A LINKED OPTIMIZATION-SIMULATION
AQUIFER MANAGEMENT MODEL

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements of
the Degree of
DOCTOR OF PHILOSOPHY
July, 1992

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AQUIFER MANAGEMENT MODEL

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ACKNOWLEDGEMENTS

My sincere gratitude is warmly extended to my principal advisor, Dr. A.K. Tyagi, who provided continual technical support, personal encouragement and a never ending sense of humor throughout my academic endeavors. To Dr. Rick Wilson, I owe an unpayable debt for his contributions and assistance in the areas of management sciences and for helping me keep the goal in sight. I am forever thankful to Dr. Don Snethen for his help and encouragement in beginning this work and stalwart support throughout its completion. To Dr. Vernon Mast, I owe many thanks for his technical suggestions and for maintaining the mental challenge. To Dr. Doug Kent, I am forever grateful for his contributions and friendship. Collectively, these committee members provided the technical foundation and motivation to insure the completion of this work. Thank you.

My special thanks and heartfelt gratitude go to Ms. Jan Clyne. The many hours that she has spent typing, editing, organizing, and retyping this dissertation will always be remembered and appreciated. Without her efforts, this work would never have been accomplished.

To Mr. Jim Ferree, City Manager, and the City of Enid, Oklahoma, I owe many thanks. Not only for providing me the opportunity to carry out this work, but for continual

assistance and support over the past five years. Special thanks go to Mr. Lester Long and the staff of the City of Enid Water Production Department. These people exemplify the best of the best.

Finally, I owe everything to my wife, Fawn. She has provided encouragement, support and often shouldered immense responsibilities over the past three years to allow me to pursue my graduate studies. I will never be capable of repaying my debt to her. Without her and my children, Spencer, Gus and our forthcoming third to arrive in September, none of this work would mean anything to me. Thank you.

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CHAPTER I

INTRODUCTION

General

Water is the single most valuable resource upon which all life depends. Groundwater is a major source of this resource. Approximately half of the U.S. population, and about 95% of the rural population, rely on groundwater to meet the demand for domestic, agricultural, environmental, and industrial uses. Due to the increasing demand for groundwater from competing users, it is essential that groundwater resources be adequately managed to insure that the most beneficial uses of the resource are realized and the integrity of the aquifer is protected.

The management of groundwater resources involves the allocation of groundwater supplies to competing water users. Conflicting objectives and complex hydrologic, environmental, legal, political and economic constraints often result in complications which must be resolved when developing a groundwater management plan. The recent development of mathematical management models has provided valuable tools which are useful in defining optimal groundwater management alternatives for complex systems which would otherwise be extremely difficult and often impossible to identify. An important class of model developed for this purpose is the combined optimization-simulation model. A combined model considers the particular behavior of a groundwater system and determines the best operating policy under the objectives and restrictions dictated by the water resources manager (Gorelick, 1983). This type of model has been successfully applied to a broad range of groundwater management problems including those which involve planning, design, construction, and wellfield operations.

Combined optimization-simulation aquifer management models are formulated to solve the governing groundwater flow equations in conjunction with optimization techniques. Models of this type can be grouped into two general categories: groundwater hydraulic management models and groundwater policy evaluation and allocation models (Gorelick, 1983). The referenced categories distinguish between models in which management decisions are primarily concerned with groundwater hydraulics and those used to inspect policy evaluation as well as economics of water allocation. In the first category, models are formulated to manage groundwater stresses such as pumping and recharge. The second category involves models used to inspect complex economic interactions within the system or complex allocation problems. In both categories, the management model employs optimization techniques which are used to optimize an objective, such as minimization of costs or maximization of pumpage, subject to algebraic constraints which limit or specify the values of decision variables such as local drawdown, hydraulic gradients or pumping rates.

An important class of groundwater management problems involves the determination of the optimal operational schedule for a specific groundwater system. The objective of the water resource manager is to determine how an existing groundwater production system should be operated over a given planning period to satisfy an exogeneous water demand while minimizing the total cost for extraction. The integrity of the aquifer must also be considered in the development of the optimal management scenario. A groundwater management model can be developed to solve this problem using the combined optimization-simulation approach. This type of model is based on an economic objective function which is constrained by explicit operational and hydrologic limitations. The economic objective function must accurately address the various costs associated with groundwater production. These costs include the energy costs associated with the operation of the well equipment, the cost of the water which often includes royalty or lease requirements and the costs associated with operating and maintaining the well. These costs usually vary between individual wells within an existing system and are related to the physical and hydrologic characteristics of the well site, the size and age of the well equipment, the location and accessibility of the well site and the type of water rights agreement which pertains to the well. The groundwater production costs can vary significantly between individual wells within an existing system due to variations among these economic factors. It is essential that the economic parameters be completely quantified for each well within an existing system before a useful management model can be implemented for system optimization. When the groundwater system is optimized, the production costs are minimized, the life of the groundwater supply is maximized and the integrity of the aquifer is protected. With the use of a groundwater management model, the groundwater resource manager has a dynamic tool which allows for the rapid adjustment to varying demands for water and changes in operational status, with a high level of confidence that system operation is efficient and cost effective.

Objective of the Study

The objective of this research is to develop a groundwater management model for use in determining optimal operations alternatives for existing groundwater production systems. The potential exists for significant economic savings if the optimal production schedule is identified and implemented for an existing water production system given a target water demand and a specific planning period. The success of this approach is dependent on the accurate quantification of the economic factors which control the cost of water production for each well within the system.

The type of management model to be developed is classified as a combined optimization-simulation aquifer management model. The model formulation provides for the coupling of a groundwater simulation model and an optimization management model. Due to the availability of numerous excellent groundwater simulation models and optimization models, previously developed groundwater optimization-simulation models are used. Development of the appropriate objective function, identification of constraints and the coupling of the discrete models represent a primary objective of this research.

Once formulated, the combined optimization-simulation model will be used to evaluate operational scenarios for the existing City of Enid groundwater production system. The City of Enid water production system is comprised of one hundred forty six (146) wells which produce water from three (3) aquifers. The wells are located in five (5) separate wellfields which include: the Enid, Drummond, Ames, Ringwood and Cleo Springs wellfields. Due to the large number of wells in the system, the resulting water production capacity exceeds the average demand by approximately 60 percent. The excess capacity of the system provides flexibility which can result in significant economic savings through optimization. The ultimate objective of this research is to develop a groundwater management tool which can be used by the water resources manager to define optimal production schedules to meet anticipated demands for specified planning periods.

Scope of the Study

The scope of the research involves the development of a combined optimization-simulation aquifer management model for the existing groundwater production system which serves the City of Enid, Oklahoma. Regional and site location maps are presented in Figures 1.1 and 1.2. The initial phase of the study is a comprehensive review of the literature to ascertain the state of development for combined optimization-simulation aquifer management models with specific emphasis on applications to optimization of existing wellfield operations. Following the completion of the literature study, a characterization of the regional and wellfield hydrogeology is developed. In addition, a detailed analysis of the existing water production system is performed. The data derived from the hydrogeologic and water production system characterizations is used to develop the system operational parameters required for the development of the groundwater management model. A data base is developed for the existing groundwater production system using data acquired over a twenty four (24) month period. The data includes aquifer hydraulic data, drawdown versus pumpage relationships, system operations data and economic data. The data is used in the development of an optimization management model formulated using mathematical programming techniques and groundwater simulation models for each wellfield. The combined groundwater optimization-simulation management model is developed by linking the

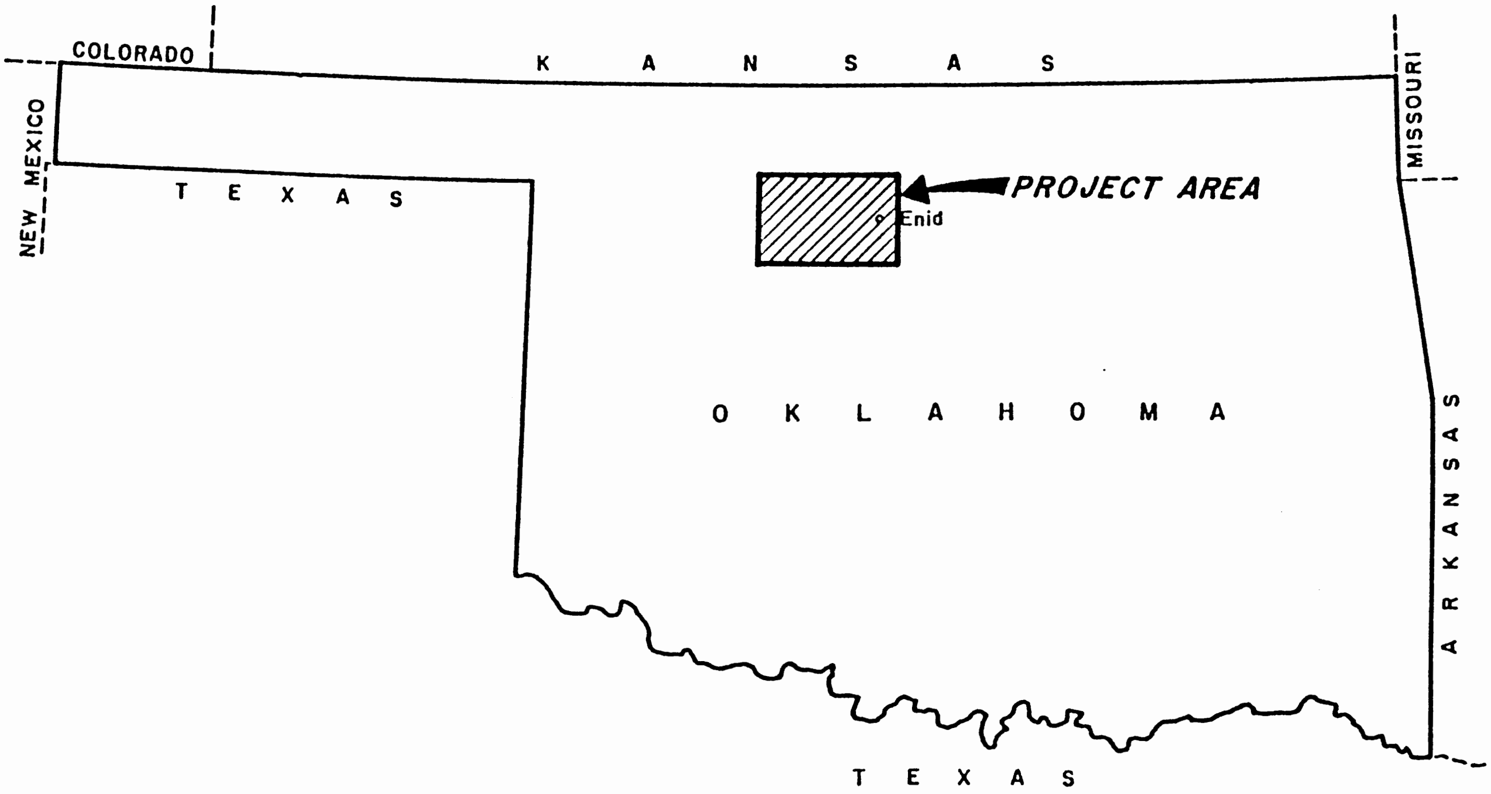

FIGURE 1.1 REGIONAL LOCATION MAP

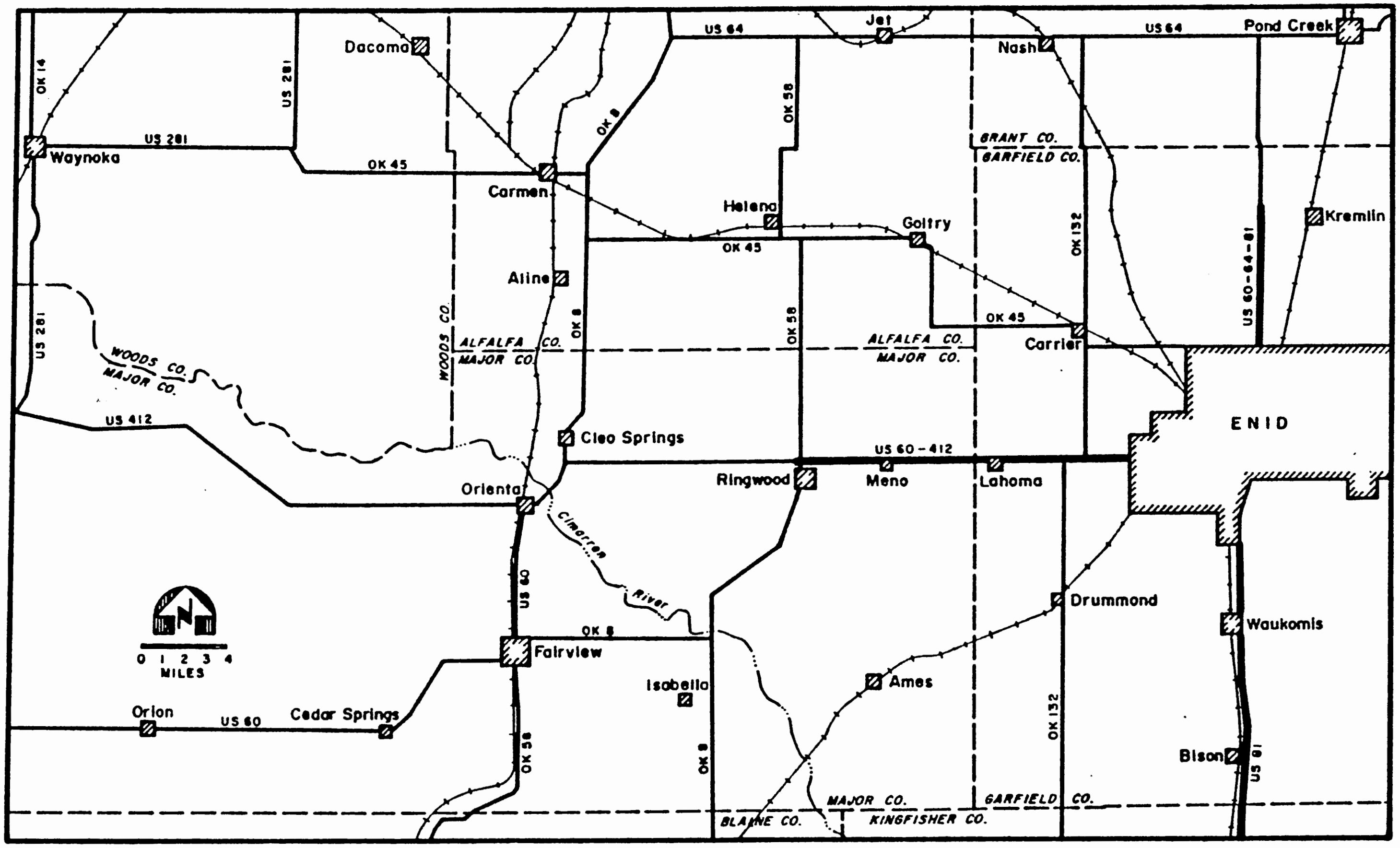

FIGURE 1.2 SITE LOCATION MAP

individual models using an input and output control algorithm. The resulting management model represents a dynamic tool which can be used by the water resources manager to evaluate alternative production schedules and through an iterative process define the optimal management scenario. The final phase of the study demonstrates the utility of the management model through a comparative study of historical production records to an optimal production scenario as determined with the use of the model for a twelve (12) month period. Conclusions and recommendations for further study are also presented.

CHAPTER II

REVIEW OF LITERATURE

Background

The management of groundwater resources involves the allocation of groundwater supplies to competing demands and uses. This resource allocation problem is characterized by conflicting objectives and complex hydrologic, environmental, political and economic constraints (Willis & Yeh, 1987). To maximize the benefit of the resource allocation, it is necessary to optimize the management of the available groundwater resources. Under an optimal management scenario, the costs, impacts and benefits are considered when selecting the resource management alternative for a specific groundwater system.

The development of numerical simulation models over the past three decades have provided groundwater resource managers with a quantitative technique for conceptualizing and evaluating aquifer systems. Models have become tools to evaluate the response of an aquifer to various stresses, including those due to natural and manmade conditions. Although simulation models provide the water resource manager with important tools for evaluating the groundwater system, these predictive models do not identify the optimal operational policies for an aquifer system. In contrast, groundwater optimization models can identify the optimal operational alternatives which comply with the objectives of the water resource manager and constraints of the groundwater system (Willis & Yeh, 1987).

An important class of management model has been developed through combining a mathematical groundwater simulation model with an optimization model. A combined optimization-simulation model can be used to evaluate the particular behavior of a given groundwater system and determine the best operating policy under the objectives and restrictions defined by the water resource manager (Gorelick, 1983). The development of this type of management model has primarily occurred within the past two decades. The capacity of the earlier models was minimal due to the limited capacity of available digital computers.

With the rapidly advancing state of technology available in computers and the increasing capabilities of numerical optimization-simulation models, the potential capabilities of combined optimization-simulation models has increased dramatically. In recent years, combined optimization-simulation models have been developed to determine optimal pumping and recharge rates subject to restrictions on drawdown, hydraulic gradients and water demands. This type of model has also been used to identify optimal locations for future wells in a wellfield, evaluate groundwater allocation policies, analyze the efficiency and economics of groundwater management methodologies and solve certain groundwater quality management problems (Gorelick, 1983). As the evolution of the combined optimization-simulation aquifer management model continues, it is probable that the use of this type of management approach will become an essential tool for all groundwater resources managers.

Numerical Groundwater Simulation Methods

A system that can approximate the response of an aquifer flow system is defined as a model of that system. Simulation of the aquifer flow system can be accomplished through operation of the model, evaluation of the results, and recalibration of the model until a point is reached where the simulated behavior of the aquifer flow system matches the observed behavior.

Several different types of models have been developed to simulate groundwater flow systems. Some of these include: sand tank models, electric analog models, viscous fluid models, analytical and semi-analytical models. These models all have significantly contributed to our knowledge of groundwater flow systems, but currently the most widely used method of simulating groundwater flow systems is with the use of numerical models. Specifically, complex groundwater systems are most frequently simulated by numerical analysis techniques using finite difference methods and finite element methods.

To model a groundwater flow system, the system must be decomposed into its basic components. In general, the following parameters comprise the system components:

1. Infiltration of precipitation
2. Subsurface inflow
3. Infiltration from stream beds and/or irrigation canals
4. Infiltration from agricultural irrigation
5. Infiltration from artificial recharge
6. Subsurface outflow
7. Discharge into stream beds and/or irrigation canals
8. Evaporation
9. Evapotranspiration by vegetation
10. Groundwater pumpage

The concept of continuity requires that the groundwater flow system be balanced, i.e. the inflows minus the outflows equal the change in storage of the system. Accurately modeling a groundwater flow system requires that all of the system components be properly analyzed and quantified and all interrelationships determined. Due to the limited amount of data that is typically available for a specific groundwater flow system, it is usually impossible to completely quantify all components of a system.

Because it is very difficult to completely quantify all components of a groundwater flow system, it is generally necessary to simplify the model. By simplifying the groundwater flow model, significant mathematical difficulties can be avoided. Although the resultant groundwater flow system is a simplification of the actual system, the model can generally be calibrated to very closely simulate the actual system.

One of the most commonly used numerical methods for solving boundary value problems is the method of finite differences. A numerical solution of the basic non-linear partial differential equation for groundwater flow can be obtained through a finite difference approach. This approach initially involves replacing the governing differential equation with an approximating difference equation in such a manner that the budgetary requirements of the original difference equation are approximately conserved. The continuous region for which a solution is desired is replaced by an array of discrete points. This allows reduction of the groundwater flow system to a system of algebraic equations which are solved with the use of iterative techniques (Domenico, 1972).

Finite difference techniques have been applied with the aid of digital computers to a wide variety of aquifer conditions. Some of these applications include steady and non-steady analyses of one, two and three dimensional flow in non-homogeneous, anisotropic aquifers under confined and unconfined conditions. In addition, problems have been solved involving evapotranspiration, induced infiltration from rivers, flow from springs, contaminant transport, turbulent flow phenomena and unsaturated flow (Prickett, 1975).

The finite element method involves a solution of the differential flow equation which is obtained by finding a solution for hydraulic head that minimizes an equivalent variational functional.

The flow system is considered as a general system of energy dissipation for which the hydraulic head solution is found as the hydraulic head distribution that minimizes the rate of energy dissipation (Bouwer, 1978).

The application of the finite element computer model to a groundwater flow system requires that the aquifer be divided into a number of subregions or finite elements which are triangular or quadrilateral for 2-D systems and tetrahedral or parallelapiped for 3-D systems. The elements should be as disordered and non-uniform as possible to prevent biased solutions. The irregular shape of the elements also facilitates representation of irregular boundaries.

Numerous numerical groundwater models have been developed over the past three decades. Heijde and Beljin (1988) performed a comprehensive assessment of sixty four (64) mathematical groundwater models. These included both numerical, analytical and semi-analytical models. Based on the results of the assessment, it is apparent that existing mathematical groundwater models are capable of simulating groundwater flow conditions in a variety of aquifer types, which exhibit extremely complex characteristics. It is important to note however that in many cases, the lack of quantity or quality of data significantly restricts model utility.

Optimization Methods for Groundwater Management

Optimization is defined by Webster as "...making as perfect, effective or functional as possible." In general, optimization methods applied to water resources problems involve the formulation of a mathematical model. The model typically incorporates the significant characteristics of the system, addresses the interrelationships among system components, defines a specific goal and sets forth internal and external system limitations.

All optimization models are comprised of the following three fundamental components (Major & Lenton, 1979):

1.) Parameters: These are typically numerical values which describe quantified properties inherent to the system under consideration. Parameters are generally specified and remain constant unless manually varied by the user.

2.) Variables: These typically define the behavior and performance of the system under consideration. In the formulation of the model, they represent the system characteristics of interest.

3.) Constraints: These are the relationships and/or controls which describe the system's operation on the parameters and variables. They are typically mathematical statements which limit the results of the model to solutions which are acceptable.

These three components are generally present in all mathematical models. Optimization models are a specific class of model which is characterized by a mathematical statement of the objective function and a formal search procedure for identifying values of those decision variables which either maximize or minimize the objective function. The development of an objective function for any system requires a complete understanding of all parameters and constraints which control the system. It is also essential that a thorough knowledge exist regarding the relationship between the system variables and the other fundamental components of the system. Although it is often difficult to determine the proper objective function in an optimization model formulation, it is an essential feature of the ultimate management model and must be accomplished (Gorelick, 1983).

Optimization procedures, which are commonly applied to groundwater management problems, may be arranged into four general categories based on the mathematical characteristics of the models. These categories include: 1) Linear Programming; 2) Integer Programming; 3) Nonlinear Programming; and 4) Dynamic Programming (Major & Lenton, 1979). These procedures are mathematical programming techniques which can be used to solve groundwater optimization models which are linear or nonlinear and deterministic or stochastic (Willis & Yeh, 1987).

Linear programming optimization procedures can be applied if the objective function and all of the constraint equations can be expressed in linear, algebraic form with known, constant coefficients. Linear programming problems are solved using the simplex algorithm, which is an algebraic iterative method. Although the linearity restrictions are frequently severe, linear programming is commonly applied in groundwater optimization problems because it is often possible to develop a linear objective function, and constraints, through acceptable simplification of the system being modeled (Major & Lenton, 1979).

Linear programming methods have also been extended to address optimization problems which involve an objective function which is subject to constraints which include random variables. In cases of this type, stochastic linear programming has been applied (Willis & Yeh, 1987).

Integer programming is directly related to linear programming because all of the constraint equations and the objective function must be linear. The principal difference between the methods results because the decision variables are allowed to take on only integer values. The use of integer variables results in an increased ability of the model to express various planning conditions and interrelationships (Major & Lenton, 1979). A further extension of the integer programming procedure results in the mixed integer programming procedure. The principal difference between these two methods is that only a portion of the decision variables are integers in the mixed integer programming method.

Nonlinear programming problems differ from the linear programming problem because the objective function and/or one or more of the constraint equations involve nonlinear terms. Due to the nonlinearity of the system, the mathematics involved in the formulation and solutions of nonlinear models are much more complicated than the linear case. Due to the increased complexity, the computational effort is significantly greater when compared to linear programming models. Nonlinear programming models can, however, effectively address nonseparable objective functions and nonlinear constraints which the other common mathematical programming techniques cannot solve (Willis & Yeh, 1987). Algorithms to solve some special cases of nonlinear programming problems, including the quadratic programming problem, have been developed which greatly decrease the computational effort required for problem solution (Major & Lenton, 1979).

Dynamic programming is a procedure for optimizing multi-stage decision processes. It represents a solution procedure that can be used to solve highly complex linear or nonlinear problems which contain a large number of decision variables by decomposing the problem into a series of subproblems which can be solved recursively (Willis & Yeh, 1976). When the sequential nature of a system can be established and the number of state and decision variables are manageable, the computational procedures are practical. Dynamic programming has been used extensively to solve groundwater optimization problems in recent years. The success of this technique can be attributed in part to its efficiency in incorporating nonlinear constraints and objectives. In addition, the procedure is capable of addressing stochastic or random variables in the formulation of the problem (Willis & Yeh, 1987). The principal limitation of the procedure relates to the number of state variables that can be incorporated into the recursive equations.

Selection of an appropriate optimization procedure is often a difficult exercise. Many factors must be addressed during the process of model evaluation for a specific problem, but ultimately a balance must be made between the validity and computability of the model. Validity of the model will depend on the spatial and temporal resolution inherent to the model, the accuracy of the parameters and input data provided, and the correctness of the mathematical relationships assumed. The computability of the model is a function of the complexity, scope, number of variables, and level of detail required. Computability can generally be evaluated based on the effort required to solve for the optimal solution (Major & Lenton, 1979).

Groundwater Management Models

The management of groundwater as a valuable resource and aquifers as dynamic storage systems within a complex economic environment may be formulated as a mathematical programming problem (Schwartz, 1976). The use of mathematical programming techniques in the development of groundwater management models has occurred primarily over the past three decades.

Some of the earliest work which attempted to develop a mathematically based groundwater management methodology was documented by Tyson and Weber (1964). This work was conducted by the State of California and incorporated the use of a digital computer to develop and test a two-dimensional groundwater model of the major groundwater basins in southern California. The project resulted in the development of an acceptable model which was calibrated and used to evaluate the dynamic behavior of the aquifer. Once developed, the model was used to perform operational analyses of the water production systems within the aquifer.

Deininger (1970) described the use of systems analysis and operations research techniques for the planning, design and operation of water supply systems. Specifically, the application of these techniques were discussed with reference to optimizing the operations of a simplistic, hypothetical wellfield. Optimization in this case was defined as the operational methodology which would result in maximum yield, or alternatively, the minimum cost of production subject to operational and hydrologic constraints. To obtain the optimal solution, an objective function was formulated which included operational cost parameters and system variables which were a function of well discharge. The objective function was constrained by the well specific pumping capacities, the allowable drawdown in each well and the allowable drawdown at the boundaries of the wellfield. The drawdown characteristics were incorporated directly into the objective function using the response equation developed by Theis for non-equilibrium flow. The resulting objective function which was developed was nonlinear. The recommended solution procedure involved an iterative approach, using quadratic programming techniques.

Maddock (1972) developed a groundwater management model which incorporated mixed integer programming techniques. The model was developed specifically to assist the groundwater system manager in determining the least cost operation of existing wells, in determining the least cost spatial and temporal development of new wells, and in determining a least cost water transmission system. The mixed integer quadratic programming model was capable of minimizing pumping costs plus fixed costs for well and pipeline construction. A constraint set was developed as a response matrix, which was defined by an algebraic technological function. The response coefficients related drawdown values to pumpages at each well. The quadratic portion of the objective function was made separable by a transformation that enabled solution by a combination of mixed integer and separable programming. A sensitivity and error analysis was applied to the model to evaluate the effects of alternative management scenarios on economic and hydrologic factors. The sensitivity analysis determined a ranking of factors in terms of error effects and in terms of priority for further data collection activities.

Aguado and Remson (1974), Aguado (1979) pioneered the development of the embedding method for the hydraulic management of groundwater systems which uses mathematical programming formulations that incorporate groundwater variables directly as decision variables in the objective function. In the model which was developed, the partial differential equations describing groundwater flow were approximated by finite differences and the resulting linear algebraic simultaneous equations were embedded as constraints in a linear programming formulation. The optimization goals, which are formulated in the objective function, included the groundwater variables directly. Using one and two dimensional examples, it was demonstrated that the physical behavior of a groundwater system could be included as an integral component of an optimization model. Finite difference approximations were used to simulate steady and unsteady state flow.

Alley, Aguado and Remson (1976) extended the use of the embedding method to two dimensional transient conditions. Specifically, this technique was applied to a hypothetical confined, heterogeneous, isotropic aquifer. Finite difference equations were written for each node and the set of linear equations comprised the matrix of node equations. The objective function which was formulated incorporated the hydraulic variables, including potentiometric head, as decision variables in the linear programming management model. The objective function was constrained by pumping and minimum potentiometric heads at specific nodes. The transient behavior of the hypothetical system was simulated by creating successive management models. Each model was for a specific time step and the optimal solution for the one time step was defined as the initial conditions for the next time step.

Alley, et.al. (1976) applied the linear programming management model to study the feasibility of disposing of wastewater through injection into an aquifer. The object of the study was to minimize total pumpage from potential wells. The system was modeled as steady state. Based on the results of the study it was determined that the proposed management solution was not feasible.

Aguado (1979) summarized the development of the embedding technique for groundwater system optimization. The approach to optimal aquifer management which incorporates groundwater variables directly as decision variables in linear programming models was presented. Specifically, a thorough discussion was presented of the methodology for embedding the finite difference approximations of the groundwater flow equations as constraints directly into the linear programming formulation which can include economical, political, or social, quantifiable decision variables and constraints. The optimization goals which are formulated in the objective function is capable of including groundwater variables.

The methodology was developed and its feasibility tested using simple examples. In addition, the management model was used to define an optimal plan for dewatering a construction site. Other components of the study included a sensitivity analysis, to evaluate the effects of variations in hydraulic parameters, grid size, and aquifer conditions on the optimal solution. The case where both total pumping costs and fixed development costs were considered was explored using the formulation of the "fixed-charge problem" which incorporated the use of mixed integer linear programming techniques. Finally, the linear programming management model was applied to a hypothetical sea water intrusion problem. Using this method, an optimal strategy for preventing encroachment of sea water in a coastal aquifer while maintaining fresh water pumpages was determined.

Aguado and Remson (1980) discussed the formulation and application of a management model which incorporated mixed integer linear programming techniques. This model was developed to address the installation costs of water production system as well as the operational costs. The model was applied to a construction site dewatering problem and was used to determine optimal well locations and discharge schedules required to maintain water levels below a specified level. The objective was to minimize the sum of fixed costs due to well installation and variable costs due to steady state pumping.

Schwarz (1976) discussed the development and application of linear models for groundwater management. The applications of linear programming to groundwater management were categorized as those based on influence equations and those based on transformation equations. Influence equations, or response equations, describe the behavior of the aquifer due to pumpage, recharge or other stresses at a specific location. Principles of super-position are used to study collective effects from a number of individual stresses. Transformation equations were defined as the continuity equations which describe the behavior of a groundwater system which has been discretized into a finite number of cells. The study concluded that the transformation model was preferable for a system which could be discretized into a small number of cells with time variations of the objective function. The influence model was determined to be less restrictive by the number of cells but was less adaptive to time varying conditions.

Bostock, Simpson and Roefs (1977) described an aquifer management model which is capable of comparing uniform grid wellfield costs for alternative well capacity-density combinations required to meet a specific groundwater demand. The method was formulated to account for uncertainties in the spatial distribution of hydraulic conductivity within an aquifer using Baysian decision theory. The model used the response matrix methods to evaluate the hydraulic components of the system. The objective function was developed to include the economic variables associated with the construction, replacement and operation of an unknown number of wells. The objective function was minimized to define a combination of well spacing and production rates which resulted in the least cost for a given demand. Uncertainty in aquifer hydraulic conductivity at potential well sites was evaluated by averaging the possible outcomes over all wells in accordance with a probability density function for hydraulic conductivity values. The model was demonstrated using hypothetical, simplistic examples.

Willis and Newman (1977) applied the embedding method in the development of a groundwater management model. The model was formulated as a problem in optimal control and was predicated on a Galerkin finite element formulation of flow in hetergeneous, anisotropic porous media. The management problem consisted of a nonlinear objective function subject to linear constraints. The model was applied to a hypothetical, confined aquifer. The objective of the application was to determine the optimal well development locations given a finite number of potential sites and determine the optimal production schedules from the selected wells to meet an exogenous water demand over a sequence of planning periods.

Remson and Gorelick (1980) summarized the use of linear programming management models which embed groundwater variables directly in the objective function as decision variables. It was observed that the management solutions satisfied spatial and temporal discretized numerical approximations of the governing differential equations. The resulting management solution is capable of identifying the optimal locations and stress magnitudes to achieve specified management objectives. Several methods for incorporating physical groundwater variables into groundwater management models were demonstrated using three hypothetical examples.

Elango and Rouve (1980) described a systematic study regarding the performance of an embedded type finite element based linear programming model. It was suggested that this type of model formulation benefits from the ability of the finite element method to represent the hydraulics of the flow in the aquifer for complex boundary geometries and conditions, heterogeneity, and anisotropy of the medium. Two simplistic, hypothetical steady state examples were evaluated using the model. The sensitivity of the model to element geometry and configuration was analyzed. The results of the study indicated that the model was capable of determining an optimal solution for a medium sized problem but limitations were expected as the number of system constraints increased.

Heidari (1982) described the application of a groundwater management model, which incorporated linear programming optimization methods, to an actual aquifer management problem in Kansas. The response matrix approach was used to approximate groundwater behavior in an unconfined aquifer. The response matrix was utilized in a linear program which maximized pumping rates over time. Total pumping during each time period was required to meet demands. Each pumping rate was limited by water rights. Drawdown at any time was limited to a predetermined percentage of the total saturated thickness.

Gorelick (1983) comprehensively reviewed the state of distributed parameter groundwater management modeling methods. A classification system was proposed for groundwater management models based on the intended use and the internal computational formulations. Two general categories were proposed which included: 1) hydraulic management models; and 2) policy evaluation and allocation models. In addition, methods for managing groundwater quality were reviewed for both the steady and transient states. An excellent presentation of previously documented work in the area of groundwater management modeling was presented.

Comparisons of various models and model applications were discussed.

Willis and Liu (1984) formulated a multi-objective optimization model designed to assist in the allocation of groundwater to competing demands over a series of planning periods. The model incorporated response equations to accommodate the hydraulic behavior of the groundwater system. The equations were developed for a heterogeneous, isotropic aquifer system using the Galerkin finite element method. Steady state and transient solutions were obtained which related the hydraulic head and the initial state of the system, boundary conditions, and the planning or management policies. Parametric linear programming was used to generate optimal planning policies, define a set of non-inferior solutions and a relationship between the total water deficit, the maximum pumping rate and the minimum permissible head values in the aquifer system. The management model was applied to a regional groundwater basin in Taiwan.

Tung and Koltermann (1985) developed a distributed parameter groundwater management model using finite difference approximations of the groundwater flow equations in a confined aquifer to evaluate various computational characteristics of the model. The resulting system of simultaneous equations was embedded in a linear programming optimization model, which used hydraulic heads and pumpages as decision variables. The model was applied to several hypothetical examples of varying size and complexity and to an actual case study. Based on the results of this work it was determined that grid spacing, time step increments, pumpage constraints and the number of constraints significantly affected the execution characteristics of the model. The study concluded that the embedding technique was useful for small management problems but had inherent computational difficulties with large systems of considerable heterogeneity. It was suggested that the response matrix approach be preferentially selected over embedding techniques for complex systems until improvements are made in computational efficiency and stability.

Knapp and Feinerman (1985) discussed the concept of optimal steady state with reference to groundwater management. Specifically, a dynamic programming approach was described for lumped parameter and distributed parameter systems. It was suggested that dynamic programming has an advantage over optimal control methods, due primarily to its ability to accommodate both stochastic and deterministic problems. The model was demonstrated using a simplistic, hypothetical, hetergeneous confined aquifer.

Danskin and Gorelick (1985) developed a model for the optimal allocation of water resources within a combined multi-aquifer groundwater and surface water system in California. The complex groundwater system was analyzed using a transient, quasi-three-dimensional model which considered the nonlinear behavior of the unconfined aquifer. The surface water system included streams and reservoirs which provided recharge to the uppermost aquifer.

Nonlinear streamflow-recharge relationships were developed using field data. The management model used constrained optimization to minimize the cost of allocating surface water subject to physical and economic restrictions. Results of the study demonstrated that a combined hydrologic and economic management model can be used to evaluate management practices of a complex hydrogeologic system. The study illustrated that a primary benefit derived from the management model is the ability to evaluate alternative operational policies.

Casola, Narayanan, Duffy and Bishop (1986) developed an optimal control management model for spatial and temporal allocation of groundwater. The management model integrated a physically based finite difference groundwater model and a linear-quadratic optimal control model. The optimal control model maximized a time-variant objective function composed of the gross benefits from the derived demands for water, estimated by a linear programming model of the regions agricultural economy and the pumping costs estimated by a Taylor's series approximation of an empirical cost function. The groundwater flow equations were developed as a two-dimensional deterministic set of finite difference equations. The model was applied to a groundwater basin in southwestern Utah.

Yazicigil and Rasheeduddin (1987) developed a combined optimization-simulation groundwater management model for a multi-aquifer system. The use of the embedding technique as a mechanism for coupling the groundwater simulation model with the optimization model permitted the researchers to study alternative groundwater management scenarios in a hypothetical multi-aquifer system under steady state and transient conditions. Constraint and weighting multi-objective programming techniques were used to develop trade-off curves relating the sum of hydraulic heads in the entire system, as well as in individual aquifers, at various water production targets. The model enabled the determination of optimal allocation of wells in different aquifers and the pumping rates required to achieve a system wide maximum head distribution while satisfying the water production targets, well capacity restrictions, and lower bounds on hydraulic heads at critical locations. It was concluded that the use of trade-off curves enhanced the water resource manager's ability to identify the optimal development scenario from a set of alternatives by considering other technological, financial and legal constraints.

Chau (1987) evaluated the long term groundwater withdrawal potential of a regional confined aquifer in Alberta using a combined optimization-simulation model. The model incorporated a groundwater flow model formulated by the Galerkin finite element method and an optimization model based on linear programming formulation. The model permitted simultaneous determination of pumpages and hydraulic heads in accordance with the objective of maximizing total withdrawal at pumping sites. The system constraints included drawdown, water demand, hydraulic gradient and the hydraulics of groundwater flow. Trade-off curves were used to evaluate the interdependency of groundwater withdrawals among various industrial users.

Claborn and Rainwater (1988) developed a groundwater management model using enumeration techniques for application to the daily operations of a municipal water supply system in Texas. The model was used to estimate the optimal combination of wells, within an existing system, which were required to meet the demand flow rate. The optimal condition was defined as that which resulted in the least cost of pumping. The optimal pumping schedule was defined when the total power used by the system was minimized. Due to computational limitations, it was concluded that the use of the proposed model was not feasible for most groundwater production systems. An approximate solution methodology was presented which incorporated a ranking technique to identify the least cost production schedule. The approximate solution formulation was used to solve a hypothetical system which included ten (10) wells. In addition, the method was used to evaluate alternative operational scenarios for an existing municipal wellfield which contained twenty six (26) wells.

Lee (1990) extended the work of Claborn and Rainwater (1988) through the development of a computer algorithm to optimize daily wellfield operations. The algorithm incorporated implicit enumeration techniques to evaluate an economic objective function. Based on the results of the study, it was concluded that the model adequately determined optimal wellfield operational scenarios for small water production systems. The algorithm had limited capabilities to evaluate systems of significant size.

Danskin and Freckleton (1989) applied a combined groundwater optimization-simulation management model to solve high groundwater problems in a groundwater basin in California. To evaluate the problem, linear programming techniques were coupled with groundwater response matrices. The goal of the effort was to determine the most efficient pumping plan to reduce hydraulic heads. The groundwater system was simulated using a transient, three-dimensional finite element model.

Peralta, Azarmnia and Takahashi (1991) compared the computational characteristics of embedding and response matrix techniques for maximizing steady-state groundwater extraction. Specifically, the techniques were evaluated in terms of computational efficiency and memory requirements. A hypothetical groundwater system was used to compare the techniques. Based on the results of the comparison, it was concluded that a steady state embedded model required less processing time than a comparable response matrix model. In addition, the embedded model sometimes required less memory than a response matrix model. In general, as the complexity of the system increases, the advantages of the embedded method outweigh those of the response matrix method.

