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OPTIMAL MANAGEMENT OF IRRIGATION AND VADOSE ZONE PESTICIDE TRANSPORT

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ABSTRACT

A management model is developed for maximizing crop yield while avoiding unacceptable pesticide leaching. Utilized constraint equations: maintain a soil moisture volume balance, describe downward pesticide transport, and limit the amount of pesticide reaching groundwater. The reported optimization model is the first which includes unsaturated zone pesticide transport. It is designed to help prevent nonpoint-source contamination of shallow groundwater aquifers. The model computes optimal irrigation amounts for given soil, crop, chemical, and climate data and irrigation frequencies.

The model is tested for different irrigation scenarios. The modeling approach is promising as a tool to aid developing environmentally sound agricultural production practices. It allows estimation of trade-offs between crop production and groundwater protection for different management strategies.

More frequent irrigation tends to give better crop production and less solute movement. Yield/environmental quality trade-offs are smaller for deeper groundwater tables. Trade-offs also decrease with increased irrigation frequency.

1. INTRODUCTION

Approximately 2.6 billion pounds of pesticides are used in the United States each year (EPA 1986). Agricultural use accounts for more than 60% of all pesticides used in the U. S. (EPA 1986). Pesticides are used to enhance the quantity and/or quality of agricultural products by attacking and controlling undesirable pests. In high doses, many pesticides harm humans, causing cancer, birth defects, genetic mutations, nerve damage, and other problems. Pesticide migration from agricultural fields may stress receiving stream ecosystems as well as contaminate groundwater, which is an important water source for rural America (Mott and Snyder 1987).

Widespread contamination of groundwater by pesticides has been reported throughout the United States. According to Parsons and Witt (1988), and Hind and Evans (1988), at least 73 pesticides which cause cancer and other harmful effects have been found in ground water in at least 34 states.

Such findings have increased efforts to protect surface and ground water from pesticide contamination. Researchers have described computer models for simulating pesticide leaching response to irrigation. After making many simulations, the best irrigation plan can be identified. However, this repetitive trial and error is tedious. It does not readily yield information concerning trade-offs between yield enhancement and pesticide leaching prevention.

In contrast, optimization models identify the best operational policies for given objectives and constraints. As a by-product of the optimization process, the trade-offs are also determined (Willis and Yeh, 1987). Here we refer to such a model, which contains simulation equations and operation research style optimization abilities, as a simulation/optimization (s/o) model. Differences between simulation and s/o models include the following.

- The simulation model will require as input, values of system stresses, such as irrigation amount. A s/o model will compute optimal system stresses for the management goal subject to all utilized constraint equations and bounds on variables. For example, a s/o model will employ user-input upper and lower bounds on decision variables (stresses imposed by management). Here, this s/o model can use upper and lower limits on acceptable values of irrigation amounts. The model will compute optimal irrigation amounts which lie within those bounds.
- A simulation model will compute system response to imposed stimuli for one time step at a time. It will solve these either serially or simultaneously for that time step. A s/o model will solve all equations for all time steps simultaneously. Thus a s/o model might solve much larger sets of simultaneous equations. Among these simultaneous equations is an objective function. This equation represents the management objectives (to maximize or minimize something).

The s/o model calculates the management strategy which best achieves the goal stated by the objective function. Computing an optimal strategy using a simulation model requires an intelligent trial and error approach. Although possible for simple problems, it is virtually impossible to determine optimal strategies for complex systems using simulation modeling alone.

There has been a need for an s/o model that will save time and effort and determine an optimal irrigation strategy for a specific situation. Having such a model will avoid the necessity of performing exhaustive simulations that might not come up with that optimal strategy. An s/o model that links on-farm water management and pesticide leaching is presented here. The model develops optimal water management strategies that maximize crop yield without violating imposed management and environmental constraints. Thus, the model determines the crop yield trade-offs involved in protecting shallow groundwater.

The model described here contains embedded constraint equations which simulate: (1) crop yield response to irrigation, (2) deep percolation of irrigation water, (3) pesticide decay, and (4) pesticide transport through the vadose zone. The optimization is nonlinear in objective function and constraints. Some constraints are nonsmooth, having discontinuous derivatives.

As detailed later, crop yield response to irrigation follows the methodology of Doorenbos and Kassam (1979). Deep percolation and pesticide movement processes follow that of Nofziger and Hornsby (1986) in their CMLS (Chemical Movement in Layered Soils) model. For clarity, a full presentation of the s/o model is included in Appendix A. Symbols used in the model are in Appendix B. The presented s/o model must include simulation equations. The simulation approach used in this s/o model was selected based on the following.

In some simulation models, transport processes are very simplified, so that the model can run with minimal data. Other simulation models, attempting to consider all parameters, require large amounts of detailed and difficult to obtain information. Excessive model complexity can cause unsatisfactory simulation performance. Nofziger and Hornsby (1986 and 1988), developed a model for simulating chemical movement in layered soils (CMLS) that is neither oversimplified nor overcomplicated. It accounts for the parameters that have the most significant effects on the chemical movement process. For this reason, the unsaturated water flow and chemical transport simulation approaches used by CMLS are used here. This is much preferred to embedding the Richard's equation as constraints in the optimization model.

CMLS, uses soil, chemical, crop, and climate data to estimate the movement of the chemical and the relative amount remaining in the soil profile.

maximize crop yield for the optimization period. The crop yield is computed as a fraction of the potential crop yield, which is the maximum possible yieldassuming adequacy of water and all other plant requirements. The objective function is:

$$\text{Max } Y = Y^{p}(1-R^{ms})(1-R^{dp}) \tag{1}$$

Where Y is the seasonal crop yield, Y^p is the potential (maximum) crop yield, R^{ms} is crop yield reduction due to moisture stress (insufficient water), and R^{dp} is crop yield reduction due to deep percolation (excessive leaching of nutrients).

The objective function value is maximized, subject to the following assumptions, constraint equations and variable bounds, which must be all satisfied simultaneously.

2.2 Constraints

Simulation of pesticide fate and movement within the s/o model are accomplished in three main groups of equations. Underlying assumptions of these are presented below. Then equations for pre-optimization computations and constraint equations in the s/o model are explained from a simulation perspective. Appendix B (Notation) is organized to help one understand which terms are used as input to the s/o model and which must be computed during the optimization.

Soil-Plant-Water Related Relationships. Included are equations that estimate evapotranspiration, deep percolation, and average water content in the root zone and their effects on crop yield.

Chemical-Water-Soil Related Processes. Included are equations that estimate the amount of water passing the solute depth (this water contributes to the downward movement of the chemical), the extent of the movement, and the average water content of the soil above the solute front (solute depth) when the solute depth is less than that of the root zone. Solute depth is the location of the front of the solute. It is assumed that the mass of the leached contaminant is centered at that depth.

Soil-Chemical Related Calculations. Included are equations that estimate the amount of chemical remaining in the soil (after biodegradation), compute a hypothetical concentration in the saturated zone (after the pesticide has reached the water table), and compare that concentration to the health advisory in parts per billion (ppb) set by the United States Environmental Protection Agency (EPA).

2.2.1 Soil-Plant-Water Relationships

The following assumptions apply:

1- The soil is composed of homogeneous layers (horizons).

2- Weighted average soil characteristics are assumed in the root zone in estimating the average water content.

3- Based on assumption 2, when water is applied, it fills the root zone to the average water content at field capacity and the excess leaves as deep percolation. If the amount of water infiltrating is less than the amount required to fill the root zone to average moisture content at field capacity, the moisture content is adjusted and deep percolation for the day is set equal to zero.

4- Based on assumption 2, when evapotranspiration takes place, water can be removed from the root zone until the average water content of the root zone reaches permanent wilting point.

5- No upward movement of the water is considered in the model, other than the water loss by evapotranspiration.

6- No downward movement of water occurs when the soil moisture is less than the water content at field capacity.

7- Water content in the root zone can neither decrease below average moisture content at permanent wilting nor exceed average moisture content at field capacity (i.e. no evapotranspiration occurs when moisture content in the root zone reaches permanent wilting. Deep percolation occurs when moisture content in the root zone reaches field capacity).

8- For any day, evapotranspiration is assumed to take place before water is applied. For every day, evapotranspiration is estimated, soil moisture and solute depth calculated, water is applied, and soil parameters are recalculated. Thus when the solute depth is less than the depth of the root zone, we have two daily moisture contents for the root zone and another two for the solute depth.

9- For the plant used in this model four growth stage periods are assumed: vegetative, flowering, grain yield formation, and ripening. Growth factors for these stages are assumed.

10- Potential evapotranspiration E_t^p assumes adequate moisture and is a function of type of plant and weather conditions. E_t^p is assumed known. If actual evapotranspiration is less than E_t^p crop yield will be reduced.

11- Preferential flow (flow through cracks in the soil), flow through abandoned wells, or similar kinds of flow are not considered in the model.

12- No surface runoff takes place when the irrigation water is applied. It is assumed that all of the applied irrigation water and precipitation infiltrate the soil surface.

13- This model considers only one dimensional vertical movement of water and solute. It does not directly consider the irrigation method used or nonuniformity of irrigation. However, such adjustments can be made.

Figure 1 illustrates how soil horizon information from field data is treated within the s/o model. This is necessary because the s/o model cannot handle as many layers as might exist in the field. Thus, as described below, the model is written to handle three layers.

