975) expressed the time t_c as:

$$t_c = \frac{T}{V} \tag{6.15}$$

where T represents the thickness of the soil element and V is the actual flow velocity. The actual flow velocity is equal to Darcy velocity divided by soil porosity (v/P_0). Darcy velocity v is equal to flow flux W. Soil porosity P_0 can be assumed to be equal to the saturated moisture content of the soil element θ_S. Hence, gypsum dissolution coefficient can be expressed as:

$$K = \alpha \left(\frac{W}{T\,\theta_s} \right)^{0.5} + \beta \frac{W}{T\,\theta_s} \tag{6.16}$$

Keren and O'Connor (1982) performed laboratory tests on soil samples containing 2% and 4% gypsum. From their work, they concluded that $\beta = 0$ and α may be taken as:

$$\alpha = 1.2\,\text{hr}^{0.5} \quad \text{when} \quad 0\% \leq \text{gypsum} \leq 2\%$$

$$\alpha = 2.55\,\text{hr}^{0.5} \quad \text{when} \quad 2\% < \text{gypsum} \leq 4\%$$

Gypsum dissolution at any time can be obtained as (Karajeh, 1991) :

$$C_g(t) = K(t) * \theta(t) * C_g(t-1) \tag{6.17}$$

where (t) represents the current time and (t-1) represents the previous time.

Gypsum concentration is time dependent since the water flux, moisture content and consequently the dissolution coefficient change with time. The contribution of gypsum to soluble salts can be calculated as the gypsum concentration times the corresponding flow fluxes such as runoff, percolation and lateral subsurface flow. Note that for the surface layer, total water flux W is equal to the summation of runoff, percolation and the lateral subsurface flows. On the other hand, for the other soil layers except the surface layer, the total flux W is equal to the summation of percolation and lateral subsurface flow. We may express these as:

$$R_g = C_g * R \tag{6.18}$$

$$L_g = C_g * L \tag{6.19}$$

$$I_g = C_g * I \qquad (6.20)$$

where R_g represents the gypsum contribution to the soluble salt contained in the runoff, L_g is the gypsum contribution to the soluble salt contained in the lateral subsurface flow, and I_g is the gypsum contribution to the soluble salt contained in the percolation (the salt that leaches from upper to lower soil layers).

6.5. Gypsum precipitation

When soil evaporation occurs, the dissolved gypsum components in the soil water (calcium and sulfate ions) will evapoconcentrate and, if the solubility product constant of gypsum is exceeded, calcium and sulfate ions will precipitate and become gypsum again. This gypsum precipitation will reduce the existing soluble salt concentration in the soil profile. Gypsum precipitation due to the soil water evaporation can be expressed as:

$$G_p = \sum_{l=2}^{m} EV_l * C_{g,} \qquad (6.21)$$

where Gp represents the amount of gypsum which is precipitated as a result of the soil water evaporation, EV, occurring from lower layers to the top layer. Subscript l refers to soil layers and m represents the number of soil layers contributing to soil water evaporation.

EPIC was modified in order to consider the reactivity of gypsum in the soil profile. Three subroutines were built into EPIC in order to calculate gypsum dissolution in the surface layer, gypsum dissolution in the other layers, and gypsum precipitation due to the soil water evaporation. In order to start gypsum dissolution and precipitation calculations, initial gypsum concentration in the soil profile has to be known. This information can be obtained from the field data.

6.6. Model Calibration

The salinity-extended EPIC model was calibrated with 1986 alfalfa data obtained at the Fruita Research Center, CO, by Dr. Gordon Kruse, USDA-ARS, and his associates. The Fruita Research Center is located near Grand Junction. The entire Grand Valley of Colorado is underlain by the Mancos shale, a saline geological formation deposited under marine conditions. The shale is laden with gypsum crystals along with lesser amounts of other minerals and salts. Deep percolation and seeping waters dissolve some of these minerals and carry them into the shallow ground water which eventually flows into the Colorado River system (Champion et. al., 1991). The soil at Fruita Research Center is Youngston loam. In a typical pedon, the surface layer is loam or sand clay loam, about 11 cm thick. The underlying material, to a depth of 2.4 m, is stratified loamy fine sand, silt loam, silty clay loam and very fine sandy loam. The Fruita Research Center Project was designed to have six benches, each 61m by 61m. Each bench has two small basins, north and south. Six pairs of hydraulic weighing lysimeters are placed in six of the small basins. Each lysimeter is 1.52 m by 1.22 m by 1.22 m deep. The details of the lysimeters and their setup can be obtained from Kincaid et. al. (1979). The details of the experimental site can be obtained from Champion et. al. (1991).

The data obtained at the Fruita Research Center include weather, soil, irrigation, and harvesting data. Weather data consists of daily maximum and minimum temperatures, solar radiation, wind speed, and precipitation. Daily weather data were input into the revised model. Soil data consist of soil moisture and saturated soil extract EC_e. Irrigation data involve the dates and amounts of irrigation applied to the north plot, south plot and to the lysimeters. Harvesting data consist of dates and yields from the north plot, south plot and from the lysimeters.

In the calibration of the model, the data from one of the lysimeters referenced as "3NE lysimeter" were used. Alfalfa was planted in September 1985 and harvested three times in 1986 - June 6, July 17 and August 25-, yielding a total of 16.5 ton/ha (Kruse, 1993). The ground water table was kept constant at 1.05 m from the soil surface during the alfalfa growing season in lysimeter 3NE (Kruse et al., 1993). The lysimeter 3NE was surface irrigated with the water supplied from Colorado River which had an average EC_w of 0.65 dS/m during summer time. Alfalfa in lysimeter 3NE received about 612 mm irrigation water from April 15, 1986 to September 10, 1986. Table 6.1. shows the irrigation application dates and rates. Crop growth parameters of alfalfa in EPIC were synthesized from the literature.

Total alfalfa yield, yield from each harvest, total salt in the soil profile (and/or average soil saturation extract EC_e) and profile salt distribution (soil saturation extract EC_e profile) were the primary variables in the calibration procedure.

In order to find total dissolved salt (t/ha) in a soil layer from a given soil saturation extract EC_e in that soil layer, the following linear relation is used.

$$\text{TS (t/ha)} = EC_e * 640.\ (\text{g/m}^3) * MC * ZT\ (\text{m}) * 10^4\ (\text{m}^2/\text{ha}) / 10^6\ (\text{g/t}) \qquad (6.22)$$

where TS represents total salt in the soil layer, ZT is the thickness of the soil layer and MC represents the moisture content of the soil layer.

TABLE 6.1. IRRIGATION DATA FOR LYSIMETER 3NE, 1986 Alfalfa (Kruse, 1993)

Irrigation date	Irrigation rate (mm)
4-15-1986	50.80
5- 2-1986	78.00
5-23-1986	102.36
6-12-1986	81.28
6-26-1986	82.55
7-15-1986	81.28
7-31-1986	69.34
8-15-1986	100.08
9- 9-1986	70.87
9-22-1986	79.5

In our calculations, it was assumed that:

EC_e (dS/m) * 640. = salt (mg/l) or (g/m^3) if $EC_e < 5.0$
EC_e (dS/m) * 680. = salt (mg/l) or (g/m^3) if $5.0 < EC_e < 6.0$

The total soluble salts in the soil profile is the sum of the total salts in the soil layers. In the model calculations the soil depth of 0.9m was divided into three soil layers of 0.3m thickness.

The total alfalfa yield obtained from the calibration run was 14.7 t/ha which is 1.8 ton/ha less than the observed total yield of 16.5 t/ha from three cuttings. Figures 6.1a, 6.1b and 6.1c show respectively the simulation of observed alfalfa yield (t/ha) from each of the three harvests, total soluble salts in the soil profile (t/ha), and average profile EC_e (dS/m) for the model calibration runs. Yields from three alfalfa cuttings were calibrated reasonably well. In contrast, it was not possible to fit the total mass of soluble salts nor the average soil salinity in the later portions of the growing season.

Figures 6.2a, 6.2b and 6.2c show respectively the calibration runs for measured profile soluble salts at the beginning, middle and end of the 1986 alfalfa growing season. Similarly, figures 6.3a, 6.3b, and 6.3c show respectively the simulation of measured profile ECe to a soil depth of 0.9m at the beginning, middle and end of alfalfa growing season for the model calibration. The simulated soluble salts and ECe in the lowest soil depth at the end of the growing season did not fit very well with observed data. A simple explanation is not available for why the salinity in the soil depth immediately above the water table (maintained at 1.05 m depth) should be substantially less than at the beginning or middle of the growing season.

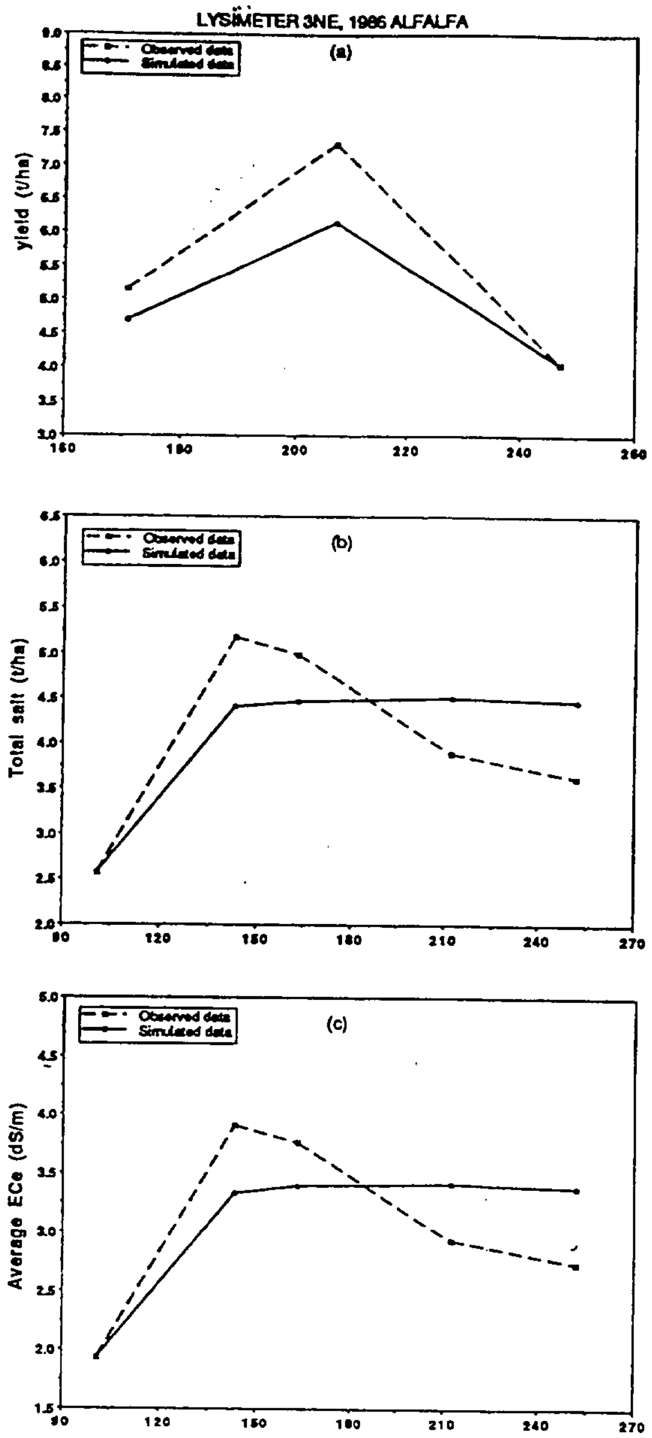


FIG.6.1 CALIBRATION RUN : Comparison of observed and simulated (a) yield from each harvest; (b) total salt in the soil profile; (c) average soil ECe, for model calibration.

