Water Supply Planning Using an Expert Geographic Information System

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ABSTRACT

An expert geographic information system (expert GIS) for long-term regional water supply planning has been developed. This system has been evaluated through a case study examining a 19-county study region in South Texas with several water supply sources and demand centers. The planning system is comprised of an expert system, which contains the logical rules and expertise of water resources planning experts; a geographic information system, which stores and analyzes spatially distributed water supply and demand data; and a network flow solver, to balance the flows in networks developed by the expert GIS with input from a water resource analyst. Commonly available water demand forecasts and water supply data are used in this new planning tool in an attempt to follow more rapidly the logic of current methods and permit plans to be updated and alternatives to be analyzed. Given annual yields for reservoirs, water demand forecasts and institutional requirements, the expert GIS calculates potential water supply deficits or excesses and suggests efficient and cost effective alternatives for developing additional water supplies in the event that deficits occur. The expert GIS system has been developed so that it can be expanded to include additional constraints and handle large water resources planning regions. Eventually, the system will be capable of analyzing entire river basins, given appropriate information concerning the supply and demand for water. The system has been successfully applied to the TWDB Coastal Bend planning region. The existence of generic categories of rules for regional water planning is evident from this case study. The categories include rules applicable on a statewide basis, a regional basis or a local basis. The local scale rules are specific to individual arcs in the network model representation and need to be entered individually. However, the application of the small sets of statewide and regional rules is sufficient to generate relatively realistic solutions.

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1.0 INTRODUCTION

A central problem in the field of water resources planning and management is the efficient allocation of water supplies to meet demands. At local planning levels, where there are typically only one or two potential sources of supply and a relatively small number of demands, efficient solutions can be found by simple inspection and common sense. At the regional level, where there are frequently a dozen or more sources of supply and many times that number of demands, the allocation of supplies to meet demands becomes more difficult. In such instances, exhaustive enumeration and the direct comparison of each of the alternatives may eventually lead to efficient solutions. As the size of the planning region expands, the number of alternative allocation possibilities explodes, and simple methods become impractical. This is very commonly the case at the statewide planning level.

The Texas Legislature mandated such statewide planning in 1957 when it created the Texas Water Development Board (TWDB). The board responded in 1961 and in 1969 by producing water plans that describe the state's water resources, quantify future water needs, and propose water supply projects to meet those needs. The scope of planning increased in the 1984 water plan, which proposed conservation and environmental protection initiatives in addition to conventional water supply projects. The current water plan, promulgated by the agency in 1990 [TWDB, 1990] and updated in 1992 [TWDB, 1992], emphasizes improved overall management of the state's existing and future water infrastructure systems and proposes that the state water plan be updated on a regular and predictable basis.

The steps taken by the TWDB in creating a state water plan can be summarized as follows:

(1) Water demands are estimated for the base planning year and for 10-year intervals into the future, out to a planning horizon of 50 years. These include municipal demands for each city of grater than 1,000 population, and agricultural, industrial and other types of water demands which are aggregated by county and estimated for each of Texas' 254 counties.

(2) Available water supplies are estimated for each water supply source: the firm yields of reservoirs, the dependable flow of rivers, and the available yield of groundwater aquifers.

(3) A reconciliation process is undertaken in which both supplies and demands are partitioned by county; the total demand and supply are computed for each county in each planning period; and a deficit is registered whenever projected demand exceeds available supply.

(4) In areas of deficit, a search is launched for nearby surplus supply sources that could be allocated to meet the deficit, and new projects necessary to develop those sources are identified and scheduled in each 10-year planning period. This involves a trial-and-error search among many alternatives.

(5) The initial plan so formed is debated at regional meetings throughout the state and adjusted on the basis of input from local officials.

The long history of water planning in Texas has created a solid basis for conceptualization of the problem and considerable operational experience with its solution. The goal of this research is to reformulate the conceptual model using a new set of information engineering tools, in order to improve the understanding of the choices being made in water planning and to increase confidence that good alternatives are being chosen as plans are formulated. The current planning process has potential for improvement in several respects.

The allocation process that has been used in current and previous water plans is heavily dependent upon the expertise and the judgment of a few professionals at the TWDB, and upon outdated Fortran computer programs with complicated data files. Extensive data related to the supply and demand for water in current and future decades are batch processed to identify potential shortfalls, without the aid of geographic display of the plans. Allocations are made on a county-by-county basis within major watersheds, based upon a prioritized list of suppliers for each demander. The list is adjusted incrementally by an expert analyst before each batch run, until demands are satisfied or until there is clear indication of the need for capacity expansion. This is a very tedious and difficult process, and the water allocations that evolve from it are an expression of the analyst's abilities to comprehend the system and improve the solution, rather than the result of a rigorous documentable procedure.

A prime motivation for this research has been a strong desire within the TWDB to automate this process without abandoning the assumptions and philosophies that have resulted in the present set of allocations. Automating this system would define the decision-making methodology, which, in turn, would result in more defensible conclusions and recommendations. It would also facilitate the investigation of alternative economic assumptions and expansion scenarios and allow for comparisons among them in order to ascertain the sensitivity of the current set of allocations to error in these assumptions and scenarios. Furthermore, the effects of political and environmental considerations could be determined in an objective manner secure from the distorting influences of unstated personal bias.

An automated set of procedures to allocate water resources in the state of Texas must take into consideration historical and political institutions as well as the relevant geographic, hydrologic, and economic data. The procedures must be consistent with earlier water planning philosophy and draw from its experience rather than abandon it.

Such a system can be devised based upon the capabilities of:

(1) a geographic information system (GIS) to store, retrieve, manipulate, update, and display spatially related data,

(2) an expert system to implement a set of logical rules that contain the skill of a professional analyst, and

(3) a network balancing system to find least-cost resource allocation solutions.

The development of the system has required several years of programming and testing. Numerous command ancillary computer programs have been written to generate data layers or coverages, create input files, transform and transfer data, and present results. The system was first tested on a small and completely contrived problem, which is presented as an example in Chapter 4. A 19-county case study problem has been undertaken with supply and demand data for the Texas Coastal Bend planning region. The results of applying the new planning system to this problem are presented in Chapter 5.

The solution of this planning problem required a creative approach to analysing geographic data that is more abstract than the digital display of map data. Nominally, this water planning problem involves consideration of five coverages: two for demands (cities and counties), and three for supplies (reservoirs, rivers, and aquifers). The problem is further complicated by the fact that four of these data layers are polygon or area coverages (cities, counties, reservoirs, and aquifers), and the other is a line coverage of rivers. Moving water from one area to another is an ill-defined problem, because the distance between two areas cannot be uniquely determined.

This dilemma was resolved by representing all supplies and demands by geographic points, and the allocation of supplies to demands by areas or straight lines between the points. Thus, each city is represented by the location of its central post office, each county and reservoir by their centroids, river supplies by their point of diversion, and groundwater aquifers by the centroid of the aquifer within each county. In this manner, the distance between each supply and demand point can be approximated, and the elevation of each supply and demand point can be found from digital elevation data. The cost of each allocation can then be estimated, based on the required flow, elevation difference, distance of travel, and type of conveyance system (pipeline, canal, etc.).

Using the point-line layout of supplies and demands, a new solution prototype is constructed combining three computerized methods—GIS, expert systems and a network solver—into a single system. The expert system applies rules which reduce the set of all possible allocations, from supplies to demands, to a set of feasible allocations. The network solver calculates the cost of each allocation in this set and finds the most cost-effective solution to meet the demands from available supplies. This system constitutes a new tool which affords an increased capacity to examine alternative scenarios and enables analysts to better address the scope and complexity of the allocations problem itself. In addition, demonstration of the efficacy of this approach to water resources problems suggests its extension to other spatially distributed planning problems such as electric power distribution, regionalization of wastewater treatment, and emergency services siting. The ability to compare total costs on successive runs affords a new and objective mechanism for determining the relative costs of arbitrarily imposed allocation rules. This is a by-product of creating an automated system in a way that separates the functionality of the data base, the rule base, and the solver.

2.0 LITERATURE REVIEW

2.1 OPTIMIZATION

Operations research methods have been extremely useful for optimizing both the design and management of water delivery systems for over three decades. In particular, linear programming techniques have been utilized effectively in the modeling and solution of complex resource allocation problems. These are most frequently solved with transportation and transshipment algorithms based upon simplex methods. The description of this methodology is standard fare in textbooks in the fields of water resources engineering [Loucks et al., 1981; Buras, 1972] and operations research [Hillier and Lieberman, 1974; Bradley et al., 1977]. Furthermore, it has been demonstrated that many resource allocation problems, as well as many other LP problems, can be represented in terms of single commodity flow within a system of nodes and arcs and solved by network simplex techniques [Jensen and Barnes, 1980]. This affords a significant advantage with respect to the visualization of the problem and also offers data storage and computational advantages compared to standard matrix methods.

The following is a discussion of representative literature from the field of water resources engineering wherein linear programming techniques were employed to solve network flow resource allocations problems.

A raw water supply master plan was prepared for the City of Boulder, Colorado [Brendecke et al., 1989]. The supply system is operated to meet municipal and industrial demands, provide minimum streamflows for Boulder Creek, and generate revenues from hydroelectric turbines installed in raw water and treated water transmission lines. The master plan was developed with the use of three applications of a network optimization tool, which uses the Out-of-Kilter network flow algorithm.

The water rights claims of many Indian reservations in the West are now under adjudication. Lord et al. [1989] sought to (1) develop a conceptual basis for determining Indian water rights; (2) develop an analytical procedure to provide the information needed to resolve water rights conflicts; and (3) apply this analytical procedure to a test case involving the Gila River Basin in Arizona. The methodological core of the research was a set of linked models, encompassing historical, hydrologic, economic, psychological, and institutional elements of the conflict. Hydrologic, institutional, and economic analyses of conjunctive management of surface and groundwater supplies are facilitated by the use of a network optimization model.

Streamflow increases that could be created by vegetation management on forest land along the upper reaches of the Colorado River was examined by Brown et al. [1988]. A network optimization model was used to simulate water flow, storage, use, and loss within the entire Colorado River Basin with and without the flow increases, according to various scenarios incorporating both current and future use levels as well as existing and potential institutional constraints.

A water resource optimization model was developed by Maddaus and McGill [1976] for use in long-range infrastructure planning for water supply and wastewater management. The model included a network analyzer to determine least-cost allocation of available sources of water supply (including reclaimed wastewater) to various demand points subject to certain physical constraints and water management policies, a recosting procedure for nonlinear cost functions, a digital groundwater model for simulating widespread changes in groundwater depth, and a salt balance model for simulating groundwater quality changes with time. The modeling system provided costs for the optimal water resource allocation for various sets of constraints as well as the environmental changes in the groundwater reservoir. The most cost-effective alternative was identified and used to develop a 50-year water supply and wastewater management plan for the Tucson, Arizona, regional area.

Fordham [1972] evaluated simulation as a planning and management tool for water resources in the Truckee and Carson River System in Nevada and California. A simulation model of the two-river system was constructed and then embodied in an optimization algorithm to develop "optimum" operating rules for the system as a whole. Since the demands on the system were incommensurate in economic terms and were greater than the available resource, the problem was resolved into one of allocation of the resource among the various demands. To accomplish this, the problem was formulated as a capacitated flow network and solved using the Out-of-Kilter algorithm. The reservoir releases and diversions from several flow traces were then subject to multiple regression analysis to determine "optimal" operating rules for the five reservoirs and for diversions within the system. Operating rules can be derived by this method which significantly improve overall system operation.

Brown et al. [1972] assessed the importance and the relationship of social-cultural, political and economic inputs to the decision-making process in water resources allocation. A resource allocation model was formulated in terms of network flows; however, it presented problems of assigning value units to political and social inputs and changing decision criteria and was ruled impractical. A new linear programming model was shown to have promise.

A study was performed to determine optimal water resource allocation in the Montana North Central Conservancy District [Foster et al., 1972]. The district covers several river basins and contains numerous existing and proposed facilities (dams, reservoirs, and diversion canals). The study determined the optimal operation method of all these facilities, along with the sizing of the proposed facilities in order to maximize given objective functions. Related efforts in optimal river basin utilization were surveyed, and linear programming was selected as an expedient optimization technique. The problem was formulated by identifying time stages which constitute a repetitive cycle such as a year. With these stages, it was possible to associate operational and capacity variables with network components, which are branches or nodes. Constraint equations were written to reflect network nodal continuity, capacity restrictions, and adjudications such as water rights. A numerical example was considered in which the existing and proposed facilities were aggregated to produce a small, tractable number of facilities. Linear programming was shown to be quite feasible as a decision-making technique for optimum water resource allocation.

The survey of optimization applied to water resource systems just presented shows that linear programming algorithms, in particular network flow algorithms, have been widely used to analyze many water planning problems in the Western United States. When the problem is properly formulated, cost effective solutions can be obtained. One limitation of optimization models is that real problems have many constraints that are difficult to express in the language of optimization and network flows. A second limitation is that optimization seeks a globally-optimal result, while in real planning problems, the participants are often more concerned with optimizing their own local situation than with producing a global optimum.

In this research, we have attempted to overcome the first limitation by using expert system rules as a constraint on the set of feasible networks that can be examined, and to overcome the second limitation by showing the degree of additional cost that is incurred when insistence on a local solution for part of a problem forces departure from the global optimum for the region.

2.2 INTELLIGENT GEOGRAPHIC INFORMATION SYSTEMS

Within the last 10 years, geographic information systems (GIS) have been employed by researchers and practitioners to store, display and relate the large amounts of spatially-based data characteristic of water resources management problems. By coupling GIS to other solution mechanisms, the obvious capabilities of GIS have been extended to facilitate analysis and decision-support for spatially distributed problems. This is often referred to as "intelligent GIS" and the following examples demonstrate recent practice.

Wright and Buehler [1990] demonstrated how the integration of GIS and expert systems technologies can be used to manage land and water resources. They devised a Bayesian ranking system called B-Infer, which is an additional component of the GRASS GIS, whose purpose is to identify good land use plans for military bases.

The Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) engineers and scientists have developed several software systems to support water resources and environmental decision making [Strzepek and Chapra, 1990]. CADSWES advanced decision support systems use high-resolution graphics, artificial intelligence, and GIS together on workstations. Two systems have been developed by CADSWES for governmental planning and management. At the Santa Ana Watershed Project Authority (SAWPA) in California, the QUEST (Quality Evaluation System) system links QUAL2E, EPA's principal stream water quality model, with pre-processors and post-processors. The system enables planners to quickly examine many alternatives for waste load allocation on streams, permitting them to develop a more comprehensive grasp of the impact of their decisions. A multifaceted decision support system was described which automates the U.S. Bureau of Reclamation's 24-month study of Colorado River tributary runoff. The system includes an intelligent user interface for the existing 24-month model, an expert system based on the knowledge of the current master engineers, and direct software links between the river model and forecasting systems. Both of these systems use a simplified GIS as a spatial display device for the river system.

Arnold et al. [1989] proposed a conceptual approach to the development of an intelligent GIS that incorporates knowledge processing capabilities for the surface water problem domain. Special attention was given to object oriented methodology, interfaces between numeric data and symbolic knowledge representation, and to dealing with uncertainty.

While the systems just described all use elements of artificial intelligence and GIS, none of them uses a full-fledged expert system and GIS, which is what has been done in the research reported here. The Nexpert Object expert system and the Arc/Info GIS are coupled to form a synthesized system for relating the spatial objects upon which expert system rules operate, which is directly connected to the corresponding geographic features and their tabular attributes in the GIS. This research is the first time this task has been accomplished in water resources planning with problems of significant spatial scale.

2.3 EXPERT SYSTEMS

Expert systems constitute a segment of computer technology in the broader field of Artificial Intelligence. These systems are characterized by a set of facts or objects and a set of rules, known collectively as a knowledge base, and they have incorporated within them an inference mechanism that allows the sequencing of processing rules to form conclusions [Jackson, 1986]. There are two types of sequencing or chaining of rules: backward and forward. Backward chaining is best seen in the classic example of expert systems—medical diagnosis. If one condition is true, check another condition upon which the first condition depends; if it is true check another, and if it is also true, continue checking and searching back through the knowledge base until a cause is identified. Conversely, forward chaining is the process of determining new conclusions from a given set of facts. For example, given the status of factors critical to the operation of each vehicle in a fleet of vehicles, and given a set of rules about the factors required for a vehicle to operate, an expert system can report which vehicles are inoperable and prepare a list of the needed repairs.

Expert systems that have been carefully designed and developed can perform in a limited domain about as well as a professionally trained human [Jackson, 1986]. The computer system relies primarily on rapid search procedures while a professional relies on more creative and connective mechanisms of associative memory (deduction, intuition, and inference). If the body of knowledge is sufficiently well defined and of moderate size, the efficiency of the search may be unimportant, and search by a machine may in fact be preferable to human reasoning in that there is no chance for oversight, and the logic of the search process is explicitly defined.

A typical expert system has a few hundred rules and definitions, and it usually contains one or more heuristic connections that allow it to cut to the essence of a problem without having to process all of the rules it contains. This closely follows the reasoning process of human experts and speeds up processing if a reliable heuristic exists. In very recent literature, some researchers have explored the utility of expert systems with respect to their ability to capture and define experience-based reasoning for decision support. The following are examples of this work.

Nieuwkamer and Winkelbauer [1992] developed a rule-based expert system named MEXSES for environmental impact assessment of water resources development projects. The system has a link with external models and makes use of their computational power during the inference process. The information in MEXSES on which the impact assessment is based, is stored in the system's knowledge base in the form of production rules. The expert system's inference engine interprets the information in the knowledge base and generates a conclusion about the environmental impact of the problem on the system under consideration. A model-specific program was created to interface with the other programs. The problem of reservoir sedimentation was selected to test the link. The main result of the integration of the reservoir sedimentation model in the hybrid rule base is that the established link demonstrated the feasibility of invoking a numerical model from the MEXSES expert system and using the model results in the reasoning process.

Palmer and Holmes [1988] described a decision support system used to aid in drought decisions. Its components included an expert system, a linear programming model, data base management tools, and computer graphics. The expert system incorporated operator experience and intuition using a rule base developed through interviews with management personnel from the Seattle Water Department. The expert system integrated the other programming techniques into a single system. A linear programming model determined system yield and optimal operating policies for past hydrologic regimes. Data base management and graphics software stored and facilitated the display of over two thousand operating policies to decision-makers. The system provided user-friendly support to help decision-makers explore a wide range of management alternatives.

Greathouse et al. [1989] report on over 40 small- and large-scale decision support systems. These range from data bases with a few obvious rules to systems capable of evaluating conditions of toxic hazard and recommending remediation measures. One of the chief advantages cited by the authors of using expert systems in environmental control is that of attaining consistency in agency response from one site to another. The systems allow for the distribution of scarce expertise and will find many uses such as report generation, emergency response assistance, hazard identification, planning and training.

When expert systems were first introduced about 10 years ago, great promise was held out for the intelligence it was thought that they would bring to problems involving complicated logic. Much of that promise faded away when it became clear that the class of problems to which expert systems can be applied is quite small, and that trying to apply expert systems to very general problems was of limited utility because there are often exceptions to rules and special cases which are sufficiently influential that they govern the final result. Experience with the use of expert systems suggests that they should be applied to problems where

(1) the logical rules that should govern the system can be explicitly identified and there really is no other way of expressing this logical system.

(2) there are a very large number of repeated applications of the same type of logical systems.

The water planning problem studied here generally satisfies these conditions because planning rules and guidelines are stated in a logical, even legal, language that is very difficult to quantify by other means, such as by writing optimization codes. Also, in Texas, the whole state is conceptually represented in a consistent way for water planning so a very wide area of repeated applications is possible.

3.0 METHODOLOGY

Developing systematic water plans for Texas has a long history which dates back to the drought of the 1950's. That event created the recognition in the state that systematic water planning was needed, led to the collection of water use data from all major water users beginning in the early 1960's, and to the development of plans for large-scale state water projects in the late 1960's and early 1970's. However, voters did not approve large scale water transfer schemes to transfer water from East Texas to the High Plains because of their high cost, and later Texas Water Plans during the 1980's and 1990's have been confined to more modest projects for water transfers within regions, and, in particular, within river basins.

The differing legal doctrines governing ground and surface water withdrawals make it much more difficult to evolve balanced plans for the conjunctive utilization of groundwater and surface water than for surface water alone. The state has more than 4500 water supply entities such as river authorities, water districts and cities, which have an uncounted number of individual water supply facilities. There is a very large number of water supply contracts between suppliers and end-use demanders, and sometimes between suppliers and wholesalers, and then between wholesalers and end-use demanders.

In this report are presented two applications of the automated planning system: (1) a special study of a hypothetical problem connecting four supplies with three demands, devised by Texas Water Development Board planning staff to typify common planning complexities and to better ascertain the sensitivity of the basic model too changes in rules or constraints; and (2) a case-study of a 19-county region in South Texas which typifies the overall planning problem.

3.1. THE TWDB WATER PLANNING PROCESS

The history of water planning in Texas has led to the creation of a simplified numerical planning scheme which identifies the principal features of the planning problem without getting immersed in the endless details relating to each particular water supply system. A number of assumptions are made.

3.1.1 Planning Horizon

A planning horizon of 50 years is adopted, beginning with a base year and continuing in 10-year intervals. For example, if 1990 is the base year, then calculations are done for conditions in years 1990, 2000, 2010, 2020, 2030, and 2040. It is inevitable that economic and population projections made over such a long horizon are uncertain. Indeed, one of the motivations for having an automated planning system is to be able to update the plans on a frequent basis as economic conditions change.

3.1.2 Annual Yield Estimates

All planning estimates are for total annual quantities in each planning year. For example, for a city, the quantity considered is the annual volume of water demand for the city, not the demand in the peak day, which is an important design criterion for city water treatment systems. The focus is on the overall water balance of the state rather than the supply and treatment system of a particular water user. Ratios of monthly to annual demand are used in estimating firm yields of reservoirs, but the planning number is still an annual yield figure. The effects of drought on demand are included by increasing the expected demand by a factor derived from historical demand data during normal and drought weather conditions.

3.1.3 Municipal Demand

The annual municipal water demand for each city greater than 1000 population is calculated as the product of population and an annual water use per capita estimate based on historical water use data. Population forecasts are made by a separate procedure which considers demographic and economic factors in each region of the state. In some Texas Water Plans, the effect of water conservation has been included by adjusting the water use per capita estimate. Municipal demand for cities of less than 1000 population and for rural residents is included in the corresponding county water demand estimates. Where a city lies across a county boundary, the portion of the city's demand in each county is estimated to allow later accounting of total demands by county.

3.1.4 Agricultural Demand

The annual irrigation water demand is calculated by taking the product of the irrigated area and an irrigation water use per unit area, determined using climatic data and a soil water balance. Crop water use estimates are done seperately for each crop. The area of each crop irrigated in each county is found by making surveys, so that an annual irrigation water demand totalled across all crops can be calculated for each county. Trends in the irrigated area from historical surveys are used to project the irrigation demand over the planning horizon in each region of the state. Irrigation water demand is an important quantity because it constitutes more than 80% of the consumptive water use in the state, that is, the water withdrawn from surface and groundwater sources that is lost to evapotranspiration. Livestock water use is based on estimates of animal populations in each county multiplied by water use per animal.

3.1.5 Industrial and Other Demands

Annual demands are computed by county for industrial water use divided into categories using the SIC, or Standard Industrial Classification, codes. Water demands are found by multiplying the units of production or dollars of value added in production, by the water use per unit of production or dollar of value added. Special demand estimates are made for very large industrial water users including steam-electric power, oil and gas refining, petrochemicals production, and mining.

3.1.6 Demand Scenarios

The total demand is aggregated for Texas' 254 counties by totalling the municipal, agricultural and industrial demands for all water users in each county. Several demand projection scenarios are constructed based on lower or higher estimates of economic and population growth in the state, normal and dry weather conditions , and alternative levels of water use efficiencies. A water allocation between supplies and demands produced by the planning system described in this report relates to a particular demand scenario.

3.1.7 Physical Water Supplies

The planning process uses physical estimates of available water supplies rather than contracted estimates. For example, a reservoir system may have a firm yield which is totally committed based on contracts for future supplies, but some of these contracts may be for industries or facilities as yet not constructed, so that the reservoir actually has additional supply capacity available beyond its present water delivery volumes. It is this physical capacity for water supply which is the focus of the planning process.

3.1.8 Naturalized Flows

The flows in the principal rivers in Texas have been affected by reservoir construction and by withdrawals along the river. Naturalized flows have been reconstructed for the principal river systems, and these flows are used for allocation of water for direct withdrawal from rivers, taking into account the simultaneous withdrawals of upstream and downstream users. A water adjudication process has been carried out in several of the major river basins where historical water rights that were not being fully utilized have been reallocated to newer water users.