First, the site's soil and crop maximum possible root depth D^{rz} (L) is assumed. Figure 1 depicts the situation when the bottom of the root zone is not coincident with the bottom of a soil layer. In this case, one real horizon is split into two horizons (each having the same properties). Thus the bottom of the upper new horizon corresponds to the bottom of the root zone.

Then, average soil properties are determined for the root zone considered in the optimization model. Considering H resultant horizons in the actual root zone and the corresponding thickness of each horizon D_h (L), the average moisture content at field capacity for the root zone, θ^{fc} (percent volume), is the thickness weighted average of those of the different root zone layers, θ_h^{fc}.

$$\theta^{fc} = \frac{\sum_{h=1}^{H} D_h \theta_h^{fc}}{D^{rz}} \qquad (2)$$

The weighted average moisture content at permanent wilting for the root zone, θ^{pw} (percent volume), is calculated by the same method.

$$\theta^{pw} = \frac{\sum_{h=1}^{H} D_h \theta_h^{pw}}{D^{rz}} \tag{3}$$

Potential evapotranspiration E_t^p (L) of the crop (assuming water is not limiting) and coefficients K_n^{yk} for the growth stages of the crop are assumed known. Here t refers to day and n refers to growth stage. Also assumed known are precipitation data and irrigation frequencies reasonable for the site's water distribution rules. Optimal irrigation amounts are computedby s/omodel usingthese dataand assumed frequencies.

It is assumed that the root zone is at field capacity at the beginning of the first day. Steps 1 to 7 (equations 4-12) are performed simultaneously for each day of the optimization:

1-The available water W_t^a (the water in the root zone that can be removed by evapotranspiration) is estimated as a function of the average water content at the end of the previous day θ_{t-1}^f, and the depth of the root zone D^{rz}

$$W_t^a = D^{rz}(\theta_{t-1}^f - \theta^{pw}) \tag{4}$$

2-Daily evapotranspiration E_t is the smaller of the available water W_t^a and the potential evapotranspiration E_t^p of the crop. In the s/o model this requiresuse of discrete nonlinear programming (DNLP) constraints. Similarly, all subsequent equations represented by min or max functions require DNLP solution.

$$E_t = \mathrm{Min}(W_t^a, E_t^p) \tag{5}$$

3-Water content of the root zone θ_t^1 after daily evapotranspiration takes place is calculated from the evapotranspiration and the average moisture content at the beginning of the day

$$\theta_t^1 = \theta_{t-1}^f - \frac{E_t}{D^{rz}} \tag{6}$$

4-Daily water infiltration I_t is calculated as the sum of infiltrating precipitation on that day, R_t, and infiltrating irrigation water, Q_t, applied to the soil if it is an irrigation day

$$I_t = R_t + Q_t \tag{7}$$

5-Soil water deficit for the root zone W_t^d (the amount of water in mm that needs to be applied for the root zone to reach field capacity) is estimated as:

$$W_t^d = D^{rz}(\theta^{fc} - \theta_t^1) \tag{8}$$

6-If the infiltrating water is less than the soil water deficit, the water content of the root zone is recalculated (modified) after I_t water infiltrates. There is no deep percolation on that day.

$$\theta_t^f=\theta_t^1+\frac{I_t}{D^{rz}} \quad \text{and} \quad D_t^p=0 \quad \text{for} \quad I_t<W_t^d \tag{9}$$

7-If the infiltrating water exceeds the soil water deficit, final moisture content for the day ,θ_t^f, equals the moisture content at field capacity. Deep percolation, D_t^p, (the water that leaves the root zone and penetrates below) equals the difference between the amount of infiltrating water and the root zone soil water deficit.

$$\theta_t^f=\theta^{fc} \quad \text{and} \quad D_t^p=I_t-W_t^d \quad \text{for} \quad I_t\geq W_t^d \tag{10}$$

8-Assume the plant has N growth stages. Each growth stage is of k days duration. A growth factor K_n^{yk} describes the sensitivity of yield to water deficit in growth stage n. The proportion of yield reduction due to moisture stress during growth period n, r_n^{ms}, is estimated as:

$$r_n^{ms}=K_n^{yk}\left(1-\frac{\sum_{t=1}^{k}E_t}{\sum_{t=1}^{k}E_t^p}\right) \tag{11}$$

9-Yield reduction due to moisture stress for the entire season R^{ms} is the maximum of the reduction in any of the growth periods.

$$R^{ms}=\mathrm{Max}(r_1^{ms},r_2^{ms},\ldots,r_N^{ms}) \tag{12}$$

10-Crop yield is commonly assumed to be reduced by over-irrigation. Excessive infiltration causes deep percolation which removes nutrients from the root zone (Doorenbos and

Kassam, 1979). It may also cause aeration and drainage problems or waterlogging. However, before crop yield reduction due to deep percolation R^{dp} is calculated, a deep percolation yield reduction factor F^{dp} must be estimated. This factor depends on soil characteristics and plant sensitivity to deep percolation.

In addition, the maximum water holding capacity of the root zone, d^n (the water available when the root zone is at field capacity), must be estimated before the model is invoked. This value is used in subsequent equation (14).

$$d^n = D^{rz} \left(\theta^{fc} - \theta^{pw} \right) \tag{13}$$

Crop yield can be reduced by deep percolation because of nutrient leaching. The seasonal crop yield reduction due to deep percolation is estimated as:

$$R^{dp} = F^{dp} \frac{\sum_{t=1}^{T} D_t^p}{d^n} \tag{14}$$

2.2.2 Simulation of Chemical-Water-Soil Related Processes

The following assumptions apply:

1- Chemicals move in liquid phase only due to soil water movement.

2- Solute depth D_t^s is the distance from the soil surface to the solute front. Leaching solutemass is assumed to be concentrated at that front.

3- The chemical is applied on a certain day at a certain depth (zero for surface application).

4- When the solute depth is less than the depth of the root zone, infiltrating water fills the soil profile above the solute front to field capacity first. The excess water contributes to an increase in the solute depth. (i.e. any infiltration that is not in excess of the amount required to fill the soil profile above the solute front to field capacity will not cause solute movement). If the infiltrating water is less than that needed to fill to the solute depth to field capacity, it is distributed into the soil layer above the solute depth.

5- The soil below the root zone is always at field capacity. Evapotranspiration occurs only from the root zone. Thus the soil beneath the root zone is not included in the calculation of moisture content.

6- When water is extracted from the root zone by evapotranspiration, it is extracted from the entire root zone. If the solute depth is smaller than the depth of the root zone, the solute depth provides only its proportion of the total water extracted.

7- When the solute depth is greater than the depth of the root zone, deep percolation (water leaving the root zone) will contribute to the downward movement of the solute front.

8- The average soil moisture content of the solute depth is assumed to equal the average moisture content of the root zone at the beginning of the simulation of the solute movement. The reason for that is that the solute depth is initially within the root zone. A different water content for the solute depth is computed for each day after that. When the solute depth exceeds the depth of the root zone, computing the water content for the solute depth becomes unnecessary.

9- In calculating moisture content of the solute depth layer, depth weighted averages (as calculated for the depth of the root zone) are applied. Non-homogeneity is considered if it exists in or under the root zone when calculating solute movement. This is applied to water content at field capacity and organic carbon content of the soil.

10- All soil water in pore spaces participate in the solute movement process.

Before an optimization begins, an initial solute depth is assumed known, D_0^s. That depth is zero for surface application or is the application depth if the pesticide is applied at a specific depth beneath the soil surface. Steps 1 to 8 below occur daily as long as the solute depth is within the root zone:

1-Average moisture content of the solute depth after evapotranspiration occurs is a function of the average moisture content of the previous day, the amount of water infiltrating, and the solute depth of the previous day. It is calculated as follows:

$$\theta_t^{1,s}=\theta_{t-1}^{f,s}-\frac{E_t}{D^{rz}} \tag{15}$$

2-Soil water deficit of the solute depth W_t^{ds} is defined as the amount of water required for the solute depth to achieve field capacity

$$W_t^{ds}= D_{t-1}^{s}(\theta^{fc}-\theta_t^{1,s}) \tag{16}$$

3-If the amount of water infiltrating the soil surface due to rain and/or irrigation is less than the solute depth soil water deficit, the moisture content increases depending on the amount infiltrating.

$$\theta_t^{f,s}=\theta_t^{1,s}+\frac{I_t}{D_{t-1}^{s}} \tag{17}$$

4-If the amount of water applied on a certain day exceeds the soil water deficit of the solute depth, the average moisture content in the solute zone is set equal to average moisture content at field capacity.

$$\theta_t^{f,s}=\theta^{fc} \tag{18}$$

5-Infiltrating water in excess of the soil water deficit of the solute depth is termed the water passing the solute front, Q_t^{pass},

6-The linear sorption coefficient (partition coefficient

$$Q_t^{pass}=I_t-W_t^{ds} \tag{19}$$

of the chemical in the soil), K_t^d, is a function of the linear sorption coefficient normalized by the organic carbon K^{oc} and the organic carbon P_t^{oc} (percent) of the soil just below the solute front. P_t^{oc} is equal to P_h^{oc} of the horizon containing the solute front as a top boundary.

$$K_t^d=P_t^{oc}\, K^{oc} \tag{20}$$

7-The retardation factor, R_t^f is a function of the bulk density of the soil, the partition coefficient K_t^d, and the moisture content at field capacity of the soil just below the solute front θ_t^{fc}.

$$R_t^f=1+\frac{\rho_t K_t^d}{\theta_t^{fc}} \tag{21}$$

8-The solute depth on a day t is a function of the water passing the solute front on that day, the retardation factor, and the moisture content at field capacity for the horizon just below the solute front.

$$D_t^s=D_{t-1}^s+\frac{Q_t^{pass}}{(R_t^f\ \theta_t^{fc})} \tag{22}$$

Once the solute depth exceeds the depth of the root zone, the water content of the solute depth is set equal to that of the root zone. The water passing the solute depth is set equal to deep percolation. Equations 20, 21, and 22 are repeated for every time step.