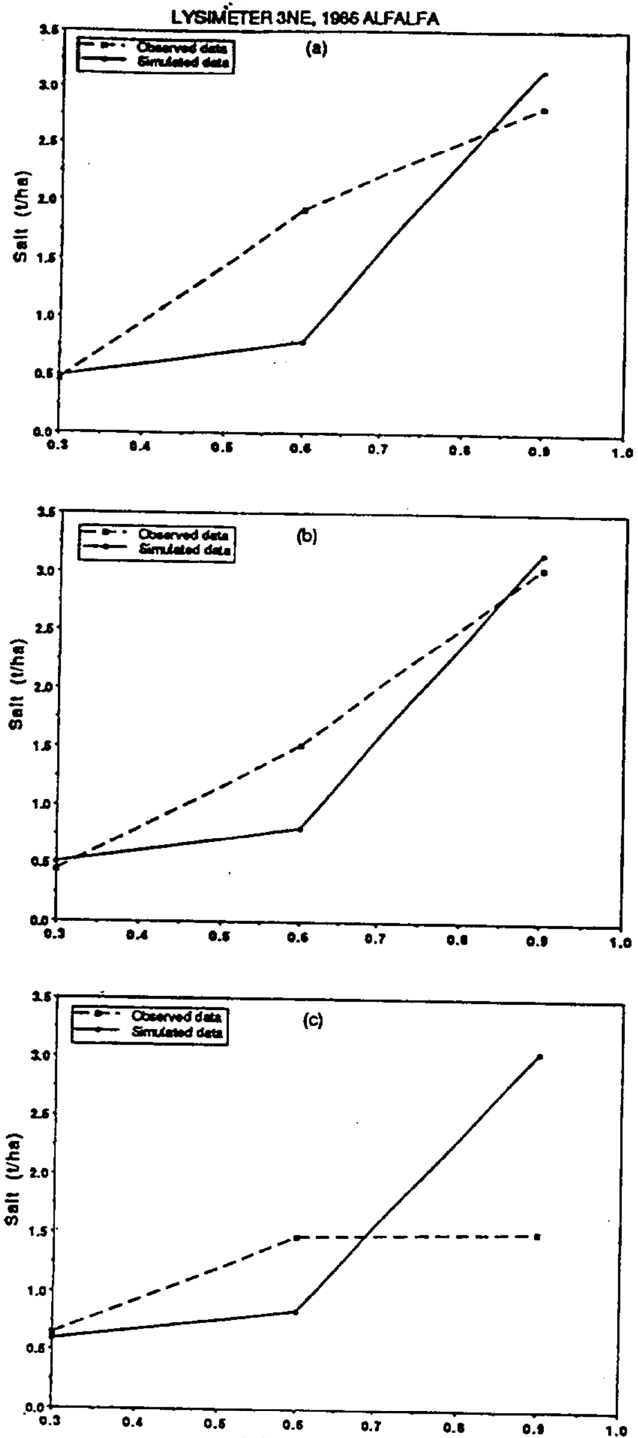


FIG.6.2 CALIBRATION RUN : Simulation of salt profile along the soil depth (a) at the beginning (May 23); (b) at the middle (June 12); (c) at the end (September 9) of alfalfa growing season.

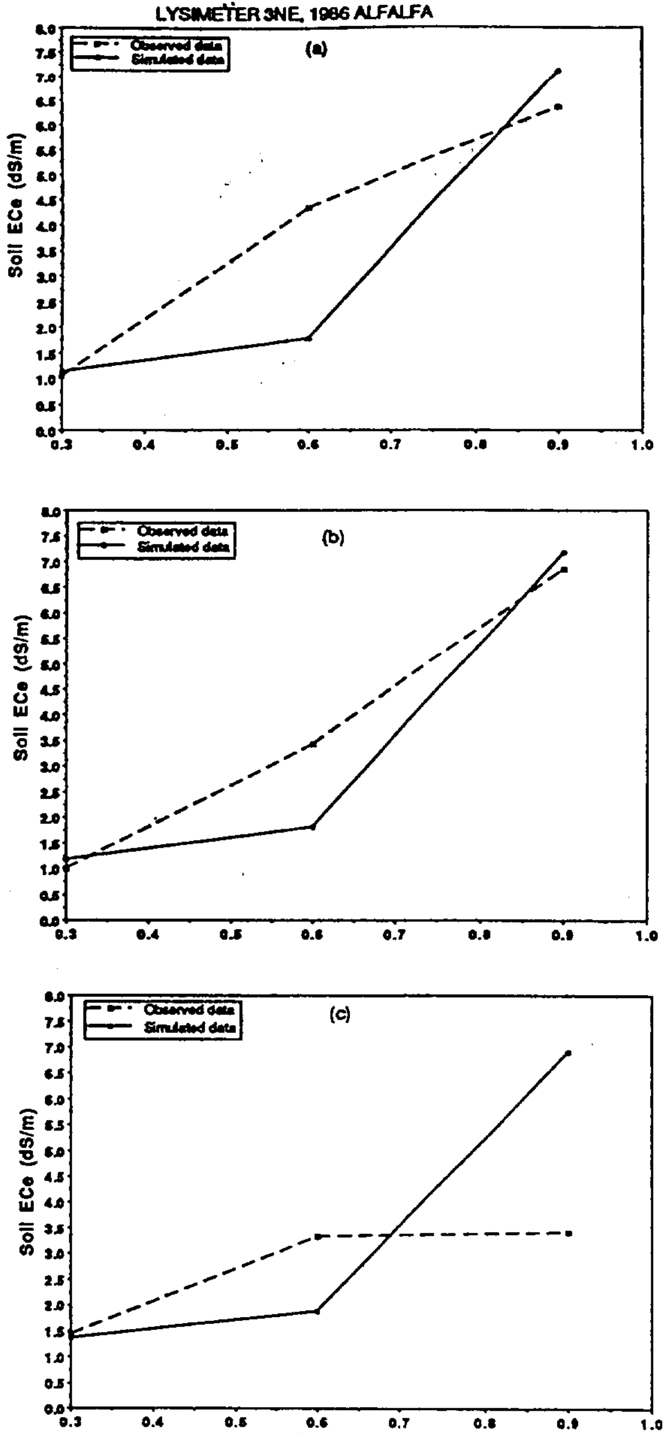


FIG.6.3 CALIBRATION RUN : Simulation of ECe profile along the soil depth (a) at the beginning (May 23); (b) at the middle (June 12); (c) at the end (September 9) of alfalfa growing season

The major calibrated model parameters which affect the alfalfa yield and soil salinity are wilting point, field capacity, saturated hydraulic conductivity, nitrate concentration, labile P concentration, biomass energy ratio, seeding rate, C50 (salinity at which crop yield is reduced 50%), PECE (empirical exponential curve fitting parameter for salinity-crop yield relationships) and initial gypsum concentration in the soil profile. Since some of these data were available on these parameters, estimated values had to be input into the model.

Tables 6.2 and 6.3 give the calibrated values for soil and crop parameters, respectively. The calibrated values of these parameters are within the ranges suggested in the literature.

TABLE 6.2. CALIBRATED VALUES OF SOIL PARAMETERS

	Soil Layer Depth (m)		
	0-0.30	0.30-0.60	0.6-0.90
Wilting Point (m/m)	0.116	0.120	0.059
Field Capacity (m/m)	0.398	0.418	0.359
Sat. Conductivity (mm/hr)	2.500	5.500	8.200
Nitrate Consent. (g/m^3)	16.00	11.00	9.000
Labile P Consent. (g/m^3)	32.00	16.00	13.00
Initial Gypsum Content. (g/L)	.0011	.0046	.0088

TABLE. 6.3. CALIBRATED VALUES OF CROP PARAMETERS

Biomass-energy ratio	50.00
Seeding Rate (kg/ha)	50.00
C50 (dS/m)	8.750
PECE	3.000

6.7. Model Validation

The calibrated values of soil and crop parameters (Tables 6.2 and 6.3) were used to validate the EPIC model extended for salinity considerations. For model validation , the observed 1988 alfalfa data obtained from the Fruita Research Center were used. The daily 1988 weather data served as input data into the calibrated model. Data from lysimeter "3NE" , used for model calibration (1986), was also chosen for model validation. Alfalfa was harvested three times in 1988- June 8, July 14 and August 24-, yielding total of 17.7 ton/ha (Kruse, 1993). During the alfalfa growing season, the ground water table was kept constant at 1.05 m (Kruse, et al., 1993). Alfalfa in lysimeter 3NE received 841 mm irrigation water from April 20, 1988 to September 16, 1988. The irrigation water supplied from the Colorado River had an average EC_w of 0.65 dS/m during the summer time. The 1988 irrigation data for this lysimeter are given in Table 6.4.

TABLE 6.4. IRRIGATION DATA FOR LYSIMETER 3NE, 1988 Alfalfa (Kruse, 1993)

Irrigation date	Irrigation rate (mm)
4-20-1988	129.54
5- 9-1988	71.12
5-26-1988	152.40
6- 9-1988	86.36
6-14-1988	111.76
6-30-1988	71.12
7-19-1988	76.20
8- 9-1988	76.20
9-15-1988	66.04

In the validation run, the model calculated a total alfalfa yield of 16.0 ton/ha , which is a reasonable estimation since the observed yield for three cuttings was 17.7 ton/ha. The difference between estimated and observed yield is 1.7 ton/ha which is only 9.6 % less than the actual yield. Figure 6.4a shows the comparison between observed and simulated alfalfa yield from each of the three harvests during the 1988 validation run. The model under predicted the yield for the first cutting but gave excellent results for the second and third cuttings.

Figures 6.4b and 6.4c respectively show the simulation of total soluble salts and average soil EC_e in the 0.9 m soil profile during the 1988 growing season. The model gave simulated soil salinity levels close to observed data, except at the end of the growing season. Note that soil samples were not taken from June 8th to September 20th, and so the salt contents and distribution in the soil profile during this period is unknown. The model calculated much higher salinities than measured values at the end of the growing season. A similar discrepancy was noted in the calibration run.

Overall, satisfactory results were obtained in the model calibration and validation runs.

