DECISION SUPPORT SYSTEM FOR CONJUNCTIVE STREAM-AQUIFER MANAGEMENT

by

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PREFACE

Although much progress has been made in the development of regional groundwater models and river basin simulation models, previous attempts at linking these two types of models into a workable conjunctive use decision support system for use in comprehensive river basin planning, management, and administration, have not been successful. With recent advances in computer hardware and software technology such as geographic information systems (GIS) and data base management system technology (DBMS), it is now possible to develop a computer based river basin decision support system for improved conjunctive use management of groundwater and surface water by linking a finite difference groundwater flow model with a river basin network model.

A microcomputer based decision support system is presented for conjunctive stream-aquifer management under prior appropriation. This has been accomplished through a synthesis of existing technology rather than development of new models. The computer-aided design and drafting package, AUTOCAD, and a powerful, low-cost, raster GIS package for PC's called IDRISI, are used for preparing and processing grid-based spatial data. These data are processed for input into MODRSP, a modified version of the USGS three-dimensional finite difference groundwater model, MODFLOW, to generate numerical groundwater response coefficients for considering distributive aquifer characteristics and realistic aquifer boundary conditions. These response coefficients are provided as input to the generalized river basin network model, MODSIM, to simulate spatially varied and time-lagged return/depletion flows from stream-aquifer interaction. The integration of GIS, DBMS, MODFLOW, and MODSIM allows analysis of conjunctive use plans capable of considering decreed flow and storage rights, river calls, exchanges, trades, and plans for augmentation. The groundwater hydrologic components provided with MODSIM include reservoir seepage, irrigation infiltration, well pumping, channel loss, channel routing, return flows, river depletion due to pumping, and aquifer storage.

To demonstrate the capabilities of the Stream Aquifer Management Decision Support System (SAMDSS), a case study is presented for a portion of the Lower South Platte River Basin, Colorado. A 370 by 140 groundwater grid network (1000 ft x 1000 ft cell) was prepared for the case study area using GIS techniques. Groundwater response coefficients were generated using MODRSP for the 200 wells and over 30 recharge sites of the Bijou Irrigation Company groundwater augmentation plan. The water right return/depletion flow account for the Bijou augmentation plan was simulated using MODSIM. A separate MODSIM network was set up for a 70 mile section of the Lower South Platte River, Colorado, between the Kersey and Balzac river gage stations, under administrative control of State Engineer's Water District #1, to simulate daily administration of a river regulated under prior appropriation water right laws. The river system network model, which included 11 existing or proposed reservoirs, 18 diversion points, 25 direct decree diversions, 10 storage decree diversions, and 75 separate water rights, was used to simulate a daily administrative river call. The effects of the Bijou augmentation plan were included in the daily simulation. Two separate prototype user interfaces, one using the Bijou augmentation plan flow account network and the other using the daily administration example, were prepared using the desktop mapping software, MAPINFO, to demonstrate some of the capabilities inherent in a successful decision support system. Computerized data available from databases maintained by the Colorado State Engineer (e.g., water rights, diversions, groundwater, and streamflow); USGS (e.g., groundwater, digital line graphs, digital land

use, digital elevation data, and streamflow); and Bureau of Census (TIGER files) were used for the study.

Results of the case study indicate that there are major differences between using groundwater response coefficients developed from preassigned stream depletion factor (SDF) values, as currently used in the basin, and those generated using a finite-difference groundwater model for the Bijou study area. An important factor not accounted for in the SDF derived coefficients is the influence of tributary flows, which account for a significant percentage of the return/depletion flows estimated from the coefficients generated from the finite-difference model.

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CHAPTER 1

INTRODUCTION

1.1 Water Rights, Conjunctive Use and Water Management in the West

Water has always played a vital role in the development of the Western U. S., and will continue to be crucial to future economic growth of the region. A common problem facing many Western states today is how to manage the intensifying competition for water by expanding urban centers, the traditional agricultural sector, and in-stream water uses dictated by environmental concerns. Confronted with the prospect of increased competition for available water and a moratorium on new large-scale water projects, water users must depend on better management of existing projects through integrated, basin-wide water management.

It is widely recognized that maximum water development in the West can only be achieved through conjunctive use of surface and groundwater resources. This is particularly important for a state such as Colorado, where 75% of the water is used for agriculture and 20% of the total water use comes from groundwater. In Colorado, 15% of the state population relies on groundwater for drinking. Irrigation is the largest user of groundwater, representing 96% of all total groundwater withdrawals. Of the 2.7 million acres irrigated in the Colorado, 1.6 million are irrigated in part with groundwater and 0.5 million acres receive groundwater as the sole source. Total groundwater withdrawals in 1980 were approximately 3 million acre feet. Kansas, Nebraska, and Idaho use about three times as much groundwater as Colorado. Wyoming, Utah, and New Mexico each use between a quarter to a half as much. In all cases, irrigation is the largest single user (Luecke,1990).

A major influence on water management in the Western States is water rights. Most Western States follow the *Doctrine of Prior Appropriation*, which requires that water first be delivered by decree to senior (in time) water right holders without regard to their location on the river (Andrews, 1987). River management and administration has become increasingly complicated as innovative water management strategies such as water exchanges, transfers, and groundwater augmentation plans have been developed which hhhelp make optimal use of water within the legal constraints.

Water law covering groundwater is less advanced than for surface water because of the complexity of the mechanics of groundwater movement, lack of specific information on the physical features of groundwater basins, and the relatively limited use of groundwater prior to fifty years ago. In almost all states, underground waters are accorded the same legal status as surface streams, with the more progressive states integrating their water laws for surface and groundwater. For example, Colorado places groundwater into tributary and non-tributary categories. Tributary groundwaters are those surface waters hydraulically connected to a natural stream and are administered under prior appropriation. Non-tributary subsurface waters are not hydraulically connected to natural streams and require special permits for withdrawal.

The complex task of river administration in Western states such as Colorado is the responsibility of the State Engineer, who supervises the day-to-day distribution of the surface waters of the state in accordance with water right priorities, statutory directives, court decisions, and interstate compacts (MacDonnell, 1988; SPBWMC, 1989). Water is withdrawn from streams under the supervision of a water commissioner assigned by the Division Engineer to a specific section of the stream. The duty of the commissioner is to monitor withdrawals in conformity with water right priorities in the stream section. The commissioner is responsible for determining where available water is to be allocated and for maintaining records on water availability and allocation. Each commissioner takes daily measurements of flows available from the river and determines eligibility of users to divert flows. Allowable diversions may be modified by deferral of water by some users, exchanges between users, availability of imported water belonging to specific users, and availability of stored water belonging to specific users. The *Water Commissioner Handbook* (Colorado Division of Water Resources, 1989) provides a list of the recognized types of river diversions: direct diversions, releases from reservoirs, diversion at an alternate point, ditch diverting from more than one stream, reservoir releasing to another reservoir, transmountain diversions, transmountain export, combined source, exchanges, trades, augmentation plans, and recharge.

When a senior water right holder is unable to divert a decreed water right, the water right holder contacts the water commissioner and places a *call* on the river (SPWMC, 1989). A *call* prohibits upstream junior water rights from diverting until the calling senior water rights have been satisfied. A water right on the main stem may place a *call* on the entire basin upstream of the calling right to ensure that the right is met before any upstream junior right diverts. A senior water right may also *dry up the river* during periods of low flow. When a call is placed by a senior right on a tributary, only the junior right upstream of the calling right within the same tributary or sub-tributary are affected by the call. A call is only placed on flows which can physically reach the senior right when that right is in priority.

The State Engineer has the authority to terminate well pumping if it results in depletion of surface flows which cause material injury to senior water rights. Serious difficulties arise in attempting to identify those pumping sources responsible for these depletions, and the amounts by which each is depleting the surface stream. It may be equally difficult to identify the surface rights that have been injured, since the stream may have been losing water to groundwater pumping over extended periods of time. The State regulates and monitors groundwater augmentation programs designed to allow pumping to continue by replacing streamflows that would otherwise be depleted.

The question of how best to achieve comprehensive river basin planning and voluntary water management through user participation is an interdisciplinary problem in which the water resource engineer plays an important role. The size and complexity of most major river basins, the administrative and legal constraints dictated by water rights issues, and the interdependence of surface and groundwater resources, has focused increasing attention on use of computer based models. Appropriate modeling technology can provide decision support for developing improved basin wide and regional strategies for daily water administration, drought contingency plans, evaluating groundwater exchange programs, managing recharge and augmentation projects, and for resolving conflicts between urban, agricultural, and environmental concerns.

1.2 Decision Support Systems in River Basin Management

There are a number of reasons why many important agencies and organizations directly responsible for water planning, management, and administration are not making routine use of computer based river basin models:

- inability of many of computer modeling systems to adequately incorporate the legal realities of water allocation under the appropriation doctrine
- complexity of modeling interconnected stream-aquifer systems and differing opinions on model practicality versus scientific soundness
- imbalance between computer modeling needs and the costs of obtaining data necessary for model calibration and validation
- inability of practitioners to understand how to use the models and lack of user-friendly interfaces for enhancing model calibration and analysis of model results
- lack of portability of many proposed decision support systems to the type of computing equipment available to practitioners
- lack of efficient interfacing of proposed models with the data base management systems already in place by water agencies

The Office of Technical Management (OTA, 1982) conducted a survey of U.S. government agencies involved in water resource modeling and concluded that computer modeling had the potential to improve the accuracy and effectiveness of information available to managers, decision makers, and scientists, but that there were a number of constraints to effective model use. On the other hand, Rogers and Fiering (1986) expressed a negative view towards water resource modeling, targeting the supposed failure of optimization techniques in improving water resources planning and management. This was counteracted by the July 1986 issue of the ASCE *Journal of Water Resources Planning and Management* (Labadie and Sullivan, 1986b; Johnson, 1986) which was devoted entirely to actual use of computerized decision support systems by water organizations and agencies. A special follow-up workshop was held by the Operations and Management Technical Committee of ASCE at Colorado State University in 1988 on *Computerized Decision Support Systems for Water Managers* (Labadie, et al., 1989) which demonstrated how mathematical modeling was being successfully used by water managers and how the tools of decision support system theory were contributing to this process.

The classic definition of a decision support system (DSS) provided by Sprague and Carlson (1982) is "...an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems." A framework for development of a DSS was proposed by Sprague (1980). The DSS software system is described as having three sets of technical capabilities: (i) data base management; (ii) model base management; and (iii) dialog generation and interface management.

The concept of computer-assisted DSS is gaining widespread acceptance in many water resource applications, such as wastewater treatment (Bertheoux, et al., 1989), river basin water management (Pinay et al., 1988), estuarine water water quality management (Camara, et al., 1990); multiple-purpose reservoir operation policies (Johnson, 1990), operation of urban water distribution networks (Boudon and Saunier, 1989), estuary water quality management (Arnold and Orlob,1989), hydropower optimization (Stover, 1991), reservoir system operations (Courtney and Whitlock, 1989), streamflow forecasting (Bradley, et al., 1989), lake water quality management (Fedra, 1988; Grobler, et al., 1987), drought management (Palmer and Holmes, 1988), and water distribution systems (Pingry, et al., 1992).

1.3 River Basin Management Models

Yeh (1985) discussed management and operations models for river basin management, and identified two basic types of simulation model:

- capacitated network simulation models or quasi-simulation models which use optimization algorithms to solve the network flow problem, insuring that available system flows are allocated to user specified operational rules and demand priorities (Texas Water Development Board, 1972; Sigvaldason, 1976; Shafer, 1979; Graham, et al., 1986; Labadie, et al., 1986a; Labadie, 1988; Farley, et al., 1989; Vassilev, et al., 1989, Brendecke et al., 1989; Law and Brown, 1989; and Chung et al., 1989).
- network simulation models which use search techniques that require reservoir releases be made in accordance with fixed operation rules based on storage and demands (HEC, 1991; Loucks and Salewicz, 1990; USBR, 1991).

Shafer (1979) showed the advantages of the quasi-simulation model, particularly for use in preserving water diversion and storage priorities established by water rights. Although there are a number of models which incorporate water rights administration, many of these are accounting models that are unable to model physical responses within a river basin (Bethel, 1986; Rau, 1987; Wurbs and Walls, 1989). Of the more common simulation models, such as HEC5 (HEC, 1991), SSARR (USACE, 1986), IRIS (Loucks and Salewicz, 1991), HYDROSS (USBR, 1991) and MODSIM (Labadie, 1988) only MODSIM has the capability of effectively modeling both complex water rights and conjunctive-use of groundwater and surface water (Graham, et al., 1986; El-Kadi, 1989).

Other examples of quasi-simulation or network flow models include: the Acres model used on the Trent River Basin, Canada (Bridgeman et al., 1989), the California State Water Project Model DWRSIM (Chung et al., 1989), REGUSE, a real time regulation model used by the Inland Waters Directorate of Canada (Farley, et al., 1989), the CASTOR group model (Vassilev et al., 1989), and CRAM (Brendecke, et al., 1989).

During the 1970's, interest in conjunctive use and coordinated management of surface and subsurface water resources by water agencies resulted in the development of a new category of groundwater model: the stream-aquifer model (Van der Heijde, 1988). CONSIM (Labadie, et al.,1983) added a groundwater component to the river basin simulation model MODSIM (Shafer, 1979) by using analytical equations to develop response coefficients to describe the stream-aquifer return/depletion flows. SAMSON (Morel-Seytoux and Restrepo, 1987) modeled stream-aquifer interaction using response coefficients developed from a finite difference model. Although SAMSON was provided with a management capability, it was designed more as a conjunctive-use watershed model (El-Kadi,1989). Maddock and Lacher (1991b) prepared a model called MODRSP, which is a modification of the USGS MODFLOW finite difference model groundwater flow model MODFLOW (McDonald and Harbough, 1988). MODRSP can be used to calculate drawdown, velocity, storage losses, and capture response functions due to external excitations such as pumping, recharge, or infiltration for multi-aquifer groundwater flow systems.

1.4 Geographic Information Systems in Water Management

Although geographic information systems (GIS) have been used extensively in a variety of water resource projects over the past 20 years, they are a relatively new tool to water managers and engineers. The reason for this is that only now are GIS systems becoming usable in a computational environment that is affordable and generally available to researchers and practitioners (Willeke, 1992). Goulter and Forest (1987) discuss how GIS can provide a number of capabilities which are useful to river basin operations and planning. They assert that GIS should not be considered a means of providing final answers to complex water resources planning issues, but view GIS as an important component of decision support systems. Capabilities recognized by Goulter and Forest (1987) include:

- ability to display and graphically summarize input data for analytical models, as well as results of application of management models using these data
- graphical display of georeferenced input data to assist in interpretation of conditions within a basin through depiction of spatial and temporal patterns
- reduction in the time required to enter data and improvement in data reliability through error reduction
- use of graphical display to improve man-machine interaction
- provide an efficient interface between the data base and operational computer models

Groundwater data bases and groundwater models have become prime targets for integration with GIS (Lanfear, 1992). Most groundwater mathematical models are based upon finite-element or finite-difference techniques composed of hundreds of grid cells. Assigning properties to cells is traditionally a time consuming and costly process. With GIS, distributed model parameters such as transmissivity or depth to bedrock can be regionalized, represented on a digital map, and related to the modeling grid. Regionalization is accomplished by digitizing existing maps or using GIS to develop maps of point data. Kilborn, et al. (1991) linked a GIS (i.e., SYSTEM 9, a vector-based GIS developed by Computer Vision, Inc.) to the U.S. EPA groundwater model designed for well head protection (WHPA) to demonstrate how GIS can extend the capabilities and usefulness of existing groundwater models.

Kernodle and Philip (1988) lists six advantages in using GIS to prepare input for a finite difference groundwater flow model:

1. attributes of area and perimeter of each polygon and attributes of arc length are automatically computed and updated by the GIS
2. both the hydrologic information being processed and the spatial discretization used in numerical model are identically distorted to any chosen map projection, allowing accurate overlay of information in a common coordinate system.
3. values are assigned to models on an objective basis; and yet information on which assignment is based is conveniently evaluated, interpreted, and revised by hydrologists to describe the geohydrologic framework
4. spatial discretization used in the model may be easily revised without concern for resultant subjective changes in representation of the geohydrologic framework
5. model input data and quality map products are essentially a single directed effort
6. data bases that are created are reusable and expandable for other investigations

A number of GIS related activities have focused on support of the three-dimensional groundwater flow model, MODFLOW (Mcdonald and Harbaugh, 1988). The USGS has developed software for using the UNIX based version of the GIS package ARCINFO to read and write MODFLOW input and output files (Kernodle and Philip, 1987; Orzol and McGrath, 1992). An interface between the raster based GRASS GIS package and MODFLOW was developed for use in a UNIX environment as part of a proposed advanced decision support system; however, it was not applied to an actual case study (Pike, et al.,1990). A vector based GIS package GEOSQL was used as part of an integrated groundwater conjunctive use management model of the San Fernando Valley (Ozbilgin et al, 1991). Although MODFLOW was the groundwater model used in the study, GIS was applied only to referencing a well data base not to integrating data with MODFLOW.

1.5 Objectives

A prototype stream-aquifer management decision support system (SAMDSS) is presented herein which is designed as a computer-aided tool for:

- drought contingency planning
- voluntary basin-wide water management
- daily administration of water rights
- maintaining daily surface water and groundwater water right accounts
- estimating consequences of groundwater pumping on administration of daily water rights
- management of recharge and augmentation projects
- regional scale river modeling to resolve conflicts between urban and agricultural water users and environmental in-stream requirements.

The SAMDSS is synthesized from existing technology, rather than requiring development of new models. Using a decision support system framework, interfaces are developed which connect the various modeling and data base components. The MODSIM river basin network flow modeling component provides the flexibility of allowing the user the option of familiar analytical procedures, or more data-intensive three-dimensional modeling techniques for stream-aquifer system management. Use of the latter is facilitated through linkage with GIS. The data base component interacts directly with existing hydrology, meteorology, water diversion, and water rights data bases actively maintained by the various agencies involved in water planning and administration. Procedures are established for simulating daily administration of conjunctive use schemes which consider decreed flow and storage rights, river calls, water exchanges, groundwater recharge measures, and the effects of well depletion SAMDSS is demonstrated on a portion of the Lower South Platte River basin in collaboration with a regional water management district. Impacts of a groundwater augmentation plan on river and tributary flow over time and space, are assessed, including the consequences of an augmentation plan on daily river administration. Although SAMDSS provides a powerful collection of tools, guidelines, and procedures that can be applied to any river basin, the sample interfaces are structured to satisfy input and output requirements for the case study only.

CHAPTER 2

STREAM-AQUIFER MANAGEMENT DECISION SUPPORT SYSTEM (SAMDSS)

2.1 Basic Framework

A workable decision support system requires a framework that renders numerous computer modeling tools and techniques easily accessible to the water resource professional and creates a modeling environment that emphasizes the needs of the decision maker. The framework for the stream-aquifer management decision support system (SAMDSS) has been prepared with these goals as the primary focus (Figure 2.1).

Although no single groundwater management model has been universally adopted by the water resource community, there are a number of well documented, technically sound, and generally accepted models for simulating most of the individual hydrologic and management components of the stream-aquifer management problem. To avoid the traditional problems involved in the development and implementation of large, customized models, several generalized, public-domain water resource models were identified and selected for use in SAMDSS.

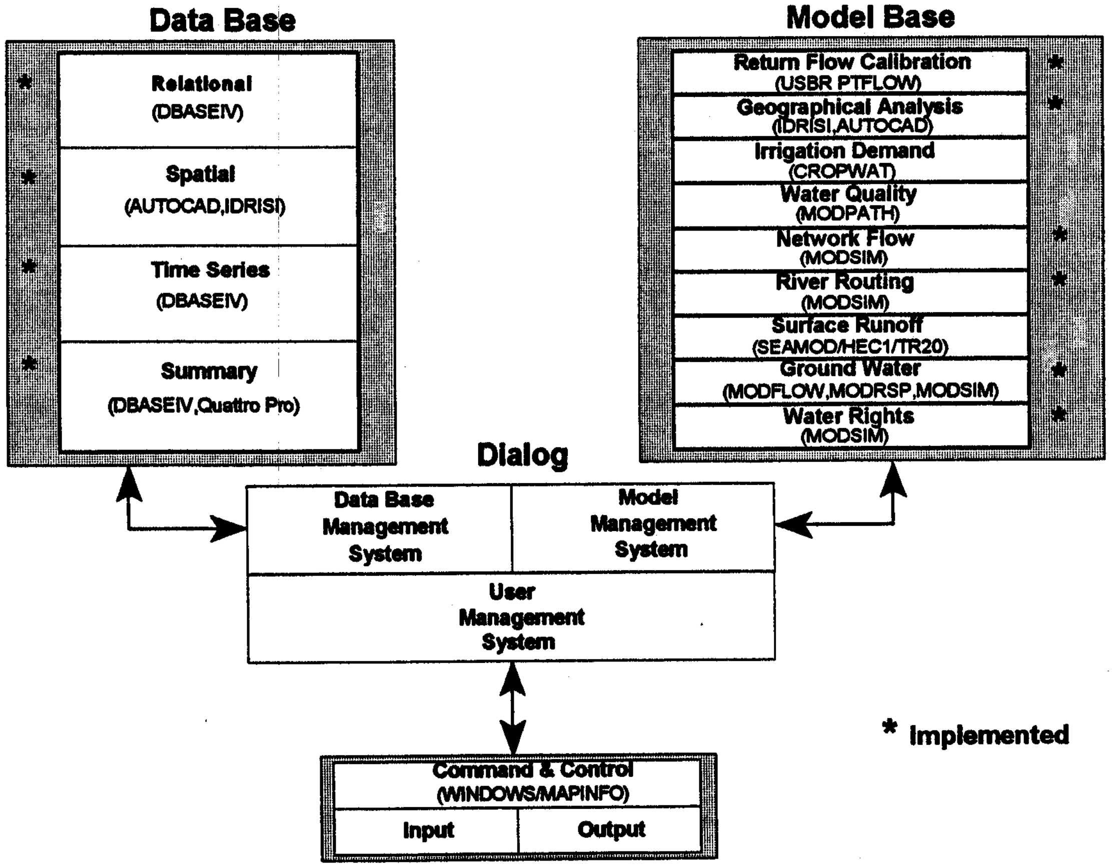


Figure 2.1 Stream-Aquifer Management Decision Support System (SAMDSS)

In order to simplify the user interface and data file development process, a number of tools, templates, and guidelines were prepared. The use of commercially available spreadsheet, data base, and geographical information system (GIS) software packages provides flexibility in developing and tailoring output formats to meet individual requirements. The use of commercial software avoids the time consuming and too often unsuccessful process of preparing computer routines for constantly changing output reporting requirements.

The use of data base management technology allows storage, retrieval, and analysis of data in formats that are interchangeable between different computer based application packages. Unlimited access to data for preprocessing and postprocessing contributes greatly to the power of the decision support system. The process of interconnecting the data base management software, the model base management software, and dialog management software is facilitated by structured all data in database format with defined fields (columns) and records (rows) saved as DBASE data base files (*.DBF). Most commercial data base and spreadsheet software packages include functionality for reading and writing data base formatted files, including query, sorting, and extraction of data. The use of files organized in data base format permits direct access to data for preprocessing, postprocessing, and general review. The process of linking models to external computerized data bases is simplified, and allows development of a *central data bank* allowing reuse of data for a wide variety of purposes.

Most traditional water resource models have been written in the FORTRAN language and use formatted ASCII text files to input and output data. Reading and writing ASCII text files in formats compatible with commercial data base and spreadsheet software requires subroutine modules written for the water resource models used in the decision support system. It is easier and more convenient to prepare utilities capable of linking the various components of the decision support system. Model input and output formats and data bases are also structured to take full advantage of the spatial and time related nature of water resources data.

The SAMDSS is constructed around an open architecture framework that permits direct access to input and output data and allows modification and verification at all levels of the modeling process. This interactive capability enhances confidence in use of the decision support system. To maximize portability and minimize cost, all development work for SAMDSS was done on MS DOS/Windows-based microcomputer hardware. UNIX based versions of most of the computer models selected for use in SAMDSS are also available. Likewise, the geographic information system (GIS) and data base management system (DBMS) requirements for SAMDSS can be satisfied through commercial software available in a UNIX operating system environment.

2.2 Capabilities

The SAMDSS is designed to:

- assist in long term river basin planning activities, daily river administration, and river management options such as groundwater augmentation
- incorporate appropriation water right features such as decreed diversions, direct releases from a reservoir to a downstream diversion point, diversions at alternate points, exchanges, trades, recharge and augmentation plans.
- represent complex river basin systems as capacitated flow networks for which highly efficient solution methods are available

- consider reservoir seepage, irrigation infiltration, channel loss, well pumping, return flows, river depletion due to pumping, and aquifer storage
- provide the option of modeling stream-aquifer return/depletion flows using groundwater response coefficients or discrete kernel values derived from analytical methods such as the Glover equations (Glover, 1977), the SDF method (Jenkins, 1968), or from numerical methods such as the finite difference model MODFLOW
- include effects of tributaries on return/depletion flow calculations in a river basin
- consider the spatial distribution of return/depletion flows along a stream
- tracks over time, from source to destination, individual return/depletion flows resulting from various geohydrologic activities
- maintains individual return/depletion flow water right accounts through identification of return and depletion flow events
- efficiently allocate river basin water resources according to user specified operational rules and demand priorities
- Interface with existing hydrologic, meteorologic, groundwater, water diversion, and water right data bases
- operate in a microcomputer environment under MS Windows
- incorporate commercial, non-proprietary, or supported public domain software.
- employ geographical information systems (GIS) and data base management system (DBMS) technology for preprocessing and postprocessing of data.
- processes data available from public domain data bases, published maps, or digital maps

2.3 Graphical User Interface Design

Simulation models predict the response of a physical system to a set of inputs, given a particular set of operating rules. With the aid of a simulation model, the consequences of variations in certain model inputs can be evaluated and the system operational characteristics modified to improve system output. This process is greatly enhanced by linkage with graphical user interfaces (GUI) with high degree of visualization capability (Fedra, 1990).

The stages of simulation can be classified as: *during* simulation, *after* simulation, and *comparison* of simulations. To represent the behavior of the system over time and to identify potential problems during simulation, it is necessary to display information during the simulation run. Display of information should be sufficiently general to allow the user to evaluate system performance against certain desired outcomes. After simulation, more detailed information can be displayed as necessary to provide valid post simulation evaluations and alterations. It should be possible to compare the results of different operating policies for the same physical system or different systems with the same geographic configuration.

Simulation output should present results in graphic or pictorial format in accordance with specified objectives. Three levels of output display have been identified: (i) the most general level involves comparison of performance against user defined threshhold values such as low, average, and high, with each node and linkage of a network schematic displayed in colors representing values of simulated variables related to specified threshold zones; (ii) the next level allows more detailed analysis and provides graphs such as time series and frequency of failure plots; and (iii) the final level provides traditional tabular output for a high degree of quantitative detail, with accompanying loss in visual and graphical clarity.

Since simulation models can be applied in many ways, users should be able to design output displays to reflect various model uses. For example, an output display demonstrating overall system performance against some desired outcome would be different than a display showing the effect of performance of an individual variable on overall system behavior, or displays tracking an individual variable performance given a selected operational policy. It is important to define study objectives and develop displays that aid in presenting output results that focus on those objectives.

In order to evaluate and improve operating policies, users should be provided with the ability to interactively change various aspects of the system. The user must have control over stopping, starting, continuing or restarting a simulation run. River basin simulation must easily accomodate changes in the physical system, as well as changes in operating policy. System evaluation with changing conditions over time are necessary when changes in the physical system and operating policy are made. Simulation systems that are dynamic in time should be capable of being halted and operating policies and system configurations altered. After changes have been made, the model process should be able to continue the simulation from the time period in which it was halted or be able to be reset back to time intervals already simulated under different conditions.

After completion of a simulation run, the GUI should allow more systematic analysis. Detailed information may be provided in the form of time series plots or display of failure frequency analysis. It should be possible to generate plots for any purpose, for any system element, and for any portion of the simulation time period. It is important to retain important aspects of the simulation output, while reducing the quantity of the information presented so that overall performance of the system can be easily evaluated. This is accomplished by creating a file during simulation and then selectively accessing data from the file for any portion of the simulation. Selected data can be stored in another file for later reading or printing. In this case, graphical display of results may not be appropriate, so tables can be displayed indicating the values and times of all failures in the specified time interval with their associated thresholds. These results are intended for more detailed analysis of the system. To assist in further analysis of simulation results, output should be available in a format that allows users to make comparisons visually, or allows more sophisticated statistical analysis. This may require output files which contain information from all streamflow sequences.

The desktop mapping software package MAPINFO for Windows (Mapinfo Corp., 1992) was selected as appropriate software to demonstrate these concepts in SAMDSS. Some of the features of MAPINFO that make it useful in the development of an effective DSS interface include:

- ability to access, update, join, and query spreadsheet, data base, and ASCII data base text files
- provide simultaneous display data tables interactively on-screen as a map view, graph or chart view, or a row and column (browse) view
- manipulate data in map or browse views
- geocode data bases to geographic or schematic maps
- thematically shade any object, line, point, polyline, or polygon
- conduct geographic searches such as within, contains, and intersects

- draw or edit lines, polylines, polygons, rectangles, arcs, circles,symbols, and text using different fonts sizes, and colors
- reposition, zoom, and scroll contents of window map
- import/export graphics from/to ASCII, DXF, or ARC/INFO formats
- create custom menus and dialog boxes.
- call and execute external programs

2.4 Data Base Management System

Where possible, the input and output data files for the various models selected for use in the SAMDSS are structured as ASCII data base text files. There are several advantages to this approach: (i) it is convenient to use readily available data base or spreadsheet software to preprocess and postprocess data; (ii) study-specific user interfaces can be developed without having to access and modify original model source code; and (iii) data from existing data bases or output from other computer models can be read directly into models as input data files. Data base files used in SAMDSS are structured to satisfy the input and output requirements required by the SAMDSS support models.

The specific data base management packages utilized in SAMDSS include:

- DBASEIV: data base management package that can be used to create, organize, and access a data base (Ashton-Tate, 1990).
- QUATTRO PRO: spreadsheet package with graphics and data base support (Borland, Inc., 1992).

For geographic information systems (GIS) and spatial data base and analysis, the following packages are utilized:

- IDRISI: grid based geographic analysis system developed at Clark University, that is designed to provide inexpensive access to computer-assisted geographic analysis technology (Eastman, 1990)
- AUTOCAD: general purpose computer aided design (CAD) program that can be used to prepare a variety of two-dimensional drawings and three-dimensional models (Autodesk, Inc., 1990)
- SURFER: powerful and flexible tool for creating contour or surface plots of three dimensional data (Golden Software, Inc., 1987)
- GCTP: the USGS General Cartographic Transformation Package ia a system of FORTRAN subroutines designed to permit the transformation of coordinate pairs from one of 20 map projections to another; it is the standard computer software used by the National Mapping Division for map projection computations

A number of data conversion routines have been prepared for converting data between various formats and preparing the data base for input to the model base for SAMDSS:

- WRTIGER: transforms Bureau of Census TIGER files to AUTOCAD DXF file format for use with AUTOCAD
- DLG: transforms USGS Digital Line Graph Files to AUTOCAD DXF file format for use with AUTOCAD

- CONVERT: adds carriage returns and line feed characters to the end of records on binary files; required for most digital data supplied by U.S. government agencies (i.e., Bureau of Census TIGER files, USGS Digital Line Graph files, USGS Digital Elevation Model files, etc.)
- IDRSS: retrieves data from IDRISI files and writes a data file for use by a spreadsheet
- SURF: reads a SURFER ASCII xxx.grd file and writes an IDRISI xxx.img file.
- MODCOEF: Reads MODRSP response coefficient data base output file and writes to tabular format for use by MODSIM
- ACDTOIDR.lsp: AUTOLISP program provided with IDRISI to transform AutoCad drawing data into IDRISI vector format.
- VECBRK.lsp: AUTOLISP program used to rasterize Autocad drawing line segments.
- VECDIST.lsp: AUTOLISP program used to output rasterized AutoCad line segment data as an IDRISI vector format or ASCII PRN format for use with a SPREADSHEET; line segment length is output as an attribute.
- VECWIDTH.lsp: AUTOLISP program used to output rasterized AutoCad line segment data as an IDRISI vector format or ASCII PRN format for use with a SPREADSHEET; line segment width is output as an attribute.

2.5 Model Base Management System

The following modeling packages comprise the model base management system portion of SAMDSS:

- MODSIM: River basin network simulation model developed at Colorado State University (Labadie, 1988)
- MODFLOW: USGS Modular Three-Dimensional Finite-Difference Groundwater Flow Model (McDonald and Harbaugh, 1988); layers can be simulated as confined, unconfined, or a combination; flow associated with external stresses, such as wells, areal recharge, evaporation, drains, and streams can be simulated
- MODRSP: developed at Arizona State University; ia modification of the USGS MODFLOW finite difference model for calculate drawdown, velocity, storage losses, and capture response functions for multi-aquifer groundwater flow systems (Maddock and Lacher, 1991a)
- PTFLOW: USBR river water balance program that can be used to calculate reach gains and losses between stream gages given diversion and inflow data

CHAPTER 3

MODSIM RIVER BASIN NETWORK FLOW MODEL

3.1 Network Flow Approach to River Basin Modeling

The simulation of large-scale, complex water resource systems requires efficient methodologies for analyzing system components in a fully integrated manner. The generalized river basin network model MODSIM employs a state-of-the-art network optimization algorithm for simultaneously assuring that water is allocated according to physical, hydrological, and institutional aspects of river basin management. The use of network flow optimization actually serves to enhance the ability to simulate complex river basin systems. Earlier versions of MODSIM have been successfully applied to a number of complex river basin systems, such as the Rio Grande River Basin (Graham, et al., 1986); the Poudre River Basin in Colorado (Labadie, et al., 1986a); the Upper Colorado River Basin (Law and Brown, 1989); and the Upper Snake River Basin (Frevert, et al., 1994). In all of these cases, some form of priority-based water allocation dominated management of the system.

MODSIM was originally an extension of the SIMYLD network simulation model developed by Texas Water Development Board (1972); hence giving the acronym MODified SIMyld (MODSIM) (Shafer, 1979). Since then, MODSIM has been extensively updated and extended far beyond the original structure of SIMYLD. SIMYLD and original versions of MODSIM employed the out-of-kilter algorithm (OKM) for solving the network flow optimization problem. The OKM is used in a number of other river basin network flow models, such as the Acres International Model (Bridgeman, et al., 1989) and the DWRSIM model employed by the California Department of Water Resources (Chung, et al, 1989).

Network flow models for river basin analysis have been criticized since it is assumed that precise objective functions must be defined for the optimization process. It is argued that it is difficult for water managers to define such functions in most cases, particularly if they require economic data. In fact, network flow optimization models may also be used for simulation purposes where only rankings or simple priority scales are provided for the optimization process. Detailed objective functions need not be defined, and the resulting simulation structure may be more efficient than standard approaches to constructing river basin simulation models. This allows analysis of large scale systems that would exceed the computational capabilities of other simulation approaches.

MODSIM currently offers a number of unique features for comprehensive river basin management and conjunctive use:

- can be used for long term planning (monthly), medium term management (weekly),and short term operations (daily) in river systems
- allows simulation of a wide variety of river basin configurations and operating conditions without requiring specification of complex IF-THEN rules governing system operation
- includes conjunctive use of surface water and groundwater and the modeling of stream aquifer interactions

- capable of directly incorporating institutional and legal structures governing water allocation
- provides for separate analysis of direct flow or natural streamflow rights and seasonal storage rights, and includes provisions for exchanges, trades and plans for augmentation
- includes no *a priori* defined operating policies, but rather relies entirely on user input data describing system features and operational requirements, which are separated from the network modeling algorithmic structure
- capable of modeling complex looped and bifurcating water system features
- allows direct inclusion of flow constraints, including both lower bounds and time variable upper bounds
- calculates system losses as a function of averaged flows and storage, such as evaporation loss, channel loss, reservoir seepage and losses from water application
- includes hydrologic streamflow routing capabilities for daily simulation
- provides graphical plots of important model output variables reflecting system performance, as well as tabulated results showing storage levels, releases, inflows, energy generation, power capacity, system losses and spills, water deliveries, shortages, instream flow requirements, and flows in any reach of the system; extensive water right account information is also provided including storage right accounts under various fill priorities.
- utilizes a state-of-the-art network flow optimization algorithm based on Lagrangian relaxation (Bertsekas, 1991)
- allows simulation of synthetic or stochastically generated inflow/demand sequences for use in Monte Carlo analysis for developing flow-duration curves and exceedance probability estimates for key variables
- allows accurate calculation of hydropower generation capacity and energy production based on power plant efficiencies which can vary with flow, head, and load factor; calculates peak vs. nonpeak and firm vs. secondary energy production
- implemented on both UNIX-based Workstations operating under X-Window, as well as on microcomputers under MS Windows
- includes an interactive graphical user interface (GUI) for drawing and editing system features, as well as a spreadsheet-style data editing capability emulating an object-oriented data base management system
- includes mechanisms for directly linking MODSIM with existing data base management systems to provide access to timely data and forecast information for real-time river basin management

3.2 Basic Assumptions

The underlying principle in the operation of MODSIM is that most physical water resource systems can be simulated as capacitated flow networks. The term *capacitated* refers to specification of strict upper and lower bounds on all flows in the network. Components of the system are represented in the network as nodes, both storage (i.e., reservoirs, groundwater basins, and storage right accounts) and non-storage (i.e., river confluences, diversion points, and demand locations) and links or arcs (i.e., canals, pipelines, natural river reaches, and decreed water rights) connecting the nodes.

In order to consider demands, inflows, and desired reservoir operating rules, several additional *accounting* nodes and linkages are created to insure the fully circulation of the network and guarantee satisfaction of flow mass balance throughout the entire system. A fully circulating network requires all nodes have both inflow and outflow links, although more than one link can connect any two nodes. It should be noted that MODSIM users are only responsible for defining the actual flow network. All *accounting* nodes and links are added automatically by the model.

A pure network optimization algorithm does not directly allow for system gains or losses as a function of flow or storage in the system. This is accounted for indirectly, however, by an iterative process which is described subsequently. Bertsekas and Tseng (1988) developed a *network with gains* minimum cost flow algorithm which is able to directly account for channel losses as a function of flow rate. Computational experience shows that computer processing time is about two to five times that of a pure network algorithm. Since return flows and stream depletions must still be computed by an iterative process on the network, it is considered more efficient to include channel loss, reservoir seepage, and infiltration losses in the iterative process and therefore be able to take advantage of the computational speed of the more efficient pure network algorithm.

There are a number of reasons why minimum cost network flow algorithms are particularly attractive for river basin modeling:

1. A network formulation of a river basin system provides a physical picture revealing the morphology of the system which is readily recognizable.
2. Network optimization techniques (particularly the Lagrangian relaxation algorithm employed in MODSIM) are specialized solution techniques which perform integer-based calculations on linear networks that are considerably more efficient than real number computations and matrix operations employed in standard linear programming codes based on extensions of the revised simplex method. Integer-based calculations are not a disadvantage since appropriate scaling of link flows can produce solutions for any desired order of accuracy.
3. Extremely large (in terms of network components) problems can be solved. Since network algorithms are highly efficient, it becomes feasible to perform several iterations so as to consider certain nonlinear or dynamic system features.
4. Changes in system components are easily accommodated by manipulation of the previously constructed network.

Important *assumptions* associated with MODSIM are listed as follows:

- All storage nodes and linkages must be bounded from below and above (i.e., minimum and maximum storage and flows must be given). The latter bounds are allowed to vary over time in the model.
- Each linkage must be unidirectional with respect to positive flow. Possible flow reversals can be modeled by assigning an additional reverse direction link between two nodes.
- All inflows, demands, system gains and losses must accumulate at nodes. Increasing the density of nodes in the network thereby increases simulation accuracy, but also increases computer time and data requirements.
- Import nodes can be designated for water entering the system from across system boundaries.

- Each reservoir can be designated as a spill node for losses from the system proper. Spills from the system are the most expensive type of water transfer, such that the model always seeks to minimize unnecessary spill. Spills may be retained in the network by specification of an additional release link from a reservoir which can be labeled as a high cost link.
- Reservoir operating policies are provided by the user in the form of desired target *end-of-period* storage volumes for each reservoir. Maximum storage capacity can be designated as spill capacity or the bottom of the flood control pool in a reservoir.

3.3 Network Flow Optimization Problem

Although technically speaking, MODSIM is an optimization model, the attempt is to employ optimization methods as an efficient mechanism for performing simulation. The minimum cost network flow problem is solved iteratively in a sequential fashion over time, so it is not a fully dynamic optimization process. Within the confines of mass balance throughout the network, MODSIM sequentially solves the following linear optimization problem via an efficient minimum cost network flow optimization algorithm over each successive time period in the simulation:

$$\textit{minimize} \sum_{\ell \in A} c_\ell q_\ell \tag{3.1}$$

subject to:

$$\sum_{j \in O_i} q_j - \sum_{k \in I_i} q_k = 0; \quad \textit{for all } i \in N \tag{3.2}$$

$$l_\ell \leq q_\ell \leq u_\ell \quad \textit{for all } \ell \in A \tag{3.3}$$

where A is the set of all arcs or links in the network; N is the set of all nodes; O_i is the set of all links originating at node i (i.e., outflow links); I_i is the set of all links terminating at node i (i.e., inflow links); q_ℓ is the integer valued flow rate in link ℓ; c_ℓ are the costs, weighting factors, or priorities per unit of flow rate in link ℓ; l_ℓ is the lower bound on flow in link ℓ; and u_ℓ is the upper bound on flow in link ℓ.