2.2.3 Soil-Chemical Related Calculations

The following assumptions apply:

1- The half-life for biochemical degradation for the chemical H^L is constant with time and depth.

2- The adsorption process can be described by a linear reversible equilibrium model. If this assumption is not valid, The depth to which the chemical will leach will depend on the concentration. This is not significant for the concentrations of interest in most agricultural applications (Nofziger and Hornsby, 1986).

The following steps are repeated for every day of the optimization period:

1-Given the half life of the chemical H^l (T) and the time since the chemical was applied, the fraction of the applied chemical that is remaining in the soil F_t is :

$$F_t = e^{\frac{-t \ln(2)}{H^l}} \tag{23}$$

2-Assume that t is the time until the center of mass reaches the water table. Also assume that all leaching pesticide reaches the water table on the same day. The amount of the pesticide that reaches the water table and is then dissolved in groundwater is F_t of the amount applied originally in grams per hectare, P^h. The resulting pesticide concentration within an assumed mixing depth is F_t^{ppb} in part per billion. Determining how much ground water the chemical will dissolve into requires many site specific assumptions. However, for illustration, a mixing depth, D^m, of 100 mm of water is assumed (if soil porosity is .25, this corresponds to a depth of 400 mm of saturated zone.

$$F_t^{ppb} = \frac{100}{D^m} F_t \, P^h \tag{24}$$

Sensitivity of the results to this assumption are examined in the sensitivity analysis.

3-Each day, the assumed concentration of the chemical in the groundwater F_t^{ppb} is divided by the health advisory F^{EPA} (ppb) set by the EPA to obtain a relative health hazard index H^h_t

$$H_t^h = \frac{F_t^{ppb}}{F^{EPA}} \tag{25}$$

4-It is assumed that groundwater having a relative health hazard index greater than 1.0 might not be healthful. Later, a bound is illustrated which assumes that the pesticide will not reach the water table on any day in which the resulting H_t^h will exceed 1.

2.2.4 Bounds on Variables

Bounds on the variables used in the model are summarized as follows:

1. Identifying irrigation and non-irrigation days

$$Q_t = 0.0 \text{ for } t \notin S^I \tag{26}$$

where Q_t is the irrigation amount applied on day t and S^I is the set of irrigation days.

2. Setting bounds on the amount of irrigation that can be applied, depending upon water rights and other considerations

$$q^u \geq Q_t \geq 0 \text{ for } t \in S^I \tag{27}$$

No upper limit on the amount of water applied was needed in the model application. Appropriate irrigation application technology is assumed so that all of the amount applied infiltrates into the soil. If that is not the case, the amount applied should be adjusted accordingly.

3. Setting bounds on the evapotranspiration

$$0.0 \leq E_t \leq E_t^p \tag{28}$$

Where E_t is the actual evapotranspiration and E_t^p is the potential evapotranspiration.

4. Constraints on the water content for the root zone

$$\theta^{pw} \leq \theta_t^f \text{ , } \theta_t^1 \leq \theta^{fc} \text{ for the rootzone} \tag{29}$$

5. Constraints on the water content for the solute zone

$$\theta^{pw} \leq \theta_t^{f,s} \text{ , } \theta_t^{1,s} \leq \theta^{fc} \text{ for the solute zone} \tag{30}$$

6. Bounds on the solute depth, to prevent unacceptable

pesticide contamination of groundwater.

$$D_t^s \leq D^{gwt} \quad \text{for } H_t^h \geq 1 \tag{31}$$

The s/o model is summarized in Appendix A. It uses the objective function, simulation equations, and the bounds on variables described above. The model maximizes crop yield subject to constraints describing water flow and solute movement (Equations 32-55). The constraint in Equation 55 prevents pesticide from reaching groundwater in such an amount that the relative health index (RHI) will exceed 1.

The model calculates the amount of water Q_t or set of Q_t's that maximize crop yield while satisfying the RHI constraint. The model is an irrigation management tool for estimating the combination of frequency and irrigation amounts that maximize production, while preserving shallow ground water aquifers from the danger of pesticides. It can be used in agricultural (cropping) settings as well as for turf in urban or recreational settings.

The model is run using representative data from Utah county for the assumed two-year period. Different scenarios are evaluated. Scenarios differ in the assumed depth to groundwater table, assumed irrigation frequencies, and numbers of different irrigation amounts that are permitted during the season. Ground water depths from 1.0 to 2.4 meters are used. Irrigation frequencies of five to twelve days and a combination of different frequencies within the season are used. Different irrigation schemes involve the following assumptions concerning how irrigation amounts can change during the irrigation season.

1-A constant irrigation application.

2-Two levels of irrigation amounts, each applied during one of two periods.

3-Three levels of irrigation, each applied during one of three different periods.

The irrigation season is divided into periods depending on how potential evapotranspiration changes with time. The results are later examined to discuss the effect of the depth to ground water, irrigation frequency, number of periods into which the season is subdivided, and level of application. Results are then summarized, organized and graphed, and trade-offs (effect of restricting groundwater contamination on max yield) are estimated.

MINOS is used to perform the optimization computations. The s/o model is written using GAMS, a high level language (Murtagh and Saunders, 1990), designed to solve large-scale optimization problems. MINOS uses different approaches to solve optimization problems of different types. For this study the nonlinear programming with discontinuous derivatives (DNLP) option is used.

The model described here is nonlinear in the objective equation and the constraints and contains nonsmooth functions.

In nonlinear optimization, global optimality of the optimal solution might not be always guaranteed. However, if the nonlinear objective and constraint functions are convex, the optimal solution obtained will be a global optimal. Otherwise, there might be several local optima, some of which will not be globally optimal. The chance of getting a global optimum is increased by choosing a starting point closer to it (Brooke and Kendrick, 1988).

The modeling methodology used consists of the following steps (Figure 2). This process is conceptually similar to that commonly used in developing optimal steady-state pumping strategies for unconfined aquifers. There, transmissivity is computed before optimization. Discretized transmissivities are then used in linear flow equations and are assumed constant in the optimization model. Optimization is performed, optimal heads are used to compute new transmissivities. The process of computing parameters and optimizing is repeated until optimal heads are the same as those used to compute the transmissivities used as input to the model. By this process, a nonlinear problem can be solved using linear equations or more simple nonlinear equations. In this pesticide/irrigation model a similar process is followed for some parameters. The steps used in this approach are:

1- Running the model in simulation mode using soil, chemical, plant, and precipitation data. Simulation mode refers to optimizing a problem having only one solution (i.e. by constraining Q to a predetermined value). In this run, an assumed irrigation strategy is used. This step is executed to generate initial guesses for the subsequent optimization's parameters and variables. A parameter is a value in the model that does not change during the execution of the model (eg. during the optimization process). A variable is a value that changes during the execution of the model. (Parameters and variables are listed in the first and second part of appendix B, respectively).

2- Running the optimization model using the output of the simulation as initial guesses for all variables. This run results in a strategy that the solution algorithm claims is optimal. However, the strategy might or not be optimal depending on the consistency between assumed parameter values and those that would result from the optimal strategy (explained below).

3- If the parameters and variables resulting from the optimization model are inconsistent with the assumed values, the model solution is considered not to have converged. In this case the simulation model is rerun using the Q_t's from the optimization model. Then, the parameters are recalculated based on that new irrigation strategy. The optimization model is run again using the simulation output as initial guess values for variables. This is repeated until the optimization output is the same as the input. This means that the irrigation amounts computed by the optimization model are the same as those entered as an initial guess.

4- If the output of the optimization model is the same as the initial guess (within convergence criteria), the model has converged. Then the solution is examined.

5- If the solution is not an optimum (no convergence), steps 1 to 4 are repeated.

6- If the solution is an optimum (the model converged), it might or might not be a global optimum. To see if a better optimal solution can be obtained, the procedure is repeated using a radically
different irrigation strategy as an initial guess. The different optimal strategies are compared. The strategy that gives the best objective values is assumed to be nearest to the global optimum, or might be the global optimum itself. The other strategies represent locally optimal solutions to the nonlinear problem.

In summary, the cycling approach is used because the model becomes extremely nonlinear if all of the involved parameters are used as variables. That will increase the number of variables and the number of equations in the optimization model. This will lead to a larger model that uses more memory and more CPU time. All of these factors would make convergence difficult.