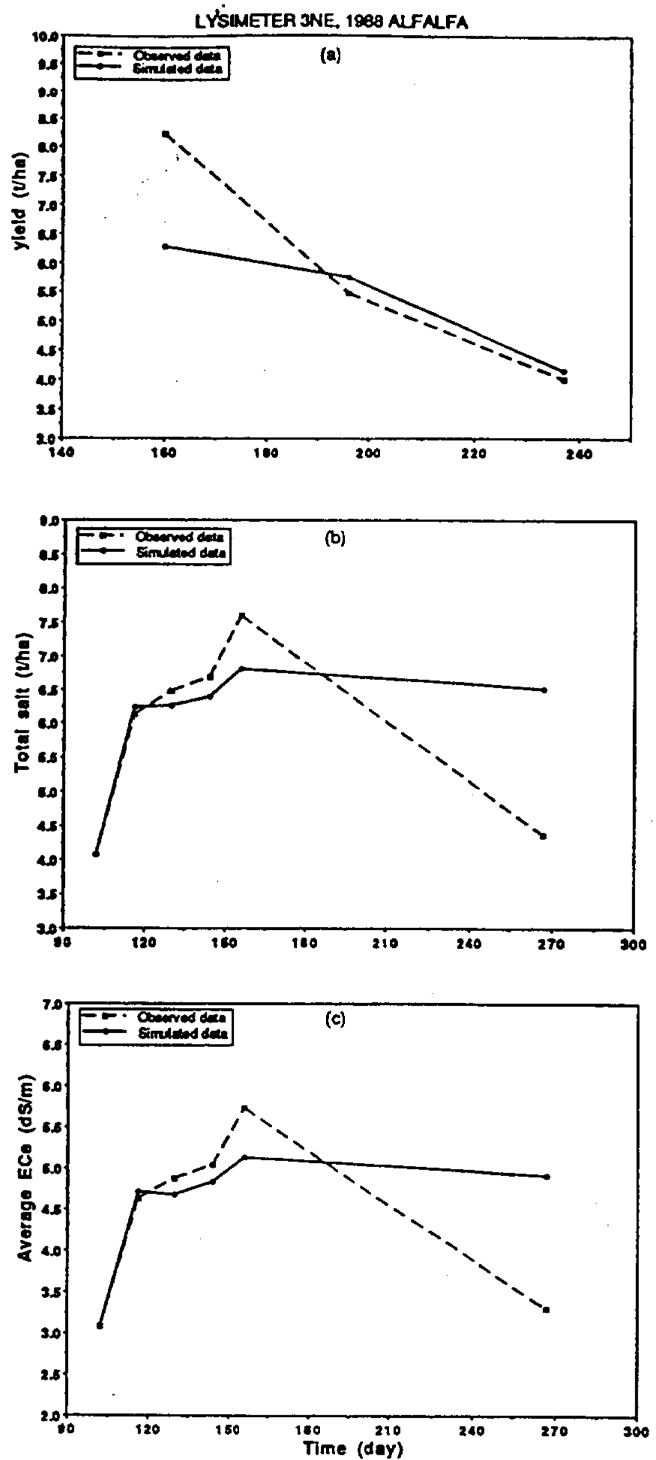


FIG.6.4. VALIDATION RUN : Comparison of observed and simulated (a) yield from each harvest; (b) total salt in the soil profile; (c) average soil ECe, for model validation.

6.8. Model Application

The model, which was calibrated with the 1986 alfalfa data from the Grand Valley in Colorado and validated with the 1988 alfalfa data from the same location, shall now be applied to simulate alfalfa grown in the Imperial Valley of California. Simulations are made for total alfalfa yield (t/ha), yield from each harvest (t/ha), total soluble salts in the soil profile (t/ha) (or average soil profile EC_e (dS/m)), and soluble soil salt concentration (or soil saturation extract EC_e) along the soil depth of 1.2m.

The main crop in the Imperial Valley is alfalfa which has a comparatively high consumptive water use. Reduction in applied irrigation water for alfalfa in this valley will save significant water that can be potentially transferred to urban use. For example, elimination of a single 4.8- inch irrigation will save about 74,400 acre- feet of water (Robinson et. al, 1992). Robinson et al (1992) are investigating the relation between water use reduction for alfalfa and resulting alfalfa yield. One of the main objectives of their study was to determine the amount of irrigation water reduction (deficit irrigation) that can be tolerated by alfalfa.

Robinson et. al. (1992) performed four different irrigation treatments - optimum check, minimum stress, short stress and long stress (Table 6.5.). The depths of irrigation water (mm) applied during each treatment are given in Table 6.6. For the optimum check treatment, alfalfa received a total of 1269 mm irrigation water. For the minimum stress, short stress and long stress treatments, alfalfa received a total of 1203 , 991 and 821 mm irrigation water, respectively. The irrigation water was supplied from the Colorado River which has an average EC_w of 1.25 dS/m (850 mg/l) (Khalid Bali, 1993).

The experimental site located on the UC Desert Research and Extension Center at El Centro in the Imperial Valley is a Holtville clay extending 60 to 90 cm in depth overlying a sandy clay. The water table in this valley fluctuates around 1.70 m (Robinson et al., 1992).

Alfalfa was planted on October 23, 1990 and the first harvest was on April 17, 1991. Seven additional harvests followed for the optimum check and minimum stress treatments in 1991. The short stress treatment had six harvests and the long stress treatment had five harvests in 1991 (Robinson et al., 1992).

Daily weather data for 1990 and 1991 in the Imperial Valley were input into the model. Initial average moisture content (in October 23, 1990) was assumed to be 0.2 as suggested by Khalid Bali (1993). The EC_e profile distribution on January 2, 1991 was assumed to be the initial salt distribution for October 23, 1990. Other related data can be obtained from Robinson et al.(1992). Since the soil at this experimental site does not contain significant gypsum (Khalid Bali, 1993), no initial gypsum content along the soil profile was assumed.

TABLE 6.5. IRRIGATION TREATMENTS (Robinson et. al. 1992)

Irrigation Treatment	Number of Irrigations			
	July	August	Septem.	October
Optimum check	3	2	2	2
Minimum stress	3	1	1	2
Short stress	3	0	0	2
Long stress	0	0	0	2

TABLE 6.6. IRRIGATION DEPTHS (mm) for EACH TREATMENT

Irrigation Date	Optimum	Minimum	Short stress	Long stress
3-18-1991	97.54	97.54	97.54	97.54
4- 8-1991	68.99	68.99	68.99	68.99
4-29-1991	95.30	95.30	95.30	95.30
5-13-1991	89.98	89.98	89.98	89.98
5-28-1991	98.88	98.88	98.88	98.88
6-10-1991	92.18	92.18	92.18	92.18
6-24-1991	76.55	76.55	76.55	76.55
7- 3-1991	61.05	62.03	62.03	
7-22-1991	98.42	93.36	85.72	
7-30-1991	60.14	48.01	51.53	
8-19-1991	121.25	111.39		
8-29-1991	53.06			
9- 9-1991	65.55	103.31		
9-25-1991	69.32			
10- 8 1991	54.85	105.37	117.22	141.26
10-29-1991	65.96	60.30	55.25	60.50

The EPIC model calibrated and validated with Colorado data was applied to simulate total alfalfa yield under each irrigation treatment described above. Table 6.7. summarizes the comparison between observed and simulated total alfalfa yield for each irrigation treatment. The total alfalfa yields were satisfactorily simulated for each treatment. The difference between observed total yield and simulated total yield is less than 10 %.

Leaf expansion, final leaf area index, and leaf duration are known to be reduced by stresses (Acevedo et al., 1971 : Eik and Hanway, 1965). Hence, in model calculations, maximum leaf area index was reduced for stress conditions.

TABLE .6.7. COMPARISON OF OBSERVED AND SIMULATED TOTAL ALFALFA YIELD (t/ha)

Treatment	Observed	Simulated	Difference	(%)
Optimum check	12.51	11.50	1.01	- 8.1
Minimum stress	11.64	10.50	1.14	- 9.8
Short stress	8.95	9.50	0.55	+ 6.2
Long stress	6.66	6.30	0.36	- 5.4

Figures 6.5a, 6.5b and 6.5c show respectively a comparison of observed and simulated yield from each harvest for the optimum check treatment and its corresponding total soluble salts in the soil profile and the average soil EC_e. The eight cuttings of alfalfa were closely simulated except the second, third and fourth cuttings. Both total soluble salts and average profile ECe were reasonably well estimated except at the end of the growing season.

Figures 6.6a, 6.6b and 6.6c show respectively the simulation of total soluble salts on June 4, September 4 and October 16, 1991 for the optimum check treatment, and figures 6.7a, 6.7b, and 6.7c give respectively the soil EC_e profile along the soil depth of 1.2m. Since the relationship between salt quantity (t/ha) and EC_e (dS/m) is linear as expressed in equation (6.22), the change in the behavior of these variables in time and space should be the similar. The results show that surface soil salinity is slightly over predicted by the model. In contrast, salinities in lower soil depth increments were reasonably well simulated.

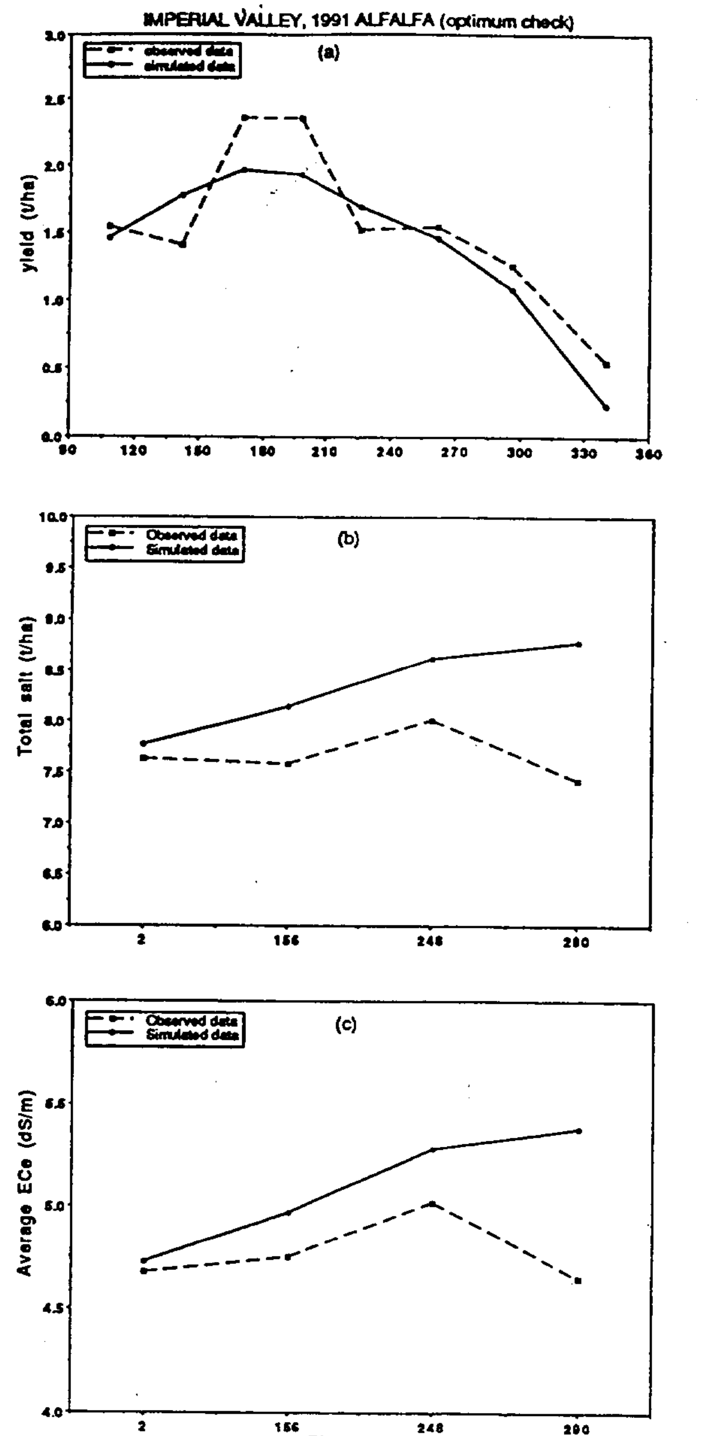


FIG.6.5. Comparison of observed and simulated (a) yield from each harvest; (b) total salt in the soil profile; (c) average soil ECe, under optimum check treatment.