3.1.9 Firm Yield of Reservoirs

The firm yield of a reservoir is the mean annual demand which can be supplied from the reservoir throughout the critical drought of record. All allocations for uninterruptable supplies are based on the firm yield. In some cases, contracts for additional supplies which can be interrupted during droughts are also made, but these secondary supplies are not considered in the planning process at the statewide level.

3.1.10 Dependable Yield of Groundwater Systems

The dependable yield of a groundwater system is equal to its mean annual recharge rate. This rate is, however, a rather elusive quantity, because the rate of recharge of some aquifers is significantly influenced by the degree to which they are pumped. Some Texas aquifers are being mined, that is, their levels are being progressively lowered by pumping in excess of annual recharge. Groundwater studies are made of each aquifer to determine its dependable supply rate. For planning purposes, the aquifers are divided by counties into separate supply sources. Groundwater availability is determined as a combination of dependable yields and managed withdrawals depending on the aquifer. One of the extensions desired by the TWDB to its present planning methods is the capacity to construct a grid over each aquifer and to evaluate the effect of pumping in each county on the overall water balance of the aquifer. Although that is not accomplished in the automated planning system presented here, the fact that this system is based on a GIS layout of the data, and that groundwater models can be connected to GIS, means that at a later time this detailed groundwater planning feature could be added to the planning system.

3.1.11 Water Allocation

The heart of the water planning process is the procedure of water allocation in which available supplies are matched with demand requirements. This is done by an allocation or matching process in which individual water sources, such as a particular reservoir or aquifer supply, are allocated to particular demands such as a city or agricultural demand in a county. This is done under the constraints that the supply allocated from a particular source cannot exceed its available capacity, and the requirements of each demand must be met. After the allocation is made, areas of deficit are located where allocated supplies are less than demand requirements, and a search is launched for additional supply sources which could meet these demands. Conceptually, a region of analysis is specified around the deficit area, potential or existing supply sources with additional unallocated capacity are identified, and cost estimation of each potential allocation among these additional sources is done to identify the most cost-effective solution. This solution has ripple effects, because a supply allocated to one demand is then no longer available to meet demands elsewhere. The current planning process involves many iterations of this process, trying at each iteration to arrive at a more reasonable and cost-effective solution from the overall viewpoint. Such a solution may not satisfy local interests, however, so compromise is required.

The water planning system in this report helps clarify the process of water allocation by using rules to describe the logic of how the allocation is actually being carried out, rather than relying solely on the intuitive judgment of the planners. The automated system allows simultaneous rather than sequential determination of allocations so that the overall cost-effective allocations are obtained. The 19-county case study region in South Texas used in this study was chosen to surround the city and region of Corpus Christi for which water supply shortages are projected in the coming decades, so allocations of supply from more distant sources are needed.

3.2 MODEL CONCEPTUALIZATION

In the water allocation problem, areally distributed entities (reservoirs, aquifer, counties, cities, etc.) are conceptualized as lumped parameter systems whose properties are assigned to representative points lying within their geographic boundaries. Thus, the real planning problem which is described in geographic space by areas, lines and points, is represented simply by points and lines, or more specifically by a directed graph; that is, by a set of nodes and arcs (directed line segments) between them. The requirements of spatial topology call for the following rules:

(1) a node is a vertex or point.

(2) an arc is a link joining a pair of nodes.

(3) a path is an ordered sequence of arcs in which the initial node of each arc is the terminal node of the preceding arc in the sequence and all of the nodes in the sequence are distinct.

(4) for an arc (i, j), node i is called the "from-node" and node j is called the "to-node".

(5) arcs can join only at nodes.

As Chen [1990] shows, a complete directed graph can consist of many disconnected subgraphs of nodes and arcs, which is how the water allocation problem actually exists. There are many local water supply systems rather than a single large interconnected system. In fact, extension of infrastructure with new pipelines or canals is sometimes used to connect previously disconnected systems in order to make better overall use of water supplies.

In the conceptual water allocation model, we distinguish two types of demands: city (>1000 population) and county demands; and three types of supplies: reservoirs, aquifers and river diversions. This classification does not allow for requirements for instream flows and for bay and estuary flows so that there are additional demands for natural resources management that need to be included later. There are at least three levels of abstraction at which this conceptual model can be expressed: (1) a geographic representation, (2) a functional representation, and (3) a planning representation, as illustrated in Figure 3.1 and described below.

In the *geographic* representation, the features making up the water system, such as cities, counties, rivers, etc., are represented in their natural GIS format, that is, as points, lines, polygons, etc., in various data layers. The geographic representation is suitable for displaying digital maps of the problem, but is limited in its use for planning because of the disconnection of features between data layers.

In the *functional* representation, the geographic features are abstracted into a node-link network, where each node represents a particular area feature (e.g., representing a county by its centroid) or a particular control point on a linear feature such as a river diversion point or a point where instream flow requirements are defined. The functional representation is a detailed schematic diagram of the physical elements in the water system. All of the elements in the functional representation are actual physical items, either those that presently exist or those that could in the future be constructed. The yields of supply sources, the demands of end users, and the capacities of transmission facilities can be defined in the functional representation, as can the costs of constructing new facilities and of transporting water through existing systems.

Finally, progressing to the *planning* representation, a further abstraction of the functional representation is made in which a new network of allocations between supply and demand nodes is defined. In the planning representation, no new node locations are defined, but what is defined are allocation arcs (and perhaps new "planning" nodes), directly connecting node locations in the functional representation. In other words, a particular arc in the planning representation is a water allocation between two node locations that may, in the functional representation, require transmission of water along several links and through various kinds of nodes. A node location in the functional representation that represents a city serving as a wholesaler may, in the planning representation, be both a supply node and a demand node, such that the total demand required for the wholesaler is the sum of its own demand and the demands of the entities it serves. Its supply capacity is equal to the sum of the supplies coming into it. Thus, the "demand" requirement for a particular city node in the planning representation can be greater than the physical demand required by that city in the functional representation. It is in the creation of the planning representation that the legal, environmental and institutional constraints may be brought to bear, such as limitations on interbasin water transfers, rules about water supply districts supplying the cities within their region, and so on.

For implementation in a GIS, the planning representation has the significant advantage that all supplies and demands are represented as points, and they can be collected into a single data layer. Moreover, a particular allocation plann can be displayed as a geographic coverage of lines between points of supply and demand, which is a very useful mechanism for planners to visualize the planned allocation.

Ignoring for the moment the particular way in which entities are represented in a GIS—an expert system, data files, or a network flow algorithm—let us consider real water systems and the way in which they can be symbolized. That is, we want to create abstractions of water entities at various levels, so as to clarify the basic nature of the problem we are examining. Once an adequate conceptual model that reflects the elements and issues we wish to consider in the real system is constructed, then we can turn to the available technologies and discuss how to represent the conceptual model by means of various kinds of computer programming and software tools. It may occur that the practicalities of that process will force compromises on the conceptual model.

3.2.1 Water Entities

Water entities are defined as geographic features which store, transmit, or use water (see Table 3.1). There are two types of each kind of entity. Storage entities consist of surface storage facilities (reservoirs or lakes), and subsurface storage facilities (aquifers). Transmission entities consist of surface channels (rivers, canals), and pipelines. Usage entities consist of cities greater than 1000 population, and counties.

Natural resource entities such as bays, estuaries, fish hatcheries, endangered species habitats, and the like, typically require that water be released for their use or maintenance. They can be either real usage entities (bay and estuary) requiring water to be released that is then lost from the system, or they can be transmission entities upon which instream flow requirements are defined.

Each of the storage and usage entities is assumed to be a spatially discrete areal feature (at the geographic and functional representation levels) whose properties can be attached to a point located within its actual (planning level) geographic extent, though not necessarily at its centroid. These are then referred to as storage and usage nodes, respectively. Each of the transmission entities is a linear feature which can be symbolized by a straight line or a set of straight lines connecting actual geographic points on the feature.

3.2.2 Nodes

The above discussion implies that there are five kinds of nodes. These nodes and their respective symbolic representations are presented in Table 3.1. In the event that a particular geographic entity, such as an aquifer, is too large to be represented as a single entity, it can be broken into several entities connected by a natural transmission system as shown in Figure 3.2.

3.2.3 Arcs

All arcs are directed arcs, that is, they have a from-node and a to-node. A supply is a combination of a node and an outgoing arc as in Figure 3.3a. A demand is a combination of a node and an incoming arc as in Figure 3.3b. The instream flow at a particular point on a river would thus be symbolized as in Figure 3.4a, while bay and estuary flow would appear as in Figure 3.4b at the end of the river transmission path.

3.2.4 Allocations

An allocation is a physical transfer of water between two nodes in the network. The nodes may be close together or far apart, and the allocated water may be transmitted through several nodes between its origin and its destination. Thus, we have a supply node, a demand node, and an allocation which passes between them. The allocation is a defined quantity (and sometimes defined quality) of flow. These relationships are depicted in Figure 3.5. The cost C associated with an allocation is a function of the volume of water moving through the transmission entities. An allocation arc is described by 5 attributes as shown in Table 3.2.

3.2.5 Wholesalers

A water entity that both supplies and demands water functions as a wholesaler. Thus, the conceptualization of a large city having a supply from a reservoir that then serves a smaller neighboring city might look like Figure 3.6. In the planning network representation, the supplier-wholesaler-demander relationship is modeled as in Figure 3.8.

3.2.6 Allocation network

An allocation X_{ij} is the amount of water allocated from node i to node j. This is symbolized by an arc (i, j) between two nodes of the network. Allocations are characterized by the amount of water transferred between them W, by its quality q and the transport cost $C(i, j, W)$ which is a function of the amount of water shipped along the arc and the route of the arc. If we assume that demander j pays supplier i the cost $C(i, j, W)$ of delivering amount of water W, then we can represent the allocation as

$$X_{ij} = X(i, j, W, q, C)$$

The allocation of water from a supply node i must not exceed the available supply S_i at that node, or

$$\sum_i X_{ij} \leq S_i$$

where S_i is the capacity of the i-th supply. Similarly, the allocation of water to a demand node j must be less than the amount D_j demanded at that node, or

$$\sum_j X_{ij} \geq D_j$$

3.2.7 Cost apportionment

Suppose a particular allocation X_{ij} involves a cost to a supplier of C_s and a cost to a demander of C_d simply to achieve the transfer of water and in addition the demander has to pay the supplier P for the water received. The total real cost in economic terms is $C_s + C_d$ but the suppliers cost is $C_s - P$ and the demanders cost is $C_s + P$ as shown in Figure 3.8.

The total net cost or benefit to the suppliers of all such allocations is

$$C_i = \sum_i (C_s - P)_{ij}$$

where $(C_s - P)_{ij}$ is the net cost or benefit of allocation X_{ij}. Similarly, the total net cost to the demander is

$$C_j = \sum_j (C_s + P)_{ij}$$

If there are a number of alternative plans or strategies by which allocations can occur which will meet all demands of j's, then the strategy which is optimal for each individual supplier is that which maximizes their net benefit or minimizes their net cost. The equilibrium strategy in the Nash sense is that strategy for which no supplier and demander can move to an alternative allocation and increase their benefits or decrease their costs. The choice of the payments P for each allocation is thus a decision problem to be solved after the allocation of flows has been done for a particular strategy.

This cost allocation problem is very complicated, and while it is investigated in this report by using a simplified hypothetical system, a general solution for water planning which simultaneously allocates water and costs according to objective criteria has not been devised. What is presented is a water allocation system using the planning representation of the problem, assuming pre-specified cost apportionment when a particular node serves as a wholesaler between a supply node and a demand node.

3.3 MODEL IMPLEMENTATION

The basic elements required for the solution of the water supply allocation problem considered in this research are summarized in Table 3.3. The problem is to find the set of water allocations which best distribute the available supplies to meet the demands.

A set of potential links or arcs P_{ij}, $i = 1,..., N; j = 1,..., M$ exists between the supplies and demands. Each potential arc has an associated vector of characteristics $\vec{c}$ which includes intrinsic characteristics of the arcs (e.g., the unit cost and feasibility of transporting water on an arc). These characteristics are determined from logical rules or as functions of other characteristics. An allocation X_{ij} is the amount of flow in an arc from a source i to a demand j. These allocations are the decision variables for the water allocation problem.

Three distinctly separate software components are used in an integrated fashion to solve the water allocation problem:

(1) A geographic information system (GIS) to store the data and create geographic displays of alternative water allocation plans,

(2) An expert system to modify the characteristics of the potential arcs between supplies and demands to allow for rules or constraints on the planning process, and

(3) A network flow solver to balance the flows on the resulting network in order to satisfy the demands at minimum cost.

3.3.1 Geographic Information System

The first step is to load all of the pertinent data into the GIS. Items that are alike are stored together in the data base and related to the whole by their geographic coordinates through the process of creating a GIS coverage. A coverage is a tabular organization of like items, (e.g., points, lines, and polygons) wherein the geographic features appear as rows in the table and the characteristics of the features, known as attributes, appear as columns. A coverage is analogous to a layer in a multi-layer thematic map. The number of coverages and the number of items in each coverage is virtually unlimited. For example, a single coverage might detail municipal boundaries; another might identify the location of water meters; several might be employed to describe the extent of vegetation communities and soil types. The themes are countless and depend upon the kinds of data available and the types of problems that are at hand. Whereas the coverages are composed of elemental items such as points, lines, and polygons, the elements themselves may have attached to them other attributes such as identification numbers, names, dates, physical quantities, status flags, etc. GIS capabilities with respect to selective retrieval and depiction are obvious, but of equal importance is their capacity to be utilized as data base managers to efficiently store, modify, update, and relate large amounts of information.

Initially, all the data are stored in three GIS coverages (see Table 3.4). Two point coverages, SUPPLY and DEMAND, are defined to contain the raw data describing the supply and demand information. A line coverage, PARC, describing the potential arcs or links by which water may be delivered is generated from the information in the SUPPLY and DEMAND coverages and from external definitions and assumptions. The first and second group of attributes of the PARC coverage are inherited from the endpoints of the allocation arc, i.e., the corresponding entry in the SUPPLY and DEMAND coverages. The third group of attributes in the PARC coverage are evaluated separately in the GIS, expert system, or network flow solver as needed. This third group of attributes contains the intrinsic qualities of an allocation arc such as its length, capacity, unit transport cost, flow, and feasibility. Figure 3.9 depicts these tables and their structure. The GIS affords powerful capabilities with respect to manipulating the data within coverages. Several functions aid in the creation and maintenance of the data sets. Other functions are available for computing distance, area, line intersections, polygon overlays, etc. Selective depiction of the data contained within the coverages is also facilitated by the GIS.

3.3.2 Expert System

The data structures used in the GIS and expert system are different and yet they have some striking similarities. Since the GIS is a relational database and the expert system is an object-oriented expert system shell, the transfer of data between them requires a translation of the data structures. The GIS database is organized in tabular form: three coverages with attribute tables, each with multiple rows and multiple columns. Each coverage in the GIS corresponds to a class of objects in the expert system. Each of the rows in the coverage attribute table becomes an object in a class and all of the GIS tabular attributes become properties of the associated object in the expert system. Objects inherit their property types and in some cases their property values from their parent class. These two data models, relational data base and object oriented, have a direct correspondence. As the data are transferred from the GIS to the expert system, it is necessary to translate from relational database structures to object-oriented data structures. The mapping of items into the object oriented data structures is controlled by data import specifications prior to the actual transfer. This translation is quite straightforward and is handled routinely by the data import/export features of the GIS and expert system software. The object oriented data structure is depicted in Figure 3.11.

Central to the expert system is a production system which consists of a rule-set, a rule-interpreter, and working memory. Working memory is examined and modified by this production system as it applies the rule-interpreter to the rule-set. In backward chaining, the rules are triggered by an initiating suggested hypothesis which, in conjunction with the backward chaining of successive hypotheses controls the activation and selection of subsequent rules at each cycle of logic processing.

In the water allocation problem, the rules have the effect of modifying the set of values associated with the attributes of the PARC objects. By this process, the cost and feasibility of individual objects (arcs) within the PARC class may be adjusted by the actions of rules that refer to the class as a whole. Rules may also refer to individual objects or to sub-classes of objects.

After the data represented in the class of potential arcs have been processed in the expert system, the modified data set is transferred back to the GIS and the PARC coverage is updated with the updated information.

3.3.3 Network Flow Solver

The next step is to find the least cost set of flows on the network of allowable arcs remaining after the expert system rule processing. This solution must satisfy the water demands without exceeding either the available supply or the arc capacities. This is a classic problem in Operations Research known as the transportation problem and is easily conceptualized in the network form as depicted in Figure 3.11.

The nodes on the left-hand side of the network shown in Figure 3.11 represent the sources of supply, and the nodes at the right represent the demands. The lines between nodes indicate the allowable arcs, and the information in brackets and parentheses indicates the costs and constraints for the problem. This characterization of the transportation problem may be formulated as a linear programming problem as follows:

Minimize $$\sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij}$$

Subject to

$$\sum_{j=1}^{n} x_{ij} \le s_i \qquad \forall_i$$

$$\sum_{i=1}^{m} x_{ij} = d_j \qquad \forall_j$$

$$x_{ij} \ge 0 \qquad \forall_i, \forall_j$$

A slightly more general network flow model can more accurately represent the water allocation problem we are considering here. In particular, intermediate nodes can be used to portray transshipment points in the network. Transshipment arises when we consider run-of-river sources and large municipalities acting as wholesalers of water to smaller demanders. The depiction of the network is presented in Figure 3.12. This mathematical programming model can be solved by network simplex techniques as described by Jensen and Barnes [1981].

Once the network flow problem is solved, the flow on each arc is returned to the GIS PARC coverage and inspection is performed to determine if any assumptions of the planning process have been violated. If necessary, the problem can be resolved using the flows from previous iterations to update the assumptions. This step may be necessary because the unit transport cost is itself a function of the decision variable, flow.

Table 3.1 Water Entities or Features Which Store, Transmit, and Use Water

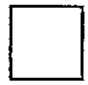
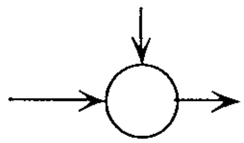
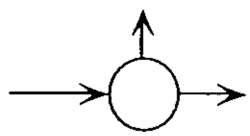
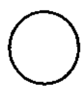
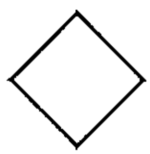
Water Entities	Description	Symbol
Storage Entities	Surface storage (reservoir or lake)	
	Subsurface storage (aquifer)	
Transmission Entities	Natural channel (river, canal, subsurface leakage)	
	Pipeline	
	Return flow	
	Diversion	
Usage Entities	City (pop. > 1000)	
	County	
	Natural resources	

Table 3.2 Attributes of a Water Allocation From a Supply *i* to a Demand *j*

Attribute	Symbol	Units
Source node (origin)	S	(x-y coords)
Demand node (destination)	D	(x-y coords)
Amount	W	(ac-ft/yr)
Quality (perhaps several constituents)	q	(mg/l)
Cost	C	($)

Table 3.3 Attributes of a Water Allocation Problem

Set	Symbol	Characteristics
Water supplies or sources	$s_1 \cdots s_N$	$a_1 \cdots a_I$
Water demands	$d_1 \cdots d_M$	$b_1 \cdots b_J$
Potential arcs	$P_{11} \cdots P_{NM}$	$c_1 \cdots c_K$
Allocations	$X_{11} \cdots X_{NM}$	

Table 3.4 Coverages in the Water Allocation GIS Data Base

Coverage	Symbol	Attributes
SUPPLY	$S \circeq \{s_1, s_2, \cdots s_n\}$	$A \circeq \{a_1, a_2, \cdots a_i\}$
DEMAND	$D \circeq \{d_1, d_2, \cdots d_m\}$	$B \circeq \{b_1, b_2, \cdots b_j\}$
PARC	$P \circeq \{p_{11}, p_{12}, \cdots, p_{1m}, \cdots, p_{n1}, \cdots, p_{nm}\}$	$C \circeq \{a_1, \cdots, a_i, b_1, \cdots, b_j, e_1, \cdots, e_k\}$

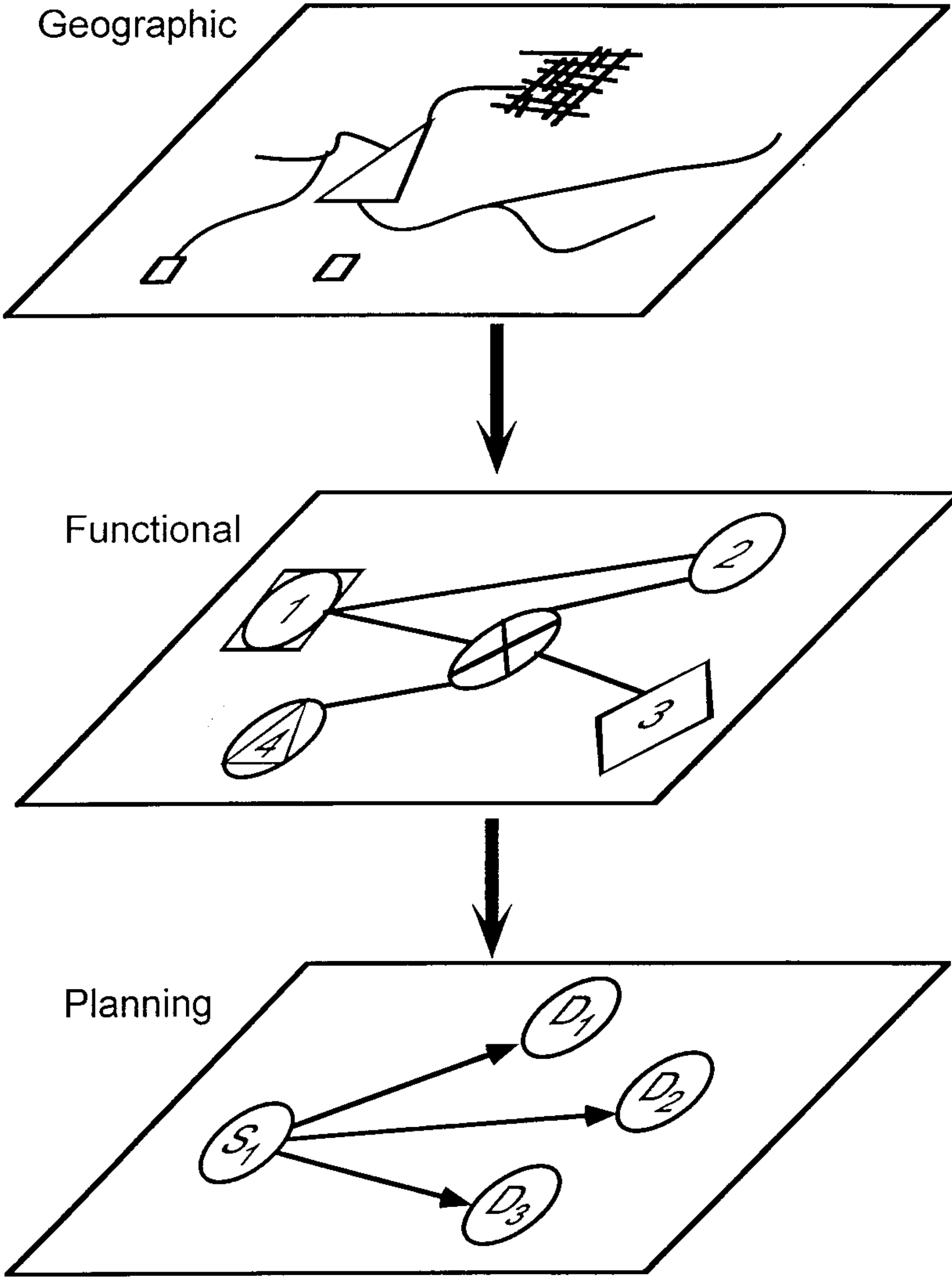


Figure 3.1 Levels of abstraction in the water allocation problem.

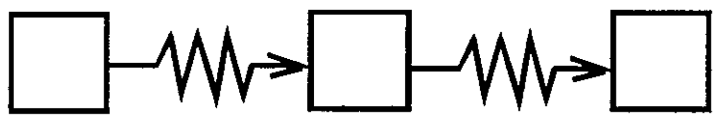


Figure 3.2 Functional level representation of a water entity decomposed into three component parts that have natural transmission routes between them.