Equation 3.2 insures that total flow out of any node equals total flow into that node, and are referred to as *node constraints*. Equation 3.3 specifies finite lower and upper bounds on all arc or link flows, and are called *arc constraints*. The terms *arc* and *link* are used synonymously in this formulation. Notice also that this formulation allows several arcs to share the same node pair. All flows are assumed to be described in volume units per time interval selected for the simulation, and are assumed to be uniformly distributed over the time interval. Therefore, MODSIM is capable of modeling only average flow conditions rather than peak flow conditions over the specified time interval. The following sections describe how complex river basins can be simulated by appropriate definition of the variable bounds and costs associated with the above network flow optimization problem.

The data base for the network optimization problem is completely defined by the *link parameters* for each link ℓ: $[l_\ell, u_\ell, c_\ell]$, as well as the sets O_i, I_i, N and A. The link parameters are automatically defined by MODSIM, based on data provided by the user.

An example fully circulating network is shown in Figure 3.1. Nodes 1, 2, and 3 are actual, physical system nodes. Node 1 is a reservoir, node 3 is a demand diversion, and node 2 is an intermediate node. Nodes and links which appear as dashed lines represent special *accounting* nodes and links. That is, they are not part of the physical system, but are included to properly account for mass balance throughout the entire system. Notice that there are always six accounting *nodes*, but the number of *accounting links* is directly related to the size of the physical system network.

The accounting nodes are designated as follows:

I: *accounting inflow node:* for collecting total system inflows and initial reservoir storage to be distributed to appropriate locations by accounting links

D: *accounting demand node*: accumulates all flows used to meet demands on the system

S: *accounting storage node*: accumulates all end-of-period or carryover storage from reservoirs

SP: *accounting spill node*: accumulates the total volume of spill from storage nodes in the system due to insufficient reservoir capacity; spills are assumed to be uncontrollable and unusable downstream

M: *accounting mass balance node*: maintains overall mass balance for the network

GW: *accounting groundwater node*: maintains interactions between groundwater and surface water, including return flows and stream depletions due to pumping ; individual groundwater storage nodes may be created by the user.

MODSIM employs an efficient primal-dual network optimizationalgorithm incorporating a dual coordinate ascent procedure based on Lagrangian relaxation, as developed by Bertsekas (1991). Comparative studies have shown Lagrangian relaxation to be far superior to the out-of-kilter (OKM) algorithm (Clausen, 1968), as well as other primal-based network algorithms (Bertsekas and Tseng, 1988). A detailed discussion of the Lagrangian relaxation algorithm can be found in Appendix A of this Report.

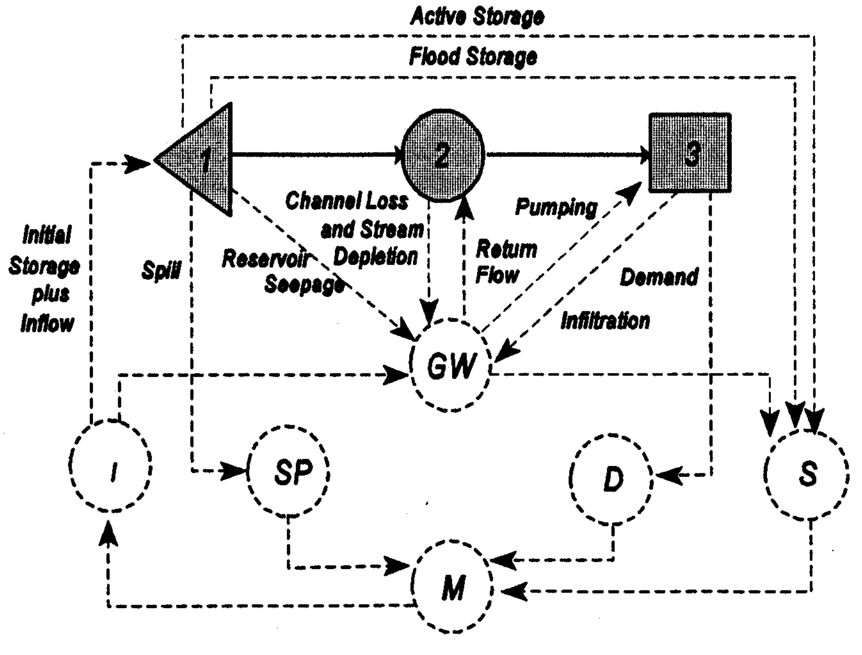


Figure 3.1 Network Structure for MODSIM with Accounting Nodes and Links

Most of the applications of network algorithms in river basin management have been applied in a sequential static mode. That is, anticipation of future conditions is not directly incorporated into current decisions. The network optimization is applied to the current period only. End-of-period storage from these calculations then provide the starting storage levels for the next period, and so on. This approach is advantageous in that there is no presumption of knowing with certainty what future inflows to the system will be. However, there are often seasonal water supply forecasts available from spring snow pack data and other information. A procedure is described subsequently in which these forecasts may be input into MODSIM, and reservoir operating targets adjusted according to this forecast information.

3.4 Unregulated Inflows and Basin Import

MODSIM does not incorporate a watershed runoff model, so all system inflows must be precalculated by the user and input to MODSIM. Unregulated inflows may be based on historical data, future forecasts, drought scenarios, or synthetic generation of streamflows. Any real node in the system can be an inflow node. They are connected by accounting links which are directed from the accounting inflow node **I** to each point of inflow. Any node can be designated as an inflow node, including a reservoir. In Figure 3.2, real nodes 1, 2, 3, and 4 are automatically connected by MODSIM to accounting node **I**, which is automatically given a unique integer designation in the model (dashed lines represent accounting nodes or links). The inflows to nodes 3 and 4 are defined by setting the lower and upper bounds on these accounting links equal to the inflow I_j, thereby guaranteeing that exactly those specified inflows are input. A cost of zero is assigned to these links since these are natural inflows. For accounting links from the accounting inflow node **I** to reservoirs, the links now include any carryover storage S_0 from the previous period, in addition to the unregulated inflow. That is, the available water for the current period in reservoir j is $I_j + S_j$ for nodes $j = 1,2$.

MODSIM allows consideration of up to 10 possible *import nodes*, representing nodes receiving water from transbasin diversion projects. In contrast with unregulated inflows, imported water is entered as annual, quarterly, or weekly total flows, depending on whether a monthly, weekly

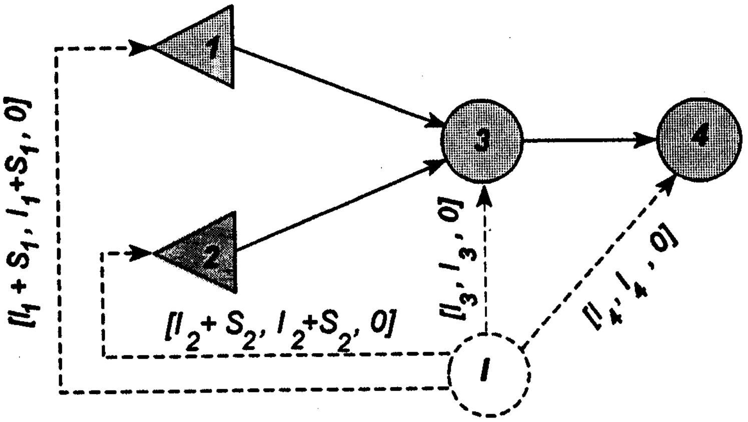


Figure 3.2. Accounting Unregulated Inflow Links Plus Initial Storage

or daily time interval, respectively, is employed. Fractional coefficients are entered for each time period to reflect temporal distribution of imported water. These flows are simply added to the link bounds for accounting unregulated inflow links where basin import is occurring.

3.5 Reservoir System Operations

In addition to inflow links, the two reservoirs in Figure 3.2 are connected by two additional accounting links for specifying total carryover storage to the next time period. These links originate at each reservoir and accumulate at an accounting carryover storage node S, as shown in Figure 3.3. Link [1] is called the accounting active storage link, and link [2] is the accounting flood storage link. The lower bounds on the active storage links are the minimum reservoir storage or dead storage S_{imin} $(i=1,2)$. The upper bounds are user specified end-of-period target storages T_i which represent ideal guidecurve levels for active storage for the current period. However, if the lower bound on the accounting inflow arc to the reservoir in question is less than the lower bound on the active storage arc, the lower bound on the active storage arc is replaced by the lower bound on the corresponding inflow arc. This condition is necessary to insure network feasibility and, subsequently, that mass balance is maintained.

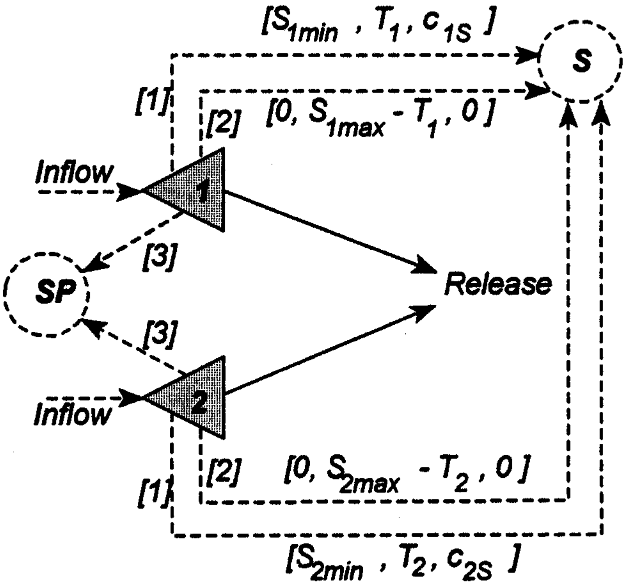


Figure 3.3. Accounting Active and Flood Storage Links

If a large inflow occurs, storage may exceed the target active storage level. Any excess storage is carried in link [2]. Its lower bound is zero (indicating no excess storage above target level T_i) and $(S_{imin} - T_i)$ is its upper limit, which represents the maximum excess space above the target level. Note that an infeasibility can occur if the inflow to a reservoir, including carryover storage, is less than the dead storage level S_{imin}. If this happens, S_{imin} is automatically reset by MODSIM for that period to correspond to the actual inflow plus carryover storage.

In some cases, it may be desirable to use operating rules which specify release guidelines rather than storage guide curves for each time period. This is easily accomplished by specifying an additional *flow-through demand* node downstream of the reservoir with the desired release levels designated as flow-through demands. These releases can be dependent on storage levels by using the *hydrologic state* option for the flow-through demands. Flow-through demands are described in more detail in a subsequent section.

$$c_{iS} = -(1000 - 10 \cdot OPRP_i) \tag{3.4}$$

If inflows are large such that spillage must occur, the spills are carried in accounting link [3] and collected at the accounting artificial spill node **SP**. Its lower limit is zero and its upper limit is set at a very large default value. Again, spills are assumed to be lost from the water supply system. If this is not desirable, an additional spill link may be specified downstream of the reservoir and given a high cost by the user. This link can carry any additional spill flow above the downstream release or channel capacity.

The costs c_{iS} on the accounting active storage links are computed as follows to reflect storage right priorities. For reservoir i, the user selects priority $OPRP_i$ as an integer number between -999 and +999. Note that a lower number represents a higher priority; that is, a reservoir given a priority of -999 would receive the highest rank in the basin for conserving storage. MODSIM computes the actual a cost c_{iS} associated with the accounting link for carryover storage as:

Notice that c_{iS} is a negative number, which in a cost minimization objective, actually represents a benefit associated with carryover storage. It is actually possible to supply $OPRP_i$ values up to +999, but it can be seen that values above +100 translate into actual positive costs on the accounting carryover storage links. The cost associated with flow in the accounting flood storage link is always set at zero. The costs on the accounting spill links are given the highest positive number of any link.

3.6 Hydrologic States and Inflow Forecasts

MODSIM computes the system hydrologic state by considering current reservoir storage levels and inflows to a certain user specified subset of reservoirs in the system that best represent hydrologic conditions in the basin. Associated with each of these states (classified as average, dry, and wet) is a corresponding set of operating rules with ranking priorities. These three hydrologic states are computed at the beginning of each period for the user selected reservoir subset through the following analysis:

$$R_t = \sum_{i \in H} [S_{it} + I_{it}] \tag{3.5}$$

$$W = \sum_{i \in H} S_{i\max} \tag{3.6}$$

where H is the set of node numbers of reservoirs in a specified subset defining the hydrologic state; t is the current period of operation; I_{it} is the specified or forecasted unregulated inflow to reservoir i for period t; S_{it} is the beginning storage in reservoir i, period t; and $S_{i\max}$ is the storage capacity for reservoir i.

The user also specifies upper and lower bounds on the average state as fractions of the total subsystem storage capacity:

$$\left.\begin{aligned} LB_t &= x_{1t}W \\ UB_t &= x_{2t}W \end{aligned}\right\} \tag{3.7}$$

where LB_t is the lower bound on the *average* state for period t; UB_t is the upper bound on the *average* state for period t; x_{1t} is the fraction defining the lower limit on *average* state for period t; and x_{2t} is the fraction defining the upper limit on *average* state for period t

The hydrologic states for period t are defined as:

Dry: $R_t < LB_t$
Average: $LB_t \leq R_t \leq UB_t$
Wet: $R_t > UB_t$

Reservoir targets T_{it} are assumed to be constant with these hydrologic states, as shown in Figure 3.4. With the above method of calculating target operating rules, target storage levels can only vary within a computation cycle (e.g., one year for monthly analysis; one quarter for weekly analysis; or one week for daily analysis), although separate target storage levels can be specified for each hydrologic state. An option has been included in MODSIM, however, whereby the user can input separate target storage T_{it} levels for each reservoir i and for each period t throughout the entire simulation. This option is particularly valuable during model calibration and allows input of actual measured storage levels in the system over the historical period in order to compare computed downstream flows with gaged flows.

It is possible to utilize the hydrologic state option in MODSIM for incorporation of inflow forecasts on specification of reservoir target operating rules. This is accomplished by adding a *dummy* reservoir with *zero* capacity to the network, but not directly connecting it to the network proper. It is

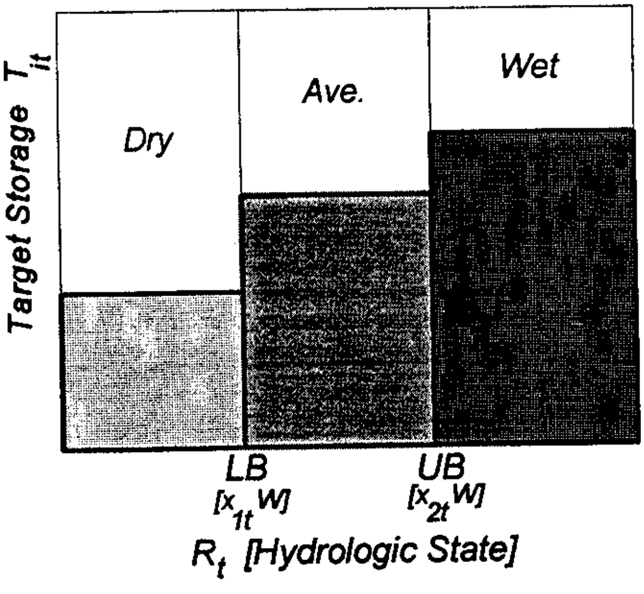


Figure 3.4 Definition of Hydrologic States

of course indirectly connected via the *accounting* links and nodes. This reservoir may be included in the hydrologic state subsystem of reservoirs. Input files may be prepared representing seasonal forecast information that would be available at each subsequent time period of operation. MODSIM then utilizes this information to define the hydrologic state of the system, and therefore modify user selected reservoir operating targets accordingly.

MODSIM allows only three differing priorities for any node (storage and/or demand) corresponding to wet, average, or dry conditions as calculated by the above procedure. For analysis of drought contingencies, the user can consider these states as driest, drier, and average, if desired. An additional option has been included which enables the user to input a separate priority for any node for each cycle of the analysis. This expanded capability means that instead of a maximum of three priorities associated with a wet, average, or dry state, a varying priority can be input for each year, quarter, or week. A quarter is assumed to be 12 weeks long in the current version of MODSIM.

3.7 Evaporation Loss

Evaporation loss is calculated in MODSIM as a function of average surface area in the reservoir over the current period. Since average surface area in a reservoir is normally unknown until calculations are completed for the current period, an iterative process is usually required for accurate calculation of evaporation loss. A procedure is adopted in MODSIM, however, which does not required successive iterations to estimate evaporation loss. For each reservoir i, compute:

$$E_{imax} = e_i \cdot [A_i(S_i) + A_i(S_{i\max)}]/2 \tag{3.8}$$

$$E_{imin} = e_i \cdot [A_i(S_i) + A_i(S_{i\min)}]/2 \tag{3.9}$$

$$E_{itarget} = e_i \cdot [A_i(S_i) + A_i(T_i)]/2 \tag{3.10}$$

where e_i is net evaporation rate (i.e., evaporation rate less rainfall rate) for reservoir i (e.g., feet per month) for the current period; $A_i(S_i)$ is the (interpolated) area-capacity table for reservoir i, S_i is storage at the beginning of the current period, S_{imax} is the maximum capacity, S_{imin} is dead storage, and T_i is user supplied target level.

The storage link parameters are then adjusted as follows:

for active storage links:

$$[0, (S_{imax} - T_i) + (E_{imax} - E_{itarget}), 0]$$

for flood storage links:

$$[(S_{imin} + E_{imin}), (T_i + E_{itarget}), c_{iS}]$$

In this formulation, link upper bounds are adjusted to carry sufficient flow to include evaporation loss, and the lower bound on the active storage link is increased so that when evaporation is removed, it will not be violated. After calculations for the current period are completed, flows in the carryover storage links (i.e., the total end-of-period storage, plus evaporation loss) are adjusted such that evaporation loss is removed so as to provide carryover storage for the next period:

1. An initial guess EVP_i of evaporation loss is first made. The total carryover storage, including evaporation loss, is:
$$q_{itotal} = (q_{iS(active)} - q_{iS(flood)})$$

2.. The current estimate of actual end-of-period storage is
$$S_{ifinal} = q_{itotal} - EVP_i$$

3. Compute the average surface area A_{iave} over the period for each reservoir i:
$$A_{iave} = 0.5 \cdot [A_i(S_i) + A_i(S_{ifinal})]$$

   and update the evaporation estimate EVP_i as
$$EVP_i = e_i \cdot A_{iave}$$

4. Return to Step 2 and repeat until successive evaporation estimates converge within a predefined error tolerance.

Evaporation loss is not directly calculated for other water bodies such as streams in MODSIM. For streams, however, channel loss coefficients may be appropriately increased to account evaporation losses, or properly adjusted to consider a net loss term which includes rainfall. Since channel loss coefficients are allowed to vary seasonally (e.g., monthly), adjustments for evaporation and rainfall can also be made seasonally.

3.8 Hydropower Calculations

MODSIM accepts a variable number of elevation-area-capacity data points for any reservoir. Elevations need only be input if hydropower is generated at a storage node. Setting them to zero indicates that there is no hydropower at that node. Tailwater effects on net head are not directly considered, but can be indirectly incorporated through adjustments to the turbine efficiency tables or addition of block loading estimates to the power plant elevation levels.

MODSIM computes both power capacity and energy production in a hydroelectric system. The basic power equation used in MODSIM is:

$$P = K \cdot Q \cdot H \cdot e(Q,H) \tag{3.11}$$

where P is mean power output in kilowatts; Q is reservoir release (volume/period); H is mean effective head (i.e., *(mean gross head on turbines) - (mean tailwater elevation) - (head loss)*); e is overall plant efficiency, which can be entered as a table of values as a function of discrete release rates Q and heads H (note: these tables can include consideration of hydraulic losses and tailwater affects during high flow periods); and K is a constant based on selected units, which equals 1.403×10^{-1} for Q in AF/month and head in ft; 6.1006×10^{-3} for Q in AF/wk; 3.729 for Q in $10^6 m^3$/mo and head in m; 16.214 for Q in $10^6 m^3$/wk; etc.

Pumped storage projects can be indirectly considered by simply increasing the operating hours per period, or load factor. All hydropower plants are assumed to be downstream of storage projects.

The user can enter the average number of on-peak hours in each selected period in order to calculate energy production during the period. If on-peak hours are entered which are less than total hours in the period, it can be assumed that there is downstream reregulation capability. In this case, it is assumed that water is released through the turbines during on-peak hours only, as reflected in a higher rate of release during the shorter period, but the same total volume of release during the period. Otherwise, the model assumes that releases can be made during off-peak periods.

3.9 Consumptive Demands and Instream Flow Requirements

Consider the example network shown in Figure 3.5, where the two demand nodes 3 and 4 are isolated. Though not considered in this example, nodes 1 and 2 could be specified as demand nodes, since a storage node can also be a demand node, as well as an inflow node. The model automatically creates accounting links which originate at each demand node and accumulate at a single accounting demand node **D**. The link parameters are shown, with demands D_3 and D_4 specified for each node.

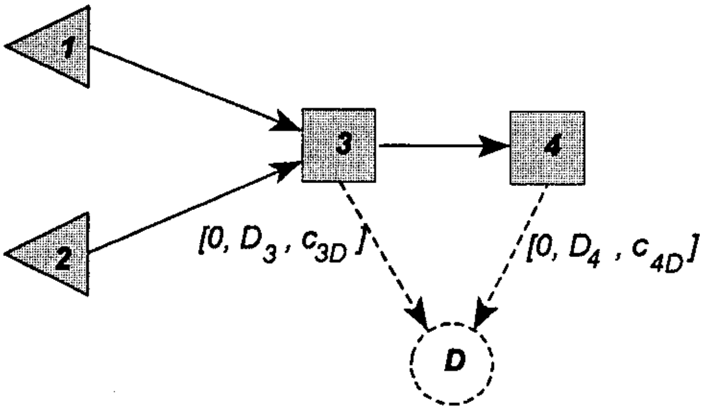


Figure 3.5. Accounting Demand Links and Node

Demands may be defined as:

- historical diversions
- decreed water right amounts
- predicted agricultural demands based on consumptive use calculations (performed outside the model)
- projected municipal and industrial demands:

The link costs on the accounting demand links are calculated as follows:

$$c_{iD} = -(1000 - 10 \cdot DEMR_i) \tag{3.12}$$

As with reservoir priorities $OPRR_i$, the user must select priorities $DEMR_i$ for demands between -999 and +999. These priorities must be selected in relation to reservoir storage priorities.

If shortages must occur, then demands with lower priority (i.e., junior water rights) are denied flow first. For inefficient water application, MODSIM is capable of calculating return flows via groundwater or surface water. Calculation of return flows is described in more detail in a subsequent section.

Figure 3.6 illustrates a situation where a particular demand may own several direct diversion rights on natural flow in the river. In this case, the user may specify several links as shown, with the capacity of each link corresponding to the decreed amount for each water right. Time variable decrees may be specified through use of *variable capacity links*. The user must directly assign the (negative) link costs c_i, c_j, and c_k to these links that will provide the proper ranking for the water rights in relation to other specifications of $DEMR_i$ and $OPRR_i$ in the basin.

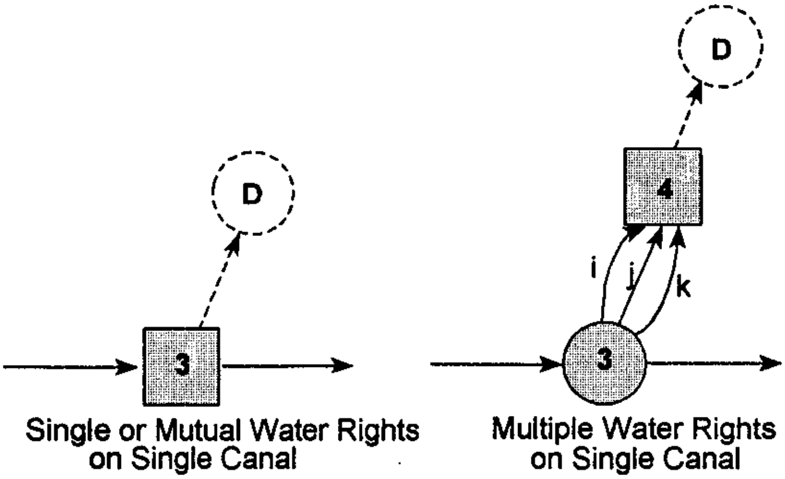


Figure 3.6. Use of Several Links for Multiple Water Rights

It should be noted that in this case, the user should assign a priority to the demand at node 4 equal to +100, since this corresponds to assigning a zero cost to the accounting demand link connecting node 4 with the accounting demand node **D**. Otherwise, a *double counting* of demand priority will occur, since it is assumed that the direct (negative) link costs assigned to links *i, j,* and *k* correctly specify the water right priorities. The demand assigned to node 4 may correspond to consumptive use or other estimates of actual demand. In this way, the maximum possible total delivery will be dictated by the lower of the sum of the decreed water rights and the demand assigned to node 4. The demand amount specified may be further limited by the capacity of the diversion structure or structures delivering the flow.

As illustrated in Figure 3.7, MODSIM also provides for demands for water which are not terminal; i.e., instream flow demands which *flow through* the demand node and remain in the network for possible downstream diversion. In effect, this would correspond to demands with 100% return flow which is unlagged. This includes demands for instream flow uses for navigation, water pollution control, fish and wildlife maintenance and recreation. *Flow-through demands* are also useful for augmentation plans, exchanges between basin water users, and development of reservoir release operating rules.

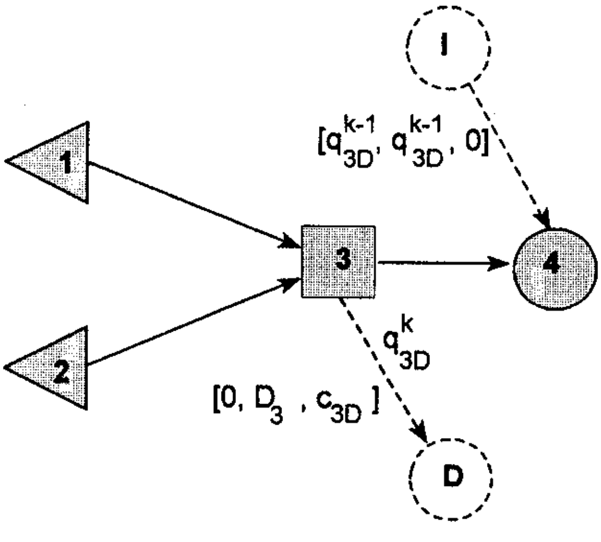


Figure 3.7. Illustration of Flow-Through Demands

In effect, the flow-through demand operates by iteratively removing flow as a demand from the network, but then replacing the flow at one or more specified (usually the next downstream) node(s), with any fractional division of flow to downstream nodes specified by the user. For purposes of instream flow requirements, usually only one downstream *accrual node* is specified. It should be emphasized that, in effect, it is as if the flow never actually left link *[3,4]*. Reference to link *[i,j]* indicates a link originating at node *i* and terminating at node *j*. This notation is only possible if there is one unique link connecting node *j* from node *i*. The flow diverted into link *[3,D]* is replaced by adding it as an inflow to the designated accrual node 4 via the accounting arc connected to the accounting initial storage and inflow node I.

The *superscript* k in Figure 3.7 represent an iteration counter, since flow-through demand returns must be calculated iteratively. In the first iteration, the demand is treated as a consumptive demand and flow is delivered according to priority through solution of the network algorithm. At the next iteration, the flow q_{3D} actually observed to have been delivered in link *[3,D]* is then added to the accounting inflow link returning flow to the accrual node 4, and the network is solved once again. This solution process continues until successive estimates of returns to node 4 agree. Note that the flow in link *[3,4]* does not actually represent the total instream flow. Flows leaving node 4 would better represent the actual flows in link *[3,4]*, assuming there are no other demands or inflows at node 4. The output report for demand node 3 will properly consider the actual flow in link *[3,4]* as related to the instream flow requirement.

An option is available in MODSIM for specifying a *bypass credit link* as a means of improving convergence of the flow-through demand iterative process. In Figure 3.7, the bypass credit link would be specified as link *[3,4]*. Figure 3.8 illustrates the iterative process where, for iteration $k=1$, flow q_{34} is initialized to demand D_3; i.e., the demand at node 3 is temporarily turned off and the network is solved. At the next iteration, the actual flow observed in link *[3,4]* from the current network solution is then subtracted from D_3 and the net flow becomes the new upper bound for link *[3,D]*. This represents the additional flow required to satisfy the flow-through demand. This additional flow, however, will be supplied only if there is sufficient flow available and the priority is

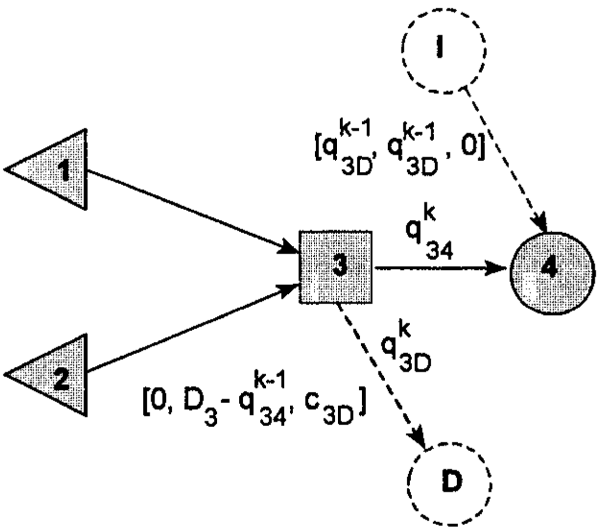


Figure 3.8. Flow-Through Demands with Bypass Credit Link

senior enough to meet the instream flow demand. With use of the bypass credit link, if there is already sufficient flow in the link to satisfy the instream flow demand, then no iterations are required and the demand is considered to be satisfied.

The use of a flow-through demand for minimum streamflow requirements has two primary advantages: (i) the flow-through demand can be assigned a priority similar to any other demand in the basin, and (ii) simply setting a fixed lower bound on the link corresponding to a minimum streamflow requirement can result in the network algorithm converging to an infeasible solution if there is insufficient flow available to meet the demand. The flow-through demand can receive a shortage similar to any other demand, depending on the relative ranking of the water right priority. An additional advantage of the flow-through demand is that it may be used to divide flow according a predetermined fractional distribution.

The terminal downstream node in a river basin system should always be specified as a demand node. If there are senior downstream water rights, then two terminal demand nodes are necessary. One specifies the senior downstream water right and its associated priority. The other is set to a very high value, but given a priority value *DEMR* of 100, which corresponds to a zero cost. This demand receives all excess flows that cannot be captured or used upstream. Note that if the priority of the terminal demand is set to 99, then reservoirs will be drained to their target storage levels, since a zero value is always assigned to storage in a reservoir above the target level. The user can therefore specify whether flood pool waters should always be released, or if they should be stored temporarily.

3.10 Water Exchanges and Credits

The ability for water users to formulate exchange agreements and plans for augmentation have become an important part of water administration in many highly appropriated river basins. For example, a water user may own storage rights in a reservoir from which it is physically impossible for the owner to directly receive releases. In this case, the owner may enter into an exchange agreement whereby direct river flow is diverted out of priority by the storage right owner, with an equal amount of flow released from the reservoir to satisfy senior water right holders that would be otherwise injured. MODSIM provides a variation on the flow-through demand concept to allows users to define *exchange demands* and *exchange links.*

As illustrated in Figure 3.9, an exchange demand is defined based on flow occurring in a another link in the basin. The demand in this case is conditioned solely on the amount of flow in the link being *watched* by the demand. A credit demand is established based on flow in the watch link. Again, an iterative structure is required where, initially, the demand is set to zero. Upon solution of the network flow algorithm, whatever flow was observed in the watch link is then assigned as a demand in the exchange demand, and the network solution is repeated. Since it is important that the flow in the watch link agrees with the flow diverted to the demand, iterations proceed until the flows are equalized.

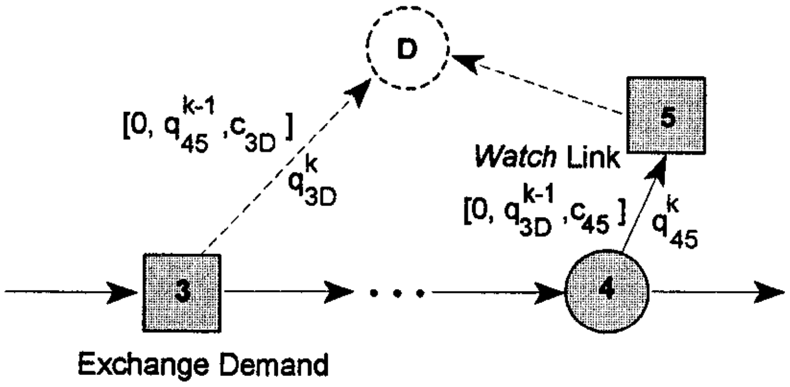


Figure 3.9. Illustration of Exchange Demand and Watch Link

An exchange link operates in much the same way as an exchange demand, except that the upper bound on the exchange link is set based on the flow observed in the watch link. Again, (negative) costs assigned to the exchange link must insure that senior water right holders are not injured as a result of the exchange. A similar iterative process occurs with the exchange link as with the exchange demand, until flows in the watch link agree with flows diverted in the exchange link.

3.11 Link Capacities and Losses

All physical links in the network must be bounded from above and below. MODSIM includes the capability of allowing the user to input a constant bound for each link, or varying daily, weekly or monthly maximum flow limits for certain specified *variable capacity* links. The latter are useful for considering seasonal influences in canal capacities and maintenance schedules. In addition, to variable capacity links, MODSIM allows specification of *seasonal capacity links*, whereby a total seasonal maximum flow through a particular link may be specified. Once the seasonal maximum is exceeded, the link is effectively *turned off*, and no further flows can be made through the current season. For monthly time steps, for example, a season would be considered as one year in length. The initial month or time period (i.e., time $t = 1$) results in seasonal flow capacities being reinitialized to the specified maximum capacity as input by the user.

Minimum flow capacities may also be assigned to any link in the network, but care must be taken to avoid infeasible solutions. Improperly assigned minimum and maximum flow capacities on links are the major reasons for network solutions terminating in infeasibility errors.

For certain problems where it would be desirable to include pumping costs, MODSIM provides the option of user input of costs for any linkage in the network. Negative costs can be entered to represent benefits, such as from low head hydropower production. Costs (positive or negative) can be assigned to any link by the user to discourage or encourage, respectively, flow in that particular link according to predefined operational criteria. It must be remembered, however, water rights are included, then any link costs introduced by the user must set at small relative values that will not disrupt the distribution of flows according to the water right priorities.

MODSIM includes the capability of removing channel losses directly. A loss coefficient cl_{ij} for any link $[i,j]$ can be defined in the input data. This coefficient represents the fraction of flow at the head of the link that is lost during transition through the link. An iterative procedure is employed in MODSIM for calculating channel losses, as illustrated in Figure 3.10. First, network flows are initially solved via the Lagrangian relaxation algorithm with *no losses* assumed. The losses in each link are computed by multiplying the loss coefficient by the calculated flows from the initial solution. This loss is removed during the next iteration by an accounting link to the accounting groundwater **GW** node with both lower and upper bounds equal to the amount of loss. The network flow algorithm is then solved again. If current flows in the reach agree with those found in the previous iteration, then convergence has occurred. Otherwise, the procedure is repeated with channel losses defined on the bounds of the accounting link updated to reflect current flows in the real link. This process continues until successive link loss estimates agree within a specified error tolerance. Currently, the error tolerance is based on aggregate losses over the entire network, rather than each individual loss term. Channel losses may also reappear as lagged return flows to any user specified downstream nodes.

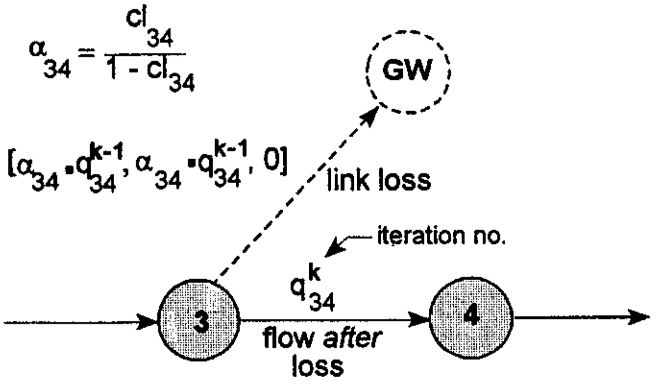


Figure 3.10. Iterative Procedure for Link Loss Calculations

3.12 Streamflow Routing

For simulation of daily stream flow, it may be necessary to consider channel routing. This is accomplished in MODSIM by designating a network link as a *routing link*. Inflow to this link is distributed over time in accordance with routing coefficients calculated by MODSIM using the Muskingum formula. Alternatively, the user may directly input any desired routing coefficients and lagging factors. The MODSIM routing module assumes that outflow from a routing reach is a linear function of inflow to the reach, where the basic routing equation is:

$$O_n = C_1 I_n + C_2 I_{n-1} + C_3 I_{n-2} + \cdots \tag{3.13}$$

where O_n is the ordinate of the outflow hydrograph at time *n*; I_n is the ordinate of the inflow hydrograph at time *n*; and C_1, C_2... are routing coefficients.

The coefficients C_1 ,C_2 ,.... are determined internally by MODSIM using the following Muskingum routing equations:

$$\begin{aligned} C_1 &= (\Delta t - 2XK)/(2K(1-X) + \Delta t) \\ CC &= ((2K(1-X) + \Delta t) - 2\Delta t)/(2K(1-X) + \Delta t) \\ C_2 &= C_1 \cdot CC + (\Delta t + 2KX)/(2K(1-X) + \Delta t) \\ C_i &= C_{i-1} \cdot CC \qquad for \;\; i > 2 \end{aligned} \tag{3.14}$$

where Δt is the routing time element; K is the Muskingum routing parameter having units of time; and X is the Muskingum dimensionless routing parameter between 0 and 0.5.

It is important to note that the downstream node for a routing reach should not be assigned as a demand node because it will interfere with the routing calculation. To avoid negative coefficients the Muskingum K should be greater than or equal to $\Delta t /[2 \cdot (1-X)]$ and less than or equal to $\Delta t/2X$. The user must input flood wave travel time K, routing time Δt, and the Muskingum routing parameter X. The actual Muskingum coefficients are calculated by MODSIM and stored in an ASCII output file for review by the user.

3.13 Reservoir Storage Rights and Accounts

For reservoirs with storage right accounts, it is necessary to treat them as offstream reservoirs, even if they are actually on-stream reservoirs. As shown in Figure 3.11 , the reservoir is represented as off-stream storage, with an accrual link and a release link returning to the river. Each storage account in the reservoir must be treated as a separate *account reservoir*. The *account* reservoir should not be confused with the terms *accounting nodes and links*, since the former is a real node which is supplied by the user. Notice that flow must be allowed to bypass the reservoir, which, for an onstream reservoir, represents flow passing through the reservoir and being called to meet senior demands downstream. In effect, nodes 2,3, and 4 all represent a single reservoir containing two storage accounts.

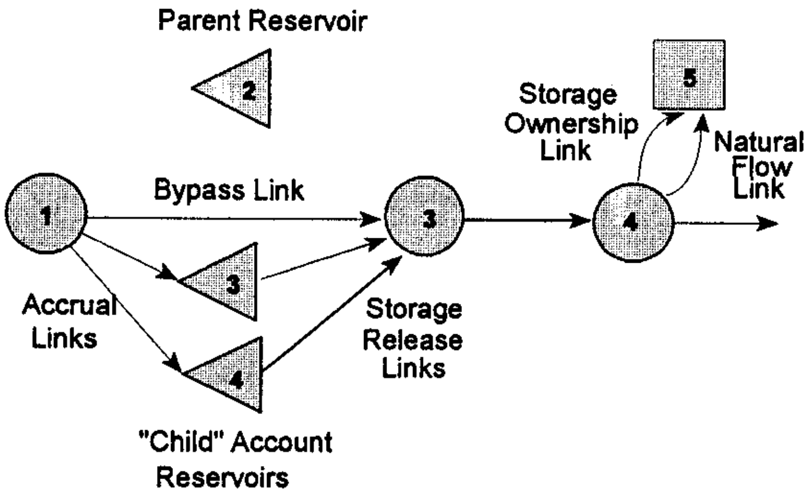


Figure 3.11. Storage Accounts and Storage Ownership

The accrual links can be assigned negative costs as related to a fill decree priorities. They can also be specified as a variable capacity links if the there are time limitations on the fill period. Zero capacities can be set for those periods where the reservoir is not allowed to fill. In addition, the accrual link can be specified as a seasonal capacity link, with the seasonal capacity corresponding to the amount of the fill decree.

Inflows and outflows based on water right allocation can be directed to and from a water right account reservoir. Because account storage volume generally depends on reservoir evaporation, this account reservoir can be associated with a *parent* reservoir that will adjust water right account storage volumes for total reservoir evaporation. Evaporation data are read in for the parent reservoir, as well as the area-capacity-elevation tables. Total volume is determined from the volumes of the water right reservoirs attached to the *parent* reservoir. It is not necessary to provide formal links connecting the parent reservoir to the system network or to its associated water right reservoirs. Inflow and outflow should not be directed to the *parent* reservoir. All network linkages should be directed to the *child* or water right account reservoirs. For the latter, evaporation data and area-capacity tables need not be defined. Total evaporation loss calculated for the parent reservoir is allocated to each storage account according to the fraction of contents in each account in relation to total contents in the reservoir at the beginning of the period.

It is not unusual for reservoir decreed water rights to be specified as a total annual volume. A provision has been added to MODSIM that allows a storage account to annually impound only the decreed amount each year. The model maintains a running total of the stored amounts in each water year and allows storage to occur when the running total is less than the decreed storage capacity. This is done by assigning a maximum accumulated amount equal to the storage decree to the reservoir inflow accrual link. Once this maximum value is reached, the maximum link capacity is set to zero and no flow is allowed through the link. The accumulated flow volume through the link is set back to zero, or the carryover storage in that account from the previous season, at the start of each accrual season. The desired starting month for the accrual season is specified by the user.

