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Maximizing Conjunctive Use of Surface and Ground Water Under Surface Water Quality Constraints

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MAXIMIZING CONJUNCTIVE USE OF SURFACE AND GROUND WATER UNDER SURFACE WATER QUALITY CONSTRAINTS

ABSTRACT

A simulation/optimization (s/o) model is presented to address the increasingly common conflicts between water quantity and quality objectives. The model can assist water resources analysts in selecting compromise strategies for stream/aquifer systems in which the stream gains water from the aquifer. The water quantity objective is to maximize steady conjunctive use of groundwater and surface water resources. The water quality objective is to maximize waste loading from a sewage treatment plant (STP) to the stream without violating downstream water quality beyond acceptable limits. The STP discharge is proportional to human population.

The two objectives conflict because an increase in groundwater extraction reduces dilution of the stream water contaminants. The result is a decrease in the STP waste loading to the stream and the waste-producing human population that can be supported. The tradeoff between objectives is illustrated graphically via sets of noninferior solutions. The sets of noninferior solutions are prepared using the E-constraint method and assuming different upstream flow rates.

The s/o model includes superposition expressions

describing head and flow responses to decision variables (pumping, diversion, and loadings) and regression expressions describing contaminant concentration responses to these decision variables. Modeled contaminants include: 5-day biochemical oxygen demand, dissolved oxygen, nitrogen (organic, ammonia, nitrite, and nitrate), organic and dissolved phosphorus, total dissolved solids, and chlorophyll-a.

INTRODUCTION

Water resources system management can involve conflicting objectives and complex hydrologic, environmental, and economic constraints. The interdependence of hydrologic components and flows can cause further complexities. Conjunctive use of ground and surface water resources is generally necessary to satisfy the ever-increasing demand for water. However, integrated water management requires good knowledge of how surface water diversion and groundwater pumping affect flows within and between ground and surface water resources.

Conjunctive water management is especially challenging when it must consider environmental objectives. Surface water quality is affected by the amount and type of pollution discharge into it. Both point and nonpoint sources can affect streams. Treated municipal wastewater discharges usually enter streams via point sources. The contaminants are diluted and diminished with time and distance. The quality of stream inflows, including stream/aquifer interflow, affects the self-purification ability of streams.

The objective of this paper is to present a new management model which computes optimal conjunctive water use strategies for a stream/aquifer system. The model maximizes water development while assuring that downstream water quality criteria are satisfied.

RELATED RESEARCH

Computer simulation models using numerical techniques have been developed successfully to describe and evaluate stream/aquifer systems. Simulation models can be used to predict impacts upon stream/aquifer system due to various stimuli. However, it is difficult or unlikely to be able to compute optimal management alternatives using a simulation model alone. A combined simulation/optimization (s/o) model is needed to consider the impacts upon stream/aquifer system flows and concentrations while simultaneously computing optimal management strategies.

Conjunctive water use management

An s/o model for conjunctive water use can be developed using either embedding or response matrix techniques. In the embedding approach, discretized finite difference or finite element approximations of flow equations are embedded directly as constraints in the s/o model[30]. Users of the embedding technique for solving groundwater management problems include Alley et al.[2], Remson and Gorelick[23], Willis and Yeh[30], Peralta et al.[17,18,19], and Gharbi and Peralta[8].

The response matrix technique employs a two-step process. First, an external simulation model is used to compute system responses (aquifer head, stream flow, etc.) to unit stimuli (pumping and diversion). Then, an assemblage of system responses, a response matrix, is incorporated in the s/o model using superposition and linear system theory. Reilly et al.[22] have described superposition and linear system theory for groundwater systems. Theis or Boussinesq equations are generally used for generating these coefficients. Young and Bredehoeft[31], Haimes and Dreizin[10], Peralta et al.[20], and Peralta and Aly[16] applied the response matrix technique in their s/o models to optimize conjunctive use of ground and surface water resources.

Most of these models used coefficients relating groundwater extraction to aquifer head. Constraints in one response matrix s/o model use coefficients relating pumping and/or diversion to aquifer head, stream flow, stream stage, and stream/aquifer interflow[16]. That model uses the U.S. Geological Survey modular finite-difference groundwater flow model (MODFLOW[13]) and a stream flow routing package (STR) by Prudic[21] to develop the coefficients. MODFLOW uses a quasi 3-D groundwater flow equation for simulating the aquifer system. STR uses the nonlinear Manning equation to calculate the stream stage for a particular stream flow. The nonlinearity in a system can be addressed using a cycling procedure[16]. By analogy, cycling causes a linear expression (line) to ever more closely approximate the tangent to an optimal point on a nonlinear expression (curve). The cycling process is described in the subsequent section.

Surface water quality management

Many surface water quality s/o models incorporating the Streeter-Phelps oxygen sag equation (or modification thereof) have been developed[5,6,11,12,24,25,26,27,29]. These models used several optimization algorithms and utilized deterministic and/or stochastic approaches. However, these models are limited to point source loading and did not include spatially varied flow or waste loading. These models are also limited to modeling biochemical oxygen demand and dissolved oxygen as water quality parameters.

Several surface water quality simulation models calculate changes in concentrations of many constituents simultaneously. For example, QUAL2E[4], an U.S. Environmental Protection Agency (USEPA) model, is able to simulate biochemical oxygen demand (BOD), dissolved oxygen (DO), nitrogen species (organic-, ammonia-, nitrite-, and nitrate-nitrogen), organic and dissolved phosphorus, chlorophyll-a, and total dissolved solids, a conservative material.

QUAL2E simulation abilities are detailed and complex. It uses finite-difference approximation of advective-dispersive contaminant transport equation to simulate transport in streams. The reaction term in the equation can simulate processes such as: BOD aerobic decay and settling; organic nitrogen decay and settling; ammonia decay and benthos source production; nitrification; non-conservative material decay and settling; background phosphorus benthos source production and sediment oxygen demand; reaeration; and algae growth, production, respiration, and settling. (All of these processes can be incorporated within the presented s/o model via simplified regression equations).

Using a simulation model to find the best loading strategies while attempting to satisfy many water quality criteria requires much trial and error. Furthermore, it is unlikely that one will obtain an optimal strategy for a complex system using a simulation model alone. Thus, an s/o modeling approach and model are needed for optimally managing surface water quality for multiple constituents in a stream/aquifer system.

Alley[1] described the use of regression equations in groundwater quality s/o modeling. Here, we show the first use of regression equations depicting the effect of waste loading at downstream locations within a nonlinear s/o conjunctive water use model. The methodology for developing regression equations and coupling it within a conjunctive water use management model is the focus of this study.

This work expands previous conjunctive water use management studies by simultaneously: optimizing point source loading; constraining a wide variety of water quality constituents; maximizing conjunctive water use; and addressing a system in which stream/aquifer interflow is affected by the waste loading and groundwater pumping being optimized. The presented multiobjective s/o model optimizes steady conjunctive water use for a stream/aquifer system in which the stream is receiving (1) a point source--nonindustrial municipal (domestic) wastewater, after primary and secondary treatment in a sewage treatment plant (STP); and (2) high quality stream/aquifer interflow from an initially under-utilized groundwater system. The interflow provides dilution of stream contaminants.