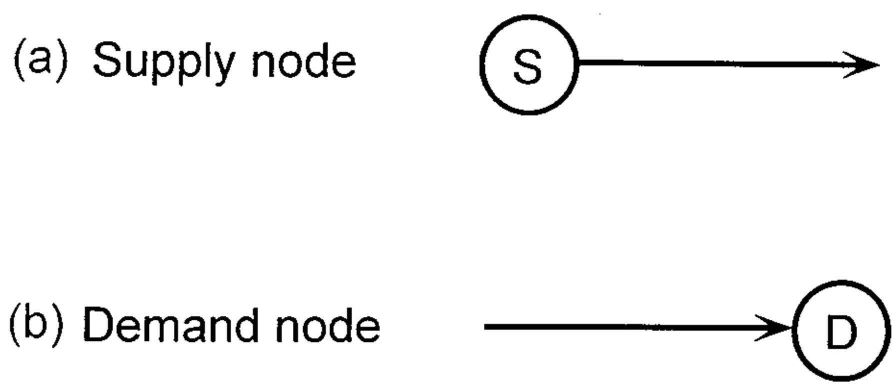


Figure 3.3 (a) Functional level representation of a supply node; and (b) functional level representation of a demand node.

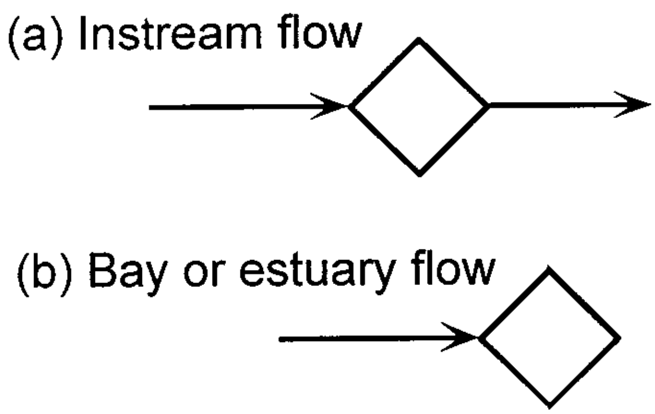


Figure 3.4 Functional level representation of a natural resources node, (a) represents an instream flow, and (b) represents a bay or estuary release.

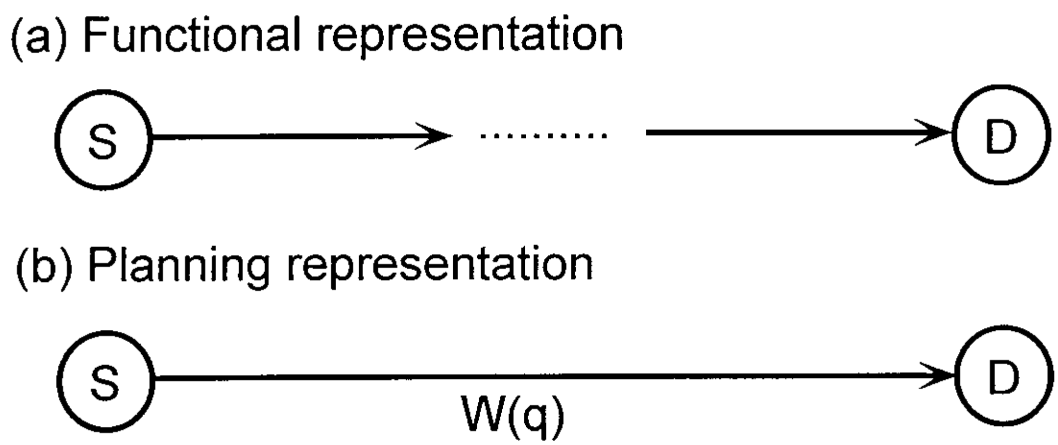


Figure 3.5 Representation of an allocation, *W(q)*, (a) functional representation, and (b) planning representation

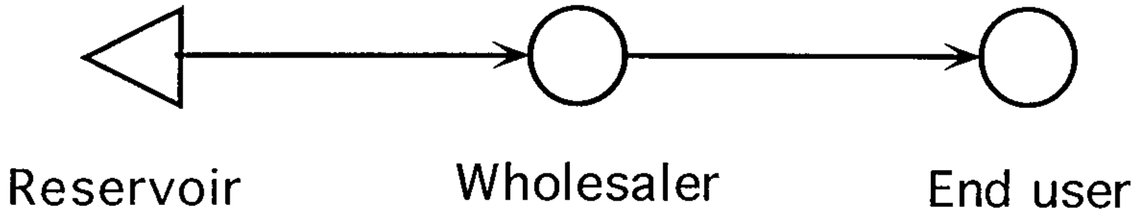


Figure 3.6 Functional representation of a supplier, a wholesaler, and a demander of water.

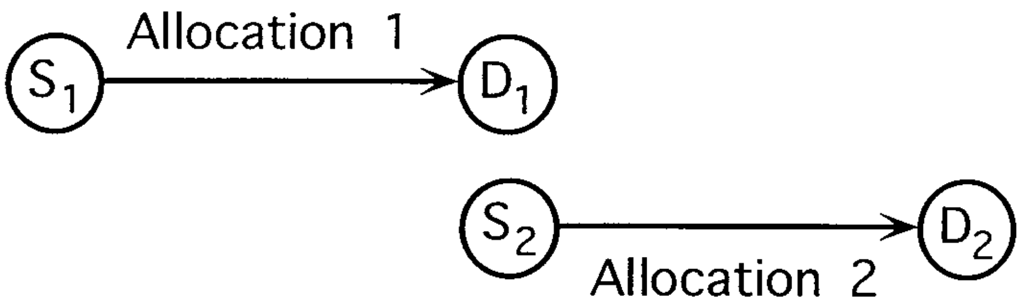


Figure 3.7 Planning representation of a supplier, a wholesaler, and a demander of water.

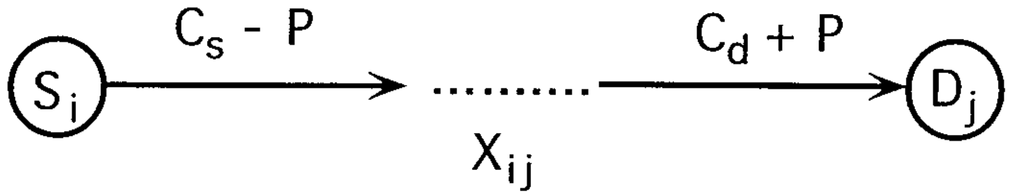


Figure 3.8 Representation of supplier, wholesaler, and demander costs for delivering water.

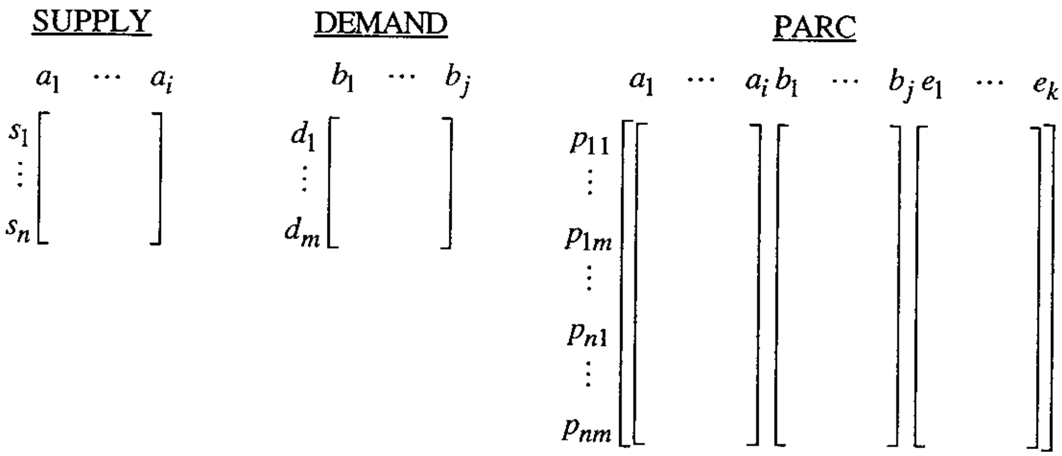


Figure 3.9 Water allocation problem GIS coverages.

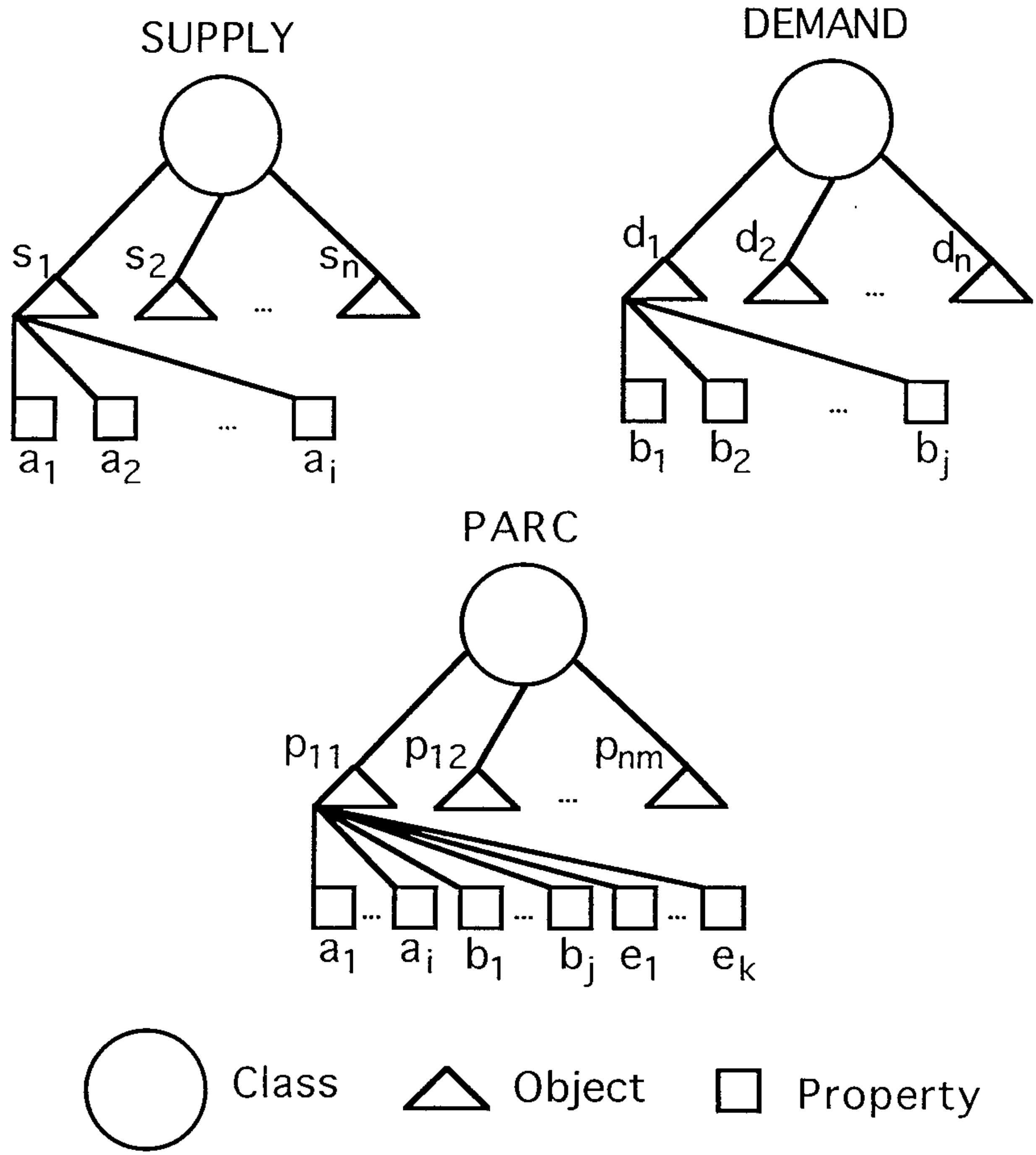


Figure 3.10 Object oriented data model in the expert system.

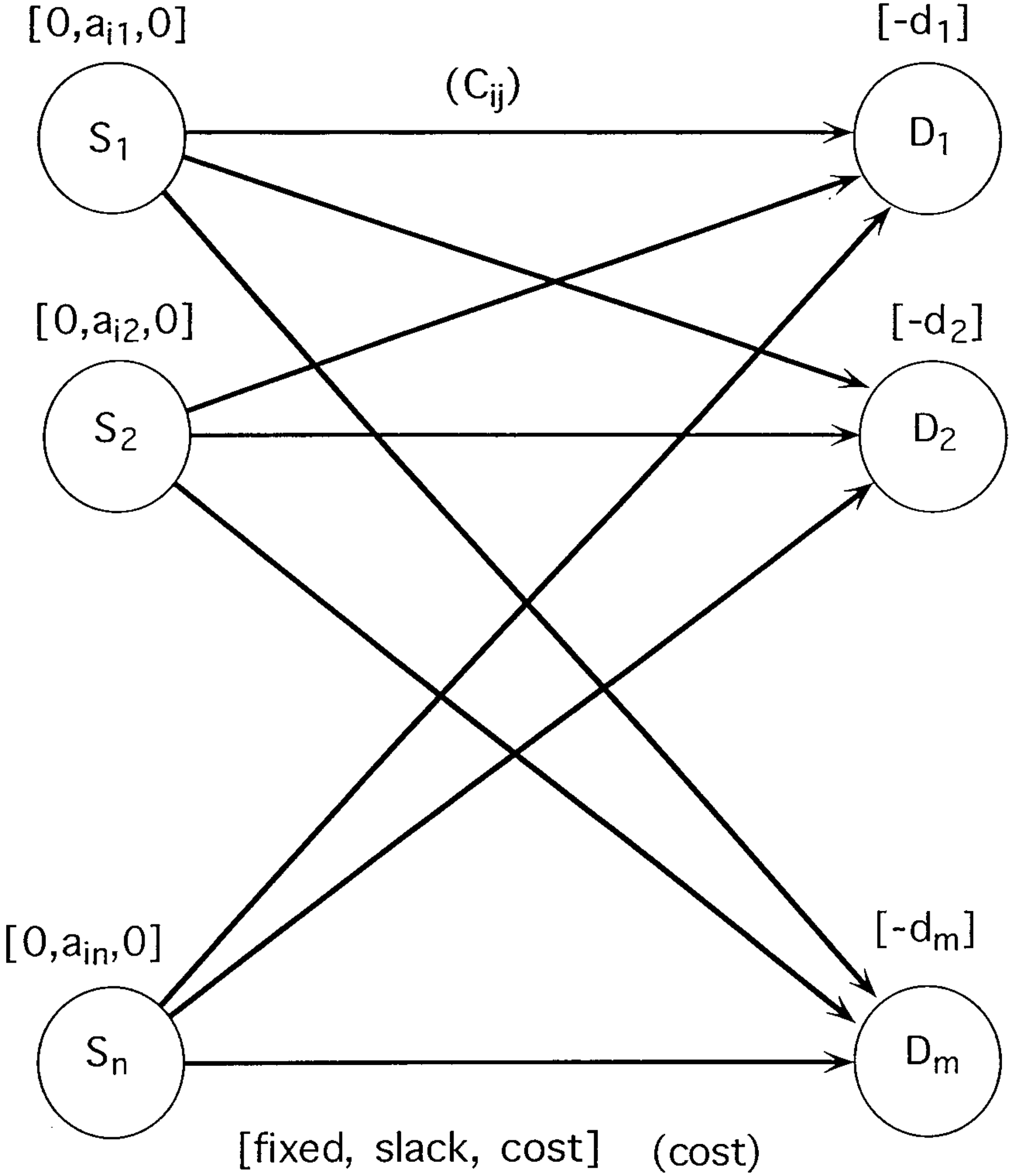


Figure 3.11 Network representation of a transportation problem.

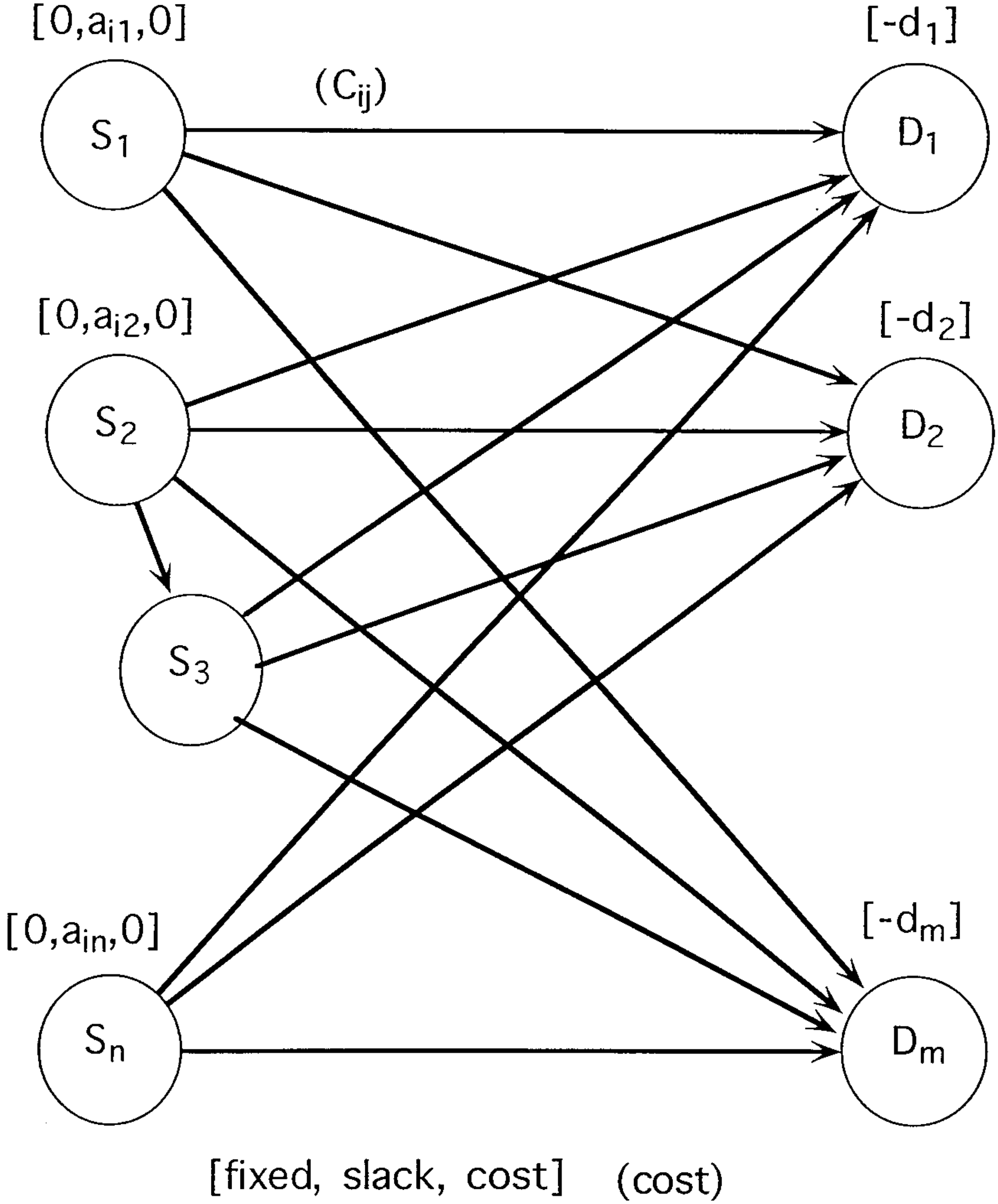


Figure 3.12 General network representation of a transshipment problem.

4.0 SOLUTION OF AN EXAMPLE PROBLEM

4.1 Introduction

From the description presented in Chapter 3 of the conceptual model underlying the planning system, it is obvious that this model is complicated, both by the nature of the planning problem itself, and by the way in which this problem is represented in the three different software systems (GIS, expert system, network flow algorithm) whose interconnected operation is used to solve the planning problem.

Recognizing these complications, Texas Water Development Board planners created a simplified example problem on which solution strategies could be attempted without inducing all the additional complexity found in real systems with a large number of supply and demand nodes. In this chapter, the solution of this problem is described, and the application of the planning system to the 19-county South Texas study region is presented in Chapter 5.

The example problem is depicted in Figure 4.1, with pertinent data listed in Table 4.1. There are four potential sources of supply (the Up river and Down river diversions, the reservoir and the well field) and three demands (small towns #1 and #2, and the large city between them). The data pertaining to these entities can be converted into the GIS coverages SUPPLY and DEMAND based upon the structures in Tables 4.2 and 4.3. A third coverage can be generated from the combination of supply and demand data. This coverage, named PARC for "potential arc," consists of the set of all possible links or arcs between supplies and demands. These are the arcs of the network flow model, and ultimately, when the network is "solved", the flow in each arc represents the allocation of water from its source to its demand. The structure of the data for the PARC coverage is shown in Table 4.4. The formulation of the GIS coverages takes the problem from the geographic representation of the problem to a functional representation as shown in Figure 3.1. At this level of representation, the different supplies and demands are clearly identified and the various possible links between them indicated.

The first nine attributes in the PARC coverage are inherited from the source and demand coverages. The lower bound is almost always set to zero. The upper bounds are initially set to the maximum amount that could ever be expected to flow in the arc, which, in most cases, is the lesser of: (1) the full capacity of the supply end of the arc; or (2) the full demand of the demand end of the arc. The unit cost for each arc represents the cost to transport a unit of flow in the arc and must be determined from an appropriate cost function. Flow is set initially to the upper bound and feasibility is set to 0, meaning that the arc is feasible. These values are decision variables in later steps of the solution procedure.

The GIS provides a great deal of flexibility for augmenting or modifying the structures and the data set. For example, if it becomes important to identify those items in the source coverage that fall within the boundaries of an aquifer recharge zone, the GIS facilitates this determination with its polygon overlay functions and the information can be incorporated into the individual records of the coverage appropriately. Similarly, the demand coverage can be easily aggregated or disaggregated with respect to demands of particular types or water quality requirements using the features of the GIS database manager. These features are not needed for solution of the example problem, however.

Once the SUPPLY, DEMAND, and PARC coverages are defined, the data is transferred to the expert system for rule processing. Through this translation process the three GIS coverages, SUPPLY, DEMAND, and PARC, are converted to classes of objects in the expert system. The expert system then invokes a set of logical rules that result in the modification of some attributes of the class PARC's objects. These rules are derived from the expertise and experience of planning professionals within the TWDB and the authors. Some of these rules will eliminate obviously unacceptable transfer links or arcs. Other rules eliminate or penalize certain arcs due to their political or environmental attributes, while still others impose the effects of water rights requirements. Some simple examples are shown in Table 4.5.

In the first example rule, all potential arcs with unit transport cost greater than 100 are eliminated from the network. In the second example, arcs are eliminated that connect demands in one water control and improvement district (WCID) to supplies in another. The third rule penalizes links that send water from west to east. The infeasibility flag is set equal to the number of the rule that caused the allocation to be considered infeasible. This information is used in post-processing to analyze the sensitivity of the resulting solution to changes in the rule set.

After applying the rules, the expert system then transfers the information back to the GIS and the coverages are updated with modified cost and infeasibility information. At that time the coverages are transferred from the GIS to the network generator to create an input data set for the network solver.

A network model is a natural tool for the abstraction of this problem. The nodes of the network represent supply or demand points in the system and the arcs represent the pipelines, canals, rivers, etc. necessary to transport water from one point to another.

Capacities and unit transport costs are incorporated into the node and arc elements and the linkages are configured to closely model transportation relationships that occur in practical operational systems. Run-of-river and demander-wholesaler relationships are easily portrayed in the network diagram. Figure 4.3 displays the network representation of the example problem defined in Figures 4.1 and 4.2. The numbers shown in the square brackets near each supply node are (1) any fixed flow that must pass through a supply, (2) the firm yield of the supply and (3) the costs in place of the supply, respectively. The numbers shown in the square brackets to the right of each demand node are the demands for that node. The numbers shown in the parentheses on each arc are the unit transportation costs along the arc.

A critical element in the success of this method is the automatic and accurate determination of the costs on all of the arcs that link the potential sources to the demands. It is, in large part, these costs that determine the resulting solution. The costs of source water are represented in the network on those links that run from the master source node to the individual source nodes. These costs are reported by the suppliers and are a part of the raw data set. More problematical are the transport costs. There are as many of these as there are potential arcs in the network; that is to say there are too many of these to deal with individually. The costs must be determined automatically as the potential arcs are set up. This is accomplished in a cost function subroutine that has been designed in a modular fashion so that it can be revised and expanded as improvements warrant. It may be that the perfect transport cost function will never be developed, but by making things modular, improvements can be incorporated into the procedure without necessitating wholesale restructuring of the data base in the GIS or the rule set in the expert system.