Although accrual to the storage accounts via the accrual links in Figure 3.11 are governed by the normal, priority based allocation process of MODSIM, once water is available in a storage account, it must be released to the owner as needed to meet demands. This implies a process which is *not* governed by a priority-based network flow allocation process. The storage ownership link shown in Figure 3.11 is related to one of the accrual links to the child account reservoirs. This guarantees that the owner of the storage right will receive water from the correct account.

In order to allow for allocation of releases from storage accounts to the owners of those accounts, MODSIM includes an additional iterative step which is performed after allocation of all natural flows or direct diversions according to water right priority. The *storage allocation step* follows the *natural flow allocation step* in MODSIM. During the natural flow allocation step, releases are not allowed from the storage accounts, and diversions to the storage ownership links are also temporarily *turned off*. The storage allocation step is only performed in MODSIM if storage ownerships exist in the network.

The *storage allocation step* proceeds as follows:

1. After all natural flows and direct diversions have been allocated in the natural flow allocation step, demands with storage ownerships are evaluated as to any shortages which have been incurred. It is important to note that demands with storage ownerships must be introduced as off-line demand nodes (as in Figure 3.11) in the network structure, with separate links to the demand designated as either storage ownership links or direct diversion right links. Demands may of course have several storage ownerships as well as several natural flow rights.
2. MODSIM evaluates the volume available in the storage account, and releases via the outflow links an amount which is the *lower* of the volume available *versus* the shortage incurred by the storage account owner. This is accomplished by executing the network flow algorithm with storage account outflow link bounds fixed to assure release of the correct amount of water.
3. During the storage allocation step, all direct flow diversions allocated during the natural flow allocation step are *frozen* to these values by assigning the lower bounds on these natural flow links equal to the amount of flow allocated. MODSIM automatically assigns much larger negative costs to the storage ownership links than the natural flow links during the storage allocation step, which assures that storage owners receive the releases from their accounts that they are entitled to.
4. MODSIM maintains a separate accounting of each storage ownership which keeps track of accruals to the account, releases, and other debits such as allocation of evaporation loss. Again, once an account has received its designated seasonal accrual, then no additional accrual is allowed to take place until the next accrual season.

In some cases, owners of storage accounts may not be able to physically receive reservoir releases from their accounts. In this case, MODSIM allows exchange mechanisms to take place whereby releases are made to downstream senior water right holders, and in return, the storage right owner is allowed to divert water out of priority. Since all natural flow links are frozen to allocations obtained during the natural flow allocation step, there is no danger of senior water right holders being injured by this procedure. However, it is possible, in certain situations, that although a storage owner has a certain amount of water available for release for exchange purpose, there may be insufficient flow available for upstream diversion to the storage right owner. In this case, MODSIM monitors how much flow the storage owner was actually able to divert, and then reduces the amount available to be released from the storage account during the next cycle of iterations.

CHAPTER 4

STREAM-AQUIFER MODELING COMPONENTS

4.1 Introduction

The stream-aquifer module within MODSIM allows consideration of reservoir seepage, irrigation infiltration, pumping, channel losses, return flows, river depletion due to pumping, and aquifer storage. Other features modeled include: overbank storage, channel routing, and divided flows. Stream-aquifer return/depletion flows can be simulated using response coefficients calculated using the one dimensional equations developed by Maasland (1959), Glover (1960), and McWhorter (1972). Alternatively, groundwater response coefficients estimated from other methods such as the stream depletion factor (SDF) method (Jenkins, 1968), the three-dimensional finite difference groundwater model MODRSP/MODFLOW (Maddock and Lacher, 1991a), or the discrete kernel generator GENSAM (Morel-Seytoux and Restrepo, 1987), can be read into MODSIM from external data files.

4.2 Groundwater Flow Equations

The mathematical flow equation for general two dimensional flow in an unconfined groundwater aquifer can be derived from Darcy's Law and the principle of mass continuity. The resultant equation is a nonlinear, second-order pjartial differential equation known as the Boussinesq equation (Willis and Yeh, 1987):

$$\frac{\partial}{\partial x}(K_x b\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y b\frac{\partial h}{\partial y}) + Q = S\frac{\partial h}{\partial t} \qquad (4.1)$$

where K_x,K_y is hydraulic conductivity along the x,y axes (Lt^{-1}); h is potentiometric head (L); Q is net groundwater withdrawal per unit area (Lt^{-1}); S is storage coefficient (L^{-1}); and t is time (t).

Where variation in saturated thickness is small and the specific yield/storage coefficient is assumed constant, the governing groundwater equation can be written as a linear form of the Boussinesq equation:

$$T(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}) + Q = S\frac{\partial h}{\partial t} \qquad (4.2)$$

where T is transmissivity (L^2t^{-1}) = Kb, K is hydraulic conductivity ($L^{1}t$), and b is saturated thickness (L).

Maddock (1974) showed that if the ratio of drawdown to saturated thickness is less than 20 percent, then for a nonlinear free-surface model (i.e., the Boussinesq equation), the linear contribution is between 75 to 100 percent of drawdown due to pumping. Accuracy of the linear model increases as the drawdown to saturated thickness ratio decreases. If the ratios are large, the Dupuit assumptions and the nonlinear flow equations are invalid.

Since the governing groundwater equation is linear and time invariant, linear system theory can be applied via the *principle of superposition* (Bear, 1979). This principle states that the presence of one boundary condition does not effect the response produced by the presence of other boundary conditions and that there are no interactions among the responses produced by the various boundary conditions. It is then possible to analyze the effect of individual events and then linearly combine the results.

Glover and Balmer (1954) and Glover (1968) presented an analytical procedure for determining depletion of flow in a nearby stream caused by pumping a well. Depletion flows were calculated using the distance of the well from the river, the properties of the aquifer (i.e., storage coefficient and transmissivity), time of pumping and time from start of pumping. The following assumptions apply:

1. aquifer is unconfined, homogeneous, isotropic, and of infinite extent
2. river is straight, fully penetrates the aquifer and is a constant head source.
3. water table is initially horizontal and water is released instantaneously from storage.
4. well fully penetrates the aquifer.
5. pumping is steady and drawdown is small compared to aquifer thickness.
6. residual effects of previous pumping are negligible.

According to Glover (1968), the ratio of the rate of stream depletion to the rate of well discharge is:

$$\frac{Q_s}{Q_w} = 1 - erf\left(\frac{a}{\sqrt{4tT/S}}\right) \tag{4.3}$$

where Q_s is rate of stream depletion; Q_w is rate of well discharge; a is perpendicular distance from well; t is pumping time; T is transmissivity; S is specific yield; and $erf(z)$ is the error function.

Glover (1977) extended the analytical approach to include bank storage, line source, return flows from irrigation, and intermittent well operation. Willis and Yeh (1987) presented a list of fifteen analytical response equations. Warner et al (1989) reviewed various analytical solutions to the artificial recharge problem, including Glover (1960), Hantush (1967), Rao and Sarma (1981), and Hunt (1971). The Hantush and Glover solutions were shown to be identical and were highly recommended for rectangular basins. It was also suggested that solutions for circular basins may be replaced by solutions for square basins with equivalent area. Madsen (1988) concluded that analytical models are not ideal for verifying the influence of existing wells on stream depletion, but are suitable as a tool for estimating impacts of new wells on streamflow depletion. Madsen (1988) also showed that analytical methods often overestimate stream depletion by failing to account for resistance near the stream.

The major disadvantage of the analytical method is that nonpoint sources of flow are often approximated as point sources (Warner et al., 1986). Other limitations of analytical methods such as Glover's method include (Morel-Seytoux and Zhang, 1990):

- method of averaging transmissivities over a heterogeneous aquifer is arbitrary
- procedure for calculating depletion from a certain reach (not the entire river) is inconvenient, involving numerical integration, or inaccurate because of steady state assumptions
- In most cases, the river is not straight

Qazi and Danielson (1974) used a computer program based on the Glover equations to evaluate augmentation plans for wells, recharge lines, and pit operations in an alluvial aquifer. Contributory effects of only those pumped wells or recharge sources requiring evaluation are determined, which are independent of other interactions already in process such as: effects of precipitation, surface water application, evapotranspiration, or other wells, reservoirs, and ditches. Labadie, et al. (1983) used analytical solutions embedded in a conjunctive use model to consider groundwater pumping (Glover, 1977), reservoir seepage (Glover, 1977), canal seepage (McWhorter, 1972), irrigation recharge (Maasland, 1959) and bank storage (Glover, 1977). Hantush and Marino (1989) developed a chance constrained stream-aquifer management model based on the Hantush (1959) analytical solution. Male and Mueller (1992) used the equations of Jenkins (1968) to develop a groundwater management model for prescribing groundwater use permits in Massachusetts.

4.3 Discrete Kernel/Response Functions

Most groundwater management scenarios require information only on select events in an aquifer. Extraneous information on drawdown and flow rates at noncritical locations is not only unnecessary but computationally prohibitive. Applying linear system theory to the groundwater equation allows the use of Green's function to solve the resulting non-homogeneous boundary value problem (Maddock, 1972). Response of the groundwater system due to external excitations such as pumping, recharge, or infiltration at any point in space and time can be expressed as a set of unit coefficients independent of the magnitude of the excitation. Integrated with a finite difference groundwater model, resultant flows can be superimposed to determine net effects at a single location due to a series of excitations or at a series of locations due to a single excitation.

It is convenient to express the Boussinesq equation in terms of water table drawdown:

$$S\frac{\partial s}{\partial t} - \frac{\partial}{\partial x}(T\frac{\partial s}{\partial x}) - \frac{\partial}{\partial y}(T\frac{\partial s}{\partial y}) = Q_p \tag{4.4}$$

where T aquifer transmissivity; s is water table drawdown; Q_p is groundwater withdrawal rate at well p; S is storage coefficient; t is time (t); and x,y are horizontal coordinates.

This equation can be solved using Green's function (Maddock, 1972):

$$s_w(t) = \int_0^t k_{wp}(t-\tau)Q_p(\tau) \tag{4.5}$$

where $s_w(t)$ is drawdown at aquifer point w due to a single well pumping Q_p at point p; and k_{wp} is the kernel function (Green's function) of aquifer drawdown at w due to a unit impulse excitation at p. The discrete form of the convolution equation for a heterogeneous aquifer with finite boundaries is (Maddock, 1972; Morel-Seytoux and Daly, 1975):

$$s_w(n) = \sum_{p=1}^{P}\sum_{\nu=1}^{n} \delta_{wp}(n-\nu+1)Q_p(\nu) \tag{4.6}$$

where $s_w(n)$ is drawdown from an initially horizontal (or initially steady) water table at any aquifer point w at the end of the n^{th} period; $Q_p(\upsilon)$ is the mean pumping rate from well p during the period υ (pumped volume for the period); P is the total number of excitation points or wells; δ_{wp} is the discrete kernel coefficient; and $\delta_{wp}(n)$ represents the drawdown at the end of period n if a unit volume of water was withdrawn during the first week from well p and well pumping terminated indefinitely thereafter.

Maddock (1974), Morel-Seytoux and Daly (1975), and Illangasekare and Morel-Seytoux (1982) extended the Green's function or discrete kernel approach to the case of stream aquifer interactions by treating the stream as an imposed boundary condition:

$$s_w(n) = \sum_{p=1}^{P} \sum_{\nu=1}^{n} \delta_{wp}(n-\nu+1) Q_p(\nu) + \sum_{r=1}^{R} \sum_{\nu=1}^{n} \delta_{wr}(n-\nu+1) Q_r(\nu) \tag{4.7}$$

where $Q_r(\upsilon)$ is the mean pumping rate from the r^{th} reach of the river during the υ^{th} period; and R is the number of reaches. It can be shown that the flow between a stream and an aquifer is proportional to a difference in the drawdowns to the stream surface level and to the aquifer water table. The coefficient of proportionality or streambed conductance depends on the streambed characteristics and shape of the stream cross section (Bouwer, 1978; McDonald and Harbaugh, 1988):

$$Q_r = C_r(r_r - s_r) \tag{4.8}$$

where C_r is streambed conductance; r_r is stream surface drawdown; and s_r is aquifer water table drawdown.

Through substitution and use of linear system theory, Morel-Seytoux and Daly (1975) and Maddock and Lacher (1991a) show that assuming: (i) a head gradient between the river and the aquifer; (ii) the head gradient is in the vertical direction; (iii) water flows only through the streambed; (iv) the streambed has vertical conductivity and no storage; (v) the river stage remains unchanged by any flow between the river and the aquifer; (iv) the flow between the river and aquifer is linear; and (v) the stream water level does not fall below the bottom of the streambed, then for a discrete number of river reaches and pulse pumping:

$$Q_r(n) = \sum_{p=1}^{P} \sum_{\nu=1}^{n} \delta_{rp}^{n}(\nu) Q_p(\nu) \tag{4.9}$$

where $Q_r(n)$ is return volume to reach r during the n_{th} period; $Q_p(\upsilon)$ is volume pumped at well p during the υ^{th} period; P is total number of pumping wells; and $\delta_{rpn}(\upsilon)$ is the stream capture response function and represents the quantity of flow captured through the r^{th} river reach in the n^{th} stress period due to unit pumping from the p^{th} well during the υ^{th} stress period when linearity is maintained.

Maddock (1972) first introduced the concept of a response function for a groundwater system, with drawdown in response to pumping stress modeled by a two-dimensional linear partial differential equation. This allowed an explicit coupling of a groundwater simulation model with a quadratic programming management model to optimize an economic objective of minimizing pumping costs subject to satisfying specified demands. Maddock (1974) used Green's function to extend this approach to the case of stream-aquifer interactions.

Again, based on linear system theory and the Green's function, Morel-Seytoux and Daly (1975) developed a finite difference model to generate any aquifer response as an explicit function of pumping rates, which they referred to as a *discrete kernel generator*. The discrete kernel method has been utilized extensively as a tool for solving complex groundwater management problems (Morel-

Seytoux, et al., Illangasekare, 1987; Illangasekare and Morel-Seytoux, 1982; Illangasekare and Brannon, 1987; and Illangasekare and Morel-Seytoux, 1986).

4.4 Parallel Drain Analogy for Stream-Aquifer Systems

The interaction of a water table aquifer receiving recharge from irrigation and precipitation, and an interconnected stream, can be modeled utilizing the method developed by Maasland (1959). This method was developed for a parallel drain system and can be applied to a stream-aquifer system as well. The idealized parallel drain system is shown in Figure 4.1.

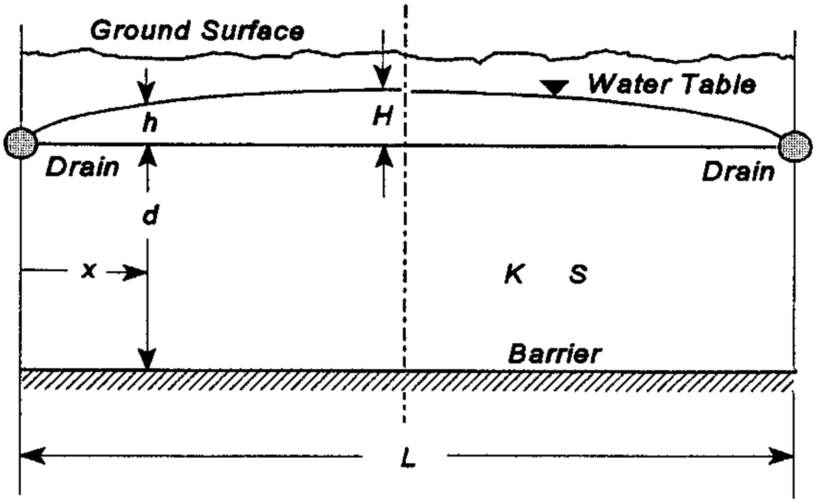


Figure 4.1. Parallel Drain Analogy for Stream-Aquifer Systems

The nonlinear partial differential equation for one-dimensional groundwater flow is

$$K\frac{\partial}{\partial x}(d+h)\frac{\partial h}{\partial x} = S\frac{\partial h}{\partial t} \tag{4.10}$$

where K is permeability of the aquifer; d is original saturated thickness; S is specific yield; h is height of the water table measured from the assumed original stable water table level; x is distance measured along the path of flow; and t is time.

By assuming h is small compared to d, the linearized form of equation 4.10 is:

$$\alpha\frac{\partial^2 h}{\partial x^2} = \frac{\partial h}{\partial t} \tag{4.11}$$

where $\alpha = T/S$; T is transmissivity, which is equal to $K \cdot d$; and the boundary conditions are:

$h = 0$ when $x = 0$ for $t > 0$
$h = 0$ when $x = L$ for $t > 0$
$h = H$ when $t = 0$ for $0 < x < L$

Maasland (1959) obtained the solution as

$$h = \frac{4H}{\pi} \sum_{n=1,3,5\ldots}^{\infty} \frac{1}{n} \exp\left(\frac{-n^2\pi^2\alpha t}{L^2}\right) \sin\left(\frac{n\pi x}{L}\right) \tag{4.12}$$

where H is initial uniform height of recharge water and L is spacing of the parallel drains.

The volume of water remaining to be drained is

$$V_d = S\int_0^L h\,dx \tag{4.13}$$

and the fraction remaining to be drained is

$$F = \frac{V_d}{V} \tag{4.14}$$

where initial drainable volume is

$$V = S \cdot H \cdot L \tag{4.15}$$

Therefore

$$F = \frac{S\int_0^L h\,dx}{S \cdot H \cdot L} \tag{4.16}$$

Substitution of h from equation 4.12 and integration results in:

$$F = \frac{8}{\pi^2} \sum_{n=1,3,5\ldots}^{\infty} \frac{1}{n^2} \exp\left(-n^2\pi^2\frac{\alpha t}{L^2}\right) \tag{4.17}$$

This represents the fraction of the total initially drainable volume in the aquifer at the end of time t that is available for flow to the drains. For any time t from the beginning of recharge, F can be predetermined. The difference of successive F values over two adjacent time periods represents the flow fraction to the drains during that time interval.

4.5 Return Flow Calculations

Consider the idealized stream-aquifer system as shown in Figure 4.2. The river is assumed to be located at the center of the valley. The solution described above can be applied directly with L equal to the valley width. The analogy is applicable since the middle section of the parallel drains is a no-flow boundary and is analogous to either the left boundary or the right boundary of the stream-aquifer system. If the parallel drain system is divided in half at the no flow boundary and rearranged to bring the drains into coincidence, the direct analogy with the stream-aquifer system is evident. The drains are replaced by the river and the flow to the drains represents return flow to the river.

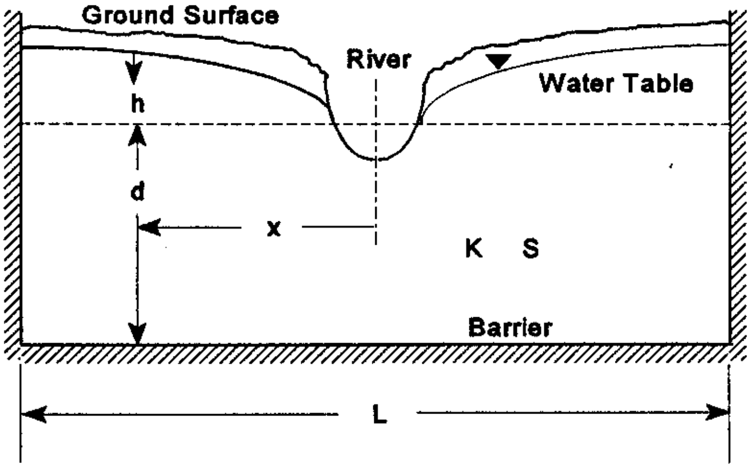


Figure 4.2. Idealization of Stream-Aquifer System (Glover, 1977)

When the river is not located at the center of the valley, the above solution (equation 4.17) is still applicable with L equal to twice the width W of either side of the valley (i.e., $L^2 = 4W^2$). Fraction F can be determined for each side of the valley and return flows computed separately.

Let N be the total number of time intervals of length Δt and I_k the recharge rate during the *k-th* time interval, where $k < N$, as shown in Figure 4.3.

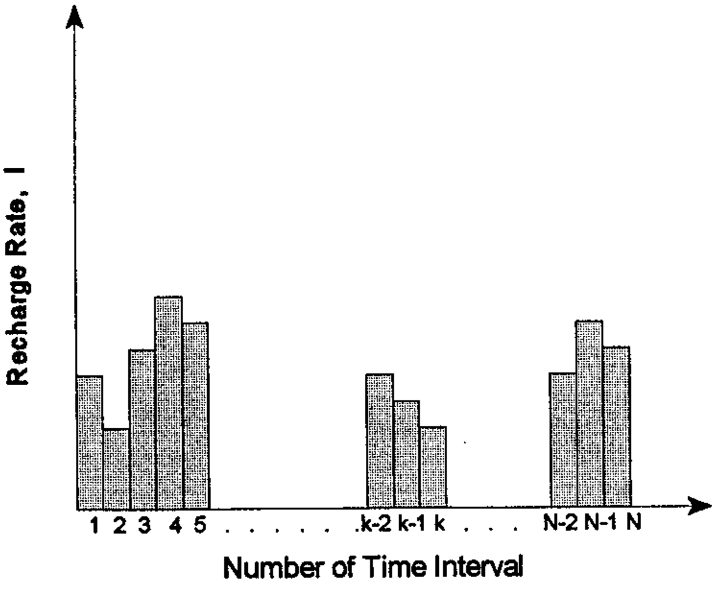


Figure 4.3. Series of Recharge Events

The fraction of return flow to the river during time interval k is

$$F_{k-1} - F_k = \frac{8}{\pi^2}\Big[\sum_{n=1,3,5...}^{\infty} \frac{1}{n^2} \exp\Big(-n^2\pi^2\frac{\alpha(k-1)\Delta t}{L^2}\Big) - \sum_{n=1,3,5...}^{\infty} \frac{1}{n^2} \exp\Big(-n^2\pi^2\frac{\alpha k\Delta t}{L^2}\Big)\Big] \tag{4.18}$$

Define

$$\delta_k = F_{k-1} - F_k \tag{4.19}$$

where δ_k is a unit response or discrete kernelfor a recharge rate I of unity. Therefore, for demand node i and any current time period considered, the total return flow IRF_{ik} from previous and current time periods due to groundwater recharge is

$$IRF_{ik} = \sum_{\tau=1}^{k} I_{i\tau} \cdot \delta_{i,k-\tau+1} \ ; \quad \delta_{i,k-\tau+1} = 0 \ for\, k-\tau+1 > N \tag{4.20}$$

where response $\delta_{i,k-\tau+1}$ is the discrete kernel coefficient defined for node i, period k-τ+1.

In MODSIM, upper bounds on return flow links (Figure 3.1) are adjusted iteratively. The iteration procedure is as follows:

1. In the first iteration, all upper bounds are set equal to return flows computed from previous development activities, which can be read in as input data. The return flow from current activities are yet unknown. The total return flow from all links is computed.
2. MODSIM is now run for the current period using these bounds. Return flows from all sources are recomputed using available link flows obtained from this solution. The total return flow is computed and compared to the previous estimate. If the difference of the total return flow is within specified tolerance limits, the solution is assumed to have been found; otherwise step two is repeated until convergence is achieved.

4.6 Stream Depletion from Pumping

The same approach used for calculating return flows is also applied to calculation of stream depletion due to pumping PSD_{ik}, where

$$PSD_{ik} = \sum_{\tau=1}^{k} P_{i\tau} \cdot \alpha_{i,k-\tau+1} \ ; \quad \alpha_{i,k-\tau+1} = 0 \ for\, k-\tau+1 > N \tag{4.21}$$

In the case of groundwater withdrawal $P_{i\tau}$, the same principles described above is applicable to determining response coefficent kernels $\alpha_{i,k-\tau+1}$. Here, it is river depletion that is considered rather than return flows to the river. Since the computation is sequentially carried out period by period in MODSIM, the current period stream-aquifer interactions are contingent upon stresses during previous periods. Therefore, it is recommended to run MODSIM for an initial N periods for start-up or

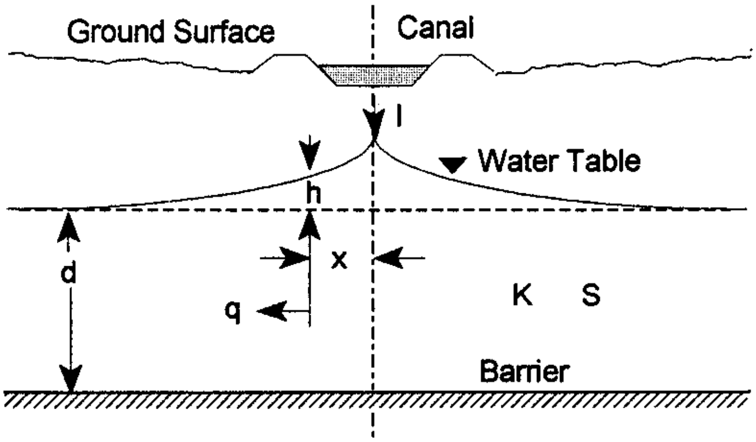


Figure 4.3. Illustration of Line Source for Canal Seepage

initialization purposes, such that after N periods, the model output can be trusted to properly account for past history. Specification of N is left up to the user.

4.7 Canal Seepage

Seepage from a canal or a stream is assumed to correspond to a line source of recharge water. For a one-dimensional line source in an infinite aquifer, as shown in Figure 4.3, the governing flow equation is (McWhorter, 1972)

$$\alpha\frac{\partial^2 q}{\partial x^2} = \frac{\partial q}{\partial t} \tag{4.22}$$

where x is the Cartesian coordinate in the horizontal plane and q is the flow rate or Darcy velocity, calculated as:

$$q = -K\frac{\partial h}{\partial x} \tag{4.23}$$

The solution is (McWhorter, 1972):

$$q = \frac{I}{2}erfc\,(\frac{x}{\sqrt{4\alpha t}}) \tag{4.24}$$

where I is the one dimensional magnitude of the source in units of length per unit time, with *erfc(z)* representing the complementary error function:

$$erfc(z) = \frac{2}{\sqrt{\pi}}\int_{z}^{\infty} e^{-u^2}du \tag{4.25}$$

assuming the following boundary and initial conditions:

$$q = \frac{I}{2} \quad at\ x = 0$$

$$q = 0 \quad as\ x \dashrightarrow \infty \tag{4.26}$$

$$q = 0 \quad at\ t = 0;\ \ for\,all\,x$$

Now define $q_0 = I/2$ as the applied line source flow rate in the aquifer at the line source location. Note that the denominator of two is necessary since q can flow in two horizontal directions. Integrating equation 4.23 from zero to t results in the ratio of the volume of flow applied up to time t:

$$\frac{v}{q_0 \cdot t} = \left(\frac{x^2}{2\alpha t} + 1\right) erfc\left[\frac{x}{\sqrt{4\alpha t}}\right] - \left[\frac{x}{\sqrt{4\alpha t}} \frac{2}{\sqrt{\pi}} \exp\left(-\frac{x^2}{4\alpha t}\right)\right] \tag{4.27}$$

This solution is for a continuous application of a line source. After termination of the source, the residual effect still contributes flow to the stream. The residual is taken into account by assuming an imaginary pumping source at the same location and initiating pumpage at the same rate as the recharge source from the time recharge terminates. The volume ratio at any time after recharge ceases is the difference between the volume ratio obtained if recharge had continued and the volume ratio obtained from pumping of the imaginary pumping source. For a discrete time interval, if the applied line source volume equals one, the volume ratio is in essence the unit response of line source or canal seepage.

Let ϕ represent the unit response of canal seepage. Then for canal link ℓ, the total return flow $CRF_{\ell k}$ from canal seepage $C_{\ell 1}, C_{\ell 2}, \ldots, C_{\ell k}$ during each time interval k is

$$CRF_{\ell k} = \sum_{\tau=1}^{k} C_{\ell\tau} \cdot \phi_{\ell,k-\tau+1}\ ; \quad \phi_{\ell,k-\tau+1} = 0 \ \ for\ k-\tau+1 > N \tag{4.28}$$

4.8 Point Source Water Application

Reservoir seepage RS_{ik} is defined as a point source application for storage node i, time period k. The effect on the stream corresponds to the effect of a recharge well, which in turn has the same absolute flow magnitude as a pumping well, with the flow direction reversed. This solution turns out to be exactly the same as that for the line source solution (Glover, 1977). Therefore, $C_{\ell\tau}$ is replaced with $RS_{i\tau}$ in equation 4.28, with the resulting return flow defined as RRF_{ik}. Again, there is little error in assuming reservoir seepage as a point source, as long as the reservoir surface area is small in comparison with the area of the subsystem containing it.

For reservoir i during time period k, the total return flow RRF_{ik} from reservoir seepage, based on current and previous period seepage, is

$$RRF_{ik} = \sum_{\tau=1}^{k} RS_{i\tau} \cdot \phi_{i,k-\tau+1}\ ; \quad \phi_{i,k-\tau+1} = 0 \ \ for\ k-\tau+1 > N \tag{4.29}$$

4.9 Stream Depletion Factor Method (SDF)

Jenkins (1968) solved the Glover equation graphically by developing dimensionless curves and tables to compute the rate and volume of stream depletion by wells. The stream depletion factor (SDF) was arbitrarily chosen as the time in days where the volume of stream depletion is 28 % of the net volume pumped during time t, and can be expressed as:

$$SDF = a^2 S/T \tag{4.30}$$

where a is perpendicular distance from the pumped well to the stream (L); S is specific yield of the aquifer (dimensionless); and T is transmissivity (L^2/T).

In a complex system, the value of *SDF* at any location depends on the integrated effects of irregular impermeable boundaries, stream meanders, aquifer properties, areal variation, distance from the stream, and hydraulic connection between stream and aquifer. The basic assumptions are similar to those associated with the Glover equation:

1. transmissivity does not change with time, and drawdown is negligible when compared to saturated thickness
2. temperature of the stream is assumed to be constant and the same as the temperature of water in the aquifer
3. the aquifer is isotropic, homogeneous, and semi-infinite in areal extent
4. the stream forming the boundary is straight and fully penetrates the aquifer
5. water is released instantaneously from storage
6. the well is open to the full saturated thickness of the aquifer
7. pumping rate is steady during any period of pumping.

Moulder and Jenkins (1969) introduced the *SDF* concept to a digital model and the USGS used it to generate groundwater response coefficients for developing regional models (Taylor and Luckey, 1972; Hurr, 1974; Hurr and Burns, 1980; and Warner et al., 1986) and groundwater *SDF* contour maps (Hurr, et al., 1972).

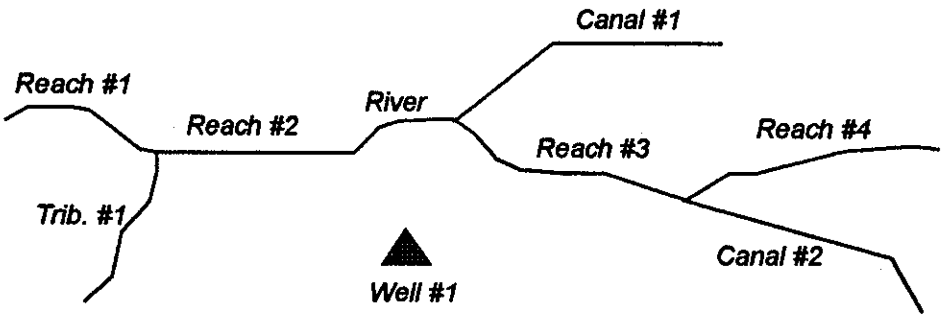
4.10 Finite Difference Groundwater Models

The partial differential equation for groundwater movement in a heterogeneous and anisotropic medium can be solved using finite difference or finite element numerical methods (Willis and Yeh, 1987). The finite difference method uses a finite set of discrete points or grids to represent the system and replaces the partial differential equations with terms calculated from differences in potentiometric head at these grid points. The result is a system of simultaneous linear difference equations. Figure 4.5 compares a network formulation and a finite difference grid structure for a river basin system.

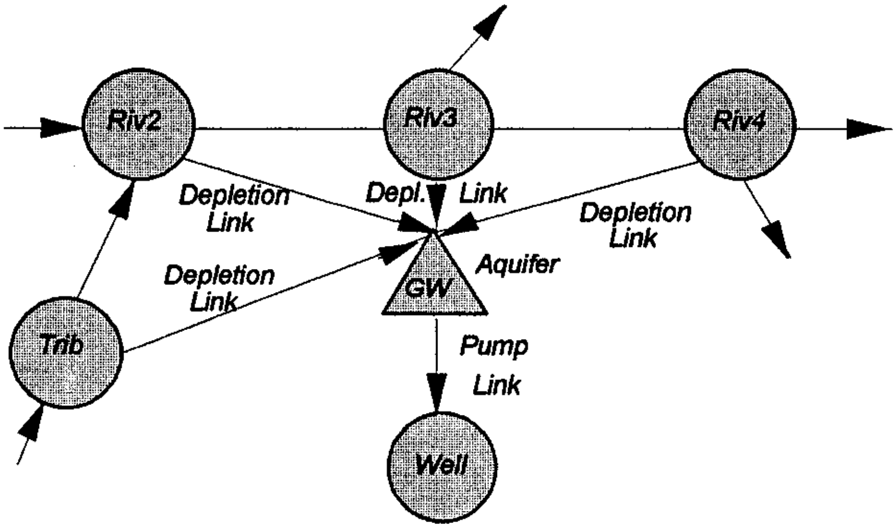
The finite element method is generally formulated using the method of weighted residuals, with co-location and Galerkin the most popular solution techniques. The finite elementmethod also requires discretization of the groundwater system, making it is less amenable to efficient solution strategies than the classical finite difference approach. The finite element procedure must generate a more accurate solution for a given number of equations, which can only be achieved by proper choice of nodal locations or through use of higher order accurate approximations (Pinder, 1988). Output from finite element numerical models includes drawdown and flow at each grid for each time period. For regional aquifer models, computational time can be quite extensive.

Lee, et al. (1980) used a digital finite difference model to determine the feasibility of a demonstration recharge project located in the South Platte River basin in northeastern Colorado. Maurer (1986) used the USGS finite difference model MODFLOW (McDonald and Harbough, 1988) to simulate the effects of groundwater development in the Carson Valley, Nevada on the Carson River. Hartwell (1987) compared results from a model based on the Glover solution, the SDF method, and a finite difference model for a recharge site along the along the South Platte River, Colorado. The use of the finite difference model was recommended in this study, which can be run with relatively few idealizing assumptions and can easily be calibrated to produce more accurate return flow values than the other methods. Stoertz and Bradbury (1989) used MODFLOW to map regional recharge areas.

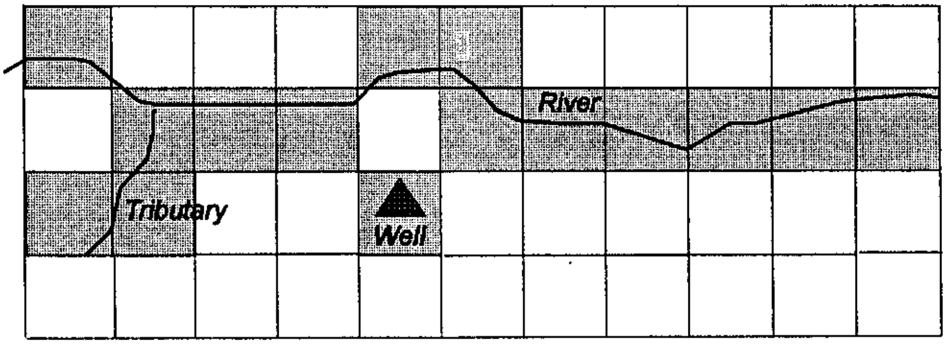
The data requirements for the USGS Modular Three-Dimensional Finite-Difference Groundwater Flow Model MODFLOW are shown in Table 4.1, along with indications as to which input data types can be prepared with the aid of geographic information systems (GIS). Application of GIS to preparation of input data files for MODFLOW is detailed in the following chapter.



PHYSICAL CONCEPTUAL MODEL



NETWORK MODEL



FINITE DIFFERENCE MODEL

Figure 4.5. Comparison Between Network Model and Finite Difference Grid Structure for River Basin

The file input structure for MODFLOW allows input to be collected as needed from a number of different files. The user assigns unit file names to those options to be included in the running of the program. Each unit file name refers to an actual input data file. Most of the data submitted by the user will be made up of one or two dimensional data arrays. The program allows the user to define the structure of the input data arrays and the file locations. For example, transmissivity data for an aquifer can be read in from the *Block Centered Flow File*, along with other miscellaneous data, or it can be read in separately from a user assigned file. The data can also be read in any format defined by the user. MODFLOW output can be manipulated in the same manner.

Maddock and Lacher (1991a) have developed MODRSP, a modified version of MODFLOW, to calculate the volume of water captured, volume of storage loss, drawdown, and velocities from pumping stresses at specified locations and times in multiple aquifer systems. The concept of MODRSP is expanded to cover response functions for stream-aquifer leakage, reduction of evapotranspiration, flows to and from constant head boundaries, and increases or decreases in natural recharge or discharge from head dependent boundaries. MODRSP was selected as the most appropriate numerical model for determining response function coefficients for several reasons. MODRSP allows the modeling of a multi-aquifer groundwater flow system as a linear system with irregularly shaped areal boundaries and non-homogeneous transmissivity and storativity qualities. The aquifer must first be defined in terms of boundary conditions and the aquifer parameters of transmissivity and specific yield. The model initializes all heads to zero. Since MODRSP is a linear model, transmissivity and storage coefficients are considered constant. The user selects the grid location of the well and the type and location of the response for which the response coefficients are to be calculated.

If spatially distributed stream-aquifer response coefficients have been generated using MODRSP they can be used to allocate groundwater return/depletion flows to multiple return/depletion flow node locations any where in the river basin network system as shown in Figure 4.5.

MODRSP calculates responses for one well at a time over the total simulation period assuming a unit stress has been applied during the first period and discontinued for the remainder of the simulation. MODRSP assumes that stream-aquifer interaction is independent of the location of the stream reach within the grid cell, the level of water in the stream is uniform over the reach, and constant over each stress period. This implies that conditions of flow in the stream do not vary significantly during stress periods. If streams go dry or overflow their banks during a stress period, it is assumed such events are of short duration and have negligible effect on stream-aquifer interaction. Because of this it is not necessary to read in the river stage height and the head at the bottom of the streambed in defining river reach data. Output for the response coefficient data generated by the model can be output formatted or unformatted and includes well grid location, response grid location, stress period, and calculated response coefficient for that period.

Because MODRSP is a modification of the USGS MODFLOW finite difference groundwater model, it uses many of the same input data and file structures as MODFLOW. However, there are several major differences between the two programs. For example all starting heads are set to zero in MODRSP so a starting head input file is not required. Because MODRSP is a linear model, transmissivity and storage coefficient are considered constant and must be entered as input data. For the MODRSP well package, it is not necessary to read in pumping values. The MODRSP river package does not require data on river stage height and the head at

Table 4.1 Use of GIS for MODFLOW Input Data Requirements

DATA	GIS?	DATA	GIS?
1. Basic Data		**5. River Package**	
• Boundary Conditions	YES	• Number of Reaches	YES
• Starting Years	YES	• Location	YES
• Simulation Period	NO	• Head	YES
2. Block-Flow Centered		• Hydraulic Conductivity	YES
• Type of Aquifer	NO	• Bed Elevation	YES
• Anistropy	YES	**6. Evapotranspiration Package**	
• Grid Size (row x col)	YES	• Location	YES
• Specific Yield	YES	• Elevation of ET Surface	YES
• Transmissivity	YES	• Max. ET Rate	YES
• Hydraulic Conductivity	YES	• ET Extent Depth	YES
• Bottom of Aquifer	YES	**7. Recharge Package**	
3. Well Package		• Location	YES
• Number	YES	• Recharge Amount	YES
• Location	YES	**8. Solution Procedure**	NO
• Discharge	YES		
• Period	YES		
4. Drainage Package			
• Number	YES		
• Location	YES		
• Drain Elevation	YES		
• Hydraulic Conductivity	YES		

the bottom of the streambed. Output for the response coefficient data generated by MODRSP can be printed to a file as formatted or unformatted data. Typical database structure for response coefficient output data is presented in Table 4.2.

Table 4.2. MODRSP Response Coefficient Database Output File

```
RIVER CAPTURE RESPONSE FUNCTIONS
================================

 RIVER              PUMP
 REACH              WELL               TIME
   #    K    I    J    #     K    I    J  PER       RF [0]
 ______________________________________________________________
```

The following modifications were made to MODRSP:

- The program was compiled to run under Microsoft WINDOWS using Microsoft FORTRAN 5.1. This allows resizing of the array dimension variable LENX up to the limits allowed by extended memory. On an IBM-compatible personal computer using a DOS operating system with 8 MB memory, the program MODRSP was successfully run with LENX set at 7.5 million.
- The modules RRIV.FOR and RPGM.FOR source code were modified to reduce unnecessary output to a river response file. In line 1 of the RRIV input file, field 41 to 50, a decimal value for the variable, RDROP, can be input. Response coefficients lower than this value will not be printed to the river response output file. This reduces the size of river response output file by eliminating zero value response functions.
- The modules RRIV.FOR and RPGM.FOR code were modified to terminate a computer processing loop for a specific well when the calculated response coefficient values fall below a specified lower limit.
- The modules RRIV.FOR and RPGM.FOR were modified to read in a river reach file that assigns a specific river reach value to each river reach grid cell and then sums the response coefficients by river reach.
- The module RPGM.FOR was modified to read in a recharge site file that assigns a recharge site number to each well grid cell number.