3. APPLICATION, RESULTS, AND DISCUSSION

3.1 Application

The model was run for a 2-year period (1985-1986) using data from Utah County, Utah. A time step size of one day was used for the entire period. The Vineyard soil of Utah County is assumed (Table 1). The pesticide used for the study is atrazine (Table 2.).

Daily precipitation and potential evapotranspiration data for the crop in the study area are given in Appendix D. The crop used in the optimization was maize. A 90 cm maximum rooting depth was assumed. The growth factors for the crop growth stages are listed in table 3 (Neale, 1990).

The model solves about 2900 equations simultaneously to compute values for 2600 variables. The model was run on the VAX VMS 6250 and CRAY Y-MP/832. On either, it takes 5 to 15 cycles to converge. The time needed for convergence is from one to several hours depending on the computer and initial guess.

An optimization model can function as a simulation model if it is so constrained that there is only one solution possible. For example, by setting the upper and lower boundaries of Q equal, the model will simulate pesticide movement for the assumed q's. The simulation ability of the optimization model was verified by comparison with CMLS. The models were run using data for a 6-year

period to compare their results. They were run using the same chemical, soil, precipitation, and plant data for the period 1980 to 1986. Figure 3. indicates that the results from CMLS and those of the optimization approach do not differ significantly. The difference is caused by the reduction in the number of soil layers and the averaging of soil characteristics which are necessary to reduce the size of the problem and make convergence feasible.

The model was used to compute optimal strategies for scenarios involving different irrigation frequencies, application schemes, and pesticide movement constraints. Fixed irrigation frequencies ranged from five to twelve days. Another irrigation frequency involves more frequent irrigation at the beginning of the season and less frequent irrigation later in the season as the roots of the crop penetrate the soil and have access to more water. The applied frequency was 5 days in May and June and 10 days in July, August, and September. The run numbers for this schedule are shown in the final row of Table 4.

Four irrigation application schemes were used. These are distinguished by the degree to which irrigation amount was permitted to vary during the season (Figure 4). Scheme A permitted no variation. Only a single optimal irrigation amount was allowed to be computed. Scheme 2 permitted applying a different amount before june 9 than afterwards. Illustrated schemes represent feasible water management practices for Utah irrigation.

Table 4 illustrates the run numbers for the basic optimizations performed. The runs are divided into two major categories. The first category includes runs not employing chemical constraints (MAX YIELD, NO WATER QUALITY CONSTRAINT). These runs are classified according to the frequency (first column) and the four irrigation schemes involved (described above). Abbreviations composed of a number and a letter are used to describe a run. The number stands for the irrigation frequency. Values '5,6,...,12' stand for 5 to 12 day constant irrigation frequencies. The '510' value in the first column refers to a combination of 5 and 10 day frequencies.

The letter in this category's run numbers stands for the irrigation scheme. Letters A through D correspond to those schemes shown in Figure 4.

The second major caegory includes optimization runs using pesticide constraints (Equations 23-25 and 31). All of these use irrigation scheme A. These are classified according to frequency and depth to water table. Groundwater depths of 1.3 to 1.8 meters are used to show how proximity of the water table to the ground surface affects acceptable irrigation practices and crop yield. The names for the runs are composed of a combination of a number and a letter, denoting irrigation frequency and groundwater table depths, respectively.

In essence, for runs in the first category, the s/o model minimizes the loss of yield due to water insufficiency plus the loss due to excessive leaching (irrigation excess). This is valuable because fixed irrigation frequencies and amounts are common practice. This model can improve that practice. In second category runs the model does the same thing while assuming that the health advisory level does not exceed 1 when the pesticide reaches the water table. In these runs the model minimizes the yield reduction while halting or delaying the leaching pesticide enough to satisfy the water quality constraint.

3.2. RESULTS AND DISCUSSION

Results are listed in Tables 5 and 6 for optimization runs of categories one and two of table 4, respectively. Shown are the frequency, the amount of water applied in each period, the seasonal amount applied, the yield as a percent of the maximum (potential) yield, and the solute depth at the end of the optimization period. A blank field in a row means that the field in not applicable for that run. Sample results are graphed in Figures 5 and 6.

The following conclusions apply to the scenarios involving maximizing yield without chemical constraints (Table 5).

1- For scenarios using the first irrigation scheme (scheme A), more frequent irrigation tends to give higher yield with less seasonal irrigation consumption.

2- For scenarios within scheme B, more frequent irrigation gives higher crop yield for less water use. The resulting solute depth decreases with more frequent irrigation, however, the trend is not as clear as with the first irrigation scheme. The results from this irrigation scheme are significantly better than those of the first scheme, in terms of water use, solute depth, and yield.

3- The general trend for the scheme C scenarios is the same. More frequent irrigation tends to give more yield and less solute movement for less seasonal water consumption. This scheme is significantly better than the previous scheme in yield, solute depth, and seasonal water use.

4- The scenarios within the fourth irrigation scheme give better yield, less solute depth, and significantly less water requirement. The weekly frequency is the best.

5- Scenario 510A (having a combination of 5 and 10-day frequencies and an unchanging irrigation application amount) gives extremely

high solute depths, low yield, and high water consumption.

6- Scenario 510B (having a change in application rate with the change of frequency) did significantly better.

In summary, yield increases and solute depth decreases as irrigation frequency and freedom to change irrigation amount increases. These trends were not completely unioform with change in frequency because precipitation and potential evapotranspiration are not uniform in time (Appendix C). Thus changing the frequency changed the optimization problem being solved by the s/o model. Nevertheless the trends are obvious.

One verification of the s/o model can be easily demonstrated by the following. Fig 7 contains the results of a single optimization run and many runs in simulation mode for the simplist case, scheme A (constant Q, constant irrigation frequency). This illustrates how the optimization model calculates the optimal irrigation amount for that scenario. Because of dimensionality, scheme A is the only scheme that can be graphed. The number of simulations required to address the othe schemes would be exhaustive. Furthermore, a simulation model alone could not compute strategies wich would simultaneously satisfy the water quality constraints as is done below.

Review of Table 6, results of scenarios maximizing yield while considering water quality constraints, gives the following:

1- The closer the water table is to the ground surface, The more frequent the irrigation necessary to protect the groundwater from pesticide contamination. If the water table is close to the ground surface, and irrigation is infrequent very low crop yield will result.

2-As distance to the water table increases, irrigation frequency can decrease without reducing crop yield. As frequency increases, the pesticide constraint becomes less tight or becomes unnecessary because the optimal strategy does not cause the solute to reach the groundwater table. A tight constraint is one which prevents the value of the objective function from improving further. In this case a tight water quality constraint prevents yield from being as good as it would be otherwise.

Figure 8 illustrates how results of group 2 optimizations can be summarized to show the trade-off between maximizing crop yield and protecting shallow groundwater from pesticide contamination. This shows how crop yield must be reduced by reducing irrigation to prevent contamination. The trade-offs tend to increase as the depth to the groundwater table decreases. They also tend to decrease as irrigation frequency increases.

4. SENSITIVITY ANALYSIS

Sensitivity analysis was conducted to evaluate the effect of assumed parameters on optimal q, solute movement and crop production. Solute depth decreased with increase in bulk density (Figure 9), potential evapotranspiration, water content at field capacity, partition coefficient, and organic carbon. Solute depth increased with increase in water application and maximum rooting depth. Water content at permanent wilting had no significant effect on the solute movement.

Crop yield increased with increased water content at field capacity, precipitation, or maximum root depth. Crop yield decreased with increasing deep percolation factor (Figure 10) and water content at permanent wilting. Figure 10 was developed forscheme A scenario.

It shows that the optimal strategy (irrigation application) does not change significantly with the change in the factor. This suggests that for comparative purposes, the values of some parameters are not very important. However, for reliable application in the field good parameter estimates are important.

5. SUMMARY

An optimization model was developed which explicitly describes the relationship between irrigation management and pesticide leaching through the unsaturated zone. The model maximizes crop yield subject to constraints. Constraints include nonlinear solute movement equations, volume balance equations, and an upper limit on the concentration of the chemical after it mixes with groundwater.

All previous work done in the subject involved empirical methodologies or simulation models. The simulation models compare the simulated response of the system to known management stimuli (i.e. irrigation amount). In contrast, the presented optimization model computes the optimal irrigation amount for the tested scenarios.

This model satisfies a need to optimize irrigation while preventing non-point source contamination of shallow ground water aquifers. This model finds the optimal irrigation amount for a given irrigation frequency and given soil, crop, chemical, and climate data. It allows the comparison of optimal strategies computed for each different scenario and gives the trade-offs involved in the process of protecting ground water aquifers. This model is a potentially important management tool. Its results are easy to understand and interpret.