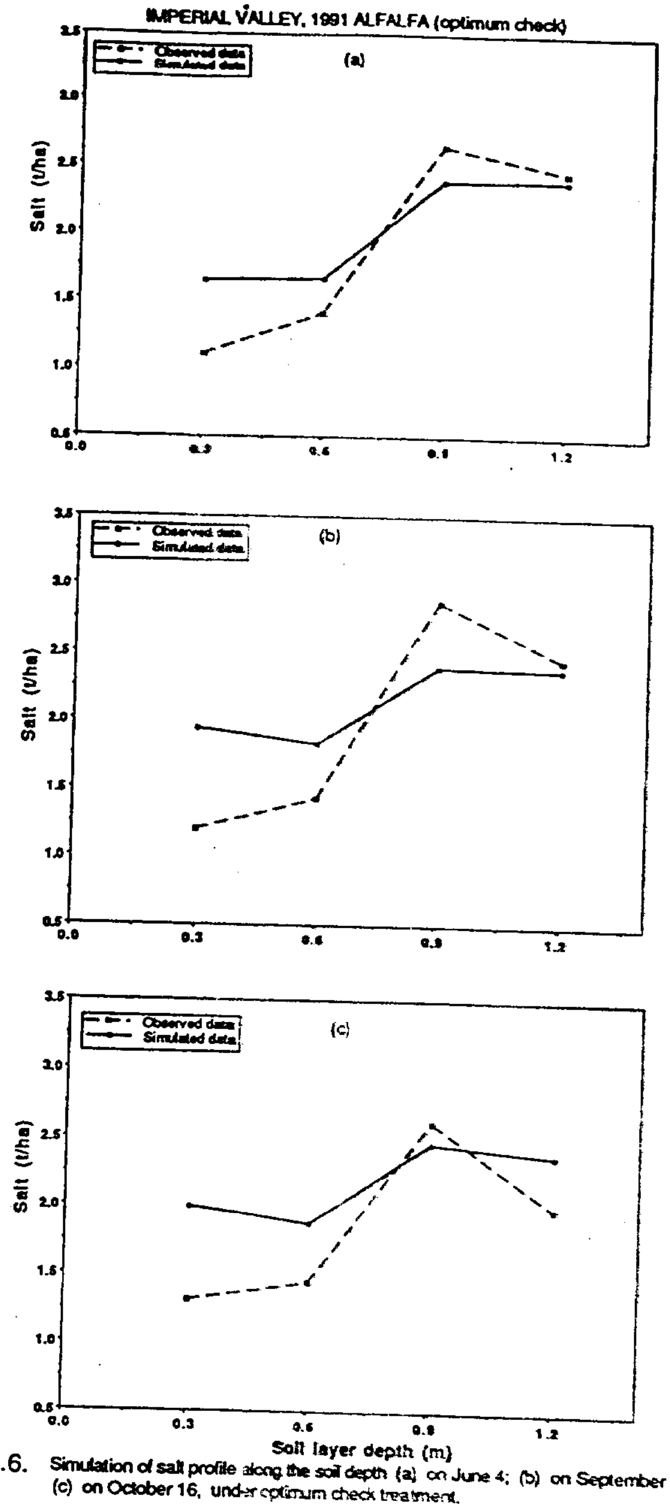


FIG.6.6. Simulation of salt profile along the soil depth (a) on June 4; (b) on September 4; (c) on October 16, under optimum check treatment.

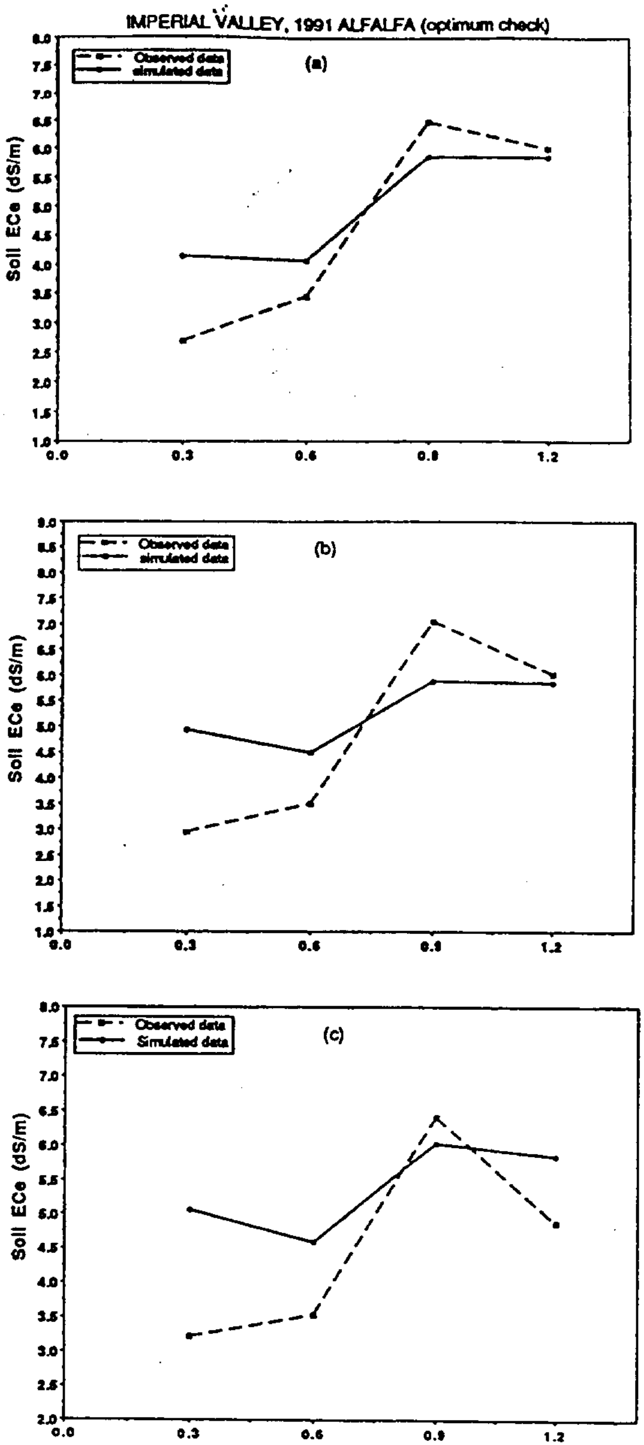


FIG.6.7. Simulation of ECe profile along the soil depth (a) on June 4; (b) on September 4; (c) on October 16, under optimum check treatment.

Since the observed salinity data are given in terms of soil saturation extract EC_e (dS/m), we will present only the simulation of EC_e in time and space for the stress treatments for brevity's sake.

For the minimum stress treatment, figures 6.8a and 6.8b show the comparison of observed and simulated yield from each of the eight cuttings and average soil EC_e, respectively. As in the optimum check treatment, yields of alfalfa cuttings were closely simulated except for the third and fourth cuttings. The average soil ECe was also closely simulated. Figures 6.9a, 6.9b and 6.9c show more details on profile soil EC_e to the 1.2 m depth for June 4, September 4 and October 16, 1991, respectively, for the minimum stress treatment. The model satisfactorily simulates EC_e by profile depth.

For the short stress treatment, figure 6.10a shows the simulation of observed alfalfa yield from each of the six harvests. The short stress treatment was started in August, 1991. It can be seen that the model estimates the observed yield reasonably well until the beginning of the imposed stress. The deviation noted for the fifth cutting may be because the model uses plant growth parameters obtained under optimal conditions. Figure 6.10b shows the simulation of average soil EC_e (dS/m) that fits observed data quite well except for the fourth soil salinity measurement.. Figures 6.11a, 6.11b and 6.11c respectively show the profile soil EC_e to a soil depth of 1.2 m for June 4, September 4 and October 16, 1991 for the short stress treatment. The simulated EC_e profile on June 4 is quite satisfactory (Fig.6.11a). After the onset of imposed stress in June, the simulated profile ECe diverges in the 0.9 m soil depth. It seems that the simulation of profile EC_e becomes more difficult as the stress is prolonged (compare Figures 6.11a, 6.11b, and 6.11c). Mention of fluctuating water table at the 1.2 m depth was made by Robinson et al. (1992) which would affect profile soil salinity.

For the long stress treatment, figure 6.12a shows the simulation of observed alfalfa yield for each of the five harvests. The long stress treatment was started in July 1991. The model under predicted the third cutting and over predicted the fourth cutting. Figure 6.12b shows the comparison of observed and simulated average soil EC_e, and it can be seen that the model simulates average soil EC_e reasonably well in the upper root zone. Figures 6.13a, 6.13b and 6.13c show respectively the simulation of profile soil EC_e to a soil depth of 1.2m for June 4, September 4 and October 16, 1991 for the long stress treatment. The simulated EC_e profile on June 4 is quite satisfactory (see Fig.6.13a). This is because the stress was initiated after June 1991. However, the simulated EC_e profile on September 4 and October 16 show increasing divergence in the 0.9 m soil depth. It can be concluded that when the stress period gets prolonged the estimation of EC_e profile by the model becomes more difficult.

In summary, the EPIC model extended for salinity can simulate total yield, yield from each harvest, total soluble salts in the soil profile and profile soil EC_e quite satisfactorily under optimum check and minimum stress treatments. The model is not capable of accurately simulating the yield from each harvest and soil EC_e profile for the short and long stress treatments. However, the model can estimate total yield and total soluble salts under short and long stress treatments reasonably well. The long-term impacts of buildup in soil salinity under deficit irrigation needs to be considered for sustainable irrigated agriculture.

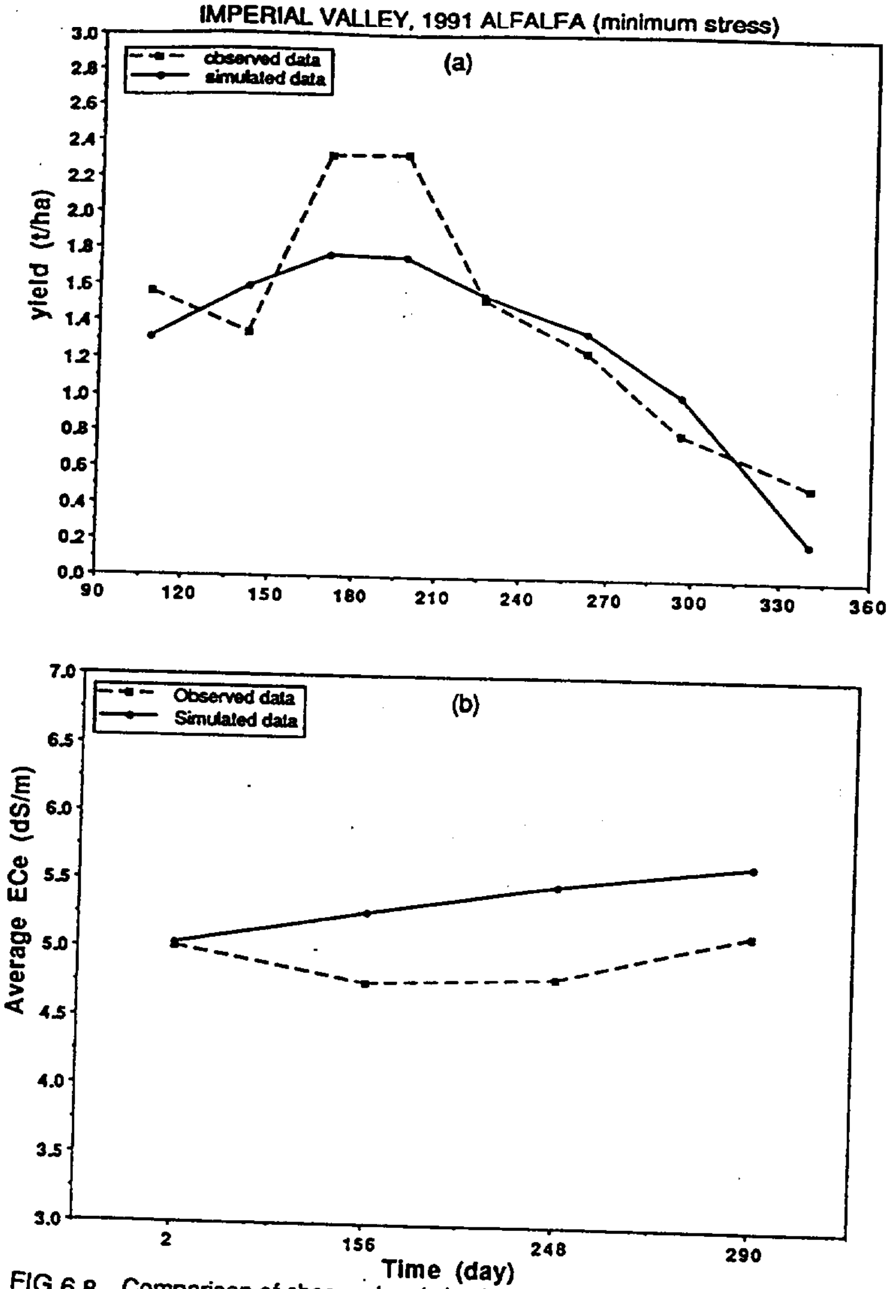


FIG.6.8. Comparison of observed and simulated (a) yield from each harvest; (b) average soil ECe, under minimum stress treatment.