The computer model seeks to: (1) maximize water supplied (Z_1) by extracting groundwater and diverting surface water, and (2) maximize the human population (Z_2) that can provide treated waste via STP to the stream without degrading downstream water quality beyond prespecified limits. The two objectives conflict because an increase in groundwater extraction and diversion reduces dilution of the stream water contaminants. The result is a decrease in the capacity of the stream to accept human-generated discharge from the STP. This study is aimed at presenting best compromise levels of Z_1 and Z_2.

Conflicting goals of this management problem can be addressed using multiobjective programming (MOP). MOP aims at generating a set of best compromise levels of conflicting goals and selecting one with the aid of decision maker(s). Objectives specification, plans generation, and plan selection are the steps of MOP. The best compromise levels of Z_1 and Z_2 in this problem are developed using the E-constraint method[7]. In the E-constraint method, one objective is optimized while other objectives are used as bounded constraints. Here, the objective of maximizing the total water supplied is included as the objective function. The human population objective is included as a constraint, which will be tight for each noninferior solution[7].

The optimal solution to a MOP problem is termed a noninferior solution. A noninferior solution is a solution for which the increase in the value one objective will require decrease in the values of other objectives. Here, sets of noninferior solutions are presented graphically for different upstream flow rates to illustrate how to assist decision makers in plan selection.

MODEL DEVELOPMENT

The s/o model developed here is applied to a hypothetical study area (Figure 1). The principal objective is to maximize the water provided from stream diversions and groundwater pumping wells to meet water demand. Let $g(\hat{a})$, in m^3/s, be the steady groundwater extraction rate at cell $\hat{a}$, and $d(\hat{e})$ in m^3/s, be the steady diversion rate at reach $\hat{e}$.

$$\mathit{MAXIMIZE}\ Z_1 = \sum_{\hat{a}=1}^{M^p} C^p(\hat{a})\ g(\hat{a}) + \sum_{\hat{e}=1}^{M^d} C^d(\hat{e})\ d(\hat{e}) \qquad (1)$$

where $C^p(\hat{a})$ and $C^d(\hat{e})$ are weighting coefficients for pumping (1) and diversion (1), respectively. By changing the values of coefficients, they can be used for economic optimization and emphasizing or deemphasizing specific decision variables.

A variable can be made ineffective in the objective function by setting its weighting coefficient equal to zero. M^p and M^d are the total numbers of pumping cells and diversion locations, respectively.

The objective function in equation (1) is subject to several constraints, including a lower bound (Z_2^L) on the constraint objective (Z_2). The constraint objective is to maximize the human population for which a stream system can satisfactorily assimilate the waste. Z_2 is calculated by dividing the optimal steady flow rate through the STP, $q^p(1)$ in m^3/s, by a specified per capita waste generation rate (q^{pcg} in $m^3/s \cdot capita$).

$$\frac{q^p(1)}{q^{pcg}} = Z_2 \geq Z_2^L \tag{2}$$

The values of Z_2^L represent the minimum number of people to be served by the STP for a particular optimization run. This constraint objective will be tight for a noninferior solution. The range of Z_2^L for which the two objectives conflict is from $Z_{2 \text{ at maximum } Z1}$ to maximum Z_2. To construct one set of noninferior solutions, the value of Z_2^L is varied systematically from one extreme to the other and one optimization is performed for each selected value of Z_2^L.

The principal and constraint objectives are subject to two sets of constraints: (1) surface water quality constraints expressing STP contaminant removal efficiencies, reactions and contaminant transport, and stream water quality limitations; and (2) stream/aquifer system response constraints for aquifer head, stream reach outflow, and stream/aquifer interflow.

Constraints for the surface water quality components

The constituents modeled and constrained are 5-day biochemical oxygen demand (BOD_5), dissolved oxygen (DOX), organic nitrogen (OGN), ammonia nitrogen (NH_3), nitrite nitrogen (NO_2), nitrate nitrogen (NO_3), organic phosphorus (OGP), dissolved phosphorus (DSP), chlorophyll-a (CHA), and total dissolved solids (TDS). Simulation of the transport of the j^{th} constituent is represented via the following regression equations. The development of a regression equation is explained in the subsequent section.

$$\tilde{n}(\hat{u},j) = \beta^{sri}(j) \sum_{\breve{u}=1}^{M^{sri}} \tilde{n}^{sri}(\breve{u},j) + \beta^{ov}(j) \sum_{\breve{u}=1}^{M^{ov}} \tilde{n}^{ov}(\breve{u},j) + \beta^{p}\, \tilde{n}^{p}(1,j) \quad \textbf{(3)}$$

$$\tilde{n}(\hat{u},DOX) = \beta^{o}(DOX) + \beta^{sri}(DOX) \sum_{\breve{u}=1}^{M^{sri}} \tilde{n}^{sri}(\breve{u},DOX) + \beta^{ov}(DOX) \sum_{\breve{u}=1}^{M^{ov}} \tilde{n}^{ov}(\ddot{u},DOX)$$
$$+ \beta^{p}(DOX)\, \tilde{n}^{p}(1,DOX) + \beta(BOD)\, \tilde{n}(\hat{u},BOD) + \beta(TON)\, \tilde{n}(\hat{u},TON) + \beta(CHA)\, \tilde{n}(\hat{u},CHA) \quad \textbf{(4)}$$

where $\tilde{n}^{x}(i,j)$ is the mass flow rate of the j^{th} constituent in the i^{th} reach of the x^{th} type of source location (superscripts sri, ov, and p represent stream/aquifer interflow, upstream, and STP, respectively), and is expressed as $\tilde{n}^{x}(i,j) = q^{x}(i) \cdot C^{x}(i,j)$, in g/s except for chlorophyll-a which is in mg/s; $\tilde{n}(\hat{u},j) = q^{s}(\hat{u}) \cdot C(\hat{u},j)$, is the j^{th} constituent mass flow rate at reach $\hat{u}$ (control location); $q^x(i)$ and $q^s(\hat{u})$ are flow rates in m^3/s; $C^x(i,j)$ and $C(\hat{u},j)$ are concentrations in mg/L except for chlorophyll-a concentration, which is in $\mu g/L$; $\beta^x(j)$ and $\beta(j)$ are regression coefficients describing the contribution of specific mass flow rate to $\tilde{n}(\hat{u},j)$; and M^{sri} and M^{ov} are numbers of stream/aquifer interflow reaches and upstream sources to the stream above the control location, respectively.

Equation 3 predicts the j^th constituent (except dissolved oxygen) mass flow rate at a control location as a function of its mass flow rate from stream/aquifer interflow, upstream, and STP. Equation 4 predicts the dissolved oxygen mass flow rate at a control location as a function of its mass flow rate from stream/aquifer interflow, upstream, and STP, and mass flow rates of BOD_5, total nitrogen, and chlorophyll-a at the control location.