Summary

The development of combined optimization-simulation management models for groundwater systems is well documented in the literature. A combined model is useful in evaluating the behavior of a specific groundwater system and identifying optimal management methodologies given the objectives of the water resources manager and the constraints of the system. Models have been formulated to solve several distinct types of groundwater management problems including the determination of optimal pumpage schedules to maximize yield, minimize operational costs and control groundwater gradients. Management models have been developed to solve steady-state and transient conditions, two and three dimensional groundwater flow systems in heterogeneous aquifers. Response matrix techniques and embedded methods have been incorporated into various models which have been solved using both finite element and finite difference procedures. A variety of optimization methods have been used including linear, nonlinear, and dynamic programming techniques. Based on a review of the literature it is evident that a significant effort has been made toward the development and refinement of combined optimization-simulation groundwater management models. It is also evident that the vast majority of the models which have been previously developed have been applied primarily to hypothetical, simplistic systems. The degree to which this class of model has been developed and applied to an existing groundwater system, and specifically a municipal groundwater production system, is extremely limited. In those few cases where an application to an existing system was documented, the objectives were primarily related to regional water resource allocation issues. Very little work has been documented pertaining to the use of combined optimization-simulation models to develop and evaluate management alternatives for the operation of large, existing, complex groundwater production system.

Based on the results of a review of the literature, it is apparent that combined optimization-simulation management models are valuable tools when used to evaluate groundwater management alternatives. Additional model development and application to existing systems is warranted. It is concluded that this class of model is particularly well suited for evaluating alternative management methodologies for large, existing groundwater production systems. With the benefit of a management model, the water resources manager can adequately define optimal production schedules to meet the demand for water while insuring that the integrity of the aquifer is protected. Without the benefit of this type of model, it is unlikely that the optimal management scenario could be identified, resulting in unnecessary costs and potential risks to the aquifer.

CHAPTER III

WATER PRODUCTION SYSTEM

General

The City of Enid water production system includes one hundred forty six (146) wells which produce drinking water from three (3) aquifers. Approximately 80 percent of the demand is produced from the Cimarron River Terrace Aquifer and the underlying Permian redbed sedimentary formations. The remaining 20 percent is produced from the Enid Isolated Terrace Aquifer. The maximum production capacity of the system is approximately 27 MGD. The average daily demand is approximately 11 MGD and the peak demand is approximately 18 MGD. Due to the exceptionally high quality of the groundwater in the region, chlorination and fluoridation are the only treatment processes required.

Water wells within the system vary in depth from less than 50 feet to approximately 200 feet. Water is pumped from individual wells through a system of collection, booster pumping facilities and transmission pipelines to the two main pumping facilities in Enid. The water is treated at these facilities and discharged into the municipal water distribution system.

Historical Development

In 1893, the Chicago, Rock Island and Union Pacific Railroads established the original town site of Enid prior to the settlement of the Cherokee Strip. The town site was located adjacent to Government Springs along the Chisholm Trail, which was extensively used to drive cattle from the west to stockyards and railroad in Kansas. On September 16, 1893 the Cherokee Strip of the Oklahoma Territory was opened for settlement and almost instantly the town of Enid began. A post office and land office were erected, followed rapidly by businesses and homes (O.G.&E., 1989).

Enid had a population of 3,444 by 1900 and in 1907, when Oklahoma attained statehood, the population had increased to approximately 10,000. The population continued to increase until the early 1980's when it peaked at approximately 58,000. Groundwater has historically been the sole source for the municipal water production system.

The initial municipal wells were developed in the late 1890's. These wells were completed in the Enid Isolated Terrace Aquifer in areas immediately west of the original townsite. These facilities included nine (9) wells in the King Farm wellfield and a well gallery at the site of the original water plant. As the demand for water increased, additional wells were developed in the Van Buren, Northwest and Carrier wellfields which produced water from the Enid Isolated Terrace Aquifer. By 1950, the wells within the

King Farm wellfield had been abandoned and the demand for municipal water was being met with thirty two (32) wells. The average capacity of these wells was 2.3 MGD, with a maximum capacity of 3.85 MGD (Black & Veatch, 1955), (E.T. Archer, 1944). These wells collectively comprise the Enid Wellfield.

The demand for water approached the safe yield of the Enid Isolated Terrace Aquifer in 1944, prompting an extensive study to identify additional water supplies (E.T. Archer, 1944). It was determined at that time that additional groundwater resources could be economically developed in the terrace deposits along the Cimarron River near the town of Ames. Opposition of landowners and irrigation interests effectively blocked attempts by Enid to develop wells in the terrace deposits and the City was forced to evaluate the Permian redbed strata for potential water resource development. The preliminary analyses indicated that wells could be successfully completed in the Permian strata and by 1955, thirty two (32) wells were completed in the Permian bedrock. These 32 wells collectively comprise the Drummond Wellfield. The average capacity of the Enid water production system in 1955 was 5.0 MGD, with a maximum capacity of 12.0 MGD (Black & Veatch, 1955).

Increasing demand for water, coupled with a three year drought between 1951 and 1954 resulted in the need for additional water resources. Although attempts by Enid to develop wells in the Cimarron River Terrace Aquifer had been successfully blocked by local landowners, the City was successful in leasing water rights from the St. Louis & San Francisco Railroad. Five (5) wells were developed in the terrace deposits within the railroad right-of-way, near Ames. These wells represent the initial development of the Ames Wellfield.

No significant expansions were made to the water production system from the mid-1950's until the late 1960's. In 1969, the City of Enid was again faced with a critical water supply problem. Maximum day usages were exceeding the safe yield of the existing water supply system (HTB, 1969).

In the early 1970's, Enid successfully leased the water rights to a significant area underlain by Cimarron River Terrace deposits, in the vicinity of Ames. During a ten (10) year period a total of thirty three (33) wells were completed in the Ames Wellfield. Thirty (30) of these are completed in the terrace deposits. The remaining three (3) are completed in the Permian strata (HTB, 1969). In 1980, the average water demand was approximately 14 MGD and the maximum demand was 21 MGD (Benham, 1982).

In the early 1980's, the City of Enid was not only facing a water shortage, but due to the rapid growth in population and new construction, was experiencing problems supplying adequate volumes and pressures in the water distribution system. A study was conducted to identify and evaluate alternative water sources.

Based on the results of that study, it was recommended that additional groundwater resources be developed in the Cimarron River Terrace Aquifer. A total of fifty nine (59) additional wells were completed in the Cimarron River terrace deposits between 1983 and 1985. Twenty eight of these wells comprise the Ringwood Wellfield and thirty one (31) wells are located in the Cleo Springs Wellfield. This improvement provided an additional 10.5 MGD capacity to the water production system.

Due to the large number of wells in the system, the resulting water production capacity exceeds the average demand by approximately 60 percent. Based on projected growth in population and water usage, it is anticipated that the current system will be adequate to meet the water demands of Enid through the year 2015.

Wellfields

The City of Enid water production system extracts water from one hundred forty six (146) wells. These wells are located in five (5) wellfields which include the Enid, Drummond, Ames, Ringwood and Cleo Springs wellfields. A location map is shown in Figure 3.1. A schematic illustrating the principal components of the water production system is presented in Figure 3.2. Multi-stage vertical turbine pumps, as illustrated in Figure 3.3, are

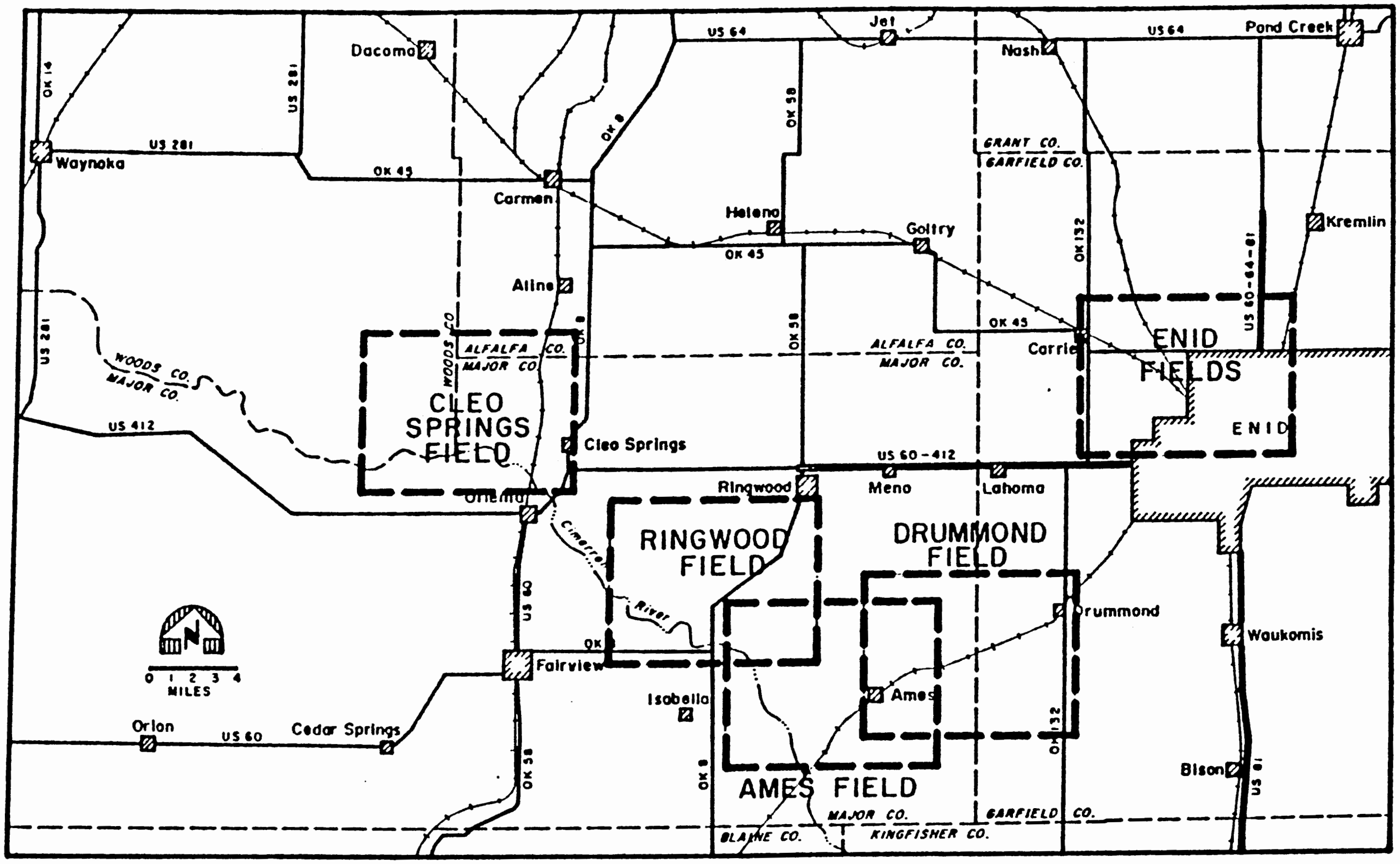

FIGURE 3.1 WELLFIELD LOCATION MAP

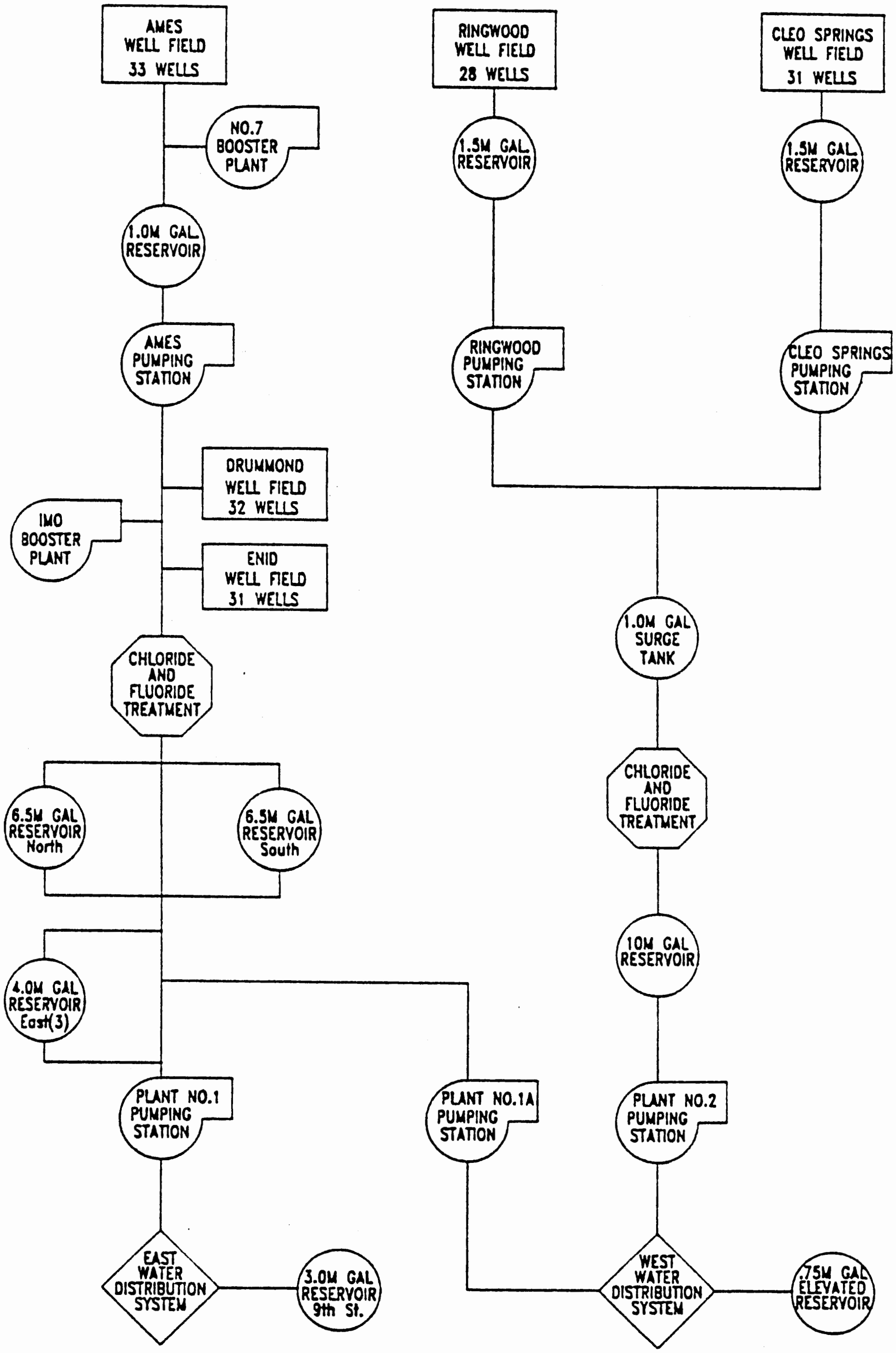

FIGURE 3.2 WATER PRODUCTION SYSTEM SCHEMATIC

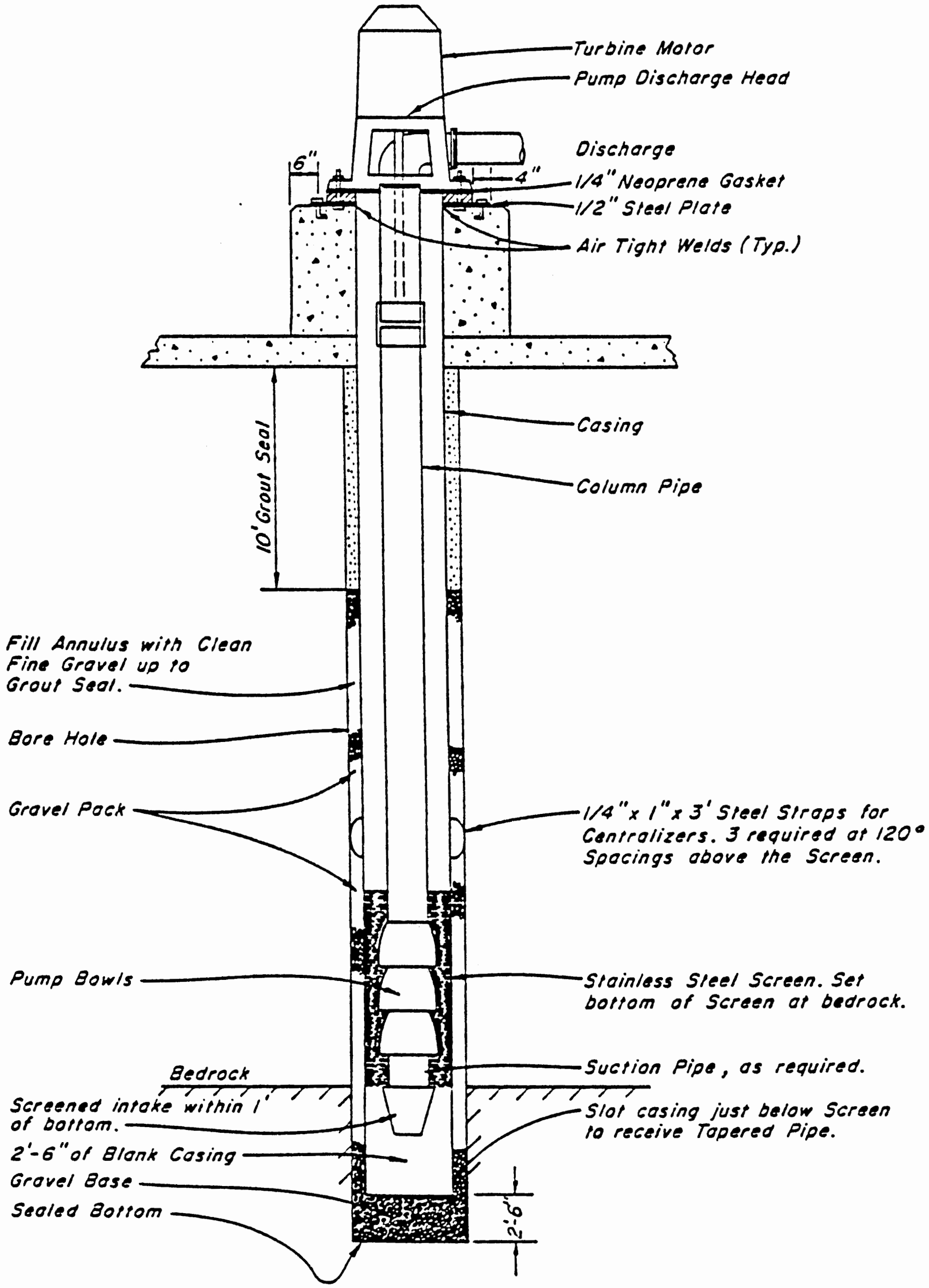

FIGURE 3.3 TYPICAL WATER PRODUCTION WELL

used exclusively within the system. Monitoring wells are installed at numerous locations within each wellfield to evaluate the condition of the aquifer. A typical monitoring well installation is shown in Figure 3.4.

Enid Wellfield

The Enid Wellfield is located immediately northwest of Enid and includes those wells which were originally developed as the Plant, Van Buren, Northwest and Carrier wellfields. The wellfield consists of thirty two (32) wells which are completed in the Enid Isolated Terrace Aquifer. The depth of these wells vary from thirty five (35) feet to eighty (80) feet. A wellfield location map is presented in Figure 3.5.

The total production capacity of the Enid Wellfield is approximately 2.5 MGD. Well capacities range from 40 GPM to 120 GPM. Individual well data is presented in Table 3.1. Water which is produced from the Enid Wellfield is pumped through a system of collection and transmission pipelines to the City of Enid Plant No. 1.

Drummond Wellfield

The Drummond Wellfield is located southwest of the town of Drummond and consists of thirty one (31) wells. These wells produce water from the Permian strata. The depth of these wells vary from fifty five (55) feet to two hundred

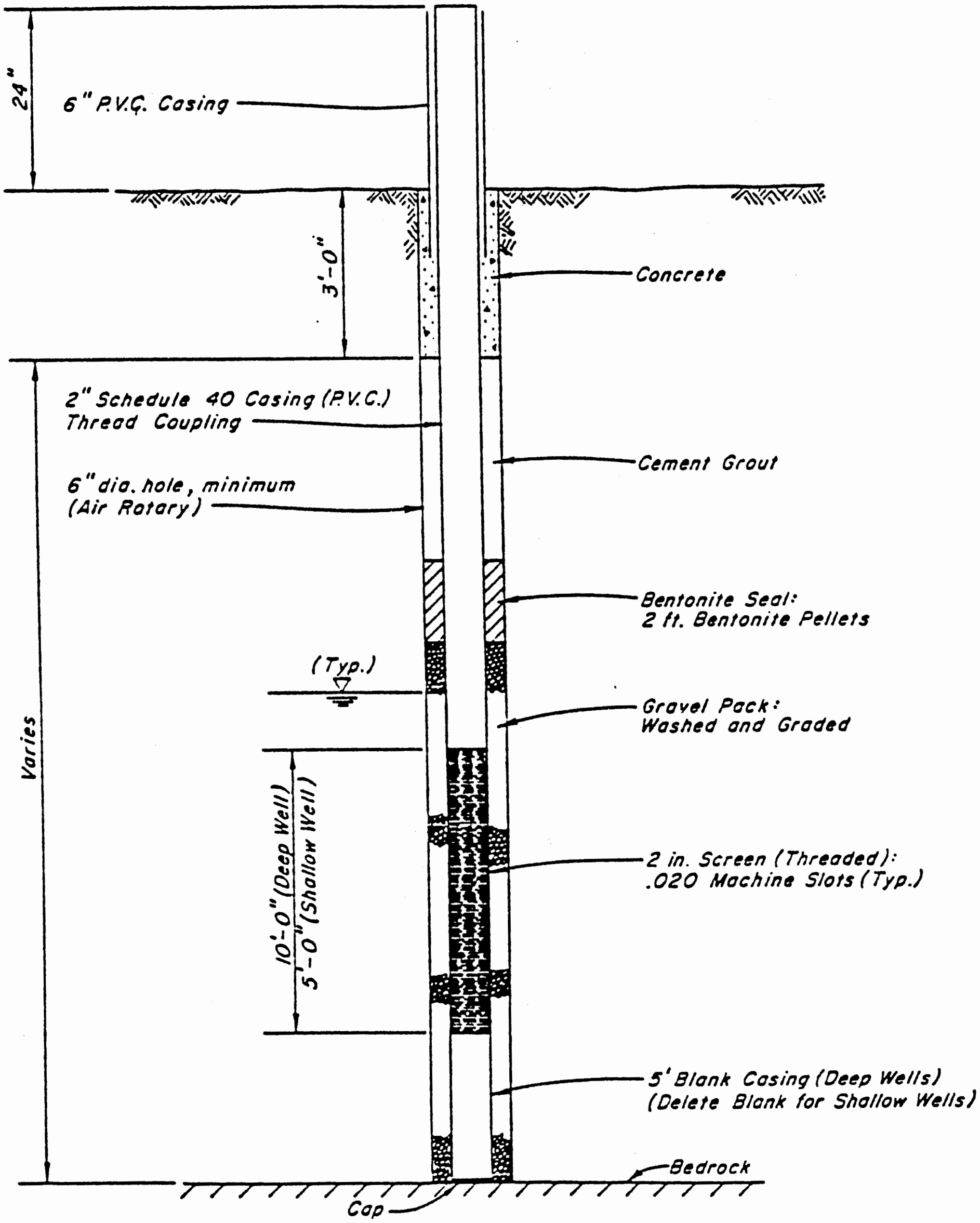

FIGURE 3.4 TYPICAL OBSERVATION WELL

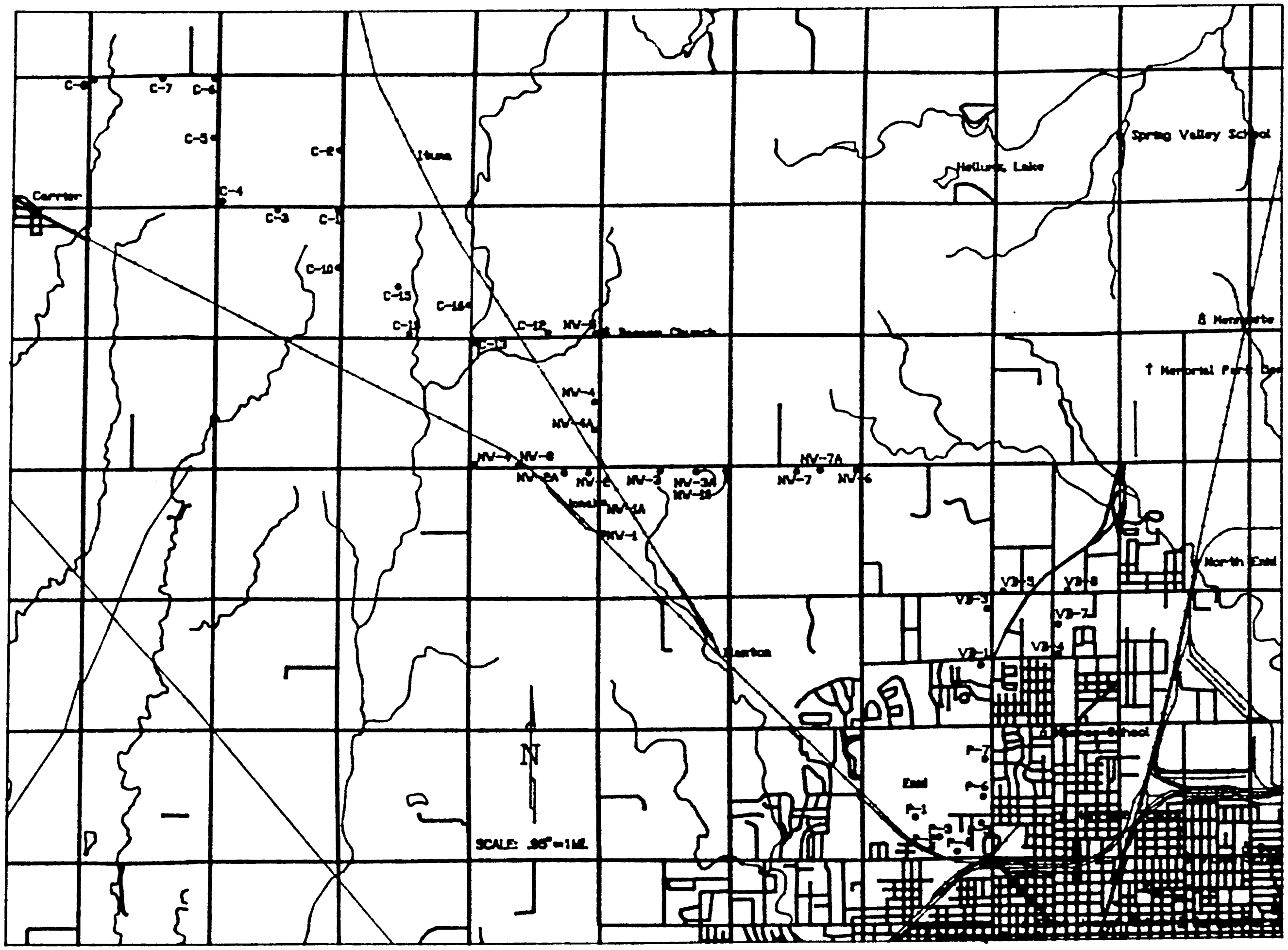

FIGURE 3.5 ENID WELLFIELD

TABLE 3.1

ENID WELLFIELD WELL DATA

WELL ID NUMBER	PUMP CAPACITY	PUMP TYPE	WELL DEPTH	WELL DIAMETER	SCREEN LENGTH
C-2	40 GPM	VERTICAL TURBINE	78.00	12"	5.00
C-3	75 GPM	VERTICAL TURBINE	80.00	12"	5.00
C-11	75 GPM	VERTICAL TURBINE	36.00	12"	5.00
C-12	100 GPM	VERTICAL TURBINE	49.00	12"	5.00
C-13	75 GPM	VERTICAL TURBINE	35.00	12"	5.00
C-15	50 GPM	VERTICAL TURBINE	47.00	12"	5.00
C-16	100 GPM	VERTICAL TURBINE	79.00	12"	10.00
NW-1	40 GPM	VERTICAL TURBINE	62.00	12"	5.00
NW-2	50 GPM	VERTICAL TURBINE	65.00	12"	10.00
NW-3	103 GPM	VERTICAL TURBINE	74.00	12"	5.00
NW-6	87 GPM	VERTICAL TURBINE	52.00	12"	5.00
NW-7	50 GPM	VERTICAL TURBINE	66.00	12"	5.00
NW-8	75 GPM	VERTICAL TURBINE	77.00	12"	5.00
NW-9	120 GPM	VERTICAL TURBINE	53.00	12"	5.00
NW-10	95 GPM	VERTICAL TURBINE	74.00	12"	5.00
P-1	75 GPM	VERTICAL TURBINE	51.00	12"	5.00
P-3	100 GPM	VERTICAL TURBINE	50.00	12"	10.00
P-4	70 GPM	VERTICAL TURBINE	49.00	12"	6.00
VB-1	100 GPM	VERTICAL TURBINE	67.00	12"	10.00
VB-3	50 GPM	VERTICAL TURBINE	55.00	12"	5.00
VB-4	50 GPM	VERTICAL TURBINE	53.00	12"	5.00
VB-5	50 GPM	VERTICAL TURBINE	56.00	12"	5.00
VB-7	50 GPM	VERTICAL TURBINE	58.00	12"	5.00
VB-8	65 GPM	VERTICAL TURBINE	54.00	12"	5.00

ten (210) feet. A wellfield location map is presented in Figure 3.6.

The total production capacity of the Drummond Wellfield is approximately 4.5 MGD. Well capacities range from 40 GPM to 280 GPM. Individual well data is presented in Table 3.2 Water produced from the Drummond Wellfield is pumped through collection lines directly into the main transmission pipeline which links the Ames Booster Station to City of Enid Plant No. 1.

Ames Wellfield

The Ames Wellfield is located in the vicinity of the town of Ames and consists of thirty-three wells. Thirty (30) of these wells produce water from the Cimarron River Terrace Aquifer and three (3) produce from the underlying Permian strata. The depth of these wells vary from forty (40) feet to one hundred seventy (170) feet. A wellfield location map is presented in Figure 3.7.

The total production capacity of the Ames Wellfield is approximately 9.6 MGD. Well capacities range from 42 GPM to 412 GPM. Individual well data is presented in Table 3.3. Water produced from the Ames Wellfield is pumped through a system of collection and transmission pipelines to the Ames Booster Station. The water is pumped from the booster station, through a primary transmission pipeline to City of Enid Plant No. 1.

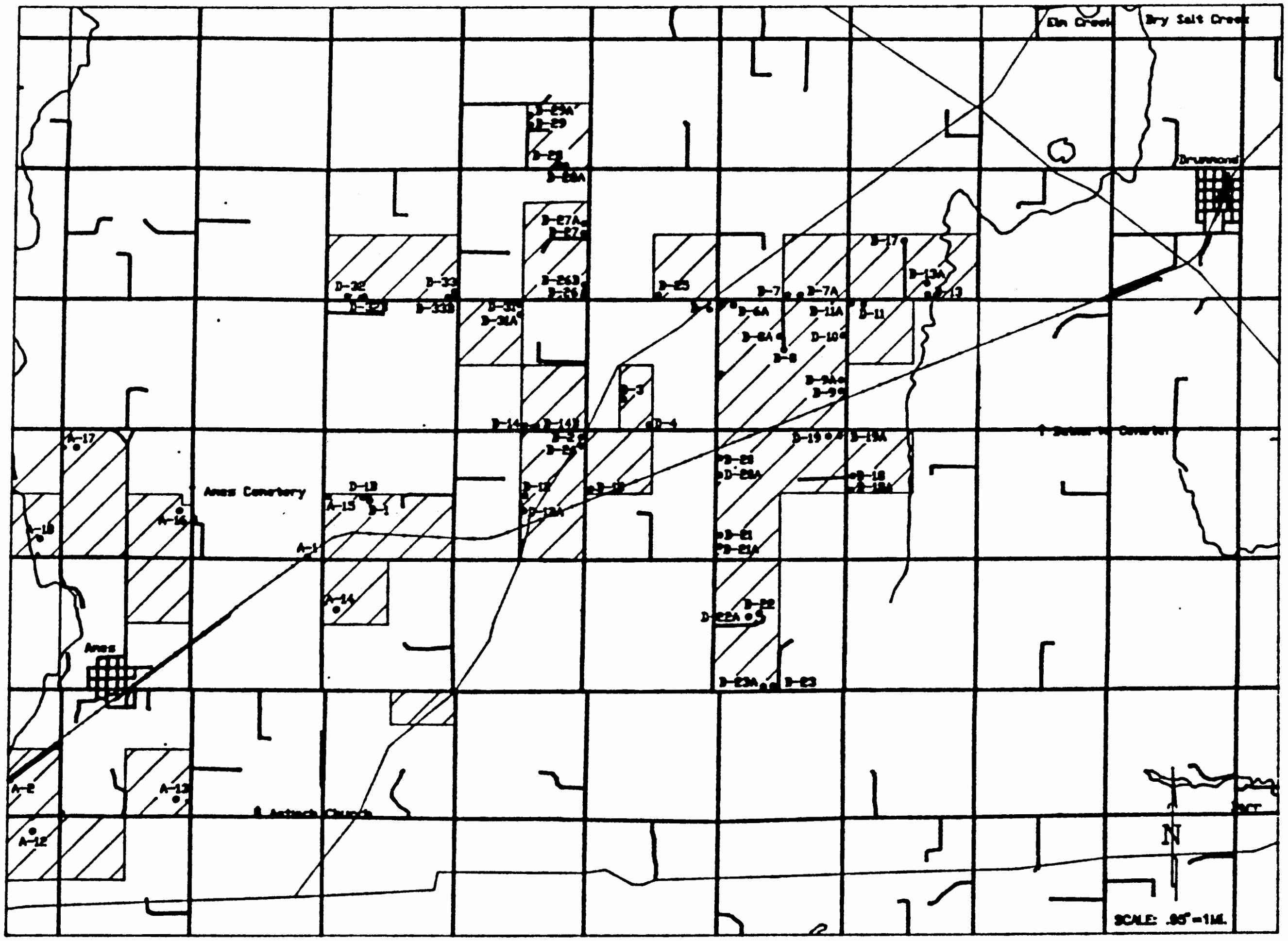

FIGURE 3.6 DRUMMOND WELLFIELD

TABLE 3.2

DRUMMOND WELLFIELD WELL DATA

WELL ID NUMBER	PUMP CAPACITY	PUMP TYPE	WELL DEPTH	WELL DIAMETER	SCREEN LENGTH
1	200 GPM	VERTICAL TURBINE	210.00	15.5"	N/A
2	128 GPM	VERTICAL TURBINE	178.00	15.5"	N/A
3	76 GPM	VERTICAL TURBINE	120.00	12"	N/A
4	250 GPM	VERTICAL TURBINE	200.00	12"	90 FT
5	60 GPM	VERTICAL TURBINE	130.00	12"	N/A
6	75 GPM	VERTICAL TURBINE	130.00	12"	N/A
7	180 GPM	VERTICAL TURBINE	81.00	12"	N/A
8	120 GPM	VERTICAL TURBINE	130.00	12"	N/A
9	48 GPM	VERTICAL TURBINE	61.00	12"	N/A
10	228 GPM	VERTICAL TURBINE	130.00	12"	N/A
11	125 GPM	VERTICAL TURBINE	130.00	12"	N/A
12	80 GPM	VERTICAL TURBINE	146.00	12"	N/A
13	200 GPM	VERTICAL TURBINE	55.00	12"	N/A
14	40 GPM	VERTICAL TURBINE	209.00	15.5"	N/A
15	70 GPM	VERTICAL TURBINE	210.00	12"	N/A
17	53 GPM	VERTICAL TURBINE	68.00	12"	N/A
18	125 GPM	VERTICAL TURBINE	84.00	12"	N/A
19	132 GPM	VERTICAL TURBINE	108.00	15.5"	N/A
20	250 GPM	VERTICAL TURBINE	110.00	12"	N/A
21	218 GPM	VERTICAL TURBINE	120.00	12"	N/A
22	340 GPM	VERTICAL TURBINE	105.00	12"	N/A
23	225 GPM	VERTICAL TURBINE	105.00	12"	N/A
25	280 GPM	VERTICAL TURBINE	120.00	12"	N/A
26	125 GPM	VERTICAL TURBINE	209.00	15.5"	N/A
27	72 GPM	VERTICAL TURBINE	150.00	12"	N/A
28	90 GPM	VERTICAL TURBINE	242.00	15.5"	N/A
29	200 GPM	VERTICAL TURBINE	203.00	15.5"	N/A
31	180 GPM	VERTICAL TURBINE	209.00	15.5"	N/A
32	240 GPM	VERTICAL TURBINE	220.00	15.5"	N/A
33	50 GPM	VERTICAL TURBINE	262.00	15.5"	N/A

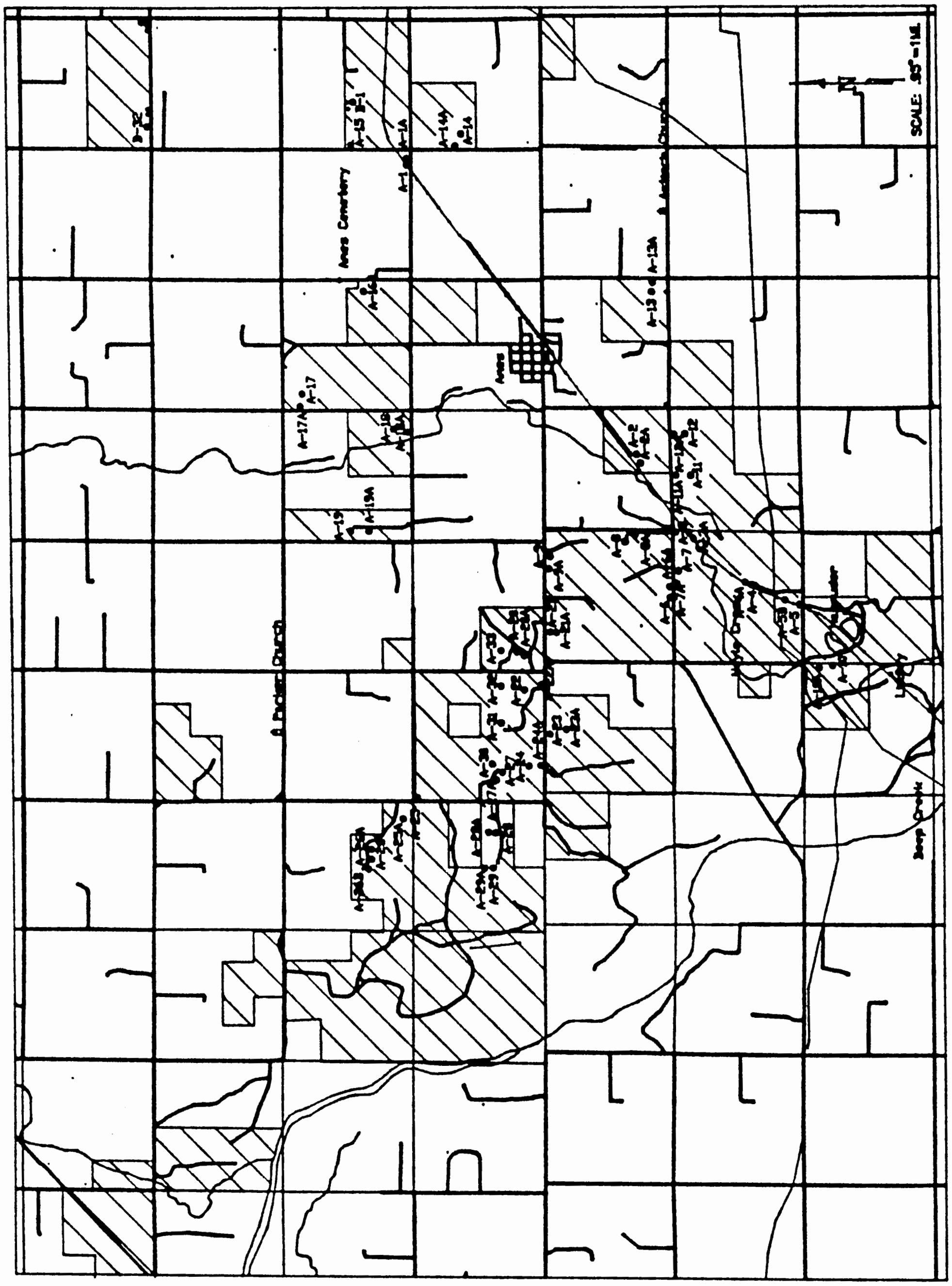

FIGURE 3.7 AMES WELLFIELD

TABLE 3.3

AMES WELLFIELD WELL DATA

WELL ID NUMBER	PUMP CAPACITY	PUMP TYPE	WELL DEPTH	WELL DIAMETER	SCREEN LENGTH
1	200 GPM	VERTICAL TURBINE	62.00	12"	15.00
2	250 GPM	VERTICAL TURBINE	67.00	12"	20.00
3	200 GPM	VERTICAL TURBINE	60.00	12"	15.00
4	100 GPM	VERTICAL TURBINE	54.00	12"	15.00
5	100 GPM	VERTICAL TURBINE	52.00	12"	15.00
6	300 GPM	VERTICAL TURBINE	145.00	12"	N/A
7	150 GPM	VERTICAL TURBINE	51.00	12"	5.00
8	200 GPM	VERTICAL TURBINE	144.00	12"	N/A
9	300 GPM	VERTICAL TURBINE	160.00	12"	N/A
10	42 GPM	VERTICAL TURBINE	38.00	12"	10.00
11	386 GPM	VERTICAL TURBINE	65.00	12"	10.00
12	108 GPM	VERTICAL TURBINE	60.00	12"	10.00
13	221 GPM	VERTICAL TURBINE	49.00	12"	10.00
14	95 GPM	VERTICAL TURBINE	72.00	12"	10.00
15	412 GPM	VERTICAL TURBINE	170.00	12"	N/A
16	187 GPM	VERTICAL TURBINE	59.00	12"	10.00
17	158 GPM	VERTICAL TURBINE	53.00	12"	12.00
18	247 GPM	VERTICAL TURBINE	57.00	12"	12.00
19	202 GPM	VERTICAL TURBINE	58.00	12"	10.00
20	288 GPM	VERTICAL TURBINE	87.00	12"	10.00
21	309 GPM	VERTICAL TURBINE	75.00	12"	8.00
22	212 GPM	VERTICAL TURBINE	83.00	12"	10.00
23	119 GPM	VERTICAL TURBINE	65.00	12"	16.00
24	76 GPM	VERTICAL TURBINE	83.00	12"	8.00
25	179 GPM	VERTICAL TURBINE	50.00	12"	10.00
26	213 GPM	VERTICAL TURBINE	61.00	12"	10.00
27	246 GPM	VERTICAL TURBINE	75.00	12"	10.00
28	261 GPM	VERTICAL TURBINE	57.00	12"	10.00
29	211 GPM	VERTICAL TURBINE	53.00	12"	15.00
30	375 GPM	VERTICAL TURBINE	68.00	12"	10.00
31	199 GPM	VERTICAL TURBINE	76.00	12"	10.00
32	293 GPM	VERTICAL TURBINE	77.00	12"	10.00
33	267 GPM	VERTICAL TURBINE	79.00	12"	10.00

Ringwood Wellfield

The Ringwood Wellfield is located southwest of the town of Ringwood and consists of twenty eight (28) wells. These wells produce water from the Cimarron River Terrace Aquifer. The depth of these wells vary from fifty five (55) feet to one hundred (100) feet. A wellfield location map is presented in Figure 3.8.