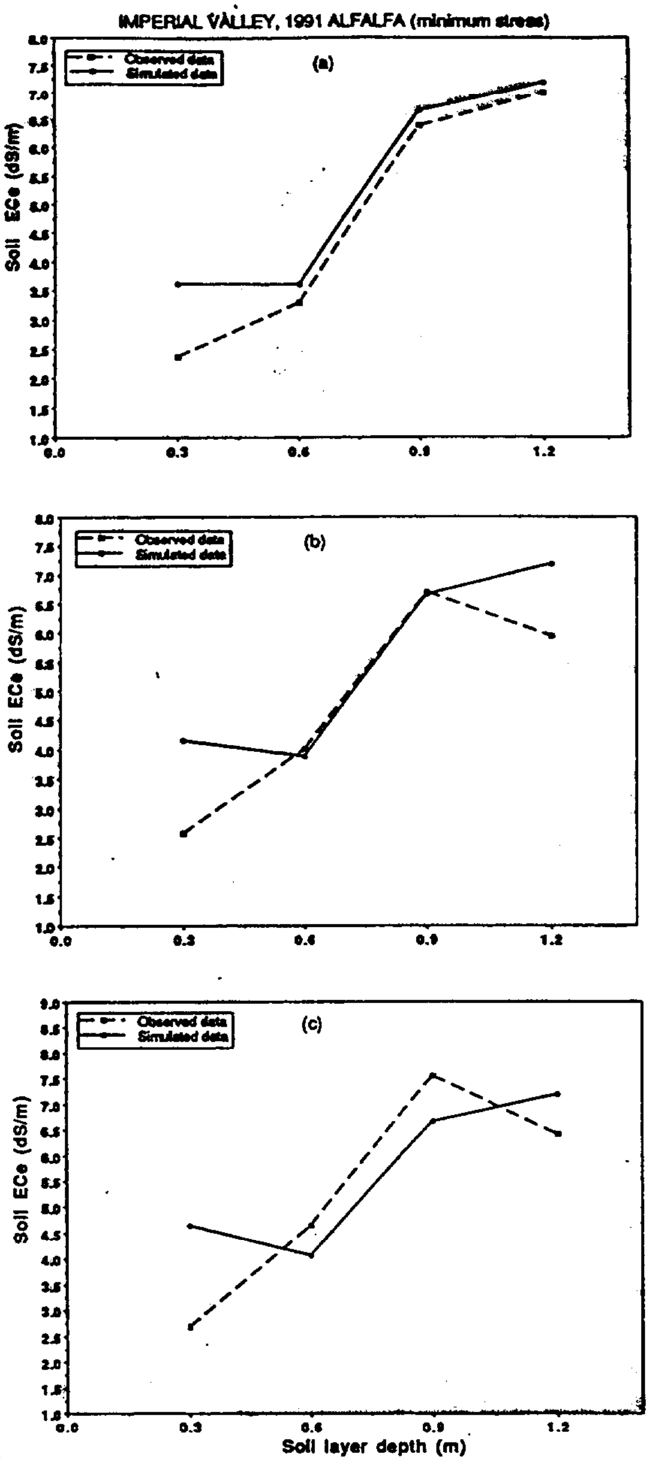


FIG.6.9. Simulation of ECe profile along the soil depth (a) on June 4; (b) on September 4; (c) on October 16, under minimum stress treatment.

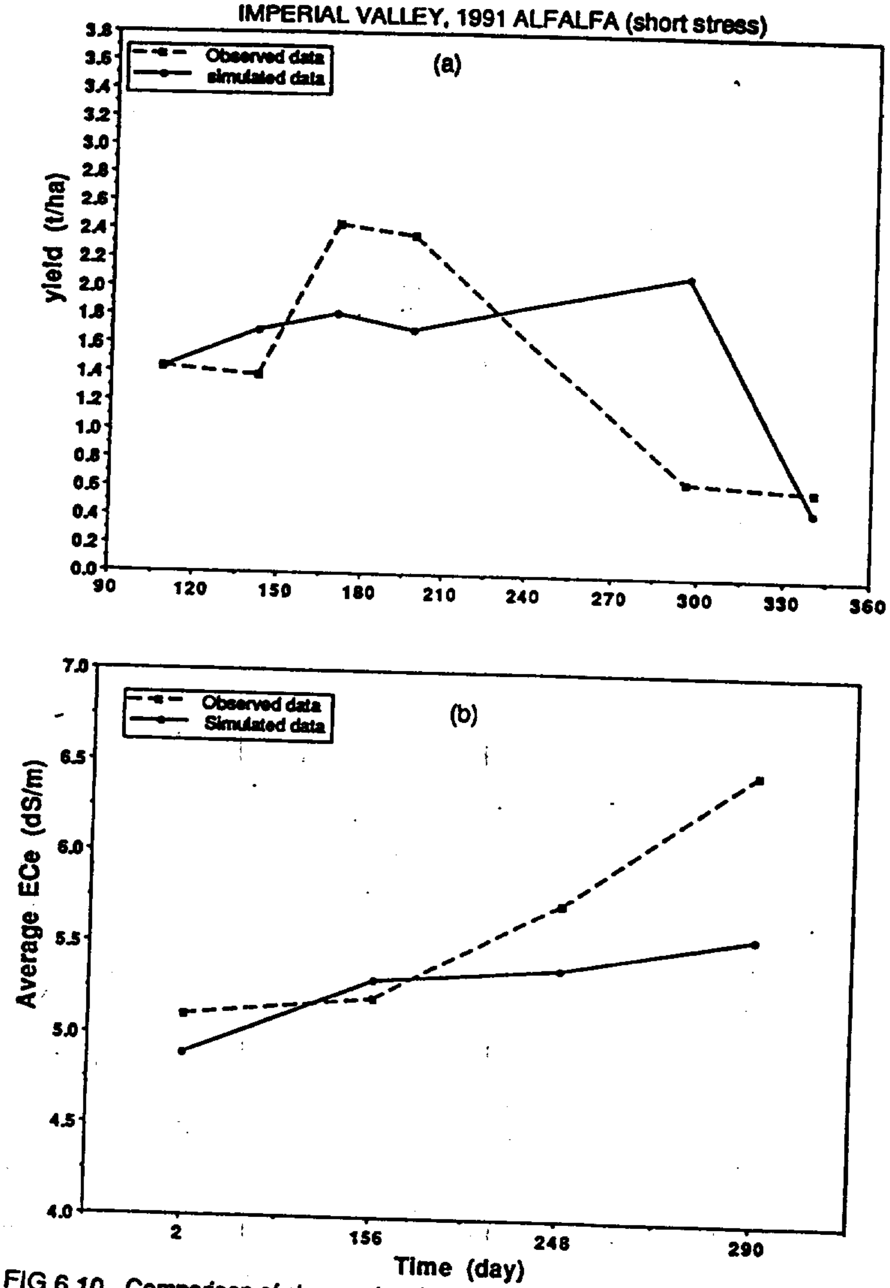


FIG.6.10. Comparison of observed and simulated (a) yield from each harvest; (b) average soil ECe, under short stress treatment.

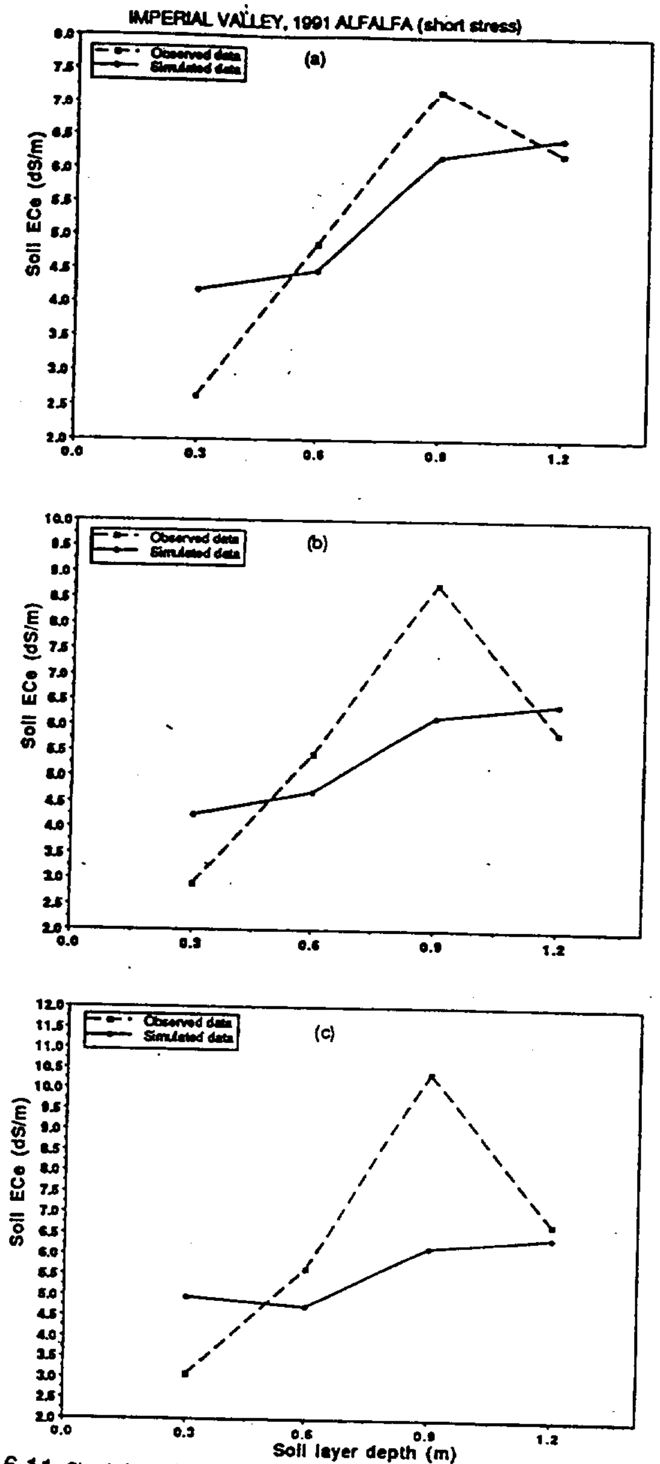


FIG.6.11. Simulation of ECe profile along the soil depth (a) on June 4; (b) on September 4; (c) on October 16, under short stress treatment.