Constraints expressing stream/aquifer system response

Influence coefficients are used in the constraint equations to describe aquifer head, stream reach outflow, and stream/aquifer interflow of a steady state stream/aquifer system:

$$h(\hat{o}) = h^{non}(\hat{o}) + \sum_{\hat{a}=1}^{M^p} \delta^h(\hat{o},\hat{a}) \frac{g(\hat{a})}{g^{ut}(\hat{a})} + \sum_{\hat{e}=1}^{M^d} \beta^h(\hat{o},\hat{e}) \frac{d(\hat{e})}{d^{ut}(\hat{e})} \tag{5}$$

$$q^s(\hat{u}) = q^{snon}(\hat{u}) + \sum_{\hat{a}=1}^{M^p} \delta^s(\hat{u},\hat{a}) \frac{g(\hat{a})}{g^{ut}(\hat{a})} + \sum_{\hat{e}=1}^{M^d} \beta^s(\hat{u},\hat{e}) \frac{d(\hat{e})}{d^{ut}(\hat{e})} \tag{6}$$

$$q^{sri}(\tilde{u}) = q^{srinon}(\tilde{u}) + \sum_{\hat{a}=1}^{M^p} \delta^{sri}(\tilde{u},\hat{a}) \frac{g(\hat{a})}{g^{ut}(\hat{a})} + \sum_{\hat{e}=1}^{M^d} \beta^{sri}(\tilde{u},\hat{e}) \frac{d(\hat{e})}{d^{ut}(\hat{e})} \qquad (7)$$

where $\delta^h(\hat{o},\hat{a})$ and $\beta^h(\hat{o},\hat{e})$ are, respectively, the influence coefficients describing effect of groundwater pumping at cell $\hat{a}$ and stream diversion at reach $\hat{e}$ on aquifer head $h(\hat{o})$ at cell $\hat{o}$. Similarly, influence coefficients $\delta^s(\hat{u},\hat{a})$ and $\beta^s(\hat{u},\hat{e})$ describe stream flow $q^s(\hat{u})$ at reach $\hat{u}$; and $\delta^{sri}(\tilde{u},\hat{a})$ and $\beta^{sri}(\tilde{u},\hat{e})$ describe stream/aquifer interflow $q^{sri}(\tilde{u})$ at reach $\tilde{u}$. $h^{non}(\hat{o})$, $q^{snon}(\hat{u})$, and $q^{srinon}(\tilde{u})$ are nonoptimal aquifer head, stream reach outflow, and stream/aquifer interflow, respectively. $g^{ut}(\hat{a})$ and $d^{ut}(\hat{e})$ are specified unit pumping and stream diversion rates used to generate influence coefficients. The first summation on the right hand sides of Equations 5-7 describes the effect of optimal pumping on respective state variables. The second summation describes the effect of optimal diversions including STP discharge (a negative diversion). Here, $d(1)$ is synonymous with $q^p(1)$ used within Equations 3 and 4.

Table 1 lists decision and state variables, and fixed parameters used in this s/o model. Lower and upper bounds are utilized for groundwater pumping, stream diversion, aquifer head, stream reach outflow, stream/aquifer interflow, and concentration of modeled constituents at the control location.

APPLICATION AND RESULTS

Study area, background, and assumptions

A hypothetical study area (Figure 1) is formulated to show applicability of the presented s/o model. A suburban community is discharging its wastewater, after treatment by a sewage treatment plant (STP). Stream flow is sustained by upstream inflows and flows from a single layer alluvial unconfined aquifer. These good quality flows dilute the STP effluent. Average daily per capita domestic flow (q^{pcg}) of 70 gallons (270 liters)[14] is assumed.

Assume that the regional water resources management agency desires to increase water use by installing pumping wells and diverting surface water. To illustrate the effects of these developments, the area is divided into 100 cells of uniform size of 1500 m by 500 m. The aquifer has no flow boundaries on the east and west. North and south boundaries provide constant bedrock recharge to the aquifer. Rainfall in the area recharges the aquifer at a rate of 300 mm per year.

The homogeneous unconfined aquifer has a hydraulic conductivity of 5.21 x 10^{-5} m/s, saturated thickness of 53 m, and specific yield of 0.2. Twenty cells are selected as potential groundwater extraction (pumping) locations. Aquifer heads at these potential pumping locations are prevented from dropping too much by using lower bounds.

The stream exhibits excellent saturated hydraulic connection with the aquifer. The stream has an average width of 10 m and an average depth of 3 m. The stream is divided into 20 equal reaches of 1500 m length. These reaches have streambed conductance of 0.3473 m^2/s. The STP is located 1.5 km from the west end and is discharging its effluent to the stream. Existing water users have permits to divert at two locations downstream. Figure 1 shows these diversion locations and the water quality monitoring location (also termed a control location) on the stream. The monitoring location is upstream of diversions to ensure permissible quality of diverted water. The stream bottom is 50 m above a horizontal datum.

Contaminant concentrations in upstream inflow, STP effluent, and stream/aquifer interflow are assumed known (Table 2). Table 3 specifies ranges and fixed flow rates used in the simulation and/or s/o models. Table 2 also provides imposed water quality criteria. These criteria, which combine constituent limits normally applied for agriculture, drinking water, aesthetics, and fisheries, are imposed at the control location.

Modeling procedure

The s/o modeling procedure consists of detailed simulation of the hydrologic system, optimization, and post-optimization simulation, results comparison, and closure (Figure 2).

1A. Developing surface water quality response *expressions*. Simulation of contaminant concentration response to mass flow stimuli and reactions is expressed via regression equation. Regression equations are developed using the following steps:

i. Three values for flow rate and concentration for each constituent in upstream, STP effluent, and stream/aquifer interflow are assumed, based on historical stream data, forecasted data, and expected STP treatment efficiencies (see Table 3 for ranges of flow rates used);

ii. QUAL2E is run for the unique assigned combination of flow rates and concentrations in upstream, STP, and stream/aquifer interflow;

iii. Results (flow rate and concentration of each constituent) are noted at the control location; and

iv. Multiple regression is performed to analyze the results for each constituent. The form of equation 3 is found to be best for predicting the concentrations of all constituents except dissolved oxygen. Equation 4 is the best for dissolved oxygen.

Steps (ii) and (iii) are repeated systematically to carry out step (iv) as shown in Figure 2. Loops around steps (ii) and (iii) can be imagined as six nested DO-loops in a typical FORTRAN program. Processing in the two innermost loops is as follows. The innermost loop for the variable 'C_{ij}^{d}' depicts that the concentration of all the constituents in stream/aquifer interflow are changed simultaneously and assigned assumed values three times while all other variables are held constant. Three simulation runs are made and recorded. Then, we go to the second innermost loop. Stream/aquifer interflow (Q_i^d) values in all reaches are changed simultaneously and assigned their second assumed values. The innermost loop is completed as described. A total of 729 simulation runs is made.

1B. Developing stream/aquifer system influence coefficients.

The response matrix technique is utilized to simulate stream/aquifer system hydraulic responses to stimuli (pumping, diversion, and loading). The MODFLOW/STR model is used to generate influence coefficients.

i. The stream/aquifer system is simulated for nonoptimal and specified unit stimuli to generate influence coefficients; and

ii. Influence coefficients for the desired locations and variables are collected and organized as superposition expressions (equations 6 through 8).