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APPENDIX A
THE OPTIMIZATION MODEL

(Note, all equations contain subscript t are used for t=1 to T.)
The objective function

$$\text{Max } Y = Y^{p}(1-R^{ms})(1-R^{dp}) \tag{32}$$

Subject to:

$$R^{ms} = \text{Max}(r_1^{ms}, r_2^{ms}, \ldots, r_N) \tag{33}$$

$$r_n^{ms} = K_n^{yk}\left(1 - \frac{\sum_{t=1}^{k} E_t}{\sum_{t=1}^{k} E_t^{p}}\right) \tag{34}$$

$$R^{dp} = F^{dp} \frac{\sum_{t=1}^{T} D_t^{p}}{d^{n}} \tag{35}$$

$$\theta_t^{1} = \theta_{t-1}^{f} - \frac{E_t}{D^{rz}} \tag{36}$$

$$\theta_t^{f} = \text{Max}\left(\theta_t^{1} + \frac{I_t}{D^{rz}}, \theta^{fc}\right) \tag{37}$$

$$W_t^{a} = D^{rz}(\theta_{t-1}^{f} - \theta^{pw}) \tag{38}$$

$$E_t = \text{Min}(W_t^{a}, E_t^{p}) \tag{39}$$

$$\theta_t^{1,s} = \theta_{t-1}^{f,s} - \frac{E_t}{D^{rz}} \tag{40}$$

$$\theta_t^{f,s} = \text{Max}\left(\theta_t^{1,s} + \frac{I_t}{\text{Min}(D^{rz}, D_{t-1}^{s})}\ ,\ \theta^{fc}\right) \tag{41}$$

$$W_t^{ds} = [\text{Min}\ (D_{t-1}^{s}, D^{rz})]\ (\theta^{fc} - \theta_t^{1,s}) \tag{42}$$

$$D_t^{s} = D_{t-1}^{s} + \frac{I_t - W_t^{ds}}{(R_t^{f}\ \theta_t^{fc})} \tag{43}$$

$$D_t^{p} = \text{Max}(I_t - W_t^{d}, 0) \tag{44}$$

$$W_t^{d} = (\theta^{fc} - \theta_t^{1})\ D^{rz} \tag{45}$$

$$I_t = R_t + Q_t \tag{46}$$

$$F_t = e^{\frac{-t\ \ln(2)}{H^{1}}} \tag{47}$$

$$F_t^{ppb} = \frac{100}{D^{m}} F_t\ P^{h} \tag{48}$$

$$H_t^{h} = \frac{F_t^{ppb}}{F^{EPA}} \tag{49}$$

BOUNDS ON VARIABLES:

$$Q_t = 0.0 \text{ for } t \notin S^{I} \tag{50}$$

$$q^{u} \geq Q_t \geq 0 \text{ for } t \in S^{I} \tag{51}$$

$$0.0 \leq E_t \leq E_t^{p} \tag{52}$$

$$\theta^{pw} \leq \theta_t^{f}\ ,\ \theta_t^{1} \leq \theta^{fc} \text{ for the rootzone} \tag{53}$$

$\theta^{pw} \leq \theta_t^{f,s}$, $\theta_t^{1,s} \leq \theta^{fc}$ for the solute zone **(54)**

$D_t^s \leq D^{gwt}$ for $H_t^h \geq 1$ **(55)**

APPENDIX B
NOTATION

The following symbols are used

List of terms that are known (input):

D^{gwt} depth to the ground water (L)

D^{m} mixing depth of the chemical in ground water (L)

D^{rz} maximum depth of the root zone (L)

D_h depth (thickness) of horizon h (L)

d^{n} maximum water holding capacity of the root zone (L)

D_0^{s} solute depth at the beginning of the optimization (L)

E_t^{p} crop potential evapotranspiration for day t (L)

F^{EPA} concentration limit for the chemical in drinking water set by the EPA (ppb)

F^{dp} deep percolation yield reduction factor

H number of horizons in the root zone

h index for the horizon

H^{l} half life of the chemical in the soil (T)

K^{oc} linear sorption coefficient normalized by organic carbon

k_n^{yk} growth factor for growth stage n.

k index of the day in growth stage n.

K number of days in growth stage n.

n index for the growth stages of the plant

N the number of growth stages for the crop

P_t^{oc} organic carbon content of the soil horizon just below the solute depth

P_h^{oc} organic carbon content of soil horizon h

P^h amount of chemical applied (gm/ha)

R_t precipitation for day t (L)

S^I the set of irrigation days

t index for the day of optimization (day)

T last day of the optimization (day)

Y^p potential crop yield for the season (M)

θ_h^{fc} average moisture content at field capacity for horizon h

θ_h^{pw} average moisture content at permanent wilting point for horizon h

θ^{fc} average volumetric moisture content at field capacity for the root zone

θ^{pw} average moisture content at permanent wilting for the root zone

List of terms which are initially unknowns (output):

D_t^p deep percolation on day t (L)

D_t^s solute depth on day t (L)

E_t actual crop evapotranspiration for day t (L)

F_t fraction of the chemical remaining in the profile on day t

F_t^{ppb} concentration of the chemical remaining in the soil profile on day t (ppb)

H_t^h relative health hazard index

I_t water infiltration for day t due to precipitation and/or irrigation (L)

K_t^d linear sorption coefficient of the chemical in the soil just below the solute depth for day t

Q_t optimal irrigation amount for day t (L)

Q_t^{pass} the water passing the solute front on day t. It is equal to the deep percolation if the solute depth is greater than the maximum depth of the root zone (L)

R_t^f retardation factor of the chemical in the soil just below the solute depth for day t

r_n^{ms} yield reduction proportion due to moisture stress in growth stage n

R^{ms} yield reduction due to moisture stress over the entire season (%)

R^{dp} yield reduction due to deep percolation

W_t^a depth of water available in the root zone (L)

W_t^d soil water deficit for the root zone (L)

W_t^{ds} soil water deficit for the solute depth (L)

Y actual crop yield for the season (M)

θ_t^1 average moisture content for the root zone after evapotranspiration takes place

θ_t^f average moisture content for the root zone after infiltration takes place

$\theta_t^{1,s}$ average moisture content for the solute depth after evapotranspiration takes place

$\theta_t^{f,s}$ average moisture content for the solute depth after infiltration takes place

θ_t^{fc} average volumetric moisture content at field capacity for the soil just below the solute depth for day t

ρ_t average bulk density for the soil just below the root depth for day t (M/L^3)

APPENDIX C
PRECIPITATION AND POTENTIAL EVAPOTRANSPIRATION DATA

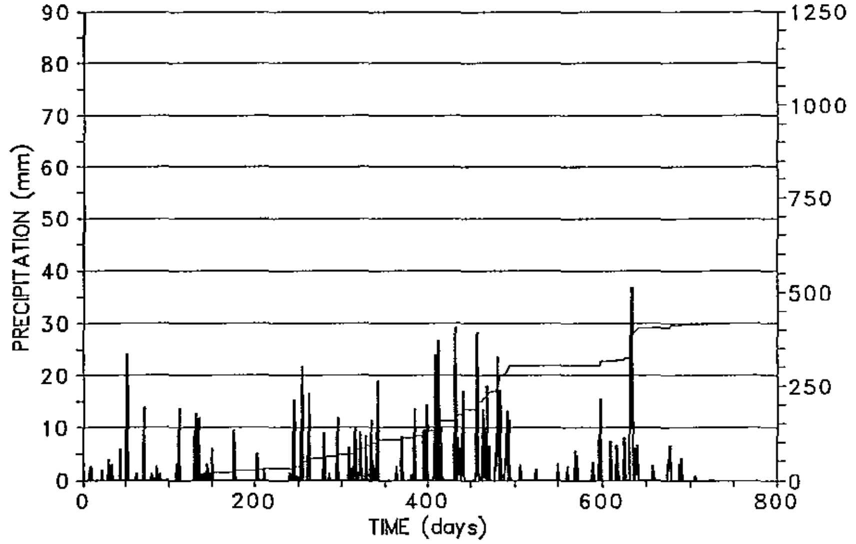


FIGURE C-1 Precipitation Data for 1985 and 1986.