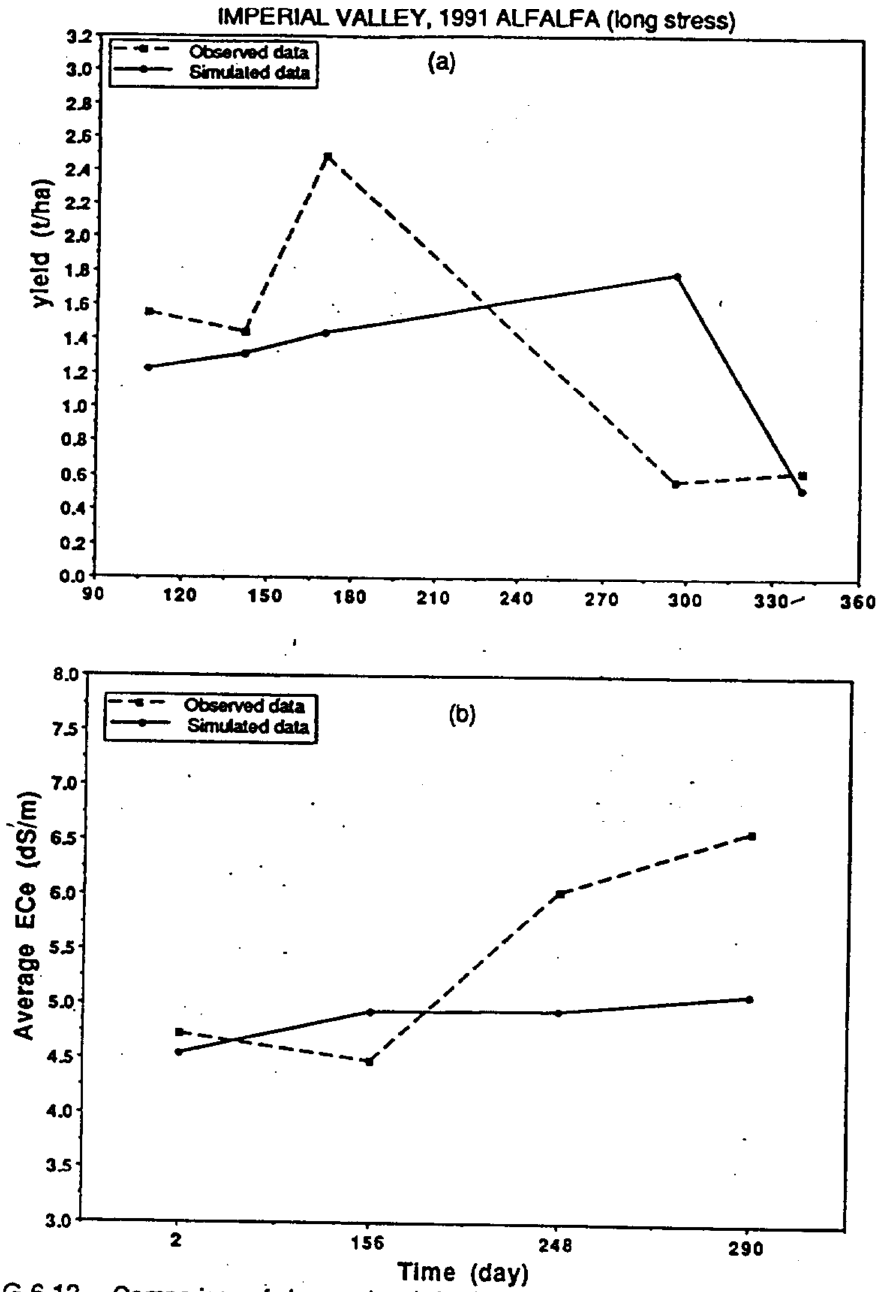


FIG.6.12. Comparison of observed and simulated (a) yield from each harvest; (b) average soil ECe, under long stress treatment.

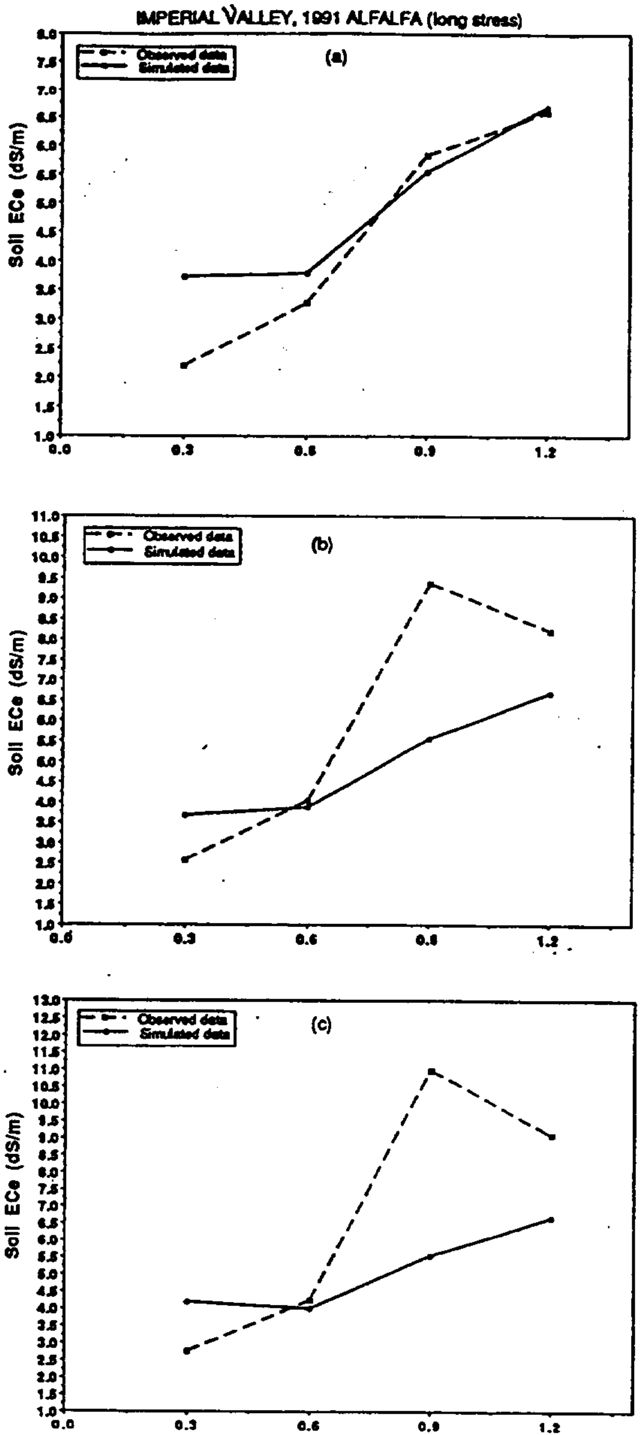


FIG.6.13. Simulation of ECe profile along the soil depth (a) on June 4; (b) on September 4; (c) on October 16, under long stress treatment.

6.9. Model Sensitivity Analysis

A sensitivity analysis was performed in order to investigate the effects of change in salt concentration in irrigation water on total alfalfa yield under the different irrigation treatments described in the previous section. Table 6.8 shows the results of this analysis. It can be seen that an increase in salt concentration in irrigation water results in a decrease in total alfalfa yield under all the irrigation treatments.

TABLE 6.8. COMPARISON OF TOTAL ALFALFA YIELDS (t/ha)
(under different salt concentrations in irrigation water, mg/l)

Treatment	$C_{ir} = 425$	$C_{ir} = 850$	$C_{ir} = 1700$	$C_{ir} = 3400$
Optimum check	11.70	11.50	10.80	10.00
Minimum stress	10.70	10.50	10.00	9.50
Short stress	9.60	9.50	8.90	8.60
Long stress	6.40	6.30	6.00	5.70

6.10. Economic Analysis

This section evaluates the results from the previous section in an economic framework. Alfalfa production in the Imperial Valley for 1991 under the four different irrigation treatments and four different salt concentrations in irrigation water (from Table 6.8) is the basis for the economic analysis. Additionally, following the economic approach from Robinson et al (1992), seven alfalfa output price levels will be used. These levels are from $130/ton to $70/ton at $10/ton increments. The hypotheses are as follows: As salt concentrations in irrigation water increase, profits should decline; and the more stressed the alfalfa with deficit irrigation, the less return to farmers in profits. The later situation is to determine how much farmers should be compensated (the loss in profits due to irrigation treatments other than the optimum) to deficit irrigate their crop. Payment would come in the form of dollars from urban water users for water given up in agricultural use.

The cost analysis is based upon the surveys of growers who listed their costs for input items presented in "Guidelines to Production Costs and Practices" Circular 104-F Imperial County

1991-1992 by Cooperative Extension Staff, University of California (Robinson et al, 1992). The following Table 6.9 shows the costs used in this analysis:

Table 6.9. Alfalfa Production Costs (Robinson et al, 1992)

	Custom Rate($/Ac)	Cost($/Ac)	Labor($)
Weed Control	4.90	24	
Irrigation		11.5/AF	3.23/AF
Fertilization	6.00		
Insect Control	4.90	11.50	
Land Rent		190	
Amortization	273/3		
Swather	7.50		
Rake	4.50		
Bale	10.50/ton		
Haul & Stack	0.25/bale with 16 bales/ton		

The profit analysis is based on the costs of production and the total revenue from seven different output prices for alfalfa. The following four tables (6.10 - 6.13) display the profits for each of the four irrigation treatments. The rows of each table are the four different concentrations of salt in the irrigation water. The seven columns of each table correspond to the output prices of alfalfa in $/ton.

Table 6.10. Optimum Irrigation

Profits for 7 levels of output price (per hectare)

salt conc.	$130/t	$120/t	$110/t	$100/t	$90/t	$80/t	$70/t
425	$731	$614	$497	$380	$263	$146	$29
850	$708	$593	$478	$363	$248	$133	$18
1700	$627	$519	$411	$303	$195	$87	$-21
3400	$534	$434	$334	$234	$134	$34	$-66

Table 6.11. Minimum Stress Irrigation

Profits for 7 levels of output price (per hectare)

salt conc.	$130/t	$120/t	$110/t	$100/t	$90/t	$80/t	$70/t
425	$629	$522	$415	$308	$201	$94	$-13
850	$606	$501	$396	$291	$186	$81	$-24
1700	$548	$449	$348	$248	$148	$48	$-52
3400	$491	$396	$301	$206	$111	$16	$-79

Table 6.12. Short Stress Irrigation

Profits for 7 levels of output price (per hectare)

salt conc.	$130/t	$120/t	$110/t	$100/t	$90/t	$80/t	$70/t
425	$492	$396	$300	$204	$108	$12	$-84
850	$480	$385	$290	$195	$100	$5	$-90
1700	$411	$322	$233	$144	$55	$-34	$-123
3400	$377	$291	$205	$119	$33	$-53	$-139

Table 6.13. Long Stress Irrigation

Profits for 7 levels of output price (per hectare)

salt conc.	$130/t	$120/t	$110/t	$100/t	$90/t	$80/t	$70/t
425	$148	$84	$20	$-44	$-108	$-172	$-236
850	$137	$74	$11	$-52	$-115	$-178	$-241
1700	$102	$42	$-18	$-78	$-138	$-198	$-258
3400	$68	$11	$-46	$-103	$-160	$-217	$-274

As shown, the profits to farmers are greatly affected by salt concentration level in the irrigation water. The magnitude to which profits are affected differs depending on the price of output and the irrigation treatment. The incentive values for farmers to adopt a certain deficit irrigation plan is also displayed in these tables. These values are found by calculating the difference between the profits for optimal water treatment and one of the three deficit irrigation strategies corresponding to a given output price and salt level.