The total production capacity of the Ringwood Wellfield is approximately 4.8 MGD. Well capacities range from 43 GPM to 167 GPM. Individual well data is presented in Table 3.4. Water produced from the Ringwood Wellfield is pumped through a system of collection and transmission pipelines to the Ringwood Booster Station. The water is pumped from the booster station, through a primary transmission pipeline to City of Enid Plant No. 2.

Cleo Springs Wellfield

The Cleo Springs Wellfield is located west of the town of Cleo Springs and consists of thirty one (31) wells. These wells produce water from the Cimarron River Terrace Aquifer. The depth of these wells vary from twenty one (21) feet to eighty four (84) feet. A wellfield location map is presented in Figure 3.9.

The total production capacity of the Cleo Springs Wellfield is approximately 5.5 MGD. Well capacities range from 50 GPM to 230 GPM. Individual well data is presented in Table 3.5. Water produced from the Cleo Springs

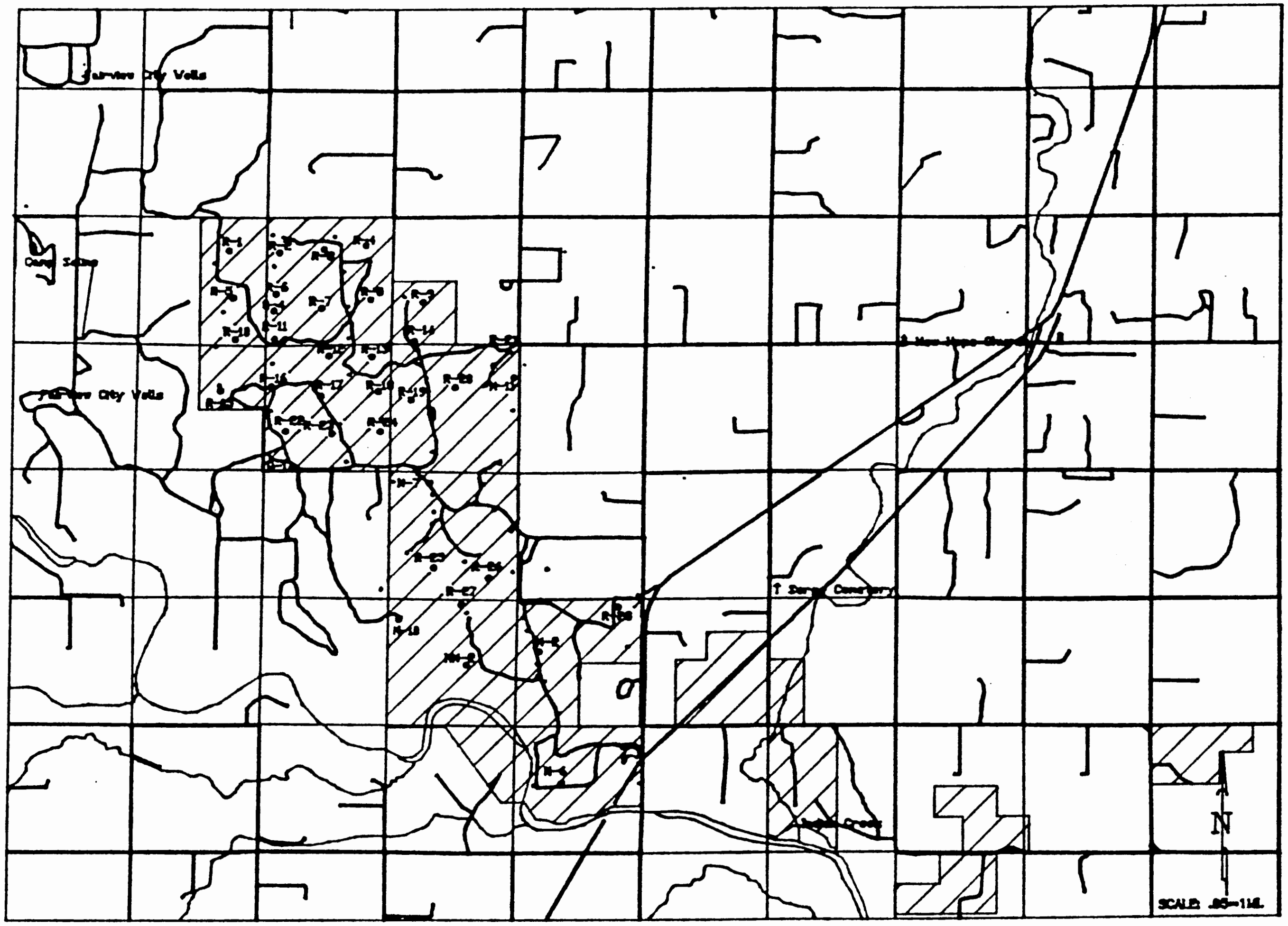

FIGURE 3.8 RINGWOOD WELLFIELD

TABLE 3.4

RINGWOOD WELLFIELD WELL DATA

WELL ID NUMBER	PUMP CAPACITY	PUMP TYPE	WELL DEPTH	WELL DIAMETER	SCREEN LENGTH
1	100 GPM	VERTICAL TURBINE	63.50	16"	12.00
2	108 GPM	VERTICAL TURBINE	72.00	16"	13.00
3	150 GPM	VERTICAL TURBINE	78.00	16"	16.00
4	57 GPM	VERTICAL TURBINE	85.00	16"	17.00
5	110 GPM	VERTICAL TURBINE	56.00	16"	11.00
6	63 GPM	VERTICAL TURBINE	67.00	16"	13.00
7	105 GPM	VERTICAL TURBINE	73.50	16"	14.00
8	160 GPM	VERTICAL TURBINE	79.00	16"	16.00
9	115 GPM	VERTICAL TURBINE	78.00	16"	13.00
10	160 GPM	VERTICAL TURBINE	63.00	16"	12.00
11	160 GPM	VERTICAL TURBINE	68.00	16"	13.00
12	160 GPM	VERTICAL TURBINE	69.00	16"	13.00
13	127 GPM	VERTICAL TURBINE	64.00	16"	12.00
14	53 GPM	VERTICAL TURBINE	62.00	16"	11.00
15	160 GPM	VERTICAL TURBINE	84.00	16"	10.00
16	160 GPM	VERTICAL TURBINE	54.00	16"	9.00
17	160 GPM	VERTICAL TURBINE	66.00	16"	11.00
18	81 GPM	VERTICAL TURBINE	62.00	16"	12.00
19	51 GPM	VERTICAL TURBINE	54.00	16"	10.00
20	83 GPM	VERTICAL TURBINE	59.00	16"	10.00
21	93 GPM	VERTICAL TURBINE	65.00	16"	10.00
22	56 GPM	VERTICAL TURBINE	57.00	16"	9.00
23	79 GPM	VERTICAL TURBINE	79.00	16"	9.00
24	127 GPM	VERTICAL TURBINE	58.00	16"	10.00
25	150 GPM	VERTICAL TURBINE	101.00	16"	13.00
26	150 GPM	VERTICAL TURBINE	83.00	16"	13.00
27	160 GPM	VERTICAL TURBINE	85.00	16"	14.00
28	160 GPM	VERTICAL TURBINE	55.00	16"	13.00

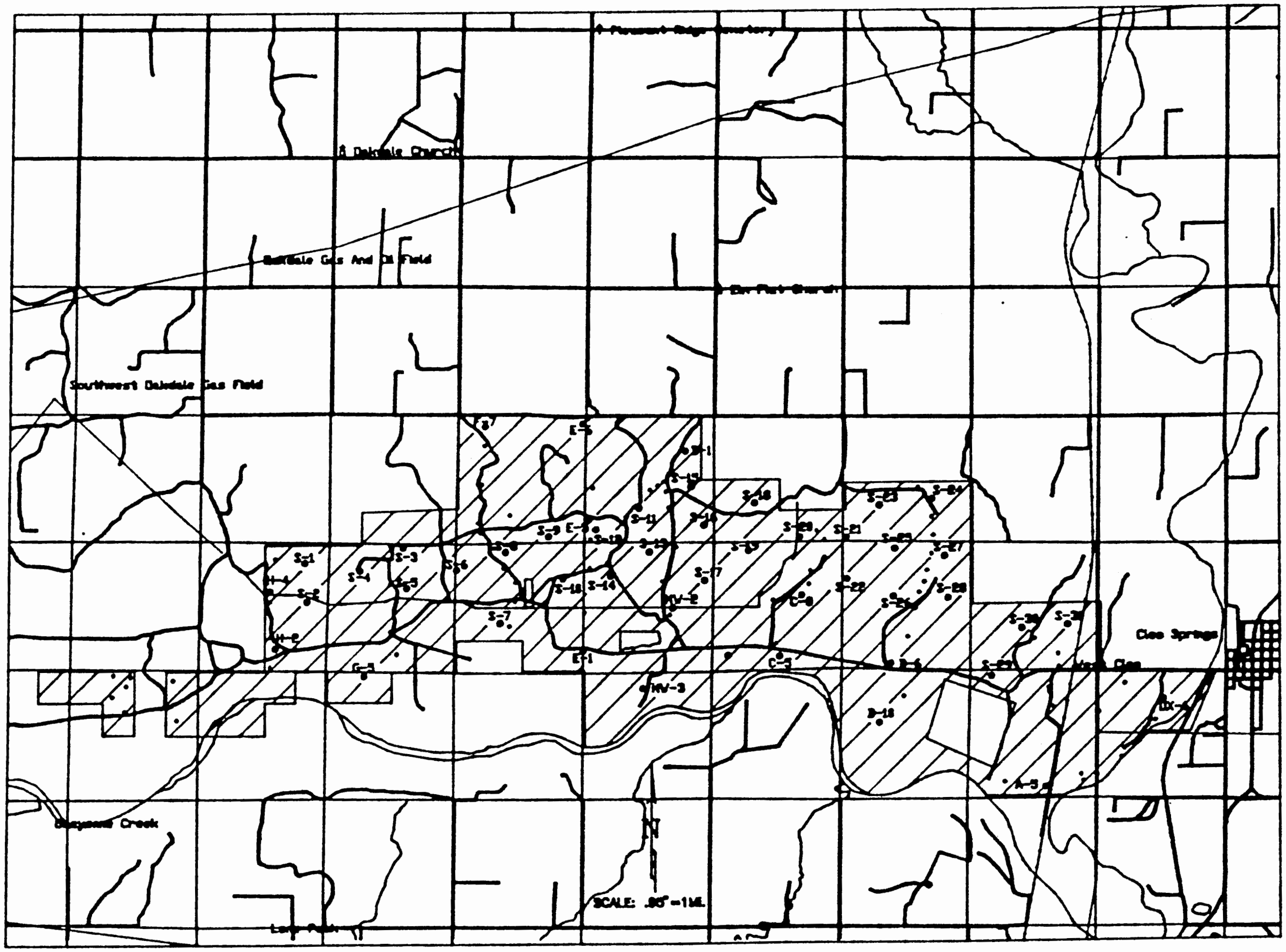

FIGURE 3.9 CLEO SPRINGS WELLFIELD

TABLE 3.5

CLEO SPRINGS WELLFIELD WELL DATA

WELL ID NUMBER	PUMP CAPACITY	PUMP TYPE	WELL DEPTH	WELL DIAMETER	SCREEN LENGTH
1	55 GPM	VERTICAL TURBINE	63.00	16"	12.00
2	90 GPM	VERTICAL TURBINE	53.00	16"	12.00
3	85 GPM	VERTICAL TURBINE	64.00	16"	14.00
4	140 GPM	VERTICAL TURBINE	70.00	16"	13.00
5	67 GPM	VERTICAL TURBINE	47.00	16"	9.00
6	110 GPM	VERTICAL TURBINE	48.00	16"	10.00
7	230 GPM	VERTICAL TURBINE	21.00	16"	HORIZONTAL
8	100 GPM	VERTICAL TURBINE	55.00	16"	11.00
9	50 GPM	VERTICAL TURBINE	52.00	16"	8.00
10	60 GPM	VERTICAL TURBINE	48.00	16"	12.00
11	120 GPM	VERTICAL TURBINE	77.00	16"	15.00
12	70 GPM	VERTICAL TURBINE	78.00	16"	12.00
13	160 GPM	VERTICAL TURBINE	67.00	16"	14.00
14	145 GPM	VERTICAL TURBINE	52.00	16"	12.00
15	160 GPM	VERTICAL TURBINE	84.00	16"	15.00
16	135 GPM	VERTICAL TURBINE	72.00	16"	14.00
17	50 GPM	VERTICAL TURBINE	58.00	16"	13.00
18	160 GPM	VERTICAL TURBINE	68.00	16"	16.00
19	125 GPM	VERTICAL TURBINE	74.00	16"	15.00
20	150 GPM	VERTICAL TURBINE	68.00	16"	15.00
21	160 GPM	VERTICAL TURBINE	77.00	16"	16.00
22	150 GPM	VERTICAL TURBINE	63.00	16"	13.00
23	160 GPM	VERTICAL TURBINE	76.00	16"	16.00
24	50 GPM	VERTICAL TURBINE	64.00	16"	14.00
25	160 GPM	VERTICAL TURBINE	63.00	16"	15.00
26	160 GPM	VERTICAL TURBINE	56.00	16"	14.00
27	90 GPM	VERTICAL TURBINE	58.00	16"	14.00
28	105 GPM	VERTICAL TURBINE	52.00	16"	12.00
29	105 GPM	VERTICAL TURBINE	21.00	16"	HORIZONTAL
30	140 GPM	VERTICAL TURBINE	56.00	16"	11.00
31	155 GPM	VERTICAL TURBINE	51.00	16"	10.00

Wellfield is pumped through a system of collection and transmission pipelines to the Cleo Springs Booster Station. The water is pumped from the booster station, through a primary transmission pipeline to City of Enid Plant No. 2.

Water Usage

Water usage from the City of Enid system increased steadily from the late 1890's until the early 1980's. Usage rates paralleled population trends which peaked in the spring of 1983 at approximately 57,800 (personal communication with Chris Henderson, City of Enid). At that time, the average demand was approximately 15 MGD and the maximum demand exceeded 22 MGD.

Since 1984, water usage has steadily declined. Water production data is presented in Figure 3.10 for the period from January 1984 through December 1991. This declining trend in usage is related to the depressed economy associated with developments in the oil, natural gas and agricultural industries. Population began to decrease dramatically in 1984 and continued to decrease through 1991. This was verified by the 1990 U.S. Census which reported a population of 45,309. In addition to declining population, the closure of several major industrial facilities, which were significant water users, contributed to the reduction in water consumption.

Although it is difficult to accurately predict the growth rate of a community, Enid has positioned its economy

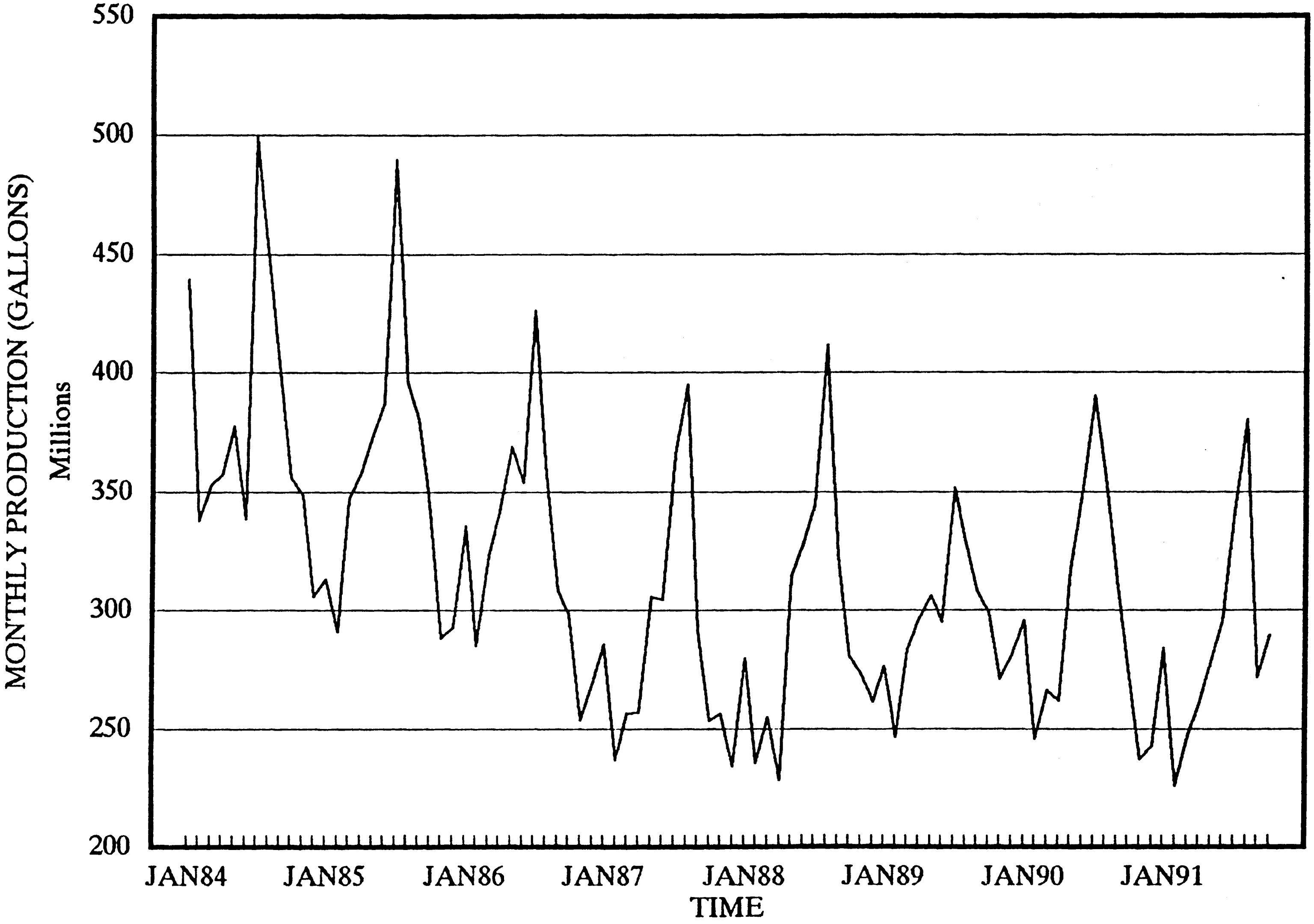

FIGURE 3.10 CITY OF ENID HISTORIC WATER PRODUCTION

to serve as the primary center of commerce and health care for northwestern Oklahoma and southwestern Kansas. Based on historical trends, it is probable that population and water usage will increase in the future. Future increases are anticipated to be moderate and will probably parallel the 2.1 percent annual growth rate which was observed between 1910 and 1980 (Benham, 1982). Based on historic data, the average per capita usage rate, exclusive of major water users, is approximately 160 GPD (Benham, 1982). The historic ratio of peak day demand to average day demand is equal to approximately 2.0 (HTB, 1969). Assuming major water users, including industries, etc. consume 5 MGD, it is estimated that the existing City of Enid water production system has the capacity to supply a population of approximately 69,000. If the 2.1 percent growth rate is realized, the existing system should be sufficient to supply the demands of Enid through the year 2015.

Operational Cost Factors

There are three (3) major parameters which dictate the cost of production for an individual well within the City of Enid water production system. These factors include: 1) electrical power usage; 2) water rights/royalty arrangements; and 3) system operation and maintenance requirements. The costs associated with these parameters are exclusive of costs associated with transmitting water to the main pumping facilities, treatment and distribution system pumping.

To successfully optimize a groundwater production system, it is essential that the operational cost factors for each well be evaluated. The individual factors which must be quantified include:

1. Pump Capacity (gallons/day)
2. Electrical Usage/Consumption Parameter (kwh/gallon)
3. Electrical Utility Cost Parameter ($/kwh)
4. Base Utility Demand Fee Parameter ($/day)
5. Base Royalty Cost Parameter ($/day)
6. Production Royalty Cost Parameter ($/gallon)
7. Operation and Maintenance Cost Parameter ($/day)

The identification of these parameters constitutes a significant effort. In some cases, this data can be derived from historical production data, provided complete and accurate records are maintained. Based on a review of the production records for the City of Enid system, it was determined that the records were insufficient to determine the required operational cost factors. Therefore, a comprehensive data acquisition program was implemented which resulted in a significant modification in operational procedures. In addition, a major portion of the system required additional instrumentation to provide the necessary water usage data.

Operational changes were initially undertaken in January 1989. A sufficient data base was accumulated by October

1991 to estimate the operational cost factors for each well within the system. The economic cost parameters for each well are presented in Table 3.6. A description of the individual parameters is presented in the following sections.

Electrical Utility Costs

The City of Enid water production system is supplied by two (2) utility companies. These utilities serve spatially different locations within the wellfields. Approximately 75 percent of the wells are supplied by Oklahoma Gas and Electric Company (O.G.&E.) and the remaining twenty five percent (25%) are supplied by Alfalfa Electric Cooperative (AEC). The cost to supply electrical power to an individual well is based on a base demand charge and a usage rate per kilowatt hour (kwh).

The base demand charge is related to the motor size at each well. Base demand charges for wells supplied by O.G.&E. are uniform for all wells within the system. Base demand charges for wells supplied by AEC are variable, depending on the individual pump motor size. Usage rates also differ between individual utility companies. O.G.&E. applies a fixed usage rate which remains constant. AEC applies a differential usage rate which depends on the total monthly consumption of electrical power. A comparison of the electrical utility cost factors for each utility company is presented in Table 3.7.

TABLE 3.6

WELL PRODUCTION COST PARAMETERS

WELL ID NO.	PUMP CAPACITY (GAL/DAY)	(*=EST.) ELECTRICAL USEAGE RATE (KWH/GAL)	ELECTRIC RATE ($/KWH)	BASE DEMAND RATE ($/DAY)	BASE ROYALTY RATE ($/DAY)	PRODUCTION ROYALTY RATE ($/GALLON)	O & M RATE ($/DAY)	WELL STATUS ID
AMES-1	288000	0.0006993	$0.04916	$0.36700	$0.27400	$0.0000000	$7.01	1
AMES-2	361440	0.0011098	$0.04916	$0.36700	$0.00000	$0.0000872	$8.31	1
AMES-3*	60480	0.0012849	$0.04916	$0.36700	$0.00000	$0.0000872	$8.31	1
AMES-4*	66240	0.0012849	$0.04916	$0.36700	$0.00000	$0.0000872	$7.79	1
AMES-5	109440	0.0027400	$0.04916	$0.36700	$0.00000	$0.0000872	$7.01	1
AMES-6	460800	0.0016679	$0.04916	$0.36700	$0.00000	$0.0000872	$8.05	1
AMES-7	73440	0.0019873	$0.04916	$0.36700	$0.00000	$0.0000872	$7.27	1
AMES-8	171360	0.0011439	$0.04916	$0.36700	$0.00000	$0.0000872	$8.05	1
AMES-9	381600	0.0012500	$0.04916	$0.36700	$0.00000	$0.0000872	$7.53	1
AMES-10*	60480	0.0012849	$0.08500	$6.53300	$0.00000	$0.0000872	$7.27	10000
AMES-11	555840	0.0017498	$0.04916	$0.36700	$0.00000	$0.0000872	$8.05	1
AMES-12	155520	0.0018562	$0.04916	$0.36700	$0.00000	$0.0000872	$7.27	1
AMES-13	318240	0.0013275	$0.04916	$0.36700	$0.00000	$0.0000872	$8.05	1
AMES-14	136800	0.0019983	$0.04916	$0.36700	$0.00000	$0.0000872	$7.53	1
AMES-15	593280	0.0007669	$0.04916	$0.36700	$0.00000	$0.0000872	$7.79	1
AMES-16	269280	0.0005959	$0.04916	$0.36700	$0.00000	$0.0000872	$7.79	1
AMES-17	227520	0.0011512	$0.04916	$0.36700	$0.00000	$0.0000872	$7.79	1
AMES-18	355680	0.0009744	$0.04916	$0.36700	$0.00000	$0.0000872	$7.53	1
AMES-19*	290880	0.0012849	$0.08500	$1.63300	$0.00000	$0.0000872	$8.31	1
AMES-20	414720	0.0002057	$0.08500	$5.13300	$0.00000	$0.0000872	$8.57	1
AMES-21*	444960	0.0012849	$0.08500	$5.83300	$0.00000	$0.0000872	$7.79	1
AMES-22	305280	0.0020998	$0.08500	$1.16700	$0.00000	$0.0000872	$8.31	1
AMES-23	171360	0.0002638	$0.08500	$5.13300	$0.00000	$0.0000872	$8.05	1
AMES-24	109440	0.0002557	$0.08500	$3.73300	$0.00000	$0.0000872	$8.05	1
AMES-25	257760	0.0012849	$0.08500	$2.56700	$0.00000	$0.0000872	$8.31	1
AMES-26	306720	0.0009790	$0.08500	$2.80000	$0.00000	$0.0000872	$8.57	1
AMES-27	354240	0.0016756	$0.08500	$5.13300	$0.00000	$0.0000872	$8.57	1
AMES-28*	375840	0.0012849	$0.08500	$1.16700	$0.00000	$0.0000872	$8.57	1
AMES-29	303840	0.0001160	$0.08500	$1.16700	$0.00000	$0.0000872	$8.31	1
AMES-30*	540000	0.0012849	$0.08500	$1.16700	$0.00000	$0.0000872	$8.57	1
AMES-31	286560	0.0012681	$0.08500	$5.83300	$0.00000	$0.0000872	$8.05	1
AMES-32	421920	0.0029558	$0.08500	$1.16700	$0.00000	$0.0000872	$8.57	1
AMES-33*	384480	0.0012849	$0.08500	$1.16700	$0.00000	$0.0000872	$8.57	1
CARRIER-2	57600	0.0019335	$0.04916	$0.36700	$0.27400	$0.0000000	$6.49	1
CARRIER-3	108000	0.0021573	$0.04916	$0.36700	$0.27400	$0.0000000	$5.72	1
CARRIER-11	108000	0.0015833	$0.04916	$0.36700	$0.27400	$0.0000000	$5.72	1
CARRIER-12	144000	0.0011799	$0.04916	$0.36700	$0.27400	$0.0000000	$5.98	1

TABLE 3.6 (Continued)

WELL ID NO.	PUMP CAPACITY (GAL/DAY)	(*=EST.) ELECTRICAL USEAGE RATE (KWH/GAL)	ELECTRIC RATE ($/KWH)	BASE DEMAND RATE ($/DAY)	BASE ROYALTY RATE ($/DAY)	PRODUCTION ROYALTY RATE ($/GALLON)	O & M RATE ($/DAY)	WELL STATUS ID
CARRIER-13	108000	0.0012719	$0.04916	$0.36700	$0.27400	$0.0000000	$5.72	1
CARRIER-15	72000	0.0033953	$0.04916	$0.36700	$0.27400	$0.0000000	$7.53	1
CARRIER-16	144000	0.0012125	$0.04916	$0.36700	$0.27400	$0.0000000	$7.01	1
CLEO SPRINGS-1	79200	0.0003434	$0.08500	$1.16700	$0.00000	$0.0000000	$7.27	1
CLEO SPRINGS-2	129600	0.0002820	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
CLEO SPRINGS-3	122400	0.0004199	$0.08500	$1.16700	$0.00000	$0.0000000	$7.27	1
CLEO SPRINGS-4	201600	0.0003201	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
CLEO SPRINGS-5	96480	0.0004141	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
CLEO SPRINGS-6	158400	0.0003909	$0.08500	$1.63300	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-7	331200	0.0002639	$0.08500	$1.16700	$0.00000	$0.0000000	$8.57	1
CLEO SPRINGS-8	144000	0.0003257	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
CLEO SPRINGS-9	72000	0.0004693	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
CLEO SPRINGS-10	86400	0.0003627	$0.08500	$1.16700	$0.00000	$0.0000000	$7.27	1
CLEO SPRINGS-11	172800	0.0003697	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
CLEO SPRINGS-12	100800	0.0004125	$0.08500	$1.40000	$0.00000	$0.0000000	$7.79	1
CLEO SPRINGS-13	230400	0.0003877	$0.08500	$0.16700	$0.00000	$0.0000000	$8.31	1
CLEO SPRINGS-14	208800	0.0004032	$0.08500	$1.40000	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-15	230400	0.0004630	$0.08500	$1.16700	$0.00000	$0.0000000	$8.31	1
CLEO SPRINGS-16	194400	0.0004599	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-17	72000	0.0004514	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
CLEO SPRINGS-18	230400	0.0004131	$0.08500	$1.16700	$0.00000	$0.0000000	$8.31	1
CLEO SPRINGS-19	180000	0.0004501	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-20	216000	0.0004298	$0.08500	$1.40000	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-21	230400	0.0004451	$0.08500	$1.16700	$0.00000	$0.0000000	$8.31	1
CLEO SPRINGS-22	216000	0.0003459	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-23	230400	0.0003371	$0.08500	$1.16700	$0.00000	$0.0000000	$8.31	1
CLEO SPRINGS-24	72000	0.0005413	$0.08500	$1.16700	$0.00000	$0.0000000	$7.01	1
CLEO SPRINGS-25	230400	0.0002424	$0.08500	$1.16700	$0.00000	$0.0000000	$8.31	1
CLEO SPRINGS-26	230400	0.0007330	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
CLEO SPRINGS-27	129600	0.0003534	$0.04916	$0.36700	$0.00000	$0.0000000	$7.79	1
CLEO SPRINGS-28	151200	0.0003800	$0.04916	$0.36700	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-29	331200	0.0002809	$0.04916	$0.36700	$0.00000	$0.0000000	$7.53	1
CLEO SPRINGS-30	201600	0.0003012	$0.04916	$0.36700	$0.00000	$0.0000000	$8.05	1
CLEO SPRINGS-31	223200	0.0002539	$0.04916	$0.36700	$0.00000	$0.0000000	$8.31	1
DRUMMOND-1	288000	0.0013566	$0.04916	$0.36700	$0.00000	$0.0000872	$7.79	1
DRUMMOND-2	184320	0.0015287	$0.04916	$0.36700	$0.00000	$0.0000872	$7.01	1
DRUMMOND-3	109440	0.0014332	$0.04916	$0.36700	$0.27400	$0.0000000	$7.27	1

TABLE 3.6 (Continued)

WELL ID NO.	PUMP CAPACITY (GAL/DAY)	(*=EST.) ELECTRICAL USEAGE RATE (KWH/GAL)	ELECTRIC RATE ($/KWH)	BASE DEMAND RATE ($/DAY)	BASE ROYALTY RATE ($/DAY)	PRODUCTION ROYALTY RATE ($/GALLON)	O & M RATE ($/DAY)	WELL STATUS ID
DRUMMOND-4*	360000	0.0015734	$0.04916	$0.36700	$0.27400	$0.0000000	$7.79	10000
DRUMMOND-5	86400	0.0024206	$0.04916	$0.36700	$0.27400	$0.0000000	$6.75	1
DRUMMOND-6*	108000	0.0015734	$0.04916	$0.36700	$0.27400	$0.0000000	$7.27	10000
DRUMMOND-7*	259200	0.0015734	$0.04916	$0.36700	$0.27400	$0.0000000	$7.27	1
DRUMMOND-8	172800	0.0015107	$0.04916	$0.36700	$0.27400	$0.0000000	$7.53	1
DRUMMOND-9	69120	0.0012455	$0.04916	$0.36700	$0.27400	$0.0000000	$7.01	1
DRUMMOND-10	328320	0.0011565	$0.04916	$0.36700	$0.27400	$0.0000000	$7.79	1
DRUMMOND-11	180000	0.0011447	$0.04916	$0.36700	$0.27400	$0.0000000	$7.27	1
DRUMMOND-12	115200	0.0011058	$0.04916	$0.36700	$0.27400	$0.0000000	$7.53	1
DRUMMOND-13*	288000	0.0015734	$0.04916	$0.36700	$0.27400	$0.0000000	$8.05	10000
DRUMMOND-14	136800	0.0014610	$0.04916	$0.36700	$0.00000	$0.0000872	$6.49	1
DRUMMOND-15	593280	0.0014829	$0.04916	$0.36700	$0.00000	$0.0000872	$6.75	1
DRUMMOND-17	227520	0.0027765	$0.04916	$0.36700	$0.27400	$0.0000000	$7.79	1
DRUMMOND-18	355680	0.0013338	$0.04916	$0.36700	$0.27400	$0.0000000	$6.75	1
DRUMMOND-19	290880	0.0011800	$0.04916	$0.36700	$0.27400	$0.0000000	$7.01	1
DRUMMOND-20	414720	0.0011094	$0.04916	$0.36700	$0.27400	$0.0000000	$7.27	1
DRUMMOND-21	444960	0.0009364	$0.04916	$0.36700	$0.27400	$0.0000000	$7.27	1
DRUMMOND-22*	305280	0.0015734	$0.04916	$0.36700	$0.27400	$0.0000000	$8.57	10000
DRUMMOND-23*	171360	0.0015734	$0.04916	$0.36700	$0.27400	$0.0000000	$6.75	10000
DRUMMOND-25	257760	0.0008398	$0.04916	$0.36700	$0.27400	$0.0000000	$7.79	1
DRUMMOND-26	306720	0.0024075	$0.04916	$0.36700	$0.00000	$0.0000872	$7.01	1
DRUMMOND-27	354240	0.0010721	$0.04916	$0.36700	$0.27400	$0.0000000	$6.75	1
DRUMMOND-28*	375840	0.0015734	$0.04916	$0.36700	$0.00000	$0.0000872	$6.75	10000
DRUMMOND-29*	303840	0.0015734	$0.04916	$0.36700	$0.27400	$0.0000000	$7.79	10000
DRUMMOND-31	286560	0.0024894	$0.04916	$0.36700	$0.00000	$0.0000872	$7.53	1
DRUMMOND-32	421920	0.0020733	$0.04916	$0.36700	$0.27400	$0.0000000	$7.27	1
DRUMMOND-33	384480	0.0025496	$0.04916	$0.36700	$0.27400	$0.0000000	$6.49	1
NORTHWEST-1	57600	0.0085249	$0.04916	$0.36700	$0.00000	$0.0000872	$6.49	1
NORTHWEST-2	72000	0.0011193	$0.04916	$0.36700	$0.27400	$0.0000000	$6.49	1
NORTHWEST-3	148320	0.0010847	$0.04916	$0.36700	$0.00000	$0.0000872	$6.49	1
NORTHWEST-6	125280	0.0015000	$0.04916	$0.36700	$0.00000	$0.0000872	$6.49	1
NORTHWEST-7	72000	0.0037500	$0.04916	$0.36700	$0.00000	$0.0000872	$6.49	1
NORTHWEST-8*	108000	0.0028694	$0.04916	$0.36700	$0.00000	$0.0000872	$7.01	1
NORTHWEST-9	172800	0.0012377	$0.04916	$0.36700	$0.00000	$0.0000872	$6.49	1
NORTHWEST-10*	136800	0.0028694	$0.04916	$0.36700	$0.00000	$0.0000872	$6.75	1
PLANT-1	108000	0.0002381	$0.04916	$0.36700	$0.00000	$0.0000000	$6.24	1

TABLE 3.6 (Continued)

WELL ID NO.	PUMP CAPACITY (GAL/DAY)	(*=EST.) ELECTRICAL USEAGE RATE (KWH/GAL)	ELECTRIC RATE ($/KWH)	BASE DEMAND RATE ($/DAY)	BASE ROYALTY RATE ($/DAY)	PRODUCTION ROYALTY RATE ($/GALLON)	O & M RATE ($/DAY)	WELL STATUS ID
PLANT-3	144000	0.0028694	$0.04916	$0.36700	$0.00000	$0.0000000	$5.98	10000
PLANT-4	100800	0.0028694	$0.04916	$0.36700	$0.27400	$0.0000000	$6.24	10000
RINGWOOD-1	144000	0.0004956	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-2	155520	0.0004677	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
RINGWOOD-3	216000	0.0004558	$0.08500	$1.16700	$0.00000	$0.0000000	$7.27	1
RINGWOOD-4	82080	0.0005309	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-5	158400	0.0004626	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
RINGWOOD-6	61920	0.0005519	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-7	151200	0.0005090	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
RINGWOOD-8	230400	0.0005286	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
RINGWOOD-9	165600	0.0004118	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
RINGWOOD-10	230400	0.0005088	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
RINGWOOD-11	230400	0.0005322	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
RINGWOOD-12	230400	0.0004356	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
RINGWOOD-13	182880	0.0005093	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
RINGWOOD-14	76320	0.0005606	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-15	230400	0.0004728	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
RINGWOOD-16	230400	0.0004393	$0.08500	$1.16700	$0.00000	$0.0000000	$8.05	1
RINGWOOD-17	230400	0.0005578	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-18	116640	0.0004392	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-19	73440	0.0005560	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-20	119520	0.0004819	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-21	133920	0.0004540	$0.08500	$1.16700	$0.00000	$0.0000000	$7.01	1
RINGWOOD-22	80640	0.0008643	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-23	113760	0.0005399	$0.08500	$1.16700	$0.00000	$0.0000000	$7.53	1
RINGWOOD-24	240480	0.0008919	$0.08500	$1.16700	$0.00000	$0.0000000	$7.79	1
RINGWOOD-25	230400	0.0007124	$0.08500	$2.80000	$0.00000	$0.0000000	$7.79	1
RINGWOOD-26	216000	0.0006723	$0.08500	$1.86700	$0.00000	$0.0000000	$7.79	1
RINGWOOD-27	230400	0.0002329	$0.08500	$2.33300	$0.00000	$0.0000000	$8.05	1
RINGWOOD-28	230400	0.0008457	$0.08500	$2.56700	$0.00000	$0.0000000	$7.27	1
VAN BUREN-1	144000	0.0011827	$0.04916	$0.36700	$0.27400	$0.0000000	$7.01	1
VAN BUREN-3	72000	0.0015784	$0.04916	$0.36700	$0.27400	$0.0000000	$5.72	1
VAN BUREN-4	72000	0.0015936	$0.04916	$0.36700	$0.00000	$0.0000000	$5.98	1
VAN BUREN-5	72000	0.0013745	$0.04916	$0.36700	$0.27400	$0.0000000	$5.98	1
VAN BUREN-7	72000	0.0012719	$0.04916	$0.36700	$0.00000	$0.0000000	$6.49	1
VAN BUREN-8	93600	0.0017607	$0.04916	$0.36700	$0.27400	$0.0000000	$5.98	1

TABLE 3.7

ELECTRICAL UTILITY COST COMPARISON

Utility	Wells Supplied	Base Demand Charge	Base Usage Rate	Differential* Usage Rate
O.G.&E.		$11/mo	$0.04916/Kwh	---
AEC		$35-$196/mo	$0.0850/Kwh	$0.0450/Kwh

*Differential usage rate is applied to monthly usage in excess of 6500 Kwh for an individual well.