2. Optimization. The optimization model being solved consists of equations 1 through 8. Optimization is performed using the Modular In-core Optimization System (MINOS) solver[15].

3. Post-optimization simulation, results comparison, and closure. After optimization, we use MODFLOW/STR and QUAL2E to simulate in detail how the system will respond to the optimal strategy computed by the s/o model. We compare the results simulated by these models. If system responses computed by the s/o model and QUAL2E/MODFLOW/STR simulation are effectively the same, we state that they have converged. Since the optimal strategy satisfies all constraints, we can stop. Until convergence is achieved, we redevelop equations 3, 4, and 6-8 as described. Each pass through equations 3, 4, and 6-8 is termed a cycle.

When the end step of Figure 2 is reached, one has computed an optimal strategy for a posed scenario. A scenario consists of a particular combination of constraints for which a unique optimal solution is computed.

Tested schemes, scenarios, and results

We develop optimal conjunctive water use and loading strategies for several scenarios within each stream flow scheme. Schemes differ in the upstream inflow that is assumed. The basic scheme assumes that the 7-day average minimum stream flow occurring once in 10 years (7Q10) is 1.5 m^3/s. This specified probability of occurrence for stream flow makes stream water quality management nondeterministic in nature. A set of noninferior solutions for this scheme is developed by changing Z_2^L incrementally from $Z_{2 \text{ at maximum } Z1}$ to maximum Z_2. For each different value of Z_2^L, a noninferior solution is computed (Figure 3). Also shown are two other sets of noninferior solutions developed for schemes having upstream inflows of 1.6 and 1.4 m^3/s. These sets of noninferior solutions show sensitivity of optimal strategies to nondeterministic upstream flows. Each point on a particular set of noninferior solutions represents one optimal strategy that satisfies all imposed constraints.

The upper limit on total nitrogen concentration (20 mg/L) at the control location is tight for all three sets of noninferior solutions. These curves appear to be linear except at their ends. The nonlinearities at the ends of each set of noninferior solutions result from stream/aquifer interflow upper and lower bounds becoming tight.

The two conflicting objectives represented by these sets of noninferior solutions are (1) maximizing the total water supplied from ground and surface water resources, and (2) maximizing the population for which the stream system can handle the waste. Along any set of noninferior solutions, as supplied water increases, the STP discharge that can be accepted decreases (i.e., increasing groundwater pumping decreases stream/aquifer interflow and dilution and decreases the permissible STP discharge). These sets of noninferior solutions help management understand the tradeoff between the two objectives. The tradeoff is the slope of a curve (the change in amount of water supplied per unit change in human population). Since the three sets of noninferior solutions in Figure 3 appear parallel, the tradeoff is the same for each.

Management can select compromise strategies as best suit their needs. Assume a water supply requirement of 1500 LPS (34 MGD) for a compromise solution. The human population that can be supported depends on the upstream flow. The STP can discharge treated wastewater generated by populations of 228,000; 238,000; and 248,000 for upstream flows of 1.4 m^3/s, 1.5 m^3/s, and 1.6 m^3/s, respectively. For these compromise solutions, optimal STP discharges are 15.96, 16.66, and 17.36 MGD, respectively. Table 4 provides these optimal conjunctive water use and loading strategies (solutions A_1, A_2, and A_3) at different upstream inflows and a known STP effluent quality. The upper bound on total nitrogen concentration (20 mg/L) was tight for all strategies comprising the sets of noninferior solutions. Sensitivity analysis showed that an increase of up to 10% in human population is permitted by relaxing this tight bound.

It is appropriate to verify that the regression approach accomplishes its goal. This is done by using the optimal strategy as input to QUAL2E, simulating system response and checking the concentration at the control location. Table 4 shows concentrations computed by s/o model, and those subsequently simulated by QUAL2E as a result of implementing the optimal strategy. The regression approach is satisfactorily accurate when compared with QUAL2E simulation results. This is illustrated via Table 5, which provides the statistics of comparison of constituent concentration at the control location predicted by s/o model with those subsequently simulated by QUAL2E. It appears that NO_2 and DOX are less accurately estimated than other constituents. However, relative values in Table 4 and 5 show that the estimation differences are less than 0.30 ppm and 1.00 ppm, respectively, which are acceptable given common variances in field values and monitoring error. Furthermore, because a lower bound is used on DOX and DOX is slightly underestimated, an optimal strategy is conservative in assuring that the DOX bound is satisfied. As explained earlier, more accuracy can be achieved by continuing cycling.

SUMMARY

A method for incorporating surface water quality constraints within conjunctive water use simulation/ optimization models for hydraulically connected stream/ aquifer systems, is presented. It provides means for addressing conflicts between maximizing water use and maximizing waste loading. This increasingly common conflict arises when increasing water use reduces the dilution needed to increase loading. Optimal steady conjunctive water use and waste loading strategies are computed which do not violate downstream water quality constraints. Transport of constituents in the stream is represented via regression equations. Considered constituents are 5-day biochemical oxygen demand, dissolved oxygen, total dissolved solids,

nutrients (nitrogen and phosphorus), and chlorophyll-a.

The presented s/o model utilizes the response matrix approach for representing volumetric and head responses to hydraulic stimuli. It includes regression equations to describe surface water quality response to management. Tradeoffs between water use and wastewater loading are presented.

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Table 1. Decision and state variables, and fixed values

Source/Location	Decision and State Variables	Fixed Values
Surface Water Quality Component:		
Point Source (STP)	Flow Rate, Population*.	Per Capita Flow, Removal Efficiencies, Domestic (non-industrial municipal) Waste Characterization, and Effluent Concentrations.
Stream/aquifer Interflow	Flow Rate.	Concentrations.
Control Location	Flow Rate, and Concentrations.	
Upstream		Flow Rate, and Concentrations.
Conjunctive Water Use Component:		
	Pumping*, Diversion*, Stream/aquifer Interflow, Stream Reach Outflow, Aquifer head.	Unit pumping and Diversion, Recharge, Conductance, Boundary Fluxes, Permeability.

* Decision variable.

Table 2. Assumed fixed concentrations from upstream, STP and stream/aquifer (S/A) interflow and maximum values for agricultural use

Constituent		Upstream mg/L	STP mg/L	S/A interflow mg/L	Maximum Value[b] mg/L
Five-day Biochemical Oxygen Demand	(BOD$_5$)	5.00	62.00	5.00	15.00[c]
Organic Nitrogen	(OGN)	2.00	15.00	0.00	10.00
Ammonia Nitrogen	(NH$_3$)	2.00	32.00	0.00	15.00
Nitrite Nitrogen	(NO$_2$)	0.10	0.20	0.03	1.00[d]
Nitrate Nitrogen	(NO$_3$)	5.00	9.20	5.00	10.00[d]
Total Nitrogen	(TON)	9.10	56.40	5.03	20.00[c]
Organic Phosphorus	(OGP)	2.00	3.00	1.00	5.00
Dissolved Phosphorus	(DSP)	2.00	5.60	1.00	5.00
Total Phosphorus	(TOP)	4.00	8.60	2.00	5.00[c]
Chlorophyll-a (μg/L)	(CHA)	2.00	3.00	0.00	5.00
Dissolved Oxygen	(DOX)	6.00	3.00	4.00	5.00[d]
Total Dissolved Solid	(TDS)	160.00	800.00	160.00	350.00

[a] Typical values adopted from Metcalf and Eddy Inc.[14] for nonindustrial municipal (domestic) wastewater after it has received primary and secondary treatment.