4.11 Simulation of Stream Boundaries

Finite difference numerical solution of the groundwater flow equations requires the assignment of boundary conditions, which generally correspond to hydrologic boundaries. Boundary conditions used in groundwater flow models include (Willis and Yeh,1987):

- constant head boundary (Direchlet conditions): e.g., an aquifer adjacent to a lake or a large perennial stream
- no-flow boundary (Neumann condition): special case of the general mathematical boundary condition which specifies a prescribed flow across the boundary; e.g., an impermeable aquifer boundary.
- constant inflow or flux (Neumann conditions): where a portion of the boundary has specified flow crossing the boundary independent of head; e.g., recharge from precipitation or irrigation.
- inflow dependent on head (Cauchy): flow across a boundary is a linear function of the head difference across the boundary; e.g., leakage through a riverbed, a drain, or through evapotranspiration.

Since analytical solutions assume an aquifer of infinite areal extent, analytical equations generally do not directly simulate streams or other bodies of surface water adjacent to an aquifer (Kraeger-Rovey ,1990). Using the principle of superposition, a line along which the head is constant can be defined within the idealized, infinite aquifer. The aforementioned Glover equation for determining stream depletion due to pumping of a well in an adjacent aquifer uses this procedure (Glover, 1977). The linear constant head representation may be acceptable for simulating a stream boundary in cases where a large, perennial stream flows in a reasonably straight line past an aquifer and the natural or induced seepage from the stream into the aquifer is considerably less than the streamflow (Kraeger-Rovey, 1990).

Earlier numerical models represented a stream or body of surface water as one or more constant head grid cells or nodes at the proper location within the groundwater model grid or mesh (Trescott, et al.,1976pl; Morel-Seytoux and Restrepo, 1987). This procedure provided greater flexibility in locating stream reaches within the model domain than the straight line representation required for analytical models. It also offered the advantage that each stream or water body cell could be assigned its own head value (Kraeger-Rovey, 1990).

Most numerical groundwater models now offer the capability of computing seepage across the stream-aquifer interface through a series of production terms. These terms can be assigned to each grid cell or node adjacent to a stream reach. The stream reach is assumed to have a constant water surface elevation during the simulation time step, but can vary period by period and reach to reach (McDonald and Harbaugh, 1988; Zhang, 1990; Maddock and Lacher, 1991a).

This procedure offers two advantages over the use of constant head cells (Kraeger-Rovey, 1990). Instead of replacing an entire grid or node of the aquifer with a cell or node that represents a body of surface water, grid cells or nodes in which stream reaches are located are realistically modeled as part of the aquifer, and the head in these cells can vary. The capability exists to simulate the effect on seepage of a restricting streambed layer having lower hydraulic conductivity than the underlying aquifer material. This capability allows the head in the aquifer to fall below the level of the streambed.

The major disadvantage of this procedure is that a continuity check on streamflow is required. An adjustment of stream depth and seepage conditions caused by gains and losses in streamflow due to seepage interactions with the adjacent aquifer may be required. These considerations are important when the rate of seepage between the aquifer and the stream is a significant fraction of total streamflow. Results of using fixed-head stream representations in systems that include groundwater dependent streams is over-prediction of seepage from the stream, under-prediction of water level declines in the aquifer, and inaccurate prediction of the actual effect of system stresses on streamflow (Kraeger-Rovey, 1990). Stream-aquifer modification packages (Miller, 1988; Schenk, et al., 1990) to the MODFLOW groundwater program are now available which include continuity and river stage estimates for calculating variable stream head values.

4.12 Streambed Conductance

The general equation for hydraulic conductance between a stream and an underlying aquifer can be expressed as (McDonald and Harbaugh,1988):

$$Conductance = \frac{K \cdot L \cdot W}{M} \tag{4.31}$$

where K is hydraulic conductivity of streambed material; W is stream width; M is distance of flow taken as thickness of streambed layer; and L is length of stream as it crosses a node or grid.

McDonald and Harbaugh (1988) advise that if reliable field measurements of stream seepage and associated head difference are available, they should be used to estimate streambed conductance. Otherwise, a conductance value must be arbitrarily chosen more adjusted during model calibration. Equivalent conductances can be developed to simulate calibrated seepage flows.

Kraeger-Rovey (1990) cautions against misapplication of the conductance factor due to a lack of understanding and consensus among hydrologists and modelers on the behavior and nature of the seepage-restricting streambed and limitations on the use of the equations for seepage through it.

Maurer (1986), in modeling the Carson Valley, Nevada, identified several factors that presented complications in estimating hydraulic conductivity of a streambed for use in MODFLOW, such as variation in streambed areas due to changes in flow or dredging and cleaning of drains. Instead of attempting to account for these factors, conductances were assumed to be similar over major parts of the system. Streambed area was assumed to represent the total flooded area of each cell, including streams, ditches, and flooded fields. The thickness was assumed to one foot, due to frequent dredging of ditches and the practice of flood irrigation, the thickness was assumed to be one foot.

Schenk, et al. (1990) suggest that the hydraulic conductivity of the grid cell be used in calculation of conductance if a silt layer does not exist on the stream bottom. If a silt layer is present, and there is a hydraulic connection between the river and the grid cell, an equivalent hydraulic conductivity should be calculated:

$$Equivalent\ K = \frac{d}{(\frac{d_1}{K_1} + \frac{d_2}{K_2})} \tag{4.32}$$

where d is total thickness of silt layer and underlying grid cell; d_1 is thickness of silt layer; K_1 is hydraulic conductivity of silt layer; d_2 is thickness of grid cell below stream bottom; and K_2 is hydraulic conductivity of the grid cell. The hydraulic conductivity K and thickness M of the silt layer should be used in the calculation of the streambed conductance if head in the grid cell is below the river bottom and the flow is unsaturated.

Peters (1978), Illangasekare (1978), Morel-Seytoux and Restrepo (1987), and Zhang (1990) suggest the following equation based on the method of flow nets:

$$Conductance = \frac{T}{e}L(\frac{W_p+2e}{e+10W_p}) \tag{4.33}$$

where T is transmissivity of the aquifer underlying the reach; e is average saturated thickness of the aquifer along the reach; L is length of reach; and W_p is wetted perimeter of stream equal to width of the reach.

In cases where the streambed is clogged, the following formula is proposed (Morel-Seytoux and Restrepo,1987; Zhang,1990):

$$\Gamma_c = \Gamma\frac{1}{1+\frac{z_c\Gamma}{W_pLK_c}} \tag{4.34}$$

where Γ_c is streambed conductance adjusted for clogging; Γ is streambed conductance; z_c is thickness of clogging layer; K_c is hydraulic conductivity of clogging layer; L is length of reach; and W_p is wetted perimeter of stream equal to width of reach.

Restrepo (1988) in a first step calibration of the SAMSON model for the South Platte River adjusted clogging factors to balance return flows calculations.

4.13 Calibration of Stream-Aquifer Models

It is possible to estimate reach gains and losses along the various reaches of a river system where adequate streamflow and diversion records are available. Estimates of historical river return/depletion flows on a reach by reach basis can be useful in the development and calibration of stream-aquifer models. For most conjunctive use models, it is the river return/depletion flows which are the dependent variables. Knowing actual historical values allows the user to calibrate various parameters and coefficients to reproduce the historical return/depletion flow values.

The program PTFLOW (USBR, 1989) is a useful tool for calculating historic return/depletion flows along a river system. The PTFLOW program performs several computations:

- calculates reach gains and losses between stream gages
- prorates reach gains and losses between diversions and inflow points.
- calculates point flow upstream and downstream of diversions.
- calculates point flow upstream and downstream of inflow locations and tributaries.
- calculates point flow at gage locations for years with missing gage records.

Reach gains and losses are defined as the cumulative impacts on streamflow due to unmeasured tributary and overland inflows, irrigation return flows, ground water discharge, channel infiltration, evapotranspiration due to riparian vegetation, precipitation over the channel, stream evaporation, and unmeasured diversions.

The PTFLOW computer program is general in nature and can be used on any river. The model uses traditional FORTRAN read and write card formats for data input and output. The input data requirements for the USBR South Platte River Point Flow Study Computer Model (PTFLOW) are shown in Table 4.3. Although data input to the PTFLOW model is read from a single file, a user can collect data from various external databases and consolidate the data into a single file using a standard ASCII file text editor. The proposed external database structure for two of the input data groups are shown in Table 4.4.

The PTFLOW program was modified to allow output as an ASCII database text file using the following structure:

Field	Field Name	Type	Width	Decimal
1	MILEAGE	Numeric	5	1
2	YEAR	Numeric	4	
3	MONTH	Numeric	2	
4	TYPE	Character	4	
5	FLOW	Numeric	6	1

where MILEAGE is CDATA or river station mileage number.; YEAR is flow year; MONTH is flow month; GAGE is gage flow; GAIN is reach tributary inflow; DIVR is reach diversion flow; PTBL is flow below the gage, tributary inflow, or diversion point; PTAB is flow above the gage, tributary inflow, or diversion point; and FLOW is flow value.

Table 4.3. USBR PTFLOW Model Input Requirements

ISTUDY :	STUDY NUMBER
ISTART :	FIRST CALENDAR YEAR OF STUDY
IEND :	LAST CALENDAR YEAR OF THE STUDY
NG :	NUMBER OF LINE GROUP HEADINGS
NL :	NUMBER OF LINE HEADINGS
NC :	NUMBER OF CONSTANT 'CDATA' VALUES (MILE LOCATIONS)
NA :	NUMBER OF AVERAGE MONTHLY 'ADATA' CONSTANTS
NH :	NUMBER OF MONTHLY INPUT 'HDATA' TO BE READ
IFRST :	FIRST CALENDAR YEAR OF INPUT DATA
NYI :	NUMBER OF YEARS OF 'HDATA' TO BE READ
NCL :	NUMBER OF COMMENT LINES TO BE READ
NPT :	FLAG TO READ 'HDATA' ONE YEAR AT A TIME. (0-NO/1-YES)
IUNIT :	OUTPUT IN CFS OR AF (0-AF/1-CFS)
NTAB :	NUMBER OF SUMMARY TABLES
IRTAB :	NUMBER OF REACH BALANCE TABLES
TBMIL :	MILE MARKER FOR GENERATING SUMMARY TABLE
IRBEG :	MILE MARKER TO BEGIN REACH BALANCE TABLE
IREND :	MILE MARKER TO END REACH BALANCE TABLE
ITBEL :	ELEMENT CODE FOR GENERATING SUMMARY TABLE GAGE FLOW : 1 POINT FLOW AB TRIB OR DIVERSION : 2 TRIBUTARY INFLOW : 3 DIVERSION : 4 REACH GAIN : 5 POINT FLOW BL TRIB OR DIVERSION : 6
IGROUP :	NUMBER LINES TO BE PRINTED AFTER EACH LINE GROUP HEADING
TITLE :	TITLE CARDS (2 LINES)
COMMENT:	COMMENT CARDS (NUMBER SPECIFIED BY NCL)
CDATA :	CONSTANT MILE LOCATIONS
OP :	ALPHA CODE FOR TYPE OF HDATA THAT WILL BE INPUT AT EACH LOCATION
CNAME :	CDATA DESCRIPTION

Table 4.4. USBR PTFLOW Model Input Database Structure

1. Constant Mile Data Location:

```
CDATA OP  CNAME  (F10.0,A1,10A4)
 101.6* KERSEY GAGE
 103.6- HOOVER CANAL
 119.7+ RIVERSIDE OUTLET CANAL
```

2. Monthly Input Flow data:

CDATA	Mon1	Mon2	Mon3	Mon4	Mon5	Mon6	Mon7	Mon8	Mon9	Mon10	Mon11	Mon12
101.631	28.5	21.2	28.1	23.0	31.7	24.4	7.2	8.2	8.2	12.7	24.8	33.4
103.631	.0	.0	.0	.0	.3	.3	.0	.0	.1	.6	.4	.0
106.531	4.7	11.2	7.3	2.8	.0	.0	.0	.0	.0	.0	.0	8.5
107.331	29.6	8.4	6.1	5.8	6.5	1.6	1.1	1.1	.8	2.0	11.8	15.6
114.431	.0	4.8	2.0	6.8	10.0	11.9	7.2	7.2	7.0	12.0	12.9	.0

CHAPTER 5

DATA BASE MANAGEMENT AND GIS

5.1 Role of GIS in SAMDSS

Geographic information systems (GIS) provide a number of concepts and tools which have become essential in the implementation of an effective water management decision support system. A few of the characteristics often attributed to GIS (Loucks, et al., 1985b; Goulter and Forest, 1987) include: the ability to display and graphically summarize data input and output, improve data input and editing, provide an effective interface between models, modelers and data bases, and improve comprehension of spatial and time varying information.

GIS software can be classified as vector based or raster based. Vector based software describes all entities as points, lines, or polygons which can be specified by geographical coordinates. Associated data located in a separate data base can be linked to each entity. Raster based software uses a grid system, with each cell assigned a single representative attribute. Vector based software is attractive for plotting maps and presentation of data base attributes. The raster format is useful for combining and analyzing different categories of information. Both formats are required for proper GIS management. SAMDSS integrates several GIS and spatial analysis tools and software packages such as AUTOCAD (CAD/CAM, vector), IDRISI (raster), and SURFER (surface modeling). A number of support utilities were written to convert USGS DLG, USGS DEM, and TIGER files into AUTOCAD DXF and IDRISI file format. The USGS General Cartographic Transformation Package (GCTP) was modified to support AUTOCAD DXF file format.

GIS procedures and techniques are used to:

- transform coordinates between geometric (latitude-longitude), Universal Transmercator, and Albert systems for use in AUTOCAD; the USGS Coordinate Transformation Package was modified for use with DXF file format for this purpose.
- read and process commercially available digitized map files; the WRTIGER, DLG, and CONVERT programs were written for this purpose.
- transfer GIS related data between various software packages; ACDTOIDR.lsp, VECDIST.lsp, VECWIDTH.lsp, IDRSS.exe, SURF.exe, and MODCOEF.exe were written for this purpose.
- digitize, edit, present, analyze, and geocode vector data using AUTOCAD.
- convert vector files to raster images using IDRISI.
- convert contour data to digital elevation grid format using IDRISI and SURFER.
- convert point data to digital elevation grid model format using kriging or distance weighted averaging using IDRISI or SURFER.
- map algebra through overlays, reclassification, summary, group selection, and data manipulation using IDRISI, AUTOCAD, DBASEIV, and QUATTRO PRO.
- prepare input files for use in the finite difference groundwater flow models MODFLOW and MODRSP using IDRISI and DBASEIV.
- estimate actual grid cell river reach lengths using AUTOCAD.
- assign attribute data to vector based points, lines, or polygons using AUTOCAD.

5.2 Data Sources

One of the aims in the design of SAMDSS is to create the ability to link with external computerized data bases developed by local, state and federal government agencies involved in data collection and distribution of water related information. The USGS and the Census Bureau are the primary government agencies involved in digitizing maps and preparation of coordinate linked geographical data bases. The USGS and EOSAT (1990), a private government contractor, are responsible for LANDSAT maps. The USGS and the USEPA have formal water related data bases such as WATSTOR and STORET. The U.S. Soil Conservation Service maintains maps and digitized data records on soil classification, land cover, drainage and runoff potential. Most states have a department of water resources, a division of natural resources, or a department of agriculture which maintains irrigation and water related data records. Most irrigation and water conservancy districts, cities, and ditch companies also support computerized data bases.

A large amount of digital data are available for most locations throughout the United States, and these data can be used directly in the SAMDSS:

5.2.1 Digital Elevation Model (DEM): USGS

USGS DEM data consist of arrays of regularly spaced elevations:

- **7.5-minute**
  source: interpolation from stereo model digitized contours used for 7.5 minute topographic maps; DLG hypsography and hydrography.
  coverage: 7.5 minute topographic map (1:24,000)
  coord. system: UTM (NAD 27)
  spacing: 30 meters
  accuracy: 15 meters

- **1-degree**
  source: topographic maps ranging from 7.5-minute to 1 by 2 degree series.
  coverage: 1 degree by 1 degree; 1/2 block of 1 by 2 degree topographic map (1:250,000)
  coord. system: Lat-Long (WGS)
  spacing: 3 arc seconds latitude; 3 arc seconds longitude; 1201 elevations per profile
  accuracy: 130 meters horizontally and 30 meters vertically

5.2.2 Digital Line Graphs (DLG): USGS

USGS DLG data are digital representations of cartographic information, with options of 80 byte record lengths and UTM coordinate system:

- **large-scale**
  source: 7.5 minute topographic maps (1:24,000)
  coverage: 7.5 minute topographic map; 60 square miles; 6-1/2 miles wide by 9 miles high; 1 inch = 2000 ft

content: nine categories: hypsography (contours), hydrography (water), vegetative surface cover, non-vegetative, boundaries, survey control markers, transportation, manmade features, and U.S. Public Land Survey System (township, range, section).
structure: vector format: points, lines, and areas with associated attribute codes

- **intermediate-scale**
  source: 30 by 60 minute topographic maps (1:100,000)
  coverage: 30 by 30 minute; 1/2 block of 30 by 60 minute topographic map; distributed as four 15 by 15 minute cells or 16, 7.5 by 7.5 minute cells; 789-1083 square miles
  content: nine categories: hypsography (contours), hydrography (water), vegetative surface cover, non-vegetative, boundaries, survey control markers, transportation, manmade features, and U.S. Public Land Survey System (township, range, section).
  structure: vector format: points, lines, and areas with associated attribute codes

- **small-scale**
  source: National Atlas maps (1:2,000,000)
  coverage: 1:2,000,000 map; sold in multi-state units.
  content: three categories: hydrography, boundaries, and transportation.
  structure: vector format: points, lines, and areas with associated attribute codes

5.2.3 Land Use and Land Cover (LULC): USGS

The USGS LULC data base provides information on urban or developed land, agricultural land, range land, forest land, water, and wetlands.

scales: 1:250,000 or 1:100,000
content: nine major classes: urban, agricultural land, rangeland, forest land, water areas, wetland, barren land, tundra, perennial snow; each major class composed of several minor classes (i.e., streams, canals, lakes, reservoirs, bays, and estuaries); associated map data consist of separate files on political units, census tracts, hydrologic units, and federal land ownership.
structure: vector (GIRAS) or composite theme grid cell polygon (CTGC) format with associated attribute codes, with the latter divided into four hectare (10 acre) cells.

5.2.4 Geographic Names Information System (GNIS): USGS

The USGS GNIS automated data system standardizes and disseminates information on geographic names:

- *National Geographic Names Data Base (State)*:
  State files on towns, schools, reservoirs, etc., found on USGS topographic maps; 15 descriptive elements, including geographic coordinates.
- *National Atlas Data Base (Concise):*
  Contains information on geographic names in the National Atlas of the U.S., including geographical coordinates.

5.2.5 LANDSAT: USGS/EOSAT

The USGS/EOSAT LANDSAT data are Multispectral Scanner (MSS) satellite photos:

coverage: 185 x 170 km for full scene; 3484 pixels by 2983 lines for each quadrant; 80 meter interval.
options: available as LTWG CCT BSQ, BIL, or Band Interleaved by Pixel-Pair (BIP-2); 4 bands

5.2.6 Topographically Integrated Geographic Encoding and Referencing System (TIGER): Census Bureau

The Census Bureau TIGER line files are a compilation of digital maps of the entire U.S., with an accompanying data base that integrates accurate map data with related geographic information and population statistics.

application: for use with general geographic planning and demographic studies, rather than detailed engineering studies.
source: urban areas: Census Bureau Dime files, which compile information from city and county maps.
rural areas: USGS 1:100,000 maps, which are more accurate than Dime files.
coverage: by county
content: five feature categories: roads, railroads, pipelines, hydrography, and political boundaries; types of associated data include feature names, political boundaries, Census geography, address range, zip codes.

5.3 Data Conversion

Since most software packages have there own own unique data input file formats, use of data compiled or developed in another software format normally requires some type of data transformation. The better commercial software packages generally contain data export and import modules for enhancing compatibility. AUTOCAD requires a DXF file format, whereas IDRISI provides a number of modules for converting various data types such as DLG, CTGC, AUTOCAD, ARCINFO, and LANDSAT.

The U.S. Bureau of Census TIGER files (Bureau of the Census, 1989) provide invaluable data for use in the Stream-Aquifer Management Decision Support System (SAMDSS). Figure 5.1 shows steps used to extract digital map data from TIGER files for import into AUTOCAD. TIGER files are available on CDROM for the entire United States. Each CDROM holds a single state, with data listed by county. Of the six files or *Record Types*, only the first two are necessary to develop digital maps:

- basic data records (individual feature segment records)
- shape coordinate points (feature shape records)

Each segment record contains a unique 10-digit record number, a feature class code, and beginning and ending latitude/longitude coordinates. The feature shape records contain the unique 10-digit record number and the intermediate latitude/longitude coordinate values that describe the shape of those feature segments that are not straight. Two files must be linked and written to a DXF file for use with AUTOCAD, with each segment coded as an AUTOCAD polyline and associated with an AUTOCAD layer corresponding to the feature class code. This is the purpose of the WRTIGER program. WRTIGER requires that the record 1 file be named TIGER1 and the record 2 file be named TIGER2. Output is to a file called TIGOUT.dxf. Because of the original format for the TIGER files found on the CDROM they must be converted from files with record length of 228 byte to record lengths of 80 byte. The CONVERT.exe program does this. It is important to sort both of the TIGER record files before running WRTIGER.exe. Each file should be sorted on the 10-digit record number, which was accomplished using DBASEIV for this study. Once the DXF file has been prepared it can be imported directly into AUTOCAD for viewing.

A conversion program DLG.exe was written to transfer USGS optional format DLG files to AUTOCAD DXF format files. Use of DLG.exe requires the input file be named DLG1 and have a record length size of 80 bytes, with output going to a file called DLG.dxf. The Program CONVERT can be used to assign variable length records to the 80 byte record length format required by DLG.exe. Details on digital line graph types and file structure can be found in the USGS National Mapping Technical Instructions Data Users Guide 1-3 (USGS, 1990a,b,c).

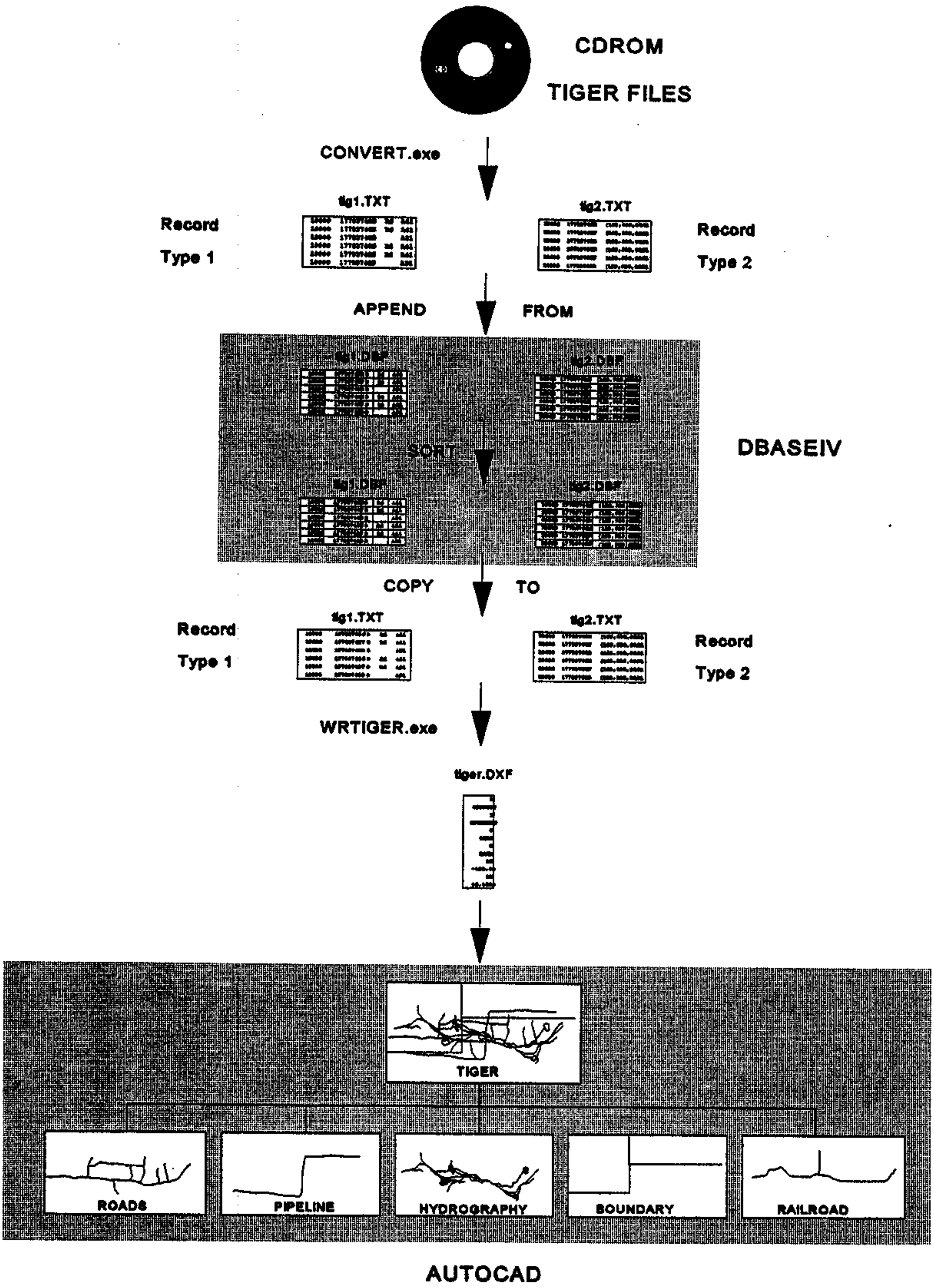


Figure 5.1. Procedures for Converting TIGER Files into AUTOCAD DXF Format

5.4 Using GIS to Prepare Data for MODFLOW/MODRSP

One useful application of GIS is in the preparation and processing of data for input into MODFLOW, the USGS Modular Three-Dimensional Finite Difference Grjoundwater Flow Model. Table 4.1 listed MODFLOW data requirements and indicated the types of data that can be generated through GIS. Specific details on how GIS can be used for preparation and presentation of data for use in a finite difference groundwater model are given in Appendix B.

Well data represent an important data type stored in public domain databases, as shown in Figure 5.2. Examples of public domain databases are the USGS Ground Water Site Survey Database (GWSI) or the Colorado State Engineer Office Well File. Typical data available from these databases are: depth of well, ground surface elevation at well, specific capacity, transmissivity, well location, pumping capacity, seasonal water levels, and well use.

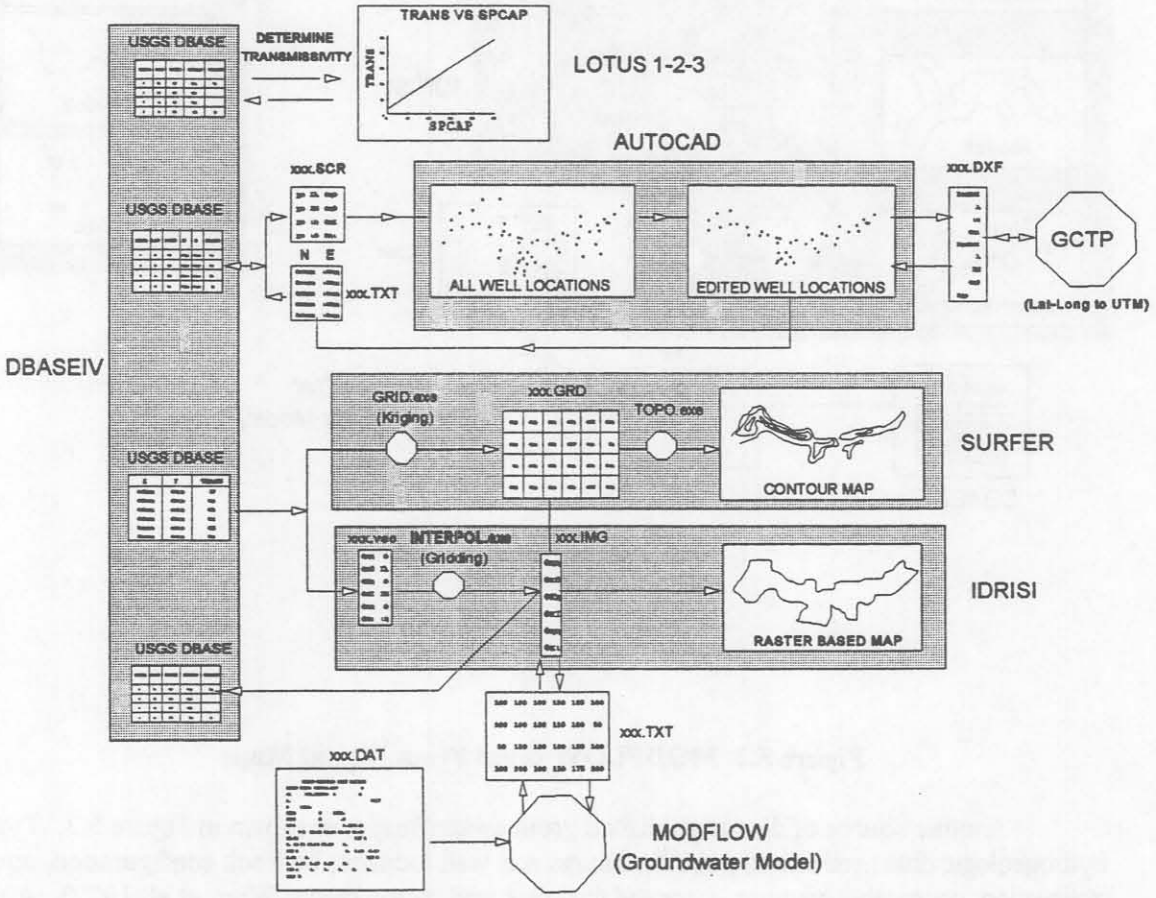


Figure 5.2. MODFLOW Input from Database

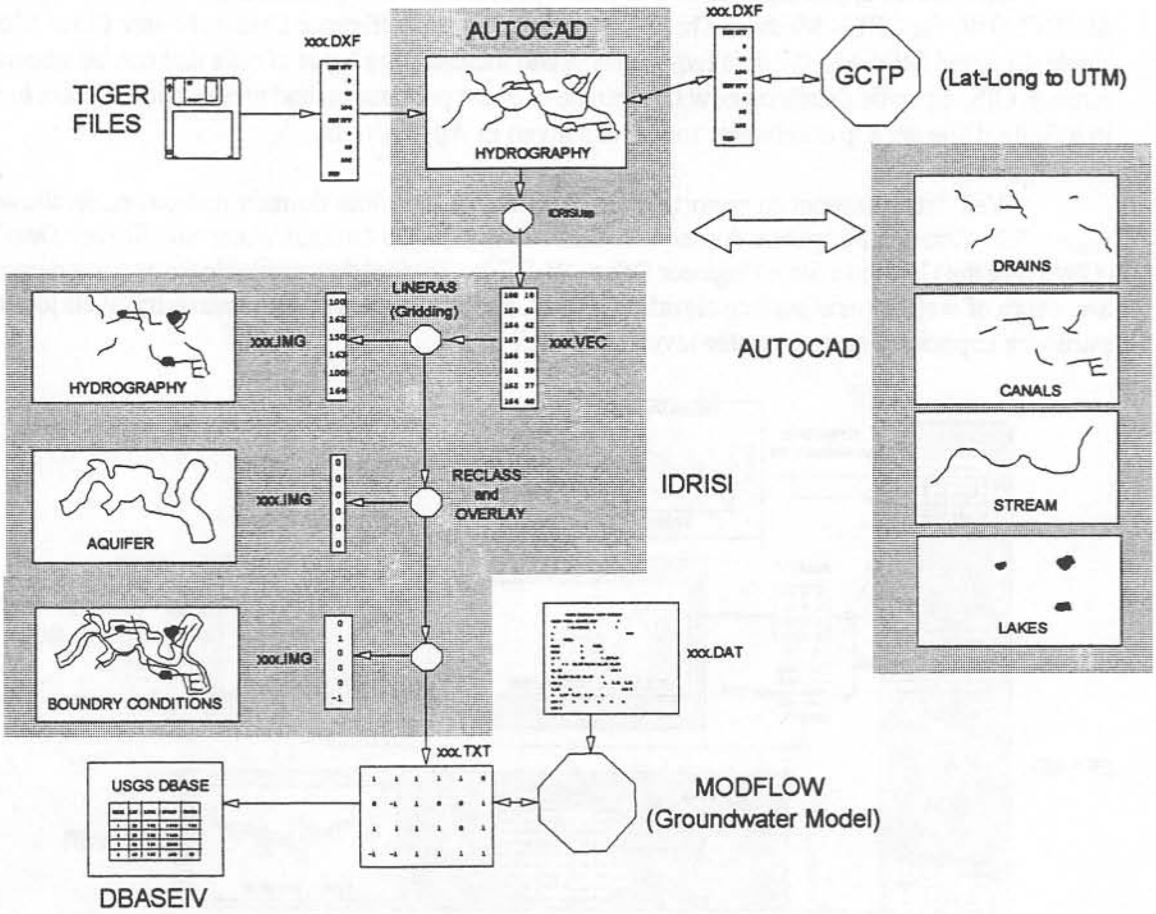


Figure 5.3 MODFLOW Input From Digital Maps

Another source of data is published groundwater maps, as shown in Figure 5.3. Typical hydrogeologic data available as published maps are: well location, bedrock configuration, aquifer delineation, water table contours, saturated thickness, and transmissivity (Hurr, et al.,1972). A third source of data is digital maps and related data, as presented in Figure 5.4. Examples of these types of data are Department of Census Topographically Integrated Geographic Encoding and Referencing System (TIGER) for hydrography, roads, and political boundaries; USGS Digital Elevation Model (DEM) for ground surface elevations; USGS Digital Line Graphs (DLG) for hydrography, roads, public land survey, and contours; USGS Land Use and Land Cover (LULC) for nine major land classes such as urban, agricultural, etc.; USGS LANDSAT data, USGS AVHRR Vegetative Index data; and SCS soil classification maps.

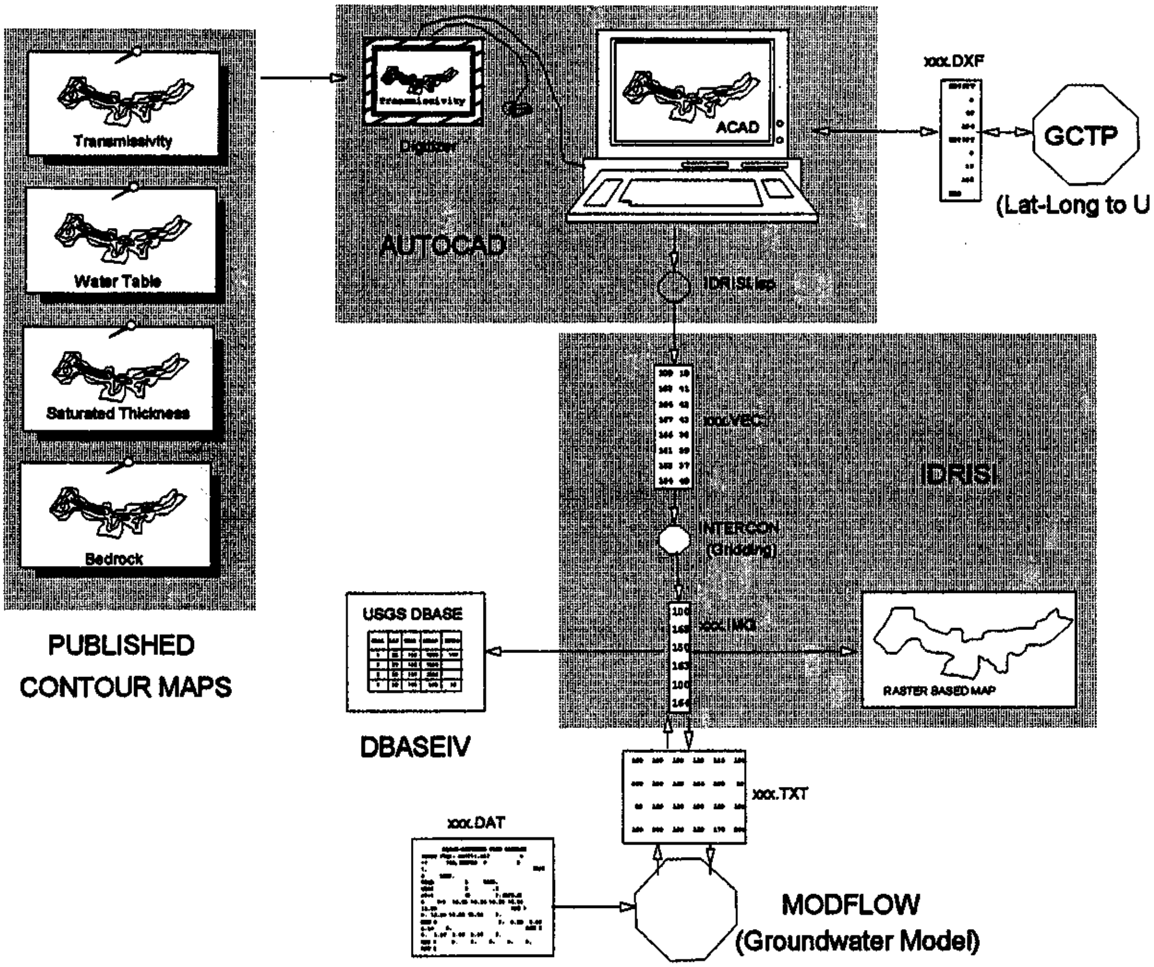


Figure 5.4 MODFLOW Input From Published Maps

5.5 Generating Stream-Aquifer Response Coefficients Using MODRSP

SAMDSS uses MODRSP (Maddock and Lacher,1991a) to generate stream-aquifer response coefficients based on a finite difference numerical solution to the groundwater flow problem. The general procedures required to generate spatially distributed stream-aquifer response coefficients for use in a stream-aquifer management model are shown in Figure 5.5. Detailed procedures can be found in Appendix C.

GIS and DBMS procedures are powerful tools that are well suited for preprocessing data for use with MODRSP. Aquifer transmissivity, boundary, well, and river input data files used by MODRSP can all be prepared using GIS and DBMS procedures.

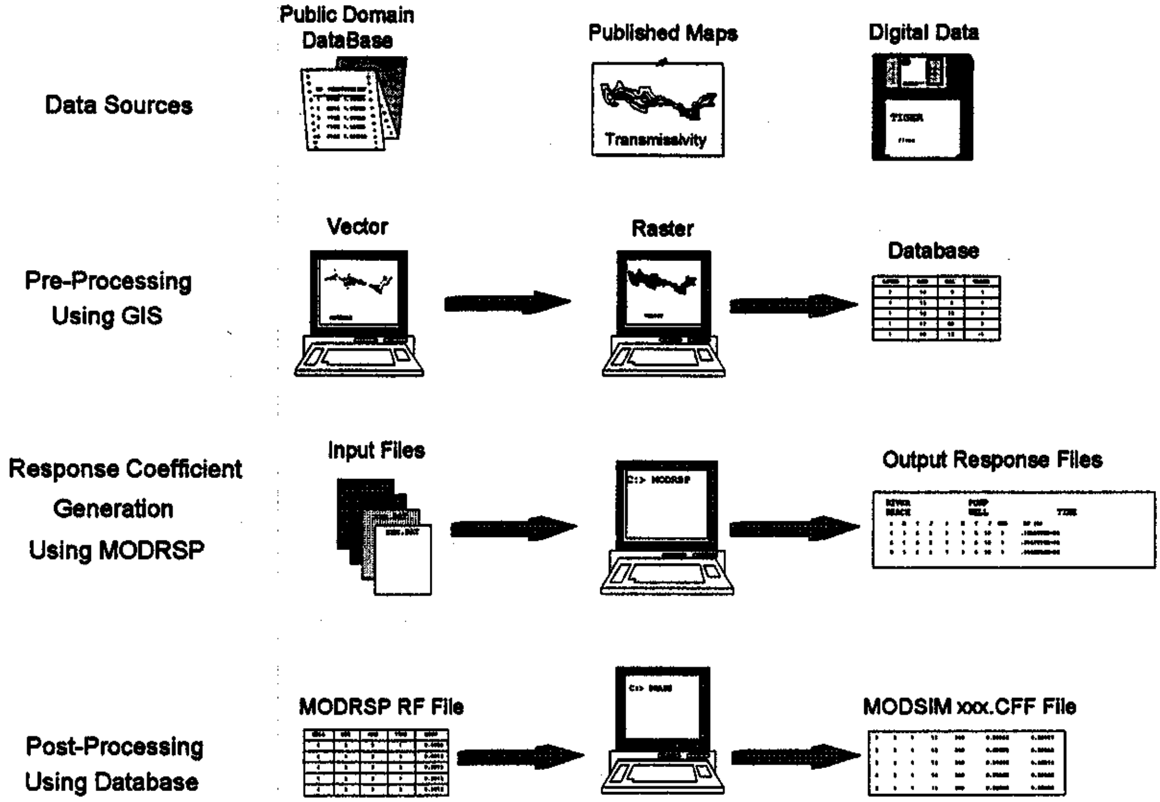


Figure 5.5 Using MODRSP to Create Response Coefficients

The procedures for preparing an aquifer transmissivity file are shown in Figure 5.6. Assuming that transmissivity contour maps are available, SAMDSS uses AUTOCAD software to digitize these data. The data are then written as IDRISI vector files and converted to IDRISI raster format. IDRISI commands can then be used to interpolate between the contour line values and assign transmissivity values to each grid cell. The IDRISI output file can be read directly into MODSRP.