6.11. References

Acevedo, E., Hsiao, T.C., and Henderson, D.W., 1971. " Immediate and subsequent growth responses of maize leaves to changes in water status". *Plant Physiol.* 48:631-636.

Champion, D.F., Kruse, G.E., Olsen, R.S., and Kincaid, D.C., 1991. " Salt movement under level-basin irrigation ". *Journal of Irrigation and Drainage,* ASCE, Vol.117, no:5, pp:642-655.

Eik, K., Hanway, J.J., 1965. " Some factors affecting development and longevity of leaves of corn". *Agron. J.* 57: 7-12.

Karajeh, F.F., 1991. " A numerical model for management of subsurface drainage in agroforestry systems ". *Ph.D. dissertation* submitted to University of California, Davis, CA.

Kemper, W.D., Olsen, J., and De Mooy, C.J., 1975. " Dissolution rate of gypsum in flowing water ". *SSSAJJ* 39, pp:458-463.

Keren, R., and O'Connor, G.A., 1982. " Gypsum dissolution and sodic soil reclamation as affected by water flow velocity ". *SSSAJ,* 46, pp:726-732.

Khalid Bali, 1993. " Personal Communications". *Desert Research and Extension Center,* Farm Adviser, University of California.

Kincaid, D.C., Kruse, G.E. and Duke, H.R., 1979. " Paired hydraulic weighing lysimeters for evapontraspiration measurements ". *presentation in winter meeting* of ASAE, New Orleans, LA.

Kovda, V.A., 1983. "Loss of productive land due to salinization ". *Ambio,* 12(2), pp:91-93.

Kruse, G., 1993. " Personal communications ". *USDA-ARS and Colorado State University,* Fort Collins, CO.

Kruse, E.G., Champion, D.F., Cuevas, D.L., Yoder, R.E. and Young, D., 1993. " Crop water use from shallow, saline water tables ". *ASAE,* Vol.36. no:3, pp:697-707.

Robinson, E.F., Teuber, L.R. and Loomis, S.R., 1992. " Alfalfa water stress management during summer months in Imperial Valley for water conservation ". *Annual report* supported by Metropolitan Water District of Southern California, The Water Resources Center, University of California and Imperial Valley Conservation Research Center Committee.

San Joaquin Valley Drainage Program, 1990. " A management plan for agricultural subsurface drainage and related problems on the Westside San Joaquin Valley ". *Final report* by US DOI (BOR, FWS, GS) and California Resources Agency (DWR, F&G).

Sharpley, A.N and Williams, J.R., 1990. " EPIC- Erosion/Productivity Impact Calculator: 1. model documentation :. U.S. Department of Agriculture Technical Bulletin, no. 1768.

Tanji, K.K., 1990. "Agricultural salinity assessment and management". Manual No. 71 *Published by Amer. Soc. Civil Engrg.*, New York, NY, 619p.

CHAPTER VII. NITRATE-AND SALT- SENSITIVE AREAS

7.1 Areas of Concern

California's irrigated agriculture is intensively practiced on about 4.12 million ha throughout the state. Nitrate and salinity are two of most pervasive agricultural nonpoint source pollution problems. Nitrates in ground waters are of concern due to human health effects. Ingestion of high nitrate waters may result in infant methemoglobinemia. Nitrate is also suspected of causing nitrate-induced cancer by reacting with secondary nitrogen compounds forming a N-nitroso compound, but this has not been clearly established. California's MCL (Maximum Contaminant Level) for nitrate in drinking water is 45 mg/L nitrate or 10 mg/L nitrate-nitrogen.

Two major reports on nitrates have been published by state agencies. The State Water Resources Control Board (Anton et al., 1988) focused on nitrates in drinking waters while the California Department of Food and Agriculture (CDFA, 1989) examined agricultural uses of N fertilizers and manures.

Figure 7.1 shows well locations where the nitrate levels were measured at 45 mg/L or greater during the period 1975 through 1987 (CDFA, 1989). And figure 7.2 shows well locations where the nitrate levels were between 20 and 44 mg/L during the period 1975 through 1987. The sources of nitrates in ground waters are manifold including fertilizer N, animal manures, septic tanks, land treatment of treated sewage and industrial effluents, landfills and native soil N. Anton et al. (1988) reported that about 10% of the well waters tested in over 38,000 wells exceeded the state MCL of 10 ppm nitrate-nitrogen. Most of this nitrate data came from deeper municipal wells. Of prime concern are the many thousands of shallower individual domestic wells which are not tested often and more vulnerable to nitrate pollution than deeper wells.

Areas in California sensitive to nitrate accumulation in ground waters from agriculture may be related to a number of factors and conditions (CDFA, 1989). Nitrate-sensitive areas are located in regions where high rates of N are applied to high cash value crops; coarse textured soils having high infiltration rates, high permeability in the vadose zone, and low denitrification potential; leaching of nitrates from crop root zone is high due to either rainfall rates or irrigation exceeding evapotranspiration; and warmer temperatures which enhances rates of N mineralization.

Potential BMPs for nitrogen were presented in Chapter 1 along with BMPs for on-farm water management. Potential BMPs are intended to improve the efficiency of nitrogen use in crop production and prevent excessive losses of nitrogen to the off-site environment. These nitrogen BMPs include application of recommended rates of nitrogen for each crop taking into account nitrogen credits for residual inorganic soil nitrogen, mineralization of soil organic nitrogen, nitrogen in applied irrigation water, and any other sources of available nitrogen. Nitrogen fertilizers should be judiciously applied when leaching potential is high and crop nitrogen requirement is low.

Potential BMPs for on-farm water management include scheduling irrigation using real-time weather data (e.g., CIMIS), selecting proper irrigation method for site specific conditions, improving uniformity distribution in water application, land grading, shortening length and using tailwater recovery system for furrow irrigation, practicing cut-back irrigation and surge flow irrigation for furrow, border and basin irrigation, and use of sprinkler and drip/trickle irrigation methods where feasible.

Improved water management on the farm is clearly an important source control for both nitrates and salinity. A reduction in subsurface drainage will minimize leaching losses of nitrates from the crop root zone. Jacques Franco, Program Coordinator of CDFA's Fertilizer Research and Education Program, stated " Applying water in a way that minimizes deep percolation is a best management practice that can have the biggest impact".

A potential exists for creation of GIS maps showing nitrate-sensitive areas. For instance, Zhang (1993) has carried out a landscape study of nitrates in ground waters in Western Tulare County. Elevated levels of nitrate in ground waters were correlated to annual net nitrogen loadings and soil nitrate leaching potential. The net nitrogen loading is estimated from the difference between applied nitrogen and nitrogen removed by crops, and hence is the potentially leachable soil nitrogen. The soil nitrate leaching potential was related to soil hydraulic conductivities. In general, high nitrate concentrations in well waters in Western Tulare County are associated with high or moderate leaching potential (coarse textured soils) and moderate net nitrogen loadings (e.g., citrus and vines)

Salinity is of concern for many beneficial uses of water including drinking water, irrigation supply, fish and wildlife, and industrial water supply. The sources of salinity in ground waters are diverse, too, like nitrogen. These sources include salts in applied waters, chemical weathering of soil minerals, salts in applied fertilizers, soil amendments and animal manures, rising shallow ground waters, and seawater intrusion..

Figure 7.3 shows a location map of salt-affected soils in areas where irrigated agriculture is practiced. The presence of saline ground waters in California may be frequently related to the salinity of overlying soils, with some exceptions. The exceptions include sea water intrusion in coastal areas and rising saline connate and other salinized waters (Tanji, 1990). A large portion of saline/sodic lands are found in the San Joaquin Valley . Other salt-impacted areas include the Imperial Valley, Upper Santa Ana River Basin , Salinas Valley., and Sacramento Valley.

Backlund and Hoppes (1984) presents Table 7.1 which indicates that salinity in irrigated lands is often associated with high water table and other water quality problems. About 28% of the irrigated lands are affected by salinity or sodicity, 26% by high water table conditions and 33% by water quality problems. BMPs for salinity control were given in Chapter 1 along with BMPs for on-farm water management.

Potential BMPs for management of saline waters include appraising the irrigation water for salinity, sodicity and specific ion effects. BMPs for management of saline soils or to prevent salt buildup include maintaining a salt balance in the root zone. Minimizing leaching fraction will reduce the amount of salts derived from chemical weathering of soil minerals and promote the precipitation of soluble salts such as calcium carbonate. Uniform distribution of applied water is a key water and salt management option.

The above BMPs for nitrogen, salts and water can be assessed with evaluation models such as EPIC as was done in this project.. The interactions between nitrogen and water as well as between salinity and water are substantial and need to be considered. Simulation models offers an opportunity to evaluate complex scenarios for site-specific conditions and BMPs.

A recent report from the National Research Council (1993) suggests that protection of the nation's water quality is strongly linked to maintaining soil quality. Other suggestions include the need for systems appraisal to solve problems in agricultural systems, targeting of federal support programs, the need for research and development in new agricultural production technologies and management methods, and the persuasion of farmers to adopt BMPs and serve as stewards of our land and water resources. A four- prong problem solving strategy was recommended: (i) Broaden the approach to protecting soil quality, (ii) Increasing efficiency in the use of fertilizers, pesticides, and irrigation water, (iii) Reducing farm erosion and runoff, and (iv) Creating and protecting edge-of-the-field buffer zones.

Table 7.1 Extent of salinity, drainage and other water quality problems in irrigated lands in California in millions of hectares after (Backlund and Hoppes, 1984).

Location	Total irrigated area	Affected by salinity/sodicity	Affected by high water table	Affected by poor water quality
San Joaquin Valley	2.3	0.89	0.61	0.93
Sacramento Valley	0.85	0.08	0.16	0.12
Imperial Valley	0.20	0.08	0.20	0.20
Other areas	0.77	0.12	0.12	0.12
Total	4.12	1.17	1.09	1.37

7.2 References

Anton, E.C., J.F. Barnickol, and D.R. Schnable. 1988. Nitrates in drinking waters. Report to the Legislature. Report No. 88-11 WQ. Division of Water Quality. State water Resources Control Board, Oct. 1988. 59 pages.