Water Rights Costs

Under Oklahoma law, groundwater is allocated for reasonable use based on a hydrologic survey of the fresh groundwater basin. Based on the results of the hydrologic survey, a maximum annual production is determined which is based upon the land surface area overlying the groundwater basin. In order to obtain a permit to construct a well and withdraw groundwater, it is necessary to own the surface rights to the land on which the well is to be located or hold a valid right from the surface owner permitting withdrawal of water (OWRB, 1985).

There are essentially five (5) different types of water rights agreements which individually apply to wells within the City of Enid water production system. These agreements include: 1) annual lease; 2) royalty; 3) royalty with minimum production; 4) royalty with minimum fee, and 5) ownership in fee simple. These agreements are described below.

Annual Lease. The annual lease agreement provides that parties which own the water rights be paid an annual lease payment by the City of Enid. This payment represents full compensation for all water produced from the leased property during the calendar year. Annual lease agreements were used exclusively until the City of Enid began developing water production capabilities within the Cimarron River Terrace Aquifer, in the early 1970's. Negotiations with landowners at that time resulted in the structuring of the initial production based royalty agreements (Personal communication with Lester Long, City of Enid). In 1991, there were thirty six (36) wells produced under annual lease agreements. These agreements provide for annual lease fees which range from $100 to $300 per well.

Royalty. The royalty agreement provides that parties which own the water rights be paid a production based fixed royalty. The City of Enid has no minimum production obligation under this arrangement. In 1991, there was one (1) well produced under royalty agreement. This agreement provides that the fixed royalty is adjusted periodically, based on fluctuations in the U.S. Department of Commerce Consumer Price Index (CPI). In 1991, the royalty amount was $0.0872 per one-thousand (1000) gallons pumped.

Royalty With Minimum Production. The royalty with minimum production agreement provides that parties which own the water rights be paid a production based fixed royalty which is an identical arrangement as the royalty agreement; however, there is an additional stipulation in the agreement that requires a minimum production rate be continuously maintained. If the minimum production rate is not maintained, a minimum royalty is paid based on the minimum production rate. In 1991, there were five (5) wells produced under royalty with minimum production agreements. These agreements provide that a minimum of 100 GPM per 160 acres be produced. If average production falls below this rate, a royalty payment is determined based on the minimum production rate. If average production exceeds this rate, the royalty payment is determined based on actual usage. In 1991, the fixed royalty amount was $0.0872 per one-thousand (1000) gallons produced. This figure is adjusted periodically in the manner discussed under the royalty agreement.

<u>Royalty With Minimum Fee</u>. The royalty with minimum fee agreement provides that parties which own the water rights be paid a production based fixed royalty which is identical to the royalty agreement, with an additional stipulation in the agreement which requires a minimum annual royalty be met. If the production based royalty is determined to be less than the minimum royalty stipulated in the agreement, the minimum royalty is paid. If the annual production based royalty exceeds the minimum, then the minimum royalty is disregarded. In 1991, there were forty (40) wells produced under royalty with minimum fee agreements. These agreements

provide that if the total annual production based royalty is determined to be less than $2,000 per 640 acres, then the royalty payment shall be calculated based on the minimum fee. If the annual production based royalty exceeds the minimum fee, then the royalty payment is determined based on actual usage. In 1991, the fixed royalty amount was $0.0872 per one-thousand (1000) gallons produced. This figure is adjusted periodically in the manner discussed under the royalty agreement.

Ownership In Fee Simple. The City of Enid either owns the surface rights or has purchased the water rights to a significant area beneath which groundwater is extracted. In these areas, the water rights are owned in fee simple. In those areas where this situation exists, the initial cost to acquire water rights was high, but no annual costs are associated with maintaining those water rights. In 1991, there were sixty four (64) wells produced on land which the City of Enid owned the water rights in fee simple.

Operation and Maintenance Costs

The costs associated with operating and maintaining wells within the City of Enid water production system are a function of several factors. These include: 1) size and type of pump; 2) age and condition of the equipment (i.e. pump, motor, electrical control system, valves, etc.); and 3) proximity of the well to maintenance resources. Collectively, these factors result in differential maintenance and operation costs among individual wells within the system.

The type and size of equipment which comprises an individual well varies considerably within the system. The major differences between wells relate to the level of technical sophistication of the electrical control system. The oldest wells are controlled by a very basic, manual control system. The newer wells utilize microprocessor technology to control well operations. Maintenance costs increase dramatically between the manual systems and the microprocessor systems. Maintenance costs are also a function of equipment size. As motor and pump sizes increase, maintenance costs generally increase.

The age and condition of existing equipment varies significantly throughout the system. This is a result of staged development of water production facilities over nine decades. In addition, adequate maintenance has occasionally been sacrificed during economically depressed periods.

The final factors which affect the cost of operating and maintaining the water production system are distance of the individual wells from maintenance facilities and the accessibility of each well site. As distance increased and site accessibility decreases, the cost to operate and maintain a well increases. Due to the significant distances between wellfields and the remote nature of some areas within the wellfields, these factors significantly impact the cost of system maintenance and operation.

It is often difficult to equitably distribute operation and maintenance costs for a large system to individual components within the system. A method to approximate this distribution process was developed using an importance weighting approach. Using this technique, an importance weight is assigned to the following factors:

1. Age of well
2. Pump size
3. Distance of well site from maintenance facility
4. Well site accessibility

An estimate of individual operation and maintenance costs for each well is determined by initially calculating the importance weighting coefficient for each well. Applicable importance weighting coefficient values are presented in Table 3.8. Using the well specific coefficients and the estimated total system operation and maintenance costs, an average cost for operation and maintenance of each well can be estimated. Operation and maintenance costs for the Enid water production system typically range from $17,000 to $42,000 per month under normal operating conditions.

TABLE 3.8

OPERATION AND MAINTENANCE COST COEFFICIENTS

EQUIPMENT AGE

WELL AGE (YEARS)	IMPORTANCE WEIGHTING COEFFICIENT
50+	10
41 - 50	9
31 - 40	8
21 - 30	7
11 - 20	6
0 - 10	5

PUMP SIZE

PUMP SIZE (GPM)	IMPORTANCE WEIGHTING COEFFICIENT
250+	10
201 - 250	9
151 - 200	8
101 - 150	7
51 - 100	6
1 - 50	5

WELL DISTANCE

WELL DISTANCE FROM MAINTENANCE FACILITY	IMPORTANCE WEIGHTING COEFFICIENT
41+	10
31 - 40	9
21 - 30	8
11 - 20	7
0 - 10	6

WELL ACCESSIBILITY

WELL SITE ACCESSIBILITY	IMPORTANCE WEIGHTING COEFFICIENT
Unimproved trail	10
Unimproved road	9
Graded road	8
Gravel road	7
Surfaced road	6

CHAPTER IV

HYDROGEOLOGIC SETTING

General

The study area is located in north-central Oklahoma within the Central Redbed Plains geomorphic province of Oklahoma (Johnson, 1972). Topography in the region is characterized as gently rolling to rugged in areas where the Permian formations are exposed to rolling sand dunes where the Cimarron River and Enid Isolated Terrace deposits are exposed. Elevations range from approximately 1100 feet above mean sea level (MSL) to approximately 1400 feet. Maximum local relief is approximately 100 feet.

The region is predominately rural with several small towns scattered throughout. The City of Enid is the principal population center, with a 1990 population of approximately 47,000. The other towns in the region have populations typically less than 2500. The total population within the study area is approximately 65,000. Land use in the region is devoted to wheat cultivation, livestock grazing and production of oil and gas.

Groundwater resources are extremely important to the region. All water used within the region is pumped from wells with the exception of natural precipitation. The principal sources of fresh water within the study area are the Cimarron River Terrace and Alluvium deposits, the Enid Isolated Terrace deposits and the Cedar Hills Sandstone Formation within the Permian Redbed sequence. The majority of water produced is used for both private and municipal drinking water supplies, livestock and irrigation.

Climate

The climate within the project area is classified as subhumid (Thornthwaite, 1941). The mean annual temperature at Enid is 60.0 degrees Fahrenheit. Temperatures in excess of 100 degrees in the summer months and below 0 degrees in the winter months are observed but not common. Pertinent weather statistics are presented in Table 4.1 (OG&E, 1989.)

TABLE 4.1

WEATHER STATISTICS

Temperatures:	
Winter Average (Dec., Jan., Feb.)	38.5 degrees
Spring Average (Mar., Apr., May)	58.8 degrees
Summer Average (June, July, Aug.)	80.9 degrees
Fall Average (Sept., Oct., Nov.)	61.8 degrees
Precipitation:	
Average Annual Rain	30"
Average Annual Frozen	12"

The region receives an annual rainfall of approximately 30 inches with an additional 12 inches of frozen precipitation. The majority of the rainfall is received in the late spring and early fall during short, intense thunderstorms.

Due to the size of the project area and local variations in precipitation, often resulting from the same storm event, it was determined that precipitation recording devices should be installed in close proximity to the wellfields. Continually recording tipping bucket precipitation gages were installed in all wellfields except the Enid wellfield where an existing station previously existed. The precipitation data acquired with this equipment was useful in evaluating total precipitation, intensity patterns and spatial variation. Precipitation data was used in conjunction with groundwater monitoring to estimate aquifer recharge rates.

Geology

The geologic units exposed in the study area range in age from Permian to Quaternary. The most significant water bearing Quaternary deposits include the Cimarron River Terrace and Alluvial deposits and the Enid Isolated Terrace deposits. The underlying Permian sedimentary formations include some units which are locally important for water resources. A regional geologic map is shown in Figure 4.1 and a generalized stratigraphic section is shown in Figure 4.2.

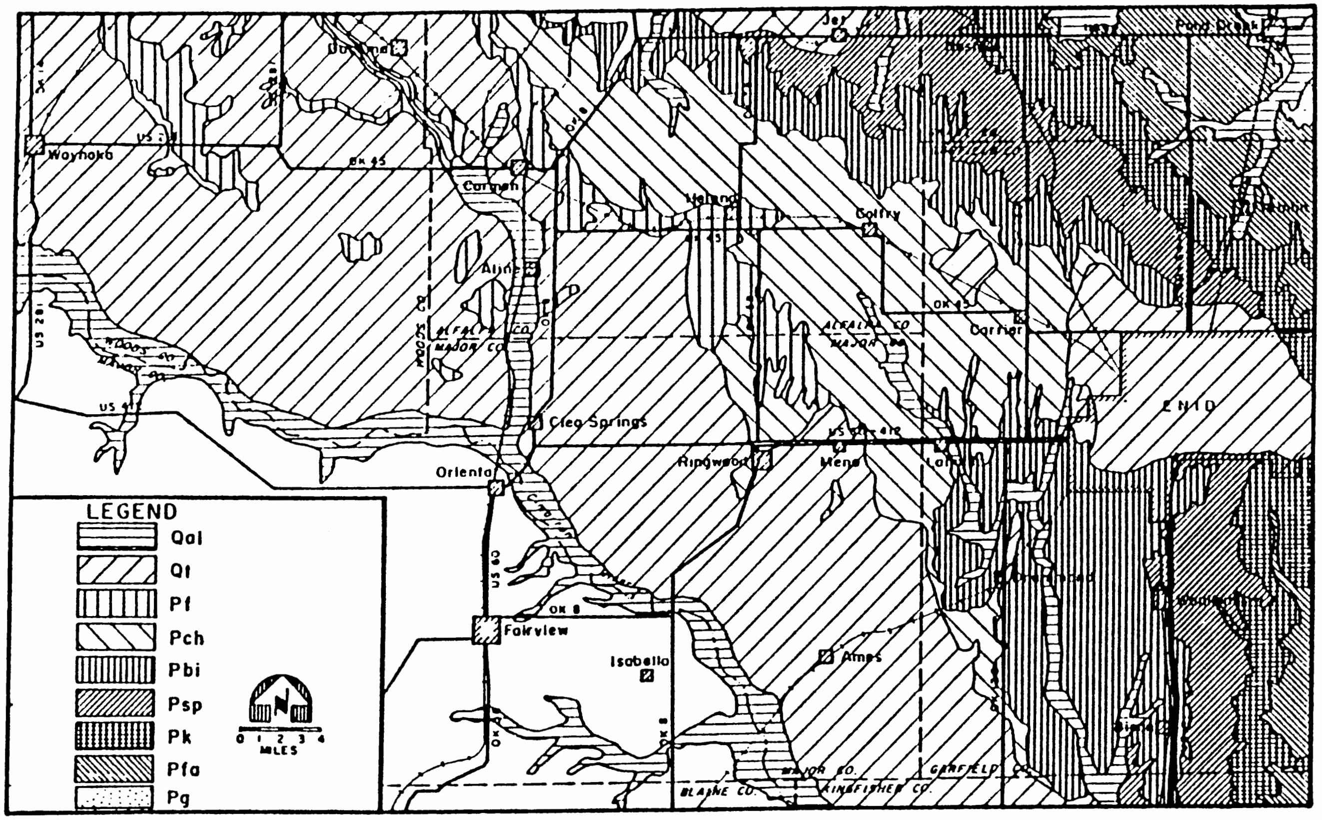

FIGURE 4.1 REGIONAL GEOLOGIC MAP

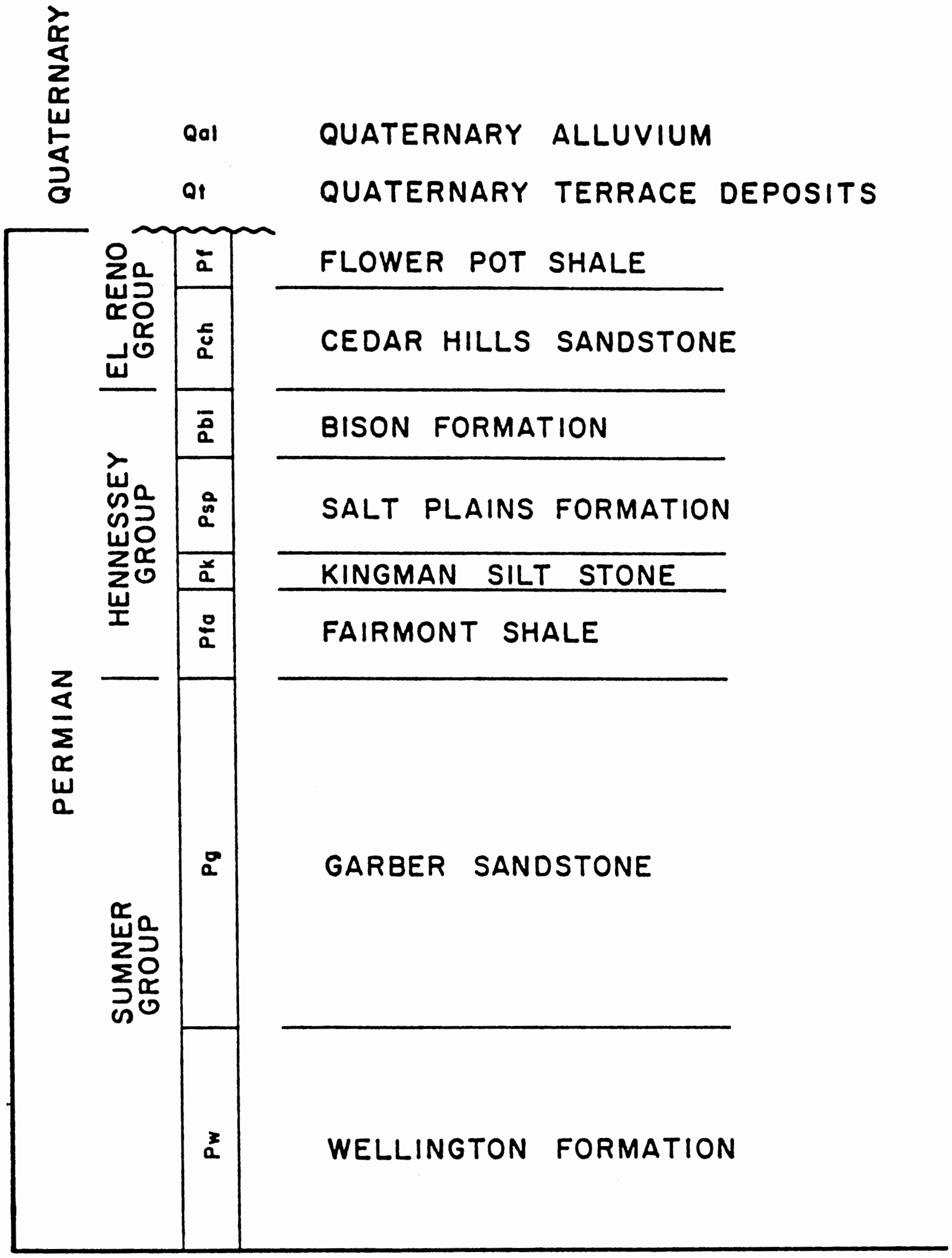

FIGURE 4.2 GENERALIZED STRATIGRAPHIC SECTION

Permian System

Essentially, all of the study area is underlain by shale, sandstone, siltstone and mudstone of Permian age (Bingham and Bergman, 1980), (Morton, 1980). The sedimentary sequences have an average dip of 17 feet per mile to the south-southwest and are either exposed or are unconformably overlain by terrace or alluvial deposits. The Permian units are classified as the Hennessy Group and the El Reno Group of the Cimarron Series.

The Fairmont Shale is the oldest of the Hennessy Group. It outcrops in the eastern most limits of the study area and is described by Bingham and Bergman (1980) as a red-brown shale with many thin layers of calcitic siltstone in the upper 60 feet. The unit averages 150 feet thick.

The Kingman Formation conformably overlies the Fairmont Shale. This unit also outcrops in the eastern limits of the study area and is in contact with the eastern limit of the Enid Isolated Terrace deposits. Bingham and Bergman (1980) describe this unit as mainly red-brown with several thin layers of greenish-gray and orange-brown calcitic siltstone. The average thickness of the unit is 70 feet.

The Salt Plains Formation conformably overlies the Kingman Formation and outcrops to the north and south of Enid. This unit is in contact with the Enid Isolated Terrace deposits. This formation is described by Bingham and Bergman (1980) as mainly red-brown shale with several thin beds of orange-brown fine-grained sandstone. The average thickness is estimated to be 160 feet.

The Bison Formation, which is the youngest unit in the Hennessy Group, conformably overlies the Salt Plains Formation. This unit outcrops to the south and northwest of Enid and is in contact with the Enid Isolated Terrace deposits and shares a very small contact with the Cimarron River Terrace deposits in the southeast portion of the study area. Bingham and Bergman (1980) describe this unit as mainly red-brown shale and greenish-gray/orange-brown calcitic siltstone with minor sandstone. This unit ranges in thickness up to 120 feet.

The Cedar Hills Sandstone of the El Reno group conformably overlies the Bison Formation. This unit is in contact with the western limits of the Enid Isolated Terrace deposits and is in contact with the Cimarron River Terrace deposits for a considerable distance. Morton (1980) describes this formation as orange-brown to greenish-gray fine-grained sandstone and siltstone with some red-brown shale. The Cedar Hills Sandstone has an average thickness of 180 feet, but forms channel deposits (Kent, 1982) which result in locally variable thicknesses. The Cedar Hills Sandstone is an important aquifer in localized areas within the study area.

The Flower Pot Shale conformably overlies the Cedar Hills Sandstone and is the youngest Permian formation exposed in the study area. The unit outcrops in several locations throughout the western half of the study area and is in contact with the Cimarron River Terrace deposits for a considerable distance. Morton (1980) describes this formation as red-brown silty shale with some thin gypsum and dolomite beds and fine-grained sandstone beds in the upper 50 feet. Halite beds are also locally present in the upper portions of this unit. The unit varies in thickness from 180 feet to 430 feet, increasing gradually in thickness to the south.

The Permian bedrock in the study area are unconformably overlain by alluvial and eolian deposits of Quaternary age. The deposition of these unconsolidated deposits was preceded by a significant period of erosion which is evidenced by the removal of all sediments deposited after the mid-Permian (Reed, et.al., 1952). This erosion resulted in an extremely irregular bedrock surface.

Cimarron River Terrace and Alluvial Deposits

The Cimarron River Terrace deposits are located along the northeast side of the Cimarron River and extend for approximately 110 miles from near the town of Waynoka southeastward to Guthrie. The deposits are Quaternary in age and unconformably overlie Permian redbed formations previously described. Reed, et.al. (1952) described the terrace deposits as interfingering lentils of unconsolidated clay, sandy clay, sand, and gravel. The coarser materials (i.e. sands and gravels) are poorly sorted, although some of the finer grained sands and gravels near the base of the deposits are very well sorted. The sediments range in color from black to reddish-brown. Cross-bedding is present in the sand and gravel lenses and the majority of the individual grains are moderately well rounded. Rounded clasts of the underlying redbed formations are common in the lower few feet of the terrace deposits, immediately above the contact with the Permian redbed formations.

The terrace deposits vary in thickness due to the irregularly of the bedrock surface upon which they were deposited. In general, the terrace deposits are not found southwest of the Cimarron River and they decrease gradually in thickness to the northeast where they eventually feather out against the underlying Permian redbed formations.

Eolian dune deposits are located at various locations within the Cimarron River Terrace formation. These deposits are comprised primarily of loose to friable brown to reddish-brown fine to coarse wind blown sand. Gould (1905) suggested that the dune deposits were formed in-place through the decomposition of pre-existing terrace deposits by wind, precipitation and gravity. Reed, et.al. (1952) concluded that the in situ decomposition and winnowing of the underlying terrace deposits and more recent alluvium was the most probably method of deposition for the dune deposits.

The terrace deposits within the study area are essentially horizontal with minor deviations due primarily to depositional environment. The deposits are thickest in the areas where dune development exists, where in excess of 120 feet of unconsolidated sediments have been encountered. The contact with the underlying Permian units is often difficult to define from drillers' logs, which is apparently due to terrace deposition on an extremely weathered surface and the incorporation of material from the underlying units as detritus in the lower terrace deposits.

Cimarron River Alluvial deposits are located along the recent limits of flooding. The alluvium of the Cimarron River is lithologically similar to the terrace sediments and in most areas they are indistinguishable. In general, the alluvial deposits are thinner than the adjacent terrace deposits with observed thicknesses ranging from 25 feet to 75 feet (Reed, et.al., 1952).

The alluvium of the major tributary streams within the study area is similar in origin and general lithologic characteristics to both the Cimarron River Terrace and Alluvial deposits. The principal differences are that the alluvial deposits associated with Eagle Chief and Turkey Creeks are thinner and less extensive. In addition, there is typically increased clay contents within these alluvial deposits.

Enid Isolated Terrace Deposits

The Enid Isolated Terrace deposits are located in Garfield County in the vicinity of Enid and extend over approximately 81 square miles. The deposits are Quaternary in age and unconformably overlie Permian redbed formations previously described.

The Enid Isolated Terrace deposits were found by Kent (1982) to be composed primarily of discontinuous layers of clay, sandy clay, sand and gravel. The coarser grained sediments are not typically well sorted although well sorted deposits were identified locally. The color of the deposits vary laterally and vertically but generally are brown to reddish-brown. The lower strata within the terrace deposits is typically coarser grained and the lower most lenses often include rounded clasts of the underlying Permian redbed formations which vary in size from pebbles to cobbles. Because this detritus is present, it is often difficult to define the Permian redbed - Enid Isolated Terrace contact from drillers' logs.

The thickness of the Enid Isolated Terrace deposits vary significantly within the study area due primarily to the undulating Permian surface upon which they were deposited.

The deposits are essentially horizontal, but may vary locally due primarily to depositional environment. The average thickness of the Enid Isolated Terrace deposits is 60 feet (Kent, 1982).

Surface Water Hydrology

The entire study area, with the exception of a small area north of Enid, lies within the Cimarron River drainage basin. The Cimarron River flows from its headwaters in New Mexico southwestward through western Oklahoma and ultimately discharging into Keystone Reservoir in Creek County, Oklahoma. The Cimarron is a well developed, mature river with a well defined channel and flood plain. The principal sources of flow within the river are snow melt from the Rocky Mountains, storm water runoff and seepage. The Cimarron River is a gaining stream within the study area. Gaging stations maintained by the U.S. Geological Survey are located upstream near Waynoka and downstream near Dover. Monthly and annual mean discharges for these gage locations are presented in Table 4.2. It is apparent from the Waynoka gage data that the streamflow within the Cimarron River has been historically intermittent.

Surface drainage within the study area is typically well developed in areas where Permian redbed deposits are exposed and poorly developed in areas underlain by terrace deposits. Surface drainage to the Cimarron River is discharged through four southward flowing streams. These streams include Eagle Chief Creek, Indian Creek, Hoyle Creek and Turkey Creek. Eagle Chief, Indian and Turkey Creeks are perennial streams which are continuously recharged through seepage from the terrace deposits. Hoyle Creek is an intermittent stream which is also recharged through seepage

TABLE 4.2

CIMARRON RIVER DISCHARGE STATISTICS

	MEAN DISCHARGE (CFS)	
MONTH	USGS GAGE WAYNOKA,OK	USGS GAGE DOVER,OK
JANUARY	79.20	221.00
FEBRUARY	175.00	651.00
MARCH	147.00	716.00
APRIL	89.10	267.00
MAY	644.00	5817.00
JUNE	903.00	2850.00
JULY	366.00	1388.00
AUGUST	12.70	292.00
SEPTEMBER	0.00	98.90
OCTOBER	60.10	837.00
NOVEMBER	308.00	1788.00
DECEMER	127.00	276.00

REFERENCE: WATER RESOURCES DATA:OKLAHOMA,1982.

from the terrace deposits but due to seasonal fluctuations of the surface of the groundwater goes dry in most summers (Reed, et.al., 1952).

The northeastern portion of the study area lies within the Salt Fork drainage basin. Minor surface drainage development in this basin is present within the study area. Sand Creek, the largest of these streams, is located north of Enid and flows to the northeast. The divide between the Cimarron River basin and the Salt Fork basin is approximately defined by the St. Louis - San Francisco railroad which lies northwest of Enid and connects the towns of Carrier, Goltry, Carmen and Dacoma.

Groundwater Hydrology

Occurrence and Movement of Groundwater

Groundwater is present in the pore spaces of the unconsolidated terrace and alluvial deposits and in the fractures and solution cavities of certain units within the Permian sedimentary formations. In general, groundwater occurs under either confined or unconfined conditions within the study area. Confined conditions exist when the potentiometric head exceeds the elevation at the top of the overlying impermeable unit. Unconfined conditions exist where the upper surface of the water is not confined by an overlying impermeable unit and the water surface is free to fluctuate. Reed, et.al. (1952) and Kent (1982) determined that the Cimarron River Terrace and Enid Isolated Terrace deposits were unconfined aquifers. Locally, however, the presence of laterally continuous layers of clay and silt resulted in aquitards and locally confined conditions. From a regional perspective, the classification of these deposits as unconfined aquifers is appropriate.

The occurrence of groundwater within the Permian redbed formations is important because a significant portion of Enid's water production is derived from wells which produce from these deposits. Reed, et.al. (1952) determined that the groundwater within Permian bedrock is under confined conditions and presented examples of artesian wells completed in these units. Kent (1982) treated the Enid Isolated Terrace deposits and the underlying Permian Cedar Hills Sandstone as an undifferentiated unconfined aquifer due to the similar lithologic and hydraulic characteristics of the units. Reed, et.al. (1952) noted that calcite filled fractures and cavities abundant in outcrops and core samples of the Permian formations throughout the study area. In addition, essentially all of the Permian strata within the area are calcareous. He postulated that groundwater occurs and moves through the fractures and dissolution cavities which result from the removal of soluble materials within discrete units. This phenomena has resulted in an extremely complex aquifer system, within the Permian redbed formations, which exhibits variable permeability and storage characteristics both laterally and vertically. The complexity of this aquifer is obvious when comparing the depths and production rates for water wells which produce from this strata.

The general direction of groundwater flow within the Cimarron River Terrace deposits is from northeast to southwest, towards the Cimarron River (Reed, et.al., 1952). The groundwater surface is an irregularly sloping surface which corresponds in general with the slope of the underlying surface of the Permian strata. Spatial variations in lithologies contribute to the undulating groundwater surface geometry. The regional slope of the groundwater surface averages approximately 0.35 percent.

The general direction of groundwater flow within the Enid Isolated Terrace deposits is from northwest to southeast (Kent, 1982). The groundwater surface generally follows the topography and slopes approximately 0.35 percent. The groundwater surface gradient is relatively uniform except in the proximity of the aquifer boundary where locally steep gradients are associated with seeps and springs (Kent, 1982).

Groundwater flow direction within the Permian strata is extremely variable and is partially controlled by the local lithologies and the structural characteristics of the strata. It appears that the orientation and density of fracture patterns control groundwater flow direction. Flow direction also tends to follow the topography of the surface of the Permian strata. In general, the regional flow direction within the Permian strata is from northeast to southwest, towards the Cimarron River.

The direction of groundwater movement within the Cimarron River and stream alluvial deposits is normal to the axis of the channel. These streams are all receiving recharge through seepage as groundwater discharges from the adjacent alluvial deposits.

Hydraulic Characteristics

Hydraulic characteristics of the groundwater system describe the ability of the aquifer materials to transmit and store water in the subsurface. These characteristics include saturated thickness, hydraulic conductivity, and storativity. In the following sections, the alluvial deposits and the adjacent terrace deposits are not differentiated.

Saturated Thickness. Saturated thickness refers to that portion of the total thickness of the aquifer in which voids between the particles or open spaces within fractures are completely filled with water. Because the elevation groundwater surface is continually fluctuating, due to climatic changes and the effects of pumping, the saturated thickness of the aquifers continually changes.

Kent (1982) studied the hydrogeology of the Enid Isolated Terrace Aquifer and summarized the variation of saturated thickness based on available well data and computer simulation techniques. The results of that study indicate the saturated thickness within the aquifer varies from zero feet at the outermost limits of the aquifer to a maximum of approximately 55 feet. Approximately 90 percent of the area underlain by the Enid Isolated Terrace Aquifer has a saturated thickness of less than 30 feet.

Reed, et.al. (1952) studied the hydrogeology of the Cimarron River Terrace Aquifer and related alluvial aquifers. In that study, approximately 200 wells were used to evaluate the lithologic and hydraulic characteristics of this aquifer. Based on that data, it was determined that the saturated thickness of the Cimarron River Terrace Aquifer ranges from zero feet at its northeast contact with the Permian strata to in excess of 80 feet at several locations within the study area. The variability of the aquifer saturated thickness is related to the undulating surface of the underlying Permian redbed formations. It was demonstrated that the groundwater surface tends to follow that surface.

No definite data is available regarding the saturated thickness of the water bearing units within the Permian strata. An engineering report by Black & Veatch (1955) describes the Permian redbed aquifers as shale formations with interbedded lenses of sandstone and siltstone which contain many small cavities, fractures and solution channels.

These units appear to be discontinuous as has been demonstrated by numerous attempts to drill offset wells which yield essentially no water in close proximity to wells with significant production capacities. In many locations, wells which were completed in these aquifers encountered confined conditions. Black & Veatch (1955) reported that the water in the Permian bedrock aquifers was often under artesian conditions. Water in the area west of Drummond was encountered at depths from 60 to 150 feet, but the associated potentiometric head often rose to within 30 feet of the ground surface. Further, it was reported that significant declines (i.e. 6-11 feet) in the potentiometric surface were observed at distances of 500 feet from pumping wells over a five year period.

Based on the available data, it was concluded that the aquifers within the Permian redbed strata are probably discrete beds or in series of beds within the sedimentary sequence which contain lithologies prone to dissolution (i.e. calcareous units) and are fractured. These units are bounded vertically by layers of low permeability and are laterally discontinuous. Due to the dipping orientation of the Permian strata, it is expected that unconfined conditions occur near the outcrop and confined conditions occur downdip, except in locations where pumping has lowered the potentiometric surface below the base of the upper confining layer. The saturated thickness of these aquifers is estimated to vary from zero feet at the outcrop to the thickness of the permeable beds.

Transmissivity. Hydraulic conductivity describes the ability of an aquifer to transmit water. Horizontal movement of water is commonly described by transmissivity, which is the product of the horizontal hydraulic conductivity and saturated thickness of the aquifer.

Due to the unavailability of aquifer test data, Kent (1982) used an indirect method for approximately the transmissivity of the Enid Isolated Terrace Aquifer. This technique involved the calculation of a weighted average transmissivity value based on lithologies and saturated thickness data obtained from well logs. Based on the results of that study it was determined that the average transmissivity for the aquifer is 9,500 gpd/ft.

Reed, et.al. (1952) conducted aquifer performance tests at nine (9) wells completed in the Cimarron River Terrace Aquifer located within the study area. In each test drawdowns were measured in observation wells in proximity to the pumping wells and the data was analyzed using the standard graphical method developed by Cooper and Jacob. Based on the results of that study it was determined that the average transmissivity for the aquifer is 20,000 gpd/ft. The values ranged from 6,000 to 76,000 gpd/ft.

Reed, et.al. (1952) also conducted aquifer performance tests at three (3) wells completed in the Permian redbed strata. No reliable transmissivity or storativity data was obtained from these tests. It was determined that because the flow system was predominated by flow through fractures, the conditions of the Cooper-Jacob method of analysis were violated, rendering the results invalid.

Nine (9) single well pump tests were conducted to evaluate the aquifer characteristics in each of the five (5) wellfields. Each of the pump tests were run continuously for a minimum of three (3) days. Pressure transducers with data acquisition units were installed to measure and record time versus drawdown data during each test. The data was recovered from the field and reduced using the AQTESOLV statistical solution code developed by Geraghty and Miller (1991). The results of the pump tests are presented in Table 4.3.

Storativity. The storage coefficient of an aquifer is the quantity of water the aquifer will yield per unit area per unit decline in the hydraulic head. This coefficient is expressed as a dimensionless value. In an unconfined aquifer, water is derived by actual dewatering of the aquifer material. Under these conditions, the storage coefficient is referred to as specific yield. In a confined aquifer, water is derived from the expansion of the water and compaction of the aquifer materials.

Kent (1982) evaluated the aquifer performance and water supply capabilities of the Enid Isolated Terrace Aquifer using computer modeling techniques. It was determined in that study that specific yield of the Enid Isolated Terrace Aquifer averaged 0.295.

TABLE 4.3

AQUIFER PUMP TEST RESULTS

WELL I.D.	TRANSMISSIVITY (SQ.FT./MIN)	STORAGE COEFFICIENT
AMES 26	21.10	0.123
AMES 8	1.51	0.016
DRUMMOND 26	0.32	0.009
DRUMMOND 2	1.46	0.016
CLEO SPRINGS 31	4.87	0.001
CLEO SPRINGS 27	3.51	0.002
RINGWOOD 24	5.25	0.185
RINGWOOD 22	2.24	0.024
ENID WELLFIELD (NE/4 SEC.10,T23N,R7W)	6.54	0.026

Reed, et.al. (1952) performed nine (9) aquifer performance tests on wells which produce water from the Cimarron River Terrace Aquifer within the study area. Specific yield values from these tests were determined to vary from 0.018 to 0.131, with an average value of 0.065. It is reported in that study that above average percentages of fine-grained materials were present in most of the wells tested which probably resulted in lower specific yield values. The investigators concluded that a specific yield of 0.100 was representative of the upper portion of the terrace deposits but 0.150 was more realistic for the entire saturated thickness.

Reed, et.al. (1952) also performed three (3) pumping tests at wells completed in the Permian redbed strata within the study area. It was determined in that study that because the flow system within these formations is dominated by fracture flow, the storage coefficients which were determined were invalid.

Inflow and Outflow

A water budget is central to essentially all investigations which include a hydrologic component. A water budget summarizes the separate components of inflow, outflow and storage for a particular system. Common sources of inflow include precipitation, leakage from surface water bodies, underflow and recharge wells. Sources of outflow include evapotranspiration, seepage, pumpage and underflow.

These sources, as they pertain to the study area, are discussed below.

Inflow Sources

Precipitation. The poorly developed system of surface water drainage within the areas underlain by terrace deposits, in combination with the presence of predominately sandy soils, result in relatively high infiltration characteristics. In addition, the undulating topography results in many shallow depressions which make excellent natural recharge basins within these areas.

Reed, et.al. (1952) studied the relationship between precipitation and groundwater level fluctuations in 26 monitoring wells within the Cimarron River Terrace Aquifer. The data acquired in that study reflected recharge from precipitation varied from 6.62 to 25.95 percent with an average of 14.45 percent. Assuming a normal annual rainfall of 30 inches, the estimated average annual recharge to the Cimarron River Terrace Aquifer would be approximately 4.3 inches.

Kent (1982) evaluated well hydrographs and precipitation hydrographs from the Enid Isolated Terrace Aquifer to estimate recharge from rainfall. Based on this data, it was determined that the percentage of rainfall recharging the aquifer through infiltration from precipitation is approximately 7 percent. Assuming a normal annual rainfall of 30 inches, the estimated annual recharge to the Enid Isolated Terrace Aquifer would be approximately 2.1 inches.

Due to the local variability and fracture controlled nature of groundwater flow within the Permian redbed strata, it is difficult to assign a regional value for recharge to these aquifers. Reed, et.al. (1952) suggested that the inherent low permeability of the formations prevents large-scale movement of water. Therefore, it was concluded in that study that regional recharge to the Permian redbeds was probably negligible.

Streams. Essentially all streams within the study area derive a portion of their flow from groundwater seepage. Reed, et.al. (1952) reported that no significant recharge to the Cimarron River Terrace Aquifer is contributed from streams. Kent (1982) reported that the total annual recharge to the Enid Isolated Terrace Aquifer streams was approximately 0.6 percent of the total.

Underflow. Underflow often occurs where two aquifers are in contact. Kent (1982) determined that the Enid Isolated Terrace Aquifer received minor, yet significant, underflow from the Permian Cedar Hills Sandstone. Using computer simulation techniques, it was concluded in that study that approximately 10.5 percent of the total annual inflow to the Enid Isolated Terrace Aquifer resulted from underflow from Permian strata.

Reed, et.al. (1952) concluded that due to the low inherent permeability of the Permian strata it is probable that the recharge to the Cimarron River terrace Aquifer from the underlying sedimentary formations is minimal. It was noted that during aquifer performance tests on wells which were completed in the Permian strata, that there was leakage between the aquifers.

Outflow Sources

Evapotranspiration. Evapotranspiration is the mechanism by which groundwater is discharged in to the atmosphere through evaporation and by live vegetation. This component of the water budget is very difficult to quantify due to the variability of factors which affect it. These include temperature, wind velocity, humidity, soil type, depth to water, type of vegetation and vegetation density. Reed, et.al. (1952) concluded that, due to the depth to the surface of groundwater throughout the majority of the study area, and the type and density of vegetation within the region, groundwater losses due to evapotranspiration are probably negligible. Kent (1982) also did not consider evapotranspiration losses in the water budget for the Enid Isolated Terrace Aquifer.

Seepage. Discharge of groundwater through seepage into the Cimarron River and streams within the study area provide the major source of base flow for these streams. In addition, there are numerous small springs within the region that discharge continuously. Reed, et.al. (1952) performed stream measurements during periods of no precipitation. Based on that study it was determined that approximately 13 million gallons per day were discharged from the Cimarron River Terrace deposits into Eagle Chief Creek, Indian Creek, Hoyle Creek, Preacher Creek and Turkey Creek. An additional 360,000 gallons per day per mile were estimated to discharge into the Cimarron River through seepage (Reed, et.al., 1952).

Underflow. As previously discussed, it is probable that some outflow occurs through underflow to adjacent aquifers, but the total discharges are relatively minor.

Pumpage. Groundwater is pumped continuously from all aquifers within the study area. The principal water producers are private wells for domestic use, livestock watering wells, agricultural irrigation wells and municipal water supply wells. There are in excess of a thousand wells within the study area. Most of these produce an average of less than ten (10) gallons per minute. The City of Enid is the single largest producer of groundwater in the region with one hundred forty six (146) municipal production wells and an average daily production of approximately 11 million gallons.

CHAPTER V

GROUNDWATER FLOW MODEL

General

The principal use of the linked optimization-simulation aquifer management model is to define an optimal groundwater production schedule which meets explicit operational criteria at minimum cost, while simultaneously complying with operational and hydrologic constraints. A groundwater flow model is required to evaluate the impacts on the aquifer from a trial optimal groundwater production schedule. Specifically, it is essential that the drawdown effects from a trial optimal groundwater production schedule be predicted and compared to predetermined allowable limits. If the trial optimal groundwater production schedule results in violations of allowable drawdown, the trial optimal production schedule is invalid and an alternative must be defined. In the development of the aquifer management model, a drawdown limit of one-half the aquifer saturated thickness, under steady-state conditions, is used. For this case, steady-state conditions are assumed to be free of any stresses, including pumpages.