The groundwater system boundary data used by MODRSP requires that each finite grid be assigned a boundary value:

No flow:		0
Constant head:	<=	-1
Underflow:	>=	+1

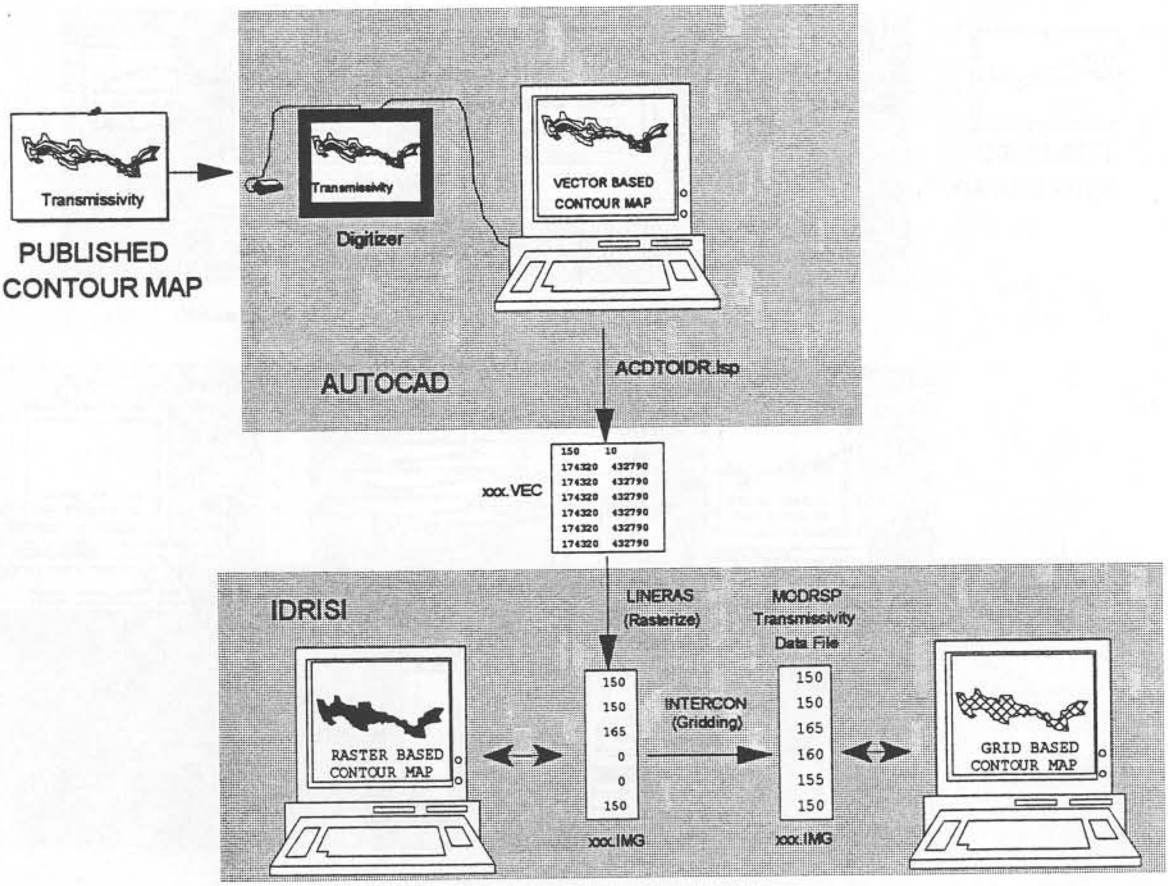


Figure 5.6 MODRSP Transmissivity File

A raster based aquifer file must first be developed designating those cells inside the aquifer (+1) and those outside (0). This file is then combined with a separate raster file identifying the aquifer cells that are reservoirs, ponds, or perennial streams. For the example shown in Figure 5.7, it is assumed that aquifer boundary data are available from a published map which can be digitized into AUTOCAD. The hydrography data are read into AUTOCAD from TIGER files. Two separate IDRISI vector files are first created from the AUTOCAD data, then processed into raster format, and finally overlain using IDRISI software. The IDRISI output raster file is in a format that can be read directly by MODRSP.

MODRSP requires a well file to identify the location of each cell in the finite difference model for which response coefficients are to be generated. In a groundwatermanagement model, these grid related response coefficients can represent a single well, several wells located within a grid, or be combined with response coefficients developed for other grids to model return flows from groundwater recharge, reservoir seepage, or channel loss.

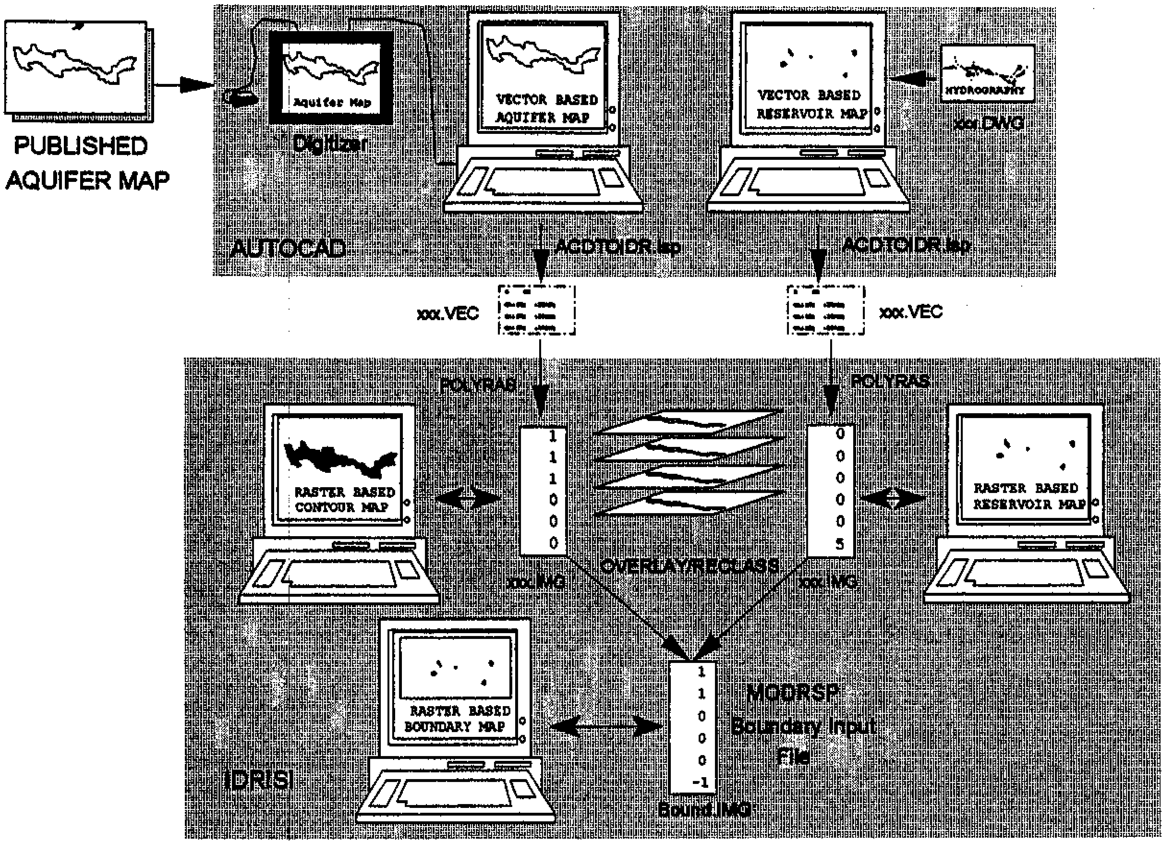


Figure 5.7. MODRSP Boundary File

The steps required to develop a MODRSP well file are shown in Figure 5.8. The example assumes that well or recharge locations are available from published maps and non-geographical related data are available from a separate computer database. The well file used by MODRSP requires the number of wells and their row/column locations. The process of identification of row/column grid locations for a single well is different than for a reservoir or a channel. Well data are treated as point data, and can be associated with a single grid cell. In situations where more than one well is located in the same grid cell, the response coefficients can be generated for the grid cell and assigned to all wells in the grid. Channels or drains are treated as line data, and must generally be represented by more than one grid cell. Response coefficients are generated for each grid cell occupied by the channel. The results are added together to form one set of response coefficients. Reservoirs and ponds are treated as polygons. They also usually cover more than a single grid cell, and the response coefficients generated for a single cell must be combined into a single set. In all cases, it is important that each well, channel, or reservoir be assigned a unit number and that response coefficients generated for a grid cell can be identified with this unit number using DBMS procedures.

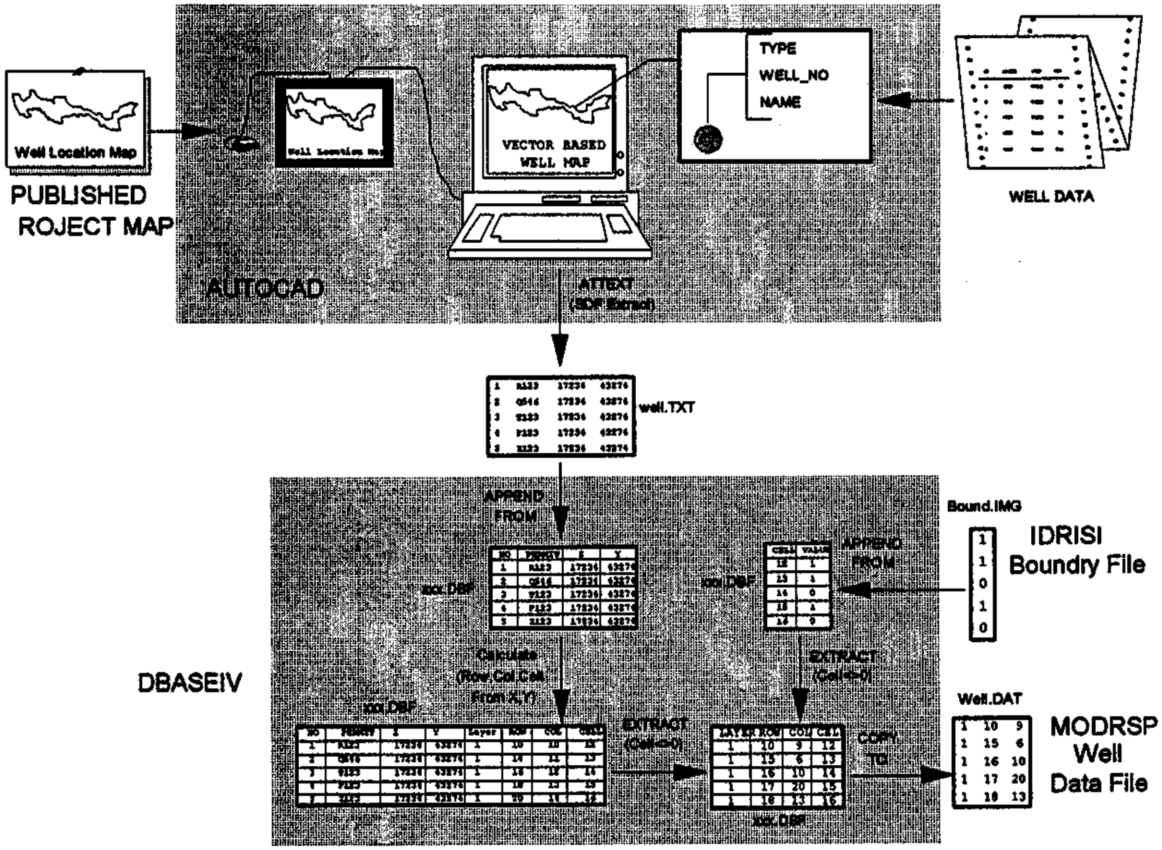


Figure 5.8. MODRSP Well File

To determine return/depletion flow effects on a stream, MODRSP requires a river input file. Procedures for preparing a MODRSP river input file are shown in Figure 5.9. The river data file provides the number and location of river segments in the finite difference model. Each grid containing a river cell must be labeled in the river file by layer, row, and column. A streambed conductance must also be assigned to each river cell. MODRSP calculates a series of time based response coefficients at each river cell location as a result of unit pumping in each cell listed in the well file.

Since a river reach may be represented by more than one grid cell, it is generally necessary to combine response coefficients from several grid cells into a single set for use in a groundwater management model. For this reason, it is important to record which grid cells are associated with which river reaches. Streambed conductance must be calculated outside of MODRSP. GIS and DBMS techniques are useful for generating and managing this type of information.

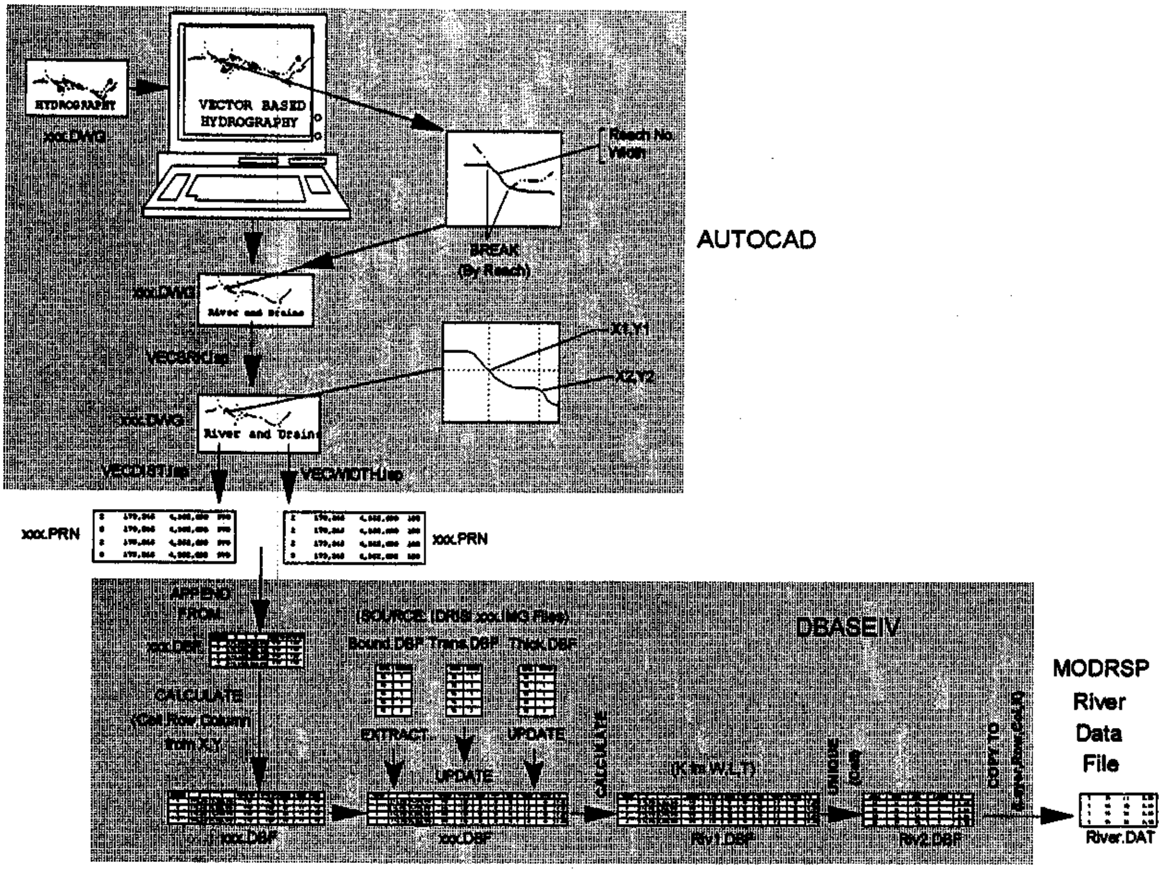
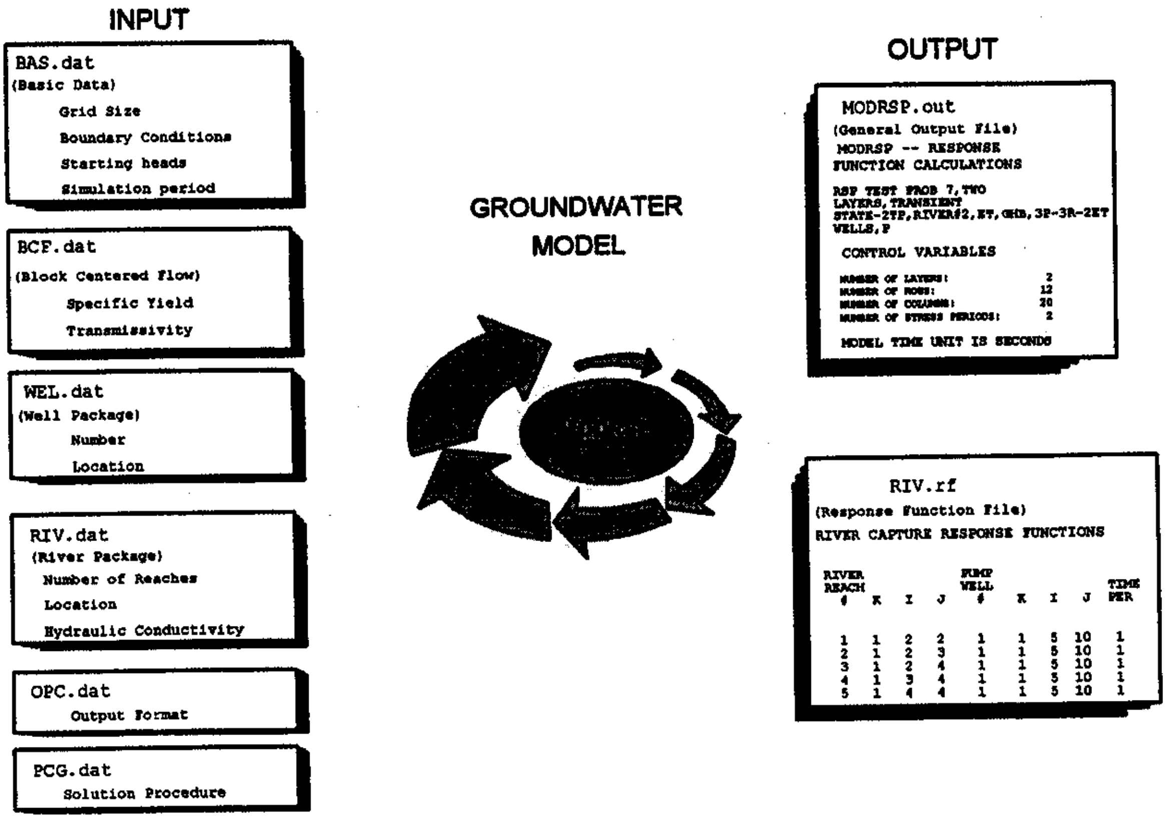


Figure 5.9. MODRSP River File

In this example it is assumed that river and stream hydrography data can be read from TIGER files, River conductance can be expressed as a function of stream width, aquifer saturated thickness, grid reach length, and aquifer transmissivity. Stream width data are available from cross-section surveys, and saturated thickness and transmissivity contour maps are also available.

Figure 5.10 shows the input and output files used by MODRSP for generating stream-aquifer response coefficients. Input and output requirements are described in a well documented MODRSP user manual (Maddock and Lacher,1991b).

To execute the program, the user simply types MODRSP at the DOS prompt. The screen clears, the title MODRSP appears, and the user is prompted to supply the names of the various modules input and output file names, as shown in Figure 5.11.



```
MODRSP -- RESPONSE
FUNCTION CALCULATIONS

RSP TEST PROB 7,TWO
LAYERS,TRANSIENT
STATE-2TP,RIVER#2,ET,GHB,3P-3R-2ET
WELLS,P

 CONTROL VARIABLES

 NUMBER OF LAYERS:               2
 NUMBER OF ROWS:                12
 NUMBER OF COLUMNS:             20
 NUMBER OF STRESS PERIODS:       2

 MODEL TIME UNIT IS SECONDS
```

```
RIVER CAPTURE RESPONSE FUNCTIONS

RIVER                   PUMP
REACH                   WELL                    TIME
  #     K    I    J      #     K    I    J      PER

  1     1    2    2      1     1    5   10      1
  2     1    2    3      1     1    5   10      1
  3     1    2    4      1     1    5   10      1
  4     1    3    4      1     1    5   10      1
  5     1    4    4      1     1    5   10      1
```

Figure 5.10. Executing MODRSP

```
                                         MODRSP

MAIN OUTPUT FILE (ODF)        ON UNIT 36       ASSIGN TO FORMATTED FILE: MDRSP.OUT
BAS                           ON UNIT 35       ASSIGN TO FORMATTED FILE: RBAS
BCF                           ON UNIT  2       ASSIGN TO FORMATTED FILE: RBCF
WEL                           ON UNIT  3       ASSIGN TO FORMATTED FILE: RWEL
RIV                           ON UNIT  9       ASSIGN TO FORMATTED FILE: RRIV
      RIVER CAPTURE RF        ON UNIT 54       ASSIGN TO FORMATTED FILE: RIV.RF
PCG                           ON UNIT 13       ASSIGN TO FORMATTED FILE: PCG
BOUNDARY ARRAY                ON UNIT 25
OPC                           ON UNIT 12       ASSIGN TO FORMATTED FILE: OPC
ROW TRANSMISSIVITY            ON UNIT 26
```

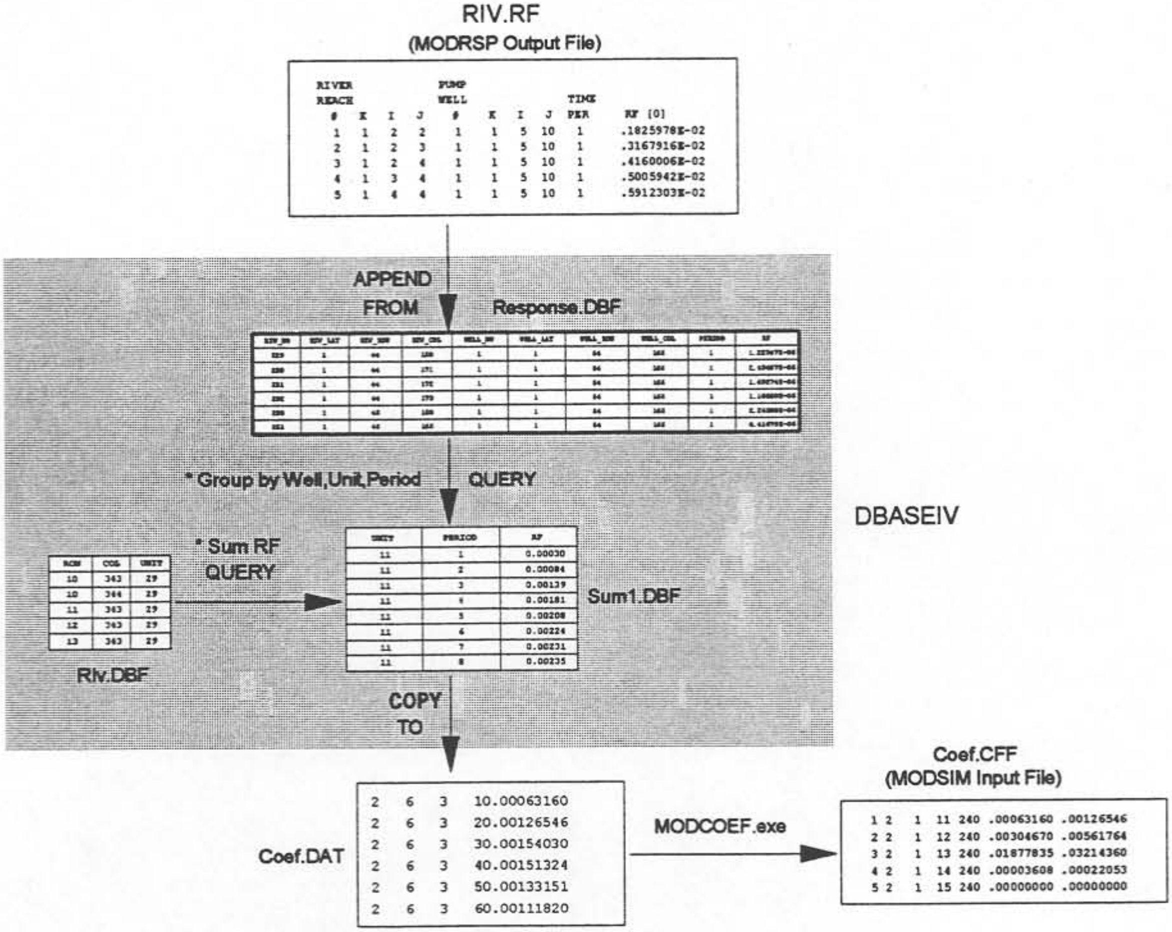
Figure 5.11. MODRSP Input Screen

The number of output files created by MODRSP depends on the packages being used. For stream-aquifer functions where only river response is being calculated, only two output files are created: the main output file (MDRSP.OUT) and the river response file (RIV.RF), which is the river response file containing the groundwater response coefficients.

The procedures used to post-process MODRSP response file data for use in MODSIM are summarized in Figure 5.12. The coefficients output from MODRSP represent groundwater flow responses over a user defined time period at a single river grid due to the pumping of a unit discharge for a single period at a single well. These results must be summarized by river reach and by source before they can be used in a stream-aquifer management model. This can be a one, two, or three step process depending on whether each record in the well data file represents a single well a segment of channel reach or reservoir, or if more than one well is located in a grid cell. MODRSP determines the effects of well pumping on individual river reach grid cells. Usually most river reaches will be made up of a number of grid cells. Data base concepts can be used to summarize MODRSP response coefficients by river reach.

For reservoirs or channels where more than one cell grid is used to represent the reservoir or channel system, the response coefficients of several grids can be superimposed. Input of the response coefficients generated by MODRSP into a MODSIM river basin network requires preparation of a node source file and a node river reach reference file. These files should each have two fields: one with a MODRSP well or reach number and the other with the corresponding MODSIM node number. Using database techniques, the well and reach numbers assigned by MODRSP in the response output files can be linked with the node reference files and the MODRSP unit numbers can be replaced with the proper MODSIM node values.

The groundwater response coefficient file required by MODSIM can be created by running the Program MODCOEFF.exe using the well response file created from MODRSP as input, which produces a MODSIM response coefficient file.



```
RIVER              PUMP
REACH              WELL              TIME
  #   K   I   J     #    K   I   J   PER      RF [0]
  1   1   2   2     1    1   5  10    1     .1825978E-02
  2   1   2   3     1    1   5  10    1     .3167916E-02
  3   1   2   4     1    1   5  10    1     .4160006E-02
  4   1   3   4     1    1   5  10    1     .5005942E-02
  5   1   4   4     1    1   5  10    1     .5912303E-02
```

ROW	COL	UNIT
10	343	29
10	344	29
11	343	29
12	343	29
13	343	29

UNIT	PERIOD	RF
11	1	0.00030
11	2	0.00084
11	3	0.00139
11	4	0.00181
11	5	0.00208
11	6	0.00224
11	7	0.00231
11	8	0.00235

```
2   6   3   10.00063160
2   6   3   20.00126546
2   6   3   30.00154030
2   6   3   40.00151324
2   6   3   50.00133151
2   6   3   60.00111820
```

```
1 2   1  11 240 .00063160 .00126546
2 2   1  12 240 .00304670 .00561764
3 2   1  13 240 .01877835 .03214360
4 2   1  14 240 .00003608 .00022053
5 2   1  15 240 .00000000 .00000000
```

Figure 5.12. MODSIM Coefficient File

CHAPTER 6

CASE STUDY: LOWER SOUTH PLATTE RIVER BASIN

6.1 Purpose

A case study is presented for a portion of the Lower South Platte River Basin, Colorado, in order to demonstrate the capabilities of the Stream Aquifer Management Decision Support System (SAMDSS). The case study was carried out with the following purposes:

- conduct a resource inventory to determine sources and types of data available for a conjunctive use decision support system
- develop stream-aquifer response coefficients for the study area using GIS and a finite difference groundwater flow model
- simulate the water right return/depletion flow accounts for a groundwater augmentation plan
- simulate daily administration of a river regulated under prior appropriation water right laws
- present procedures for integrating a groundwater augmentation plan with daily administration of water rights

6.2 Study Area Description

The South Platte River begins in the Rocky Mountains of central Colorado and flows northeast across the Great Plains, joining the north branch of the Platte River in Nebraska and eventually draining into the Missouri River. The total drainage area of the basin is 24,000 square miles with 80% located within the State of Colorado. The Lower South Platte basin represents the section of the river from the Denver gaging station to the Julesburg gaging station at the Colorado-Nebraska border (Figure 6.1).

The Lower South Platte basin has a semi-arid climate with an average annual precipitation of 16 inches, with 70-80% occurring as summer rainfall. Other features include warm summers, cold winters, low humidity, abundant sunshine, considerable wind, frequent tornadoes and hailstorms. The average July temperature is about 74°F and the average January temperature is 25°F with temperatures ranging from 108 to -33°F.

The Lower South Platte basin consists of rolling hills and valleys. The study area is underlain by unconsolidated fill deposits from the Pleistocene and recent age consisting of mixtures of clay, silt, sand, and gravel. The alluvium has been deposited in a broad channel eroded into a bedrock formation of sedimentary rocks ranging in age from Cretaceous to Pliocene. The formations include Pierre shale, Fox Hills sandstone, and Laramie, Chadron, Brule, and Ogallala formations.

Since the bedrock formations are relatively impermeable, the valley fill alluvium contains an unconfined aquifer with a water table sloping toward the South Platte River from both sides of the valley. The alluvial aquifer ranges from one to nine miles in width, with aquifer water depths from 10 to 100 feet, saturated thickness depths up to 240 feet, aquifer transmissivity

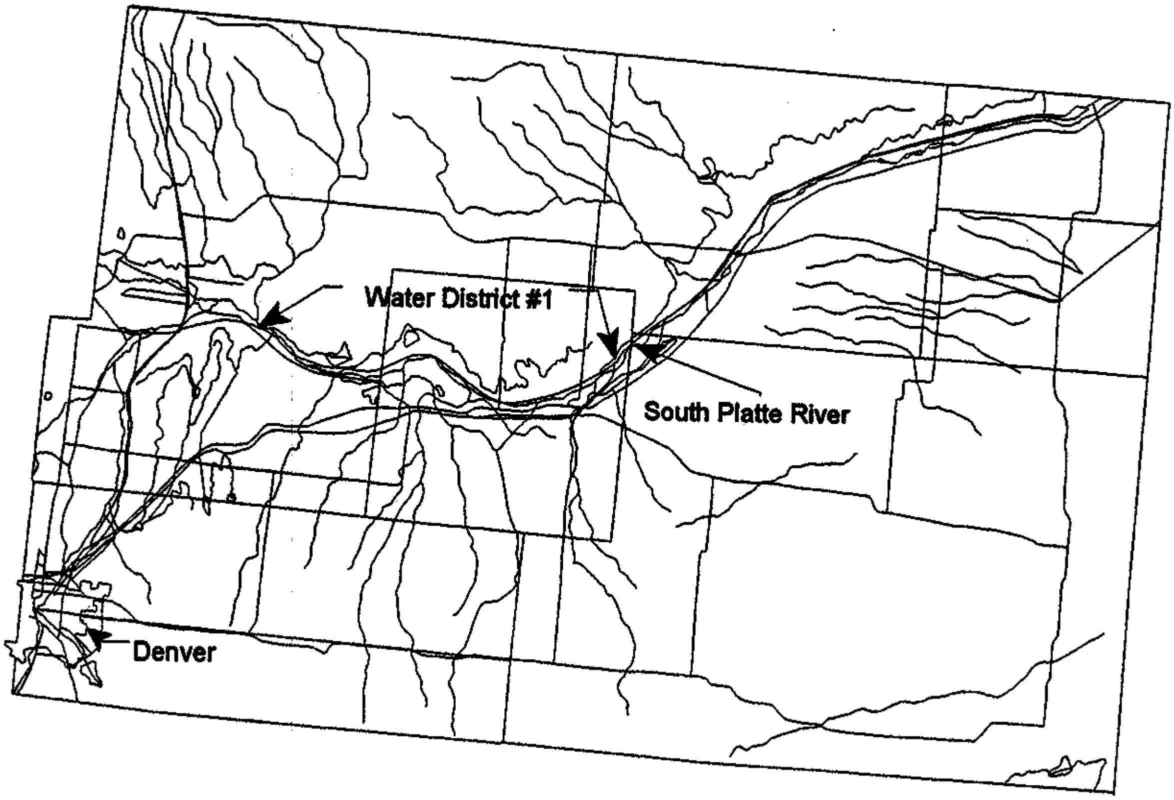


Figure 6.1. Map of Lower South Platte River Basin, Colorado; Source: USGS 1:2,000,000 DLG Data

up to 1,200,000 gal/day/ft, average specific yield of 0.16, and an aquifer storage capacity estimated at 3.5 million ac-ft (Hurr et al., 1975).

The primary source of natural streamflow in the basin is from snowmelt, with 70-80% occurring during the months of April through July. South Platte flow data for the period 1931 through 1983 are available as part of the South Platte Point Flow Study (USBR, 1989). Annual flows in the Lower South Platte at the Denver gaging station averaged 230,000 acre-feet per year for the 53 years of data. The average annual outflow at the Nebraska-Colorado border was 360,000 acre-feet per year. Annual river diversions for the Lower South Platte were 1,150,000 acre-feet per year, with tributary inflows estimated at 480,000 acre-feet per year. Return flows, primarily due to irrigation recharge to the aquifer, are estimated at 750,000 acre-feet per year (USBR, 1989). Although streamflow in the South Platte is variable seasonally, annually, and spatially, it is generally an effluent or gaining stream.

Irrigation is the primary consumptive use of water in the Lower South Platte River basin. Typical irrigated crops include corn, sugar beets, beans, and alfalfa, with the growing season generally from April to October. Recharge to the aquifer has been estimated at 50% of applied water on irrigated land (Hurr et al., 1975). A number of off-stream reservoirs have been constructed to store irrigation water, although it is estimated that 25-65% of reservoir water is lost to seepage and evaporation.

The Lower South Platte River basin currently lacks a significant on-stream storage project, although several projects have been proposed. The lack of in-stream storage has reinforced the need for development of integrated conjunctive use schemes in the basin for surface water and groundwater.

6.3 Water Rights Administration

Allocation of water in the study area is subject to the Doctrine of Prior Appropriation. The Office of the Colorado State Engineer (SEO) has the responsibility of administering all water in the State. The State is divided into water divisions, with each water division subdivided into water districts. The Lower South Platte River is in Division #1 and includes three water districts (1,2, and 64), not including tributaries. Each water district is under supervision of a Water Commissioner. The main branch of the Lower South Platte River from Denver to the Nebraska border extends for 260 miles, has 64 points of diversion and 138 major surface water rights (SPBWMC, 1989).

Division #1, Water District #1 covers a 70 mile stretch of the South Platte River from Kersey to Balzac (Figure 6.1). There are five reservoirs, 15 major river diversions, 35 major water right decrees, 11 major tributary inflows, and three active gage stations. Table 6.1 shows the distribution of water rights for District #1.

Since wells are included in the priority system, pumping is not allowed when a senior water right places a call on the river. To protect senior surface water rights and prevent the interruption of well pumping during the irrigation season, well owners are allowed to implement a groundwater augmentation plan. This allows replacement of well depletion flows through groundwater recharge, water exchanges, and water trades. Water District #1 has over 5000 decreed wells, 27 conditional or approved augmentation plans, and 32 monitored groundwater recharge sites (SEO database).

Table 6.1. W.D. #1 Cumulative Diversion Rights (SPBWMC, 1989)

Admin. Date	Diversion Rights
01/01/1860	0
01/01/1865	0
01/01/1870	5
01/01/1875	11
01/01/1880	17
01/01/1885	35
01/01/1990	65

6.4 Bijou Irrigation System

Bijou Irrigation Company operates one of the major irrigation systems in District #1. Complete details on the Bijou Irrigation System are available from the Bijou Irrigation System Plan of Augmentation Engineering Report (HRS, 1983). The Bijou system diverts irrigation water from the South Platte River into the Bijou Canal. The offtake is located 13 miles downstream of the Kersey gage station and just east of the town of Hardin. Surface water is delivered to laterals at various points along the main canal for irrigation and groundwater recharge. The Bijou Canal has a capacity of 600 cfs at the headgate and is 40 miles in length. The canal also carries releases from Empire Reservoir, exchange water, and inflow to Bijou #2 Reservoir. The Bijou system has an irrigated command area of 24,000 acres with 2,000 acres irrigated solely from surface diversions.

The average annual surface water supply to the Bijou Canal is 69,380 acre-feet (1960-1980). Water delivered into Bijou #2 Reservoir cannot be returned to the canal for irrigation purposes; however, it can be delivered to Bijou Creek for augmentation purposes. Remaining water in the reservoir is lost through evaporation and recharge to groundwater through seepage. Bijou Canal has up to 43% main canal conveyance losses and an estimated 35% loss below the headgate laterals. The average annual crop irrigation requirement for the system is 39,793 acre-feet (1960-1980). Ditch water supplies an annual average of 25,850 acre-feet, with the remaining water supply from pumping groundwater.

A groundwater augmentation plan for the Bijou Irrigation Company was prepared by HRS (1983) to replace depletions that would otherwise accrue to the South Platte River as a result of well pumping used to meet irrigation demands. A map showing the location of the various components of the augmentation plan is presented in Figure 6.2.

The Bijou Irrigation Company Augmentation Plan has an original appropriation date of 1972, which was updated in 1986. The plan involves 196 individual wells and a groundwater recharge program that includes recharge from Bijou Canal, Bijou Reservoir #2, several creeks, and a number of small recharge ponds. Effects on the South Platte River from pumping and recharge are determined for the augmentation plan using stream depletion factor (SDF) values taken from USGS SDF hydrogeologic maps (Hurr et al., 1972). The canal and creeks are divided into reaches based on average SDF values. The original augmentation plan used the USGS computer program SDFDEP (Hartwell, 1987) to determine stream accretion and depletion. The SDFDEP computer program uses the Glover analytical method (Glover,1977) to generate groundwater response coefficients. The original augmentation plan was prepared using historical data, with groundwater pumping estimated as that portion of calculated historical crop water requirement that could not be met through surface diversions. It was anticipated that records of measured recharge supplied to each site would be maintained on a regular basis and that well use would be estimated from crop water requirement calculations.

At the present time, a water right augmentation account is prepared for the Bijou system on a monthly basis by the Northern Colorado Conservancy Water District (NCCWD) and is submitted to the Office of the State Engineer (SEO) for use in administering water in the South Platte River. The current calculation procedure for preparing the water right account balance uses SDF recharge site values, measured channel inflow and outflow, and estimates of surface area evaporation to calculate monthly recharge credits. Account debits due to well pumping are estimated based on calculated irrigation crop demands minus irrigation water supplied through measured surface diversions. Irrigation demands are determined for each of the 200 wells. Blaney-Criddle evapotranspiration values are calculated from actual climatological data. Irrigated area, crop distribution, and cropping patterns are provided by the Bijou Irrigation Company members.

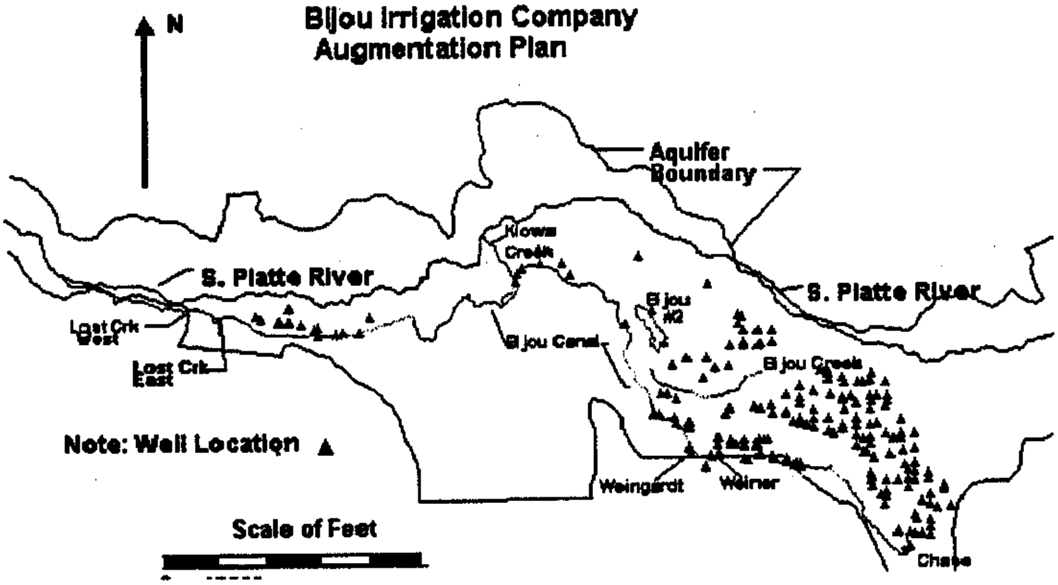


Figure 6.2. Bijou Irrigation Company Augmentation Plan

If during the irrigation season there is a call for water by a senior water right owner and the Bijou Augmentation account for the month shows a negative balance, then the Bijou Irrigation Company must provide supplemental water to the SEO to offset the negative balance, or face the possibility have having its member wells temporarily shut down. Supplemental water can come from exchanges, trades, and upstream reservoir releases.

6.5 Groundwater Management Issues

Important issues related to groundwater management in the basin include: stream depletion caused by wells operating under an augmentation plan; stream accretion resulting from recharge under augmentation plans; and the net effect on the river and its tributaries resulting from operation of wells and recharge projects. Because of lags in the response time between pumping and the resultant river depletion, pumping at a well site during the irrigation season may have minor affects on a river source during the irrigation months. It is possible that the major affects of well pumping during the irrigation season may not impact the river source until the off-season winter months when there is no irrigation call on the river by senior water right owners and therefore no legal consequences resulting from the pumping.