Initially, the cost subroutine was a very simple function of distance, thus allowing the other parts of the system to be developed and tested without having to wait on the perfection of the transport cost function. A more complex subroutine has been developed incorporating TWDB pipe cost analysis techniques [TWDB, 1967, 1977]. Unfortunately, the unit transport cost of an arc is a function of the flow in the arc, which is not known *a priori*. As a first approximation, the unit transport cost on an arc is computed assuming that the arc is flowing at full capacity. The system is then solved as a linear programming problem by the network simplex algorithm [Jensen and Barnes, 1981]. The resulting flows are then compared to the assumed flows. If a discrepancy is present, the new flows are used to update unit transport cost estimates and the system is then re-solved. This process is continued until convergence is achieved.

As an alternative to the network simplex method of solving the network flow problem, the out-of-kilter algorithm has also been coded and tested. Comparison indicates that network simplex is typically 30 percent faster than the Out-of-Kilter method.

If a feasible solution to the network flow problem exists, flows on each arc (allocations) are determined such that total system cost is minimized and all demands are met. However, some rule sets may so severely constrain the network flow problem that a feasible solution can not be found. In this case, the rule set must be examined and constraints relaxed to allow a feasible solution to be found. This process provides valuable information to the analyst regarding the nature of the rules imposed on the system and their overall effect on system design and allocations.

The final allocations and costs are transferred back to the GIS, which affords facilities to present the results in map form for easier interpretation. Also within the GIS, provision exists to compare consecutive runs thereby enabling the analyst to see the effects of changes to the rules or changes to the network itself.

4.2 RESULTS FROM SOLUTION OF THE EXAMPLE PROBLEM

The problem depicted in Figure 4.2 attempts to capture in microcosm the kinds of issues that appear in larger scale water allocation problems. In this example (1) the distances and elevations may favor one solution over another; (2) there is not enough inexpensive groundwater to serve every demand; (3) the large city is in a position to act as a water wholesaler to the smaller towns; (4) the capacity at Source S3 is dependent upon the amount taken from S2; and (5) institutional considerations such as water rights might impose constraints of their own.

The solution of this problem begins by transforming the raw data shown in Figure 4.2 into GIS SUPPLY, DEMAND, and PARC coverages. The attribute tables for these coverages are shown in Tables 4.6, 4.7, and 4.8, respectively.

The TWDB programs PIPE-D [TWDB, 1977] and PIPE-X [TWDB, 1977] have been incorporated into the system to estimate pipe diameter requirements and unit transport costs. The method relies on the pipeline end elevations, transport length, a set of empirical equations to determine a cost per thousand gallons of flow in the reach, and an assumed flow rate in the line. Then the GIS coverages are transferred to the expert system and converted into classes of objects with properties corresponding to the GIS attributes.

Next, a set of logical rules is invoked by the expert system which results in the modification of the cost and feasibility properties of selected objects in class PARC. The information is then transferred back to the GIS and the coverages are modified appropriately.

A network generator program translates the GIS SUPPLY, DEMAND, and PARC coverage information into an ASCII input data file structured according to the input requirements of the network simplex program. Then the solver is run. If a network flow solution exists, an ASCII output file containing the resulting solution is written and then used to update the GIS PARC coverage the results are displayed.

The assumed values of flow are examined and if necessary the problem is restarted with adjusted initial flows and their associated unit costs.

4.2.1 Rule Set No. 1 - No Rules

The results of the first case, where no rules are imposed on the system and all allocation arcs are included as feasible in the network flow solver, are shown in Table 4.9 and Figure 4.4. Water is allocated from supply S1 to demand D1, from S2 and S4 to D2, and from S2 to D3. The total system cost to meet all demands is $239,900.

4.2.2 Rule Set No. 2 - Distance Rules

The results of the next case, where a distance rule is applied, are shown in Table 4.10 and Figure 4.5, the expert system applies a rule that eliminates arcs with unit cost greater than $100 per AF. Although this removes two arcs from the analysis, the allocations are unchanged from the previous case. Again the total cost is $239,900.

4.2.3 Rule Set No. 3 - Distance and WCID Rules

In the third case, no water is allowed to be transferred out of a water control and improvement district number 100. The results of this solution are shown in Table 4.11 and Figure 4.6. This forces the inexpensive groundwater (source S4) to be allocated to the small town (demand D1). Other allocations adjust as necessary to meet demands and the resulting total cost is $261,000.

4.2.4 Rule Set No. 4 - Penalized Distance and WCID Rules

The final case, the results of which are shown in Table 4.12 and Figure 4.7, demonstrates the effect of a adding a rule that introduces a cost reduction on arcs that transfer water from a wholesaler (city D2) to another demand location (demand locations D1 or D3). Total cost is $256,500. Note that the inexpensive groundwater from source S4 goes unallocated.

Although much more is needed with respect to capturing the knowledge and experience of experts, these brief examples demonstrate that the pieces of the system can be made to work in concert in such a way as to arrive at solutions similar to those of a professional analyst.

Table 4.1 Example Problem Data

Water Entity	Symbol	Supply (AF)	Demand (AF)	Cost in place ($/AF)	Elevation (ft AMSL)
Up river	S_1	500	–	10	1100
Reservoir	S_2	3500	–	20	800
Down river	S_3	$3500-\sum_j X_{2j}$	–	25	750
Well Field	S_4	1100	–	1	1100
Small town #1	D_1	–	500	–	1000
Large city	D_2	–	2000	–	850
Small town #2	D_3	–	1000	–	700

Table 4.2 SUPPLY Coverage Attributes

Description	Symbol
Identification Number	SUPSRC_ID
Transfer Flag	XSRC
Water District Id #	WCIDS
Latitude	LATS
Longitude	LONS
Elevation	ELEVS
Capacity	EXTQS
Cost in place	CIPL
Placename	NAMES

Table 4.3 DEMAND Coverage Attributes

Description	Symbol
Identification Number	DEMAND_ID
Transfer Flag	XDEM
Water District Id #	WCIDD
Latitude	LATD
Longitude	LOND
Elevation	ELEVD
Capacity	EXTQD
Cost in place	CIPL
Placename	NAMED

Table 4.4 PARC Coverage Attributes

Description	Symbol
Identification Number	PARC_ID
Source latitude	LATS
Source longitude	LONS
Source elevation	ELEVS
Source water district id	WCIDS
Demand latitude	LATD
Demand longitude	LOND
Demand elevation	ELEVD
Demand water district id	WCIDD
Lower bound	LOWB
Upper bound	UPPB
Unit transport cost	COST
Amount of flow	FLOW
Infeasibility	NFEAS

Table 4.5 Example Expert System Rules

Rule	Conditions	Hypothesis	Action
1.	If PARC object COST > 100	Allocation too expensive	Set NFEAS = 1
2.	IF PARC object WCIDS ≠ WCIDD	Transfer of water outside district	Set NFEAS = 2
3.	If PARC object LONS > LOND	Transfer of water from west to east	Set NFEAS = 3

Table 4.6 Example Problem SUPPLY Coverage

SUPSRC_ID	XSRC	WCIDS	LATS	LONS	ELEVS	EXTQS	CIPL	NS
1	0	800	30.10	99.06	1100.	500	10	S1
2	0	700	30.05	99.06	800.	3500	20	S2
3	2	700	30.00	99.06	750.	0	25	S3
4	0	100	30.09	99.02	900.	1100	1	S4

Table 4.7 Example Problem DEMAND Coverage

SUPSRC_ID	XDEM	WCIDD	LATD	LOND	ELEVD	EXTQD	ND
1	0	100	30.10	99.00	1000.	500	D1
2	1	200	30.05	99.00	850.	2000	D2
3	0	300	30.00	99.00	700	1000	D3

Table 4.8 Example Problem PARC Coverage

ID #	Lower Bound	Upper Bound	Cost	Flow	Infeasibility
S001D001	0	500	79	500	0
S001D002	0	500	45	500	0
S001D003	0	500	60	500	0
S002D001	0	500	101	500	0
S002D002	0	3500	52	3500	0
S002D003	0	1000	60	1000	0
S003D001	0	500	107	500	0
S003D002	0	3500	58	3500	0
S003D003	0	1000	60	1000	0
S004D001	0	500	90	500	0
S004D002	0	1100	45	1100	0
S004D003	0	1000	60	1000	0
D002D001	0	500	95	500	0
D002D003	0	1000	60	1000	0

* Columns for LATS, LONS, ELEVS, WCIDS, LATD, LOND, ELEVD, and WCIDD are not shown.

Table 4.9 Example Problem Updated PARC Coverage - Rule Set 1

ID #	Lower Bound	Upper Bound	Cost ($/AF)	Flow (AF)	Feasibility
S001D001	0	500	79	500	0
S001D002	0	500	45	0	0
S001D003	0	500	60	0	0
S002D001	0	500	101	0	0
S002D002	0	3500	52	900	0
S002D003	0	1000	60	1000	0
S003D001	0	500	107	0	0
S003D002	0	3500	58	0	0
S003D003	0	1000	60	0	0
S004D001	0	500	90	0	0
S004D002	0	1100	45	1100	0
S004D003	0	1000	60	0	0
D002D001	0	500	95	0	0
D002D003	0	1000	60	0	0

Table 4.10 Example Problem Updated PARC Coverage - Rule Set 2

ID #	Lower Bound	Upper Bound	Cost ($/AF)	Flow (AF)	Feasibility
S001D001	0	500	79	500	0
S001D002	0	500	45	0	0
S001D003	0	500	60	0	0
S002D001	0	500	101	–	2
S002D002	0	3500	52	900	0
S002D003	0	1000	60	1000	0
S003D001	0	500	107	–	2
S003D002	0	3500	58	0	0
S003D003	0	1000	60	0	0
S004D001	0	500	90	0	0
S004D002	0	1100	45	1100	0
S004D003	0	1000	60	0	0
D002D001	0	500	95	0	0
D002D003	0	1000	60	0	0

Table 4.11 Example Problem Updated PARC Coverage - Rule Set 3

ID #	Lower Bound	Upper Bound	Cost ($/AF)	Flow (AF)	Infeasibility
S001D001	0	500	79	0	0
S001D002	0	500	45	500	0
S001D003	0	500	60	0	0
S002D001	0	500	101	–	2
S002D002	0	3500	52	1500	0
S002D003	0	1000	60	1000	0
S003D001	0	500	107	–	2
S003D002	0	3500	58	0	0
S003D003	0	1000	60	0	0
S004D001	0	500	90	500	0
S004D002	0	1100	45	–	3
S004D003	0	1000	60	–	3
D002D001	0	500	95	0	0
D002D003	0	1000	60	0	0

Table 4.12 Example Problem Updated PARC Coverage - Rule Set 4

ID #	Lower Bound	Upper Bound	Cost ($/AF)	Flow (AF)	Infeasibility
S001D001	0	500	79	0	0
S001D002	0	500	45	500	0
S001D003	0	500	60	0	0
S002D001	0	500	101	–	2
S002D002	0	3500	52	2000	0
S002D003	0	1000	60	1000	0
S003D001	0	500	107	–	2
S003D002	0	3500	58	0	0
S003D003	0	1000	60	0	0
S004D001	0	500	90	0	0
S004D002	0	1100	45	–	3
S004D003	0	1000	60	–	3
D002D001	0	500	**10**	500	0
D002D003	0	1000	**10**	0	0

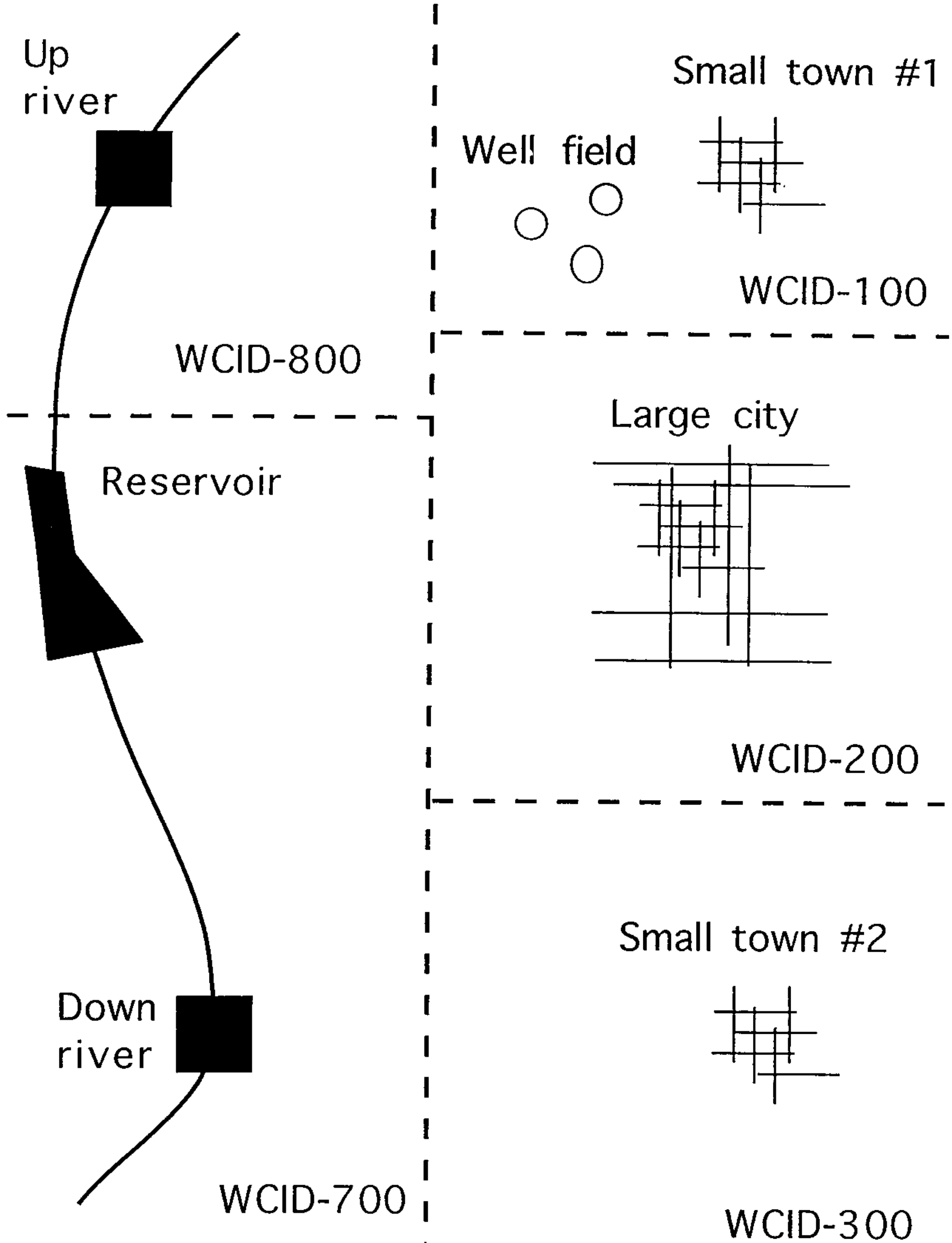


Figure 4.1 Geographic representation of example problem.

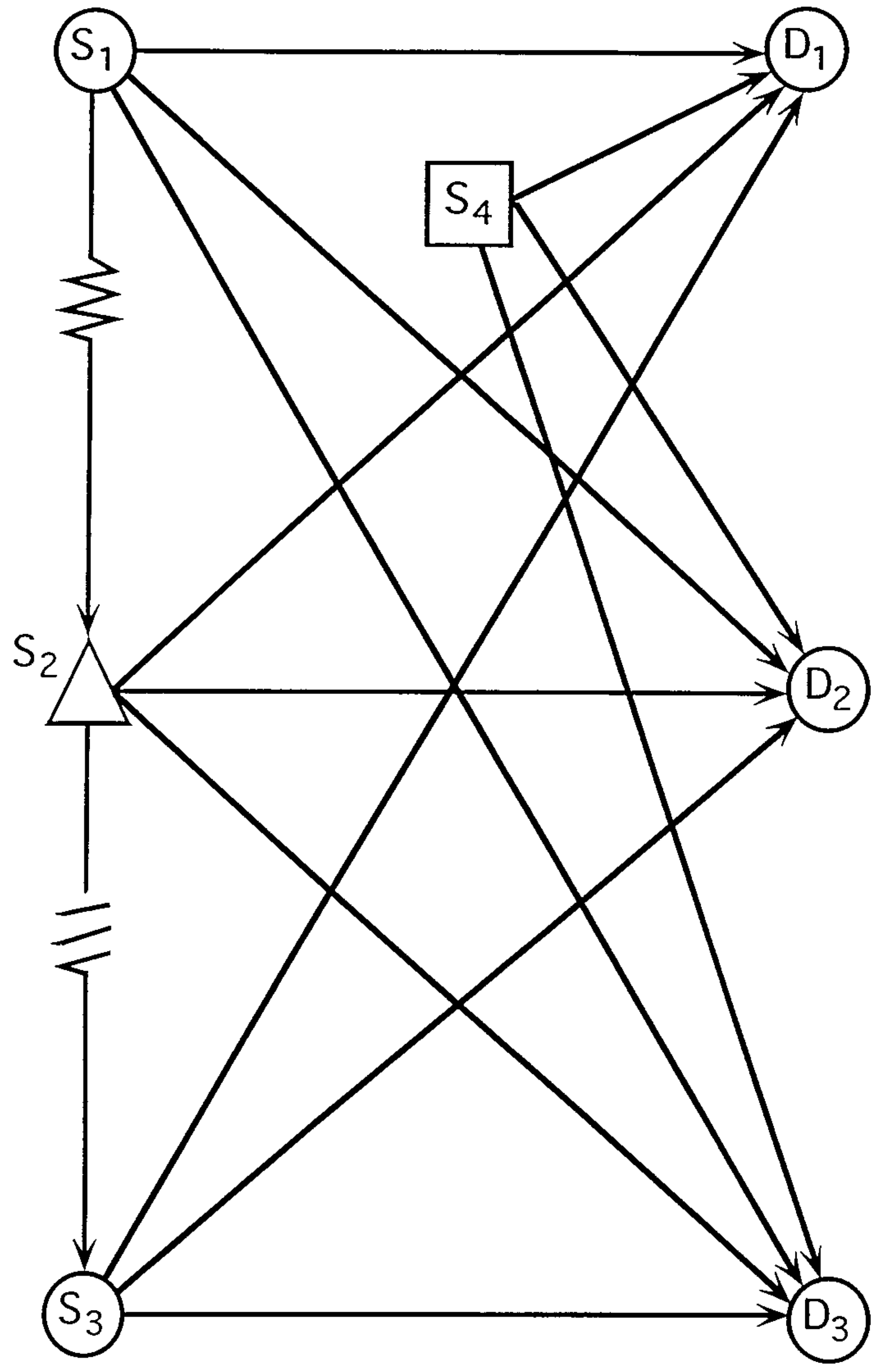


Figure 4.2 Functional representation of example problem.

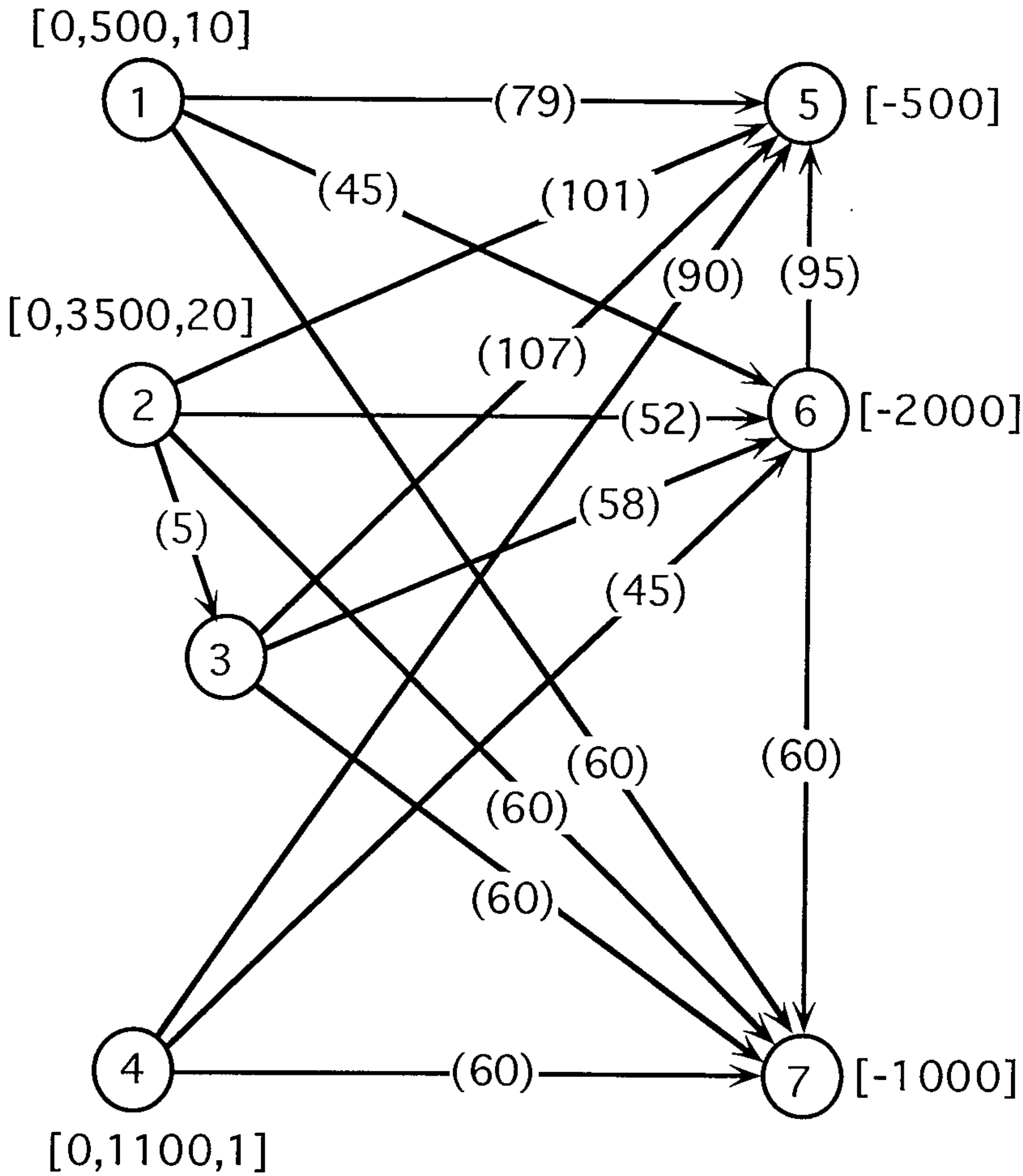


Figure 4.3 Planning representation of example problem.

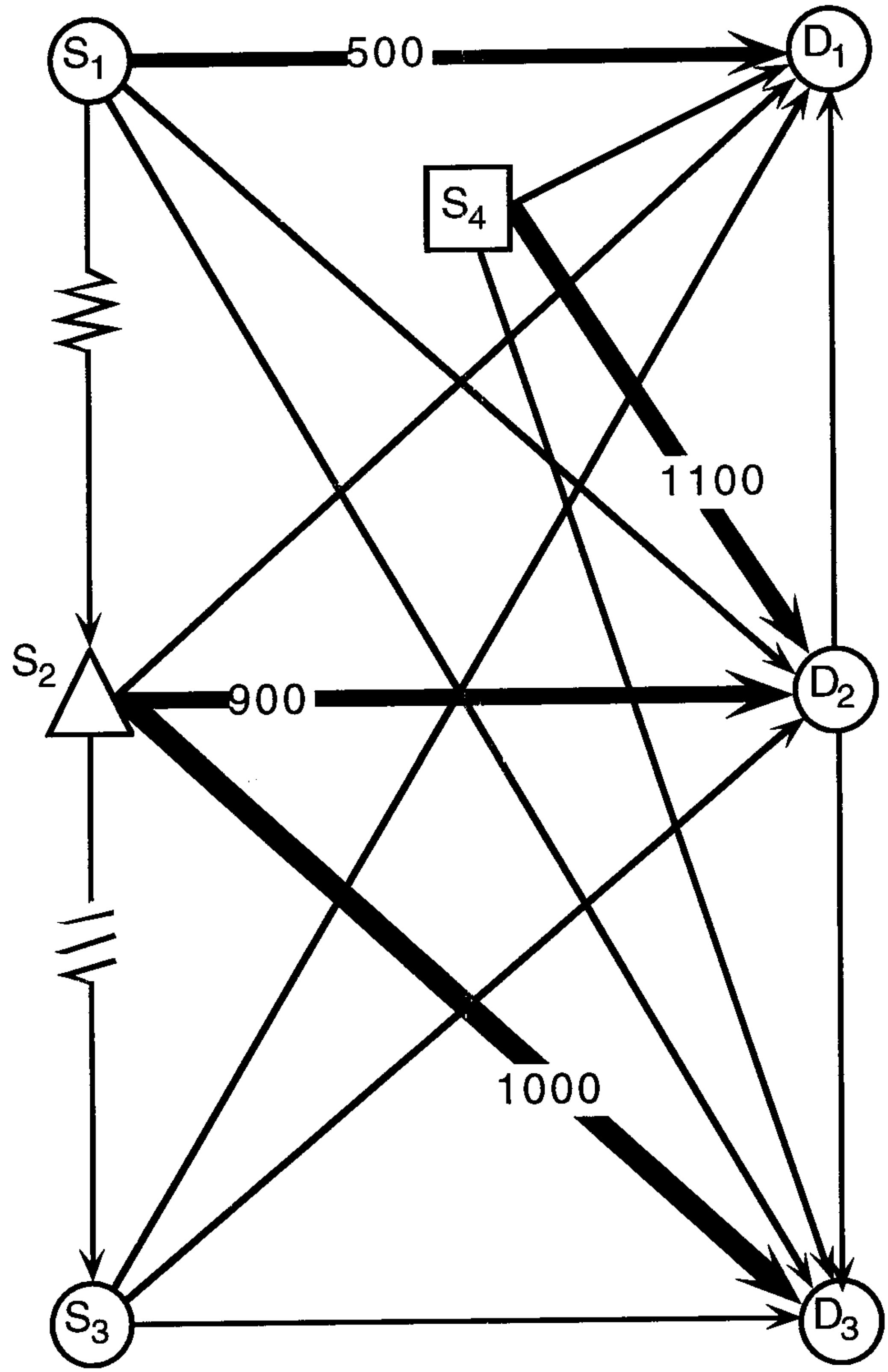


Figure 4.4 Solution of example problem - Rule set 1.