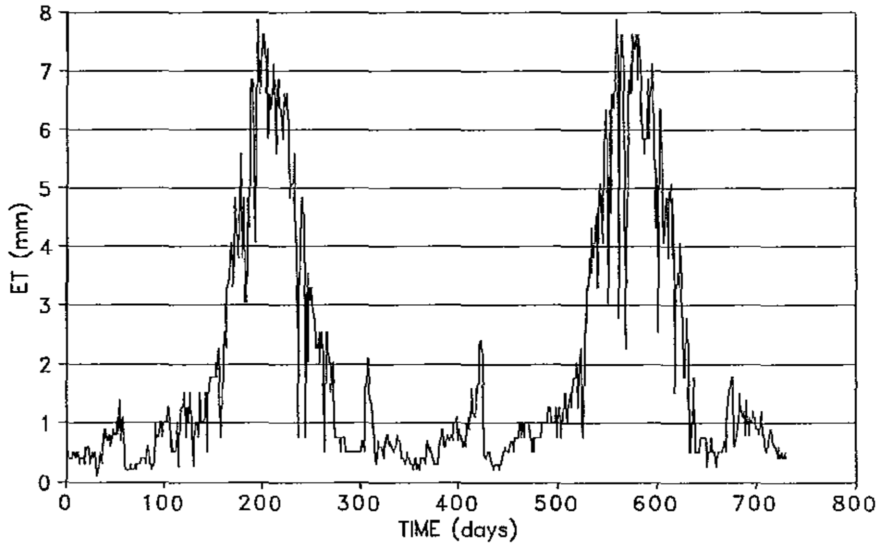
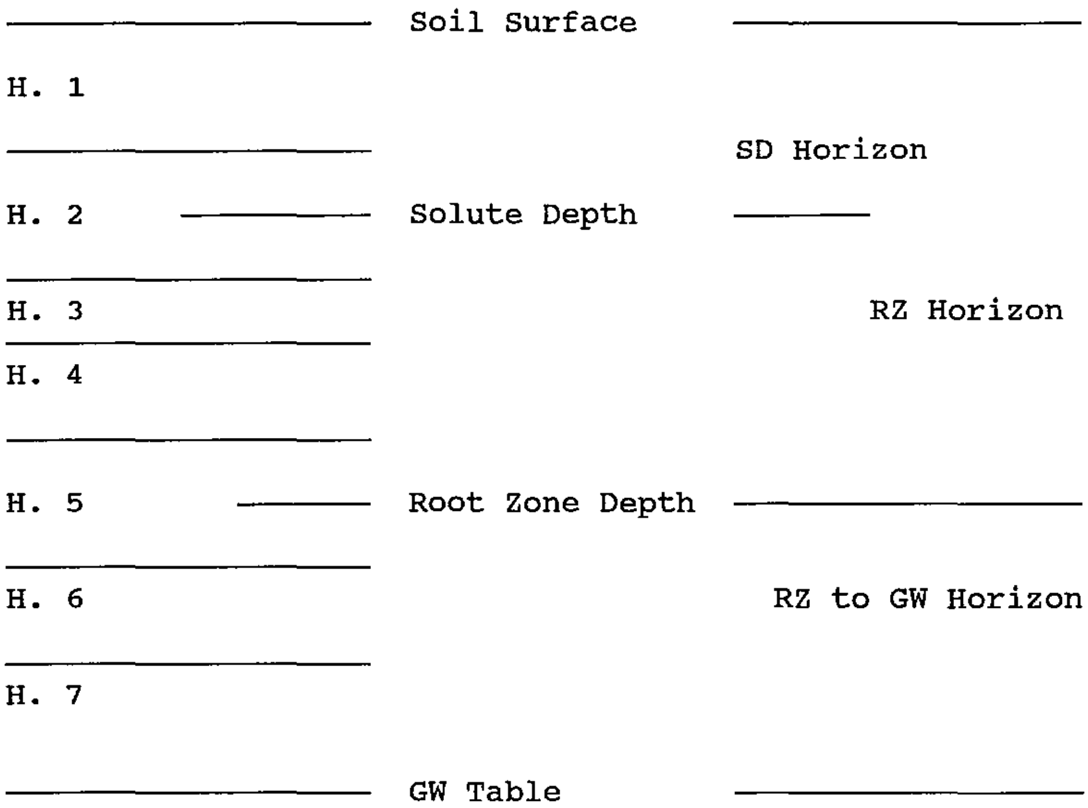


FIGURE C-2 Potential Evapotranspiration Data for 1985 and 1986.

APPENDIX D
GRAPHS AND TABLES OF THE RESULTS



(1) Given Soil Section   (2) Significant Elevations   (3) Transformed Soil Section

H. is a soil horizon
RZ is the root zone
SD is the solute depth (this changes with time)
GW is groundwater table

FIGURE 1. Given Soil Horizons and Soil Sections Transformed for the Optimization Model

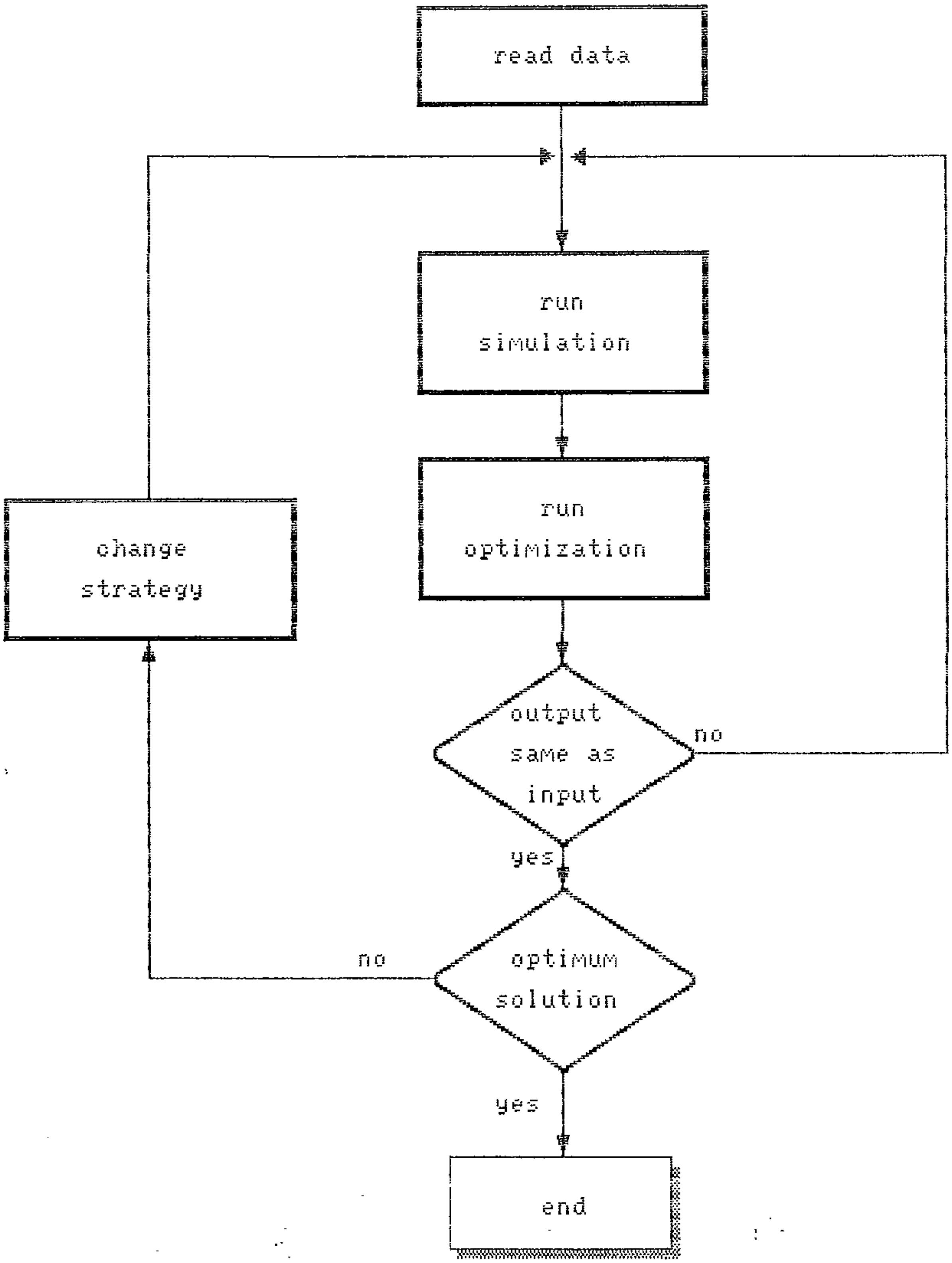


FIGURE 2. Flow Chart of the Cyclical Optimization Process

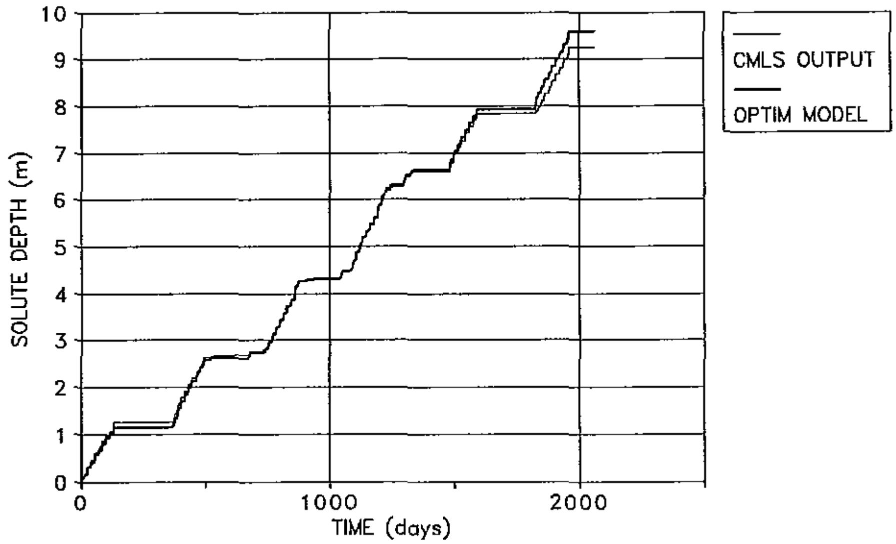


FIGURE 3. Comparison Between Output from the Procedure Used by This Model and That of CMLS.