Well locations, recharge sites, aquifer boundary conditions, and aquifer characteristics impact the net balance of depletion and accretion spatially along the river system. It is important that the degree of injury to senior water rights over time and the location of those water rights injured be identified. Effective river administration requires a daily accounting of the affects of an augmentation plan. The management of a groundwater augmentation program requires an understanding of the consequences of various recharge projects.

6.6 Inventory of Data Resources

An inventory of data resources was carried out as part of the SAMDSS implementation process. Although a number of the data sets reviewed are unique to Colorado, most of the data required to support SAMDSS are available from local, state, or federal agencies involved in collecting and monitoring water resource data in other States.

The type and amount of data available from the U.S. Geological Survey (USGS) is quite extensive. The USGS *Ground Water Site Survey Database* (GWSI) includes data on depth of well, ground surface elevation at a well, specific capacity, transmissivity, well location, pumping capacity, seasonal water levels, and well use. Published groundwater maps showing hydrogeology characteristics such as well location, bedrock configuration, aquifer delineation, water table contours, saturated thickness, and transmissivity are available for most major aquifers (Hurr, et al., 1972). *Digital Line Graphs* (DLG) provide digital representation of cartographic information such as hypsography (contours), hydrography (water), vegetative surface cover, boundaries, survey control markers, transportation, man made features, and U.S. Public Land Survey System (township, range, section).

Land Use and Land Cover (LULC) data provide information on nine major land classes such as urban or built-up land, agricultural land, range land, forest land, water, and wetlands. The *Geographic Names Information System* (GNIS) is an automated database system on geographic names. The *Digital Elevation Model* (DEM) provides elevation data interpolated from USGS maps. *LANDSAT* provides satellite photos and the Northern Great Plains AVHRR Data Set includes NOAA-9 Advanced Very High Resolution Radiometer (AVHRR) data at one kilometer grids for bands 1-5 afternoon satellite coverage with normalized difference vegetative index images.

Another important source of data is the Colorado Division of Water Resources. Typical databases include: the *Water Rights Database* which contains data on structure type, source, location, use, appropriation date, and decreed amount; *Diversion and Reservoir Database*, which provides information on daily diversion and reservoir levels; *Well File* which includes information on location, well number, uses, well permit number, owner, yield, depth, well elevation, appropriation date, and pumping data where available; *Aquifer Water Levels*, an annual publication of water levels in various aquifers; *Water Talk*, a telephone hookup to satellite water monitoring system that provides on-line access to streamflow at important stream gage locations; *Streamflow Database* which contains data collected from stream gage network monitoring stations; and *Daily Report of River Flows and Ditch Diversions* prepared by the Water Commissioners.

Cross section data for tributaries and streams at road crossings are available from the Bridge Division of the Colorado Department of Transportation. The U.S. Soil Conservation Service has prepared *State-County Soil Digital Data (STATSCO)* which contains information on soil type, vegetative cover, drainage potential, etc. The Colorado State Climatologist maintains a *Climatology Data Base* which contains daily data on precipitation, evaporation, temperature, and solar radiation.

A number of publications are available from the National Oceanic and Atmospheric Administration. These include: *Climatological Data of Colorado*, a monthly publication of

Colorado climatology data; *Evaporation Atlas for Contiguous 48 United States*, a published estimate of average and seasonal evaporation for free water surface; and *Mean Monthly, Seasonal, and Annual Pan Evaporation for The United States*, which provides estimated pan evaporations based on observations from Class A pans and meteorological measurements that can be used to develop free water surface maps.

The Bureau of the Census is the source for the *Topographically Integrated Geographic Encoding and Referencing System (TIGER files)*. These files are a compilation of digital maps of the entire U.S. and an accompanying data base that integrates map data with related geographic information and population statistics. The TIGER files include digitized data on hydrography, roads, and political boundaries.

The U.S. Bureau of Reclamation has conducted many river basin hydrologic studies. The *South Platte River Point Flow Study* is an historic accounting of monthly streamflows for the period 1931-1983 at defined locations along the South Platte River, taking into consideration diversions, tributary inflows, and reach gains and losses.

The Bijou Irrigation Company maintains their own detailed records. The *Augmentation Report* (HRS, 1983) provides the engineering data used to develop a plan for augmentation for 196 wells operating under the Bijou Irrigation System. The Well Consumptive Use Data Base contains data on well owner, well permit number, and net consumptive use demand for 1985-1991. The *Well Decree Data Base* contains information on well owner, well permit number, location, decreed pumping rate, and SDF. The *Recharge Accounting Forms* are monthly accounting forms on recharge amounts for the Bijou Irrigation Company. Well and recharge maps are available for the project area.

6.7 Generating Response Coefficients Using MODRSP

MODRSP was used to generate stream-aquifer response coefficients for each of the 196 wells and 32 recharge sites identified in the Bijou Augmentation Plan (Figure 6.2). The alluvial aquifer is unconfined but water table fluctuation compared with depth of saturated thickness is sufficiently small so that transmissivity can be treated as independent of head (Romero, 1990). Sets of coefficients for each well and recharge site were developed to simulate the effects of groundwater pumping and recharge on the South Platte River and its major tributaries. The Lower South Platte River was divided into 29 reaches with 11 separate tributaries (Figure 6.3).

6.7.1 Groundwater Network

The network for the finite difference groundwater model was constructed to cover all of Water District #1 located within the South Platte alluvial aquifer. The aquifer boundary was taken from USGS maps prepared by Hurr, et al. (1972). A 370 by 140 groundwater grid network with each cell having dimensions of 1000 ft x 1000 ft., as shown in Figure 6.4, was developed using GIS techniques. MODRSP transmissivity, boundary condition, river, and well data input files were also developed using the GIS and database procedures.

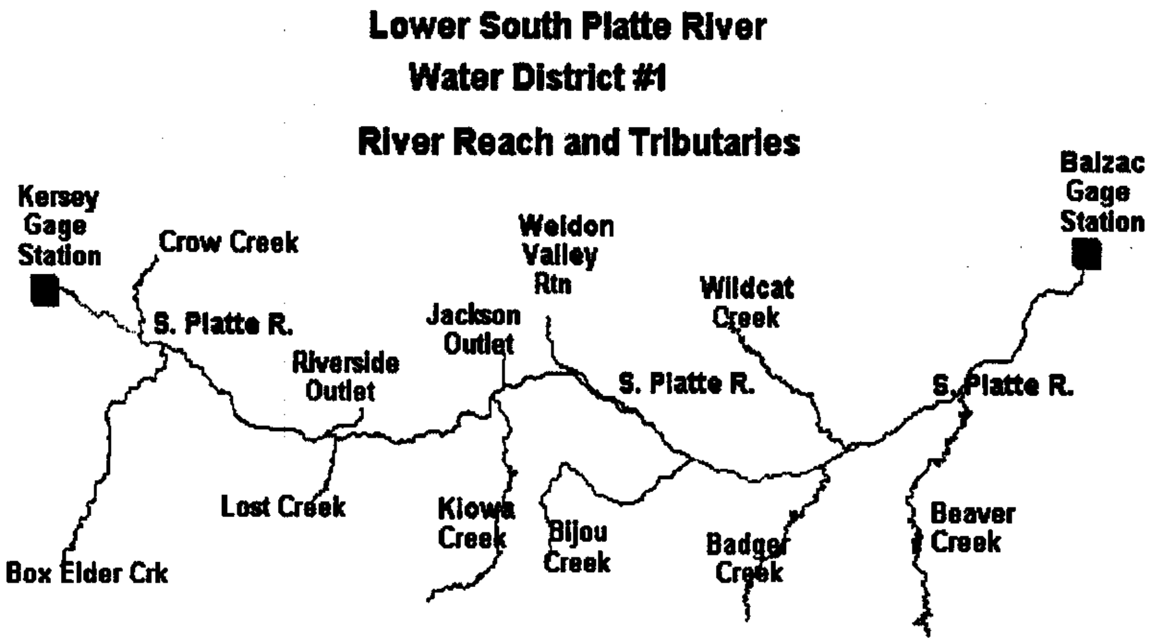


Figure 6.3. Water District #1, Lower South Platte River System

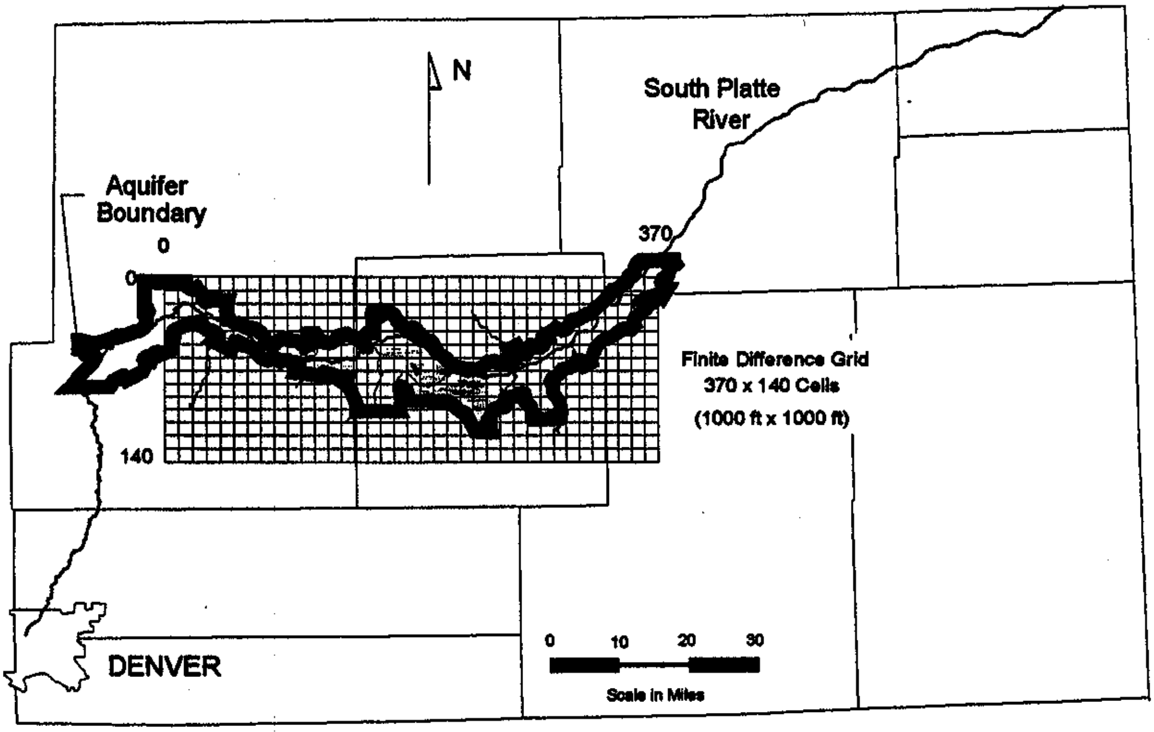


Figure 6.4. Groundwater Model Finite Difference Grid

6.7.2 Hydrography Data

Hydrography for the study area was read into AUTOCAD from Bureau of Census TIGER Files, The data were edited into single AUTOCAD polylines as shown in Figure 6.5. The USBR Point Flow Study schematic (USBR, 1989), USGS 1:100,000 County maps, the State Engineer Diversion Structure computer database for District No. 1, and South Platte Straight Line Diagram for Irrigation Division No. 1, Water District #1 (Wheeler, 1985) were used to identify individual river reaches, drains, canals, and reservoirs.

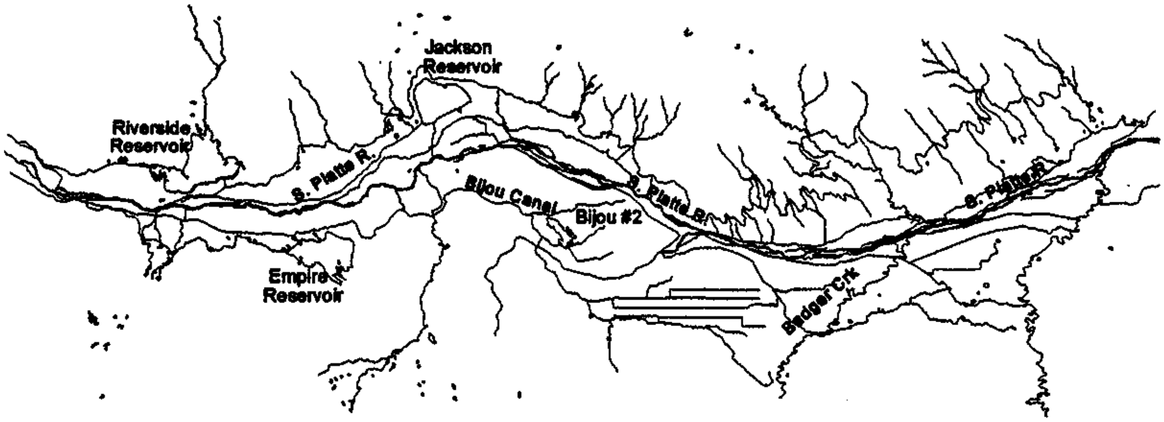


Figure 6.5. Lower South Platte Basin Hydrography; Source: TIGER Files

6.7.3 Transmissivity Data File

Aquifer transmissivity data were digitized from transmissivity maps in Hurr et al. (1972) for the Greeley, Weldonna, and Brush reaches of the South Platte River (Figure 6.6). IDRISI was used to develop a raster grid file from the contour data. Cells outside the aquifer were assigned a transmissivity value of zero. The data in 1000 gal/day/ft was converted to ft^2/sec for input into MODRSP.

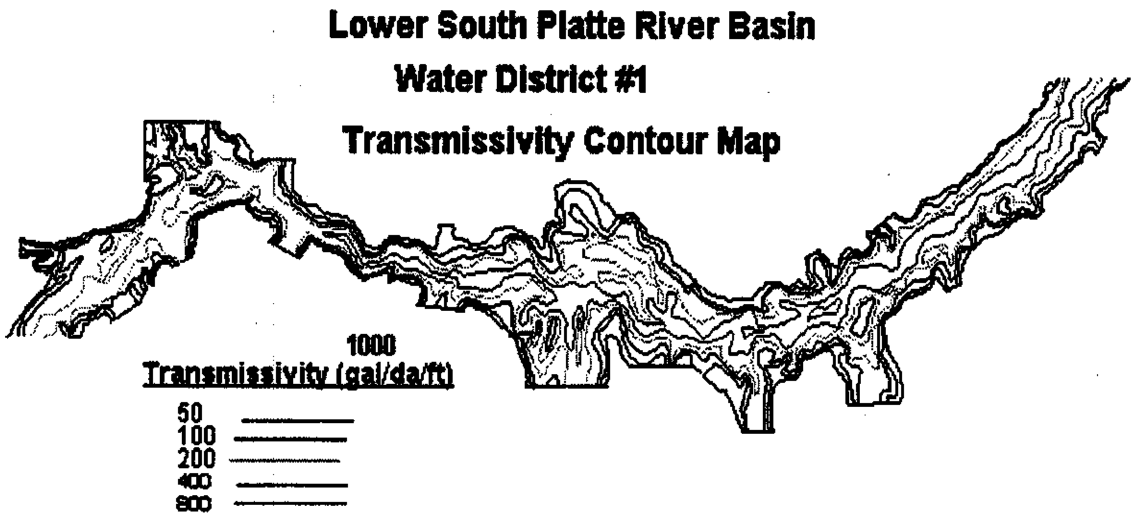


Figure 6.6. Lower South Platte Transmissivity Map

6.7.4 Boundary Data File

The boundary file was developed using IDRISI. All cells located within the aquifer were assigned a value of one, with cells outside the aquifer assigned a value of zero to represent no flow. The east and west boundaries of the aquifer were also assigned as no flow boundaries. Simulation of groundwater flow across these boundaries requires assigning appropriate recharge and discharge wells to these cells. This step is not required, however, for developing response coefficients. Reservoirs were assigned as constant head boundaries and given a value of -1.

6.7.5 Well Data Files

Three separate MODRSP well files were prepared. These files represent the Bijou irrigation wells, the Bijou recharge canals and drains, and the Bijou recharge ponds and reservoirs. Well data were digitized into AUTOCAD using the Bijou Irrigation Company Plan for Augmentation Irrigation Well Location Map (HRS, 1983). The associated grid cell, along with the groundwater grid row and column number for each well, was directly calculated from the well x,y locations provided in AUTOCAD. Although the Augmentation Plan covers 196 wells, the MODRSP well file created coefficients for only 176 wells. The calculation process was not duplicated for those wells located in common grid cells, and several wells are actually located outside the defined aquifer boundaries.

For implementation of the Bijou Augmentation Plan, the Bijou Canal, Kiowa Creek, and Bijou Creek recharge sites were subdivided into 26 separate recharge sites. Locations of the Bijou augmentation plan recharge drains and canals are available from the TIGER hydrography data. For, demarcation of individual reaches, however, it was necessary to digitize this information into the computer using the Bijou Irrigation Company Plan for Augmentation Recharge Site Stream-Depletion Factor Contour Map (HRS,1983). This reach information was then overlain on the hydrography data. Since IDRISI apparently omits several grid cells when converting from vector format to raster format, AUTOLISP (VECBRK.lsp and VECWIDTH.lsp) was used to output data for these polylines into a format that could be read by QUATTRO PRO (ACDPRNIN.wq1). QUATTRO PRO was used to calculate the finite difference groundwater model grid cell row and column locations for each site. The 26 recharge sites were defined by 246 grid cells.

Locations of four of the seven reservoir and pond recharge sites were input from the TIGER hydrography data. For the Weimer and Lost Creek East pond sites, it was necessary to digitize their locations into AUTOCAD from the Bijou Irrigation Company Plan for Augmentation Recharge Site Stream-Depletion Factor Contour Map (HRS,1983). IDRISI was used to convert the vector polygons into raster grids. IDRISI requires a vector polygon with a coverage area greater than 50% to be recognized and converted to a raster cell. The IDRISI reservoir/pond file was read into DBASEIV to separate out the reservoir and pond grid cells. The DBASE file was retrieved into a QUATTRO PRO spreadsheet to calculate the finite difference model row and column values from the grid cell values. The seven recharge reservoirs and ponds of the Bijou Augmentation Plan were covered by 25 finite difference model grid cells, with the Weimer and Lost Creek West recharge ponds falling outside the aquifer boundary.

6.7.6 River Data File

The process of identifying grid locations of the river and tributary cells is similar to that used for the recharge channel and drain well file, although more complicaterd. TIGER hydrography data were imported into AUTOCAD as polylines, edited, and then separated into river reaches and tributaries, with each river reach and tributary assigned a unit number. Since it was assumed the South Platte river acts as an hydraulic barrier, tributaries on the north side of the Platte River were not included in the analysis. AUTOLISP (VECBRK.lsp and VECWIDTH.lsp) was used to place the polylines in a format that could be read by QUATTRO PRO (ACDPRNIN.wq1). The finite difference groundwater model grid cell row and column locations for each site were then calculated. At river and tributary confluence locations, the finite difference grid cell was assigned the unit value of the river reach.

Preparation of the river file also requires a calculated river-bed material conductance value. This value was estimated from the method of flow nets (Peters, 1978; Illangasekare, 1978; Restrepo, 1988; Zhang, 1990), where:

$$Conductance = \frac{T}{e}L(\frac{W_p+2e}{e+10W_p})$$

where T is transmissivity of the aquifer underlying the reach; e is average saturated thickness of the aquifer along the reach; L is length of reach; and W_p is wetted perimeter of the stream, which is assumed to equal the width of reach with negligible error.

With transmissivitiues already available for each grid cell (Figure 6.6) as an IDRISI raster file (Figure 6.6), saturated thickness data (Figure 6.7) were digitized into AUTOCAD from USGS saturated thickness maps (Hurr, et al., 1972) for the Greeley, Weldonna, and Brush reaches of the South Platte River. The resulting contour map was transferred to IDRISI vector file format, from

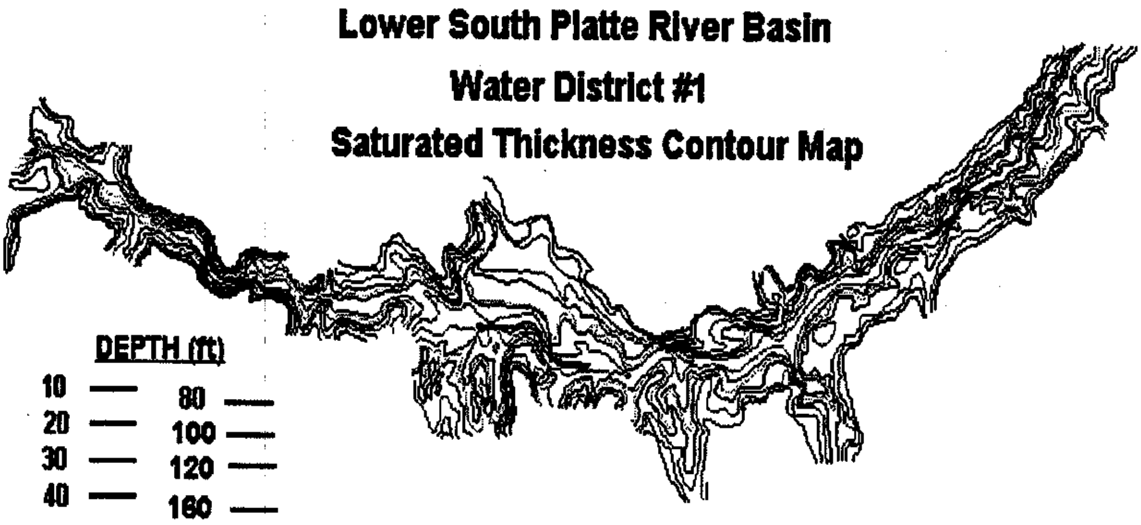


Figure 6.7. Lower South Platte Saturated Thickness Map

which IDRISI was then used to develop a raster grid file from the saturated thickness contour data. Cells outside the aquifer were assigned a saturated thickness value of zero. The IDRISI transmissivity and saturated thickness files were imported into DBASEIV and the data required for river and tributary grid cells extracted. Reach width data were assigned as a polyline width to each river reach and tributary in AUTOCAD and extracted as grid cell data using the aforementioned AUTOLISP and QUATTRO PRO files. Width data were then linked by cell to the river and tributary cell data in DBASEIV. Tributary width was derived with data from the Colorado Highway Department Bridge Division database. The South Platte River width was set at 150 ft. (50 m) based on previous South Platte River Studies (Peters, 1978; Zhang, 1990). A separate AUTOLISP program (VECDIST.lsp) was written to determine the river reach length in each grid cell. QUATTRO PRO (ADPRNIN.wq1) was used to assign a cell location to each grid and its attribute width. This information was then linked with the river and tributary data in DBASEIV. The river conductance value was calculated and the final results output from DBASEIV to an ASCII text file for use by MODRSP. The 29 river reaches and six tributaries were represented by a total of 889 grid cells.

6.7.7 Executing MODRSP

MODRSP was set up to generate response coefficients for 120 monthly periods. or ten years. Specific yield was set at a constant value of 0.16. MODRSP was run with the following input files: basic package input file, block-centered flow package input file, well package input file, preconditioned conjugate gradient file, a transmissivity data file, and a boundary condition data file. The program was run using three different well package files: a well file, a recharge file for channels and drains, and a recharge file for ponds and reservoirs. The MODRSP input and output files are listed in Appendix D. Because of the number of wells, recharge sites, and river reaches it was considered more efficient to run the program on the Colorado State University IBM RISC 6000 computer. Running on a 50 Mhz 80486 PC under Windows required about 20 minutes per well, and a DEC 5000 workstation under UNIX requiring about 10 minutes per well.

6.7.8 Post-Processing MODRSP Response Data Files

The response data file output from MODRSP was processed using DBASEIV, with cells summed by recharge and well site. Well, recharge, river reaches, and tributary site numbers were assigned actual MODSIM node values. The results were exported to an ASCII text file and run through the Program MODCOEFF.EXE. The final result was a MODSIM groundwater response coefficient file with 1079 sets of coefficient data representing monthly response data for a ten year period for 193 wells, 30 recharge sites, 13 river reaches and four tributaries. Again, several of the wells positioned outside the aquifer boundary were deleted from the analysis.

6.8 Augmentation Water Right Account Using MODSIM

6.8.1 Introduction

The Bijou Augmentation Plan (HRS,1983) was selected as the case study example. The return/depletion flow account was prepared from recharge and groundwater well data provided by The Northern Colorado Water Conservation District (NCWCD) using a monthly time step. One reason for selecting the Bijou Augmentation Plan was because of the role of the NCWCD as a consultant for the Bijou Irrigation Company. NCWCD prepares a monthly augmentation account balance which is submitted to the Office of the State Engineer, where it is used to determine potential injury to senior water rights during river administration. Due to this reporting activity, excellent records are available for the Bijou Augmentation Plan.

The present calculation procedure for the Bijou Augmentation Plan account uses calibrated SDF values (Hurr, et al., 1972; Hartwell, 1987) with the Glover analytical method (Glover, 1977). The limitations of this method have been previously documented in this report, including: lack of consideration of spatial variation in depletion and accretion; incomplete consideration of the major tributaries; and utilization of an inaccurate lumped parameter approach to consider the influence of aquifer characteristics and boundary conditions on groundwater flow responses. An improved alternative is to use response coefficients generated from a finite difference groundwater model such as MODFLOW. This case study analyzes the Bijou Augmentation Plan using both methods and compares results.

6.8.2 MODSIM Augmentation Network

The monthly water account for the Bijou Irrigation Augmentation Plan was simulated using MODSIM for a period of seven years from 1985 to 1991. The MODSIM network for the system is presented in Figure 6.8. The network was constructed with 281 nodes, 8 reservoirs, 232 demands and 81 links. Detailed input data files are listed in Appendix E.

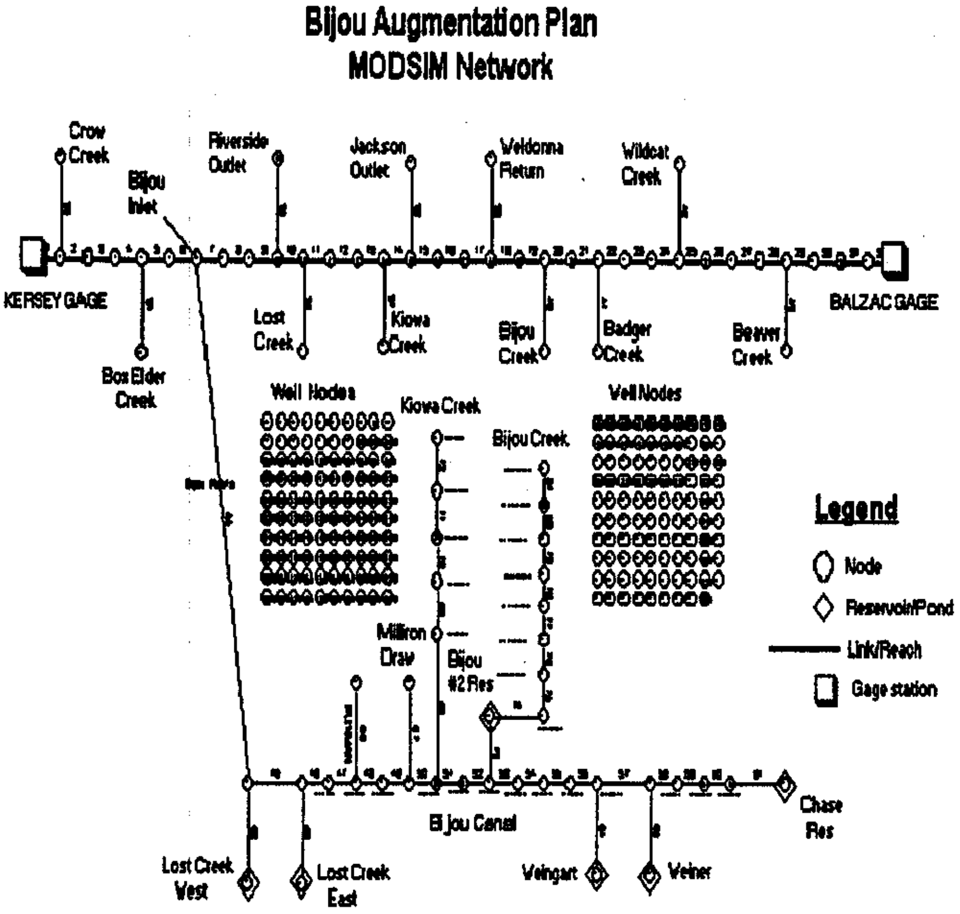


Figure 6.8. MODSIM Network for Bijou Augmentation Plan

A list of the 196 member wells covered in the Bijou Plan is presented in Appendix F. The recharge sites included in the plan are Bijou Canal, Bijou Creek, Kiowa Creek, Bijou #2 Reservoir, Milliron Draw, Chase Pond, Weingarde Pond, Kiowa Creek, Lost Creek East Pond, Lost Creek West Pond, and Weimer Pond (Table 6.2). The groundwater pumping and the monthly recharge credit data for each well and recharge site were read in as demand data. Well nodes were only allowed to meet demands through groundwater pumping, whereas recharge nodes were restricted to satisfying demands through surface diversions only. The infiltration rate was set at 0.5 for the recharge demand nodes to insure that infiltration return flow would equal the recharge demand.

Table 6.2. Bijou Augmentation Plan Recharge Sites

Site	Node	Site Name	SDF (days)	Percent Credit	Location
1	47	BIJOU CANAL: RCH #1	125	34	To Putnam
2	48	BIJOU CANAL: RCH #2	350	12	To Putnam
3	49	BIJOU CANAL: RCH #3	270	5	To Kiowa
4	51	BIJOU CANAL: RCH #4	750	11	To Kiowa
5	52	BIJOU CANAL: RCH #5	677	5	To Bijou#2 Inlet
6	53	BIJOU CANAL: RCH #6	1590	14	To Bijou#2 Inlet
7	54	BIJOU CANAL: RCH #7	3310	2	To Weingardt
8	55	BIJOU CANAL: RCH #8	4875	4	To Weingardt
9	56	BIJOU CANAL: RCH #9	5550	4	To Weingardt
10	57	BIJOU CANAL: RCH #10	5800	2	To Weingardt
11	59	BIJOU CANAL: RCH #11	5225	2	To Chase
12	60	BIJOU CANAL: RCH #12	4915	1	To Chase
13	61	BIJOU CANAL: RCH #13	7100	4	To Chase
14	62	CHASE RES	7825	100	6-2N-57W
15	63	LOST CRK WEST	30	100	23-4N-62W
16	64	LOST CRK EAST	100	100	24-4N-62W
17	65	WEINGART	5880	100	23-3N-59W
18	66	WEIMER		100	24-3N-59W
19	68	MILLIRON DRAW		100	
20	69	KIOWA CREEK: RCH #1	750	36	
21	70	KIOWA CREEK: RCH #2	480	14	
22	71	KIOWA CREEK: RCH #3	270	14	
23	72	KIOWA CREEK: RCH #4	120	22	
24	73	KIOWA CREEK: RCH #5	30	14	
25	74	BIJOU #2 RES	3310	100	
26	75	BIJOU CRK RCH #1	5070	35	
27	76	BIJOU CRK RCH #2	4320	17	
28	77	BIJOU CRK RCH #3	3630	12	
29	78	BIJOU CRK RCH #4	3000	6	
30	79	BIJOU CRK RCH #5	2430	8	
31	80	BIJOU CRK RCH #6	1920	6	
32	81	BIJOU CRK RCH #7	1470	10	
33	82	BIJOU CRK RCH #8	1080	6	

6.8.3 Simulation Using SDF Values

The first simulation run used SDF well and recharge site values given in the Bijou Augmentation Plan Report. Groundwater response coefficients were generated using the Glover module within MODSIM. Results of the recharge and depletion calculations and their effects on the South Platte River for the seven years of study are shown in Figure 6.9. Actual result tables are listed in Appendix G. It can be seen from these results

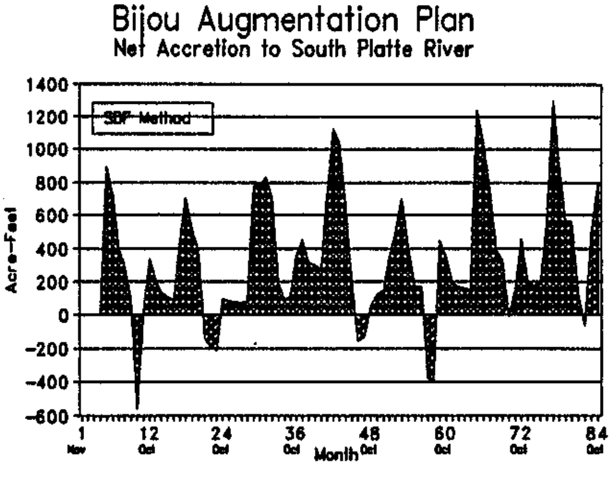


Figure 6.9. Bijou Augmentation Plan Using SDF Values

that no deficit accounts occur for this case during the entire 84 month period.

6.8.4 Simulation Using MODRSP Values

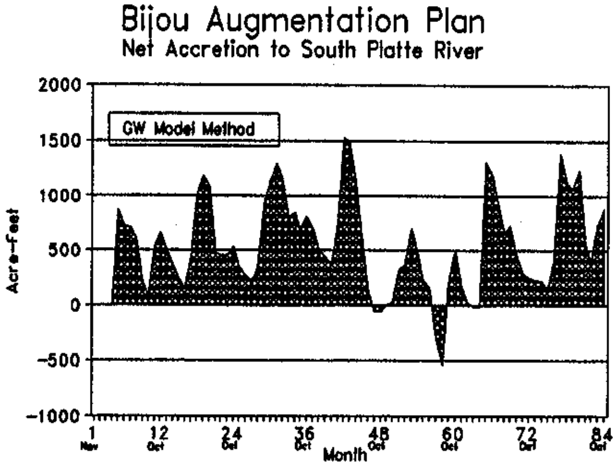


Figure 6.10. Bijou Augmentation Plan Using MODRSP Response Coefficients

The second simulation run used the response coefficient file from MODRSP. The following sites are located outside the aquifer boundary and were not included in the network calculations: Lost Creek West, Weimer Pond, Well 0400F, Well 14336F, Well 1941, Well 1942, Well 6481, Well 8209, and Well 8210. All other data remained the same. Figure 6.10 shows a plot of the monthly recharge and depletion calculations over the seven year study period. Actual result tables are given in Appendix G. In contrast with the previous run using SDF values, deficit accounts occur in seven out of the 84 months: September 1989, October 1989, November 1988, December 1988, January 1989, March 1990, and April 1991.

6.8.5 Comparison of Simulation Results

A comparison of the two simulation runs shows is presented in Figure 6.11. The finite difference method using MODRSP resulted in the larger credit account. Total net account for the seven years for the SDF method was 18,900 ac-ft and 44,200 ac-ft for the finite difference method. Average monthly return flow rate for the seven years was 225 ac-ft/month for the SDF method and 525 ac-ft/month for the finite difference method. During the critical irrigation months of July, August, September the SDF method resulted in an average of 235 ac-ft/month (July: 250 ac-ft; August:200 ac-ft; September:250 ac-ft) and the finite difference method resulted in an average of 762 ac-ft/month (July:984 ac-ft; August: 858 ac-ft; September: 444 ac-ft).

6.8.6 Comparison of Response Coefficients

Comparison of response coefficients generated by the numerical finite difference method using MODRSP and using the SDF values calculated from the analytical Glover equation for a single well located within the study area are shown in Figure 6.12.

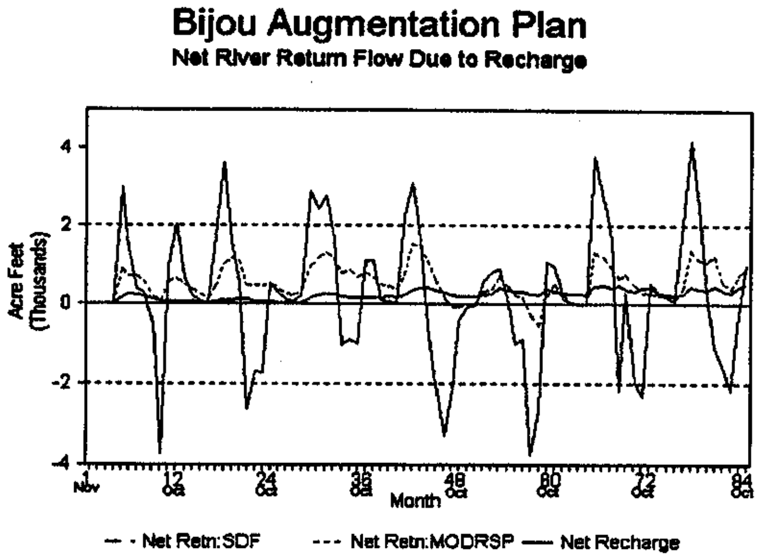


Figure 6.11. Comparison of Augmentation Plan Results (SDF vs. MODRSP)

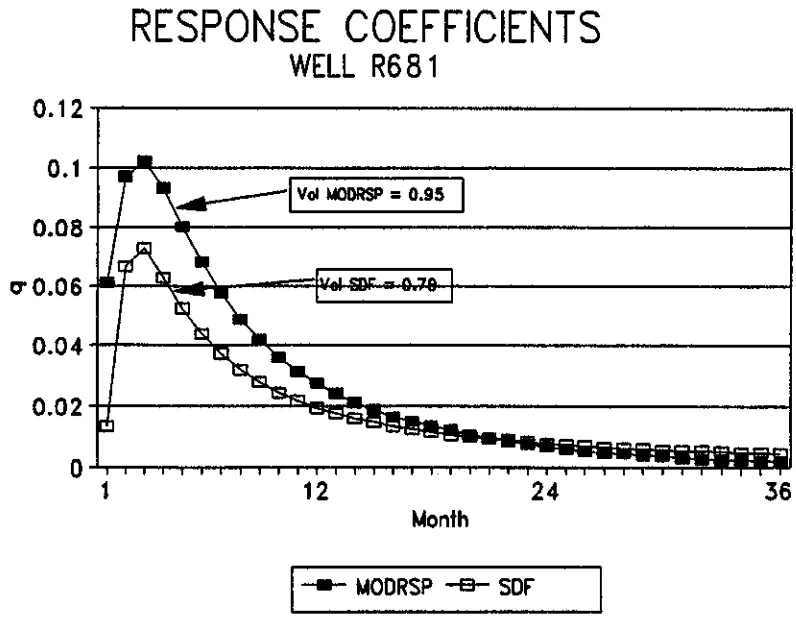


Figure 6.12. Single Well Comparison of Response Coefficients (SDF vs MODRSP)

The finite difference model produced coefficients for Well R681 that resulted in 95% of depletion flows to the well being drawn from the river and its tributaries over a seven year (84 month) period, while the SDF method accounted for only 79% of depletion flows during the same period. For the well Well R681 represented in this example, 53% of depletion flow determined using the finite difference method was drawn from tributary sources, as shown in Figure 6.13.

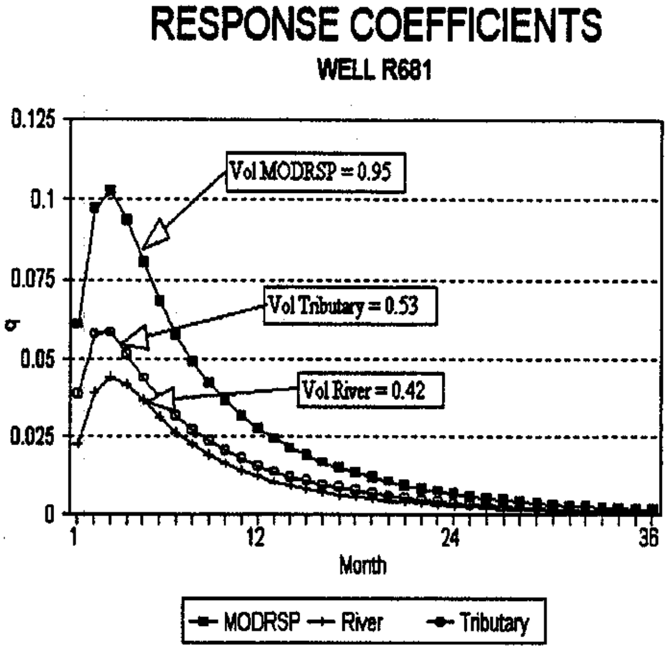
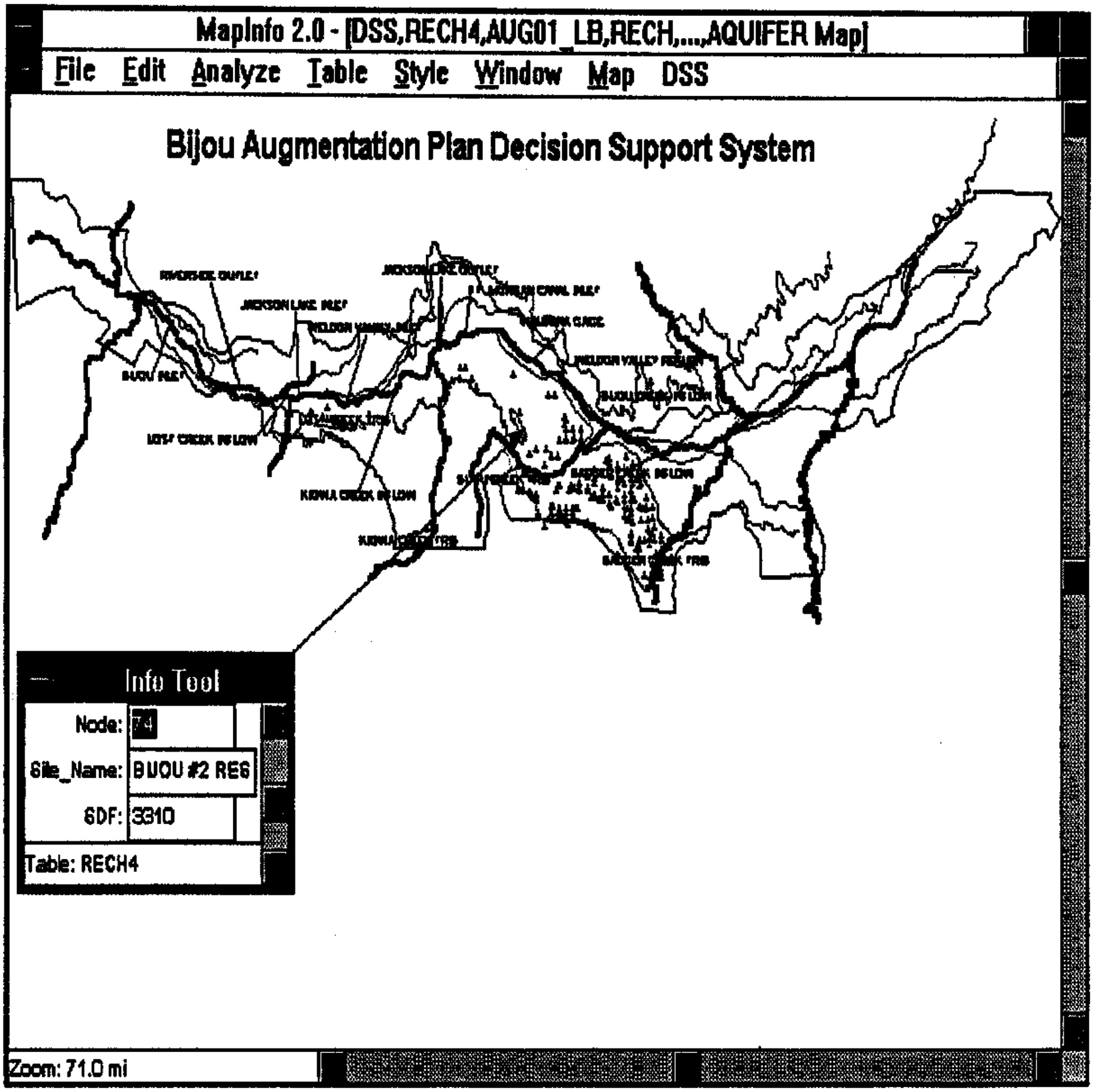


Figure 6.13. Single Well Comparison of MODRSP Tributary and River Response Coefficients

A more general review of the response coefficient data shows that for the SDF method, an average of 51% (standard deviation: 4%) of the unit response volume is returned/depleted within a seven year period. For the response coefficients derived from the finite difference method, an average of 92% (standard deviation: 4%) of the unit response volume is returned/depleted within a seven year period. A comparison between the spatial variation of the finite difference based response coefficients showed that 30% of the return/depletion flow effects directly impact flows in the river, with 70% influencing the tributaries.