[b] Standards used are NO$_2$ and NO$_3$ for drinking water; BOD$_5$, TON, TOP for unrestricted irrigation; CHA for aesthetic use; and minimum DOX for fisheries.

[c] Typical values adopted from Bouwer and Idelovitch[3].

[d] Typical values adopted from SCS-USDA[28].

Table 3. Assumed ranges of flow rates from upstream, STP, and stream/aquifer interflow used for developing regression equations

		Maximum Value		Minimum Value	
		(m^3/s)	(gal/day) x10^6	(m^3/s)	(gal/day) x10^6
Sewage Treatment Plant or Point Source Flow:	$q^{p}(1)$	1.00	22.86	0.200	4.57
Upstream:	$q^{ov}(\ddot{u})$	1.75	40.00	1.250	28.57
Diffused Sources: (Typical Flow in Reach $\bar{u}$)	$q^{sri}(\bar{u})$	0.05	1.14	0.007	0.16

Table 4. Optimal strategies (solutions A_1, A_2, and A_3) at different upstream flow rates (q^{ov}(ü))

Constituent	STP Effluent	q^{ov}(ü) @ Control Location (from s/o Model) (m^3/s) 1.40	1.50	1.60	q^{ov}(ü) @ Control Location (from QUAL2E) (m^3/s) 1.40	1.50	1.60
Concentrations:							
BOD_5 (mg/L)	62.00	12.93	12.88	12.84	12.70	12.77	12.83
OGN (mg/L)	15.00	4.13	4.14	4.15	4.14	4.16	4.18
NH_3 (mg/L)	32.00	9.42	9.42	9.41	9.56	9.56	9.55
NO_2 (mg/L)	0.20	0.26	0.26	0.26	0.55	0.54	0.54
NO_3 (mg/L)	9.20	6.19	6.18	6.18	6.23	6.22	6.21
TON (mg/L)	56.40	20.00*	20.00*	20.00*	20.48	20.49	20.48
OGP (mg/L)	3.00	1.56	1.57	1.57	1.56	1.57	1.59
DSP (mg/L)	5.60	3.04	3.05	3.06	3.22	3.23	3.23
TOP (mg/L)	8.60	4.60	4.62	4.63	4.78	4.80	4.82
CHA (μg/L)	3.00	1.87	1.90	1.92	1.91	1.94	1.97
DOX (mg/L)	3.00	5.14	5.16	5.17	5.91	5.85	5.81
TDS (mg/L)	800.0	322.6	322.0	321.6	326.9	326.4	325.8
Total Pumping (LPS)		500.0	500.0	500.0			
Total Diversion (LPS)		1000.	1000.	1000.			
STP Discharge (LPS)		699.0	729.0	759.0			
Population (in thousand)		228.0	238.0	248.0			
Total Water Supplied (MGD)		34.0	34.0	34.0			
Pumping Locations		1,3, 4,6, 10,11, 15,16, 19,20.	1,2, 3,4, 6,10, 12,15, 19,20.	1,2, 3,4, 6,10, 11,12, 19,20.			

*Tight bound.

Table 5. Statistical comparison between the s/o model results and QUAL2E simulation for constituent concentration at the control location*

Constituent	Mean Difference⁺ (%)	Standard Deviation (%)	Maximum Difference (%)	Minimum Difference (%)
BOD_5	0.95	1.40	3.79	-0.58
OGN	-0.45	0.61	0.93	-1.23
NH_3	-1.41	0.16	-1.17	-1.74
NO_2	-51.68	1.08	-50.19	-53.39
NO_3	-0.46	0.39	0.05	-1.43
TON	-2.25	0.15	-2.01	-2.53
OGP	-0.29	0.80	1.43	-1.24
DSP	-5.27	0.66	-4.23	-6.52
TOP	-3.64	0.34	-3.15	-4.43
CHA	-2.31	0.56	-1.20	-3.06
DOX	-11.89	1.94	-9.34	-16.41
TDS	-1.20	0.19	-0.96	-1.66

[*] Summary of 12 runs

[+] mean difference (%) is calculated as $[C_{regression}(\hat{u},j) - C_{QUAL2E}(\hat{u},j)]*100/C_{QUAL2E}(\hat{u},j)$.