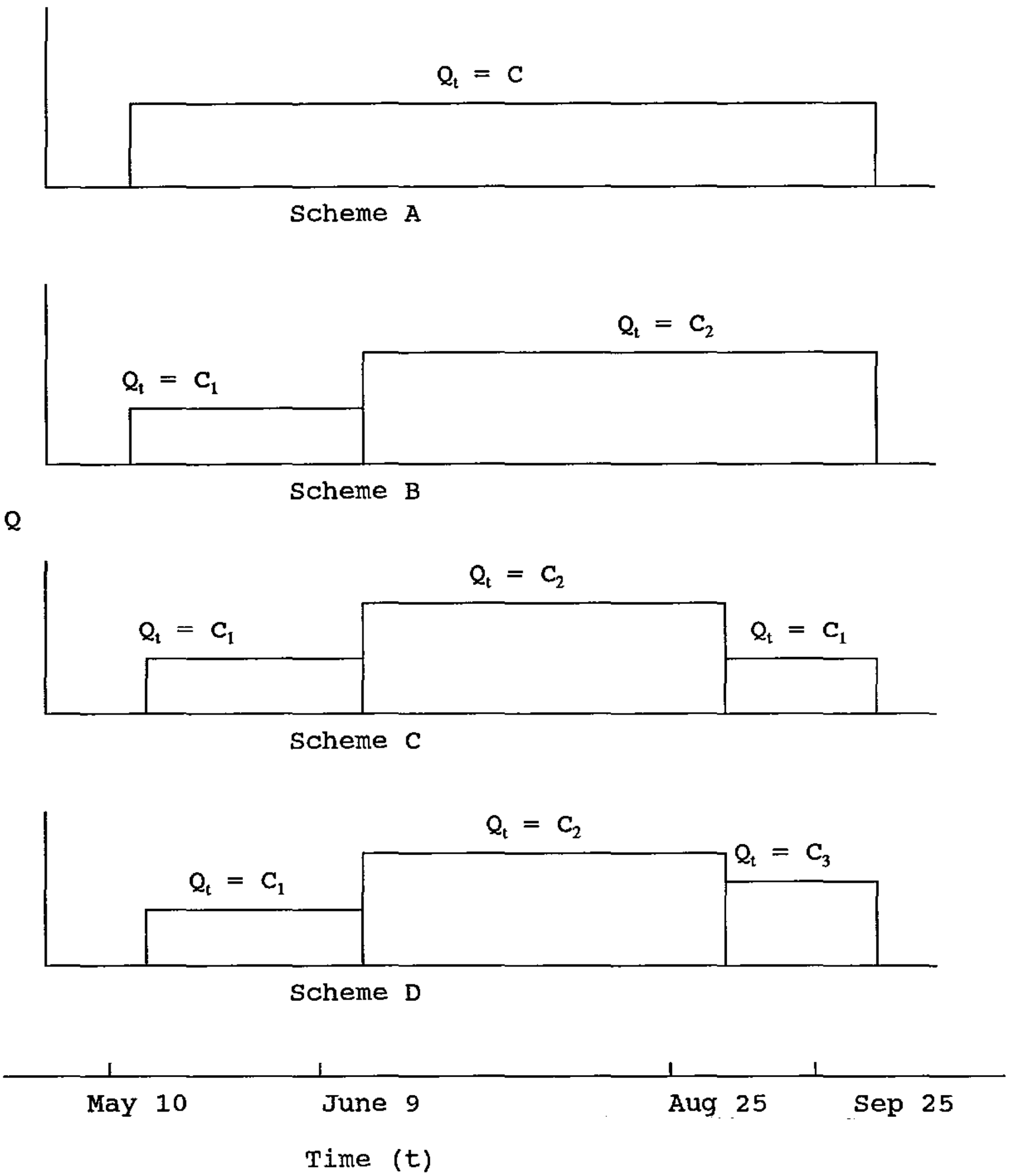


Figure 4. Irrigation Schemes
(C, C_1, C_2, and C_3 are constant values determined by the optimization model. During the blocked time periods the computed Q's are applied based on assumed frequencies.)

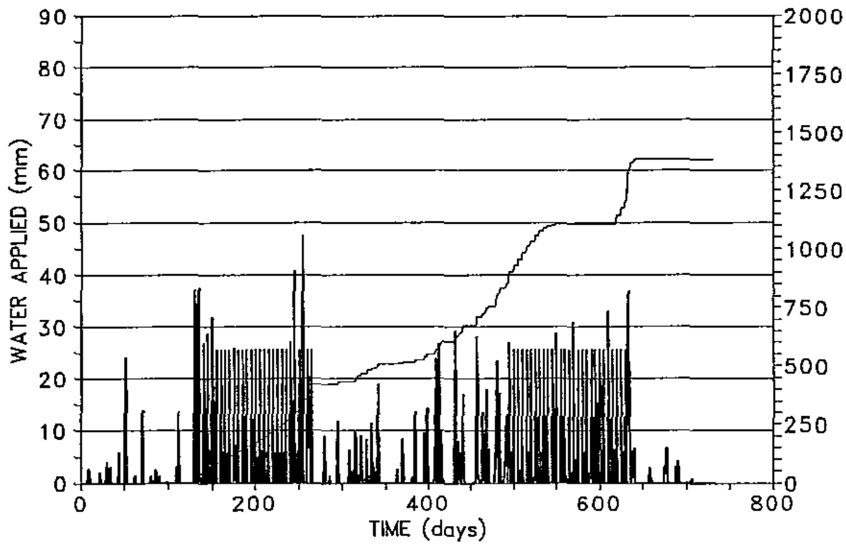


FIGURE 5. Infiltrating Water (Optimal Application + Precipitation) and Solute Depth for Scenario 5A (5-day Frequency and Constant Irrigation Application).

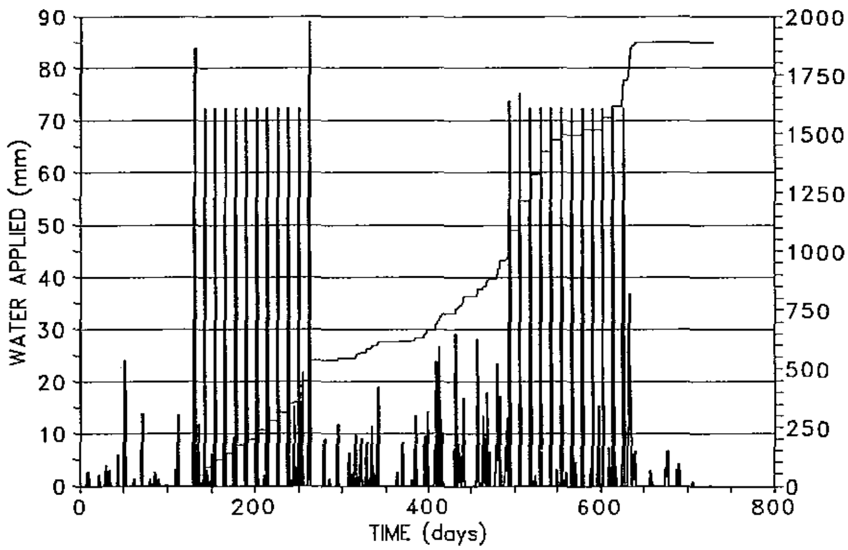


FIGURE 6. Infiltrating Water (Optimal Application + Precipitation) and Solute Depth for Scenario 12A (12-day Frequency and Constant Irrigation Application).

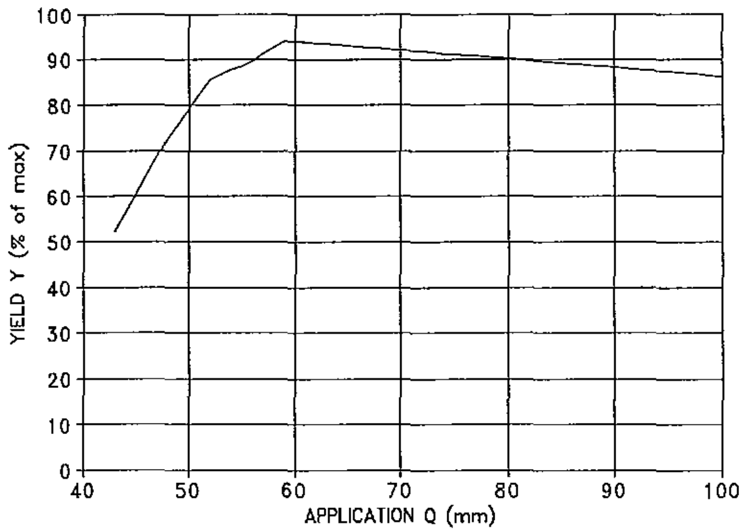


FIGURE 7. Yield as a Function of Irrigation for Scenario 10A (10-day Frequency and Constant Irrigation Application). * indicates the result from the use of the optimization model. All other values are from direct simulation.

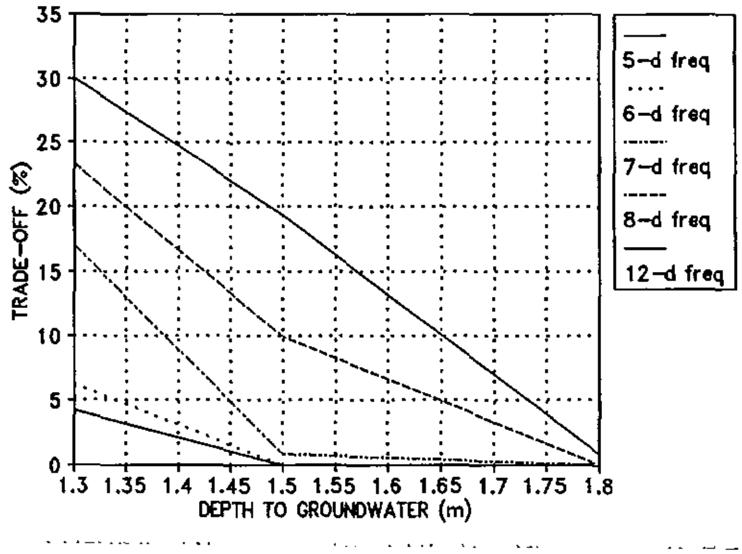


FIGURE 8. Minimum Reduction in Yield (%) Required to Satisfactorily Protect Groundwater Quality, for Known Depths to Groundwater and Irrigation Frequencies.