6.9 Augmentation Plan DSS

An interactive format was prepared in MAPINFO to demonstrate procedures for displaying spatial data output using DSS techniques. Figure 6.14 shows the general MAPINFO screen display for the Bijou Irrigation Company Augmentation Plan physical network. Three types of output display have been used: interactive maps, graphs, and data tables. Figure 6.15 shows output display capabilities for the Augmentation Plan DSS.



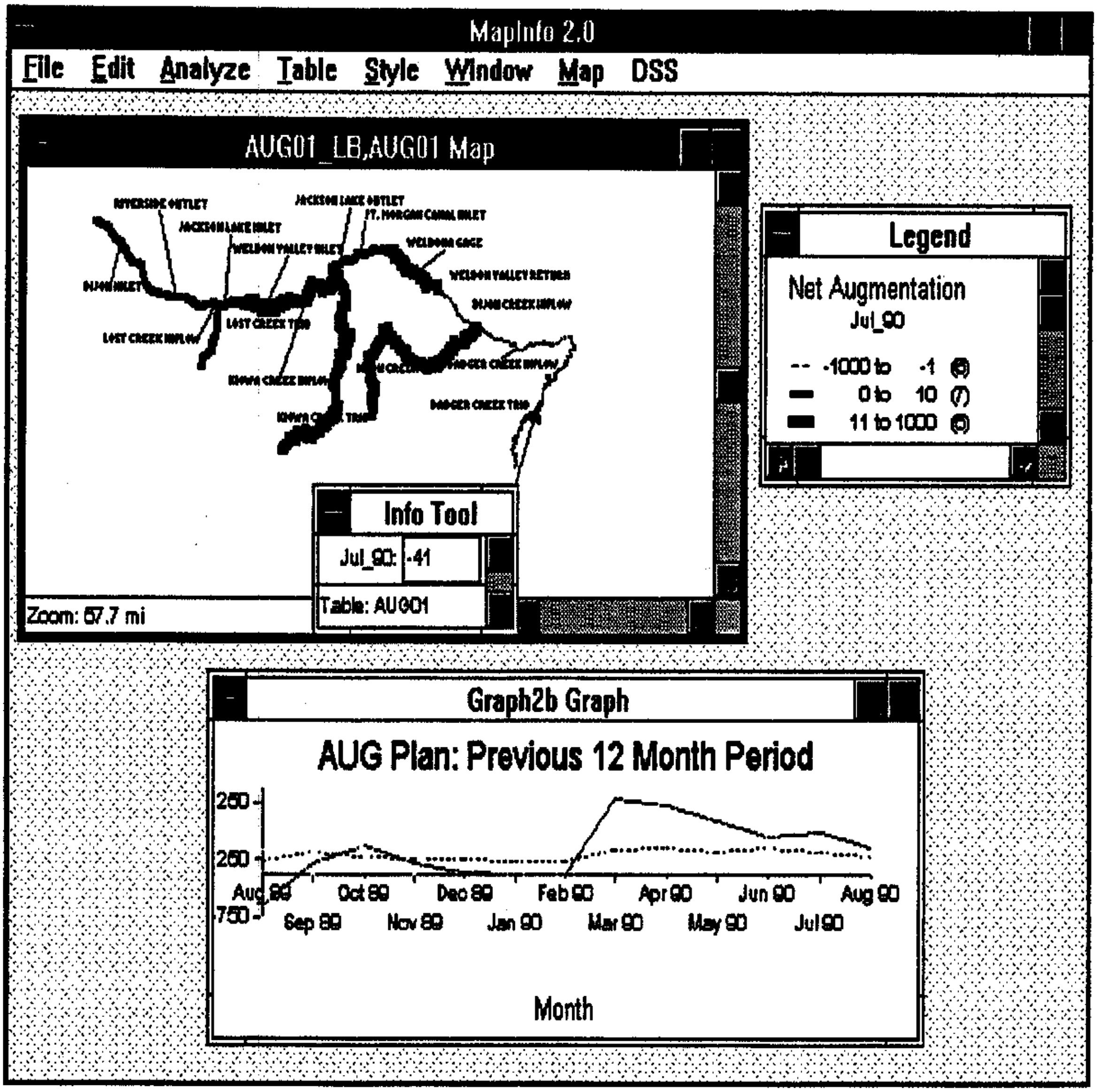
Node: 74

Site_Name: BIJOU #2 RES

SDF: 3310

Table: RECH4

Figure 6.14. Bijou Irrigation Company Augmentation Plan Network



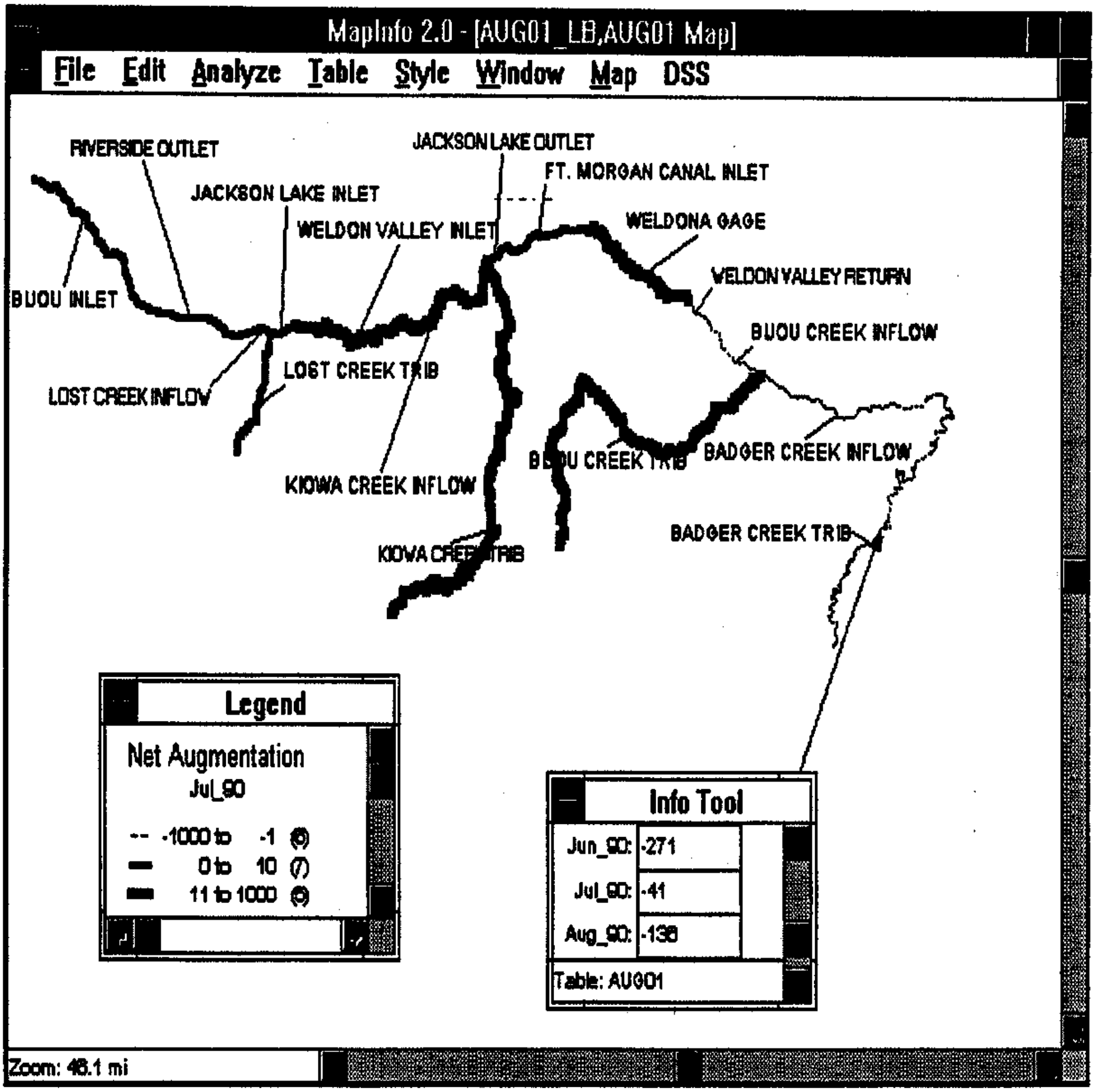
Jul_90: -41

Table: AUG01

Zoom: 57.7 mi

Figure 6.15. Augmentation Plan DSS Output Options

Figure 6.16 shows a layout map of the South Platte River and components of the augmentation plan. Red (depletion), green (accretion), and yellow (border line accretion) colors have been used to group data values that reflect the net affects of the augmentation plan on various river reaches and tributaries.



Jun_90: -271

Jul_90: -41

Aug_90: -138

Table: AUG01

Zoom: 48.1 mi

Figure 6.16. Bijou Augmentation Plan Net Streamflow Affects

6.10 Daily River Administration Using MODSIM

6.10.1 Introduction

This portion of the case study demonstrates how to integrate an augmentation plan directly into daily administration of a river regulated under prior appropriation water right laws. The MODSIM model was used to simulate daily operations of a section of the Lower South Platte River, Colorado, between the Kersey and Balzac river gage stations under administrative control of Colorado State Engineer's Water District #1. Procedures on preparing a daily administration

MODSIM network are presented that allow consideration of individual water rights, river diversions, river calls, tributary inflows, and augmentation plans.

The case study is based on data used for daily administration of the South Platte for August 15, 1990. Table 6.3 presents data taken from the August 1990 daily water reports prepared by the District No. 1 Water Commissioner. These reports provide information on river calls, historic river discharges and tributary inflows. Historical diversion data taken from the State Engineer Office (SEO) diversion database are shown in Table 6.4. A summary of the historical data used to simulate daily administration is presented in Table 6.5. Augmentation data were taken from the Bijou Augmentation Plan case study results for August 1990. The augmentation summary table is presented as Table 6.6.

6.10.2 MODSIM Daily Administration Network

The daily administration network was prepared using data from the SEO water rights database. The MODSIM network prepared for the river system is shown in Figure 6.17. The network has 158 nodes and 157 links, and includes 27 reservoirs, 18 diversion points, 25 direct decree diversions, 10 storage decree diversions, and 75 separate water rights. The network is structured to guarantee water allocation in accordance with administrative water right decrees. The network is organized so that flow accounts and operational control can be maintained at several levels, as shown in Figure 6.18.

Each water right decree is assigned as a demand node, with the demand set equal to the decreed water right and the priority equal to the State Engineer's administrative number. Since each decreed water right is usually associated with a diversion point or structure ID number, a node and corresponding structure ID link is provided upstream of each decreed water right. A structure ID can be associated with more than one decree and is the same number used by the State Engineer's Office to record actual structure diversions. Another set of nodes with a connecting link are placed upstream of the Structure ID node. This link is included to represent the actual diversion offtake canal and its headgate.

Kersey gaging station on the main stem of the South Platte River is assigned as the first upstream node, with the Balzac gaging station assigned as the terminal downstream node. Both gaging station nodes are represented as *dummy* storage nodes for several reasons. Assigning the upstream Kersey gage node as a storage node provides a reservoir source for all unmeasured or unknown excess inflows to the system required to balance the MODSIM network. Assigning the downstream Balzac gage node as a storage node provides flexibility in testing the network system by forcing unaccounted excess flows through the network system. It also allows the accounting for all downstream gage flows and downstream river calls to be maintained at the same node. The Weldona gage, located on the South Platte between the Kersey and Balzac stations, is assigned as a flow-through demand node. Tributaries are represented as links with an upstream node.

Table 6.3. Water Commissioner's Daily Report

Water District 1 Selected Daily Inflows: Source: Water Commissioner's Daily Report
Discharge in CFS
August 1990

Date	Crow Creek	Jackson Lake Outlet	Weldon Valley Return	Bijou #2 Release	Bijou Creek	Wildcat Creek	Exchange Water	Junior Ditch	Priority Date	W.D. 64 Amount	W.D. 64 Call	Upper Districts Amount	Upper Districts Call	Amount
1	5	27	35	7.5	10	10	0	Riverside Direct	5/31/07	383	2/12/04	450	5/31/07	417
2	5	27	35	7.5	10	10	0	Riverside Direct	5/31/07	383	2/12/04	450	5/31/07	417
3	5	22	35	7.5	10	10	0	L.P&B.	4/15/88	94	4/28/95	252	10/1/88	450
4	5	81	0	7.5	10	10	30	L.P&B.	4/15/88	94	7/19/86	62	10/1/88	450
5	10	59	15	7.5	10	10	30	Duel&Snyder	4/7/84	11	7/19/86	62	10/1/88	450
6	10	9	30	7.5	10	15	0	Duel&Snyder	4/7/84	11	4/28/95	252	10/1/88	450
7	20	0	70	7.5	10	15	0	Tremont	5/18/01	40	4/28/95	252	10/1/88	450
8	20	13	70	7.5	10	15	0	Tremont	5/18/01	40	4/28/95	162	10/1/88	450
9	20	13	70	7.5	10	15	0	Tremont	5/18/01	40	4/28/95	162	10/1/88	450
10	15	13	21	7.5	10	10	0	Tremont	5/18/01	38	4/28/95	162	10/1/88	450
11	15	13	21	7.5	100	10	0	Tremont	5/18/01	38	4/28/95	162	10/1/88	450
12	15	234	21	7.5	100	10	0	Tremont	5/18/01	38	4/28/95	162	10/1/88	450
13	15	234	21	7.5	20	10	0	Tremont	5/18/01	38	4/28/95	162	10/1/88	450
14	15	255	21	7.5	10	10	0	Tremont	3/1/95	38	4/28/95	162	10/1/88	450
15	8	292	47	7.5	10	10	0	Tremont	3/1/01	44	4/28/95	162	10/1/88	450
16	8	292	47	7.5	10	10	0	Tremont	3/1/01	44	4/28/95	162	10/1/88	450
17	8	218	47	7.5	10	10	0	Riverside	5/31/07	250	3/1/95	162	5/31/07	417
18	12	213	44.7	7.5	10	10	0	Riverside	5/31/07	250	3/1/95	162	5/31/07	417
19	12	218	44.7	7.5	10	10	0	Riverside	5/31/07	250	3/1/95	162	5/31/07	417
20	12	213	44.7	7.5	10	10	0	Riverside	5/31/07	350	3/1/95	162	5/31/07	417
21	18	180	62	7.5	10	10	0	Recharge	1972		3/1/95	162	1972	
22	18	167	62	7.5	10	10	0	Riverside	5/31/07	339	3/1/95	162	5/31/07	417
23	18	167	62	7.5	10	10	0	Tremont	3/1/01	45	3/1/95	162	5/31/07	417
24	18	167	62	7.5	10	10	0	Tremont	3/1/01	45	3/1/95	162	5/31/07	417
25	18	167	22	5.9	10	10	0	Tremont	3/1/01	42	3/1/95	162	5/31/07	417
26	10	185	22	5.9	10	10	0	Tremont	3/1/01	42	3/1/95	162	5/31/07	417
27	10	237	22	5.9	10	10	17	Snyder-Smith	6/18/87	20	7/19/86	62.5	4/15/88	448
28	10	237	22	5.9	10	10	50	Snyder-Smith	6/18/87	20	7/19/86	62.5	4/15/88	448
29	15	297	22	5.3	10	7	50	Snyder-Smith	6/18/87	19	6/18/87	62.5	4/15/88	448
30	15	310	22	5.3	10	7	50	Snyder-Smith	6/18/87	19	6/18/87	62	4/15/88	448
31	15	343	22	5.3	10	7	50	Snyder-Smith	6/18/87	19	6/18/87	62	4/15/88	448

Table 6.4. SEO Diversion Database Data

ID	NAME	F	U	T	IYR	MON	AMT15
501	EMPIRE RES IN D		Q	3	90	8	0
503	RIVERSIDE D INLET		1		90	8	0
503	RIVERSIDE D INLET		Q	3	90	8	0
504	ILLINOIS DITCH		1		90	8	17
507	BIJOU DITCH		1		90	8	84
507	BIJOU DITCH		Q	3	90	8	0
509	CORONA DITCH		1		90	8	0
511	WELDON VALLEY DITCH		Q	3	90	8	45
511	WELDON VALLEY DITCH		1		90	8	116
511	WELDON VALLEY DITCH		Q	7	90	8	45
514	FORT MORGAN CNL		1		90	8	0
514	FORT MORGAN CNL		Q	3	90	8	0
515	UPR PLATTE & BEAVER D		1		90	8	91
517	DEUEL A SNYDER D		1		90	8	19
518	LWR PLATTE A BEAVER D		1		90	8	97
518	LWR PLATTE A BEAVER D		Q	3	90	8	0
519	TREMONT DITCH		1		90	8	43
519	TREMONT DITCH		Q	3	90	8	0
519	TREMONT DITCH	511	1	2	90	8	0
525	TETSEL DITCH		1		90	8	16
526	JOHNSON EDWARDS D		1		90	8	26

Table 6.5. Summary of Historical Daily Data

TYPE	NAME	IYR	MON	DAY	AMT
DIVERT	EMPIRE RES IN D	90	8	15	0
DIVERT	RIVERSIDE D INLET	90	8	15	0
DIVERT	ILLINOIS DITCH	90	8	15	17
DIVERT	BIJOU DITCH	90	8	15	84
DIVERT	CORONA DITCH	90	8	15	0
DIVERT	WELDON VALLEY DITCH	90	8	15	161
DIVERT	FORT MORGAN CNL	90	8	15	0
DIVERT	UPR PLATTE & BEAVER D	90	8	15	91
DIVERT	DEUEL A SNYDER D	90	8	15	19
DIVERT	LWR PLATTE A BEAVER D	90	8	15	97
DIVERT	TREMONT DITCH	90	8	15	43
DIVERT	TETSEL DITCH	90	8	15	16
DIVERT	JOHNSON EDWARDS D	90	8	15	26
GAGE	BALZAC	90	8	15	389
GAGE	KERSEY	90	8	15	525
GAGE	WELDONNA	90	8	15	449
INFLOW	CROW_CREEK	90	8	15	8
INFLOW	JACKSON_OT	90	8	15	292
INFLOW	WELDON_RTN	90	8	15	47
INFLOW	BIJOU#2	90	8	15	8
INFLOW	BIJOU_CRK	90	8	15	10
INFLOW	WILDCAT	90	8	15	10
INFLOW	EXCHANGE	90	8	15	0

Table 6.6. Augmentation Summary Table

```
          Year:1990
           Month: August

           Aug       Daily   Flow       Flow              Monthly Account Summary:
         Network   Network Summary    Summary
REC        Node      Node  (ac-ft/mo) (cfs)
=========================================                   MODRSP Analysis
 1          7         7        0        0        PERIOD          70
 2         10        10        0        0        NET            463 ac-ft/mo  7 cfs
 3         11        11        0        0        DEPLETE        693 ac-ft/mo 11 cfs
 4         12        12        0        0        RETURN        1156 ac-ft/mo 19 cfs
 5         13        13       15        0
 6         14        14       23        0
 7         15        15        1        0                   SDF Analysis #1 (Maasland)
 8         16        16        2        0        PERIOD          70
 9         17        17       17        0        NET            -11 ac-ft/mo -0 cfs
10         18        18       -1       -0        DEPLETE        825 ac-ft/mo 13 cfs
11         20        20       -5       -0        RETURN         814 ac-ft/mo 13 cfs
12         21        21       -4       -0
13         22        22      -45       -1                   SDF Analysis#2 (Glover)
14         35        11        1        0        PERIOD          70
15         36        14       29        0        NET            315 ac-ft/mo  5 cfs
16         37        20      566        9        DEPLETE        139 ac-ft/mo  2 cfs
17         38        22     -136       -2        RETURN         454 ac-ft/mo  7 cfs
```

This framework allows considerable flexibility in the simulation of the daily administration of the network. A call placed on the river by a senior water right located in a downstream water district can be simulated by assigning the sum of all senior downstream water right flow requirements as a demand at the Balzac gaging station. The priority can be set equal to the downstream senior water right administrative number. If for some reason a user within the water district does not require or is not authorized to take water, the associated water right can be deactivated by setting the capacity of the water right link equal to zero. Otherwise, the water right link upstream of the decree node can be assigned a link capacity equal to the water right decree amount. To simulate the operation of a headgate with a measured or regulated diversion rate, the flow rate can be assigned as the link capacity on the ID structure link or as a prioritized flow-through demand.

The network model can be used for daily operation as a planning or evaluation tool. In the planning mode, it is expected that the water commissioner would know river inflow at the upstream Kersey Gage station, the downstream flow-through requirements, the senior downstream river call below the Balzac gage station, tributary inflows, and a list of users requesting water. Given this information, available water supply can be allocated by MODSIM in accordance with water right priorities. This is done by running the model without placing capacity restrictions on the various diversion and structure ID links and allowing the model to directly allocate flows according to priority.

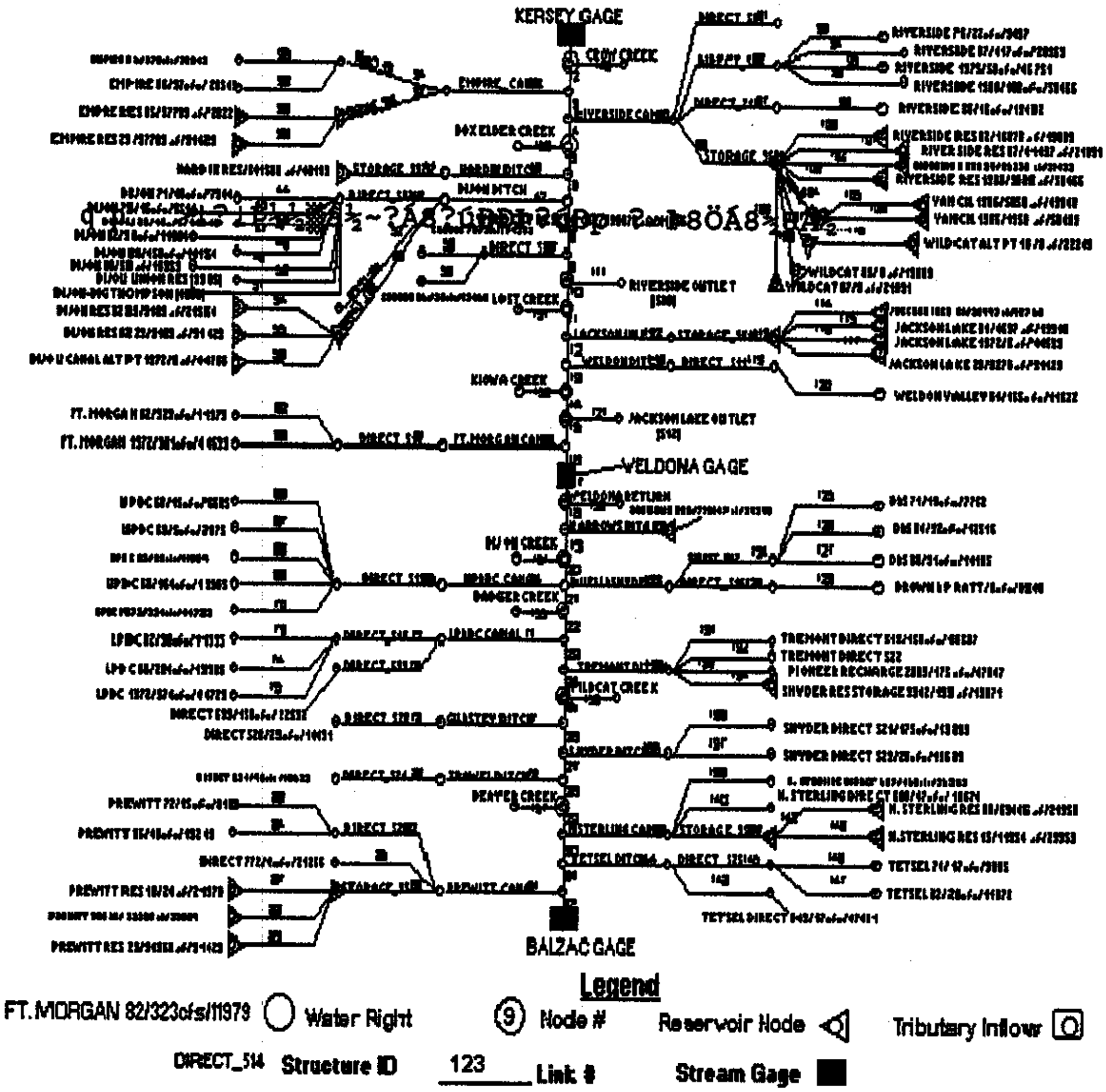
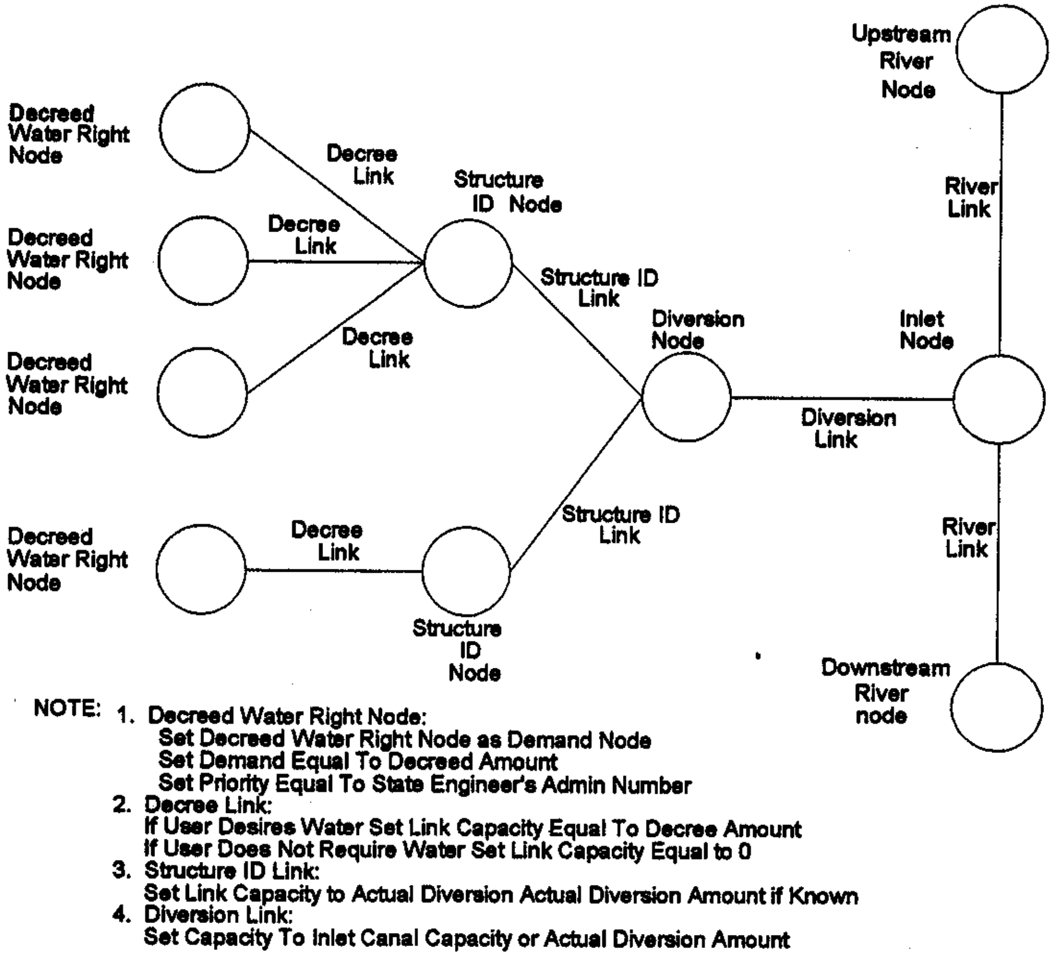


Figure 6.17. Daily Administration MODSIM Network

Once a decision has been made on how to allocate water within the water district, it is usually desirable to evaluate the consequences of the allocation and the overall response of the river system. This information can be used to better understand system performance and aid in future administrative decisions. For evaluation purposes, actual diversion amounts can be assigned to the structure ID and diversion links. Net river gains and/or lojsses can be calculated by using the model to perform a water balance based on known river inflows and outflows. This information can then be used to estimate surface flow routing coefficients or to evaluate groundwater return flow conditions.



NOTE:
1. Decreed Water Right Node:
   Set Decreed Water Right Node as Demand Node
   Set Demand Equal To Decreed Amount
   Set Priority Equal To State Engineer's Admin Number
2. Decree Link:
   If User Desires Water Set Link Capacity Equal To Decree Amount
   If User Does Not Require Water Set Link Capacity Equal to 0
3. Structure ID Link:
   Set Link Capacity to Actual Diversion Actual Diversion Amount if Known
4. Diversion Link:
   Set Capacity To Inlet Canal Capacity or Actual Diversion Amount

Figure 6.18. Network Structure for Daily Administration

6.10.3 Integration of Augmentation and Daily Administration

To integrate the Bijou Augmentation Plan into the South Platte Water District No. 1 daily administration model, MODSIM was run in evaluation mode. Two separate simulation runs were carried out. The purpose of Run #1 is to determine the amount of system flow resulting from unmeasured river losses and gains such as groundwater return flows, tributary inflows, and diversions. All gage, tributary, and diversion flows are set to historical values by assigning node inflows, demands, and variable link capacities in MODSIM. Bijou Augmentation Plan depletion and accretion flows based on the MODRSP finite difference model response coefficients are converted from acre-feet per month to average daily cubic feet per second (cfs). Augmentation flows are assigned by node inflows (i.e., accretions) or demands (i.e., depletion)s. High demand priorities for the augmentation flow depletion demands are assigned in MODSIM to insure that these depletions are met. The Kersey gage storage node is given a reservoir beginning storage component equal to 1000 cfs and a target priority that results in releases only to meet the most junior historic water right receiving water on 15 August 1990. This results in releases to balance all historic SEO diversion demands not satisfied by river, tributary inflows, and the Bijou Augmentation Plan net return flows.

For the second simulation run, the affects of the Bijou Augmentation Plan are removed. The Kersey storage node starting capacity is set to the net water balance value determined in Run #1. A target value for the reservoir is set to insure full release of the stored flow. To determine differences in the availability of water to satisfy system demands as a result of the Bijou Augmentation Plan, the demand shortages for Run #1 *with* the augmentation plan and Run #2 *without* augmentation plan are compared. The water balance to account for unmeasured net river gains/losses from Run #1 with the augmentation plan included required a net inflow of 36 cfs. The Bijou Augmentation Plan account provided a net of 7 cfs return flow. The net effect of the Bijou Augmentation Plan on system administration was to make an additional 7 cfs available for diversion to Tremont ditch to satisfy the Tremont direct water right decree dated 1901, as shown in Table 6.7.

Table 6.7. Daily Admin Diversion Allocation-With/Without Bijou Augmentation Plan

```
DAILY REPORT SOUTH PLATTE RIVER WATER DISTRICT #1:15 August 1990
                                                             Without    With
                                                         Aug Plan Aug Plan
   NODE      NAME                        PRIORITY    DEMAND   SURF_IN  SURF_IN
================================================================================
     32   PREWITT INLET                         1       389      389      389
     33   BALZAC GAGE                           2       162      162      162
     17   WELDONA GAGE                          3       449      449      449
     66   UPBC 68                            6685        15       15       15
     67   UPBC 69                            7075         5        5        5
    125   D&S 71                             7762        13       13       13
     45   BIJOU 71                           7944        40       40       40
     83   PREWITT 72                         8188        15       15       15
     46   BIJOU 73                           8511        16       16       16
    146   TETSEL 74                          9085        17       16       16
     91   ILLINOIS DIRECT 504                9497        22       17       17
     47   BIJOU 80                          11049        10       10       10
    120   WELDON VALLEY 81                  11622       165      161      161
     48   BIJOU 82                          11804        30       18       18
     68   UPBC 82                           11859        50       50       50
     73   LPBC 82                           11935        38       38       38
    126   D&S 84                            12516        32        6        6
     84   PREWITT 86                        13249        48       11       11
     69   UPBC 88                           13985       164       21       21
     74   LPBC 88                           13986       284       59       59
    131   TREMONT DIRECT 519                18687       150       36       43
```

6.10.4 Daily Administration DSS

A prototype daily administration DSS was prepared using QUATTRO PRO, MAPINFO, and MODSIM software to demonstrate procedures for managing the interface between the user and the modeling system. The DSS was designed to assist in the daily administration for Water District #1 and to consider the effects of the Bijou Augmentation Plan on daily administration. QUATTRO PRO serves as the central shell for the DSS from which MODSIM can be executed. MAPINFO software is used to display output results. Figure 6.19 shows the main menu for the daily administration DSS with options included to simplify data entry and provide graphical output display.

The input dialog menu for setting diversion flows is shown in Figure 6.20. Input and output files used by MODSIM, QUATTRO PRO and MAPINFO are prepared internally by the DSS. Output can be displayed in map, graph, or tabular format. Example output display types available in the DSS are shown in Figure 6.21.

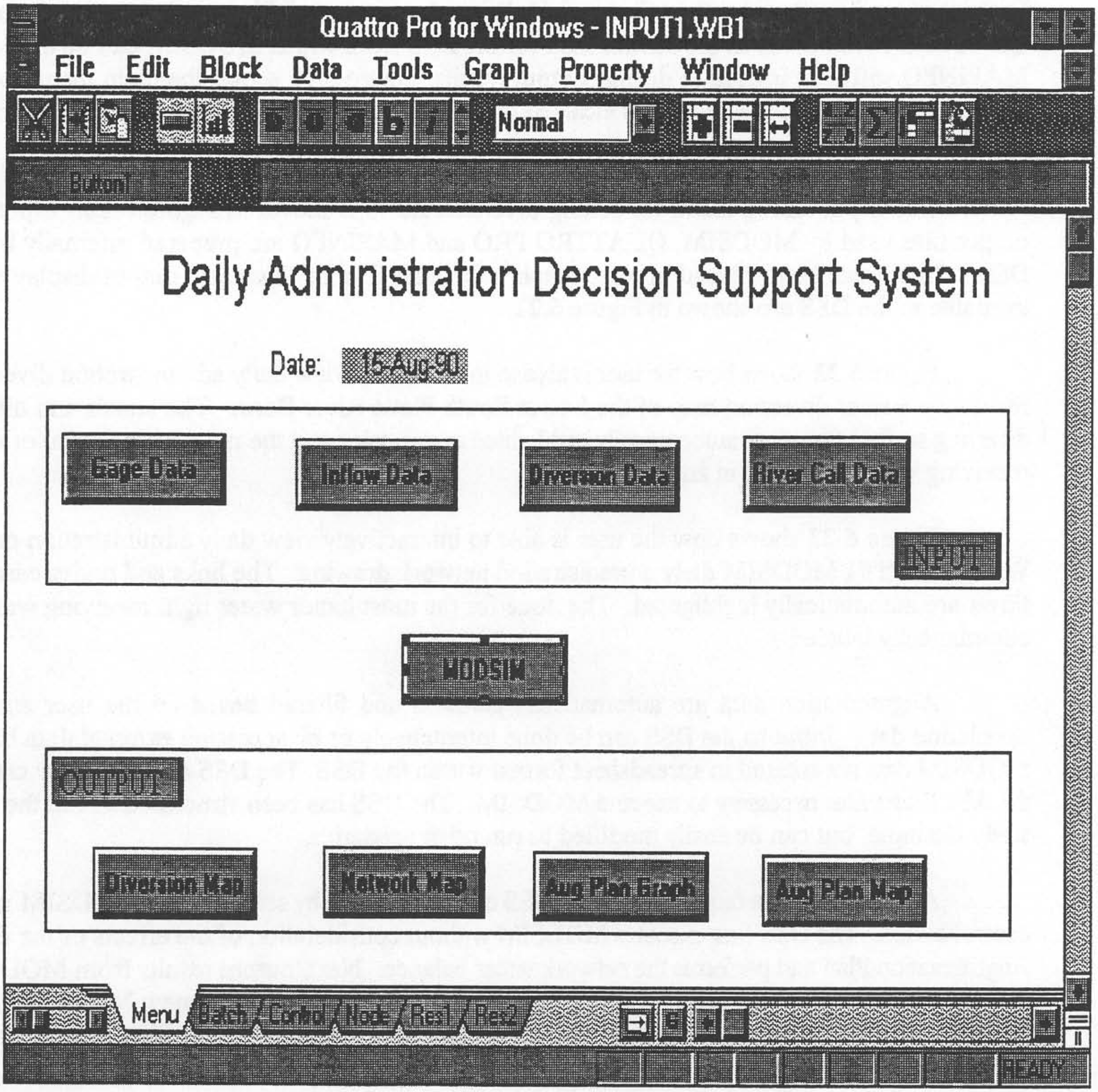
Figure 6.22 shows how the user is able to interactively view daily administration diversion results on a river diversion map of the Lower South Platte River Basin. The canals and ditches diverting surface flows are automatically highlighted in one color and the most junior canal or ditch receiving water is shaded in another color.

Figure 6.23 shows how the user is able to interactively view daily administration on the Water District #1 MODSIM daily administration network drawing. The links and nodes carrying flows are automatically highlighted. The node for the most junior water right receiving water is automatically labeled.

Augmentation data are automatically selected and filtered based on the user entered simulation date. Input to the DSS can be done interactively or by accessing external data bases. MODSIM data are entered in spreadsheet format within the DSS. The DSS automatically creates the ASCII text files necessary to execute MODSIM. The DSS has been structured to run the case study example, but can be easily modified to run other scenarios.

After entering the required data, the DSS can be executed by selecting the MODSIM menu control button. The DSS first executes MODSIM without consideration of the effects of the Bijou Augmentation Plan and performs the network water balance. Next, output results from MODSIM are imported back into the DSS. These files are used by the DSS to set up new MODSIM input files and the DSS then reruns the daily MODSIM model to account for the Bijou Augmentation Plan effects.