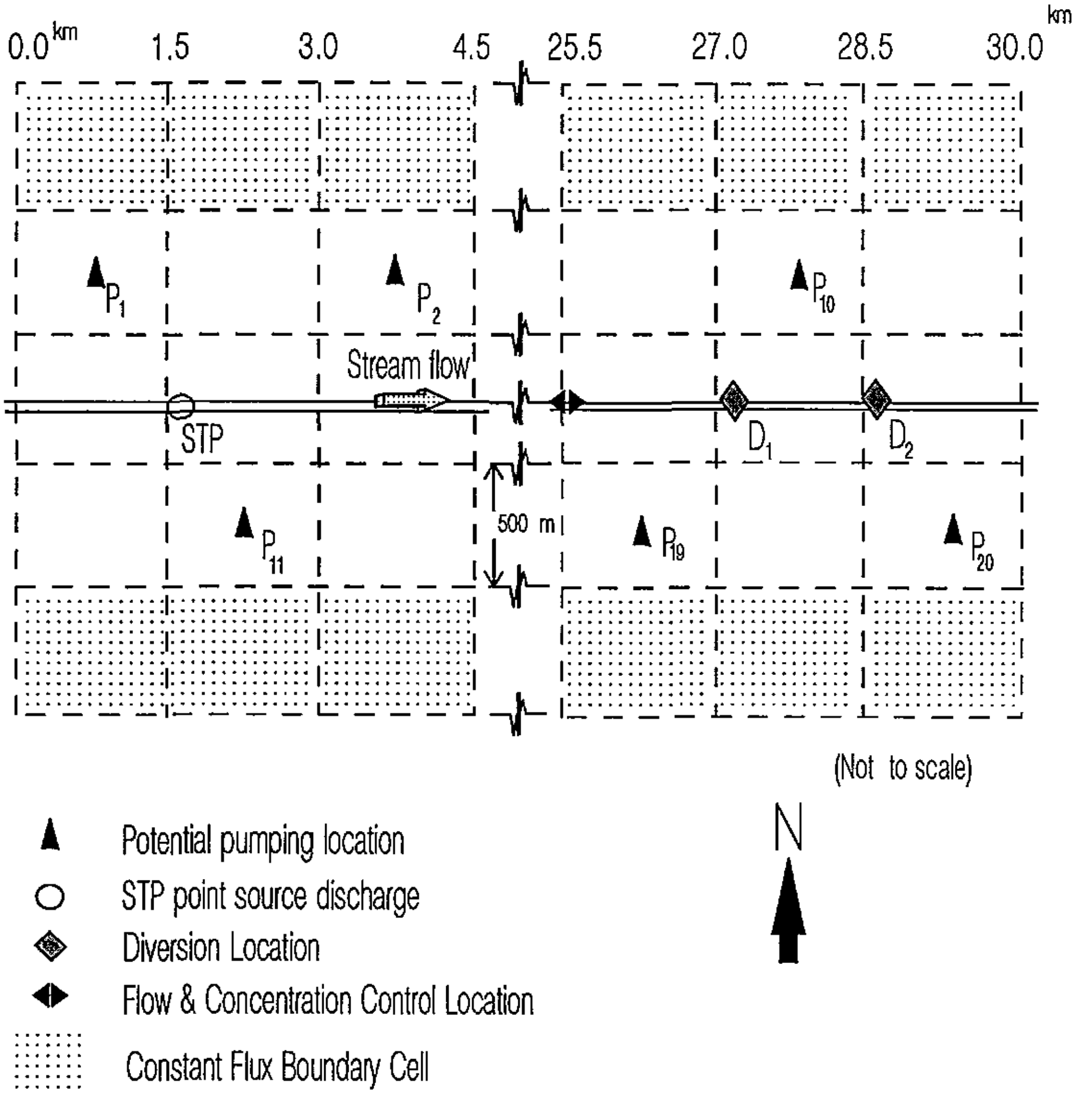
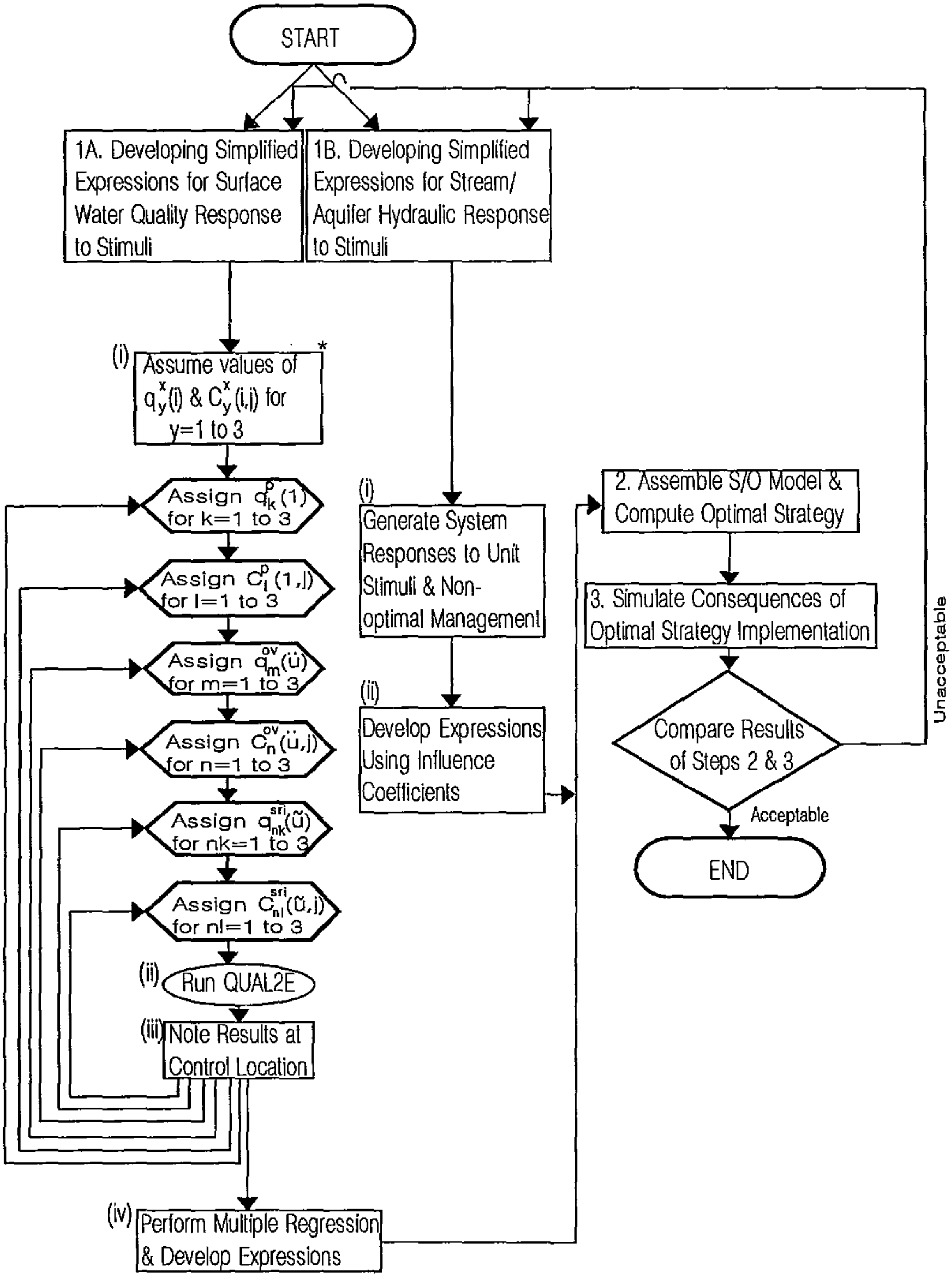