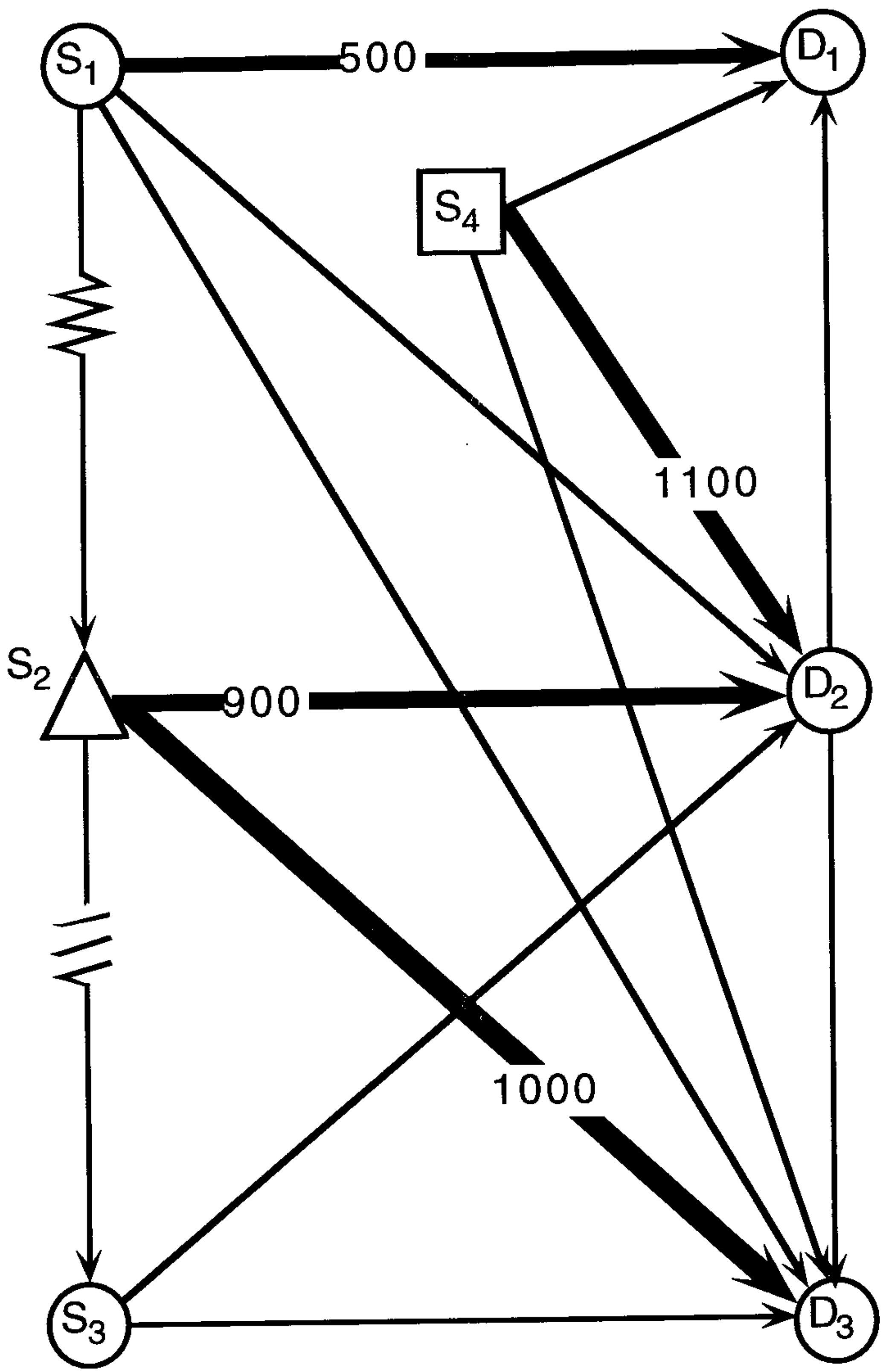


Figure 4.5 Solution of example problem - Rule set 2.

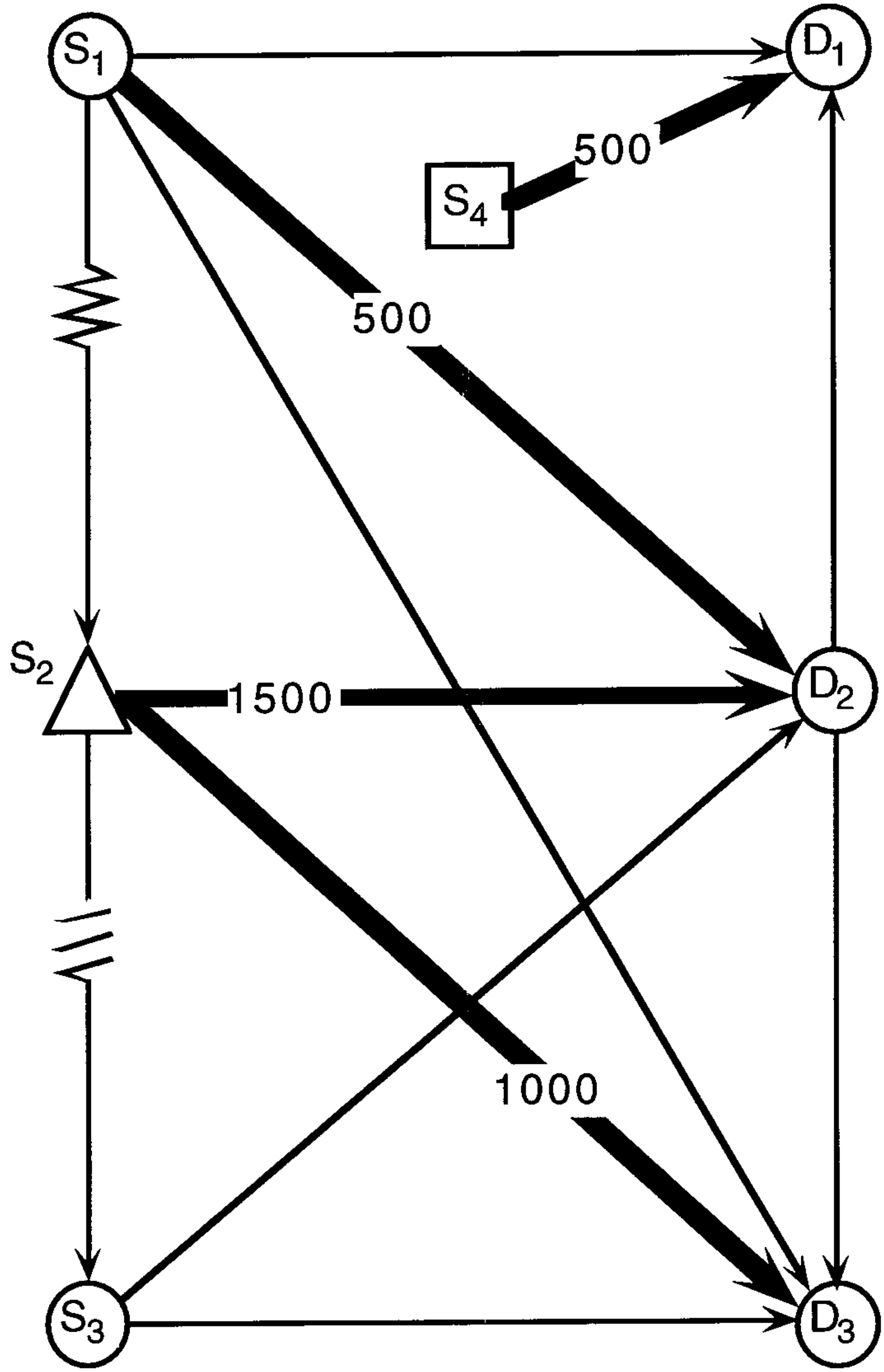


Figure 4.6 Solution of example problem - Rule set 3.

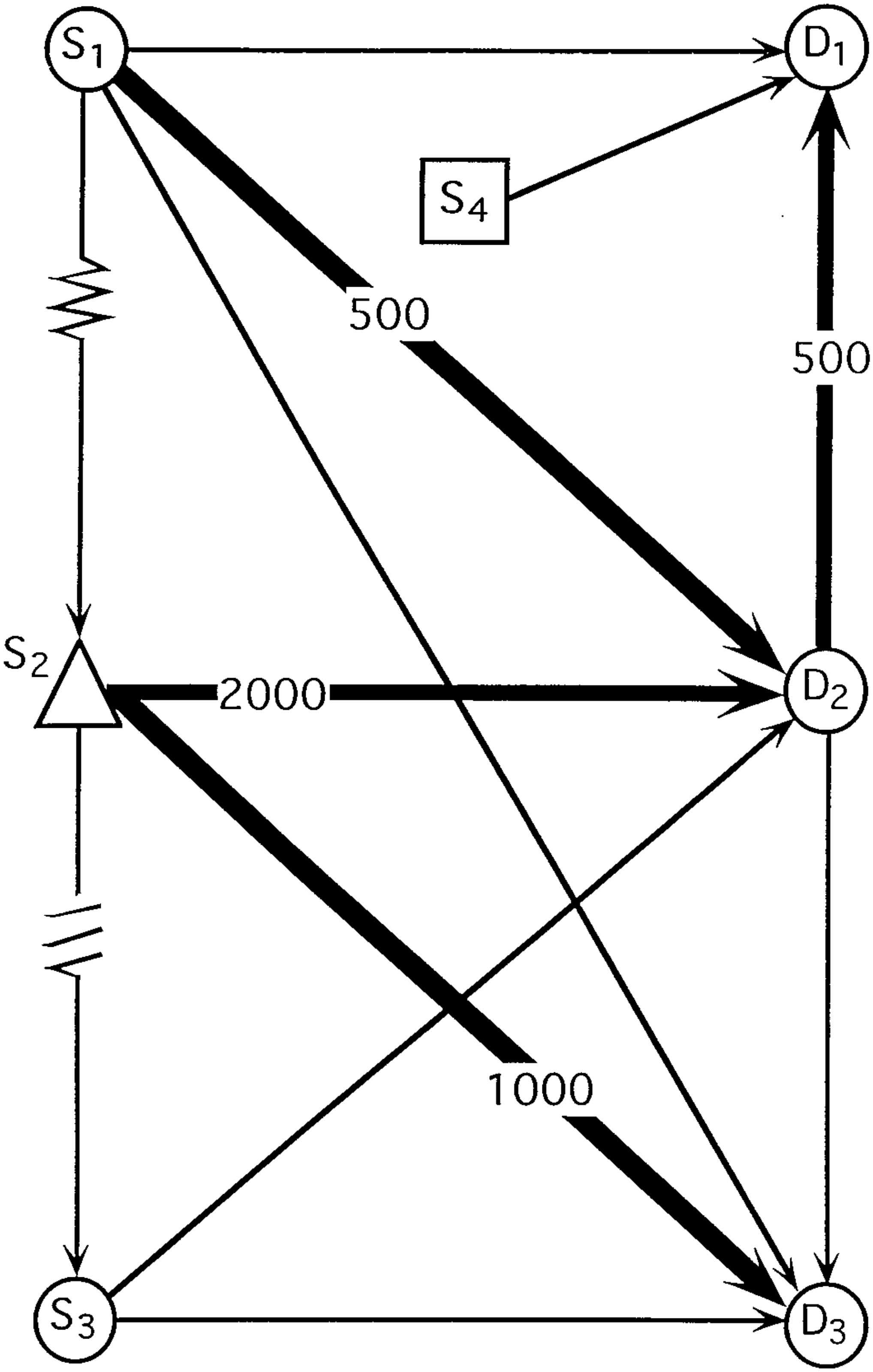


Figure 4.7 Solution of example problem - Rule set 4.

5.0 CASE STUDY - CORPUS CHRISTI, TEXAS REGION

5.1 INTRODUCTION

The fifteen separate water planning regions considered by the Texas Water Development Board in the 1992 update of the Texas Water Plan (TWDB, 1992, Fig 2-1, p. 8) are depicted in Figure 5.1. These conform to uniform service regions for state government regulatory and services purposes as required by the General Appropriations Act of the 72nd Legislature. Region 10, the Coastal Bend, is located in the central coastal plains and is comprised of the following 19 counties: Aransas, Bee, Brooks, Calhoun, DeWitt, Duval, Goliad, Gonzales, Jackson, Jim Wells, Kenedy, Kleberg, Lavaca, Live Oak, McMullen, Nueces, Refugio, San Patricio, and Victoria.

The physiography of the region is generally flat, with grassland in the humid northeast tending to brush country in the subhumid southwest. Rainfall ranges from 40 inches per year in the eastern counties to 24 inches per year in the western counties [Larkin and Bomar, 1983]. Surface water supplies exist in the regulated rivers which flow from the northwest to southeast across the region emptying into the Gulf of Mexico. These rivers include the Navidad and Lavaca in the Lavaca basin, the San Antonio, San Marcos and Guadalupe in the Guadalupe basin, and the Medina, Frio and Nueces in the Nueces basin. In addition, numerous creeks rise within the region and are exploited by agricultural users as local supplies. Surface supplies in the region are drawn directly from the rivers and are also developed in several moderate sized reservoirs, the most significant being Choke Canyon Reservoir and Lake Corpus Christi on the Nueces River. Surface water resources in Region 10 are estimated to contribute a firm yield exceeding 474,000 acre-ft per year in the year 2040.

The region also has extensive groundwater supplies. The Gulf Coastal Aquifer provides good quality and relatively inexpensive domestic water to small cities and towns in every county of the planning region. Moreover, water supplies from the Carrizo-Wilcox, Sparta Sand, and Queen City Aquifers are available to the more inland counties. Typically, ground water is one-half to one-fourth the cost of surface water within this region, and consequently, it is the demanders' first choice of supply. Groundwater resources are expected to exceed 310,000 acre-ft/year in the year 2040.

The potential sources of water supply in Region 10 for the year 2040 are listed in Table 5.1 (A more detailed list of the data appears in the Appendix). These data were extracted from information provided by the TWDB in data files: ALLOC40, RESDATA, and GWDATA [Steve Densmore, TWDB, personal commun., 1992]. Costs for groundwater were developed from information provided by TWDB staff concerning average well depths and drilling costs per foot for each aquifer in the region. Costs for the surface water for each reservoir were estimated by amortizing the costs of construction, adding the costs of operation and dividing by the firm yield. These costs of source supplies do not reflect the same degree of detailed investigation that is contained in the other data. The category 'SHORTAGE' that appears for seven counties in the table is a device employed by TWDB planners that allows flexibilities with respect to satisfying certain, local demands. As indicated in the table, there is a large supply (999,999 AF/Y) of 'shortage water' but it is available at a very high price (999 $/AF). This is the last water allocated to any purpose and prevents infeasibility in the model while identifying those demands that are, in fact, not really being met. Another modelling abstraction occurs with respect to the location of supplies that are, in the real world, widely dispersed: groundwater, shortage, and local supplies are collapsed into point entities and placed at the centroid of their respective counties.

Although 45 cities and towns are identified as having population above 1000, the city of Corpus Christi is the only large metropolitan center in the region. The present (1990) population of the region is 707,791 and is expected to rise to 1,297,523 by the year 2040. This will to result in a domestic demand of 238,283 acre-ft. per year. Farming, ranching, oil production, refining, and metals manufacturing add significantly, increasing the total demand for water in the year 2040 to 712,839 acre-ft per year. Table 5.2 lists the demand data for the year 2040, identifying 98 water demanders within the region.

As before, the data were provided by the TWDB. The particular file, NTR11, lists population estimates and water demand projections for several categories of use by cities, towns and counties in Texas. For the purpose of this investigation, three categories other than cities were created by lumping the appropriate categories found in the raw data. These are: county aggregated industrial, county aggregated agricultural, and county aggregated other domestic (not otherwise accounted for as a specified city), and these appear in the table as CA_county, CB_county, and CO_county. Such demands are distributed in the real world but are collapsed to point entities and assumed to be located at the centroid of their respective counties for modelling purposes.

Given the 44 potential sources of supply and 98 demanders, how should the water resources of this region be allocated? What other considerations, besides geography and economy, apply? Ultimately, can a list of rules be devised and implemented to capture the heuristic aspects of the planning process? The following sections outline one attempt to answer these questions.

5.2 PLAN 0 - NO RULES

This plan serves as a baseline for comparison. There were no modifications made to the initial network of potential arcs by the expert system prior to LP optimization. The network consisted of 143 nodes and 4356 arcs. The LP solution was completed in 11 seconds running on a SUN Sparc 2 Workstation. The solution puts flow on 130 arcs at a total cost of $40,000,000 and is displayed in Figure 5.2. More specific detail is provided in Table 5.3.

The resulting distribution of the region's water supplies is generally reasonable. There are, however, some allocations that do not fit present planning criteria. Many cases appear where large industrial and agricultural users obtain groundwater resources that traditionally would have been allocated to smaller municipalities. Moreover, there are cases where groundwater demanders import groundwater from another county in preference to using groundwater available in their own county. Also, there are instances where local and shortage supplies are utilized beyond county boundaries and by non-agricultural users. This has the consequent effect of forcing the intended and appropriate users of these supplies to be allocated water from somewhere else.

5.3 PLAN 4 - STATEWIDE RULES

In this plan basic rules are applied in the expert system that modify the network of potential arcs. These rules rectify modeling problems associated with locating aggregated supplies at the centroid of counties and implement basic statewide planning concepts. The network was pared of 1030 infeasible arcs and transportation costs were reset to zero on 70 others. The LP solution was completed in 7 seconds. The allocation employs 129 arcs at a total cost of $38,000,000 and is displayed in Figure 5.3. Detail is provided in Table 5.4. The following rules were applied in this scenario:

(1) Within county groundwater transport costs reset to zero. In the model, groundwater is located at the centroid of each county, resulting in a transport cost that does not actually exist.

(2) Within county local supply transport costs set to zero. As above, actual users do not need to transport this water any significant distance.

(3) Allocation of 'Local' supply to non-agricultural users infeasible. By definition, this water is only available to agricultural demanders.

(4) Local supply export infeasible. Again, by its definition, this source is not available outside of the county to which it is accounted.

(5) Shortage supply export infeasible. As above, this supply is local by defintion.

The allocations that evolve from implementing these rules exhibit the expected effects and represent a substantial improvement over the previous allocations; however, there remain general patterns of allocations that do not conform to present practice and philosophy. For example, given the types and scale of agricultural operations in this region, it is uncommon for their water supplies to be drawn from outside the users' county. Similarly, in practice in this region, industrial users do not import groundwater from other counties (precluding its use by the smaller cities and towns in the distant source counties and consequently forcing those communities to more expensive alternatives). These atypical patterns can be easily removed by including rules that prohibit such allocations. Furthermore, there are several instances where large demanders tap an entire groundwater supply dry. While this may be the optimum allocation of resources, there is a political consideration that goes beyond it in real life: no single demander is allowed to consume all of the cheapest water. Again, a rule or sequence of rules can be written to prevent such allocations. Last, there is a concern for the very small demanders. Several allocations to very small cities call for distant transport to meet these demands, when in reality, there is no economic possibility for such a transfer. Rules must be included to reserve nearby, inexpensive water supplies for these users. The rules to implement these corrections are discussed in the next section.

5.4 PLAN 9 - STATEWIDE AND REGIONAL RULES

This plan incorporates the planning considerations specific to this region. It also applies rules to specific supply sources and demanders. All previous rules apply plus the following:

(6) Groundwater import by industrial users infeasible. Prevents the dislocation of inexpensive supplies.

(7) Groundwater import by agricultural users infeasible. Agricultural users must rely on other local or shortage supplies.

(8) County Other Municipal Users dedicated up to 20% of the preferred (cheapest) source of supply. Reserves a portion of the Gulf Coast Aquifer to small demanders.

(9) Individual groundwater users limited to 40% of supply. Forces distribution of cheap supplies among several users.

(10) Twenty percent surcharge on cost in place applied to groundwater exports. Discourages groundwater transport.

(11) Surface water import by agricultural users infeasible. Dispersed, small and medium demanders cannot support this type of infrastructure.

(12) Coletto Creek to municipal and agricultural users infeasible. This reservoir is dedicated to industrial use.

(13) Jackson County agricultural users not restricted by rule 9. Jackson County agricultural demands require special consideration.

(14) Tilden to Gulf Coast, Queen City and Sparta Sand infeasible. This city is not located over these aquifers.

The network was pared of 2098 infeasible arcs and costs were modified on 2586 arcs. The lower bound was reset on 19 arcs to implement rule 8, and the upper bound was reset on 2619 arcs to implement rule 9. LP run time was 4 seconds and 147 arcs were assigned flow at a total cost of $53,000,000. The resulting allocations are displayed in Figure 5.4 and detailed in Table 5.5.

The allocations derived from this plan closely resemble the present Texas Water Plan devised by TWDB experts. The remaining difference involves the underutilization of water from surface supplies, particularly from Choke-Corpus Reservoir. In the 1990 Water Plan [TWDB,1992] this water is allocated to medium-sized and large municipal users in the nearby counties. Additional rules that favor such connections were needed to more closely match this kind of allocation logic. The results of applying these rules is discussed in the next section.

5.5 PLAN 10 - STATEWIDE, REGIONAL, AND PARC RULES

This plan further refines the planning considerations to include specifications of the attributes at the arc level. Again, all previous rules apply as well as these additional:

(15) Coletto Creek to CA_Goliad transport cost reset to zero. Corrects modeling error.

(16) Choke-Corpus to Aransas Co. municipalities discount applied. Encourages municipal use of this supply source.

(17) Choke-Corpus to Bee Co. municipalities discount applied.

(18) Choke-Corpus to Jim Wells Co. municipalities discount applied.

(19) Choke-Corpus to Kleberg Co. municipalities discount applied.

(20) Choke-Corpus to Live Oak Co. municipalities discount applied.

(21) Choke-Corpus to Nueces Co. municipalities discount applied.

(22) Choke-Corpus to San Patricio Co. municipalities discount applied.

After applying the rules, 28 additional arcs were modified to implement the cost reductions. The LP solver indicated an optimum feasible solution in 4 seconds involving 145 arcs for a total cost of $50,000,000. Figure 5.5 and Table 5.6 display the results. The desired effect is evident in the allocations from the largest surface supply in the region, Choke-Corpus with bay. Under this scenario, several of the cities in the targeted counties are receiving water from the Choke-Corpus reservoir system, and the resource is now fully utilized. The industrial demanders who were formerly allocated water experience reductions from this source and have been connected to other surface sources of supply.

5.6 ASSESSMENT OF THE COASTAL BEND REGION CASE STUDY

A detailed comparison of the allocations made by the Automated Allocations System (AAS) and the 1990 Texas Water Plan is presented in Table 5.7. Many individual discrepancies can be found, yet overall the plans are quite similar. The instances where run of river supplies are allocated from supply Guadalupe in preference to supply San Antonio are balanced later by allocations from supply San Antonio in preference to supply Guadalupe. This is a caused by the equal cost of each supply and the proximate locations designated for them. If finer definition in these allocation recommendations is desired, it may be achieved with the designation of several run of river supply locations for each. Other individual discrepancies may be addressed by writing additional rules at the Parc level, but such an effort, while it will improve the agreement between AAS and TWDB, is a move away from the goal of an automated system.