Based on a review of the hydrologic characteristics of the three (3) aquifers which individually or collectively underly the five (5) City of Enid wellfields, it was determined that a numerical groundwater flow model possessed the required flexibility to address the defined aquifer and water production system characteristics. Ultimately, the USGS MODFLOW modular finite difference groundwater flow simulation computer code developed by McDonald and Harbaugh (1984) was selected. This code employs the block-centered finite-difference solution approach to simulate groundwater flow. Layers can be simulated as confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, including wells, areal recharge, evapotranspiraton, drains and rivers can be incorporated into the model. The finite difference approximations of the governing groundwater flow equations can be solved using either the strongly implicit procedure or slice-successive overrelaxation. The governing non-linear partial differential equation for groundwater flow is which is solved by the MODFLOW code is presented in Figure 5.1. The USGS MODFLOW code is widely used within the United States and many applications are well documented in the literature.

Due to the spatial separation of the five (5) wellfields under consideration, it was determined that an individual groundwater flow model be developed for each wellfield. A two-step approach was followed during the development of each wellfield groundwater flow model. Initially, a steady-state model was developed. No stresses, such as well pumpages, were included in the steady-state groundwater flow

GROUNDWATER FLOW EQUATION

The three - dimensional movement of groundwater of constant density through porous earth material may be described by the partial - differential equation:

$$\delta/\delta x(Kxx\ \delta h/\delta x)+\delta/\delta y(Kyy\ \delta h/\delta y)+\delta/\delta z(Kzz\ \delta h/\delta z)-W=S_s\ \delta h/\delta t$$

where:

x,y and z are cartesian coordinates along the major axes of hydraulic conductivity Kxx, Kyy, Kzz;

h is the potentiometric head (L);

W is a volumetric flux per unit volume and represents sources and / or sinks of water (t^{-1});

S_s is the specific storage of the porous material (L^{-1});

t is time (t).

FIGURE 5.1 GOVERNING GROUNDWATER FLOW EQUATION models. The steady-state groundwater flow models were used to verify and refine boundary conditions and to define allowable drawdown criteria for use in transient modeling. Transient groundwater flow models were then developed for each wellfield. Each of the transient groundwater flow models includes the City of Enid production wells which may be selectively pumped on an individual basis. Because the linked optimization-simulation aquifer management model is intended for use by the water resources manager as a water production scheduling tool, the simulation period within the groundwater simulation models are predefined on a monthly basis, for January through December. This time interval can be altered at the discretion of the water resources manager. The development of each of the five (5) groundwater flow models are described below.

Model Development

Enid Wellfield

The Enid Wellfield groundwater flow model was developed by discretizing an area, which includes approximately 65 square miles, into a finite difference grid comprised of fourteen (14) rows and nineteen (19) columns. The model grid is presented in Figure 5.2. The row and column nodal spacing is 2565 feet and 2638 feet, respectively. The aquifer within the Enid Wellfield is modeled as a simple unconfined aquifer. Homogeneous, isotropic conditions were

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1 = CONSTANT HEAD NODE
2 = PUMPING NODE

FIGURE 5.2 ENID WELLFIELD GROUNDWATER FLOW MODEL GRID assumed. No flow contributions from the underlying Permian formations is included.

Aquifer thickness and basal Permian formation surface elevations were estimated from approximately 175 drillers' logs from water wells located within the wellfield limits. This data was reduced and analyzed using SURFER statistical contouring software developed by Golden Software (1990). A contour map was developed which approximated the spatial relationship of the surface of the underlying Permian formations within the model area. This data was discretized and incorporated into the Enid Wellfield groundwater flow model.

Groundwater surface elevation data was acquired for approximately 30 wells. This data was recorded on a monthly basis and represents an historical record of approximately 18 months. The groundwater surface elevation data from these wells for June 1990 was used to approximate the groundwater surface within the Enid Wellfield model area using the statistical contouring approach described above. This data was then discretized and incorporated into the Enid Wellfield groundwater flow model.

Boundary conditions for the Enid Wellfield groundwater flow model were defined using the aquifer base elevation data, groundwater surface elevation data and published hydrogeologic data. To simulate the hydrologic conditions observed within the Enid Wellfield, constant head nodes were defined along the perimeter rows and columns of the discretized finite difference model. These constant head nodes serve to maintain the regional groundwater flow gradient which is observed in the field.

Areal recharge is also introduced into the groundwater flow system as infiltrating rainfall. The recharge rate is based on an annual total infiltration of four (4) inches. No other inflows or outflows are incorporated into the groundwater flow model, except pumpages from wells.

Prior to incorporating the well stresses, the Enid Wellfield groundwater flow model was executed under steady-state conditions. This was performed to insure that simulated groundwater surface gradients and saturated thicknesses approximated the field observations. In addition, the steady-state saturated thickness data was used to define allowable drawdown limits. The maximum allowable drawdown elevations, for each well within the Enid Wellfield is presented in Table 5.1.

The transient groundwater flow model was subsequently developed for the Enid Wellfield by incorporating the City of Enid municipal supply wells. No attempt was made to identify and include other wells, such as domestic and livestock wells, within the wellfield groundwater flow. This was justified because the density of these wells is sparse and the production rates are extremely small. The transient Enid Wellfield groundwater flow model was structured to simulate monthly planning periods. The simulation period is comprised of 28-31 stress periods, each

TABLE 5.1

ENID WELLFIELD THRESHOLD DRAWDOWN DATA

WELL ID NO.	STEADY STATE G.W. ELEVATION	REDBED ELEVATION	THRESHOLD G.W. ELEVATION
C-1	1345.24	1292.00	1318.62
C-2	1341.32	1295.00	1318.16
C-3	1342.82	1288.00	1315.41
C-4	1339.29	1295.00	1317.15
C-5	1330.08	1298.00	1314.04
C-6	1330.08	1293.00	1311.54
C-7	1330.08	1295.00	1312.54
C-8	1326.91	1303.00	1314.96
C-10	1345.24	1292.00	1318.62
C-11	1348.96	1291.00	1319.98
C-12	1347.57	1279.00	1313.28
C-13	1349.14	1278.00	1313.57
C-15	1348.45	1281.00	1314.73
C-16	1348.96	1247.00	1297.98
NW-1	1339.69	1287.00	1313.35
NW-2	1345.34	1282.00	1313.67
NW-3	1342.94	1273.00	1307.97
NW-5	1347.57	1278.00	1312.78
NW-6	1326.67	1269.00	1297.84
NW-7	1333.71	1271.00	1302.36
NW-9	1348.42	1277.00	1312.71
NW-10	1339.05	1285.00	1312.03
VB-3	1284.39	1225.00	1254.70
VB-4	1279.56	1219.00	1249.28
VB-5	1295.37	1222.00	1258.69
VB-7	1279.56	1219.00	1249.28
P-1	1275.64	1226.00	1250.82
P-2	1271.14	1230.00	1250.57
P-3	1271.14	1226.00	1248.57
P-4	1271.14	1226.00	1248.57
P-5	1271.14	1226.00	1248.57
P-7	1271.14	1226.00	1248.57

one (1) day in length, depending on the month. The length of each time step was also equal to one (1) day. This structure was developed to conform with the operating policy of the City of Enid water resources manager. Under this model, any well within the system can be operated for any period and be turned on or off daily.

Drummond Wellfield

The Drummond Wellfield groundwater flow model was developed by discretizing an area, which includes approximately 40 square miles, into a finite difference grid comprised of twelve (12) rows and thirteen (13) columns. The model grid is presented in Figure 5.3. The row and column nodal spacing is 2622 feet and 2724 feet, respectively. The aquifer within the Drummond Wellfield was modeled as a simple confined aquifer. Homogeneous, isotropic conditions were assumed. No flow contributions were included from the underlying or overlying formations.

Aquifer thickness and elevation data was estimated from approximately 90 drillers' logs from water wells located within the wellfield limits. This data was reduced and analyzed using the SURFER statistical contouring software described previously. Based on a review of the drillers' log data, available published hydrogeological data and numerous discussions with local water well drillers, it was estimated the confined aquifer in the area within Drummond Wellfield groundwater simulation model is approximately 20

1	1	1	1	1	1	1	1	1	1	1	1	1
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1		2							2			1
1										2		1
1	1	1	1	1	1	1	1	1	1	1	1	1

1 = CONSTANT HEAD NODE
2 = PUMPING NODE

FIGURE 5.3 DRUMMOND WELLFIELD GROUNDWATER FLOW MODEL GRID feet thick. The average elevation at the top of the confined aquifer was estimated to be 1160 feet above MSL. This information was discretized and incorporated into the Drummond Wellfield groundwater flow model.

Potentiometric surface elevation data was acquired for approximately 33 wells. This data was recorded on a monthly basis and represents an historical record of approximately 18 months. The potentiometric surface elevation data from these wells for June 1990 was used to approximate the potentiometric surface within the Drummond Wellfield model area using the statistical contouring methodology described earlier. This data was then discretized and incorporated into the Drummond Wellfield groundwater flow model.

Boundary conditions for the Drummond Wellfield groundwater flow model were defined using the drillers' log data, potentiometric surface elevation data and published hydrogeologic data. To simulate the hydrologic conditions observed within the Drummond Wellfield, constant head nodes were defined along the perimeter rows and columns of the discretized finite difference model. These constant head nodes serve to maintain the regional potentiometric surface gradient which is observed in the field.

Initially, a steady-state groundwater flow model was developed for the Drummond Wellfield. No stresses, including pumpages, were incorporated into this model. This was performed to insure that simulated potentiometric surface gradients approximated the field observations. In addition, the steady-state potentiometric surface elevation data was used to define allowable drawdown limits. In the Drummond Wellfield groundwater flow model, allowable drawdown limits are defined as one-half the depth between the steady-state potentiometric surface and the assumed elevation at the top of the confined aquifer. The maximum allowable drawdown elevations for each well within the Drummond Wellfield is presented in Table 5.2.

The transient groundwater flow model was subsequently developed for the Drummond Wellfield by incorporating the City of Enid municipal supply wells. No attempt was made to incorporate pumpages from other wells for the reasons presented previously. The transient Drummond Wellfield groundwater flow model is structured to provide for monthly simulation periods, with 28-31 stress periods and time steps, each one (1) day in length. As described previously, this system conforms to the operational policy of the City of Enid water resources manager.

Ames Wellfield

The Ames Wellfield was developed by discretizing an area, which includes approximately 56 square miles, into a finite difference grid comprised of fourteen (14) rows and sixteen (16) columns. The model grid is presented in Figure 5.4. The row and column nodal spacing is 2639 feet and 2617 feet, respectively. The aquifer within the Ames Wellfield is modeled as a simple unconfined aquifer. Homogeneous,

TABLE 5.2

DRUMMOND WELLFIELD THRESHOLD DRAWDOWN DATA

WELL ID NO.	STEADY STATE POTENTIOMETRIC ELEVATION	TOP OF AQUIFER ELEVATION	THRESHOLD P.S. ELEVATION
D-1	1238.29	1160.00	1199.15
D-2	1231.88	1160.00	1195.94
D-3	1228.63	1160.00	1194.31
D-4	1228.63	1160.00	1194.31
D-5	1220.38	1160.00	1190.19
D-6	1220.93	1160.00	1190.47
D-7	1214.86	1160.00	1187.43
D-8	1220.38	1160.00	1190.19
D-9	1214.86	1160.00	1187.43
D-10	1214.86	1160.00	1187.43
D-11	1208.06	1160.00	1184.03
D-12	1231.23	1160.00	1195.62
D-13	1200.32	1160.00	1180.16
D-14	1231.88	1160.00	1195.94
D-15	1228.38	1160.00	1194.19
D-17	1208.44	1160.00	1184.22
D-18	1211.83	1160.00	1185.92
D-19	1215.56	1160.00	1187.78
D-20	1220.54	1160.00	1190.27
D-21	1222.99	1160.00	1191.50
D-22	1225.52	1160.00	1192.76
D-23	1229.56	1160.00	1194.78
D-25	1226.28	1160.00	1193.14
D-26	1234.68	1160.00	1197.34
D-27	1237.16	1160.00	1198.58
D-28	1240.68	1160.00	1200.34
D-29	1245.58	1160.00	1202.79
D-31	1237.77	1160.00	1198.89
D-32	1242.35	1160.00	1201.18
D-33	1240.26	1160.00	1200.13

1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
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1			2					2	2		2		2	2	1
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1	1						2		2		2				1
0	1	1	1				2	2	2						1
0	0	0	1			2	2								1
0	0	0	1			2									1
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1

0 = NO FLOW NODE
1 = CONSTANT HEAD NODE
2 = PUMPING NODE

FIGURE 5.4 AMES WELLFIELD GROUNDWATER FLOW MODEL GRID isotropic conditions are assumed. No flow contributions from the underlying Permian formations is included.

Aquifer thickness and basal Permian formation surface elevations were estimated from approximately 190 drillers' logs from water wells located within the wellfield limits. This data was reduced and analyzed using the statistical contouring methodology described previously.

A contour map was developed which approximated the spatial geometry of the surface of the underlying Permian formations within the model area. This data was discretized and incorporated into the Ames Wellfield groundwater flow model.

Groundwater surface elevation data was acquired from approximately 36 wells. This data was recorded on a monthly basis and represents an historical record of approximately 18 months. The groundwater surface elevation data from these wells for June 1990 was used to approximate the groundwater surface within the Ames Wellfield model area using the previously described statistical contouring approach. This data was then discretized and incorporated into the Ames Wellfield groundwater flow model.

Boundary conditions for the Ames Wellfield groundwater flow model were defined using the aquifer base elevation data, groundwater surface elevation data and published hydrogeologic data. To simulate the observed hydrologic conditions within the Ames Wellfield, constant head nodes were defined along all perimeter columns and rows except in the southwest corner of the model area. In this area, the Cimarron River transects the model area. Constant head nodes were assigned to nodes coinciding with the river location in this area. All nodes located southwest of the Cimarron River were designated as no-flow nodes. These constant head nodes serve to maintain the regional groundwater flow gradient which is observed in the field.

Areal recharge is also introduced into the groundwater flow system as infiltrating rainfall. The recharge rate is based on an annual total infiltration of four (4) inches. No other inflows or outflows are incorporated into the groundwater flow model, except pumpages from wells.

Prior to incorporating the well stresses, the Ames Wellfield groundwater flow model was executed under steady-state conditions. This was performed to insure that simulated groundwater surface gradients and saturated thicknesses approximated the field observations. Further, the steady-state saturated thickness data was used to define allowable drawdown limits. The maximum allowable drawdown elevations for each well within the Ames Wellfield is presented in Table 5.3.

The transient groundwater flow model was subsequently developed for the Ames Wellfield by incorporating the City of Enid municipal supply wells. Domestic, livestock and other wells were not included for the reasons described previously. The transient Ames Wellfield groundwater flow model is structured to provide for monthly simulation

TABLE 5.3

AMES WELLFIELD THRESHOLD DRAWDOWN DATA

WELL ID NO.	STEADY STATE G.W. ELEVATION	REDBED ELEVATION	THRESHOLD G.W. ELEVATION
A-1	1225.66	1175.83	1200.75
A-2	1201.10	1112.39	1156.75
A-3	1192.18	1112.13	1152.16
A-4	1179.45	1111.60	1145.52
A-5	1179.45	1106.84	1143.15
A-6	1195.31	1109.16	1152.24
A-7	1188.34	1124.89	1156.62
A-8	1195.31	1120.38	1157.85
A-9	1201.09	1127.93	1164.51
A-10	1162.43	1100.90	1131.67
A-11	1192.18	1113.06	1152.62
A-12	1195.40	1115.56	1155.48
A-13	1206.56	1166.50	1186.53
A-14	1220.73	1176.83	1198.78
A-15	1224.59	1180.93	1202.76
A-16	1225.22	1184.81	1205.02
A-17	1226.59	1190.38	1208.49
A-18	1221.26	1163.97	1192.62
A-19	1222.09	1173.79	1197.94
A-20	1203.28	1111.87	1157.57
A-21	1198.20	1122.01	1160.11
A-22	1200.01	1116.92	1158.47
A-23	1194.84	1122.67	1158.76
A-24	1195.89	1101.89	1148.89
A-25	1202.56	1179.11	1190.84
A-26	1202.56	1174.92	1188.74
A-27	1195.89	1114.64	1155.27
A-28	1190.75	1124.79	1157.77
A-29	1184.36	1126.80	1155.58
A-30	1195.90	1118.12	1157.01
A-31	1200.01	1121.38	1160.70
A-32	1200.01	1118.67	1159.34
A-33	1203.28	1113.00	1158.14

periods, with 28-31 stress periods and time steps, each one (1) day in length. As described previously, this system conforms to the operational policy of the City of Enid water resources manager.

Ringwood Wellfield

The Ringwood Wellfield groundwater flow model was developed by discretizing an area, which includes approximately 33 square miles, into a finite difference grid comprised of twelve (12) rows and eleven (11) columns. The model grid is presented in Figure 5.5. The row and column nodal spacing is 2626 feet and 2632 feet, respectively. The aquifer within the Ringwood Wellfield is modeled as a simple unconfined aquifer. Homogeneous, isotropic conditions are assumed. No flow contributions from the underlying Permian formations is included.

Aquifer thickness and basal Permian formation surface elevations were estimated from approximately 120 drillers' logs from water wells located within the wellfield limits. This data was reduced and analyzed using the statistical contouring methodology described previously. A contour map was developed which approximated the spatial configuration of the surface of the underlying Permian formations within the model area. This data was discretized and incorporated into the Ringwood Wellfield groundwater flow model.

Groundwater surface elevation data was acquired from approximately 50 wells. This data was recorded on a monthly

1	1	1	1	1	1	1	1	1	1	1
1										1
1		2	2	2						1
1		2	2	2	2					1
1		2	2	2	2		2			1
1			2	2						1
1										1
1	1				2	2				1
0	1					2		2		1
0	1	1	1		1	1				1
0	0	0	0	1	1	0	1			1
0	0	0	0	0	0	0	1	1	1	1

0 = NO FLOW NODE
1 = CONSTANT HEAD NODE
2 = PUMPING NODE

FIGURE 5.5 RINGWOOD WELLFIELD GROUNDWATER FLOW MODEL GRID basis and represents an historical record of approximately 18 months. The groundwater surface elevation data from these wells for June 1990 was used to approximate the groundwater surface within the Ringwood Wellfield model area using the previously described statistical contouring technique. This data was then discretized and incorporated into the Ringwood Wellfield groundwater flow model.

Boundary conditions for the Ringwood Wellfield groundwater flow model were defined using the aquifer base elevation data, groundwater surface elevation data and published hydrogeologic data. To simulate the observed hydrologic conditions within the Ringwood Wellfield, constant head nodes were defined along all perimeter columns and rows except along the southern boundary of the model area. In this area, the Cimarron River transects the model area from northwest to southeast. Constant head nodes were assigned to nodes coinciding with the river location in this area. All nodes located south of the Cimarron River were designated as no-flow nodes. These constant head nodes serve to maintain the regional groundwater flow gradient which is observed in the field.

Areal recharge is also introduced into the groundwater flow system as infiltrating rainfall. The recharge rate is based on an annual total infiltration of four (4) inches. No other inflows or outflows are incorporated into the groundwater flow model, except pumpages from wells.

Prior to incorporating the well stresses, the Ringwood Wellfield groundwater flow model was executed under steady-state conditions. This was performed to insure that simulated groundwater surface gradients and saturated thicknesses approximated the field observations. In addition, the steady-state saturated thickness data was used to define allowable drawdown limits. The maximum allowable drawdown elevations for each well within the Ringwood Wellfield is presented in Table 5.4.

The transient groundwater flow model was subsequently developed for the Ringwood Wellfield by incorporating the City of Enid municipal supply wells. Domestic, livestock and other wells were not included as discussed earlier. The transient Ringwood Wellfield groundwater flow model is structured to provide for monthly simulation periods, with 28-31 stress periods and time steps, each one (1) day in length. As described previously, this system conforms to the operational policy of the City of Enid water resources manager.

Cleo Springs Wellfield

The Cleo Springs Wellfield groundwater flow model was developed by discretizing an area, which includes approximately 38 square miles, into a finite difference grid comprised of nine (9) rows and sixteen (16) columns. The model grid is presented in Figure 5.6. The row and column nodal spacing is 2627 feet and 2784 feet, respectively. The

TABLE 5.4

RINGWOOD WELLFIELD THRESHOLD DRAWDOWN DATA

WELL ID NO.	STEADY STATE G.W. ELEVATION	REDBED ELEVATION	THRESHOLD G.W. ELEVATION
R-1	1245.71	1233.43	1239.57
R-2	1245.54	1228.52	1237.03
R-3	1245.54	1223.59	1234.56
R-4	1245.44	1215.62	1230.53
R-5	1241.25	1230.32	1235.78
R-6	1241.17	1221.38	1231.28
R-7	1241.17	1217.02	1229.10
R-8	1241.07	1212.12	1226.60
R-9	1240.48	1218.02	1229.25
R-10	1241.25	1218.34	1229.79
R-11	1241.17	1219.56	1230.37
R-12	1234.98	1223.82	1229.40
R-13	1234.98	1221.28	1228.13
R-14	1240.48	1221.82	1231.15
R-15	1234.37	1219.24	1226.80
R-16	1235.02	1226.38	1230.70
R-17	1235.02	1221.86	1228.44
R-18	1234.98	1221.82	1228.40
R-19	1234.34	1221.62	1227.98
R-20	1234.34	1220.79	1227.56
R-21	1231.43	1219.63	1225.53
R-22	1226.38	1226.63	1226.51
R-23	1226.76	1224.56	1225.66
R-24	1226.76	1223.35	1225.05
R-25	1197.26	1161.35	1179.30
R-26	1195.72	1161.28	1178.50
R-27	1187.42	1162.45	1174.94
R-28	1186.99	1156.54	1171.77

1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1															1
1							2								1
1			2		2	2	2	2	2	2	2				1
1	2	2	2	2	2	2	2			2	2				1
1				2				1	1			2	2		1
1	1	1	1	1	1	1	1	1	1					1	1
0	0	0	1	0	0	0	0	0	1	1	1	1	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0

0 = NO FLOW NODE
1 = CONSTANT HEAD NODE
2 = PUMPING NODE

FIGURE 5.6 CLEO SPRINGS WELLFIELD GROUNDWATER FLOW MODEL GRID aquifer within the Cleo Springs Wellfield is modeled as a simple unconfined aquifer. Homogeneous, isotropic conditions are assumed. No contributions from the underlying Permian formations is included.

Aquifer thickness and basal Permian formation surface elevations were estimated from approximately 100 drillers' logs from water wells located within the wellfield limits. This data was reduced and analyzed using the statistical contouring technique described previously. A contour map was developed which approximated the spatial configuration of the surface of the underlying Permian formation within the model area. This data was then discretized and incorporated into the Cleo Springs Wellfield groundwater flow model.

Groundwater surface elevation data was acquired from approximately 50 wells. This data was recorded on a monthly basis and represents an historical record of approximately 18 months. The groundwater surface elevation data from these wells for June 1990 was used to approximate the groundwater surface within the Cleo Springs Wellfield model area using the previously described statistical contouring methodology. This data was then discretized and incorporated into the Cleo Springs Wellfield groundwater flow model.

Boundary conditions for the Cleo Springs Wellfield groundwater flow model were defined using the aquifer base elevation data, groundwater surface elevation data and published hydrogeologic data. To simulate the observed hydrologic conditions within the Cleo Springs Wellfield, constant head nodes were defined along all perimeter columns and rows except along the southern and eastern boundaries of the model area. In these areas, the Cimarron River and Eagle Chief Creek transect the model area. Constant head nodes were assigned to nodes coinciding with the river and creek location in these areas. All nodes located south of the Cimarron River and east of Eagle Chief Creek were designated as no-flow nodes. These constant head nodes serve to maintain the regional groundwater flow gradient which is observed in the field.

Areal recharge is also introduced into the groundwater flow system as infiltrating rainfall. The recharge rate is based on an annual total infiltration of four (4) inches. No other inflows or outflows are incorporated into the groundwater flow model, except pumpages from wells.

Prior to incorporating the well stresses, the Cleo Springs Wellfield groundwater flow model was executed under steady-state conditions. This was performed to insure that simulated groundwater surface gradients and saturated thicknesses approximated the field observations. Further, the steady-state saturated thickness data was used to define allowable drawdown limits. The maximum allowable drawdown elevations for each well within the Cleo Springs Wellfield is presented in Table 5.5.

TABLE 5.5

CLEO SPRINGS WELLFIELD THRESHOLD DRAWDOWN DATA

WELL ID NO.	STEADY STATE G.W. ELEVATION	REDBED ELEVATION	THRESHOLD G.W. ELEVATION
S-1	1250.68	1245.37	1248.03
S-2	1250.68	1240.29	1245.49
S-3	1254.33	1234.45	1244.39
S-4	1251.59	1232.26	1241.93
S-5	1251.38	1240.08	1245.73
S-6	1251.38	1235.31	1243.35
S-7	1245.78	1241.78	1243.78
S-8	1250.30	1234.37	1242.34
S-9	1252.00	1248.20	1250.10
S-10	1248.52	1229.99	1239.26
S-11	1249.71	1231.32	1240.51
S-12	1249.71	1236.64	1243.18
S-13	1246.22	1224.37	1235.29
S-14	1246.22	1228.39	1237.30
S-15	1246.81	1229.95	1238.38
S-16	1246.81	1228.68	1237.75
S-17	1243.49	1226.79	1235.14
S-18	1243.78	1224.54	1234.16
S-19	1240.71	1222.89	1231.80
S-20	1240.82	1220.81	1230.81
S-21	1237.81	1214.94	1226.38
S-22	1235.60	1220.79	1228.20
S-23	1237.81	1218.91	1228.36
S-24	1234.58	1224.39	1229.49
S-25	1237.81	1214.72	1226.27
S-26	1235.60	1214.96	1225.28
S-27	1232.90	1214.94	1223.92
S-28	1232.90	1214.41	1223.66
S-29	1227.36	1219.56	1223.46
S-30	1227.36	1209.60	1218.48
S-31	1226.13	1208.09	1217.11

The transient groundwater flow model was subsequently developed for the Cleo Springs Wellfield by incorporating the City of Enid municipal supply wells. Domestic, livestock and other wells were not included for the reasons previously stated. The transient Cleo Springs Wellfield groundwater flow model is structured to provide monthly simulation periods, with 28-31 stress periods and time steps, each one (1) day in length. As previously stated, this system conforms to the operational policy of the City of Enid water resources manager.

Calibration

Each of the five (5) wellfield groundwater flow models were calibrated using existing groundwater surface and potentiometric surface elevation data. Constant head node values, aquifer characteristics and bedrock elevation values were adjusted until the simulated groundwater surface elevation and potentiometric surface elevation data approximated the measured surfaces based on available field data. The methodology which was followed initially provided for adjustment of the fixed head values for each constant head node to approximate field data. Under steady state conditions, the wellfield groundwater flow models were iteratively executed, with intermediate adjustments of the aquifer thickness, until a steady state groundwater surface was developed which approximated the field data. Subsequently, transient simulations were performed to confirm that the aquifer characteristics and recharge rates were acceptable. An example comparison of the measured vs simulated groundwater surface elevation for the Cleo Springs No. 7 well is presented in Figure 5.7.

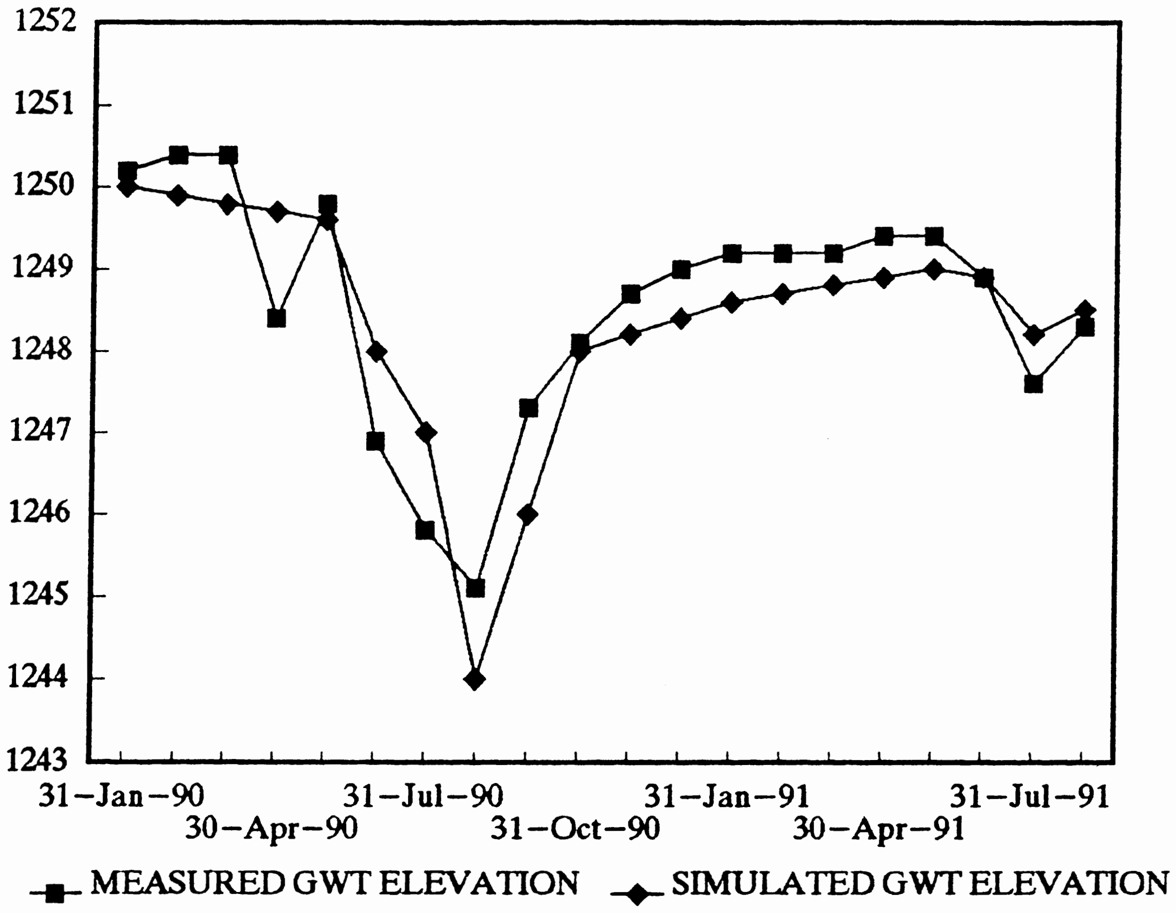

FIGURE 5.7 CALIBRATION RESULTS FOR CLEO SPRINGS WELL NO. 7

CHAPTER VI

OPTIMIZATION MODEL

General

Mathematical models have been previously used to optimize groundwater production systems. Many of these efforts have been discussed in a previous section of this report. In general, these models have been used to evaluate simplistic, hypothetical systems or relatively small systems. A very limited amount of work has been devoted to the optimization of large systems with production from multiple, isolated aquifers.

The mathematical modeling procedures which have been previously applied to aquifer management include both deterministic and stochastic approaches. The deterministic models have incorporated linear programming, integer programming, quadratic programming, goal programming, non-linear programming and dynamic programming solution methodologies. The selection of the appropriate mathematical modeling procedure for a specific system must be based on the type and availability of data, the complexity of system to be evaluated and the desired goals of the effort. In general, it is desirable to formulate the simplest model possible, which incorporates the essential components of the system while operating within the limitations of the available data. Based on a thorough analysis of the available data from the City of Enid water production system, it was determined that a linear programming model could be applied to optimize wellfield pumping schedules.

Model Development

The linear programming model which was developed consists of an objective function with one hundred forty six (146) decision variables and twenty three (23) constraints. Each of the decision variables are bounded with a specified maximum. The objective function is minimized to determine an optimal water production schedule. The model components including objective function, constraints and bounds are presented in Figure 6.1.

Objective Function

The model objective function consists of one hundred forty six (146) decision variables. These variables represent the production period, in days, that each well in the system must be pumped to meet the specified demand for water over a specified planning period. The decision variable parameters define the daily cost of production for each well. This cost includes electrical utility costs, water rights costs and operation and maintenance costs. The determination of these factors was described in an earlier

AQUIFER MANAGEMENT MODEL

MINIMIZE $Z = \Sigma\ [I_i\ (E_i + R_i + O_i)]\ X_i$
where:
i = well indices
E = energy costs per day
R = water rights costs per day
O = operation and maintenance costs per day
I = well status identifier (1:active;10000:inactive)
X = operating period for each well (days)

$E = [(P * U * C) + B]$
where:
P = pump capacity (gallons per day)
U = electrical useage rate (kwh per gallon)
C = electrical utility rate (dollars per kwh)
B = base electrical demand charge (dollars per day)

$R = [(J * P) + H]$
where:
H = base royalty rate (dollars per day)
J = production royalty rate (dollars per gallon)

CONSTRAINTS

1. **Target Water Demand**
   $(P_i * X_i) \geq D$ D = Target Water Demand (gallons)

2. **Planning Period**
   $X_i \leq Y$ Y = Planning Period (days)

3. **Unit 2 Production Requirement**
   $(P_i * X_i * J_i) \geq [(500 * 3.25) * Y / 365]$ i=A3,A5,A7

4. **Unit 3 Production Requirement**
   $(P_i * X_i * J_i) \geq [(500 * 3.00) * Y / 365]$ i=A4,A11

5. **Unit 4 Production Requirement**
   $(P_i * X_i) \geq [(576000 * Y)]$ i=A2,A12,A13

6. **Unit 5 Production Requirement**
   $(P_i * X_i * J_i) \geq [(500 * 3.00) * Y / 365$ i=A14,A15,D1

7. **Unit 6 Production Requirement**
   $(P_i * X_i) \geq [(504000 * Y)]$ i=A16,A17

FIGURE 6.1 L.P. OPTIMIZATION MODEL COMPONENTS

AQUIFER MANAGEMENT MODEL

8. **Unit 7 Production Requirement**
   $(P_i * X_i * J_i) \geq [(500 * 1.50) * Y / 365]$ i=A18

9. **Unit 8 Production Requirement**
   $(P_i * X_i * J_i) \geq [(500 * 1.00) * Y / 365]$ i=A19

10. **Unit 9 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 3.00) * Y / 365]$ i=A8,A9,A21

11. **Unit 10 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 3.25) * Y / 365]$ i=A20,A22,A31,
    A32,A33

12. **Unit 11 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 3.50) * Y / 365]$ i=A23,A24

13. **Unit 12 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 3.50) * Y / 365]$ i=A27,A28,A29,
    A30

14. **Unit 13 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 1.00) * Y / 365]$ i=A25,A26

15. **Unit 14 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 1.00) * Y / 365]$ i=D15

16. **Unit 15 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 1.00) * Y / 365]$ i=D2

17. **Unit 17 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 1.00) * Y / 365]$ i=D26

18. **Unit 18 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 2.00) * Y / 365]$ i=D14,D31

19. **Unit 19 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 0.50) * Y / 365]$ i=NW6

20. **Unit 20 Production Requirement**
    $(P_i * X_i * J_i) \geq [(500 * 0.50) * Y / 365]$ i=NW7

FIGURE 6.1 (CONTINUED)

AQUIFER MANAGEMENT MODEL

21. Unit 21 Production Requirement
$(P_i * X_i * J_i) \geq [(500 * 2.00) * Y / 365]$ i=NW8,NW9

22. Unit 22 Production Requirement
$(P_i * X_i * J_i) \geq [(500 * 1.00) * Y / 365]$ i=NW10

23. Unit 23 Production Requirement
$(P_i * X_i * J_i) \geq [(500 * 2.00) * Y / 365]$ i=NW1,NW3

FIGURE 6.1 (CONTINUED)

section of this report. For clarification purposes it is noted that differential electrical utility useage rates are not provided for in the decision variable parameters. This represents a simplification, but based on an analysis of historical electrical useage, the resulting impact on the optimal solution is negligible. Each decision variable coefficient implicitly includes a well status identifier. This value is 1.0 for all active wells and 10,000.0 for all inactive wells. Therefore, by assigning the higher value, an inactive well can effectively be taken out of the optimal solution. The optimal water production schedule is determined by minimizing the objective function. **Special consideration must be used when a well which is constrained by contractual obligations becomes inactive.** Because the contractual obligations are modeled as hard constraints, the optimal solution will include these wells unless they are explicitly excluded from the model.

Constraints and Bounds

There are twenty three (23) constraints which must be accommodated in the optimal solution. The first is the requirement that a sufficient quantity of water be pumped to supply the explicit demand on the system. The remaining constraints provide that specific minimum pumpages be met to comply with contractual obligations set forth in a number of water rights royalty agreements. Constraint Nos. 4 and 6 reflect minimum water production requirements under royalty with minimum production agreements which affect five (5) wells. Constraint Nos. 2, 3, 5, 7-22 reflect minimum water production requirements under royalty with minimum fee agreements which affect thirty eight (38) wells.

Each of the decision variables are bounded by the explicitly defined planning period. These bounds preclude a well specific production period, as determined by the model, from exceeding the planning period.

Solution Procedure

The required input for the model includes the planning period, in days, and the total anticipated water demand, in gallons, for the specified planning period. In a typical water production system application, the planning period is very often a week or month. The anticipated water demand can usually be estimated from historical water production records for similar conditions.

The optimization model is solved using the Linear Interactive Discrete Optimizer (LINDO) linear program solution software package. The solution algorithm incorporates the simplex method to solve for the optimal objective function value. The typical model solution required approximately 80 iterations and 30 CPU seconds using an IBM PC-486/33 Mhz microcomputer.

The optimal solution identifies those wells which should be operated to provide the explicitly stated water demand at the lowest cost. The number of days each of the selected wells should be operated is also defined. The calculated value of the objective function represents the total production costs associated with the selected production schedule, less costs directly related to transmitting water to main pumping and storage facilities, treatment and distribution system operation.

Sensitivity Analysis

The optimal solution to the model objective function can be significantly affected by variations in the decision variable coefficients, and the model constraints. The decision variable coefficients represent the daily production costs associated with each well. These costs include electric utility costs, water rights costs and operation and maintenance costs. These costs are quantified from historic production data and represent average approximations. These costs are functions of well production rates, collection system hydraulic characteristics, pump and motor efficiency, and groundwater or potentiometric surface at each well in the system. Obviously, these well specific characteristics are not constant and it can be concluded that the water production cost parameters are variable. Although these parameters are variable, a detailed analysis of these parameters, over a twelve (12) month period, indicates that a constant value for these parameters can be assumed without significantly compromising the model solution. The value for each decision variable coefficient was estimated to be the statistical average from a twelve month data set.

Trial model solutions reveal that each of the royalty with minimum production constraints are active for typical operational scenarios. This result indicates that production costs could be further reduced if the contractual provisions set forth in those agreements could be modified.

Finally, it must be noted that the optimization model is not capable of evaluating the ability of the underlying aquifer to produce the required water. Typically, the optimal solution requires some wells in the system to be operated constantly throughout the entire planning period. This approach can violate proper aquifer management practices. The aquifer in the vicinity of an overproduced well could become permanently damaged. In addition, the quality of water from a specific well in the system may warrant the limitation of its production. Therefore, it is important that the condition of the aquifer in the vicinity of each well be evaluated using the output data from the groundwater flow simulation model. This data is obtained by simulating the trial optimal water production scenario using the MODFLOW groundwater flow model discussed previously. If it is determined that a well should not be included in the optimal production schedule, the well status identifier should be modified appropriately prior to model execution. The details of the interrelationship between the linear programming optimization model and the groundwater flow model are presented in the following chapter.

CHAPTER VII

LINKED OPTIMIZATION-SIMULATION AQUIFER MANAGEMENT MODEL

General

The management of an aquifer which is a source of water for a large population and subject to significant water production represents a complex problem. The optimal management scenario represents a delicate balance between the water production operational schedule which will result in the least demand on physical and economic resources, and the operational production scenario which will distribute pumpages throughout the entire groundwater basin, resulting in minimal impacts to the groundwater flow system. These goals are often divergent, leaving the water resources manager with a dilemma which is difficult to resolve. Factors which must be considered when defining the optimal water production schedule include anticipated water demand, competing beneficial uses, political influences, well inventory and status, system operation and maintenance economics, contractual obligations, logistics and the hydrogeologic characteristics of the groundwater basin. In large systems which include many wells, often producing water from multiple aquifers, the identification of the optimal water production scenario becomes essentially impossible using conventional manual practices. As the number of system variables increases, along with aquifer complexity, the use of the digital computer to assist in the identification of the optimal water production scenario is essential.

One of the most powerful tools available to solve this complex problem is the combined optimization-simulation aquifer management model. This class of model can be formulated to solve the governing groundwater flow equations of the aquifer system in conjunction with the use of optimization techniques which are used to address management objectives. These objectives are frequently subject to numerous and often complex system constraints. This type of model can be formulated to define an operational scenario for an existing groundwater production system for a specific planning period which satisfies an exogeneous water demand while minimizing the total cost of extraction. These goals can be accomplished while simultaneously complying with predetermined hygrogeologic constraints. The resulting linked optimization-simulation aquifer management model represents a dynamic tool which can be used by the water resources manager to rapidly adjust the system to varying system demands with confidence that the integrity of the aquifer is protected and that system efficiency and cost effectiveness are maintained.