Fig. 1. Study area



*x denotes a particular stimuli
y denotes an index for a nested-DO loop

Fig. 2. Flow chart of cycling process to develop a single optimal strategy

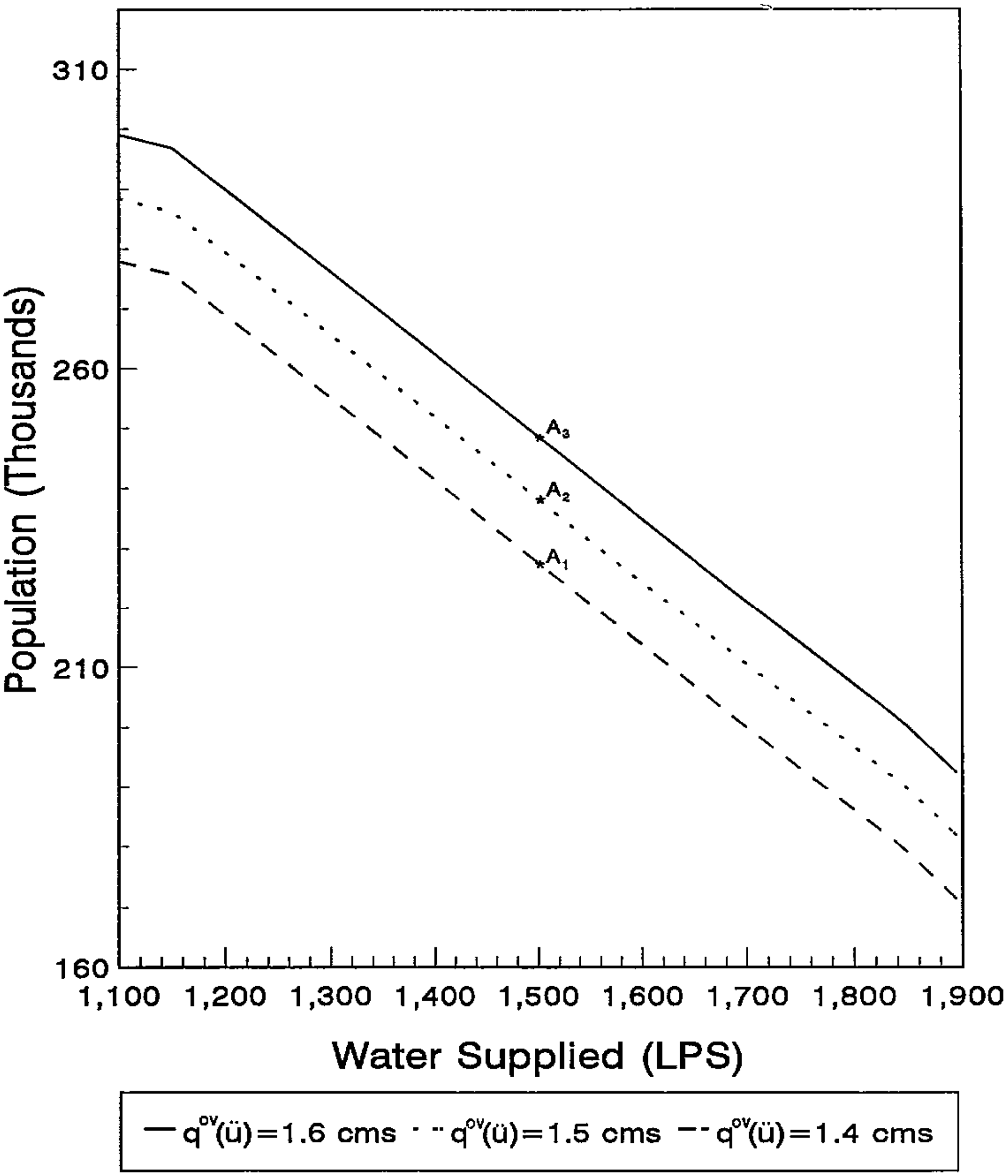
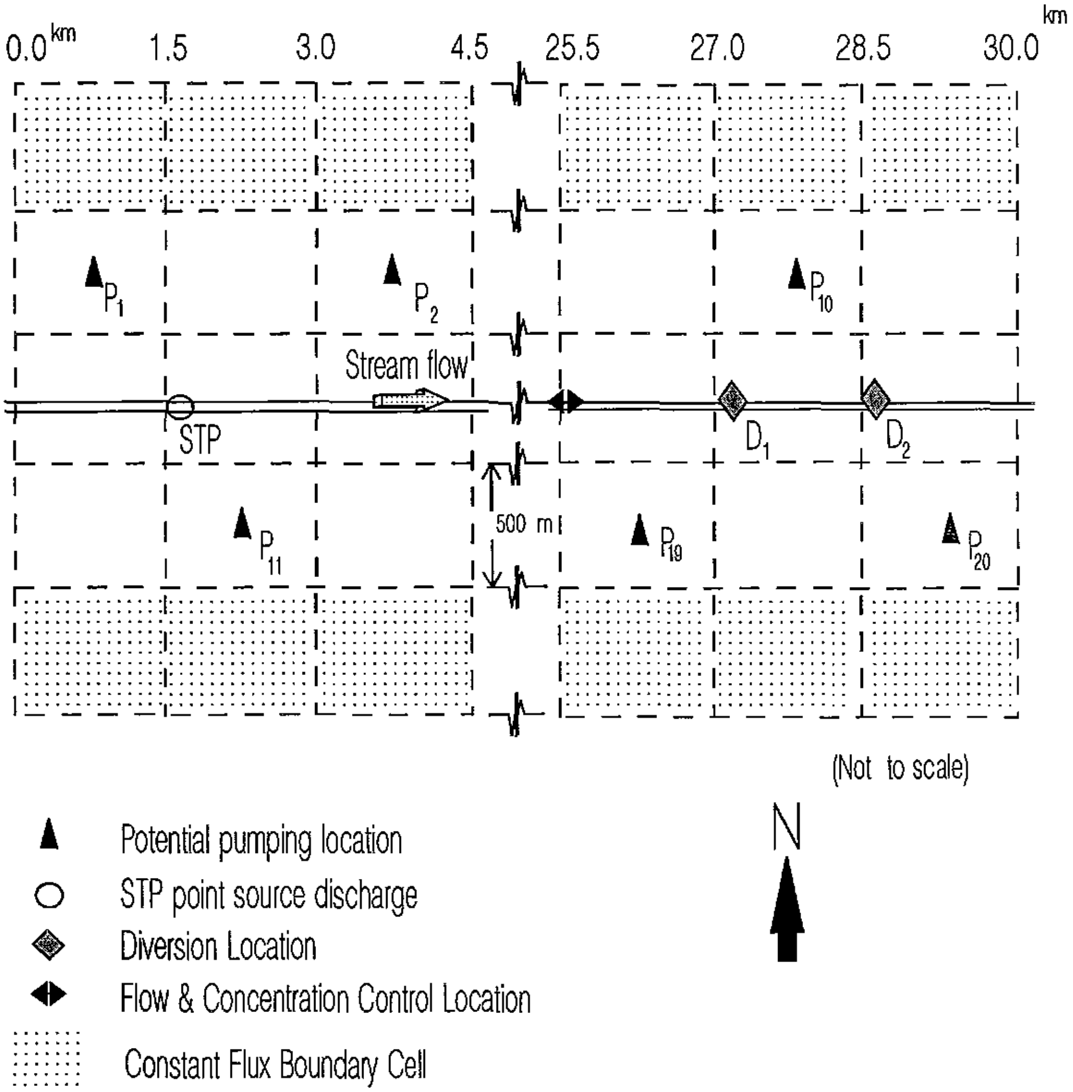
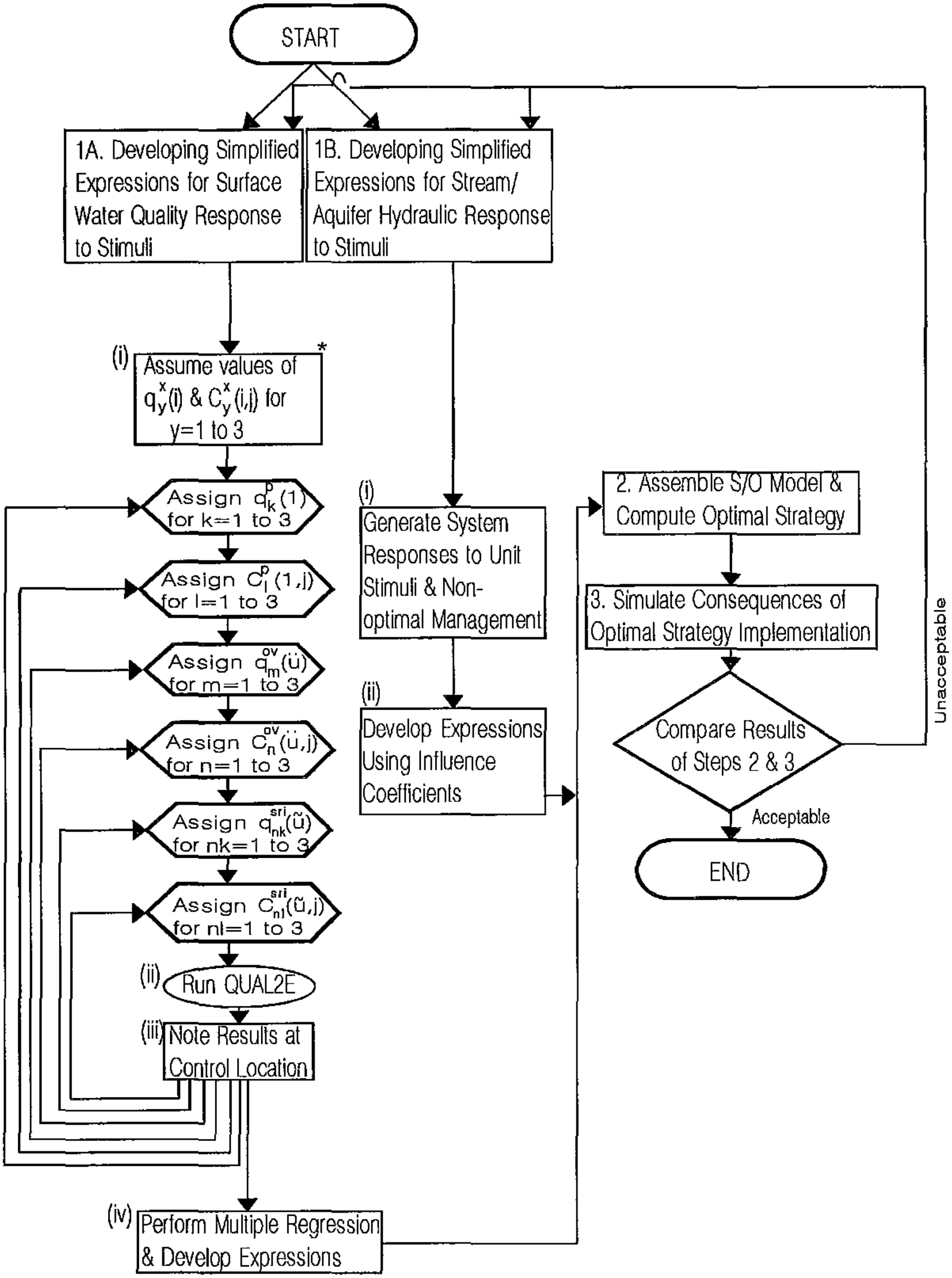