Table 5.1 Potential Supply Sources for Region 10

ID#	NAME	YIELD (AF/Y)	COST ($/AF)
1	GULF_COAST__ARANSAS	400	31
2	CARRIZO-WILCOX__BEE	394	24
3	GULF_COAST__BEE	14577	31
4	GULF_COAST__BROOKS	14577	31
5	GULF_COAST__CALHOUN	2940	31
6	LOCAL__CALHOUN	12600	10
7	SHORTAGE__CALHOUN	999999	999
8	GULF_COAST__DE_WITT	15866	31
9	GULF_COAST__DUVAL	23970	31
10	GULF_COAST__GOLIAD	12809	31
11	CARRIZO-WILCOX__GONZALES	19840	16
12	GULF_COAST__GONZALES	2083	39
13	QUEEN_CITY__GONZALES	6104	44
14	SPARTA_SAND__GONZALES	16340	49
15	LOCAL__GONZALES	4200	10
16	GULF_COAST__JACKSON	28343	39
17	SHORTAGE__JACKSON	999999	999
18	GULF_COAST__JIM_WELLS	11370	31
19	SHORTAGE__JIM_WELLS	999999	999
20	GULF_COAST__KENEDY	9550	31
21	GULF_COAST__KLEBERG	17088	31
22	GULF_COAST__LAVACA	38123	39
23	CARRIZO-WILCOX__LIVE_OAK	2399	24
24	GULF_COAST__LIVE_OAK	5242	31
25	LOCAL__LIVE_OAK	760	10
26	SHORTAGE__LIVE_OAK	999999	999
27	CARRIZO-WILCOX__MCMULLEN	7909	24
28	GULF_COAST__MCMULLEN	1838	31
29	QUEEN_CITY__MCMULLEN	1105	44
30	SPARTA_SAND__MCMULLEN	600	49
31	SHORTAGE__MCMULLEN	999999	999
32	GULF_COAST__NUECES	3254	31
33	LOCAL__NUECES	950	10
34	SHORTAGE__NUECES	999999	999
35	GULF_COAST__REFUGIO	7768	31
36	GULF_COAST__SAN_PATRICIO	5228	31
37	SHORTAGE__SAN_PATRICIO	999999	999
38	GULF_COAST__VICTORIA	41130	39
39	TEXANA	75000	43
40	CUERO_I&II	52000	49
41	GUADALUPE_RIVER	79000	40
42	COLETO_CREEK	12500	59
43	SAN_ANTONIO_RIVER	25000	40
44	CHOKE-CORPUS_w_bay	230549	43

Table 5.2 Region 10 Demand Data for the Year 2040

ID#	NAME	DEMAND (AF/Y)	ID#	NAME	DEMAND (AF/Y)
1	ROCKPORT	2324	51	CO_KENEDY	49
2	CO_ARANSAS	4426	52	CB_KENEDY	1821
3	CA_ARANSAS	554	53	KINGSVILLE	9179
4	CB_ARANSAS	107	54	CO_KLEBERG	2028
5	BEEVILLE	3730	55	CA_KLEBERG	2574
6	CO_BEE	2921	56	CB_KLEBERG	2612
7	CA_BEE	5	57	HALLETTSVILLE	831
8	CB_BEE	2590	58	SHINER	746
9	FALFURRIAS	1372	59	YOAKUM	915
10	CO_BROOKS	769	60	CO_LAVACA	1865
11	CA_BROOKS	18	61	CA_LAVACA	6933
12	CB_BROOKS	1690	62	CB_LAVACA	15216
13	POINT_COMFORT	237	63	GEORGE_WEST	592
14	PORT_LAVACA	3213	64	THREE_RIVERS	485
15	SEADRIFT	398	65	CO_LIVE_OAK	795
16	CO_CALHOUN	2219	66	CA_LIVE_OAK	16113
17	CA_CALHOUN	94914	67	CB_LIVE_OAK	4960
18	CB_CALHOUN	23235	68	TILDEN	76
19	CUERO	1831	69	CO_MCMULLEN	155
20	YORKTOWN	535	70	CB_MCMULLEN	4626
21	YOAKUM	550	71	BISHOP	848
22	CO_DE_WITT	1182	72	CORPUS_CHRISTI	119046
23	CA_DE_WITT	7212	73	PORT_ARANSAS	2161
24	CB_DE_WITT	3070	74	ROBSTOWN	2820
25	BENAVIDES	747	75	CO_NUECES	3834
26	FREER	1227	76	CA_NUECES	54448
27	SAN_DIEGO	1294	77	CB_NUECES	4354
28	CO_DUVAL	448	78	REFUGIO	439
29	CB_DUVAL	5506	79	WOODSBORO	278
30	GOLIAD	671	80	CO_REFUGIO	406
31	CO_GOLIAD	921	81	CB_REFUGIO	940
32	CA_GOLIAD	16000	82	MATHIS	1262
33	CB_GOLIAD	1934	83	ARANSAS_PASS	2010
34	GONZALES	2932	84	GREGORY	725
35	NIXON	653	85	INGLESIDE	1789
36	CO_GONZALES	2593	86	ODEM	636
37	CA_GONZALES	2672	87	PORTLAND	2980
38	CB_GONZALES	6775	88	SINTON	1416
39	EDNA	1573	89	TAFT	827
40	GANADO	418	90	TAFT_SOUTHWEST	407
41	CO_JACKSON	1338	91	CO_SAN_PATRICIO	3540
42	CA_JACKSON	66	92	CA_SAN_PATRICIO	28008
43	CB_JACKSON	61120	93	CB_SAN_PATRICIO	4672
44	ALICE	9410	94	BLOOMINGTON	515
45	ORANGE_GROVE	403	95	VICTORIA	16243
46	PREMONT	1351	96	CO_VICTORIA	4125
47	CO_JIM_WELLS	2560	97	CA_VICTORIA	79827
48	CA_JIM_WELLS	347	98	CB_VICTORIA	14985
49	CB_JIM_WELLS	4652			
50	SARITA	14			

Table 5.3 PLAN 0 - No Rules

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__ARANSAS	31		400
CA_ARANSAS		0	293
CB_ARANSAS		0	107
			400
CARRIZO-WILCOX__BEE	24		394
CA_BEE		0	5
CB_BEE		0	389
			394
GULF_COAST__BEE	31		14577
BEEVILLE		38	3730
CO_BEE		0	2921
CB_BEE		0	2201
CA_GOLIAD		26	5725
			14577
GULF_COAST__BROOKS	31		14577
FALFURRIAS		53	1372
CO_BROOKS		0	769
CA_BROOKS		0	18
CB_BROOKS		0	1690
PREMONT		61	1351
KINGSVILLE		32	9179
BISHOP		70	198
			14577
GULF_COAST__CALHOUN	31		2940
CO_CALHOUN		0	2219
CA_CALHOUN		0	721
			2940
LOCAL__CALHOUN	10		12600
CA_CALHOUN		0	12600
			12600
SHORTAGE__CALHOUN	999		999999
			0

Table 5.3 PLAN 0 - No Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__DE_WITT	31		15866
CO_DE_WITT		0	1182
CA_DE_WITT		0	7212
CB_DE_WITT		0	3070
CA_GOLIAD		30	321
VICTORIA		25	4081
			15866
GULF_COAST__DUVAL	31		23970
BENAVIDES		68	747
FREER		61	1227
SAN_DIEGO		55	1294
CO_DUVAL		0	448
CB_DUVAL		0	5506
ALICE		25	5599
CA_LIVE_OAK		20	8352
PORTLAND		40	797
			23970
GULF_COAST__GOLIAD	31		12809
CO_GOLIAD		0	921
CA_GOLIAD		0	9954
CB_GOLIAD		0	1934
			12809
CARRIZO-WILCOX__GONZ	16		19840
CUERO		48	1831
GONZALES		41	2932
NIXON		91	653
CA_GONZALES		0	2672
GANADO		92	37
HALLETTSVILLE		70	831
YOAKUM		75	915
VICTORIA		31	6262
CA_VICTORIA		26	3707
			19840
GULF_COAST__GONZALES	39		2083
EDNA		60	1573
BLOOMINGTON		84	510
			2083

Table 5.3 PLAN 0 - No Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
QUEEN_CITY__GONZALES	44		6104
YOAKUM		88	550
CB_GONZALES		0	5549
BLOOMINGTON		84	5

			6104
SPARTA_SAND__GONZALE	49		16340
PORT_LAVACA		42	3213
YORKTOWN		88	535
GOLIAD		85	671
SHINER		84	746
VICTORIA		31	5900

			11065
LOCAL__GONZALES	10		4200
CO_GONZALES		0	2593
CB_GONZALES		0	1226
GANADO		92	381

			4200
GULF_COAST__JACKSON	39		28343
CO_JACKSON		0	1338
CA_JACKSON		0	66
CB_JACKSON		0	26939

			28343
SHORTAGE__JACKSON	999		999999

			0
GULF_COAST__JIM_WELL	31		11370
ALICE		25	3811
CO_JIM_WELLS		0	2560
CA_JIM_WELLS		0	347
CB_JIM_WELLS		0	4652

			11370
SHORTAGE__JIM_WELL	999		999999

			0

Table 5.3 PLAN 0 - No Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__KENEDY	31		9550
CO_KENEDY		0	49
CB_KENEDY		0	1821

			1870
GULF_COAST__KLEBERG	31		17088
CO_KLEBERG		0	2028
CA_KLEBERG		0	2574
CB_KLEBERG		0	2612
BISHOP		72	650
PORT_ARANSAS		68	2161
CB_NUECES		45	3998
ARANSAS_PASS		67	2010
INGLESIDE		65	1055

			17088
GULF_COAST__LAVACA	39		38123
CB_JACKSON		14	14109
CO_LAVACA		0	1865
CA_LAVACA		0	6933
CB_LAVACA		0	15216

			38123
CARRIZO-WILCOX__LIVE	24		2399
CO_LIVE_OAK		0	795
CA_LIVE_OAK		0	1604

			2399
GULF_COAST__LIVE_OAK	31		5242
CA_LIVE_OAK		0	282
CB_LIVE_OAK		0	4960

			5242
LOCAL__LIVE_OAK	10		760
CA_LIVE_OAK		0	760

			760
SHORTAGE__LIVE_OAK	999		999999

			0

Table 5.3 PLAN 0 - No Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
CARRIZO-WILCOX__MCMU	24		7909
CA_LIVE_OAK		26	5115
TILDEN		172	76
CO_MCMULLEN		0	155
CB_MCMULLEN		0	2563

			7909
GULF_COAST__MCMULLEN	31		1838
ORANGE_GROVE		91	403
THREE_RIVERS		82	485
CB_MCMULLEN		0	950

			1838
QUEEN_CITY__MCMULLEN	44		1105
CB_MCMULLEN		0	1105

			1105
SPARTA_SAND__MCMULLE	49		600
GEORGE_WEST		76	592
CB_MCMULLEN		0	8

			600
SHORTAGE__MCMULLEN	999		999999

			0
GULF_COAST__NUECES	31		3254
SARITA		396	14
CO_NUECES		0	2884
CB_NUECES		0	356

			3254
LOCAL__NUECES	10		950
CO_NUECES		0	950

			950

Table 5.3 PLAN 0 - No Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
SHORTAGE__NUECES	999		999999

			0
GULF_COAST__REFUGIO	31		7768
ROCKPORT		47	1100
CO_ARANSAS		37	4426
CA_ARANSAS		78	261
POINT_COMFORT		115	237
SEADRIFT		90	398
CO_REFUGIO		86	406
CB_REFUGIO		61	940

			7768
GULF_COAST__SAN_PATR	31		5228
CO_SAN_PATRICIO		0	3540
CB_SAN_PATRICIO		0	1688

			5228
SHORTAGE__SAN_PATR	999		999999

			0
GULF_COAST__VICTORIA	39		41130
CO_VICTORIA		0	4125
CA_VICTORIA		0	22020
CB_VICTORIA		0	14985

			41130
TEXANA	43		75000
CA_CALHOUN		21	54928
CB_JACKSON		14	20072

			75000
CUERO_I&II	49		52000

			0
GUADALUPE	40		79000
CA_CALHOUN		19	24900
CA_VICTORIA		13	54100

			79000

Table 5.3 PLAN 0 - No Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
COLETO_CR	59		12500

			0
SAN_ANTONIO	40		25000
CA_CALHOUN		25	1765
CB_CALHOUN		23	23235

			25000
CHOKE-CORPUS_w_bay	43		230549
ROCKPORT		54	1224
CORPUS_CHRISTI		25	119046
ROBSTOWN		49	2820
CA_NUECES		18	54448
REFUGIO		92	439
WOODSBORO		106	278
MATHIS		62	1262
GREGORY		82	725
INGLESIDE		57	734
ODEM		78	636
PORTLAND		53	2183
SINTON		57	1416
TAFT		71	827
TAFT_SOUTHWEST		89	407
CA_SAN_PATRICIO		23	28008
CB_SAN_PATRICIO		40	2984

			217437

Table 5.4 PLAN 4 - Statewide Rules

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__ARANSAS	31		400
CA_ARANSAS		0	293
CB_ARANSAS		0	107

			400
CARRIZO-WILCOX__BEE	24		394
CB_BEE		0	394

			394
GULF_COAST__BEE	31		14577
BEEVILLE		0	3730
CO_BEE		0	2921
CA_BEE		0	5
CB_BEE		0	2196
CA_GOLIAD		26	5725

			14577
GULF_COAST__BROOKS	31		14577
FALFURRIAS		0	1372
CO_BROOKS		0	769
CA_BROOKS		0	18
CB_BROOKS		0	1690
ALICE		53	554
CB_NUECES		50	3404
INGLESIDE		67	1789

			9596
GULF_COAST__CALHOUN	31		2940
POINT_COMFORT		0	237
PORT_LAVACA		0	86
SEADRIFT		0	398
CO_CALHOUN		0	2219

			2940
LOCAL__CALHOUN	10		12600
CB_CALHOUN		0	12600

			12600
SHORTAGE__CALHOUN	999		999999

			0

Table 5.4 PLAN 4 - Statewide Rules (Continued).

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__DE_WITT	31		15866
CUERO		0	1831
YORKTOWN		0	535
YOAKUM		0	550
CO_DE_WITT		0	1182
CA_DE_WITT		0	7212
CB_DE_WITT		0	3070
CA_GOLIAD		30	992
CB_VICTORIA		24	494
			15866
GULF_COAST__DUVAL	31		23970
BENAVIDES		0	747
FREER		0	1227
SAN_DIEGO		0	1294
CO_DUVAL		0	448
CB_DUVAL		0	5506
ALICE		25	6799
CA_LIVE_OAK		20	7949
			23970
GULF_COAST__GOLIAD	31		12809
GOLIAD		0	671
CO_GOLIAD		0	921
CA_GOLIAD		0	9283
CB_GOLIAD		0	1934
			12809
CARRIZO-WILCOX__GONZ	16		19840
CA_VICTORIA		26	19840
			19840
GULF_COAST__GONZALES	39		2083
GONZALES		0	2083
			2083
QUEEN_CITY__GONZALES	44		6104
GONZALES		0	849
CO_GONZALES		0	2593
CA_GONZALES		0	2662
			6104

Table 5.4 PLAN 4 - Statewide Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
SPARTA_SAND__GONZALE	49		16340
PORT_LAVACA		42	3127
NIXON		0	653
CA_GONZALES		0	10
CB_GONZALES		0	2575
CB_VICTORIA		27	5335

			11700
LOCAL__GONZALES	10		4200
CB_GONZALES		0	4200

			4200
GULF_COAST__JACKSON	39		28343
EDNA		0	1573
GANADO		0	418
CO_JACKSON		0	1338
CA_JACKSON		0	66
CB_JACKSON		0	24948

			28343
SHORTAGE__JACKSON	999		999999

			0
GULF_COAST__JIM_WELL	31		11370
ALICE		0	2057
ORANGE_GROVE		0	403
PREMONT		0	1351
CO_JIM_WELLS		0	2560
CA_JIM_WELLS		0	347
CB_JIM_WELLS		0	4652

			11370
SHORTAGE__JIM_WELL	999		999999

			0
GULF_COAST__KENEDY	31		9550
SARITA		0	14
CO_KENEDY		0	49
CB_KENEDY		0	1821

			1884

Table 5.4 PLAN 4 - Statewide Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__KLEBERG	31		17088
KINGSVILLE		0	9179
CO_KLEBERG		0	2028
CA_KLEBERG		0	2574
CB_KLEBERG		0	2612
CO_NUECES		49	695

			17088
GULF_COAST__LAVACA	39		38123
CB_JACKSON		14	11617
HALLETTSVILLE		0	831
SHINER		0	746
YOAKUM		0	915
CO_LAVACA		0	1865
CA_LAVACA		0	6933
CB_LAVACA		0	15216

			38123
CARRIZO-WILCOX__LIVE	24		2399
GEORGE_WEST		0	592
CO_LIVE_OAK		0	795
CA_LIVE_OAK		0	1012

			2399
GULF_COAST__LIVE_OAK	31		5242
THREE_RIVERS		0	485
CA_LIVE_OAK		0	557
CB_LIVE_OAK		0	4200

			5242
LOCAL__LIVE_OAK	10		760
CB_LIVE_OAK		0	760

			760
SHORTAGE__LIVE_OAK	999		999999

			0

Table 5.4 PLAN 4 - Statewide Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
CARRIZO-WILCOX__MCMU	24		7909
CA_LIVE_OAK		26	6595
TILDEN		0	76
CO_MCMULLEN		0	155
CB_MCMULLEN		0	1083
			7909
GULF_COAST__MCMULLEN	31		1838
CB_MCMULLEN		0	1838
			1838
QUEEN_CITY__MCMULLEN	44		1105
CB_MCMULLEN		0	1105
			1105
SPARTA_SAND__MCMULLE	49		600
CB_MCMULLEN		0	600
			600
SHORTAGE__MCMULLEN	999		999999
			0
GULF_COAST__NUECES	31		3254
BISHOP		0	848
PORT_ARANSAS		0	2161
ROBSTOWN		0	245
			3254
LOCAL__NUECES	10		950
CB_NUECES		0	950
			950
SHORTAGE__NUECES	999		999999
			0

Table 5.4 PLAN 4 - Statewide Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__REFUGIO	31		7768
ROCKPORT		47	1018
CO_ARANSAS		37	4426
CA_ARANSAS		78	261
REFUGIO		0	439
WOODSBORO		0	278
CO_REFUGIO		0	406
CB_REFUGIO		0	940

			7768
GULF_COAST__SAN_PATR	31		5228
MATHIS		0	1262
ARANSAS_PASS		0	1371
GREGORY		0	725
ODEM		0	636
TAFT		0	827
TAFT_SOUTHWEST		0	407

			5228
SHORTAGE__SAN_PATR	999		999999

			0
GULF_COAST__VICTORIA	39		41130
BLOOMINGTON		0	515
VICTORIA		0	16243
CO_VICTORIA		0	4125
CA_VICTORIA		0	11091
CB_VICTORIA		0	9156

			41130
TEXANA	43		75000
CA_CALHOUN		21	50445
CB_JACKSON		14	24555

			75000
CUERO_I&II	49		52000

			0

Table 5.4 PLAN 4 - Statewide Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GUADALUPE	40		79000
CA_CALHOUN		19	30104
CA_VICTORIA		13	48896

			79000
COLETO_CR	59		12500

			0
SAN_ANTONIO	40		25000
CA_CALHOUN		25	14365
CB_CALHOUN		23	10635

			25000
CHOKE-CORPUS_w_bay	43		230549
ROCKPORT		54	1306
CORPUS_CHRISTI		25	119046
ROBSTOWN		49	2575
CO_NUECES		45	3139
CA_NUECES		18	54448
ARANSAS_PASS		59	639
PORTLAND		53	2980
SINTON		57	1416
CO_SAN_PATRICIO		43	3540
CA_SAN_PATRICIO		23	28008
CB_SAN_PATRICIO		40	4672

			221769

Table 5.5 PLAN 9 - Statewide & Regional Rules

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__ARANSAS	31		400
ROCKPORT		0	53
CO_ARANSAS		0	80
CA_ARANSAS		0	160
CB_ARANSAS		0	107
			400
CARRIZO-WILCOX__BEE	24		394
BEEVILLE		0	157
CO_BEE		0	6
CA_BEE		0	5
CB_BEE		0	157
			325
GULF_COAST__BEE	31		14577
BEEVILLE		0	3573
CO_BEE		0	2915
CB_BEE		0	2433
ARANSAS_PASS		57	1372
INGLESIDE		55	1789
CO_SAN_PATRICIO		43	2495
			14577
GULF_COAST__BROOKS	31		14577
FALFURRIAS		0	1372
CO_BROOKS		0	769
CA_BROOKS		0	18
CB_BROOKS		0	1690
KINGSVILLE		38	2344
			6193
GULF_COAST__CALHOUN	31		2940
POINT_COMFORT		0	237
SEADRIFT		0	398
CO_CALHOUN		0	1129
CB_CALHOUN		0	1176
			2940
LOCAL__CALHOUN	10		12600
CB_CALHOUN		0	12600
			12600

Table 5.5 PLAN 9 - Statewide & Regional Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
SHORTAGE__CALHOUN	999		999999
CB_CALHOUN		0	9459

			9459
GULF_COAST__DE_WITT	31		15866
CUERO		0	1831
YORKTOWN		0	535
YOAKUM		0	550
CO_DE_WITT		0	1182
CA_DE_WITT		0	6346
CB_DE_WITT		0	3070
VICTORIA		31	2352

			15866
GULF_COAST__DUVAL	31		23970
BENAVIDES		0	747
FREER		0	1227
SAN_DIEGO		0	1294
CO_DUVAL		0	448
CB_DUVAL		0	5506
ALICE		31	7249
CORPUS_CHRISTI		23	2668
PORT_ARANSAS		53	1706
CO_NUECES		42	145
PORTLAND		46	2980

			23970
GULF_COAST__GOLIAD	31		12809
CO_ARANSAS		48	1239
CO_CALHOUN		65	1090
GOLIAD		0	671
CO_GOLIAD		0	921
CA_GOLIAD		0	5123
CB_GOLIAD		0	1934
VICTORIA		38	1831

			12809

Table 5.5 PLAN 9 - Statewide & Regional Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
CARRIZO-WILCOX__GONZ	16		19840
PORT_LAVACA		45	3213
GONZALES		0	2932
NIXON		0	653
CO_GONZALES		0	2177
CA_GONZALES		0	1839
CB_GONZALES		0	2019
VICTORIA		34	7007
			19840
GULF_COAST__GONZALES	39		2083
CO_GONZALES		0	416
CA_GONZALES		0	833
CB_GONZALES		0	556
			1805
QUEEN_CITY__GONZALES	44		6104
			0
SPARTA_SAND__GONZALE	49		16340
			0
LOCAL__GONZALES	10		4200
CB_GONZALES		0	4200
			4200
GULF_COAST__JACKSON	39		28343
EDNA		0	1573
GANADO		0	418
CO_JACKSON		0	1338
CA_JACKSON		0	66
CB_JACKSON		0	24948
			28343
SHORTAGE__JACKSON	999		999999
			0

Table 5.5 PLAN 9 - Statewide & Regional Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__JIM_WELL	31		11370
ALICE		0	2161
ORANGE_GROVE		0	403
PREMONT		0	1351
CO_JIM_WELLS		0	2560
CA_JIM_WELLS		0	347
CB_JIM_WELLS		0	4548
			11370
SHORTAGE__JIM_WELL	999		999999
CB_JIM_WELLS		0	104
			104
GULF_COAST__KENEDY	31		9550
SARITA		0	14
CO_KENEDY		0	49
CB_KENEDY		0	1821
			1884
GULF_COAST__KLEBERG	31		17088
KINGSVILLE		0	6835
CO_KLEBERG		0	2028
CA_KLEBERG		0	2574
CB_KLEBERG		0	2612
CO_NUECES		55	3039
			17088
GULF_COAST__LAVACA	39		38123
HALLETTSVILLE		0	831
SHINER		0	746
YOAKUM		0	915
CO_LAVACA		0	1865
CA_LAVACA		0	6933
CB_LAVACA		0	15216
			26506
CARRIZO-WILCOX__LIVE	24		2399
GEORGE_WEST		0	592
THREE_RIVERS		0	230
CA_LIVE_OAK		0	618
CB_LIVE_OAK		0	959
			2399

Table 5.5 PLAN 9 - Statewide & Regional Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__LIVE_OAK	31		5242
THREE_RIVERS		0	255
CO_LIVE_OAK		0	795
CA_LIVE_OAK		0	2096
CB_LIVE_OAK		0	2096