The City of Enid water production system is an excellent example of a large, complex system which is extremely difficult to manage in an economically efficient manner. The system includes one hundred forty six (146) wells which are distributed throughout five (5) wellfields and extract water from three (3) aquifers. Numerous operational and economic constraints influence the development of production scenarios. The aquifers in the region are relatively shallow and vulnerable to over-production. The principal goal of the work described herein is to develop a linked optimization-simulation aquifer management model for the City of Enid groundwater production system. A comprehensive description of the Enid system is presented in previous sections of this report. In addition, the development of groundwater flow models for each wellfield and a system optimization model is developed and described. The final task of linking the previously developed groundwater flow system models and the system optimization model is described in the following sections of this chapter.

Model Development

The development of the linked optimization-simulation aquifer management model for the City of Enid water production system was accomplished in phases. Initially, a data base was developed over a twenty four (24) month period. Data which was compiled and analyzed includes hydrogeologic data, historical water production statistics, water production system operation and maintenance characteristics and water rights data. This data was then used to formulate the system optimization model and the five (5) wellfield groundwater flow models, described in previous sections of this report. Each of these individual models comprise the essential components of the linked optimization-simulation aquifer management model.

The concept of groundwater management implies a balance between extraction from the aquifer at a minimum cost while simultaneously protecting the aquifer integrity. Individually, the previously described groundwater flow system models and the system optimization model do not have the capacity to accomplish this goal. However, the balance between system efficiency and aquifer protection can be accomplished by linking the two model types together. To accomplish this linkage, a series of input/output control algorithms were developed. In addition, interface algorithms were created. The use of the input/output control and interface algorithms provided a linkage between the LINDO linear programming optimization model and the MODFLOW groundwater flow system models. The final model configuration incorporates a modular design, with each module providing a specific function. This design is desirable because it provides flexibility in model modification and future model expansion.

The basic control structure for the management model is based on a file management system which is menu driven and incorporates batch files to organize data management and program execution. There are four (4) basic modules which can be performed upon initial program execution. These modules include the following:

1. UPDATE OPTIMIZATION MODEL
2. EXECUTE OPTIMIZATION MODEL
3. UPDATE GROUNDWATER MODEL
4. EXECUTE GROUNDWATER MODEL

The basic model is formulated to provide the water resources manager with an operational tool. To facilitate this goal, the model input/output structure is developed to provide for monthly input file updating and model execution. Pre-structured input files for January through December are embedded in the system. Second and third level menus provide the water resources manager the flexibility to evaluate monthly trial water production scenarios and ultimately select the optimal production schedule. The input/output file structure is constructed to provide for automatic file updating of the subsequent months model from model output generated during model execution for the previous month, wherever possible. A schematic of the linked optimization-simulation aquifer management model is presented in Figure 7.1. A list of the individual files which comprise the model is presented in Appendix A. A description of each of the principal modules of the linked optimization-simulation aquifer management model is presented in the following sections.

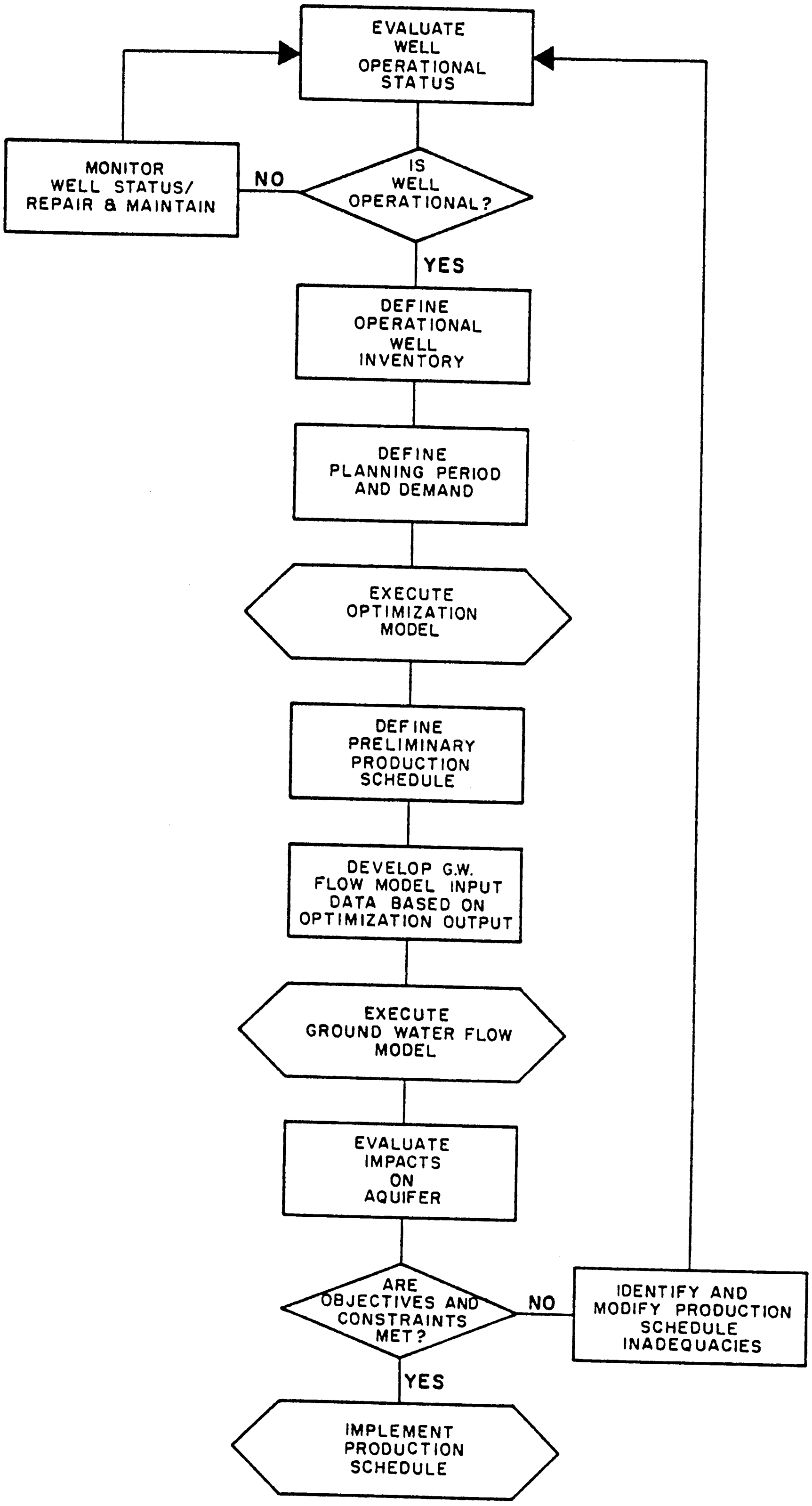

FIGURE 7.1 LINKED OPTIMIZATION-SIMULATION AQUIFER MANAGEMENT MODEL

The MENU module is the file management program which incorporates the use of screen menus to assist the user in model execution. The Hard Disk Manager software package developed by Donovan Micro Systems (1986), is used to accomplish this task within the model. This program provides the ultimate management of approximately 750 files which comprise the model. Three (3) menu levels are used which allows for adequate organization of the primary model components. Input files for the MENU module include the menu template files and the batch files used to identify pathways and locations for the principal model modules.

The LINEAR PROGRAMMING MODEL UPDATE module is accessed from the main menu. This module permits the water resources manager to define the anticipated water demand for any monthly period by creating or modifying a specified linear programming model input file. Each of the twelve (12) months can be selected from the second level menu. When selected, the linear programming data file is made available for modification through simultaneous execution of the screen editor, written by S. Reifel & Company (1986). Upon completion of the model update process, the module is exited, automatically storing the updated linear programming model input file.

The LINEAR PROGRAMMING MODEL EXECUTION module is also accessed from the main menu and comprises the linear programming optimization model executable code. Each of the twelve (12) months can be selected from the second level menu. When selected, the linear programming model automatically reads the updated file from the previously described module and executes the linear programming solution algorithm. Model output is automatically written to a data base file. At the completion of the linear programming model execution, the model output file is automatically custom formulated using the data conversion program, MALLORY. Output from this data conversion process is written to the printer in report format.

The linear programming optimization model output report specifies the trial optimal water production schedule, which includes the identity of wells to be produced and the operational period for each of the wells, in days, to meet the explicitly defined water demand. In addition, the total estimated production cost associated with the trial schedule is defined. This data must be reviewed by the water resources manager and used to update the groundwater flow model.

The GROUNDWATER MODEL UPDATE module is accessed from the main menu. This module permits the water resources manager to define the trial well pumping schedule for each of the five (5) wellfields, on a monthly basis. Each of the wellfield data files are accessed through a third level menu. The trial pumping schedules are based on the output from the previously executed linear programming optimization model. When a wellfield is selected for a specific month, the groundwater model data file is made available for modification through simultaneous execution of the screen editor, written by S. Reifel & Company (1986). Typically, five (5) data files must be modified to facilitate a one (1) month groundwater flow system simulation. Upon completion of the update process, the module is exited, automatically storing the updated groundwater model input files.

The GROUNDWATER MODEL EXECUTION module is accessed from the main menu. Each of the twelve (12) months can be selected for execution from the second level menu. When selected, the groundwater model automatically reads a series of 6-8 input files, including the files created in the previously described module, and executes the groundwater flow system solution algorithm. The groundwater flow system model package is MODFLOW, developed by the USGS (1984), and described in a previous section of this report. Model output is automatically written to an unformatted file, which contains location and potentiometric surface information. This unformatted data is automatically read by the data conversion program, POSTMOD, which was developed by S.A. Williams (1988). Output from the POSTMOD program is then custom formatted using the data conversion program SPENCER. Output from this data conversion process is written to the printer in summary report format.

The information tabulated in this wellfield groundwater/potentiometric surface elevation summary report includes the well identification number, the threshold groundwater surface elevation (i.e. allowable drawdown surface), the predicted groundwater surface elevation at the end of the simulation period, and the drawdown buffer. The drawdown buffer is an indication of how much additional pumpage can be anticipated from a specific well in future months. In addition, if the drawdown buffer is less than zero (0.0) the trial optimal production schedule is unacceptable. If the threshold values are greater than zero, the initial trial optimal water production schedule can be implemented by the water resources manager. If the trial schedule is unacceptable, the linear programming optimization model must be updated. This is accomplished through the LINEAR PROGRAMMING MODEL update and requires that the well status operator, for those wells violating the groundwater drawdown criteria, be modified from 1 to 10,000. This change will effectively remove the affected wells from the optimal solution.

Solution Procedure

The identification of an optimal water production schedule requires an iterative approach. In general, the water resources manager must anticipate a demand for water for a specified planning period. The linked optimization-simulation groundwater management model is structured using a modular system and is pre-formatted to accept twelve (12) monthly planning periods, although other planning periods are easily accommodated. After a planning period and water demand are defined, the linear programming optimization model modules are executed to update the model and generate a trial water production schedule. This schedule defines the wells which should be operated and the operational period for each well to comply with the specified objectives at the least cost. This trial schedule represents the operational scenario which will attain the specified goal, if no consideration is given to the hydrogeologic conditions of the aquifer.

Because the condition and integrity of the aquifer is extremely important, the effects of the trial optimal production schedule are evaluated through execution of the wellfield groundwater flow system models. The summary groundwater elevation report which is generated by groundwater model modules permit the water resources manager to evaluate the hydrogeologic effects of the trial production schedule on the aquifer. If it is determined that the hydrogeologic effects on the aquifer are unacceptable, the water resources manager can modify the linear programming model input and re-execute the groundwater management model.

The iterative approach allows the water resources manager to be intimately involved in the development of the water production schedule. The number of iterations required to solve for an optimal production schedule will generally be 2-5, based on trial applications. Although it would be possible to fully automate the model solution process, it is important that the water resources manager maintain an integral role in the determination of the production schedule. This is due to the wide variety of external considerations which can occur and may affect the goals of the water resources manager. Examples of external considerations which are outside the limits of this model to accommodate include political influences, regulatory requirements, unanticipated system losses or expansions, etc. The water resources manager must maintain the ability to compromise the water production economics, or even localized aquifer conditions. By maintaining the role of the water resources manager in solution procedure, the effects of any compromises can be immediately evaluated and the decisions of the water resources manager can be made with confidence.

CHAPTER VIII

MODEL APPLICATION

General

In order to evaluate the applicability of the aquifer management model, a comparative analysis was performed. Actual water production records were obtained from the City of Enid for the period beginning on January 1, 1989 and ending on December 31, 1989. Because well specific production cost data is unavailable for this twelve (12) month period, the production costs were determined for the actual production using well production cost data compiled during the development of the aquifer management model. The use of this cost data also eliminated the need to adjust for the time value of money.

Initially, the production costs were determined for each month using the actual production data. Then the total volume produced for each month and the number of calendar days in each month were used as input for the linked optimization-simulation model. The data and results are described and compared in the following sections.

Historical Production Schedule

Historically, the selection of wells for operation was based principally on demand and logistics. The number and location of wells in operation at any specific time was related to the water distribution system demand and the case by which a group of wells could be operated and maintained. This operational philosophy results in clusters of operational wells, thus minimizing the demand on operation and maintenance manpower resources.

During the period beginning on January 1, 1989 and ending on December 31, 1989, approximately 3,541 million gallons of water were produced. The total cost to produce this volume is estimated to be $478,227. The production data for this period is presented in Table 8.1. This data is graphically represented in Figure 8.1. Based on an analysis of this data, the average cost per gallon to produce water under the historical operational scenario is $0.000135.

Although this production philosophy is efficient from a maintenance and logistics perspective, it is uneconomical and represents a potential risk to the aquifer. The spatial clustering of well operations does not provide for the selective operation of the most cost effective wells. In addition, this clustering concentrates groundwater pumping from a limited area which can result in localized over production and aquifer damage.

TABLE 8.1

WATER PRODUCTION COST COMPARATIVE ANALYSIS

WATER PRODUCTION COSTS

DATE	PLANNING PERIOD (DAYS)	WATER DEMAND (GALLONS)	AQUIFER MANAGEMENT OPTIMAL SCENARIO	HISTORICAL SCENARIO	ECONOMIC OPTIMAL SCENARIO
Jan-89	31	276247000	$24,616	$39,537	$24,616
Feb-89	28	246438000	$22,812	$35,963	$21,960
Mar-89	31	283092000	$26,149	$40,651	$25,204
Apr-89	30	296257000	$27,322	$40,472	$26,271
May-89	31	305892000	$29,960	$43,853	$27,158
Jun-89	30	295251000	$29,170	$38,681	$26,186
Jul-89	31	351354000	$36,634	$46,223	$31,157
Aug-89	31	328163000	$33,508	$43,586	$29,063
Sep-89	30	308056000	$31,212	$39,251	$27,305
Oct-89	31	298973000	$29,891	$38,427	$26,562
Nov-89	30	270611000	$25,816	$34,857	$24,149
Dec-89	31	281046000	$26,691	$36,726	$25,035
	TOTAL ANNUAL COST		$343,781	$478,227	$314,666

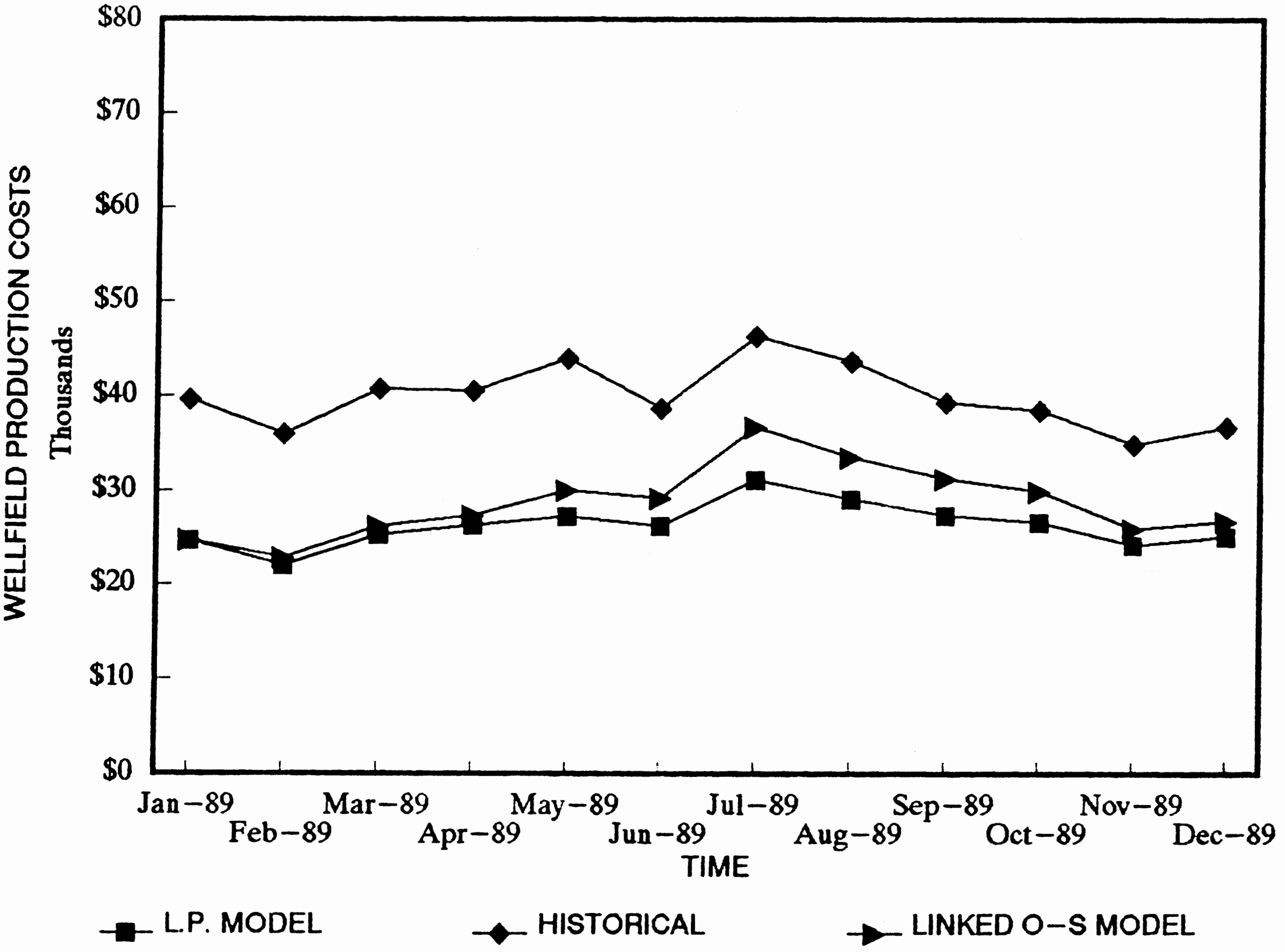

FIGURE 8.1 WATER PRODUCTION COST COMPARATIVE ANALYSIS

Optimal Production Schedule

An optimal water production scenario was also developed for the period beginning on January 1, 1989 and ending on December 31, 1989 using the historical City of Enid water useage data and the linked optimization-simulation aquifer management model. Water production schedule development was performed on a monthly basis to approximate the existing City of Enid Water Production Department management practices. The initial model input included the volume of water produced in January 1989 and a planning period of 31 days. Due to the lack of available groundwater surface elevation data for this time period, the computed steady-state groundwater surface was assumed for all wellfields. Execution of the aquifer management model resulted in a schedule of wells to include in the production schedule, which met all operational and hydrogeological criteria, and resulted in a total estimated water production cost of $24,616. This represents a 38 percent decrease, compared to the actual historic water production cost for the same period.

Based on a review of the predicted groundwater surface elevation data, it was determined that the estimated drawdown values at the Cleo Springs 7, 29 and Ringwood 15, 16 wells approached the pre-determined maximum allowable values. Therefore these wells were inactivated, prior to executing the linked optimization-simulation aquifer management model for the February 1989 planning period.

This solution procedure was followed for each of the twelve (12) monthly planning periods in 1989. The number of wells which were inactivated increased to a maximum of thirty (30) during the August through October planning periods. This period coincides with the months where the highest water production volumes occurred. An inventory of the wells which were inactivated during the model demonstration period are presented in Table 8.2. Based on a review of this data, it is apparent that the majority of the inactivated wells are located in the Ringwood and Cleo Springs wellfields. This is due to a combination of factors which include the attractive economics associated with these wellfields and the aquifer sensitivity to excessive production. The operational economics and hydrogeological characteristics of the Enid, Ames and Drummond wellfields result in decreased sensitivity to overproduction under optimal aquifer management scenarios.

The procedure that was implemented during demonstration simulation provided that a specific well was inactivated if the simulated drawdown during a planning period violated the predetermined threshold drawdown limit by one (1) foot or more. The threshold drawdown limit is based on the previously determined aquifer saturated thickness under steady state conditions. The threshold drawdown limit is equal to one-half the steady state saturated thickness. It was also necessary to inactivate adjacent wells in some areas to eliminate drawdown violations due to drawdown

TABLE 8.2

SUMMARY OF INACTIVATED WELLS

MONTH	NUMBER OF WELLS INACTIVATED	INACTIVATED WELLS
JANUARY 1989	0	ALL WELLS ACTIVE
FEBRUARY 1989	4	S-7,S-29,R-15,R-16
MARCH 1989	9	S-7,S-29,R-15,R-16,R-17,R-18,R-22,R-23,R-24
APRIL 1989	9	S-7,S-29,R-15,R-16,R-17,R-18,R-22,R-23,R-24
MAY 1989	26	S-7,S-20,S-21,S-22,S-23,S-24,S-25,S-26,S-27,S-28,S-29,R-10,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1
JUNE 1989	28	S-7,S-9,S-18,S-20,S-21,S-22,S-23,S-24,S-25,S-26,S-27,S-28,S-29,R-10,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1
JULY 1989	30	S-7,S-9,S-15,S-16,S-18,S-20,S-21,S-22,S-23,S-24,S-25,S-26,S-27,S-28,S-29,R-10,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1
AUGUST 1989	30	S-7,S-9,S-15,S-16,S-18,S-20,S-21,S-22,S-23,S-24,S-25,S-26,S-27,S-28,S-29,R-10,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1
SEPTEMBER 1989	30	S-7,S-9,S-15,S-16,S-18,S-20,S-21,S-22,S-23,S-24,S-25,S-26,S-27,S-28,S-29,R-10,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1
OCTOBER 1989	30	S-7,S-9,S-15,S-16,S-18,S-20,S-21,S-22,S-23,S-24,S-25,S-26,S-27,S-28,S-29,R-10,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1
NOVEMBER 1989	24	S-7,S-9,S-15,S-16,S-18,S-21,S-22,S-24,S-29,R-10,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1
DECEMBER 1989	23	S-7,S-9,S-15,S-16,S-18,S-21,S-22,S-24,S-29,R-11,R-12,R-13,R-14,R-15,R-16,R-17,R-18,R-19,R-20,R-22,R-23,R-24,VB-1

NOTE: R= RINGWOOD WELLFIELD ; S= CLEO SPRINGS WELLFIELD ; VB = ENID WELLFIELD interference and superposition effects. Individual wells were reactivated when the simulated groundwater surface elevation increased to a minimum height of five (5) feet above the allowable limit.

The resulting optimal water production scenario, as defined using the linked optimization-simulation aquifer management model, represents the most economically efficient operational schedule for the system which does not violate predefined hydrogeologic constraints. The total estimated cost to meet the predefined demand for water is estimated to be $343,781. The production data for this scenario is presented in Table 8.1 and graphically represented in Figure 8.1. A summary of the model output is presented in Appendix B. Based on analysis of this data, the average cost per gallon to produce water under the optimal operational scenario is $0.000097.

Comparative Analysis

A comparison of the historical and optimal water production scenarios demonstrates the potential economic benefits which may be realized by applying the aquifer management model. Water production costs are reduced by approximately $134,500 using an optimal production scenario. This represents a potential savings of approximately 28 percent. In addition, integrity of the aquifer is protected under the optimal water production scenario while the historical scenario could potentially result in localized overproduction and aquifer damage. For further comparison purposes, a water production scenario was developed using only the L.P. optimization model. This analysis was performed to provide an estimated cost associated with aquifer protection. The water production data for this economically optimal solution is presented in Table 8.1 and graphically represented in Figure 8.1. The average cost per gallon to produce water under this scenario is estimated to be $0.000089. Using this data, it is apparent that the protection of the aquifer integrity would result in an increased cost of $29,115 for the twelve (12) month planning period, or approximately $0.0000082 per gallon.

CHAPTER IX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

Summary

To properly manage a groundwater production system, the water resources manager must define a water production schedule which balances a goal of minimizing the cost of production, through the selection of those wells which can be produced for the least cost, and the need to control the drawdown effects on the aquifer. Drawdown control can be accomplished through the spatial distribution of production among wells throughout the wellfields. For the water resources manager to accomplish this balance, it is imperative that the water production system be completely quantified including production, operation and maintenance characteristics and system constraints. In addition, it is also important that the aquifer conditions be quantified so that the interrelationships between the water production system and the aquifer system can be evaluated under proposed water production scenarios. Once quantified the water resources manager can evaluate production scenarios and compare estimated production costs with the anticipated impact on the aquifer. For relatively small systems this evaluation process can be conducted manually using conventional techniques. As the size and complexity of the water production system increases, the use of conventional techniques becomes impossible. For large systems, the use of computerized aquifer management systems becomes desirable. The linked optimization-simulation aquifer management model represents a class of management system which is well suited for this application.

The use of aquifer management models is well documented in the literature over the past three decades. These types of models have been developed and applied to a wide variety of groundwater management problems. In general these models have been developed and applied to simplistic, hypothetical problems. There is very little evidence which documents the application of a linked optimization-simulation aquifer management model to a large, existing, groundwater production system. This is particularly the case for applications of this class of model to water production system operations management. This is primarily due to the significant requirements for operations and hydrogeologic data which are required to identify the system parameters and constraints.

The goal of this research was to develop a linked optimization-simulation aquifer management model which could be used by the water resources manager to define water production scenarios which meet the anticipated demand for water at a minimal cost while insuring that the integrity of the aquifer is maintained. Initially a thorough review of the literature was conducted to evaluate the state of the science and determine to what extent previous applications have addressed this issue. Based on the results of that literature review it was determined that although a significant amount of work has been conducted in the development and application of linked optimization-simulation aquifer management models, very little work has been accomplished in the area of model application to large operating systems. Therefore, it was determined that the development of a linked optimization-simulation aquifer management model for a large existing operating system was pertinent. The City of Enid's groundwater production system was selected for model development due to the size of the system and the complexity of the hydrogeology within the system. The City of Enid's groundwater production system is comprised of one hundred forty six (146) wells which are located in five (5) wellfields and produce water from three aquifers. The size and diversity of this system represents a major challenge to the water resources manager when defining the optimal groundwater production scenario. It is essentially impossible to define an optimal production schedule using manual conventional techniques.

The initial phase of model development included the complete quantification of the water production and aquifer systems. Due to a lack of available information regarding system operation and maintenance, the initial step required that a data acquisition program be implemented. Each of the wells within the system was inspected and monitored on a monthly basis over a twenty four (24) month period. The parameters which were recorded and statistically analyzed included water production, electric power consumption, indirect and direct operating and maintenance costs, and the cost for water rights. In addition, hydrogeologic parameters were monitored using a groundwater monitoring well network which included approximately two hundred (200) observation wells throughout the five (5) wellfields. To supplement the monthly groundwater surface elevation measurement data, which was acquired from each of the observation wells, a total of ten (10) continually recording groundwater elevation measurement devices were installed and three (3) continually recording precipitation gauges were installed. Selectively, the data base which was acquired over the twenty four (24) month period was used in development of the optimization and groundwater simulation models.

The groundwater model which was developed for each of the five (5) wellfields was accomplished using the USGS MODFLOW code. A separate model was constructed for each of the wellfields and incorporated the important hydrogeologic characteristics of each wellfield. Aquifer pump tests were performed in each of the wellfields to identify the required aquifer characteristics for use in the model. Each of the wellfield models were calibrated using the groundwater surface elevation and production data which was recorded over the twenty four (24) month period. Boundary conditions and aquifer characteristics were modified slightly until acceptable calibration results were generated.

The optimization model was developed using the LINDO linear programming solution code. An objective function was developed which represented the total cost of production for the water production system and included one hundred forty six (146) decision variables. The decision variables represent the production period for each well within the system. Objection function coefficients represent the cost of production associated with the daily production of each well. The objective function value represents the total cost of production associated with the selected groundwater production schedule. The objective function is constrained by the total estimated demand for water, the planning period, and the contractual requirements which apply to royalty and water rights conditions. All of the decision variables are bounded by the maximum planning period. The objective function is minimized to define the optimal solution.

To develop the linked optimization-simulation aquifer management model, it was necessary to link the groundwater flow model with the linear programming optimization model. This was accomplished with the use of a file management program, interface programs, and batch programs. The resulting groundwater management model is structured to provide the water resources manager a menu driven solution procedure which provides for updating and executing the groundwater and optimization models on a monthly basis. The solution procedure requires that the resources manager identify an anticipated demand for water for a specific month. Once defined, the optimization model is updated and then executed. The resulting output includes a schedule of wells to produce to meet the explicitly defined demands at the minimum production cost. This production schedule is then used to update the groundwater model which is executed to evaluate the impact on the aquifer from the proposed groundwater production schedule. Output from the groundwater model identifies the anticipated groundwater surface elevations at the completion of the simulation period. These water surface elevations are compared with predetermined threshold elevations to evaluate drawdown criteria at each well. If the projected drawdown exceeds the threshold value, the proposed groundwater production schedule is determined to be invalid. The affected wells are then excluded from the optimal solution through an update of the optimization model and a second iteration is performed using the previously described steps. The iterative approach is incorporated into the linked optimization-simulation aquifer management model and provides the water resources manager the opportunity to fully understand the consequences of a proposed groundwater production scenario. This knowledge provides the water resources manager the ability to make compromises, if necessary.

To evaluate the linked optimization-simulation aquifer management model, the system was applied to the City of Enid water production system to determine the optimal groundwater production scenario for the period beginning in January and ending in December of 1989. Historic groundwater production data was used and the results compared with the actual groundwater production costs associated with that period. Based on the results of that comparison, it is concluded that the linked optimization-simulation aquifer management model is extremely useful in defining optimal production schedules which meet the demands of the system and provide protection of the aquifer integrity. The total production costs associated with the optimal production scenario were estimated to be $343,781. The costs associated with the actual production scenario which was implemented in 1989 were estimated to be $478,227. The optimal production schedule represents a 28 percent decrease in the total production costs. In addition, the level of protection of the aquifer is increased using the linked optimization-simulation aquifer management model.

Conclusions

A linked optimization-simulation aquifer management model was developed and applied to a large complex existing groundwater production system. Based on the results of the application the following is concluded:

1. A linked optimization-simulation aquifer management model can be successfully applied to a large, complex groundwater production system.

2. A significant reduction in operational and maintenance costs can be achieved through the implementation of a linked optimization-simulation aquifer management model.

3. To successfully implement a linked optimization-simulation aquifer management model, it is essential that the system cost parameters and constraints be quantified. Incomplete or inaccurate data can result in significant errors in the final solution.

4. Complex solution procedures can be effectively structured to provide a "user friendly" model for use by the water resources manager.

5. Water production system operational criteria and hydrogeologic properties are dynamic and must be modified periodically to insure realistic model solutions.

6. The iterative solution methodology of the linked optimization-simulation aquifer management model is advantageous because it allows the water resources manager to actively participate in the development of water production scenarios.

Recommendations for Further Study

The formulation of the linked optimization-simulation aquifer management model represents a completion of four (4) major tasks. These are:

1. Water production system and aquifer parameter quantification.
2. Optimization model formulation.
3. Groundwater flow model formulation.
4. Linked optimization-simulation aquifer management model formulation.

The resulting model represents an iterative solution procedure within which the water resources manager provides an integral role. The goal of any further work must address the speed with which the water resources manager operates and updates the system. To accommodate this goal, the following recommendations for further work are noted:

1. It was determined during this investigation that the interrelationship between electric power consumption power at each well and the groundwater surface elevation at that well is significantly dependent on other factors which include the line pressure in the collection system. It was beyond the scope of this investigation to define that interrelationship and therefore it was necessary to approximate the electric power consumption for each well using statistical averaging techniques. Because the cost of electric power is a major component of the production costs associated with each well, it is suggested that a method for

quantifying the electric power consumption for each well based on water surface elevation and collection system line pressure be performed. The resulting model will more accurately predict the actual production costs associated with each well.

2. It is also recommended that a method of automatic data acquisition be developed which could be used to automatically collect and evaluate well specific water production parameters on a real time basis. This type of data acquisition would allow more accurate quantification of the system parameters and provide for regular updating of the model with relative ease.

3. The method of interfacing between the optimization model and the groundwater model within the linked optimization-simulation aquifer management model could be improved to more efficiently provide for model updating and trial water production schedule evaluation. In the current model, this process of updating and execution is relatively manual in nature and somewhat time consuming. The automation of this process represents a significant improvement and would provide increased ease in model execution.

4. It is recommended that an expert system be developed to provide the water resources manager assistance in modifying a trial water production schedule. This process is cumbersome within the existing model.

5. The addition of a scheduling module to the existing model is proposed. This module would use the final well production schedule output to facilitate scheduling of routine operational and maintenance resources.

6. It is recommended that water quality parameters be incorporated into the optimization component of the model as additional constraints. This addition would result in added value of the linked optimization-simulation aquifer management model to the water resources manager.

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APPENDIX A

LINKED OPTIMIZATION-SIMULATION AQUIFER MANAGEMENT MODEL

File Names and Brief Content Description

The linked optimization-simulation aquifer management model which was developed for the City of Enid water production system is comprised of 760 files. The basic structure of the model is based on the USGS MODFLOW finite difference code and the Linear Interactive Discrete Optimizer (LINDO) L.P. optimization code. Executable versions of these programs are incorporated into the model. The remainder of the files which are required to successfully execute the linked optimization-simulation aquifer management model include those which contain required data, batch files required to initiate execution of model components, output control programs required to generate model output reports and interface files required to modify internally generated output into required input format. The aquifer management model is designed to be executed from screen menus. Output is generated in printed tabular format. A brief functional description of each file by name or file name extension type is presented in the following sections.

Executable Files

MODFLOW.EXE This program is the groundwater flow numerical simulation code, developed by the USGS and capable of simulating 2D and 3D groundwater flow systems with external stresses including wells, recharge, rivers and drains.

LINDO.EXE This program is the L.P. optimization code developed by LINDO Systems, and capable of solving relatively large L.P. models with numerous constraints and bounds.

POSTMOD.EXE This program is the post processor for MODFLOW developed by S. Williams, and is capable of reformatting MODFLOW output data into a format which is easily modified for use by other programs.

EDITOR.COM This program is the screen editor developed by S. Reifel and is capable of full screen editing of computer files.

MALLORY.EXE This program is the output control for LINDO which creates the Optimal Water Production Schedule report from the L.P. model output.

AMES.EXE This program is the output control for the groundwater flow simulation model which creates the

Predicted Groundwater Surface Elevation Summary Report for the Ames Wellfield.

ENID.EXE This program is the output control for the groundwater flow simulation model which creates the Predicted Groundwater Surface Elevation Summary Report for the Enid Wellfield.

DRUM.EXE This program is the output control for the groundwater flow simulation model which creates the Predicted Groundwater Surface Elevation Summary Report for the Drummond Wellfield.

RING.EXE This program is the output control for the groundwater flow simulation model which creates the Predicted Groundwater Surface Elevation Summary Report for the Ringwood Wellfield.

CLEO.EXE This program is the output control for the groundwater flow simulation model which creates the Predicted Groundwater Surface Elevation Summary Report for the Cleo Springs Wellfield.

Batch Files

*LIN.BAT These files call data management files necessary for execution of the LINDO L.P. optimization component of the model. There are a total of twelve (12) files of this type to provide for monthly model execution.

Control files containing LINDO input and output information are called when these files are executed.

*.BAT These files call data management files necessary for execution of the MODFLOW, POSTMOD, AMES, ENID, DRUM, RING and CLEO programs. There are a total of twelve (12) files of this type to provide for monthly model execution. Control files containing MODFLOW, POSTMOD, AMES, ENID, DRUM, RING and CLEO input and output information are called when these files are executed.

MENU.BAT This file executes the file management system and initiates the Linked Optimization-Simulation Aquifer Management Model.

Menu Control Files

*.MNU These files contain the file path information required by the data file management system. There are a total of seventeen (17) of these files.

Data Management Files

AQ*.FKR These files contain input commands necessary for proper identification of input file location and format and output file location and format during LINDO program execution. There are a total of twelve (12) of these files.

*.BTR These files contain input commands necessary for proper identification of input file location and format

during the execution of the AMES, ENID, DRUM, RING and CLEO programs. There are a total of sixty (60) of these files.

AQ*.MAL These files contain input commands necessary for proper identification of input file location and format during the execution of the MALLORY program. There are a total of twelve (12) of these files.

*.MOD These files contain input commands necessary for proper identification of input file location and format during the execution of the MODFLOW program. There are a total of sixty (60) of these files.

*.POS These files contain input commands necessary for proper identification of input file location and format during the execution of the POSTMOD program. There are a total of sixty (60) of these files.

Data Files

*AQ.DAT These files contain the input data which describes the LINDO L.P. model components. There are twelve (12) of these files.

*OPT.DAT These files contain the output data from the LINDO L.P. program. This data also represents the input data for the MALLORY program. There are twelve (12) of these files.

*.BAS These files contain the input data which describes the basic groundwater flow simulation model

parameters for the MODFLOW program. There are sixty (60) of these files.

*.BCF These files contain the input data which describes the numerical flow characteristics of the groundwater flow simulation model for the MODFLOW program. There are sixty (60) of these files.

*.WEL These files contain the input data which describes the well characteristics of the groundwater flow simulation model for the MODFLOW program. There are sixty (60) of these files.

*.CON These files contain the formatted output data which describe the predicted groundwater surface elevations at the end of each planning period. This data is output from the POSTMOD program. There are sixty (60) of these files.

*.BIN These files contain the unformatted output data which describes the predicted groundwater surface elevations at the end of each planning period. This data is output from the MODFLOW program. There are sixty (60) of these files.

*.RCH These files contain the input data which describes the recharge characteristics of the groundwater flow simulation model for the MODFLOW model. There are sixty (60) of these files.

*.SIP These files contain the solution parameters to be utilized during the finite difference solution of the MODFLOW program. There are sixty (60) of these files.

*.OC These files contain the output control parameters to be utilized by the MODFLOW program. There are sixty (60) of these files.