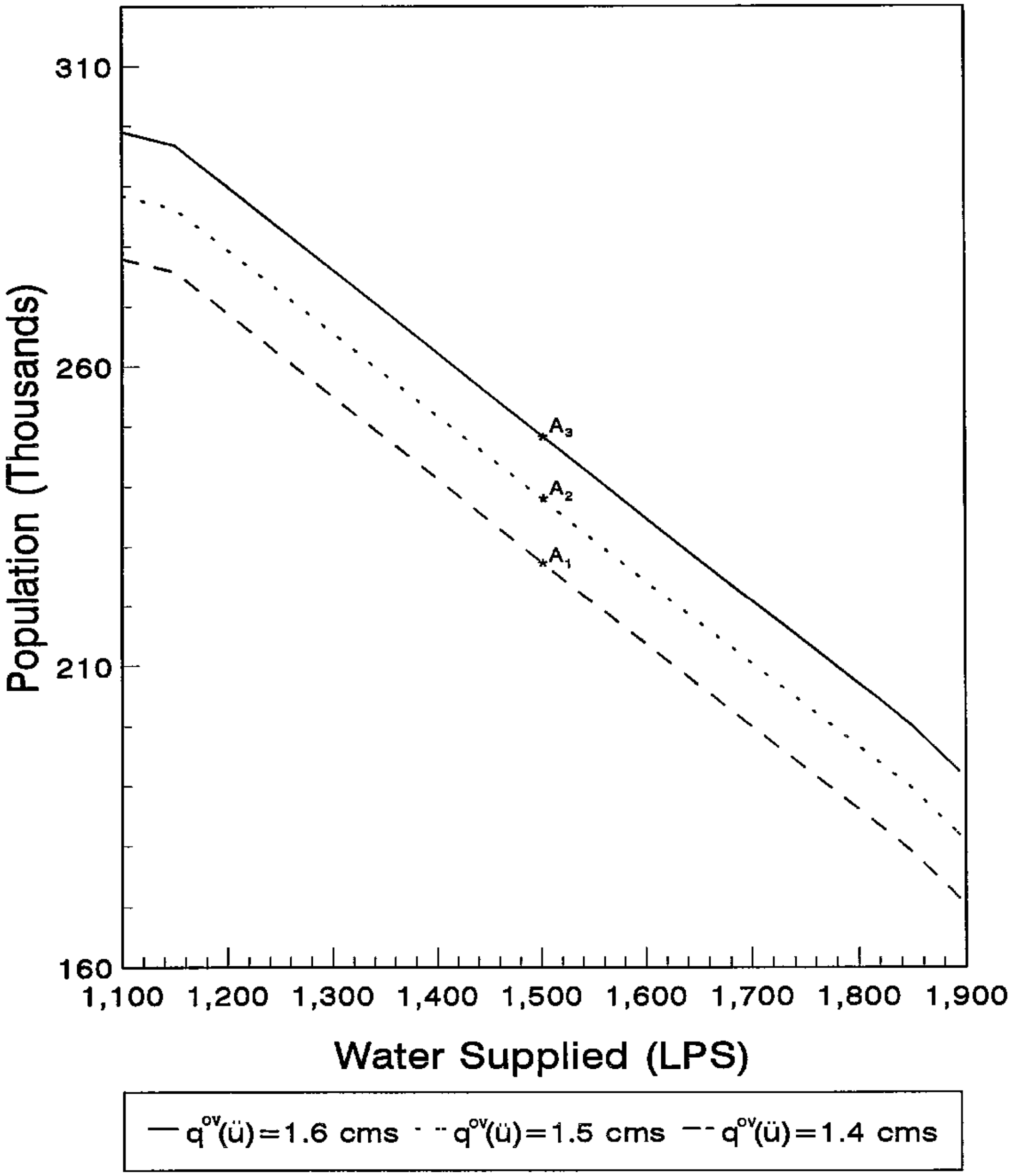
Fig. 3. Sets of noninferior solutions (human population versus water supplied for conjunctive use) as functions of upstream inflow rate.


0.0 km
1.5
3.0
4.5
25.5
27.0
28.5
30.0 km
P1
P2
P10
Stream flow
STP
D1
D2
500 m
P11
P19
P20
(Not to scale)
N
Potential pumping location
STP point source discharge
Diversion Location
Flow & Concentration Control Location
Constant Flux Boundary Cell



*x denotes a particular stimuli

y denotes an index for a nested-DO loop


Population (Thousands)
310
260
210
160
1,100
1,200
1,300
1,400
1,500
1,600
1,700
1,800
1,900
Water Supplied (LPS)
A₃
A₂
A₁
q^ov(ü)=1.6 cms
q^ov(ü)=1.5 cms
q^ov(ü)=1.4 cms