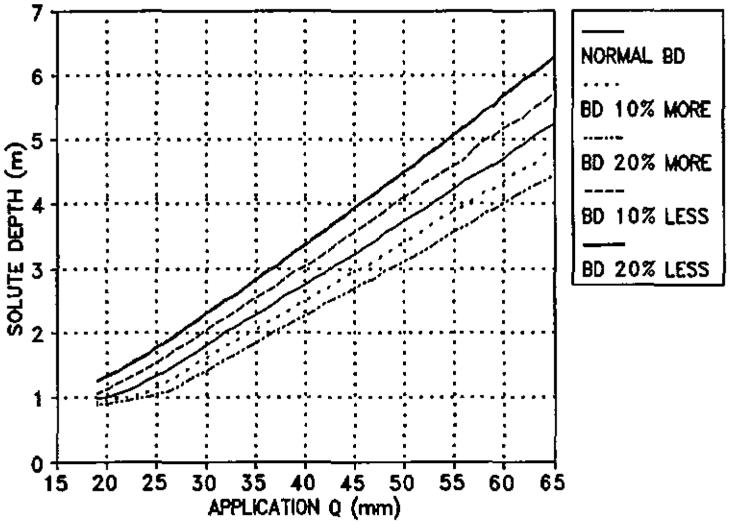


FIGURE 9. Effect of Change in Bulk Density on Estimated Solute Depth for Scenario 5A (5-day Frequency and Constant Irrigation Application).

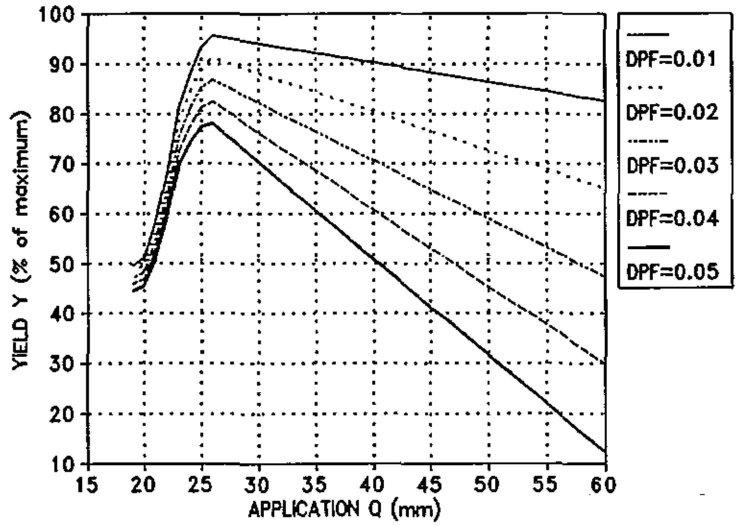


FIGURE 10. Effect of Change in Deep Percolation Factor on Estimated Yield for Scenario 5A (5-day Frequency and Constant Irrigation Application).

TABLE 1. Vineyard Soil Data.
(Eisele et. al. 1989)

Soil Name : VINEYARD — Identifier : UT0350

H	D (m)	OC (%)	BD (Mg/cu m)	Volumetric WC, (%) at -0.01 MPa	-1.5 MPa	Saturation
1	0.18	0.81	1.70	16.0	8.0	40.0
2	0.33	0.47	1.70	16.0	8.0	40.0
3	0.61	0.31	1.70	17.0	9.0	40.0
4	0.89	0.21	1.70	18.0	9.0	40.0
5	1.07	0.21	1.70	19.0	10.0	40.0
6	1.52	0.12	1.70	16.0	8.0	40.0

TABLE 2. Pesticide Data for Atrazine
(USDA-ARS 1988)

Common Name	:ATRAZINE
Partition Coefficient	:100 mg/g OC
Half-Life	:60 days
Health Advisory	:3 ppb
Use	:HERBICIDE
Trade Name	:AATREX
Trade Name	:GRIFFEX
Trade Name	:ATRANEX
Trade Name	:VECTAL SC

TABLE 3. Plant Growth Stages and Corresponding Factors
(Neale, 1990)

Growth Period	Days from Planting	Factor
Vegetative	0 to 75	0.4
Flowering	76 to 80	1.5
Yield formation	81 to 117	0.5
Ripening	118 to 135	0.2

TABLE 4. Summary of Optimization Run Identification Numbers

IRRIG. FREQUENCY (DAYS)	MAX YIELD, NO WATER QUALITY CONSTRAINT				MAX YIELD, WATER QUALITY CONSTRAINT		
	IRRIGATION SCHEME				DEPTH TO WATER TABLE (m)		
	A	B	C	D	1.3	1.5	1.8
5	5A	5B	5C	5D	5E	5F	5G
6	6A	6B	6C	6D	6E	6F	6G
7	7A	7B	7C	7D	7E	7F	7G
8	8A	8B	8C	8D	8E	8F	8G
9	9A	9B	9C	9D	9E	9F	9G
10	10A	10B	10C	10D	10E	10F	10G
11	11A	11B	11C	11D	11E	11F	11G
12	12A	12B	12C	12D	12E	12F	12G
510	510A	510B					

TABLE 5. Output for the Optimization Runs not using Pesticide Constraints

RUN #	Q (mm)	Q1 (mm)	Q2 (mm)	Q3 (mm)	YIELD (%)	SD (m)	ΣQ (mm)
5A	25.6				95.75	1.38	717.64
5B		9.14	28.57		97.56	1.07	664.05
5C		3.62	27.43		99.23	0.84	458.41
5D		0.23	26.87	4.45	99.60	0.82	431.36
6A	31.3				95.69	1.40	719.67
6B		16.32	32.09		97.40	1.05	627.82
6C		9.2	32.00		98.88	0.87	485.20
6D		0.23	31.37	11.6	99.61	0.83	424.48
7A	38.0				95.13	1.53	760.20
7B		14.69	39.73		97.43	1.07	619.39
7C		8.43	38.27		98.77	0.88	437.16
7D		0.31	38.01	6.64	99.41	0.83	370.71
8A	45.0				94.49	1.69	809.46
8B		19.9	44.97		96.92	1.14	659.02
8C		8.21	44.97		98.52	0.90	478.58
8D		0.03	44.97	8.14	98.98	0.87	428.31
9A	51.9				94.18	1.77	830.72
9B		16.07	51.92		97.16	1.12	615.58
9C		13.57	51.92		98.40	0.91	562.21
9D		7.02	51.92	13.57	98.76	0.88	446.22
10A	59.1				94.21	1.73	827.12
10B		27.47	59.08		96.51	1.15	700.62
10C		17.87	62.11		97.90	0.95	559.47
10D		6.81	59.08	15.34	98.91	0.87	486.77
11A	68.62				88.07	1.97	892.06
11B		17.05	68.62		91.38	1.17	685.69
11C		11.80	68.62		92.41	0.94	551.15
11D		0.09	68.62	3.838	93.00	0.88	423.59
12A	72.4				87.74	1.88	868.32
12B		25.1	72.00		92.67	1.16	676.18
12C		23.6	72.00		93.81	0.97	622.17
12D		0.18	72.00	24.42	94.72	0.90	433.98
510A	59.1				89.40	2.90	886.14
510B		8.24	60.09		96.94	1.15	486.54

SD is solute depth

ΣQ is seasonal irrigation amount (average of the 2-year period)

TABLE 6. Output for the Maximized Yield Runs which Utilize Water uality Constraints and Constant Irrigation Amount

MAX Y RUNS				
RUN #	Q (mm)	YIELD (%)	DEPTH TO WATER TABLE (m)	SEASONAL WATER USE (mm)
5E	24.68	91.53	1.30*	691.04
5F	25.60	95.75	1.50	717.64
5G	25.60	95.75	1.80	717.64
6E	29.97	89.46	1.30*	688.16
6F	31.30	95.69	1.50	719.67
6G	31.30	95.69	1.80	719.67
7E	34.46	78.15	1.30*	689.20
7F	37.85	94.31	1.50*	757.00
7G	38.00	95.13	1.80	760.20
8E	38.56	71.18	1.30*	694.08
8F	41.69	84.57	1.50*	750.42
8G	45.00	94.49	1.80	809.46
9E	42.04	64.79	1.30*	672.64
9F	46.86	87.20	1.50*	781.76
9G	51.90	94.18	1.80	830.72
10E	48.47	74.05	1.30*	678.58
10F	53.84	87.58	1.50*	753.76
10G	59.10	94.21	1.80	827.12
11E	51.14	52.88	1.30*	664.82
11F	57.10	75.50	1.50*	742.30
11G	65.12	85.33	1.80*	846.56
12E	57.17	57.70	1.30*	686.04
12F	62.29	68.37	1.50*	747.48
12G	71.33	86.93	1.80*	855.96

* Tight water quality constraint