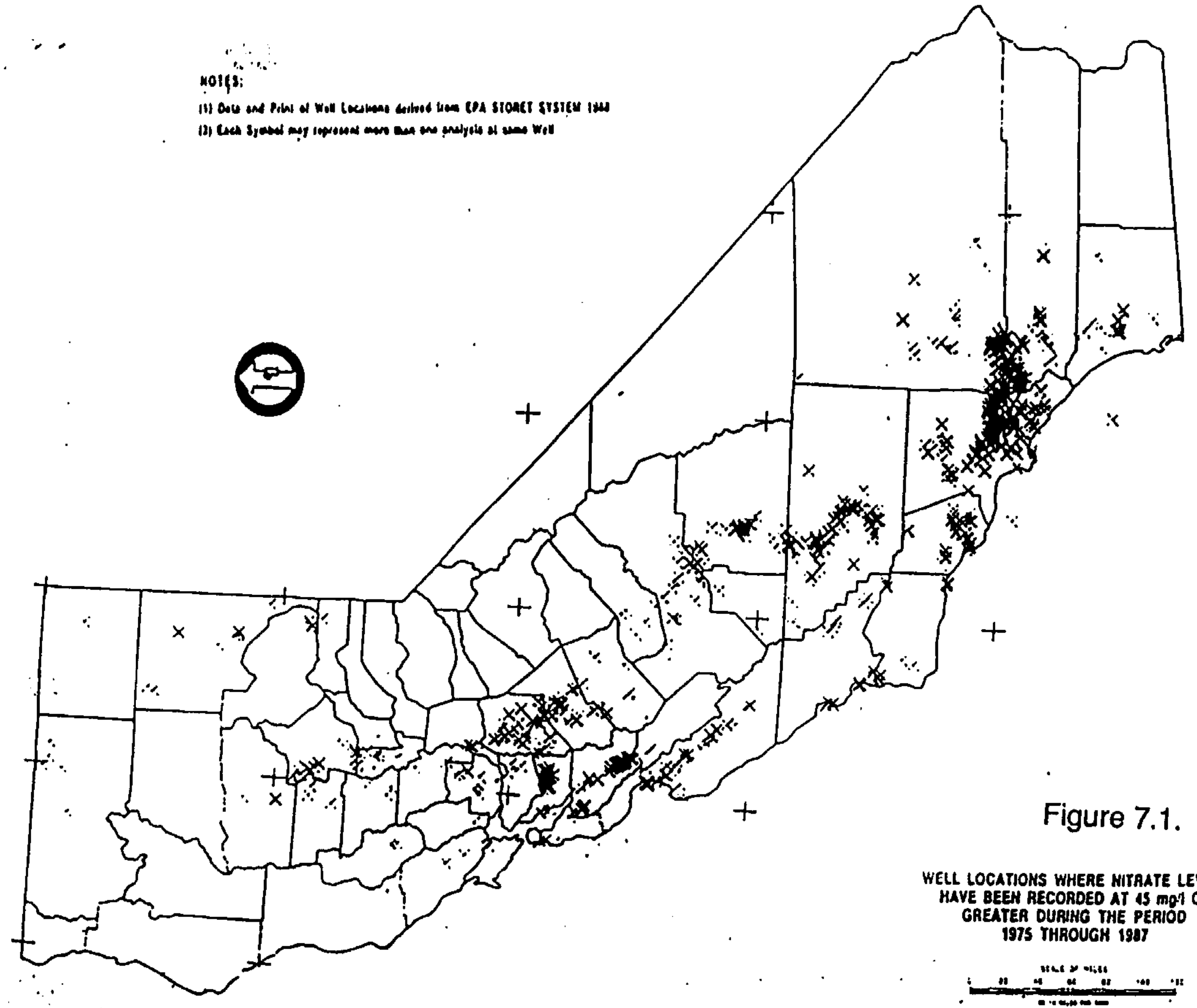
Backlund, V.L., and R.R. Hoppes. 1984. Status of soil salinity in California. California Agriculture 38(10): 8-9.

California Department of Food and Agriculture. 1989. Nitrate and agriculture in California. Nitrate Working Group, P.W. Stephany, chair. California Department of Food and Agriculture,. 65 pages.

National Research Council. 1993. Soil and Water Quality. An Agenda for Agriculture. Committee on Long Range Soil and Water Conservation, Board on Agriculture, National Academy of Science. National Academy Press. 516 pages.

Tanji, K.K., Editor. 1990. Agricultural Salinity Assessment and Management. ASCE Manual No. 71, American Society of Civil Engineers. 619 pages

Zhang, M. 1993. The impact of agriculture on ground water dynamics and qualities. Ph.D. dissertation, University of California, Davis. 237 pages.



NOTES:

(1) Data and Print of Well Locations derived from EPA STORET SYSTEM 1988

(2) Each Symbol may represent more than one analysis at same Well

Figure 7.1.

WELL LOCATIONS WHERE NITRATE LEVELS HAVE BEEN RECORDED AT 45 mg/l OR GREATER DURING THE PERIOD 1975 THROUGH 1987

NOTES:

(1) Data and Plot of Well Locations derived from EPA STORET SYSTEM 1988

(2) Each Symbol may represent more than one analysis at same Well

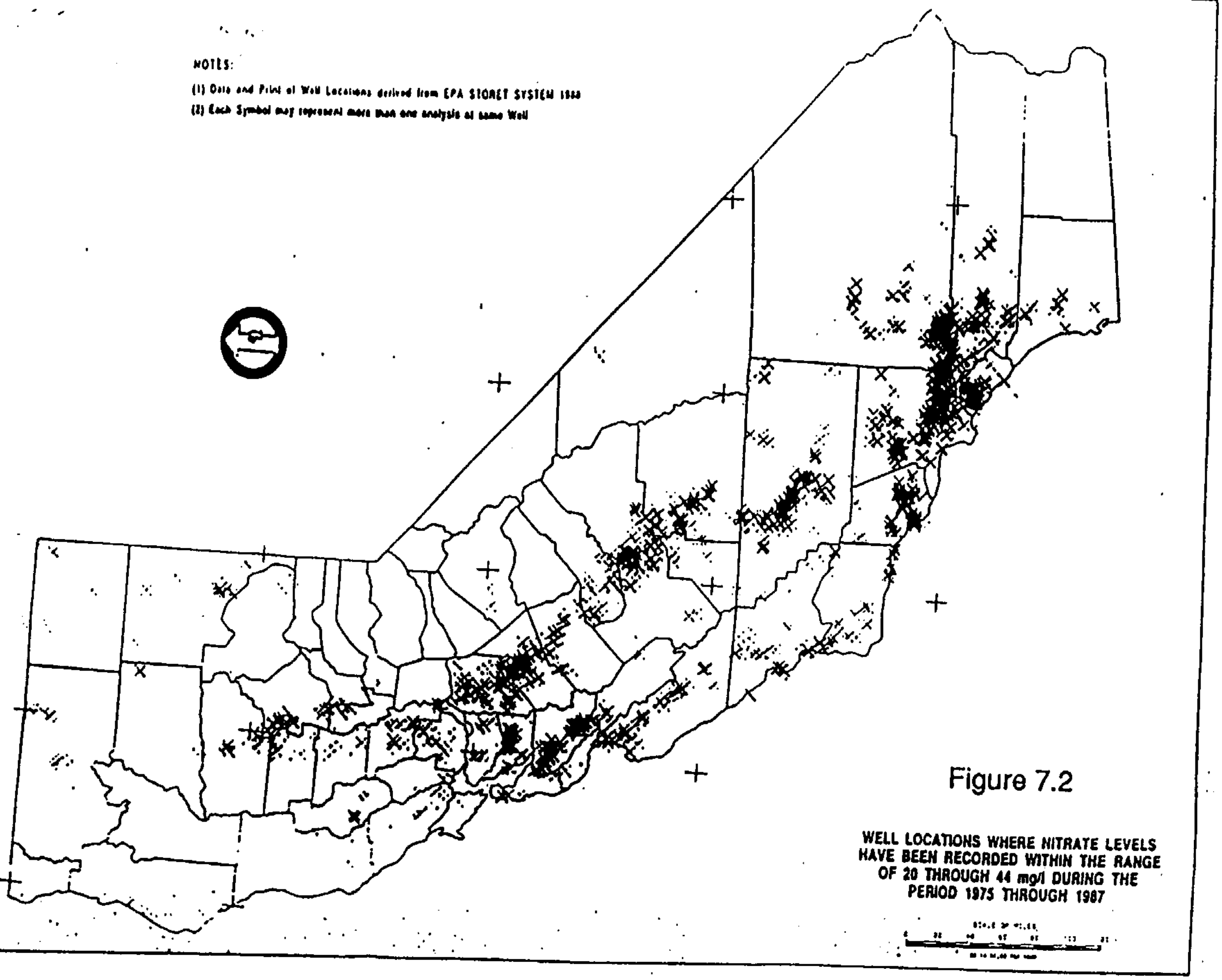


Figure 7.2

WELL LOCATIONS WHERE NITRATE LEVELS HAVE BEEN RECORDED WITHIN THE RANGE OF 20 THROUGH 44 mg/l DURING THE PERIOD 1975 THROUGH 1987

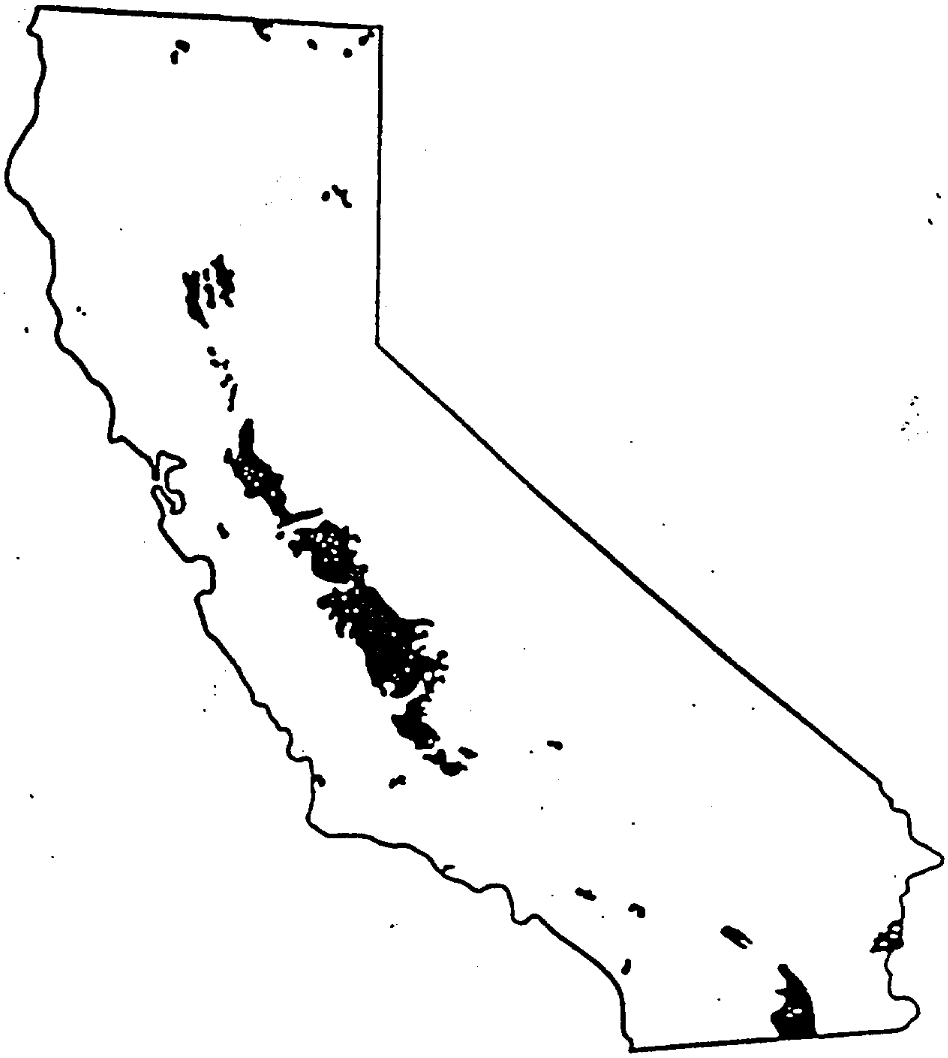


Figure 7.3 Location of salt-affected irrigated lands in California (after Backlund and Hoppes, 1984)