APPENDIX B

LINKED OPTIMIZATION-SIMULATION AQUIFER MANAGEMENT MODEL

Model Application

Summary of Output

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	31	1223.85	23.10
AMES-2	31	1199.29	42.54
AMES-3	0	1191.91	39.75
AMES-4	0	1179.38	33.86
AMES-5	0	1179.38	36.23
AMES-6	0	1195.16	42.92
AMES-7	21.6	1188.05	31.43
AMES-8	0	1195.16	37.31
AMES-9	3.8	1200.92	36.41
AMES-10	0	1162.43	30.76
AMES-11	2.6	1191.91	39.29
AMES-12	0	1195.04	39.56
AMES-13	20.9	1205.42	18.89
AMES-14	0	1220.68	21.90
AMES-15	2.5	1224.30	21.54
AMES-16	31	1223.53	18.51
AMES-17	31	1225.16	16.67
AMES-18	2.1	1219.09	26.47
AMES-19	1.7	1221.97	24.03
AMES-20	3.8	1203.11	45.54
AMES-21	0	1198.05	37.94
AMES-22	0	1199.90	41.43
AMES-23	9.9	1194.64	35.88
AMES-24	0	1195.86	46.97
AMES-25	0	1202.45	11.61
AMES-26	1.6	1202.45	13.71
AMES-27	0	1195.86	40.59
AMES-28	0	1190.69	32.92
AMES-29	5.6	1184.13	28.55
AMES-30	0	1195.86	38.85
AMES-31	0	1199.90	39.20
AMES-32	0	1199.90	40.56
AMES-33	0	1203.11	44.97
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1348.96	28.98
CARRIER-12	0	1347.57	34.29

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1349.14	35.57
CARRIER-15	0	1348.45	33.72
CARRIER-16	0	1348.96	50.98
CLEO SPRINGS-1	0	1250.39	2.36
CLEO SPRINGS-2	0	1250.39	4.90
CLEO SPRINGS-3	0	1254.23	9.84
CLEO SPRINGS-4	31	1250.00	8.07
CLEO SPRINGS-5	0	1250.99	5.27
CLEO SPRINGS-6	0	1250.99	7.65
CLEO SPRINGS-7	31	1242.92	-0.86
CLEO SPRINGS-8	0	1249.83	7.49
CLEO SPRINGS-9	0	1251.54	1.44
CLEO SPRINGS-10	0	1247.74	8.48
CLEO SPRINGS-11	31	1247.67	7.16
CLEO SPRINGS-12	0	1247.67	4.49
CLEO SPRINGS-13	31	1242.65	7.36
CLEO SPRINGS-14	31	1242.65	5.35
CLEO SPRINGS-15	31	1244.44	6.06
CLEO SPRINGS-16	0	1244.44	6.69
CLEO SPRINGS-17	0	1242.29	7.15
CLEO SPRINGS-18	31	1241.34	7.18
CLEO SPRINGS-19	0	1239.94	8.14
CLEO SPRINGS-20	31	1237.94	7.13
CLEO SPRINGS-21	31	1231.80	5.42
CLEO SPRINGS-22	31	1232.60	4.41
CLEO SPRINGS-23	31	1231.80	3.44
CLEO SPRINGS-24	0	1233.02	3.53
CLEO SPRINGS-25	31	1231.80	5.53
CLEO SPRINGS-26	0	1232.60	7.32
CLEO SPRINGS-27	31	1230.00	6.08
CLEO SPRINGS-28	31	1230.00	6.34
CLEO SPRINGS-29	31	1222.82	-0.64
CLEO SPRINGS-30	31	1222.82	4.34
CLEO SPRINGS-31	31	1224.06	6.95
DRUMMOND-1	0	1238.30	39.15
DRUMMOND-2	2.6	1231.41	35.47
DRUMMOND-3	0	1228.49	34.18

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1228.49	34.18
DRUMMOND-5	0	1219.61	29.42
DRUMMOND-6	0	1220.60	30.13
DRUMMOND-7	0	1214.53	27.10
DRUMMOND-8	0	1219.61	29.42
DRUMMOND-9	0	1211.02	23.59
DRUMMOND-10	31	1211.02	23.59
DRUMMOND-11	0	1208.02	23.99
DRUMMOND-12	0	1231.12	35.50
DRUMMOND-13	0	1200.32	20.16
DRUMMOND-14	7.1	1231.41	35.47
DRUMMOND-15	0.8	1228.20	34.02
DRUMMOND-17	0	1208.44	24.22
DRUMMOND-18	0	1211.81	25.89
DRUMMOND-19	0	1214.82	27.04
DRUMMOND-20	31	1215.69	25.42
DRUMMOND-21	31	1217.84	26.34
DRUMMOND-22	0	1225.09	32.33
DRUMMOND-23	0	1229.54	34.76
DRUMMOND-25	31	1223.36	30.16
DRUMMOND-26	1.6	1234.16	36.82
DRUMMOND-27	31	1233.05	34.47
DRUMMOND-28	0	1240.33	39.99
DRUMMOND-29	0	1245.56	42.77
DRUMMOND-31	0	1237.69	38.80
DRUMMOND-32	0	1242.35	41.17
DRUMMOND-33	0	1240.26	40.13
NORTHWEST-1	0	1339.69	26.34
NORTHWEST-2	6.6	1345.30	31.63
NORTHWEST-3	0	1342.93	34.96
NORTHWEST-6	1.9	1326.66	28.82
NORTHWEST-7	3.4	1333.68	31.32
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.6	1348.36	35.65
NORTHWEST-10	3.6	1339.02	26.99
PLANT-1	31	1275.43	24.61

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.14	20.32
PLANT-4	0	1271.14	22.57
RINGWOOD-1	0	1245.15	5.58
RINGWOOD-2	0	1243.85	6.82
RINGWOOD-3	31	1243.85	9.29
RINGWOOD-4	0	1245.05	14.52
RINGWOOD-5	0	1239.71	3.93
RINGWOOD-6	0	1240.14	8.86
RINGWOOD-7	0	1240.14	11.04
RINGWOOD-8	0	1240.55	13.89
RINGWOOD-9	0	1240.34	11.09
RINGWOOD-10	23.4	1239.71	9.92
RINGWOOD-11	0	1240.14	9.77
RINGWOOD-12	31	1232.78	3.38
RINGWOOD-13	0	1232.78	4.65
RINGWOOD-14	0	1240.34	9.19
RINGWOOD-15	31	1231.67	4.87
RINGWOOD-16	31	1323.35	1.65
RINGWOOD-17	0	1232.35	3.91
RINGWOOD-18	0	1232.78	4.38
RINGWOOD-19	0	1233.95	5.97
RINGWOOD-20	0	1233.95	6.39
RINGWOOD-21	0	1231.42	5.59
RINGWOOD-22	0	1225.75	-0.76
RINGWOOD-23	0	1226.22	0.56
RINGWOOD-24	0	1226.22	1.17
RINGWOOD-25	0	1197.16	17.86
RINGWOOD-26	0	1195.41	16.91
RINGWOOD-27	31	1186.04	11.10
RINGWOOD-28	0	1186.92	15.15
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	28	1222.98	22.23
AMES-2	28	1198.61	41.86
AMES-3	0	1191.61	39.45
AMES-4	0	1179.30	33.78
AMES-5	0	1179.30	36.15
AMES-6	0	1194.97	42.73
AMES-7	19.5	1187.83	31.21
AMES-8	0	1194.97	37.12
AMES-9	3.5	1200.75	36.24
AMES-10	0	1162.42	30.75
AMES-11	2.4	1191.61	38.99
AMES-12	0	1194.67	39.19
AMES-13	18.9	1204.81	18.28
AMES-14	0	1220.58	21.80
AMES-15	2.2	1223.97	21.21
AMES-16	28	1222.65	17.63
AMES-17	28	1224.39	15.90
AMES-18	1.9	1219.88	27.26
AMES-19	1.5	1221.81	23.88
AMES-20	3.5	1202.99	45.42
AMES-21	0	1197.92	37.81
AMES-22	0	1199.81	41.34
AMES-23	8.9	1194.52	35.76
AMES-24	0	1195.81	46.92
AMES-25	0	1202.37	11.53
AMES-26	1.4	1202.37	13.63
AMES-27	0	1195.81	40.54
AMES-28	0	1190.63	32.86
AMES-29	5.1	1183.97	28.39
AMES-30	0	1195.81	38.80
AMES-31	0	1199.81	39.11
AMES-32	0	1199.81	40.47
AMES-33	0	1202.99	44.85
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1348.96	28.98
CARRIER-12	0	1347.57	34.29

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - FEBRUARY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1349.13	35.56
CARRIER-15	0	1348.45	33.72
CARRIER-16	0	1348.96	50.98
CLEO SPRINGS-1	0	1250.14	2.10
CLEO SPRINGS-2	0	1250.14	4.65
CLEO SPRINGS-3	0	1254.03	9.64
CLEO SPRINGS-4	28	1249.46	7.53
CLEO SPRINGS-5	0	1250.60	4.87
CLEO SPRINGS-6	0	1250.60	7.25
CLEO SPRINGS-7	0	1244.58	0.80
CLEO SPRINGS-8	0	1249.50	7.16
CLEO SPRINGS-9	0	1250.96	0.86
CLEO SPRINGS-10	0	1246.98	7.72
CLEO SPRINGS-11	28	1246.57	6.06
CLEO SPRINGS-12	0	1246.57	3.39
CLEO SPRINGS-13	28	1241.15	5.86
CLEO SPRINGS-14	28	1241.15	3.85
CLEO SPRINGS-15	28	1243.13	4.75
CLEO SPRINGS-16	0	1243.13	5.38
CLEO SPRINGS-17	0	1241.10	5.96
CLEO SPRINGS-18	28	1239.92	5.76
CLEO SPRINGS-19	0	1238.86	7.06
CLEO SPRINGS-20	28	1236.18	5.37
CLEO SPRINGS-21	28	1228.94	2.56
CLEO SPRINGS-22	28	1230.65	2.45
CLEO SPRINGS-23	28	1228.94	0.58
CLEO SPRINGS-24	0	1231.51	2.02
CLEO SPRINGS-25	28	1228.94	2.67
CLEO SPRINGS-26	0	1230.65	5.37
CLEO SPRINGS-27	28	1228.21	4.29
CLEO SPRINGS-28	28	1228.21	4.55
CLEO SPRINGS-29	0	1223.53	0.07
CLEO SPRINGS-30	28	1223.53	5.05
CLEO SPRINGS-31	28	1222.98	5.87
DRUMMOND-1	0	1238.30	39.15
DRUMMOND-2	2.4	1231.12	35.18
DRUMMOND-3	0	1228.26	33.95

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - FEBRUARY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1228.26	33.95
DRUMMOND-5	0	1218.36	28.18
DRUMMOND-6	0	1219.98	29.51
DRUMMOND-7	0	1213.96	26.53
DRUMMOND-8	0	1218.36	28.18
DRUMMOND-9	0	1208.73	21.30
DRUMMOND-10	28	1208.73	21.30
DRUMMOND-11	0	1207.87	23.84
DRUMMOND-12	0	1231.00	35.38
DRUMMOND-13	0	1200.30	20.14
DRUMMOND-14	6.4	1231.12	35.18
DRUMMOND-15	0.7	1228.02	33.83
DRUMMOND-17	0	1208.42	24.20
DRUMMOND-18	0	1211.71	25.79
DRUMMOND-19	28	1210.56	22.78
DRUMMOND-20	28	1212.83	22.56
DRUMMOND-21	28	1215.22	23.72
DRUMMOND-22	0	1224.44	31.68
DRUMMOND-23	0	1229.45	34.67
DRUMMOND-25	28	1221.76	28.61
DRUMMOND-26	1.4	1233.47	36.13
DRUMMOND-27	28	1230.98	32.40
DRUMMOND-28	0	1239.82	39.48
DRUMMOND-29	0	1245.49	42.70
DRUMMOND-31	0	1237.51	38.62
DRUMMOND-32	0	1242.35	41.17
DRUMMOND-33	0	1240.23	40.10
NORTHWEST-1	0	1339.69	26.34
NORTHWEST-2	5.9	1345.28	31.61
NORTHWEST-3	0	1342.93	34.96
NORTHWEST-6	1.8	1326.64	28.80
NORTHWEST-7	3.1	1333.67	31.31
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.1	1348.31	35.60
NORTHWEST-10	3.2	1338.99	26.96
PLANT-1	28	1275.26	24.44

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - FEBRUARY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.13	20.31
PLANT-4	0	1271.13	22.56
RINGWOOD-1	0	1244.61	5.04
RINGWOOD-2	0	1242.84	5.81
RINGWOOD-3	28	1242.84	8.28
RINGWOOD-4	0	1244.31	13.78
RINGWOOD-5	0	1237.98	2.20
RINGWOOD-6	0	1237.50	6.22
RINGWOOD-7	0	1237.50	8.40
RINGWOOD-8	28	1238.11	11.45
RINGWOOD-9	0	1239.72	10.47
RINGWOOD-10	28	1239.98	8.19
RINGWOOD-11	24.9	1237.50	7.13
RINGWOOD-12	28	1231.37	1.97
RINGWOOD-13	0	1231.37	3.24
RINGWOOD-14	0	1239.72	8.57
RINGWOOD-15	0	1232.23	5.43
RINGWOOD-16	0	1230.84	0.14
RINGWOOD-17	28	1230.84	2.40
RINGWOOD-18	0	1231.37	2.97
RINGWOOD-19	0	1233.43	5.45
RINGWOOD-20	0	1233.43	5.87
RINGWOOD-21	0	1231.38	5.85
RINGWOOD-22	0	1224.94	-1.57
RINGWOOD-23	0	1225.52	-0.14
RINGWOOD-24	0	1225.52	0.47
RINGWOOD-25	0	1197.00	17.70
RINGWOOD-26	0	1195.20	16.70
RINGWOOD-27	28	1185.78	10.84
RINGWOOD-28	0	1186.83	15.06
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - FEBRUARY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	31	1222.34	21.59
AMES-2	31	1198.13	41.38
AMES-3	0	1191.35	39.19
AMES-4	0	1179.19	33.67
AMES-5	0	1179.19	36.04
AMES-6	0	1194.75	42.51
AMES-7	21.6	1187.67	31.05
AMES-8	0	1194.75	36.90
AMES-9	3.8	1200.59	36.08
AMES-10	0	1162.40	30.73
AMES-11	2.6	1191.35	38.73
AMES-12	0	1194.31	38.83
AMES-13	20.9	1204.37	17.84
AMES-14	0	1220.43	21.65
AMES-15	2.5	1223.69	20.93
AMES-16	31	1221.97	16.95
AMES-17	31	1223.81	15.32
AMES-18	2.1	1220.13	27.51
AMES-19	1.7	1221.69	23.75
AMES-20	3.8	1202.90	45.33
AMES-21	0	1197.79	37.68
AMES-22	0	1199.73	41.26
AMES-23	9.9	1194.42	35.66
AMES-24	0	1195.75	46.86
AMES-25	0	1202.32	11.48
AMES-26	1.6	1202.32	13.58
AMES-27	0	1195.75	40.48
AMES-28	0	1190.56	32.79
AMES-29	5.6	1183.91	28.33
AMES-30	0	1195.75	38.74
AMES-31	0	1199.73	39.03
AMES-32	0	1199.73	40.39
AMES-33	0	1202.90	44.76
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1348.96	28.98
CARRIER-12	0	1347.57	34.29

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - MARCH 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1349.13	35.56
CARRIER-15	0	1348.45	33.72
CARRIER-16	0	1348.96	50.98
CLEO SPRINGS-1	0	1249.94	1.91
CLEO SPRINGS-2	0	1249.94	4.45
CLEO SPRINGS-3	0	1253.80	9.41
CLEO SPRINGS-4	31	1249.12	7.19
CLEO SPRINGS-5	0	1250.32	4.59
CLEO SPRINGS-6	0	1250.32	6.97
CLEO SPRINGS-7	0	1244.90	1.12
CLEO SPRINGS-8	0	1249.25	6.91
CLEO SPRINGS-9	0	1250.40	0.30
CLEO SPRINGS-10	0	1246.39	7.13
CLEO SPRINGS-11	31	1245.43	4.92
CLEO SPRINGS-12	0	1245.43	2.25
CLEO SPRINGS-13	31	1239.93	4.64
CLEO SPRINGS-14	31	1239.93	2.63
CLEO SPRINGS-15	31	1240.72	2.34
CLEO SPRINGS-16	28.8	1240.72	2.97
CLEO SPRINGS-17	0	1239.74	4.60
CLEO SPRINGS-18	31	1238.34	4.18
CLEO SPRINGS-19	0	1237.66	5.86
CLEO SPRINGS-20	31	1234.63	3.81
CLEO SPRINGS-21	31	1226.38	0.00
CLEO SPRINGS-22	31	1228.93	0.73
CLEO SPRINGS-23	31	1226.38	-1.98
CLEO SPRINGS-24	0	1230.15	0.66
CLEO SPRINGS-25	31	1226.38	0.11
CLEO SPRINGS-26	0	1228.93	3.65
CLEO SPRINGS-27	31	1226.66	2.74
CLEO SPRINGS-28	31	1226.66	3.00
CLEO SPRINGS-29	0	1223.10	-0.36
CLEO SPRINGS-30	31	1223.10	4.62
CLEO SPRINGS-31	31	1222.11	5.01
DRUMMOND-1	0	1238.30	39.15
DRUMMOND-2	2.6	1230.88	34.94
DRUMMOND-3	0	1227.90	33.59

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - MARCH 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1227.90	33.59
DRUMMOND-5	0	1216.89	26.70
DRUMMOND-6	0	1219.17	28.70
DRUMMOND-7	0	1213.24	25.81
DRUMMOND-8	0	1216.89	26.70
DRUMMOND-9	0	1206.94	19.51
DRUMMOND-10	31	1206.94	19.51
DRUMMOND-11	0	1207.61	23.58
DRUMMOND-12	0	1230.86	35.24
DRUMMOND-13	0	1200.24	20.08
DRUMMOND-14	7.1	1230.88	34.94
DRUMMOND-15	0.8	1227.78	33.59
DRUMMOND-17	0	1208.36	24.14
DRUMMOND-18	31	1211.44	25.52
DRUMMOND-19	31	1210.75	22.97
DRUMMOND-20	31	1210.61	20.34
DRUMMOND-21	31	1213.32	21.82
DRUMMOND-22	0	1223.73	30.97
DRUMMOND-23	0	1229.30	34.52
DRUMMOND-25	31	1220.56	27.42
DRUMMOND-26	1.6	1232.74	35.40
DRUMMOND-27	31	1229.52	30.94
DRUMMOND-28	0	1239.25	38.91
DRUMMOND-29	0	1245.37	42.58
DRUMMOND-31	0	1237.21	38.32
DRUMMOND-32	0	1242.33	41.15
DRUMMOND-33	0	1240.16	40.03
NORTHWEST-1	0	1339.69	26.34
NORTHWEST-2	6.6	1335.26	31.59
NORTHWEST-3	0	1342.92	34.95
NORTHWEST-6	1.9	1326.63	28.79
NORTHWEST-7	3.4	1333.65	31.29
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.6	1348.27	35.56
NORTHWEST-10	3.6	1338.97	26.94
PLANT-1	31	1275.09	24.27

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - MARCH 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.12	20.30
PLANT-4	0	1271.12	22.55
RINGWOOD-1	0	1244.04	4.47
RINGWOOD-2	0	1241.94	4.91
RINGWOOD-3	31	1241.94	7.38
RINGWOOD-4	0	1243.60	13.07
RINGWOOD-5	0	1236.90	1.12
RINGWOOD-6	0	1235.90	4.62
RINGWOOD-7	0	1235.90	6.80
RINGWOOD-8	31	1236.84	10.18
RINGWOOD-9	0	1239.06	9.81
RINGWOOD-10	31	1236.90	7.11
RINGWOOD-11	31	1235.90	5.53
RINGWOOD-12	31	1230.38	0.98
RINGWOOD-13	0	1230.38	2.25
RINGWOOD-14	0	1239.06	7.91
RINGWOOD-15	0	1232.03	5.23
RINGWOOD-16	0	1231.47	0.77
RINGWOOD-17	0	1231.47	3.03
RINGWOOD-18	0	1230.38	1.98
RINGWOOD-19	0	1232.82	4.84
RINGWOOD-20	0	1232.82	5.26
RINGWOOD-21	0	1231.29	5.76
RINGWOOD-22	0	1224.51	-2.00
RINGWOOD-23	0	1224.83	-0.83
RINGWOOD-24	0	1224.83	-0.22
RINGWOOD-25	0	1196.81	17.51
RINGWOOD-26	0	1195.02	16.52
RINGWOOD-27	31	1185.62	10.68
RINGWOOD-28	0	1186.74	14.97
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - MARCH 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	30	1221.89	21.14
AMES-2	30	1197.78	41.03
AMES-3	0	1191.10	38.94
AMES-4	0	1179.09	33.57
AMES-5	0	1179.09	35.94
AMES-6	0	1194.56	42.32
AMES-7	20.9	1187.51	30.89
AMES-8	0	1194.56	36.71
AMES-9	3.7	1200.42	35.91
AMES-10	0	1162.37	30.70
AMES-11	2.5	1191.10	38.48
AMES-12	0	1194.02	38.54
AMES-13	20.2	1203.99	17.46
AMES-14	0	1220.28	21.50
AMES-15	2.4	1223.44	20.68
AMES-16	30	1221.46	16.44
AMES-17	30	1223.39	14.90
AMES-18	1.9	1220.15	27.53
AMES-19	1.6	1221.58	23.64
AMES-20	3.7	1202.80	45.23
AMES-21	0	1197.67	37.56
AMES-22	0	1199.66	41.19
AMES-23	9.6	1194.33	35.57
AMES-24	0	1195.69	46.80
AMES-25	0	1202.28	11.44
AMES-26	1.5	1202.28	13.54
AMES-27	0	1195.69	40.42
AMES-28	0	1190.50	32.73
AMES-29	5.4	1183.84	28.26
AMES-30	0	1195.69	38.68
AMES-31	0	1199.66	38.96
AMES-32	0	1199.66	40.32
AMES-33	0	1202.80	44.66
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1348.96	28.98
CARRIER-12	0	1347.57	34.29

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - APRIL 1989

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                                     PREDICTED
                      PRODUCTION   GROUNDWATER    DRAWDOWN
                        PERIOD       SURFACE       BUFFER
     WELL ID NO.        (DAYS)      ELEVATION      (FEET)
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      CARRIER-13             0       1349.12         35.55
      CARRIER-15             0       1348.45         33.72
      CARRIER-16             0       1348.96         50.98
    CLEO SPRINGS-1           0       1249.47          1.44
    CLEO SPRINGS-2        13.1       1249.47          3.98
    CLEO SPRINGS-3           0       1253.56          9.17
    CLEO SPRINGS-4          30       1248.77          6.84
    CLEO SPRINGS-5           0       1249.91          4.18
    CLEO SPRINGS-6           0       1249.91          6.56
    CLEO SPRINGS-7           0       1244.65          0.87
    CLEO SPRINGS-8          30       1247.88          5.54
    CLEO SPRINGS-9           0       1249.86         -0.24
   CLEO SPRINGS-10           0       1245.70          6.44
   CLEO SPRINGS-11          30       1244.52          4.01
   CLEO SPRINGS-12           0       1244.52          1.34
   CLEO SPRINGS-13          30       1238.85          3.56
   CLEO SPRINGS-14          30       1238.85          1.55
   CLEO SPRINGS-15          30       1239.10          0.72
   CLEO SPRINGS-16          30       1239.10          1.35
   CLEO SPRINGS-17           0       1238.40          3.26
   CLEO SPRINGS-18          30       1236.82          2.66
   CLEO SPRINGS-19          30       1235.22          3.42
   CLEO SPRINGS-20          30       1233.28          2.47
   CLEO SPRINGS-21          30       1223.91         -2.47
   CLEO SPRINGS-22          30       1227.45         -0.75
   CLEO SPRINGS-23           0       1223.91         -4.45
   CLEO SPRINGS-24           0       1229.05         -0.44
   CLEO SPRINGS-25          30       1223.91         -2.36
   CLEO SPRINGS-26           0       1227.45          2.17
   CLEO SPRINGS-27          30       1225.39          1.47
   CLEO SPRINGS-28          30       1225.39          1.73
   CLEO SPRINGS-29           0       1222.47         -0.99
   CLEO SPRINGS-30          30       1222.47          3.99
   CLEO SPRINGS-31          30       1221.41          4.30
      DRUMMOND-1             0       1238.29         39.14
      DRUMMOND-2           2.6       1230.66         34.72
      DRUMMOND-3             0       1227.49         33.18

      LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
                     SUMMARY REPORT - APRIL 1989
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1227.49	33.18
DRUMMOND-5	0	1215.57	25.39
DRUMMOND-6	0	1218.35	27.88
DRUMMOND-7	0	1212.56	25.13
DRUMMOND-8	0	1215.57	25.39
DRUMMOND-9	0	1205.72	18.29
DRUMMOND-10	30	1205.72	18.29
DRUMMOND-11	0	1207.29	23.26
DRUMMOND-12	0	1230.72	35.10
DRUMMOND-13	0	1200.15	19.99
DRUMMOND-14	6.9	1230.66	34.72
DRUMMOND-15	0.8	1227.47	33.28
DRUMMOND-17	0	1208.26	24.04
DRUMMOND-18	30	1211.10	25.18
DRUMMOND-19	30	1210.26	22.47
DRUMMOND-20	30	1209.08	18.81
DRUMMOND-21	30	1211.98	20.48
DRUMMOND-22	0	1223.09	30.33
DRUMMOND-23	0	1229.13	34.35
DRUMMOND-25	30	1219.63	26.49
DRUMMOND-26	1.5	1232.08	34.74
DRUMMOND-27	30	1228.53	29.95
DRUMMOND-28	0	1238.75	38.41
DRUMMOND-29	0	1245.23	42.44
DRUMMOND-31	0	1236.88	37.99
DRUMMOND-32	0	1242.31	41.13
DRUMMOND-33	0	1240.06	39.93
NORTHWEST-1	0	1339.69	26.34
NORTHWEST-2	6.4	1345.24	31.57
NORTHWEST-3	0	1342.92	34.95
NORTHWEST-6	1.9	1326.62	28.78
NORTHWEST-7	3.3	1333.63	31.27
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.5	1348.22	35.52
NORTHWEST-10	3.4	1338.94	26.91
PLANT-1	30	1274.94	24.12

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - APRIL 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.10	20.28
PLANT-4	0	1271.10	22.53
RINGWOOD-1	0	1243.63	4.06
RINGWOOD-2	0	1241.31	4.28
RINGWOOD-3	30	1241.31	6.75
RINGWOOD-4	0	1243.02	12.49
RINGWOOD-5	0	1236.20	0.42
RINGWOOD-6	0	1234.97	3.69
RINGWOOD-7	0	1237.97	5.87
RINGWOOD-8	30	1235.67	9.01
RINGWOOD-9	30	1237.37	8.12
RINGWOOD-10	30	1236.20	6.41
RINGWOOD-11	30	1234.97	4.60
RINGWOOD-12	30	1227.96	-1.44
RINGWOOD-13	30	1227.96	-0.17
RINGWOOD-14	0	1237.37	6.22
RINGWOOD-15	0	1231.71	4.91
RINGWOOD-16	0	1230.89	0.19
RINGWOOD-17	0	1230.89	2.45
RINGWOOD-18	0	1227.96	-0.44
RINGWOOD-19	0	1231.89	3.91
RINGWOOD-20	0	1231.89	4.33
RINGWOOD-21	0	1231.16	5.63
RINGWOOD-22	0	1224.15	-2.36
RINGWOOD-23	0	1224.04	-1.62
RINGWOOD-24	0	1224.04	-1.01
RINGWOOD-25	0	1196.60	17.30
RINGWOOD-26	0	1194.86	16.36
RINGWOOD-27	30	1185.50	10.56
RINGWOOD-28	0	1186.67	14.90
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	31	1221.51	20.76
AMES-2	31	1197.47	40.72
AMES-3	0	1190.88	38.72
AMES-4	0	1178.97	33.45
AMES-5	0	1178.97	35.82
AMES-6	0	1194.38	42.14
AMES-7	21.6	1187.34	30.72
AMES-8	0	1194.38	36.53
AMES-9	3.8	1200.26	35.75
AMES-10	0	1162.33	30.66
AMES-11	2.6	1190.88	38.26
AMES-12	0	1193.76	38.28
AMES-13	20.9	1203.73	17.20
AMES-14	0	1220.13	21.35
AMES-15	2.5	1223.23	20.47
AMES-16	31	1221.02	16.00
AMES-17	31	1223.05	14.56
AMES-18	2.1	1220.01	27.39
AMES-19	1.7	1221.48	23.54
AMES-20	3.8	1202.71	45.14
AMES-21	0	1197.56	37.45
AMES-22	0	1199.58	41.11
AMES-23	9.9	1194.25	35.49
AMES-24	0	1195.62	46.73
AMES-25	0	1202.25	11.41
AMES-26	1.6	1202.25	13.51
AMES-27	0	1195.62	40.35
AMES-28	0	1190.44	32.67
AMES-29	5.6	1183.79	28.21
AMES-30	0	1195.62	38.61
AMES-31	0	1199.58	38.88
AMES-32	0	1199.58	40.24
AMES-33	0	1202.71	44.57
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1348.68	28.70
CARRIER-12	31	1347.30	34.02

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1349.11	35.54
CARRIER-15	0	1348.44	33.71
CARRIER-16	31	1348.68	50.70
CLEO SPRINGS-1	0	1248.45	0.42
CLEO SPRINGS-2	31	1248.45	2.96
CLEO SPRINGS-3	31	1252.17	7.78
CLEO SPRINGS-4	31	1248.11	6.18
CLEO SPRINGS-5	0	1248.04	2.31
CLEO SPRINGS-6	31	1248.04	4.69
CLEO SPRINGS-7	0	1244.23	0.45
CLEO SPRINGS-8	31	1246.94	4.60
CLEO SPRINGS-9	0	1249.29	-0.81
CLEO SPRINGS-10	0	1245.00	5.74
CLEO SPRINGS-11	31	1243.69	3.18
CLEO SPRINGS-12	0	1243.69	0.51
CLEO SPRINGS-13	31	1237.77	2.48
CLEO SPRINGS-14	31	1237.77	0.47
CLEO SPRINGS-15	31	1237.84	-0.54
CLEO SPRINGS-16	31	1237.84	0.09
CLEO SPRINGS-17	0	1237.20	2.06
CLEO SPRINGS-18	31	1235.77	1.61
CLEO SPRINGS-19	31	1233.85	2.05
CLEO SPRINGS-20	0	1234.30	3.49
CLEO SPRINGS-21	0	1229.95	3.57
CLEO SPRINGS-22	0	1229.08	0.88
CLEO SPRINGS-23	0	1229.95	1.59
CLEO SPRINGS-24	0	1229.16	-0.33
CLEO SPRINGS-25	0	1229.95	3.68
CLEO SPRINGS-26	0	1229.08	3.80
CLEO SPRINGS-27	0	1227.14	3.22
CLEO SPRINGS-28	0	1227.14	3.48
CLEO SPRINGS-29	0	1221.90	-1.56
CLEO SPRINGS-30	31	1221.90	3.42
CLEO SPRINGS-31	31	1220.81	3.70
DRUMMOND-1	0	1238.28	39.13
DRUMMOND-2	2.6	1230.39	34.45
DRUMMOND-3	0	1227.01	32.70

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1227.01	32.70
DRUMMOND-5	0	1214.30	24.11
DRUMMOND-6	0	1217.24	26.77
DRUMMOND-7	31	1208.70	21.27
DRUMMOND-8	0	1214.30	24.11
DRUMMOND-9	0	1204.15	16.71
DRUMMOND-10	31	1204.15	16.71
DRUMMOND-11	31	1204.58	20.55
DRUMMOND-12	0	1230.54	34.92
DRUMMOND-13	0	119.82	19.66
DRUMMOND-14	7.1	1230.39	34.45
DRUMMOND-15	0.83	1227.09	32.91
DRUMMOND-17	0	1207.92	23.70
DRUMMOND-18	31	1206.58	20.66
DRUMMOND-19	31	1206.10	18.32
DRUMMOND-20	31	1207.49	17.22
DRUMMOND-21	31	1210.87	19.37
DRUMMOND-22	0	1222.50	29.74
DRUMMOND-23	0	1228.93	34.15
DRUMMOND-25	31	1218.75	25.61
DRUMMOND-26	1.6	1231.46	34.12
DRUMMOND-27	31	1227.73	29.15
DRUMMOND-28	0	1238.29	37.95
DRUMMOND-29	0	1245.07	42.28
DRUMMOND-31	0	1236.53	37.64
DRUMMOND-32	0	1242.28	41.10
DRUMMOND-33	0	1239.92	39.79
NORTHWEST-1	0	1339.69	26.34
NORTHWEST-2	6.6	1345.22	31.55
NORTHWEST-3	0	1342.91	34.94
NORTHWEST-6	1.9	1326.61	28.77
NORTHWEST-7	3.4	1333.61	31.26
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.6	1348.19	35.48
NORTHWEST-10	3.6	1338.92	26.89
PLANT-1	31	1274.81	23.99

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - MAY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.08	20.26
PLANT-4	0	1271.08	22.51
RINGWOOD-1	31	1241.95	2.38
RINGWOOD-2	31	1239.39	2.36
RINGWOOD-3	31	1239.39	4.83
RINGWOOD-4	0	1242.33	11.80
RINGWOOD-5	31	1236.17	0.39
RINGWOOD-6	0	1234.69	3.41
RINGWOOD-7	31	1234.69	5.59
RINGWOOD-8	31	1235.13	8.47
RINGWOOD-9	31	1236.64	7.39
RINGWOOD-10	0	1236.17	6.38
RINGWOOD-11	0	1234.69	4.32
RINGWOOD-12	0	1230.42	1.02
RINGWOOD-13	0	1230.42	2.29
RINGWOOD-14	0	1236.64	5.49
RINGWOOD-15	0	1231.46	4.66
RINGWOOD-16	0	1230.74	0.04
RINGWOOD-17	0	1230.74	2.30
RINGWOOD-18	0	1230.42	2.02
RINGWOOD-19	0	1231.49	3.51
RINGWOOD-20	0	1231.49	3.93
RINGWOOD-21	31	1229.85	4.32
RINGWOOD-22	0	1223.81	-2.70
RINGWOOD-23	0	1223.92	-1.74
RINGWOOD-24	0	1223.92	-1.13
RINGWOOD-25	31	1194.06	14.76
RINGWOOD-26	31	1192.93	14.43
RINGWOOD-27	31	1184.82	9.88
RINGWOOD-28	0	1186.55	14.78
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.38
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - MAY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	30	1221.20	20.45
AMES-2	30	1197.20	40.45
AMES-3	0	1190.68	38.52
AMES-4	0	1178.86	33.34
AMES-5	0	1178.86	35.71
AMES-6	0	1194.20	41.96
AMES-7	20.9	1187.19	30.57
AMES-8	0	1194.20	36.35
AMES-9	3.7	1200.10	35.59
AMES-10	0	1162.29	30.61
AMES-11	2.5	1190.68	38.06
AMES-12	0	1193.53	38.05
AMES-13	20.2	1203.44	16.91
AMES-14	0	1220.00	21.22
AMES-15	2.4	1223.06	20.30
AMES-16	30	1220.66	15.64
AMES-17	30	1222.77	14.28
AMES-18	1.9	1219.90	27.28
AMES-19	1.6	1221.39	23.45
AMES-20	3.7	1202.61	45.04
AMES-21	0	1197.44	37.33
AMES-22	0	1199.50	41.03
AMES-23	9.6	1194.16	35.40
AMES-24	0	1195.56	46.67
AMES-25	0	1202.21	11.37
AMES-26	1.5	1202.21	13.47
AMES-27	0	1195.56	40.29
AMES-28	0	1190.39	32.62
AMES-29	5.4	1183.73	28.15
AMES-30	0	1195.56	38.55
AMES-31	0	1199.50	38.80
AMES-32	0	1199.50	40.16
AMES-33	0	1202.61	44.47
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1248.45	28.47
CARRIER-12	30	1347.07	33.79

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1349.10	35.53
CARRIER-15	0	1348.43	33.70
CARRIER-16	30	1348.45	50.47
CLEO SPRINGS-1	0	1247.97	-0.06
CLEO SPRINGS-2	30	1247.97	2.48
CLEO SPRINGS-3	30	1251.45	7.06
CLEO SPRINGS-4	30	1247.41	5.48
CLEO SPRINGS-5	0	1247.06	1.33
CLEO SPRINGS-6	30	1247.06	3.71
CLEO SPRINGS-7	0	1243.78	-0.01
CLEO SPRINGS-8	30	1246.15	3.81
CLEO SPRINGS-9	0	1248.74	-1.36
CLEO SPRINGS-10	0	1244.36	5.10
CLEO SPRINGS-11	30	1243.01	2.50
CLEO SPRINGS-12	0	1243.01	-0.17
CLEO SPRINGS-13	30	1236.81	1.52
CLEO SPRINGS-14	30	1236.81	-0.49
CLEO SPRINGS-15	30	1237.19	-1.19
CLEO SPRINGS-16	30	1237.19	-0.56
CLEO SPRINGS-17	0	1236.34	1.20
CLEO SPRINGS-18	0	1237.00	2.84
CLEO SPRINGS-19	30	1233.33	1.53
CLEO SPRINGS-20	0	1235.03	4.22
CLEO SPRINGS-21	0	1232.14	5.76
CLEO SPRINGS-22	0	1230.11	1.91
CLEO SPRINGS-23	0	1232.14	3.78
CLEO SPRINGS-24	0	1229.88	0.39
CLEO SPRINGS-25	0	1232.14	5.87
CLEO SPRINGS-26	0	1230.11	4.83
CLEO SPRINGS-27	0	1227.86	3.94
CLEO SPRINGS-28	0	1227.86	4.20
CLEO SPRINGS-29	0	1221.59	-1.87
CLEO SPRINGS-30	30	1221.59	3.11
CLEO SPRINGS-31	30	1220.41	3.30
DRUMMOND-1	0	1238.27	39.12
DRUMMOND-2	2.6	1230.13	34.19
DRUMMOND-3	0	1226.51	32.20

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1226.51	32.20
DRUMMOND-5	0	1213.01	22.82
DRUMMOND-6	0	1215.99	25.52
DRUMMOND-7	30	1206.17	18.74
DRUMMOND-8	0	1213.01	22.82
DRUMMOND-9	0	1202.33	14.90
DRUMMOND-10	30	1202.33	14.90
DRUMMOND-11	30	1202.69	18.66
DRUMMOND-12	0	1230.35	34.73
DRUMMOND-13	0	1199.32	19.16
DRUMMOND-14	6.9	1230.13	34.19
DRUMMOND-15	0.8	1226.69	32.50
DRUMMOND-17	0	1207.36	23.15
DRUMMOND-18	30	1203.93	18.01
DRUMMOND-19	30	1203.37	15.59
DRUMMOND-20	30	1205.88	15.61
DRUMMOND-21	30	1209.94	18.44
DRUMMOND-22	0	1221.97	29.21
DRUMMOND-23	0	1228.73	33.95
DRUMMOND-25	30	1217.91	24.77
DRUMMOND-26	1.5	1230.89	33.55
DRUMMOND-27	30	1227.10	28.52
DRUMMOND-28	0	1237.89	37.55
DRUMMOND-29	0	1244.92	42.13
DRUMMOND-31	0	1236.19	37.30
DRUMMOND-32	0	1242.23	41.05
DRUMMOND-33	0	1239.78	39.65
NORTHWEST-1	0	1339.69	26.34
NORTHWEST-2	6.4	1345.20	31.53
NORTHWEST-3	0	1342.90	34.93
NORTHWEST-6	1.9	1326.59	28.76
NORTHWEST-7	3.3	1333.60	31.24
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.5	1348.16	35.45
NORTHWEST-10	3.4	1338.91	26.88
PLANT-1	30	1274.69	23.87

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - JUNE 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.06	20.24
PLANT-4	0	1271.06	22.49
RINGWOOD-1	30	1241.22	1.65
RINGWOOD-2	30	1238.49	1.46
RINGWOOD-3	30	1238.49	3.93
RINGWOOD-4	0	1241.85	11.32
RINGWOOD-5	30	1235.79	0.01
RINGWOOD-6	0	1234.21	2.93
RINGWOOD-7	30	1234.21	5.11
RINGWOOD-8	30	1234.81	8.15
RINGWOOD-9	30	1236.24	6.99
RINGWOOD-10	0	1235.79	6.00
RINGWOOD-11	0	1234.21	3.84
RINGWOOD-12	0	1230.81	1.41
RINGWOOD-13	0	1230.81	2.68
RINGWOOD-14	0	1236.24	5.09
RINGWOOD-15	0	1231.29	4.49
RINGWOOD-16	0	1230.72	0.02
RINGWOOD-17	0	1230.72	2.28
RINGWOOD-18	0	1230.81	2.41
RINGWOOD-19	0	1231.33	3.35
RINGWOOD-20	0	1231.33	3.77
RINGWOOD-21	30	1229.31	3.78
RINGWOOD-22	0	1223.71	-2.80
RINGWOOD-23	0	1224.03	-1.63
RINGWOOD-24	0	1224.03	-1.02
RINGWOOD-25	30	1192.82	13.52
RINGWOOD-26	30	1191.98	13.48
RINGWOOD-27	30	1184.09	9.16
RINGWOOD-28	26.6	1185.00	13.23
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - JUNE 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	31	1220.92	20.17
AMES-2	31	1196.95	40.20
AMES-3	0	1190.49	38.33
AMES-4	0	1178.74	33.22
AMES-5	0	1178.74	35.59
AMES-6	0	1194.03	41.79
AMES-7	21.6	1187.04	30.42
AMES-8	0	1194.03	36.18
AMES-9	3.8	1199.90	35.39
AMES-10	0	1162.23	30.56
AMES-11	2.6	1190.49	37.87
AMES-12	0	1193.31	37.83
AMES-13	20.9	1203.25	16.72
AMES-14	0	1219.86	21.08
AMES-15	2.5	1222.90	20.14
AMES-16	31	1220.32	15.30
AMES-17	31	1222.51	14.02
AMES-18	2.1	1219.71	27.09
AMES-19	1.7	1221.30	23.36
AMES-20	30.3	1200.67	43.10
AMES-21	0	1197.05	36.94
AMES-22	0	1199.16	40.69
AMES-23	9.9	1194.02	35.26
AMES-24	0	1195.45	46.56
AMES-25	0	1202.18	11.34
AMES-26	1.6	1202.18	13.44
AMES-27	0	1195.45	40.18
AMES-28	0	1190.19	32.42
AMES-29	31	1182.13	26.55
AMES-30	0	1195.45	38.44
AMES-31	0	1199.16	38.46
AMES-32	0	1199.16	39.82
AMES-33	0	1200.67	42.53
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	31	1348.05	28.07
CARRIER-12	31	1346.87	33.59