			5242
LOCAL__LIVE_OAK	10		760
CB_LIVE_OAK		0	760

			760
SHORTAGE__LIVE_OAK	999		999999
CB_LIVE_OAK		0	1145

			1145
CARRIZO-WILCOX__MCMU	24		7909
TILDEN		0	76
CB_MCMULLEN		0	3163
ROBSTOWN		57	2126
MATHIS		63	625
SINTON		63	1416
TAFT		73	503

			7909
GULF_COAST__MCMULLEN	31		1838
CO_MCMULLEN		0	155
CB_MCMULLEN		0	735
MATHIS		65	637
ARANSAS_PASS		63	311

			1838
QUEEN_CITY__MCMULLEN	44		1105
CB_MCMULLEN		0	442

			442
SPARTA_SAND__MCMULLE	49		600
CB_MCMULLEN		0	240

			240

Table 5.5 PLAN 9 - Statewide & Regional Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
SHORTAGE__MCMULLEN	999		999999
CB_MCMULLEN		0	46

			46
GULF_COAST__NUECES	31		3254
BISHOP		0	848
PORT_ARANSAS		0	455
CO_NUECES		0	650
CB_NUECES		0	1301

			3254
LOCAL__NUECES	10		950
CB_NUECES		0	950

			950
SHORTAGE__NUECES	999		999999
CB_NUECES		0	2103

			2103
GULF_COAST__REFUGIO	31		7768
ROCKPORT		53	2271
CO_ARANSAS		43	3107
REFUGIO		0	439
WOODSBORO		0	278
CO_REFUGIO		0	406
CB_REFUGIO		0	940
ARANSAS_PASS		61	327

			7768
GULF_COAST__SAN_PATR	31		5228
GREGORY		0	725
ODEM		0	636
TAFT		0	324
TAFT_SOUTHWEST		0	407
CO_SAN_PATRICIO		0	1045
CB_SAN_PATRICIO		0	2091

			5228
SHORTAGE__SAN_PATR	999		999999
CB_SAN_PATRICIO		0	2581

			2581

Table 5.5 PLAN 9 - Statewide & Regional Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__VICTORIA	39		41130
BLOOMINGTON		0	515
VICTORIA		0	5053
CO_VICTORIA		0	4125
CA_VICTORIA		0	16452
CB_VICTORIA		0	14985
			41130
TEXANA	43		75000
CA_CALHOUN		21	38828
CB_JACKSON		14	36172
			75000
CUERO_I&II	49		52000
CA_DE_WITT		41	866
CA_VICTORIA		28	26338
			27204
GUADALUPE	40		79000
CA_CALHOUN		19	41963
CA_VICTORIA		13	37037
			79000
COLETO_CR	59		12500
			0
SAN_ANTONIO	40		25000
CA_CALHOUN		25	14123
CA_GOLIAD		32	10877
			25000
CHOKE-CORPUS_w_bay	43		230549
CA_ARANSAS		87	394
CA_LIVE_OAK		41	13399
CORPUS_CHRISTI		25	116378
ROBSTOWN		49	694
CA_NUECES		18	54448
CA_SAN_PATRICIO		23	28008
			213321

Table 5.6 PLAN 10 - Statewide, Regional, & Parc Rules

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__ARANSAS	31		400
ROCKPORT		0	53
CO_ARANSAS		0	80
CA_ARANSAS		0	160
CB_ARANSAS		0	107
			400
CARRIZO-WILCOX__BEE	24		394
BEEVILLE		0	157
CO_BEE		0	6
CA_BEE		0	5
CB_BEE		0	157
			325
GULF_COAST__BEE	31		14577
BEEVILLE		0	3573
CO_BEE		0	2915
CB_BEE		0	2433
CORPUS_CHRISTI		34	3635
			12556
GULF_COAST__BROOKS	31		14577
FALFURRIAS		0	1372
CO_BROOKS		0	769
CA_BROOKS		0	18
CB_BROOKS		0	1690
			3849
GULF_COAST__CALHOUN	31		2940
POINT_COMFORT		0	237
SEADRIFT		0	398
CO_CALHOUN		0	1129
CB_CALHOUN		0	1176
			2940
LOCAL__CALHOUN	10		12600
CB_CALHOUN		0	12600
			12600

Table 5.6 PLAN 10 - Statewide, Regional, & Parc Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
SHORTAGE__CALHOUN	999		999999
CB_CALHOUN		0	9459
			9459
GULF_COAST__DE_WITT	31		15866
CUERO		0	1831
YORKTOWN		0	535
YOAKUM		0	550
CO_DE_WITT		0	1182
CA_DE_WITT		0	6346
CB_DE_WITT		0	3070
VICTORIA		31	2352
			15866
GULF_COAST__DUVAL	31		23970
BENAVIDES		0	747
FREER		0	1227
SAN_DIEGO		0	1294
CO_DUVAL		0	448
CB_DUVAL		0	5506
ALICE		31	5160
CORPUS_CHRISTI		23	9588
			23970
GULF_COAST__GOLIAD	31		12809
CO_CALHOUN		65	940
GOLIAD		0	671
CO_GOLIAD		0	921
CA_GOLIAD		0	5123
CB_GOLIAD		0	1934
VICTORIA		38	3220
			12809
CARRIZO-WILCOX__GONZ	16		19840
PORT_LAVACA		45	3213
GONZALES		0	2932
NIXON		0	653
CO_GONZALES		0	2177
CA_GONZALES		0	2672
CB_GONZALES		0	2575
VICTORIA		34	5618
			19840

Table 5.6 PLAN 10 - Statewide, Regional, & Parc Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__GONZALES	39		2083
CO_GONZALES		0	416
			416
QUEEN_CITY__GONZALES	44		6104
			0
SPARTA_SAND__GONZALE	49		16340
			0
LOCAL__GONZALES	10		4200
CB_GONZALES		0	4200
			4200
GULF_COAST__JACKSON	39		28343
EDNA		0	1573
GANADO		0	418
CO_JACKSON		0	1338
CA_JACKSON		0	66
CB_JACKSON		0	24948
			28343
SHORTAGE__JACKSON	999		999999
			0
GULF_COAST__JIM_WELL	31		11370
ALICE		0	2161
ORANGE_GROVE		0	403
PREMONT		0	1351
CO_JIM_WELLS		0	2560
CA_JIM_WELLS		0	347
CB_JIM_WELLS		0	4548
			11370
SHORTAGE__JIM_WELL	999		999999
CB_JIM_WELLS		0	104
			104

Table 5.6 PLAN 10 - Statewide, Regional, & Parc Rules (Continued)

SUPPLY DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GULF_COAST__KENEDY	31		9550
SARITA		0	14
CO_KENEDY		0	49
CB_KENEDY		0	1821

			1884
GULF_COAST__KLEBERG	31		17088
KINGSVILLE		0	6835
CO_KLEBERG		0	2028
CA_KLEBERG		0	2574
CB_KLEBERG		0	2612

			14049
GULF_COAST__LAVACA	39		38123
HALLETTSVILLE		0	831
SHINER		0	746
YOAKUM		0	915
CO_LAVACA		0	1865
CA_LAVACA		0	6933
CB_LAVACA		0	15216

			26506
CARRIZO-WILCOX__LIVE	24		2399
GEORGE_WEST		0	251
THREE_RIVERS		0	230
CA_LIVE_OAK		0	959
CB_LIVE_OAK		0	959

			2399
GULF_COAST__LIVE_OAK	31		5242
THREE_RIVERS		0	255
CO_LIVE_OAK		0	795
CA_LIVE_OAK		0	2096
CB_LIVE_OAK		0	2096

			5242
LOCAL__LIVE_OAK	10		760
CB_LIVE_OAK		0	760

			760

Table 5.6 PLAN 10 - Statewide, Regional, & Parc Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
SHORTAGE__LIVE_OAK	999		999999
CB_LIVE_OAK		0	1145

			1145
CARRIZO-WILCOX__MCMU	24		7909
KINGSVILLE		42	2344
TILDEN		0	76
CB_MCMULLEN		0	3163

			5583
GULF_COAST__MCMULLEN	31		1838
CO_MCMULLEN		0	155
CB_MCMULLEN		0	735

			890
QUEEN_CITY__MCMULLEN	44		1105
CB_MCMULLEN		0	442

			442
SPARTA_SAND__MCMULLE	49		600
CB_MCMULLEN		0	240

			240
SHORTAGE__MCMULLEN	999		999999
CB_MCMULLEN		0	46

			46
GULF_COAST__NUECES	31		3254
BISHOP		0	848
CO_NUECES		0	650
CA_NUECES		0	455
CB_NUECES		0	1301

			3254
LOCAL__NUECES	10		950
CB_NUECES		0	950

			950

Table 5.6 PLAN 10 - Statewide, Regional, & Parc Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
SHORTAGE__NUECES	999		999999
CB_NUECES		0	2103

			2103
GULF_COAST__REFUGIO	31		7768
CO_CALHOUN		65	150
REFUGIO		0	439
WOODSBORO		0	278
CO_REFUGIO		0	406
CB_REFUGIO		0	940

			2213
GULF_COAST__SAN_PATR	31		5228
TAFT_SOUTHWEST		0	1
CO_SAN_PATRICIO		0	1045
CA_SAN_PATRICIO		0	2091
CB_SAN_PATRICIO		0	2091

			5228
SHORTAGE__SAN_PATR	999		999999
CB_SAN_PATRICIO		0	2581

			2581
GULF_COAST__VICTORIA	39		41130
BLOOMINGTON		0	515
VICTORIA		0	5053
CO_VICTORIA		0	4125
CA_VICTORIA		0	16452
CB_VICTORIA		0	14985

			41130
TEXANA	43		75000
CA_CALHOUN		21	38828
CB_JACKSON		14	36172

			75000
CUERO_I&II	49		52000
CA_DE_WITT		41	866
CA_VICTORIA		28	15855

			16721

Table 5.6 PLAN 10 - Statewide, Regional, & Parc Rules (Continued)

SUPPLY / DEMAND	COST IN PLACE ($/AF)	TR.COST ($/AF)	AMOUNT (AF/Y)
GUADALUPE	40		79000
CA_CALHOUN		19	31480
CA_VICTORIA		13	47520

			79000
COLETO_CR	59		12500
CA_GOLIAD		0	10877

			10877
SAN_ANTONIO	40		25000
CA_ARANSAS		78	394
CA_CALHOUN		25	24606

			25000
CHOKE-CORPUS_w_bay	43		230549
ROCKPORT		13	2271
CO_ARANSAS		12	4346
ALICE		12	2089
GEORGE_WEST		23	341
CA_LIVE_OAK		41	13058
CORPUS_CHRISTI		6	105823
PORT_ARANSAS		15	2161
ROBSTOWN		12	2820
CO_NUECES		11	3184
CA_NUECES		18	53993
MATHIS		15	1262
ARANSAS_PASS		14	2010
GREGORY		20	725
INGLESIDE		14	1789
ODEM		19	636
PORTLAND		13	2980
SINTON		14	1416
TAFT		17	827
TAFT_SOUTHWEST		22	406
CO_SAN_PATRICIO		10	2495
CA_SAN_PATRICIO		23	25917

			230549

Table 5.7 Comparison of Allocations

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB 1992 WATER PLAN	(AF/Y)
ROCKPORT	2324		
GULF_COAST__ARANSAS	53	CHOKE-CORPUS w bay	2324
CHOKE-CORPUS_w_bay	2271		
CO_ARANSAS	4426		
GULF_COAST__ARANSAS	80	GULF COAST	274
CHOKE-CORPUS_w_bay	4346	CHOKE-CORPUS w bay	4152
CA_ARANSAS	554		
GULF_COAST__ARANSAS	160	GULF COAST	122
SAN_ANTONIO	394	CHOKE-CORP	432
CB_ARANSAS	107		
GULF_COAST__ARANSAS	107	GULF COAST	3
		CHOKE-CORP	14
		LOCAL SUP6	90
BEEVILLE	3730		
CARRIZO-WILCOX__BEE	157	CHOKE-CORPUS w bay	3730
GULF_COAST__BEE	3573		
CO_BEE	2921		
CARRIZO-WILCOX__BEE	6	GULF COAST	2400
GULF_COAST__BEE	2915	CHOKE-CORPUS w bay	311
		GULF COAST	210
CA_BEE	5		
CARRIZO-WILCOX__BEE	5	GULF COAST	5
CB_BEE	2590		
CARRIZO-WILCOX__BEE	157	GULF COAST	121
GULF_COAST__BEE	2433	GULF COAST	1155
		GULF COAST	422
		LOCAL SUP6	739
		GULF COAST	153
FALFURRIAS	1372		
GULF_COAST__BROOKS	1372	GULF COAST	1372
CO_BROOKS	769		
GULF_COAST__BROOKS	769	GULF COAST	769
CA_BROOKS	18		
GULF_COAST__BROOKS	18	GULF COAST	18
CB_BROOKS	1690		
GULF_COAST__BROOKS	1690	GULF COAST	62
		GULF COAST	495
		GULF COAST	524
		LOCAL SUP6	609
POINT_COMFORT	237		
GULF_COAST__CALHOUN	237	TEXANA	237

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
PORT_LAVACA	3213		
CARRIZO-WILCOX__GONZ	3213	CUERO I&II	3213
SEADRIFT	398		
GULF_COAST__CALHOUN	398	GULF COAST	398
CO_CALHOUN	2219		
GULF_COAST__CALHOUN	1129	GULF COAST	100
GULF_COAST__GOLIAD	940	TEXANA	140
GULF_COAST__REFUGIO	150	GULF COAST	350
		CUERO I&II	1606
		CANYON	8
		OTHER	15
CA_CALHOUN	94914		
TEXANA	38828	GULF COAST	1722
GUADALUPE	31480	GULF COAST	200
SAN_ANTONIO	24606	TEXANA	39959
		GULF COAST	41
		CUERO I&II	7945
		SAN ANTONI	25000
		GUADALUPE	19631
		CANYON	270
		GUADALUPE	146
CB_CALHOUN	23235		
GULF_COAST__CALHOUN	1176	GULF COAST	32
LOCAL__CALHOUN	12600	OTHER	1
SHORTAGE__CALHOUN	9459	GULF COAST	2
		GULF COAST	1976
		OTHER	6
		GUADALUPE	11285
		LOCAL SUP2	11908
		LOCAL SUP6	615
		LOCAL SUP6	2
		OTHER	3
CUERO	1831		
GULF_COAST__DE_WITT	1831	GULF COAST	1831
YORKTOWN	535		
GULF_COAST__DE_WITT	535	GULF COAST	535
YOAKUM	550		
GULF_COAST__DE_WITT	550	GULF COAST	550
		GULF COAST	915
CO_DE_WITT	1182		
GULF_COAST__DE_WITT	1182	GULF COAST	168
		GULF COAST	4
		GULF COAST	875
		GULF COAST	135
CA_DE_WITT	7212		
GULF_COAST__DE_WITT	6346	GULF COAST	20
CUERO_I&II	866	GULF COAST	47
		LOCAL SUP2	145
		CUERO I&II	7000

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
CB_DE_WITT	3070		
GULF_COAST__DE_WITT	3070	GULF COAST	36
		GULF COAST	347
		GULF COAST	1
		GULF COAST	67
		GULF COAST	1
		GULF COAST	335
		GULF COAST	666
		LOCAL SUP2	225
		LOCAL SUP2	1156
		GULF COAST	40
		GULF COAST	196
BENAVIDES	747		
GULF_COAST__DUVAL	747	GULF COAST	747
FREER	1227		
GULF_COAST__DUVAL	1227	GULF COAST	1227
SAN_DIEGO	1294		
GULF_COAST__DUVAL	1294	GULF COAST	1084
		CHOKE-CORPUS w bay	210
CO_DUVAL	448		
GULF_COAST__DUVAL	448	GULF COAST	85
		GULF COAST	363
CB_DUVAL	5506		
GULF_COAST__DUVAL	5506	GULF COAST	407
		LOCAL SUP6	137
		GULF COAST	8
		GULF COAST	97
		GULF COAST	3095
		GULF COAST	407
		LOCAL SUP6	1355
GOLIAD	671		
GULF_COAST__GOLIAD	671	GULF COAST	671
CO_GOLIAD	921		
GULF_COAST__GOLIAD	921	GULF COAST	329
		GULF COAST	467
		GULF COAST	125
CA_GOLIAD	16000		
GULF_COAST__GOLIAD	5123	GULF COAST	1690
COLETO_CR	10877	COLETO	12500
		CANYON	1810
CB_GOLIAD	1934		
GULF_COAST__GOLIAD	1934	GULF COAST	280
		GULF COAST	496
		LOCAL SUP2	660
		GULF COAST	3
		GULF COAST	495
GONZALES	2932		
CARRIZO-WILCOX__GONZ	2932	GUADALUPE R. W CUERO	2932

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
NIXON	653		
CARRIZO-WILCOX__GONZ	653	CARRIZO - WILCOX	653
CO_GONZALES	2593		
CARRIZO-WILCOX__GONZ	2177	CARRIZO - WILCOX	21
GULF_COAST__GONZALES	416	CARRIZO - WILCOX	1300
		GULF COAST	22
		OTHER	50
		QUEEN CITY	122
		SPARTA	200
		GUADALUPE R. W CUERO	393
		CANYON	700
CA_GONZALES	2672		
CARRIZO-WILCOX__GONZ	2672	CARRIZO -	674
		OTHER	20
		QUEEN CITY	125
		SPARTA	30
		CANYON	200
		LOCAL SUP2	100
		GUADALUPE	700
		RETURN FL	823
CB_GONZALES	6775		
CARRIZO-WILCOX__GONZ	2575	CARRIZO -	39
LOCAL__GONZALES	4200	CARRIZO -	22
		CARRIZO -	1710
		CARRIZO -	119
		OTHER	120
		QUEEN CITY	335
		SPARTA	245
		LOCAL SUP2	600
		LOCAL SUP2	3585
EDNA	1573		
GULF_COAST__JACKSON	1573	TEXANA	1573
GANADO	418		
GULF_COAST__JACKSON	418	TEXANA	418
CO_JACKSON	1338		
GULF_COAST__JACKSON	1338	GULF COAST	200
		TEXANA	202
		GULF COAST	700
		TEXANA	111
		GULF COAST	125
CA_JACKSON	66		
GULF_COAST__JACKSON	66	GULF COAST	66
CB_JACKSON	61120		
GULF_COAST__JACKSON	24948	GULF COAST	17050
TEXANA	36172	GULF COAST	304
		LOCAL SUP2	1598
		GULF COAST	25000
		GULF COAST	350
		LOCAL SUP2	1313
		LOCAL SUP6	77
		GULF COAST	52
		GULF COAST	4272
		LOCAL SUP2	921
		LOCAL SUP2	139

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
ALICE	9410		
GULF_COAST__DUVAL	5160	CHOKE-CORPUS w bay	9410
GULF_COAST__JIM_WELL	2161		
CHOKE-CORPUS_w_bay	2089		
ORANGE_GROVE	403		
GULF_COAST__JIM_WELL	403	GULF COAST	403
PREMONT	1351		
GULF_COAST__JIM_WELL	1351	GULF COAST	1351
CO_JIM_WELLS	2560		
GULF_COAST__JIM_WELL	2560	GULF COAST	297
CA_JIM_WELLS	347		
GULF_COAST__JIM_WELL	347	CHOKE-CORP	347
CB_JIM_WELLS	4652		
GULF_COAST__JIM_WELL	4548	GULF COAST	1048
SHORTAGE__JIM_WELL	104	GULF COAST	227
		LOCAL SUP6	13
		GULF COAST	78
		GULF COAST	270
		GULF COAST	1837
		GULF COAST	227
		LOCAL SUP2	952
SARITA	14		
GULF_COAST__KENEDY	14	GULF COAST	14
CO_KENEDY	49		
GULF_COAST__KENEDY	49	GULF COAST	49
CB_KENEDY	1821		
GULF_COAST__KENEDY	1821		
KINGSVILLE	9179		
GULF_COAST__KLEBERG	6835	GULF COAST	170
CARRIZO-WILCOX__MCMU	2344	CHOKE-CORPUS w bay	9009
CO_KLEBERG	2028		
GULF_COAST__KLEBERG	2028	GULF COAST	1700
		CHOKE-CORPUS w bay	328
CA_KLEBERG	2574		
GULF_COAST__KLEBERG	2574	GULF COAST	51
		GULF COAST	2500
		CHOKE-CORP	23
CB_KLEBERG	2612		
GULF_COAST__KLEBERG	2612	GULF COAST	542
		GULF COAST	500
		GULF COAST	341
		LOCAL SUP2	100
		LOCAL SUP2	1129

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
HALLETTSVILLE	831		
GULF_COAST__LAVACA	831	GULF COAST	831
SHINER	746		
GULF_COAST__LAVACA	746	GULF COAST	746
YOAKUM	550		
GULF_COAST__DE_WITT	550	GULF COAST	550
		GULF COAST	915
CO_LAVACA	1865		
GULF_COAST__LAVACA	1865	GULF COAST	5
		GULF COAST	20
CA_LAVACA	6933		
GULF_COAST__LAVACA	6933	GULF COAST	933
		GULF COAST	6000
CB_LAVACA	15216		
GULF_COAST__LAVACA	15216	GULF COAST	76
		GULF COAST	12235
		GULF COAST	381
		LOCAL SUP2	762
		LOCAL SUP2	1718
		GULF COAST	1
		GULF COAST	5
		GULF COAST	38
GEORGE_WEST	592		
CARRIZO-WILCOX__LIVE	251	GULF COAST	592
CHOKE-CORPUS_w_bay	341		
THREE_RIVERS	485		
CARRIZO-WILCOX__LIVE	230	CHOKE-CORPUS w bay	485
GULF_COAST__LIVE_OAK	255		
CO_LIVE_OAK	795		
GULF_COAST__LIVE_OAK	795	GULF COAST	695
		CHOKE-CORPUS w bay	100
CA_LIVE_OAK	16113		
CARRIZO-WILCOX__LIVE	959	CARRIZO -	15000
GULF_COAST__LIVE_OAK	2096	GULF COAST	927
CHOKE-CORPUS_w_bay	13058	CHOKE-CORP	186
CB_LIVE_OAK	4960		
CARRIZO-WILCOX__LIVE	959	CARRIZO -	53
GULF_COAST__LIVE_OAK	2096	CARRIZO -	2346
LOCAL__LIVE_OAK	760	GULF COAST	172
SHORTAGE__LIVE_OAK	1145	GULF COAST	1229
		GULF COAST	398
		LOCAL SUP2	55
		LOCAL SUP2	707
TILDEN	76		
CARRIZO-WILCOX__MCMU	76	CARRIZO - WILCOX	76
CO_MCMULLEN	155		
GULF_COAST__MCMULLEN	155	CARRIZO - WILCOX	155

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
CB_MCMULLEN	4626		
CARRIZO-WILCOX__MCMU	3163	CARRIZO -	165
GULF_COAST__MCMULLEN	735	GULF COAST	215
QUEEN_CITY__MCMULLEN	442	GULF COAST	215
SPARTA_SAND__MCMULLE	240	LOCAL SUP6	1237
SHORTAGE__MCMULLEN	46		
BISHOP	848		
GULF_COAST__NUECES	848	CHOKE-CORPUS w bay	848
CORPUS_CHRISTI	119046		
GULF_COAST__BEE	3635	CHOKE-CORPUS w bay	5587
GULF_COAST__DUVAL	9588	CHOKE-CORPUS w bay	113459
CHOKE-CORPUS_w_bay	105823		
PORT_ARANSAS	2161		
CHOKE-CORPUS_w_bay	2161	CHOKE-CORPUS w bay	108
		CHOKE-CORPUS w bay	2053
ROBSTOWN	2820		
CHOKE-CORPUS_w_bay	2820		
CO_NUECES	3834		
GULF_COAST__NUECES	650	GULF COAST	244
CHOKE-CORPUS_w_bay	3184	CHOKE-CORPUS w bay	105
		GULF COAST	175
		CHOKE-CORPUS w bay	3310
CA_NUECES	54448		
GULF_COAST__NUECES	455	GULF COAST	152
CHOKE-CORPUS_w_bay	53993	CHOKE-CORP	942
		CHOKE-CORP	3000
		GULF COAST	152
		CHOKE-CORP	24385
		TEXANA	25317
		TEXANA	500
CB_NUECES	4354		
GULF_COAST__NUECES	1301	GULF COAST	3
LOCAL__NUECES	950	GULF COAST	1108
SHORTAGE__NUECES	2103	GULF COAST	26
		LOCAL SUP2	912
		LOCAL SUP2	12
		GULF COAST	88
		GULF COAST	19
		GULF COAST	797
		GULF COAST	26
		LOCAL SUP2	170
		TEXANA	542
		LOCAL SUP2	288
REFUGIO	439		
GULF_COAST__REFUGIO	439	GULF COAST	439
WOODSBORO	278		
GULF_COAST__REFUGIO	278	GULF COAST	278