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - JULY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	31	1348.89	35.32
CARRIER-15	0	1348.40	33.67
CARRIER-16	31	1348.05	50.07
CLEO SPRINGS-1	31	1247.90	-0.13
CLEO SPRINGS-2	31	1247.90	2.41
CLEO SPRINGS-3	31	1251.95	7.56
CLEO SPRINGS-4	31	1247.73	5.80
CLEO SPRINGS-5	31	1246.88	1.15
CLEO SPRINGS-6	31	1246.88	3.53
CLEO SPRINGS-7	0	1243.44	-0.34
CLEO SPRINGS-8	31	1246.11	3.77
CLEO SPRINGS-9	0	1248.40	-1.70
CLEO SPRINGS-10	31	1243.74	4.48
CLEO SPRINGS-11	31	1243.33	2.82
CLEO SPRINGS-12	31	1243.33	0.15
CLEO SPRINGS-13	31	1237.95	2.66
CLEO SPRINGS-14	31	1237.95	0.65
CLEO SPRINGS-15	0	1240.49	2.11
CLEO SPRINGS-16	0	1240.49	2.74
CLEO SPRINGS-17	0	1236.77	1.63
CLEO SPRINGS-18	0	1237.92	3.76
CLEO SPRINGS-19	31	1233.94	2.14
CLEO SPRINGS-20	0	1235.65	4.83
CLEO SPRINGS-21	0	1233.06	6.68
CLEO SPRINGS-22	0	1230.75	2.55
CLEO SPRINGS-23	0	1233.06	4.70
CLEO SPRINGS-24	0	1230.41	0.92
CLEO SPRINGS-25	0	1233.06	6.79
CLEO SPRINGS-26	0	1230.75	5.47
CLEO SPRINGS-27	0	1228.35	4.43
CLEO SPRINGS-28	0	1228.35	4.69
CLEO SPRINGS-29	0	1222.23	-1.23
CLEO SPRINGS-30	31	1222.23	3.75
CLEO SPRINGS-31	31	1221.14	4.03
DRUMMOND-1	0	1238.26	39.11
DRUMMOND-2	2.6	1229.70	33.76
DRUMMOND-3	0	1225.94	31.63

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1225.94	31.63
DRUMMOND-5	0	1209.63	19.44
DRUMMOND-6	0	1214.54	24.07
DRUMMOND-7	31	1204.17	16.74
DRUMMOND-8	31	1209.63	19.44
DRUMMOND-9	0	1200.32	12.89
DRUMMOND-10	31	1200.32	12.89
DRUMMOND-11	31	1201.15	17.12
DRUMMOND-12	31	1228.80	33.18
DRUMMOND-13	0	1198.77	18.60
DRUMMOND-14	7.1	1229.70	33.76
DRUMMOND-15	0.82	1226.12	31.93
DRUMMOND-17	0	1206.72	22.50
DRUMMOND-18	31	1201.95	16.03
DRUMMOND-19	31	1201.10	13.32
DRUMMOND-20	31	1204.13	13.86
DRUMMOND-21	31	1209.04	17.54
DRUMMOND-22	0	1221.46	28.70
DRUMMOND-23	0	1228.53	33.75
DRUMMOND-25	31	1217.02	23.88
DRUMMOND-26	1.6	1230.35	33.01
DRUMMOND-27	31	1226.52	27.94
DRUMMOND-28	0	1237.50	37.16
DRUMMOND-29	0	1244.76	41.96
DRUMMOND-31	0	1235.81	36.92
DRUMMOND-32	31	1237.30	36.12
DRUMMOND-33	0	1239.18	39.05
NORTHWEST-1	0	1339.69	26.34
NORTHWEST-2	6.6	1345.19	31.52
NORTHWEST-3	0	1342.89	34.92
NORTHWEST-6	1.9	1326.58	28.74
NORTHWEST-7	3.4	1333.59	31.23
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.6	1348.13	35.42
NORTHWEST-10	3.6	1338.89	26.86
PLANT-1	31	1274.58	23.76

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - JULY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.04	20.22
PLANT-4	0	1271.04	22.47
RINGWOOD-1	31	1240.77	1.20
RINGWOOD-2	31	1237.91	0.88
RINGWOOD-3	31	1237.91	3.35
RINGWOOD-4	0	1241.50	10.97
RINGWOOD-5	31	1235.41	-0.37
RINGWOOD-6	0	1233.77	2.49
RINGWOOD-7	31	1233.77	4.67
RINGWOOD-8	31	1234.47	7.81
RINGWOOD-9	31	1235.92	6.67
RINGWOOD-10	0	1235.41	5.62
RINGWOOD-11	0	1233.77	3.40
RINGWOOD-12	0	1230.75	1.35
RINGWOOD-13	0	1230.75	2.62
RINGWOOD-14	0	1235.92	4.77
RINGWOOD-15	0	1231.11	4.31
RINGWOOD-16	0	1230.58	-0.12
RINGWOOD-17	0	1230.58	2.14
RINGWOOD-18	0	1230.75	2.35
RINGWOOD-19	0	1231.13	3.15
RINGWOOD-20	0	1231.13	3.57
RINGWOOD-21	31	1228.96	3.43
RINGWOOD-22	0	1223.64	-2.87
RINGWOOD-23	0	1224.04	-1.62
RINGWOOD-24	0	1224.04	-1.01
RINGWOOD-25	31	1191.92	12.62
RINGWOOD-26	31	1191.20	12.70
RINGWOOD-27	31	1183.46	8.52
RINGWOOD-28	31	1184.81	13.04
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - JULY 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	31	1220.67	19.92
AMES-2	31	1196.72	39.97
AMES-3	0	1190.31	38.15
AMES-4	0	1178.63	33.11
AMES-5	0	1178.63	35.48
AMES-6	0	1193.84	41.60
AMES-7	21.6	1186.88	30.26
AMES-8	0	1193.84	35.99
AMES-9	3.8	1199.65	35.14
AMES-10	0	1162.18	30.51
AMES-11	2.6	1190.31	37.69
AMES-12	0	1193.10	37.62
AMES-13	20.9	1203.05	16.52
AMES-14	0	1219.74	20.96
AMES-15	2.5	1222.76	20.00
AMES-16	31	1220.02	14.99
AMES-17	31	1222.27	13.78
AMES-18	2.1	1219.52	26.90
AMES-19	1.7	1221.20	23.26
AMES-20	3.8	1201.80	44.23
AMES-21	0	1196.90	36.79
AMES-22	0	1199.03	40.56
AMES-23	9.9	1193.83	35.07
AMES-24	0	1195.29	46.40
AMES-25	0	1202.15	11.31
AMES-26	1.6	1202.15	13.41
AMES-27	0	1195.29	40.02
AMES-28	0	1189.94	32.17
AMES-29	18.7	1182.26	26.68
AMES-30	0	1195.29	38.28
AMES-31	0	1199.03	38.33
AMES-32	0	1199.03	39.69
AMES-33	0	1201.80	43.66
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1347.90	27.92
CARRIER-12	31	1346.70	33.42

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - AUGUST 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	31	1348.70	35.13
CARRIER-15	0	1348.37	33.64
CARRIER-16	31	1347.90	49.92
CLEO SPRINGS-1	0	1248.26	0.23
CLEO SPRINGS-2	31	1248.26	2.77
CLEO SPRINGS-3	31	1251.97	7.58
CLEO SPRINGS-4	31	1247.81	5.88
CLEO SPRINGS-5	31	1246.84	1.11
CLEO SPRINGS-6	31	1246.84	3.49
CLEO SPRINGS-7	0	1243.25	-0.53
CLEO SPRINGS-8	31	1246.02	3.68
CLEO SPRINGS-9	0	1248.36	-1.74
CLEO SPRINGS-10	0	1244.01	4.74
CLEO SPRINGS-11	31	1243.74	3.23
CLEO SPRINGS-12	31	1243.74	0.56
CLEO SPRINGS-13	31	1238.47	3.18
CLEO SPRINGS-14	31	1238.47	1.17
CLEO SPRINGS-15	0	1241.52	3.14
CLEO SPRINGS-16	0	1241.52	3.77
CLEO SPRINGS-17	0	1237.44	2.30
CLEO SPRINGS-18	0	1238.69	4.53
CLEO SPRINGS-19	31	1234.48	2.68
CLEO SPRINGS-20	0	1236.18	5.37
CLEO SPRINGS-21	0	1233.57	7.19
CLEO SPRINGS-22	0	1231.20	3.00
CLEO SPRINGS-23	0	1233.57	5.21
CLEO SPRINGS-24	0	1230.77	1.28
CLEO SPRINGS-25	0	1233.57	7.30
CLEO SPRINGS-26	0	1231.20	5.92
CLEO SPRINGS-27	0	1228.75	4.83
CLEO SPRINGS-28	0	1228.75	5.09
CLEO SPRINGS-29	0	1222.54	-0.92
CLEO SPRINGS-30	31	1222.54	4.06
CLEO SPRINGS-31	31	1221.44	4.33
DRUMMOND-1	0	1238.23	39.08
DRUMMOND-2	2.6	1229.18	33.24
DRUMMOND-3	0	1225.30	30.98

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1225.30	30.98
DRUMMOND-5	0	1207.18	16.99
DRUMMOND-6	0	1213.03	22.56
DRUMMOND-7	31	1202.46	15.03
DRUMMOND-8	31	1207.18	16.99
DRUMMOND-9	0	1198.31	10.88
DRUMMOND-10	31	1198.31	10.88
DRUMMOND-11	31	1199.85	15.82
DRUMMOND-12	31	1227.84	32.22
DRUMMOND-13	0	1198.21	18.05
DRUMMOND-14	7.1	1229.18	33.24
DRUMMOND-15	0.82	1225.44	31.25
DRUMMOND-17	0	1206.05	21.83
DRUMMOND-18	31	1200.37	14.45
DRUMMOND-19	31	1199.10	11.32
DRUMMOND-20	31	1202.35	12.08
DRUMMOND-21	31	1208.16	16.66
DRUMMOND-22	0	1220.96	28.20
DRUMMOND-23	0	1228.32	33.54
DRUMMOND-25	31	1216.06	22.92
DRUMMOND-26	1.6	1229.82	32.48
DRUMMOND-27	31	1226.01	27.43
DRUMMOND-28	0	1237.15	36.81
DRUMMOND-29	0	1244.59	41.80
DRUMMOND-31	0	1235.37	36.48
DRUMMOND-32	31	1234.64	33.46
DRUMMOND-33	0	1238.29	38.16
NORTHWEST-1	0	1339.68	26.33
NORTHWEST-2	6.6	1345.17	31.50
NORTHWEST-3	0	1342.89	34.92
NORTHWEST-6	1.9	1326.57	28.73
NORTHWEST-7	3.4	1333.57	31.21
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.6	1348.10	35.39
NORTHWEST-10	3.6	1338.87	26.84
PLANT-1	31	1247.48	23.66

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
SUMMARY REPORT - AUGUST 1989

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1271.01	20.19
PLANT-4	0	1271.01	22.44
RINGWOOD-1	31	1240.47	0.90
RINGWOOD-2	31	1237.50	0.47
RINGWOOD-3	31	1237.50	2.94
RINGWOOD-4	0	1241.24	10.71
RINGWOOD-5	31	1235.10	-0.68
RINGWOOD-6	0	1233.40	2.12
RINGWOOD-7	31	1233.40	4.30
RINGWOOD-8	31	1234.17	7.51
RINGWOOD-9	31	1235.65	6.40
RINGWOOD-10	0	1235.10	5.31
RINGWOOD-11	0	1233.40	3.03
RINGWOOD-12	0	1230.58	1.18
RINGWOOD-13	0	1230.58	2.45
RINGWOOD-14	0	1235.65	4.50
RINGWOOD-15	0	1230.94	4.14
RINGWOOD-16	0	1230.39	-0.39
RINGWOOD-17	0	1230.39	1.95
RINGWOOD-18	0	1230.58	2.18
RINGWOOD-19	0	1230.93	2.95
RINGWOOD-20	0	1230.93	3.37
RINGWOOD-21	31	1228.71	3.18
RINGWOOD-22	0	1223.55	-2.96
RINGWOOD-23	0	1223.97	-1.69
RINGWOOD-24	0	1223.97	-1.08
RINGWOOD-25	31	1191.21	11.91
RINGWOOD-26	31	1190.55	12.05
RINGWOOD-27	31	1182.97	8.03
RINGWOOD-28	31	1184.45	12.68
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	30	1220.45	19.70
AMES-2	30	1196.51	39.76
AMES-3	0	1190.13	37.97
AMES-4	0	1178.51	32.99
AMES-5	0	1178.51	35.96
AMES-6	0	1193.67	41.43
AMES-7	20.9	1186.73	30.11
AMES-8	0	1193.67	35.82
AMES-9	3.7	1199.50	34.99
AMES-10	0	1162.13	30.45
AMES-11	2.5	1190.13	37.51
AMES-12	0	1192.92	37.44
AMES-13	20.2	1202.80	16.27
AMES-14	0	1219.63	20.85
AMES-15	2.4	1222.63	19.87
AMES-16	30	1219.74	14.72
AMES-17	30	1222.06	13.57
AMES-18	1.9	1219.39	26.77
AMES-19	1.6	1221.09	23.15
AMES-20	3.7	1201.98	44.41
AMES-21	0	1196.86	36.75
AMES-22	0	1199.02	40.55
AMES-23	9.6	1193.72	34.96
AMES-24	0	1195.19	46.30
AMES-25	0	1202.10	11.26
AMES-26	1.5	1202.10	13.36
AMES-27	0	1195.19	39.92
AMES-28	0	1189.85	32.13
AMES-29	5.4	1182.85	27.28
AMES-30	0	1195.19	38.18
AMES-31	0	1199.02	38.32
AMES-32	0	1199.02	39.68
AMES-33	0	1201.98	43.84
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1347.78	27.80
CARRIER-12	30	1346.56	33.28

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	30	1348.54	34.97
CARRIER-15	0	1348.34	33.61
CARRIER-16	30	1347.78	49.80
CLEO SPRINGS-1	0	1247.72	-0.31
CLEO SPRINGS-2	30	1247.72	2.23
CLEO SPRINGS-3	30	1251.86	7.47
CLEO SPRINGS-4	30	1246.96	5.03
CLEO SPRINGS-5	0	1246.43	0.70
CLEO SPRINGS-6	30	1246.43	3.08
CLEO SPRINGS-7	0	1243.06	-0.72
CLEO SPRINGS-8	30	1245.34	3.01
CLEO SPRINGS-9	0	1248.27	-1.83
CLEO SPRINGS-10	0	1243.74	4.48
CLEO SPRINGS-11	30	1243.63	3.12
CLEO SPRINGS-12	2.4	1243.63	0.45
CLEO SPRINGS-13	30	1237.00	1.71
CLEO SPRINGS-14	30	1237.00	-0.30
CLEO SPRINGS-15	0	1241.84	3.46
CLEO SPRINGS-16	0	1241.84	4.09
CLEO SPRINGS-17	0	1237.46	2.32
CLEO SPRINGS-18	0	1239.06	4.90
CLEO SPRINGS-19	30	1234.32	2.52
CLEO SPRINGS-20	0	1236.56	5.75
CLEO SPRINGS-21	0	1233.92	7.54
CLEO SPRINGS-22	0	1231.53	3.33
CLEO SPRINGS-23	0	1233.92	5.56
CLEO SPRINGS-24	0	1231.03	1.54
CLEO SPRINGS-25	0	1233.92	7.65
CLEO SPRINGS-26	0	1231.53	6.25
CLEO SPRINGS-27	0	1229.01	5.09
CLEO SPRINGS-28	0	1229.01	5.35
CLEO SPRINGS-29	0	1221.99	-1.46
CLEO SPRINGS-30	30	1221.99	3.52
CLEO SPRINGS-31	30	1220.68	3.57
DRUMMOND-1	0	1238.18	39.03
DRUMMOND-2	2.6	1228.69	32.75
DRUMMOND-3	0	1224.62	30.31

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1224.62	30.31
DRUMMOND-5	0	1205.25	15.06
DRUMMOND-6	0	1211.65	21.18
DRUMMOND-7	30	1200.98	13.55
DRUMMOND-8	30	1205.25	15.06
DRUMMOND-9	0	1196.50	9.07
DRUMMOND-10	30	1196.50	9.07
DRUMMOND-11	30	1198.73	14.70
DRUMMOND-12	30	1227.16	31.54
DRUMMOND-13	0	1197.69	17.53
DRUMMOND-14	6.9	1228.69	32.75
DRUMMOND-15	0.79	1224.77	30.58
DRUMMOND-17	0	1205.42	21.20
DRUMMOND-18	30	1199.06	13.14
DRUMMOND-19	30	1197.34	9.56
DRUMMOND-20	30	1200.72	10.45
DRUMMOND-21	30	1207.33	15.83
DRUMMOND-22	0	1220.49	27.73
DRUMMOND-23	0	1228.12	33.34
DRUMMOND-25	30	1215.11	21.97
DRUMMOND-26	1.5	1229.30	31.96
DRUMMOND-27	30	1225.54	26.96
DRUMMOND-28	0	1236.82	36.48
DRUMMOND-29	0	1244.44	41.65
DRUMMOND-31	0	1234.89	36.00
DRUMMOND-32	30	1233.03	31.85
DRUMMOND-33	0	1237.44	37.31
NORTHWEST-1	0	1339.68	26.33
NORTHWEST-2	6.4	1345.16	31.49
NORTHWEST-3	0	1342.88	34.91
NORTHWEST-6	1.9	1326.57	28.73
NORTHWEST-7	3.3	1333.56	31.20
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.5	1348.06	35.35
NORTHWEST-10	3.4	1338.86	26.83
PLANT-1	30	1274.39	23.57

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1270.99	20.17
PLANT-4	0	1270.99	22.42
RINGWOOD-1	30	1240.26	0.69
RINGWOOD-2	30	1237.20	0.17
RINGWOOD-3	30	1237.20	2.64
RINGWOOD-4	0	1241.04	10.51
RINGWOOD-5	30	1234.86	-0.92
RINGWOOD-6	0	1233.09	1.81
RINGWOOD-7	30	1233.09	3.99
RINGWOOD-8	30	1233.91	7.25
RINGWOOD-9	30	1235.43	6.18
RINGWOOD-10	0	1234.86	5.07
RINGWOOD-11	0	1233.09	2.72
RINGWOOD-12	0	1230.40	1.00
RINGWOOD-13	0	1230.40	2.27
RINGWOOD-14	0	1235.43	4.28
RINGWOOD-15	0	1230.79	3.99
RINGWOOD-16	0	1230.19	-0.51
RINGWOOD-17	0	1230.19	1.75
RINGWOOD-18	0	1230.40	2.00
RINGWOOD-19	0	1230.74	2.76
RINGWOOD-20	0	1230.74	3.18
RINGWOOD-21	30	1228.51	2.98
RINGWOOD-22	0	1223.44	-3.07
RINGWOOD-23	0	1223.86	-1.80
RINGWOOD-24	0	1223.86	-1.19
RINGWOOD-25	30	1190.64	11.34
RINGWOOD-26	30	1190.04	11.54
RINGWOOD-27	30	1182.58	7.64
RINGWOOD-28	30	1184.06	12.29
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	31	1220.24	19.49
AMES-2	31	1196.30	39.55
AMES-3	0	1189.96	37.80
AMES-4	0	1178.40	32.88
AMES-5	0	1178.40	35.25
AMES-6	0	1193.52	41.28
AMES-7	21.6	1186.59	29.97
AMES-8	0	1193.52	35.67
AMES-9	3.8	1199.38	34.87
AMES-10	0	1162.06	30.39
AMES-11	2.6	1189.96	37.34
AMES-12	0	1192.73	37.25
AMES-13	20.9	1202.64	16.11
AMES-14	0	1219.53	20.75
AMES-15	2.5	1222.52	19.76
AMES-16	31	1219.48	14.46
AMES-17	31	1221.85	13.36
AMES-18	2.1	1219.19	26.57
AMES-19	1.7	1220.99	23.05
AMES-20	3.8	1201.99	44.42
AMES-21	0	1196.81	36.70
AMES-22	0	1198.98	40.52
AMES-23	9.9	1193.65	34.89
AMES-24	0	1195.11	46.22
AMES-25	0	1202.05	11.21
AMES-26	1.6	1202.05	13.31
AMES-27	0	1195.11	39.84
AMES-28	0	1189.89	32.12
AMES-29	5.6	1183.09	27.51
AMES-30	0	1195.11	38.10
AMES-31	0	1198.98	38.29
AMES-32	0	1198.98	39.65
AMES-33	0	1201.99	43.85
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1347.66	27.68
CARRIER-12	31	1346.42	33.14

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1348.60	35.03
CARRIER-15	0	1348.31	33.58
CARRIER-16	31	1347.66	49.68
CLEO SPRINGS-1	0	1247.42	-0.61
CLEO SPRINGS-2	31	1247.42	1.93
CLEO SPRINGS-3	31	1251.69	7.30
CLEO SPRINGS-4	31	1246.50	4.57
CLEO SPRINGS-5	0	1246.05	0.32
CLEO SPRINGS-6	31	1246.05	2.70
CLEO SPRINGS-7	0	1242.84	-0.94
CLEO SPRINGS-8	31	1244.96	2.62
CLEO SPRINGS-9	0	1248.15	-1.95
CLEO SPRINGS-10	0	1243.43	4.17
CLEO SPRINGS-11	31	1243.56	3.05
CLEO SPRINGS-12	0	1243.56	0.38
CLEO SPRINGS-13	31	1236.38	1.09
CLEO SPRINGS-14	31	1236.38	-0.92
CLEO SPRINGS-15	0	1241.95	3.57
CLEO SPRINGS-16	0	1241.95	4.20
CLEO SPRINGS-17	0	1237.36	2.22
CLEO SPRINGS-18	0	1239.27	5.11
CLEO SPRINGS-19	31	1234.38	2.58
CLEO SPRINGS-20	0	1236.82	6.01
CLEO SPRINGS-21	0	1234.18	7.80
CLEO SPRINGS-22	0	1231.77	3.57
CLEO SPRINGS-23	0	1234.18	5.82
CLEO SPRINGS-24	0	1231.22	1.73
CLEO SPRINGS-25	0	1234.18	7.91
CLEO SPRINGS-26	0	1231.77	6.48
CLEO SPRINGS-27	0	1229.18	5.26
CLEO SPRINGS-28	0	1229.18	5.52
CLEO SPRINGS-29	0	1229.81	-1.65
CLEO SPRINGS-30	31	1221.81	3.33
CLEO SPRINGS-31	31	1220.35	3.24
DRUMMOND-1	0	1238.10	38.95
DRUMMOND-2	2.6	1228.24	32.31
DRUMMOND-3	0	1223.89	29.58

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1223.89	29.58
DRUMMOND-5	0	1205.51	15.32
DRUMMOND-6	0	1210.47	20.00
DRUMMOND-7	31	1199.61	12.18
DRUMMOND-8	0	1205.51	15.32
DRUMMOND-9	0	1194.96	7.53
DRUMMOND-10	31	1194.96	7.53
DRUMMOND-11	31	1197.66	13.63
DRUMMOND-12	0	1227.90	32.28
DRUMMOND-13	0	1197.16	17.00
DRUMMOND-14	7.1	1228.24	32.31
DRUMMOND-15	0.82	1224.20	30.01
DRUMMOND-17	0	1204.78	20.56
DRUMMOND-18	31	1197.86	11.94
DRUMMOND-19	31	1195.68	7.90
DRUMMOND-20	31	1199.31	9.04
DRUMMOND-21	31	1206.48	14.98
DRUMMOND-22	0	1220.00	27.24
DRUMMOND-23	0	1227.91	33.13
DRUMMOND-25	31	1214.15	21.01
DRUMMOND-26	1.6	1228.76	31.42
DRUMMOND-27	31	1225.06	26.48
DRUMMOND-28	0	1236.50	36.16
DRUMMOND-29	0	1244.29	41.50
DRUMMOND-31	0	1234.37	35.48
DRUMMOND-32	14.8	1234.80	33.62
DRUMMOND-33	0	1236.81	36.68
NORTHWEST-1	0	1339.68	26.33
NORTHWEST-2	6.6	1345.14	31.47
NORTHWEST-3	0	1342.87	34.90
NORTHWEST-6	1.9	1326.56	28.72
NORTHWEST-7	3.4	1333.55	31.19
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.6	1348.02	35.31
NORTHWEST-10	3.6	1338.84	26.81
PLANT-1	31	1274.30	23.48

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1270.96	20.14
PLANT-4	0	1270.96	22.39
RINGWOOD-1	31	1240.10	0.53
RINGWOOD-2	31	1236.95	-0.08
RINGWOOD-3	31	1236.95	2.39
RINGWOOD-4	0	1240.88	10.35
RINGWOOD-5	31	1234.65	-1.13
RINGWOOD-6	0	1232.83	1.55
RINGWOOD-7	31	1232.83	3.73
RINGWOOD-8	31	1233.67	7.01
RINGWOOD-9	31	1235.23	5.98
RINGWOOD-10	0	1234.65	4.86
RINGWOOD-11	0	1232.83	2.46
RINGWOOD-12	0	1230.22	0.82
RINGWOOD-13	0	1230.22	2.09
RINGWOOD-14	0	1235.23	4.08
RINGWOOD-15	0	1230.65	3.85
RINGWOOD-16	0	1230.01	-0.69
RINGWOOD-17	0	1230.01	1.57
RINGWOOD-18	0	1230.22	1.82
RINGWOOD-19	0	1230.57	2.59
RINGWOOD-20	0	1230.57	3.01
RINGWOOD-21	31	1228.35	2.82
RINGWOOD-22	0	1223.32	-3.19
RINGWOOD-23	0	1223.74	-1.92
RINGWOOD-24	0	1223.74	-1.31
RINGWOOD-25	31	1190.14	10.84
RINGWOOD-26	31	1189.58	11.08
RINGWOOD-27	31	1182.24	7.30
RINGWOOD-28	31	1183.87	12.10
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

LINKED OPTIMIZATION - SIMULATION AQUIFER MANAGEMENT MODEL
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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	30	1220.05	19.30
AMES-2	30	1196.11	39.36
AMES-3	0	1189.80	37.64
AMES-4	0	1178.29	32.77
AMES-5	0	1178.29	35.14
AMES-6	0	1193.38	41.14
AMES-7	20.9	1186.45	29.83
AMES-8	0	1193.38	35.53
AMES-9	3.7	1199.26	34.75
AMES-10	0	1162.01	30.33
AMES-11	2.5	1189.80	37.18
AMES-12	0	1192.56	37.08
AMES-13	20.2	1202.42	15.89
AMES-14	0	1219.43	20.65
AMES-15	2.4	1222.41	19.65
AMES-16	30	1219.25	14.23
AMES-17	30	1221.67	13.18
AMES-18	1.9	1219.06	26.44
AMES-19	1.6	1220.89	22.95
AMES-20	3.7	1201.94	44.37
AMES-21	0	1196.73	36.62
AMES-22	0	1198.94	40.47
AMES-23	9.6	1193.57	34.81
AMES-24	0	1195.06	46.17
AMES-25	0	1202.01	11.17
AMES-26	1.5	1202.01	13.27
AMES-27	0	1195.06	39.79
AMES-28	0	1189.88	32.11
AMES-29	5.4	1183.17	27.59
AMES-30	0	1195.06	38.05
AMES-31	0	1198.94	38.24
AMES-32	0	1198.94	39.60
AMES-33	0	1201.94	43.80
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1347.82	27.84
CARRIER-12	0	1346.57	33.29

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1348.64	35.07
CARRIER-15	0	1348.28	33.55
CARRIER-16	0	1347.82	49.84
CLEO SPRINGS-1	0	1247.23	-0.80
CLEO SPRINGS-2	30	1247.23	1.74
CLEO SPRINGS-3	0	1251.54	7.15
CLEO SPRINGS-4	30	1246.21	4.28
CLEO SPRINGS-5	0	1245.76	0.03
CLEO SPRINGS-6	30	1245.76	2.41
CLEO SPRINGS-7	0	1242.66	-1.12
CLEO SPRINGS-8	30	1244.68	2.34
CLEO SPRINGS-9	0	1248.03	-2.07
CLEO SPRINGS-10	0	1243.19	3.93
CLEO SPRINGS-11	30	1243.48	2.97
CLEO SPRINGS-12	0	1243.48	0.30
CLEO SPRINGS-13	30	1236.04	0.75
CLEO SPRINGS-14	30	1236.04	-1.26
CLEO SPRINGS-15	0	1241.94	3.56
CLEO SPRINGS-16	0	1241.94	4.19
CLEO SPRINGS-17	0	1237.26	2.12
CLEO SPRINGS-18	0	1239.04	4.88
CLEO SPRINGS-19	30	1234.30	2.50
CLEO SPRINGS-20	30	1234.75	3.94
CLEO SPRINGS-21	0	1229.99	3.61
CLEO SPRINGS-22	0	1229.10	0.91
CLEO SPRINGS-23	30	1229.99	1.64
CLEO SPRINGS-24	0	1230.26	0.77
CLEO SPRINGS-25	30	1229.99	3.72
CLEO SPRINGS-26	30	1229.10	3.82
CLEO SPRINGS-27	30	1226.53	2.61
CLEO SPRINGS-28	30	1226.53	2.87
CLEO SPRINGS-29	0	1221.61	-1.84
CLEO SPRINGS-30	30	1221.61	3.14
CLEO SPRINGS-31	30	1220.13	3.02
DRUMMOND-1	0	1238.01	38.86
DRUMMOND-2	2.6	1227.91	31.97
DRUMMOND-3	0	1223.22	28.91

WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1223.22	28.91
DRUMMOND-5	0	1205.07	14.88
DRUMMOND-6	0	1209.77	19.30
DRUMMOND-7	0	1201.36	13.93
DRUMMOND-8	0	1205.07	14.88
DRUMMOND-9	0	1193.96	6.53
DRUMMOND-10	30	1193.96	6.53
DRUMMOND-11	30	1196.97	12.94
DRUMMOND-12	0	1228.08	32.46
DRUMMOND-13	0	1196.69	16.53
DRUMMOND-14	6.9	1227.91	31.97
DRUMMOND-15	0.8	1223.73	29.54
DRUMMOND-17	0	1204.21	19.99
DRUMMOND-18	30	1196.81	10.89
DRUMMOND-19	30	1194.27	6.49
DRUMMOND-20	30	1198.14	7.87
DRUMMOND-21	30	1205.68	14.18
DRUMMOND-22	0	1219.53	26.77
DRUMMOND-23	0	1227.70	32.92
DRUMMOND-25	30	1213.30	20.16
DRUMMOND-26	1.5	1228.23	30.89
DRUMMOND-27	30	1224.61	26.03
DRUMMOND-28	0	1236.20	35.86
DRUMMOND-29	0	1244.14	41.35
DRUMMOND-31	0	1233.92	35.03
DRUMMOND-32	0	1237.33	36.15
DRUMMOND-33	0	1236.75	36.62
NORTHWEST-1	0	1339.67	26.32
NORTHWEST-2	6.4	1345.13	31.46
NORTHWEST-3	0	1342.86	34.89
NORTHWEST-6	1.9	1326.55	28.71
NORTHWEST-7	3.3	1333.54	31.18
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.5	1347.99	35.28
NORTHWEST-10	3.4	1338.83	26.80
PLANT-1	30	1274.23	23.41

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1270.94	20.12
PLANT-4	0	1270.94	22.37
RINGWOOD-1	0	1241.37	1.80
RINGWOOD-2	30	1237.17	0.14
RINGWOOD-3	30	1237.17	2.61
RINGWOOD-4	0	1240.81	10.28
RINGWOOD-5	30	1234.90	-0.88
RINGWOOD-6	0	1234.01	2.73
RINGWOOD-7	0	1234.01	4.91
RINGWOOD-8	30	1233.70	7.04
RINGWOOD-9	30	1235.10	5.85
RINGWOOD-10	0	1234.90	5.11
RINGWOOD-11	0	1234.01	3.64
RINGWOOD-12	0	1230.11	0.71
RINGWOOD-13	0	1230.11	1.98
RINGWOOD-14	0	1235.10	3.95
RINGWOOD-15	0	1230.59	3.79
RINGWOOD-16	0	1230.08	-0.62
RINGWOOD-17	0	1230.08	1.64
RINGWOOD-18	0	1230.11	1.71
RINGWOOD-19	0	1230.43	2.45
RINGWOOD-20	0	1230.43	2.87
RINGWOOD-21	30	1228.21	2.68
RINGWOOD-22	0	1223.24	-3.27
RINGWOOD-23	0	1223.64	-2.02
RINGWOOD-24	0	1223.64	-1.41
RINGWOOD-25	0	1192.44	13.14
RINGWOOD-26	4.3	1190.96	12.46
RINGWOOD-27	30	1182.49	7.55
RINGWOOD-28	0	1184.69	12.92
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
AMES-1	31	1219.87	19.12
AMES-2	31	1195.92	39.17
AMES-3	0	1189.65	37.49
AMES-4	0	1278.18	32.66
AMES-5	0	1278.18	35.03
AMES-6	0	1193.25	41.01
AMES-7	21.6	1186.32	29.70
AMES-8	0	1193.25	35.40
AMES-9	3.8	1199.15	34.64
AMES-10	0	1161.94	30.27
AMES-11	2.6	1189.65	37.03
AMES-12	0	1192.40	36.92
AMES-13	20.9	1202.27	15.74
AMES-14	0	1219.34	20.56
AMES-15	2.5	1222.31	19.55
AMES-16	31	1219.02	14.00
AMES-17	31	1221.48	12.99
AMES-18	2.1	1218.87	26.25
AMES-19	1.7	1220.78	22.84
AMES-20	3.8	1201.88	44.31
AMES-21	0	1196.65	36.54
AMES-22	0	1198.88	40.41
AMES-23	9.9	1193.51	34.75
AMES-24	0	1195.01	46.12
AMES-25	0	1201.97	11.13
AMES-26	1.6	1201.97	13.23
AMES-27	0	1195.01	39.74
AMES-28	0	1189.85	32.08
AMES-29	5.6	1183.21	27.63
AMES-30	0	1195.01	38.00
AMES-31	0	1198.88	38.18
AMES-32	0	1198.88	39.56
AMES-33	0	1201.88	43.74
CARRIER-2	0	1341.32	23.16
CARRIER-3	0	1342.82	27.41
CARRIER-11	0	1347.95	27.97
CARRIER-12	0	1346.69	33.41

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
CARRIER-13	0	1348.66	35.09
CARRIER-15	0	1348.26	33.53
CARRIER-16	0	1347.95	49.97
CLEO SPRINGS-1	0	1246.35	-1.68
CLEO SPRINGS-2	31	1246.35	0.86
CLEO SPRINGS-3	0	1250.31	5.92
CLEO SPRINGS-4	31	1245.70	3.77
CLEO SPRINGS-5	0	1244.35	-1.38
CLEO SPRINGS-6	31	1244.35	1.00
CLEO SPRINGS-7	0	1239.33	-4.45
CLEO SPRINGS-8	31	1243.82	1.48
CLEO SPRINGS-9	0	1247.05	-3.05
CLEO SPRINGS-10	0	1242.02	2.76
CLEO SPRINGS-11	31	1241.79	1.28
CLEO SPRINGS-12	0	1241.79	-1.39
CLEO SPRINGS-13	31	1235.18	-0.11
CLEO SPRINGS-14	31	1235.18	-2.12
CLEO SPRINGS-15	0	1237.89	-0.49
CLEO SPRINGS-16	0	1237.89	0.14
CLEO SPRINGS-17	0	1235.77	0.63
CLEO SPRINGS-18	0	1236.12	1.96
CLEO SPRINGS-19	31	1233.31	1.51
CLEO SPRINGS-20	31	1232.86	2.05
CLEO SPRINGS-21	0	1224.91	-1.47
CLEO SPRINGS-22	0	1225.01	-3.19
CLEO SPRINGS-23	31	1224.91	-3.45
CLEO SPRINGS-24	0	1228.16	-1.33
CLEO SPRINGS-25	31	1224.91	-1.36
CLEO SPRINGS-26	10.3	1225.01	-0.27
CLEO SPRINGS-27	31	1224.40	0.48
CLEO SPRINGS-28	31	1224.40	0.74
CLEO SPRINGS-29	0	1217.92	-5.54
CLEO SPRINGS-30	31	1217.92	-0.56
CLEO SPRINGS-31	31	1219.73	2.62
DRUMMOND-1	0	1237.92	38.77
DRUMMOND-2	2.6	1227.54	31.60
DRUMMOND-3	0	1222.55	28.24

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
DRUMMOND-4	0	1222.55	28.24
DRUMMOND-5	0	1204.41	14.22
DRUMMOND-6	0	1209.30	18.83
DRUMMOND-7	0	1201.91	14.48
DRUMMOND-8	0	1204.41	14.22
DRUMMOND-9	0	1193.20	5.77
DRUMMOND-10	31	1193.20	5.77
DRUMMOND-11	31	1196.52	12.48
DRUMMOND-12	0	1228.02	32.40
DRUMMOND-13	0	1196.28	16.12
DRUMMOND-14	7.1	1227.54	31.60
DRUMMOND-15	0.82	1223.25	29.06
DRUMMOND-17	0	1203.72	19.51
DRUMMOND-18	31	1195.81	9.89
DRUMMOND-19	31	1193.01	5.23
DRUMMOND-20	31	1197.04	6.77
DRUMMOND-21	31	1204.89	13.39
DRUMMOND-22	0	1219.05	26.29
DRUMMOND-23	0	1227.48	32.70
DRUMMOND-25	31	1212.53	19.39
DRUMMOND-26	1.6	1227.70	30.36
DRUMMOND-27	31	1224.16	25.58
DRUMMOND-28	0	1235.88	35.54
DRUMMOND-29	0	1243.99	41.20
DRUMMOND-31	0	1233.53	34.64
DRUMMOND-32	0	1238.64	37.46
DRUMMOND-33	0	1236.84	36.71
NORTHWEST-1	0	1339.67	26.32
NORTHWEST-2	6.6	1345.12	31.45
NORTHWEST-3	0	1342.85	34.88
NORTHWEST-6	1.9	1326.54	28.70
NORTHWEST-7	3.4	1333.53	31.17
NORTHWEST-8	0	N/A	N/A
NORTHWEST-9	5.6	1347.96	35.26
NORTHWEST-10	3.6	1338.82	26.79
PLANT-1	31	1274.16	23.34

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WELL ID NO.	PRODUCTION PERIOD (DAYS)	PREDICTED GROUNDWATER SURFACE ELEVATION	DRAWDOWN BUFFER (FEET)
PLANT-3	0	1270.91	20.09
PLANT-4	0	1270.91	22.34
RINGWOOD-1	0	1241.68	2.11
RINGWOOD-2	31	1237.47	0.44
RINGWOOD-3	31	1237.47	2.91
RINGWOOD-4	0	1240.84	10.31
RINGWOOD-5	31	1232.83	-2.95
RINGWOOD-6	0	1234.16	2.88
RINGWOOD-7	0	1234.16	5.06
RINGWOOD-8	31	1233.78	7.12
RINGWOOD-9	31	1235.03	5.78
RINGWOOD-10	31	1232.83	3.04
RINGWOOD-11	0	1234.16	3.79
RINGWOOD-12	0	1230.09	0.69
RINGWOOD-13	0	1230.09	1.96
RINGWOOD-14	0	1235.03	3.88
RINGWOOD-15	0	1230.34	3.54
RINGWOOD-16	0	1230.17	-0.53
RINGWOOD-17	0	1230.17	1.73
RINGWOOD-18	0	1230.09	1.69
RINGWOOD-19	0	1230.33	2.35
RINGWOOD-20	0	1230.33	2.77
RINGWOOD-21	31	1228.10	2.57
RINGWOOD-22	0	1223.22	-3.29
RINGWOOD-23	0	1223.57	-2.09
RINGWOOD-24	0	1223.57	-1.48
RINGWOOD-25	0	1193.44	14.14
RINGWOOD-26	0	1191.62	13.12
RINGWOOD-27	31	1182.98	8.04
RINGWOOD-28	0	1184.93	13.16
VAN BUREN-1	0	N/A	N/A
VAN BUREN-3	0	1284.39	29.69
VAN BUREN-4	0	1279.56	30.28
VAN BUREN-5	0	1295.37	36.68
VAN BUREN-7	0	1279.56	30.28
VAN BUREN-8	0	N/A	N/A

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VITA

Blaine Theodore Reely

Candidate for the Degree of

Doctor of Philosophy

Thesis: A LINKED OPTIMIZATION-SIMULATION AQUIFER MANAGEMENT MODEL

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Terre Haute, Indiana, September 26, 1956 of Robert and Elizabeth Reely. Married to Fawn K. Reely and father to Spencer, Gus and another miracle to occur in September 1992.

Education: Graduated from Mohave High School, Bullhead City, Arizona in June 1974; received Bachelor of Science Degree in Geological Engineering from University of Arizona in May 1980 and Master of Science Degree in Civil Engineering from University of Arizona in December 1985; completed requirements for Doctor of Philosophy Degree at Oklahoma State University in July 1992.

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