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION SYSTEM	(AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
CO_REFUGIO	406		
GULF_COAST__REFUGIO	406	GULF COAST	11
		GULF COAST	395
CB_REFUGIO	940		
GULF_COAST__REFUGIO	940	GULF COAST	165
		GULF COAST	25
		GULF COAST	102
		GULF COAST	271
		LOCAL SUP6	377
MATHIS	1262		
CHOKE-CORPUS_w_bay	1262	CHOKE-CORPUS w bay	1262
ARANSAS_PASS	2010		
CHOKE-CORPUS_w_bay	2010	CHOKE-CORPUS w bay	279
		CHOKE-CORPUS w bay	1
		CHOKE-CORPUS w bay	1730
GREGORY	725		
CHOKE-CORPUS_w_bay	725	CHOKE-CORPUS w bay	725
INGLESIDE	1789		
CHOKE-CORPUS_w_bay	1789	CHOKE-CORPUS w bay	1789
ODEM	636		
CHOKE-CORPUS_w_bay	636	CHOKE-CORPUS w bay	636
PORTLAND	2980		
CHOKE-CORPUS_w_bay	2980		
SINTON	1416		
CHOKE-CORPUS_w_bay	1416	GULF COAST	1416
TAFT	827		
CHOKE-CORPUS_w_bay	827	CHOKE-CORPUS w bay	827
		CHOKE-CORPUS w bay	407
TAFT_SOUTHWEST	407		
GULF_COAST__SAN_PATR	1	CHOKE-CORPUS w bay	407
CHOKE-CORPUS_w_bay	406		
CO_SAN_PATRICIO	3540		
GULF_COAST__SAN_PATR	1045	GULF COAST	690
CHOKE-CORPUS_w_bay	2495	CHOKE-CORPUS w bay	1987
		GULF COAST	522
		CHOKE-CORPUS w bay	341
CA_SAN_PATRICIO	28008		
GULF_COAST__SAN_PATR	2091	GULF COAST	5
CHOKE-CORPUS_w_bay	25917	CHOKE-CORP	27478
		GULF COAST	5
		CHOKE-CORP	520

Table 5.7 Comparison of Allocations (Continued)

AUTOMATED ALLOCATION	SYSTEM (AF/Y)	TWDB	1992 WATER PLAN (AF/Y)
CB_SAN_PATRICIO	4672		
GULF_COAST__SAN_PATR	2091	GULF COAST	43
SHORTAGE__SAN_PATR	2581	GULF COAST	2357
		GULF COAST	177
		LOCAL SUP2	50
		LOCAL SUP2	352
		GULF COAST	13
		LOCAL SUP2	69
		LOCAL SUP2	265
BLOOMINGTON	515		
GULF_COAST__VICTORIA	515	GULF COAST	515
VICTORIA	16243		
GULF_COAST__DE_WITT	2352	GULF COAST	3343
GULF_COAST__GOLIAD	3220	GULF COAST	12908
CARRIZO-WILCOX__GONZ	5618		
GULF_COAST__VICTORIA	5053		
CO_VICTORIA	4125		
GULF_COAST__VICTORIA	4125	GULF COAST	41
		GULF COAST	1859
		GULF COAST	2160
		GULF COAST	65
CA_VICTORIA	79827		
GULF_COAST__VICTORIA	16452	GULF COAST	17
CUERO_I&II	15855	GULF COAST	904
GUADALUPE	47520	GULF COAST	4729
		GUADALUPE	32000
		GUADALUPE	948
		RETURN FL	5000
		RETURN FL	20323
		CUERO I&II	15906
CB_VICTORIA	14985		
GULF_COAST__VICTORIA	14985	GULF COAST	780
		GULF COAST	7
		GULF COAST	29
		GULF COAST	1045
		GULF COAST	9541
		GULF COAST	766
		GULF COAST	1
		GULF COAST	562
		GULF COAST	1104
		GULF COAST	740
		LOCAL SUP2	300
		LOCAL SUP2	19
		GULF COAST	14
		LOCAL SUP6	77

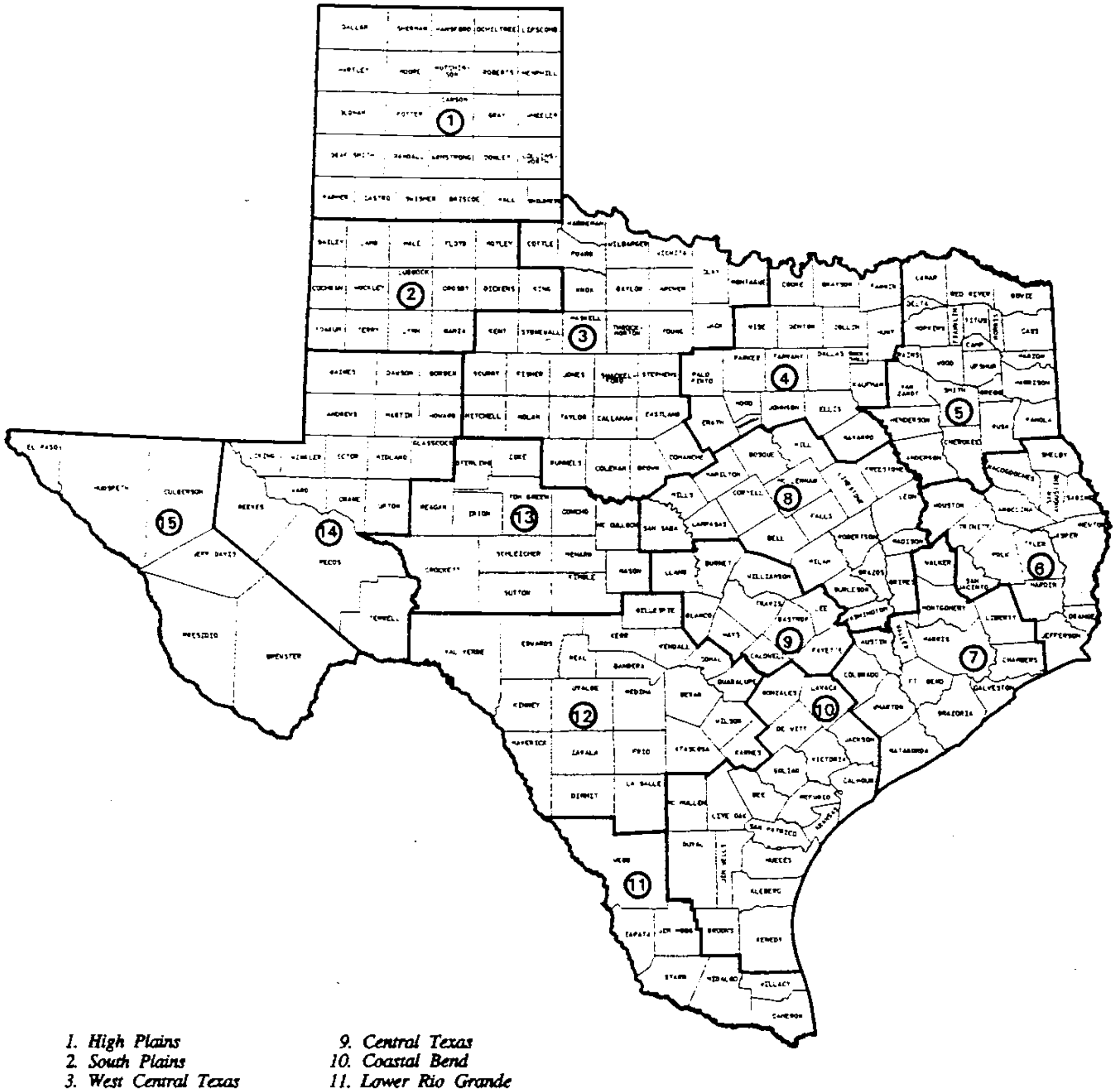


Figure 5.1 Prospective water planning regions for the 1994 Texas Water Plan.

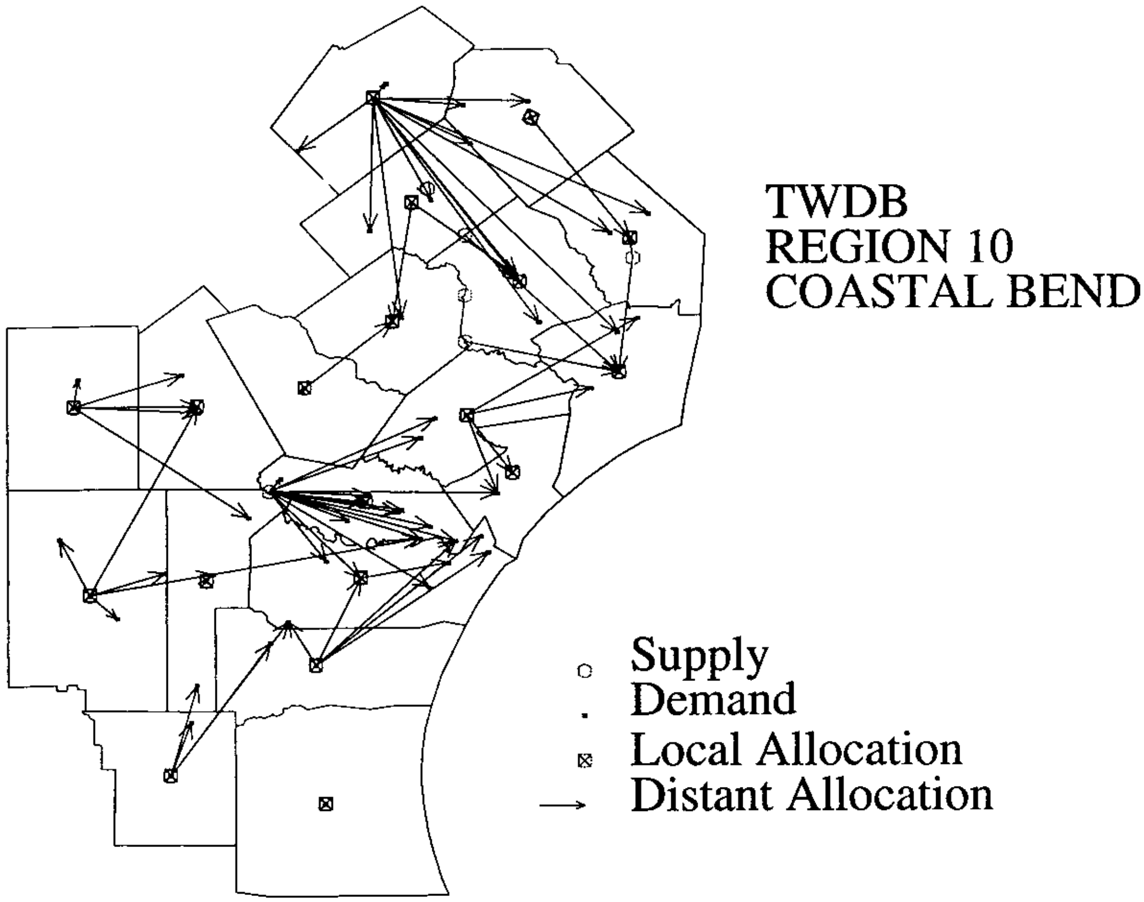


Figure 5.2 PLAN 0 - No Rules.

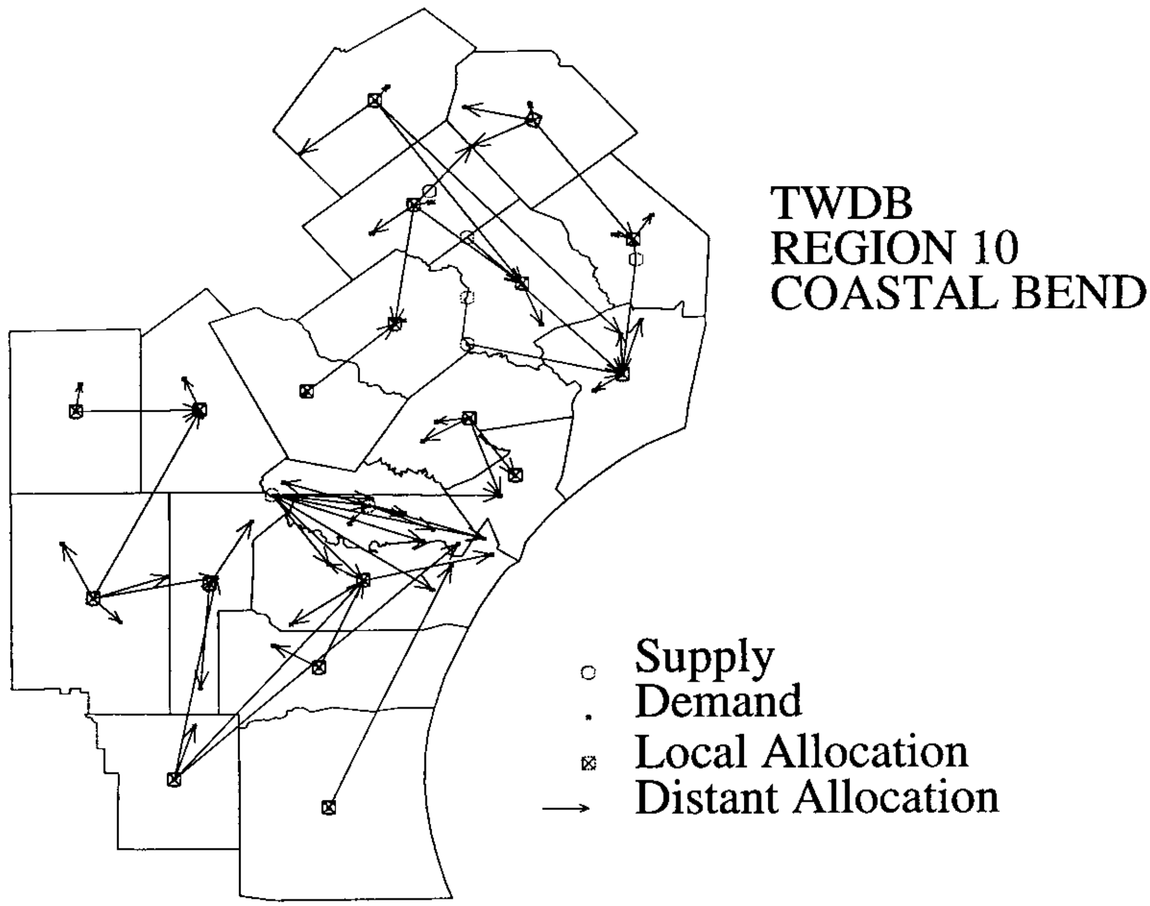


Figure 5.3 PLAN 4 - Statewide Rules.

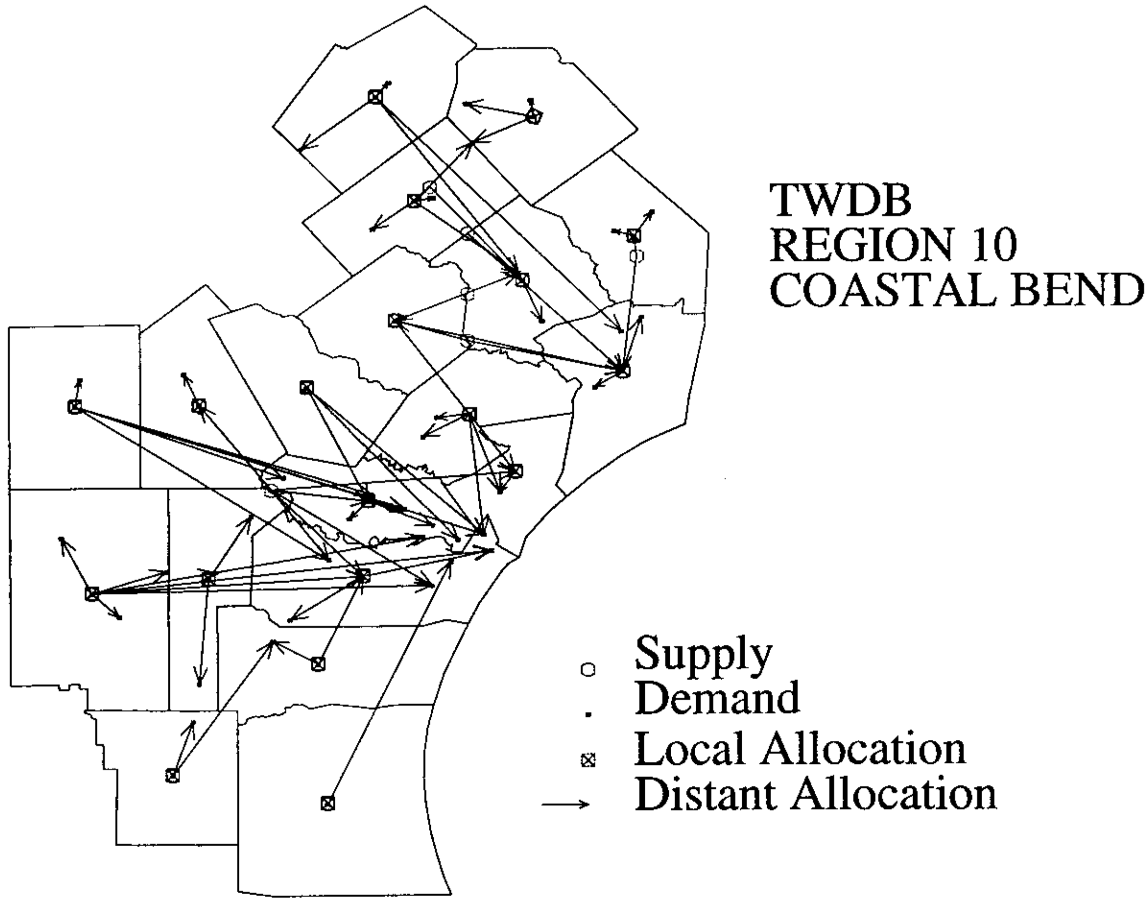


Figure 5.4 PLAN 9 - Statewide & Regional Rules.

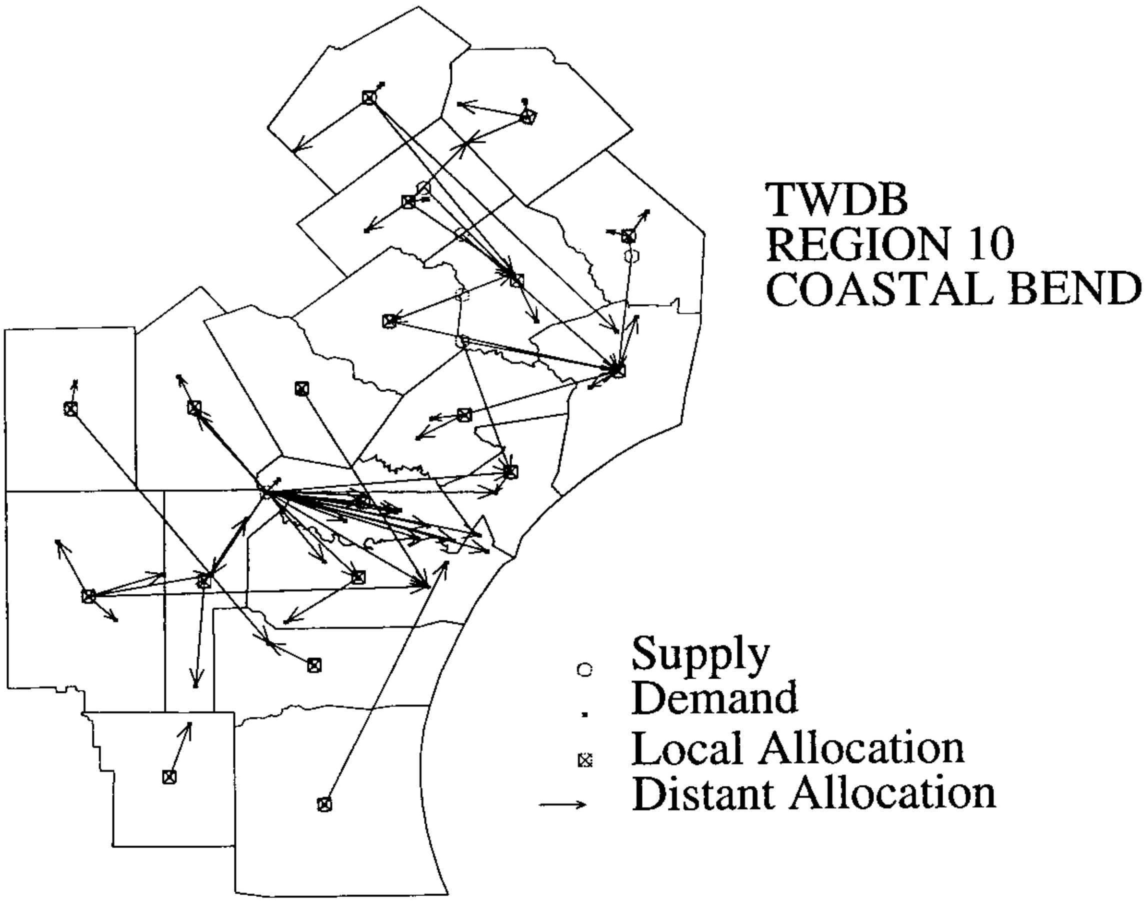


Figure 5.5 PLAN 10 - Statewide, Regional, & Parc Rules.

6.0 CONCLUSIONS

An expert geographic information system (expert GIS) for long-term regional water supply planning was developed in this research. The Automated Allocations System (AAS) has been evaluated through a small example problem developed to illustrate several features of the system, and a case study examining a 19-county study region in South Texas with several water supply sources and demand centers. The AAS is comprised of an expert system, which contains the logical rules and expertise of water resources planning experts; a GIS, which stores and analyzes spatially distributed water supply and demand data; and a network flow solver, to balance flows in the networks developed by the AAS with input from a water resource analyst. Commonly available water demand forecasts and water supply data are used in order to follow the logic of current planning methods and permit the updating and comparison of alternatives. The AAS system has been developed so that it can be expanded to include additional constraints and handle large water resources planning regions.

The system was successfully applied to the TWDB Coastal Bend planning region. The existence of generic categories of rules for regional water planning is evident from this case study. The categories include rules applicable on a statewide basis, a regional basis, or a local basis. The local scale rules are specific to individual arcs in the network model representation and need to be entered individually. However, the application of the small sets of statewide and regional rules is sufficient to generate relatively realistic solutions. A detailed comparison of the allocations made by the AAS and the 1990 Texas Water Plan was made. Many individual discrepancies were found, yet overall the plans are quite similar.

One of the original goals of this research project was to develop an expert GIS which would have the capability of aiding TWDB analysts in their work of preparing the Texas Water Plan. This objective has been met. This research has demonstrated that an automated system to allocate regional water resources can be made to produce results comparable to those of current methods by employing a GIS, an expert system, and an network flow solver. This system affords planners a process that is faster, less tedious, better documented and more rigorous and defensible than current methods. The current system is undergoing testing by TWDB personnel in an effort to fine-tune the Texas Coastal Bend region model. The task of finding a final set of detailed rules for this region is beyond the scope of this investigation and is better left to the professionals at the agency.

The research also demonstrates that there is a hierarchy of rules related to water resources allocations that can be exploited by focusing on rules that pertain to (1) statewide considerations, (2) regional considerations, (3) individual suppliers and demanders, and (4) individual arcs. This hierarchical rules structure was not anticipated at the outset of the research, and only became apparent once the data base and modeling system had been assembled and analysis of the regional planning problem undertaken. It is anticipated that other classes of rules will be identified through the continued application of the system to other regions and the further development of the system to consider additional constraints.

The modeling system makes extensive use of GIS data base management capabilities. This data model is perhaps the most important aspect of the system, as it allows the efficient and convenient construction of models representing a large number of possible water allocation scenarios. The expert system shell provides a convenient rule editing and execution facility. The hierarchical rule structure—state, regional, and local rules—is a unique feature discovered during the construction of the case study and will allow easy application of the system to other planning regions within the state.

The application of the system to other planning regions within Texas, or to the allocation of water statewide is straightforward and could be undertaken at this time. In addition, this system can be linked to more detailed hydrologic modeling systems which could provide input on the expected temporal and spatial variability of reservoir, aquifer, and river yields. Further advances and refinements in the model are needed and should be considered in future research. More work is needed to include other types of supply sources, water supply contracts, and other information (e.g., political constraints, environmental considerations). In addition, cases where certain stakeholders may be presented with a perceived "sub-optimal" solution due to the regional scale of the solution algorithm need to be investigated.

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