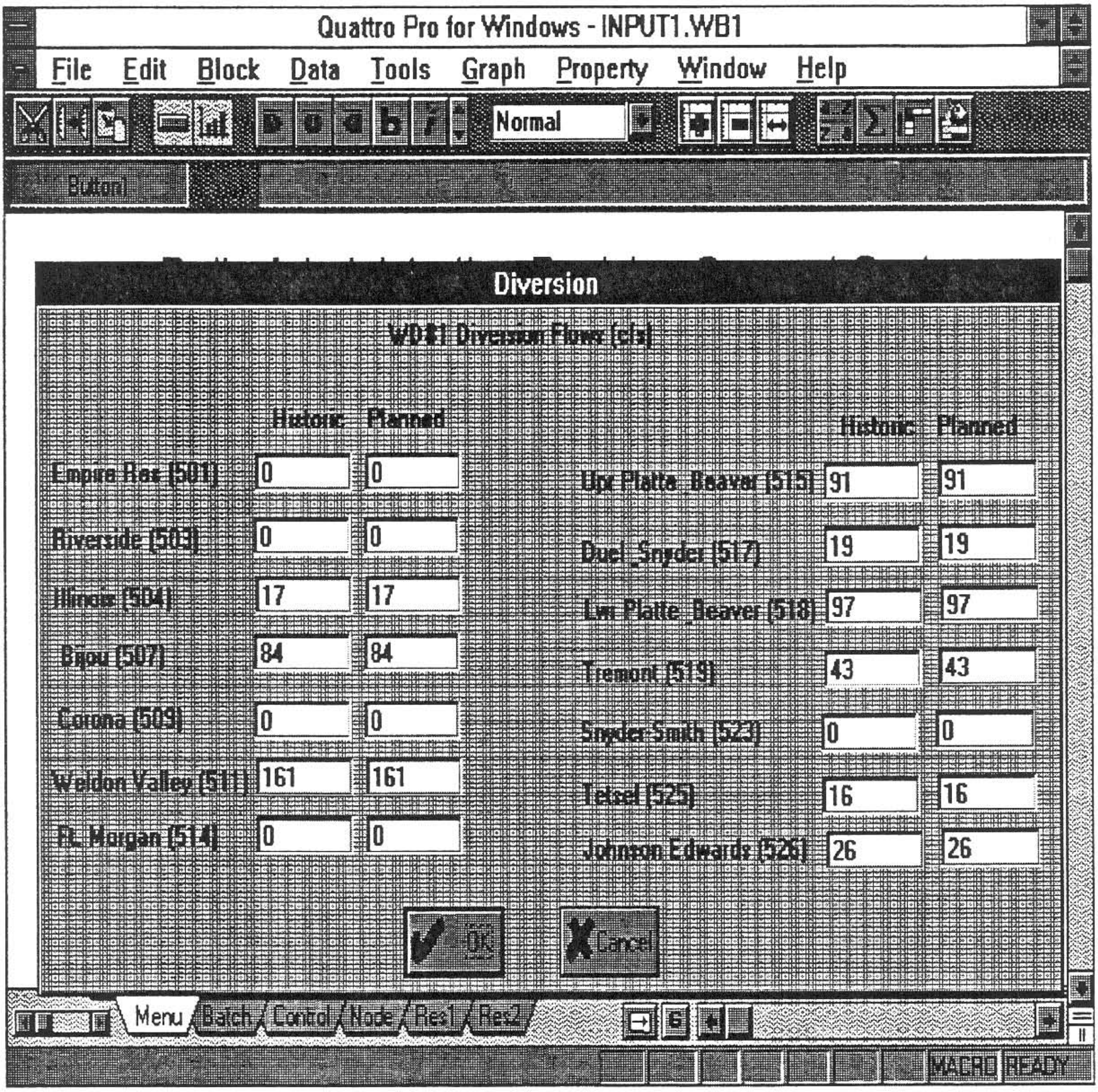
The DSS converts MODSIM output files into a database format that can be read directly by MAPINFO for displaying results. MAPINFO is accessible from within the DSS using the main menu control buttons.



Daily Administration Decision Support System

Date: 15-Aug-90

Figure 6.19. Daily Administration DSS Main Menu

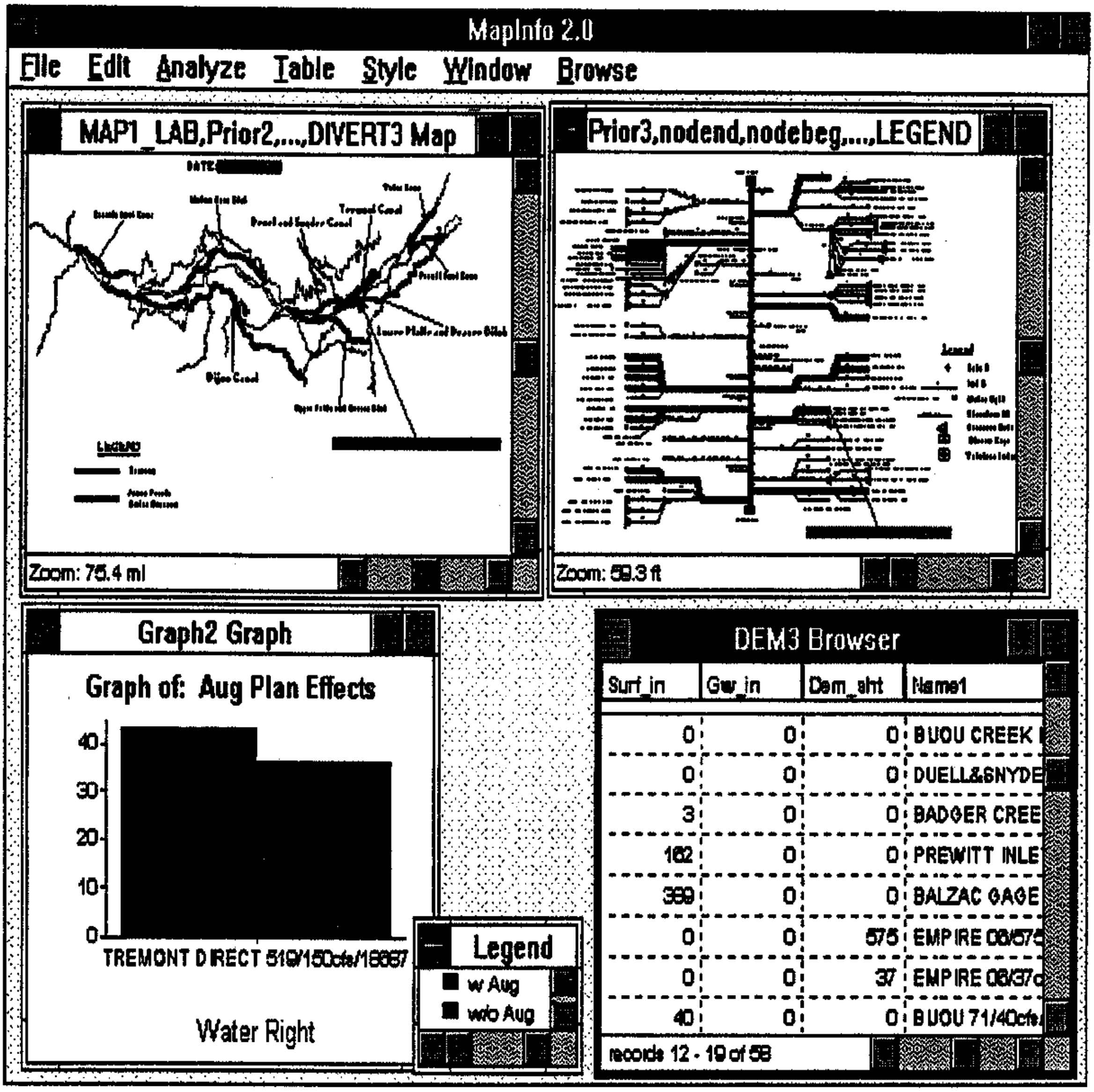


WD#1 Diversion Flows (cfs)

	Historic	Planned
Empire Res (501)	0	0
Riverside (503)	0	0
Illinois (504)	17	17
Bijou (507)	84	84
Corona (509)	0	0
Weldon Valley (511)	161	161
Ft. Morgan (514)	0	0

	Historic	Planned
Upr Platte_Beaver (515)	91	91
Duel_Snyder (517)	19	19
Lwr Platte_Beaver (518)	97	97
Tremont (519)	43	43
Snyder Smith (523)	0	0
Tetsel (525)	16	16
Johnson Edwards (526)	26	26

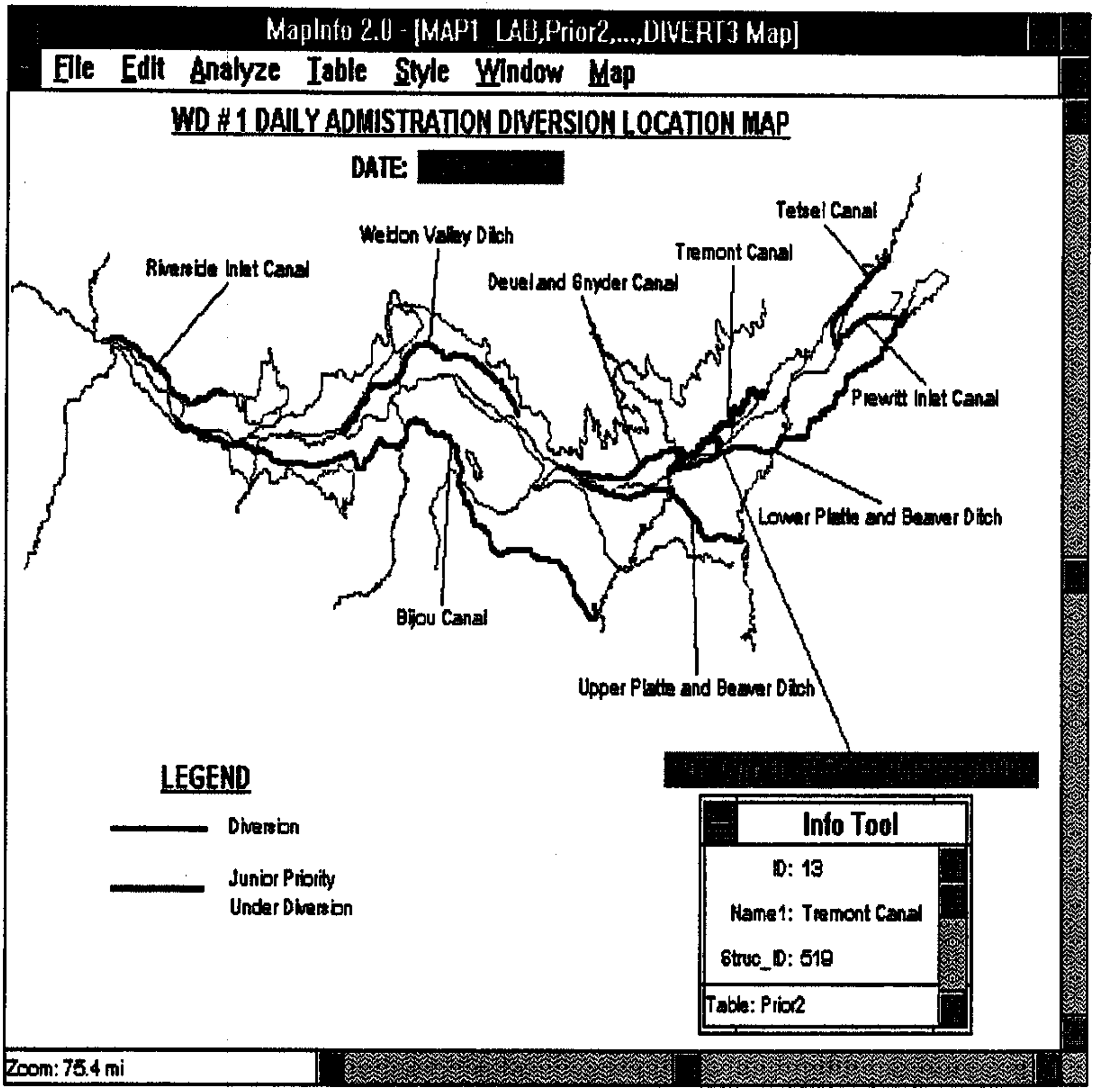
Figure 6.20. Daily Administration DSS Diversion Input Menu



Surf_in	Gw_in	Dem_sht	Name1
0	0	0	BIJOU CREEK
0	0	0	DUELL&SNYDE
3	0	0	BADGER CREE
162	0	0	PREWITT INLE
389	0	0	BALZAC GAGE
0	0	575	EMPIRE 06/575
0	0	37	EMPIRE 06/37c
40	0	0	BIJOU 71/40cfs

records 12 - 19 of 58

Figure 6.21. Daily Administration DSS Example Output



ID: 13

Name1: Tremont Canal

Struc_ID: 519

Table: Prior2

Figure 6.22. Daily Administration DSS Diversion Map

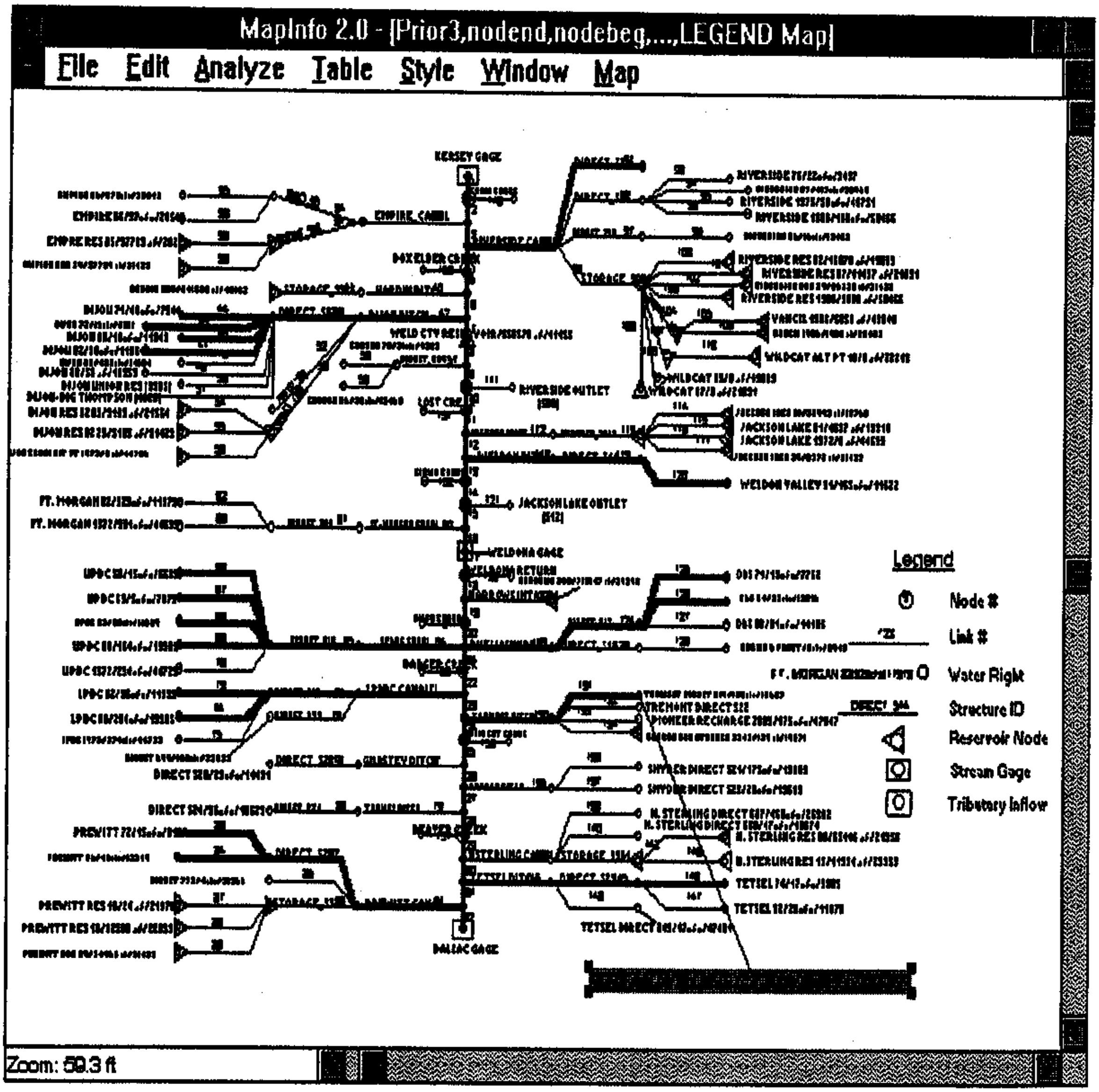


Figure 6.23. Daily Administration DSS Network Map

6.11 Discussion of Results

The case study demonstrates how decision support system concepts and techniques can successfully be applied to a conjunctive use management problem for a large regional river basin with complex water rights. The resource inventory indicates that a large amount of water resource data, sufficient to model a large river basin, are available from several sources. Unfortunately, no central resource center is in place for distributing or locating the data. To collect information and data, it is necessary to contact each agency and often different persons within the same agency. Most data are available in digital format; however, lack of compatibility in data formats complicates the transfer of files between computers. It was found that most PC based commercial software packages are able to import or export DBF (dBASE III/IV) files and system data format (ASCII text) files structured in database format. These formats were adopted for use in the DSS. Most interface software requirements needed to link DSS components can be written using the internal macro languages found in the various commercial software packages used by the DSS.

The introduction of GIS and database technology to preprocess input data and postprocess output data greatly expands the potential of groundwater models as a management tool for regional basin studies. For example, the Lower South Platte River summary data on basin diversions, tributary inflow, gage flow, and reach gain and loss were calculated by importing USBR PTFLOW model output results into DBASEIV and using the *sum* and *group by* functions. All of the major files required for executing the USGS finite groundwater model MODFLOW can be prepared using GIS and database techniques. The abilities to transfer vector based hydrography data from USGS digital databases, rasterize or grid the data using GIS software, and overlay the results with other aquifer data to prepare a file directly readable by a finite difference groundwater model as a boundary file, provides powerful computational tools It is no longer necessary to aggregate or lump physical components because of computer or data processing limitations. Individual response units, such as single wells, river reaches, tributaries, recharge sites, and recharge ponds, can be included in the modeling process as easily as aggregated data.

The case study demonstrates in detail the actual steps required to develop groundwater response coefficients for use in any river basin simulation model that has a groundwater component. Groundwater response coefficients for individual wells, canals, drains, ditches, reservoirs and pond recharge sites; and their effects on a major river and its tributaries, can be calculated. Because of the GIS and database procedures, separate sets of coefficients for individual river, canal, and drain sub-reaches can also be generated. These response coefficients, once determined, can be used repeatedly in different river basin simulations.

A 1000 ft x 1000 ft groundwater grid size for the finite difference model was selected to test the computational limits of using a small grid size in a regional model. It is common for regional studies not using GIS procedures to restrict grid size to 1 mile by 1 mile in order to simplify data entry (Maurer, 1986; Morel-Seytoux and Restrepo, 1987). Although the grid size used in the finite difference model has a major effect on computation time, the case study showed that developing a data set and executing a large groundwater model of 370 x 140 cells is manageable. One parameter in the groundwater model that needs additional attention is river bed conductance, as used in the MODRSP/MODFLOW River input data file. The technical literature provides little consensus on the physical basis for determining this important parameter.

The results of the case study have shown that groundwater response coefficients derived from a finite difference groundwater model can be integrated into a full scale river basin simulation model by using MODSIM to simulate a groundwater augmentation plan. The Bijou Augmentation Plan was selected because it is a complex system that includes 193 wells, 30 recharge sites, four tributaries, and 13 river reaches. Seven years of monthly data recharge and well pump data are also available (1984-1991). Although these hydrologic data were input from data records provided by the NCWCD, it is possible to expand the network to make these calculations within MODSIM.

MODSIM was run using two different sets of response coefficients: the numerical coefficients calculated using the MODRSP finite difference groundwater model and analytical coefficients calculated with the Glover equation using predefined SDF values. Use of the analytically based SDF coefficients produces significantly lower net river return flow values when compared with results from the numerically based finite difference coefficients (i.e., 18,900 ac-ft vs 44,200 ac-ft). This difference can be attributed to the inclusion of tributary flows in the simulation using the MODRSP finite difference coefficients.

The MODRSP finite difference coefficients generate net river return responses that follow a pattern similar to the net sum of the augmentation plan recharge and pumping flows. The distribution pattern for the SDF based net river return responses show a positive net gain in return flows over time which are substantially less dependent on the recharge/pumping flow trends. Deficits appear in 7 out of 84 months with use of the MODRSP finite difference coefficients, with deficits distributed over seven different months. On the other hand, the Glover based SDF method spawns no deficits in any of the 84 months.

The SDF coefficients produce unit response hydrographs with longer durations and lower peaks than the MODRSP coefficients. Time to peak for both methods generally occurrs in the first few periods. Because of differences in the shapes of the unit response hydrographs, the Glover-SDF derived coefficients yield results that eliminate net river depletions, while the MODRSP finite difference response coefficients only reduce and redistribute the effects on net river depletions.

The case study identifies several of the basic differences between the two methods of generating response coefficients. Although the SDF method requires less computation time than the finite difference method (i.e., 232 Glover-SDF derived unit response curves vs. 1079 MODRSP derived unit response curves), the theoretical and spatial capabilities of the response coefficients derived from a finite difference groundwater model make this methodology a more powerful tool in stream-aquifer modeling. The Glover method uses only three variables to represent aquifer characteristics: average distance from the return flow source to the well site or channel reach, an average aquifer transmissivity, and an average aquifer specific yield. The stream depletion factor (SDF) combines all these variables into a single lumped parameter. The finite difference groundwater model considers spatial variation in aquifer characteristics and the effects of complex boundary conditions. The case study demonstrates that once the MODRSP finite difference response coefficients have been prepared, they can be used in MODSIM as easily as the Glover based SDF coefficients to model stream-aquifer interaction.

The river basin simulation model MODSIM was also applied as a daily administrative model. The daily model can be used to simulate river administration regulated under prior appropriation water right laws. Procedures are presented for determining the effects of a groundwater augmentation plan on daily river administration. The MODSIM network structure proposed for the case study allows water right priorities and flow diversions by structure to be linked together in a single model. The same network can be used for daily river planning, management, and evaluation.

The use of commercial software packages to develop a prototype DSS was accomplished by integrating QUATTRO PRO, MAPINFO and MODSIM software. QUATTRO PRO serves as the shell. Output from the Bijou Augmentation Plan MODSIM study is used as input to the daily administration model. The daily administration DSS is able to run MODSIM with and without considering the effects of the Bijou Augmentation Plan. The results of the first simulation are used as input to the second simulation and MODSIM is then rerun. This is all done automatically from within QUATTRO PRO.

Results for the daily administration example showed that the influence of the augmentation plan on Water District #1 water rights administration was not significant (7 cfs), even though the Bijou Augmentation return flow did constitute up 20% of the unmeasured inflow to the river. The daily administration case study did demonstrate that the affects of an augmentation plan can be accurately quantified spatially and in time, and integrated into a river basin simulation model.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

A prototype microcomputer based Stream-Aquifer Management Decision Support System (SAMDSS) has been presented with three components: database management system, model management system, and user management system or user interface. SAMDSS includes the capability of utilizing groundwater response coefficients generated from a groundwater flow model and a management capability for analysis of various conjunctive use scenarios. SAMDSS includes use available and widely accepted water resource models. Procedures and guidelines for linking and using various predictive models are included in SAMDSS. Data files and model input and output routines are structured around database concepts. Commercial software packages such as Lotus 1-2-3 and dBASEIV are used for interfacing, presenting, summarizing, and analyzing model results. GIS and database management tools are applied to preprocessing and postprocessing data.

A number of activities were carried out to develop the working SAMDSS. The first step was preparation of the conceptual model for a conjunctive stream-aquifer management decision support system. Next, the software components and software to be used were identified. MODSIM was selected as the river basin water rights and network flow model. The USGS finite difference model MODFLOW was selected as the groundwater flow model. MODRSP, a modified version of MODFLOW, was chosen as the numerical groundwater model for generating response coefficients. The USBR program PTFLOW was identified as a model that could be used to calibrate aquifer return flows. AUTOCAD (vector) and IDRISI (raster) were selected as the GIS software packages, along with DBASEIV as the database package. LOTUS 1-2-3 and QUATTRO PRO were used for spreadsheet calculations. MAPINFO and Microsoft Windows were used in developing the prototype user interface. The DSS was structured for use in a DOS/Windows-based microcomputer environment.

SAMDSS uses stream-aquifer response coefficients to model return flow, stream depletion flow, and stream aquifer responses over time due to reservoir seepage, irrigation and precipitation infiltration, well pumping, channel conveyance losses, artificial recharge from ponds, reservoirs, channels, and wells. Response coefficients can be generated from three sources: (i) a numerical finite difference model using a discrete kernel/response function approach; (ii) analytical methods using one-dimensional groundwater equations, or (iii) using predefined SDF values. Details and provisions have been included in SAMDSS for using GIS tools and techniques for preparing and processing data for input into the various models. A source list for digital data and public domain databases was prepared. Special utility programs were written to convert data to common formats for use in SAMDSS. Where possible, input and output data files for the various models selected for use in SAMDSS were structured as ASCII database text files.

To demonstrate the capabilities of the SAMDSS, a case study was carried out on a portion of the Lower South Platte River Basin, Colorado. The case study uses actual data to develop stream-aquifer response coefficients using GIS, database technology, and the groundwater finite difference model MODRSP. The water right return/depletion flow account for the Bijou Irrigation Company groundwater augmentation plan was simulated using MODSIM. The plan involves approximately 200 wells and 30 recharge areas with data for a seven year period from 1985 to 1991. Two simulations studies were conducted:: one with stream-aquifer coefficients generated from MODRSP, and the second with groundwater response coefficients generated by MODSIM using predefined SDF values. A separate MODSIM network was constructed for the Lower South Platte River Colorado State Engineer Water District #1 to simulate daily administration of a river regulated under prior appropriation water right laws. Data provided by the State Engineer were used to demonstrate the use of MODSIM to simulate an actual river call. The simulation was carried out with and without considering the effects of the Bijou augmentation plan to show the effects of a groundwater augmentation plan on daily administration of water rights. Two separate prototype user interfaces, one using the Bijou augmentation plan flow account network and the other using the daily administration example, were constructed using MAPINFO to demonstrate some of the capabilities inherent in a successful decision support system.

7.2 Conclusions

It has long been recognized in the Western United States that maximum water development can only be met through conjunctive use of surface and groundwater. Although considerable progress has been made in the development of regional groundwater models and river basin simulation models, previous attempts at linking these two types of models into a workable conjunctive use model for comprehensive river basin planning, management, and administration have not been completely successful. With recent advances in computer hardware and software technology such as geographic information systems (GIS) and data base management system technology (DBMS), it is now possible to develop a computer based river basin decision support system for improved conjunctive use management of groundwater and surface water by linking a finite difference groundwater flow model with a river basin network model.

Although most water managers and water resource planners appreciate that computer-based decision support tools are needed to assist in developing and administering alternative water resource planning and management strategies, many of the important agencies and organizations directly responsible for water planning, management, and administration are not making effective use of these models. Computer modeling structured around decision support theory can help bridge the gap between model development and model use.

Because each river system and model user has individual requirements that many times can not be met from an *off-the-shelf* commercial package, research efforts are best directed towards development of a collection of tools with guidelines and procedures that can be effectively applied to any river basin, instead of towards the development of a single large, general, and comprehensive model.

The key to the development of computer-based decision support tools is through a synthesis of existing technology rather than development of new models. A decision support system framework can be used to develop interfaces to link various modeling and database components. The modeling component should allow the user the option of problem solving using already familiar and recognized analytical procedures or using more theoretically based techniques that take advantage of computer technology advances such as geographic information systems. The data base component should be able to interact directly with existing data bases.

Although GIS has been used extensively in a variety of water resource projects over the past 20 years, it is receiving renewed attention by many in the water resources field. One reason may be that only now are GIS systems, such as IDRISI, becoming usable in a computational environment that is affordable and generally available to researchers and practitioners. As a result, the state-of-the-art in interactive and integrated regional river basin planning and management can be implemented at a working level. Without the use of GIS and database technology, it would not be practical or cost-effective to develop groundwater response coefficients from a finite difference flow model and use these stream-aquifer response functions in a full scale river basin simulation model.

The use of a quasi-simulation model which combines simulation and optimization offers distinct advantages over a standard river basin simulation models, particularly for use in allocating water according to demands and targets based on priorities established by water rights. As compared with many of the more common river basin simulation models such as HEC5, SSARR, IRIS, HYDROSS, MODSIM is most effective for modeling complex water rights and conjunctive-use groundwater events.

One limitation in the implementation of decision support system technology has been in the time and cost required to develop a proper user interface. Modestly priced desktop mapping software packages such as MAPINFO allow users and developers to take advantage of extended memory, Windows environment, and computational speed now available on DOS based microcomputers. These packages also make it possible for non-programmers and users to tailor input and output procedures to meet individual requirements.

The use of groundwater response coefficients generated from a numerical finite difference model versus an analytical model offers the advantage of incorporating spatially distributed information in predicting groundwater flow responses. The user is able to consider the influence of distributed aquifer characteristics, aquifer boundaries, tributaries, variable stream levels, constant head reservoirs and ponds, and most importantly, the spatial distribution and location over time of depletion and return flows resulting from well pumping and groundwater recharge.

Model input and output subroutines should be programmed to read and write data in database format as ASCII text files. This makes it convenient to use readily available database or spreadsheet software to preprocess and postprocess data. Study-specific *front ends* and graphical user interfaces can be developed without having to access and modify original model source code. Data from existing databases or data output from other computer models can be read directly into models as an input data file. This allows users and developers to employ standard and commercial software for preprocessing and postprocessing data without having to modify or even access model source code. It also makes it easier to read data directly from existing databases or output data for use by another model. Finally it encourages the development of a centralized database that can be accessed by more than a single user working with a single model.

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APPENDIX A

LAGRANGIAN RELAXATION ALGORITHM FOR SOLVING MINIMUM COST NETWORKS

A.1 Problem Formulation

The minimum cost network flow problem solved in MODSIM is formulated as follows, where link *[i,j]* is designated by the node pair *[i,j]* representing the beginning and ending nodes of the link, respectively. This notation implies one unique node pair for each link, and is used for convenience in the following development only. The algorithm is actually capable of considering multiple links for the same node pair. The objective function is :

$$\min \sum_{(i,j)\in A} c_{ij}\bar{x}_{ij}$$

subject to:

$$\sum_{\{j|(i,j)\in A\}} \bar{x}_{ij} - \sum_{\{j|(j,i)\in A\}} \bar{x}_{ji} = 0 \quad \forall\ i\in N$$

$$\bar{l}_{ij} \le \bar{x}_{ij} \le \bar{u}_{ij} \quad \forall\ (i,j)\in A$$

where $\bar{x}_{ij}$ represents the flow rate in link *[i,j]*, with link parameters $[\bar{l}_{ij}, \bar{u}_{ij}, c_{ij}]$. A transformation can be performed to remove the lower bounds from this problem. Let

$$x_{ij} = \bar{x}_{ij} - \bar{l}_{ij} \quad or \quad \bar{x}_{ij} = x_{ij} + \bar{l}_{ij}$$

$$u_{ij} = \bar{u}_{ij} - \bar{l}_{ij} \quad \forall\ (i,j)\in A$$

The transformed objective function is now formulated as:

$$\min \sum_{(i,j)\in A} c_{ij}[x_{ij} + \bar{l}_{ij}]$$

Since the constant term can be removed, the objective is:

$$\min \sum_{(i,j)\in A} c_{ij}x_{ij}$$

subject to:

$$\sum_{\{j|(i,j)\in A\}} [x_{ij} + \bar{l}_{ij}] - \sum_{\{j|(j,i)\in A\}} [x_{ji} + \bar{l}_{ji}] = 0 \quad \forall\ i \in N$$

$$0 \le x_{ij} \le u_{ij} = \bar{u}_{ij} - \bar{l}_{ij} \quad \forall\ (i,j) \in A$$

or

$$\sum_{\{j|(i,j)\in A\}} x_{ij} - \sum_{\{j|(j,i)\in A\}} x_{ji} = s_i \quad \forall\ i \in N$$

where

$$s_i = \sum_{\{j|(j,i)\in A\}} \bar{l}_{ji} - \sum_{\{j|(i,j)\in A\}} \bar{l}_{ij} \quad \forall\ i \in N$$

In this formulation, all link parameter data $[u_{ij}, c_{ij}]$ and s_i are assumed to be integer.

A.2 Lagrangian Relaxation Algorithm

The solution to this problem is based on a Lagrangian relaxation algorithm developed by Bertsekas (1991). Introducing Lagrange multipliers or dual prices p_i, the Lagrangian function is defined as:

$$L(x,p) = \sum_{(i,j)\in A} c_{ij} x_{ij} + \sum_{i\in N} p_i \Big[s_i - \sum_{\{j|(i,j)\in A\}} x_{ij} + \sum_{\{j|(j,i)\in A\}} x_{ji} \Big]$$

Note that:

$$\sum_{(j,i)\in A} p_i x_{ji} = \sum_{(i,j)\in A} p_j x_{ij}$$

Therefore:

$$L(x,p) = \sum_{(i,j)\in A} [c_{ij} + p_j - p_i]\, x_{ij} + \sum_{i\in N} s_i p_i$$

Instead of attempting to directly solve the original minimum cost network flow problem, the goal is to successively obtain updated dual price vectors p that solve the following *dual problem*:

$$\max\ \phi(p)$$

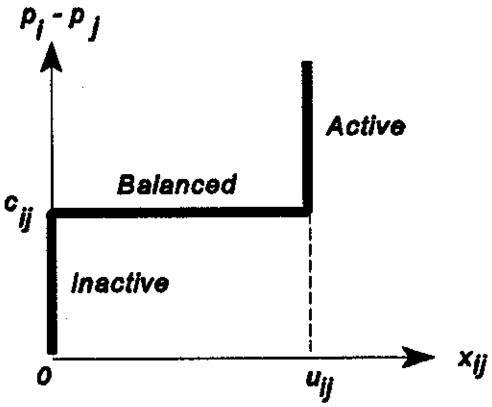
where

$$\phi(p) = \sum_{(i,j)\in A} \phi_{ij}(p_i - p_j) + \sum_{i\in N} s_i p_i$$

with

$$\phi_{ij}(p_i - p_j) = \min_{0\le x_{ij}\le u_{ij}} (c_{ij} + p_j - p_i)x_{ij}$$

$$= \begin{bmatrix} (c_{ij} + p_j - p_i)u_{ij} & \text{if } p_i > c_{ij} + p_j \\ 0 & \text{if } p_i \le c_{ij} + p_j \end{bmatrix}$$



Solution of the dual problem results in solution of the original minimum cost network flow problem. Notice that in the dual problem, the node mass balance constraints are temporarily *relaxed* since they are placed in the objective function via the Lagrangian function; hence, the term *relaxation algorithm.* The link capacity constraints remain explicitly accounted for. The objective is to find the optimal dual price vector p that will result in a solution that will fully satisfy the node mass balance constraints. The advantage of this approach is that the inner minimization problem as defined by $\phi_{ij}(p_i - p_j)$ is extremely easy to solve. The following complementary slackness conditions are optimality conditions associated with flow in link *[i,j]* for a given dual price vector p:

inactive arc $[x_{ij} = 0]$ *if:* $p_i < c_{ij} + p_j$
balanced arc $[0 \le x_{ij} \le u_{ij}]$ *if:* $p_i = c_{ij} + p_j$
active arc $[x_{ij} = u_{ij}]$ *if:* $p_i > c_{ij} + p_j$

The basic duality result of linear programming states that: If a feasible flow vector x^* and a price vector p^* sastisfy the complementary slackness conditions, then x^* is an optimal solution of the minimum cost flow problem and p^* is an optimal solution of the dual problem. The optimal solution of the dual problem is found using a coordinate-wise dual ascent algorithm.

Define the surplus g_i of node i as the difference between the total inflow into node i, less the total outflow from node i:

$$g_i = \sum_{\{j|(j,i)\in A\}} x_{ji} - \sum_{\{j|(i,j)\in A\}} x_{ij}$$

At the start of an iteration, an integer flow-node price pair (x,p) is assumed to be available which satisfy complementary slackness. The current iteration will indicate: (i) if the primal problem is infeasible (i.e., node surplus $g_i < 0$ for some i); (ii) if (x,p) is optimal (i.e., $g = 0$ for all i, implying that x is feasible and, since complementary slackness is satisfied, is also optimal); or (iii) if a new pair can be found improves the dual objective function (i.e., $g_i > 0$ for at least one node i). For the latter case, the iteration begins by selecting node k such that $g_k > 0$. The iteration maintains the two sets: S and L ; where $S \subset L$. At the initial iteration, set $S = \{\emptyset\}$ and $L = \{k\}$. A label is also maintained for all nodes $\in L$ which is an incoming arc to that arc.

The goal is to maximize the dual objective function, which will result in solution to the original minimum cost network flow problem. A dual ascent direction is defined using the nodes contained in set S. Since set S usually contains a single node, the search procedure generally proceeds in one coordinate direction at a time. Dual prices are changed in the dual ascent direction so as to increase the dual objective function. Since the goal is to eventually achieve a solution where all $g_i = 0$, a flow augmentation step occurs in the algorithm where a path through the network is defined from a node k where $g_k > 0$ to a node j, where $g < 0$. This means that flow can be increased along that path, resulting in improved node surplus conditions for both nodes.

A.3 Typical Relaxation Iteration

0. INITIALIZATION

Select a node k with node surplus $g_k > 0$ [if no such node can be found, then the solution is optimal or infeasible]

$$g_k = \sum_{(j,k)\in A} x_{jk} - \sum_{(k,j)\in A} x_{kj} + s_k$$

- Let the set of labels $L = \{k\}$
- Let the direction vector set $S = \{\emptyset\}$

1. CHOOSE A NODE TO SCAN

```
•   IF $S = L$ [i.e., we are sure of ascent direction]
        GOTO Step 4 and perform price change
    ELSE
        select node $i$ which is contained in the current set of labels, but not in the
        current direction vector set; i.e., select $i \in L - S$
        $S: = S \cup \{i\}$
        GOTO Step 2
```

2. LABEL NEIGHBORING NODES OF i

- Check the directional derivative of the dual objective:

$$y'(p;d_S) = \sum_{(j,i):\,active,\,j\notin S,\,i\in S} u_{ji} - \sum_{(i,j):\,active\ or\ balanced,\,i\in S,\,j\notin S} u_{ij} + \sum_{i\in S_i} s_i$$

where direction vector $d_S = (d_1,\ldots,d_N)$, with

$$d_i = \begin{bmatrix} 1 & if\, i\in S \\ 0 & if\, i\notin S \end{bmatrix}$$

- IF $y' > 0$, then current direction d_S is an ascent direction
  GOTO price change [Step 4]

ELSE add to labeled set of neighboring nodes that can eventually result in identification of a flow augmentation path from node k to node j:
$L = L + \{j\}$ for all nodes j such that:

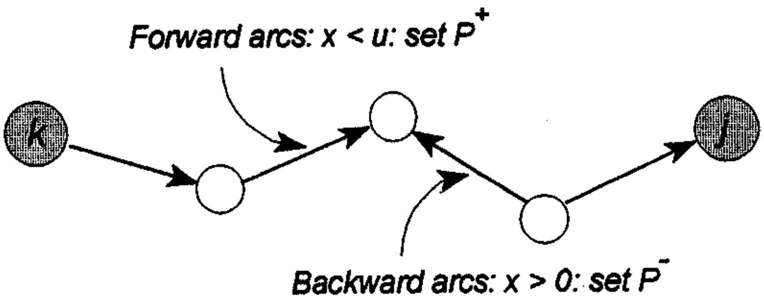
- link (j, i) is balanced and $x_{ji} > 0$ [assign label (j, i)], or
- link (i, j) is balanced and $x_{ij} < u_{ij}$ [assign label (i, j)]

IF for every node j added to L, we have $g_j > 0$, then we have not yet found a flow augmentation path: RETURN to Step 1
ELSE: Select one of the nodes j with: $g_j < 0$; GOTO Step 3

3. FLOW AUGMENTATION

A flow augmentation path P has been found starting at node k and ending at the node j found in Step 2. Since $g_k > 0$ and $g_j < 0$, then flow can be increased along the path such that g_k will decrease towards zero, and g_j will increase towards zero, subject to limitations.

Path P is constructed by tracing labels backward starting from j, where P^+ is the set of all forward arcs and P^- is the set of backward arcs:



Calculate:

- For all links in P^+, ADD δ to the current flows.
- For all links in P^-, SUBTRACT δ from the current flows.
- GOTO NEXT ITERATION.

$$\delta = \min \begin{cases} g_k \\ -g_j \\ (u_{mn} - x_{mn}) \quad \forall (m,n) \in P^+ \\ (x_{mn}) \quad \forall (m,n) \in P^- \end{cases}$$

4. **PRICE CHANGE**

Set

$$\begin{aligned} x_{ij} &= u_{ij} \quad \forall \text{ balanced links } (i,j) \text{ with } i \in S, j \notin S \\ x_{ji} &= 0 \quad \forall \text{ balanced links } (j,i) \text{ with } i \in S, j \notin S \end{aligned}$$

Let

$$\gamma = \min \begin{cases} \{c_{ij} - (p_i - p_j)\} \mid x_{ij} < u_{ij},\ i \in S, j \notin S \\ \{-c_{ji} - (p_i - p_j)\} \mid x_{ji} > 0\ ,\ i \in S, j \notin S \end{cases}$$

Set

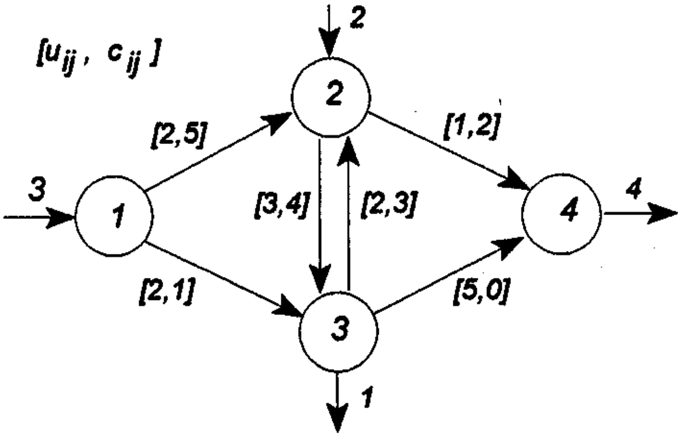
$$p_i = \begin{cases} p_i + \gamma \quad IF\ i \in S \\ p_i \quad OTHERWISE \end{cases}$$

GOTO NEXT ITERATION

A.4 Example Problem

Consider the example network below, where exogenous flows are shown as supply and demand entering and leaving (respectively) each node. The link parameters are shown on each link, with all lower bounds set to zero. The objective is to find the minimum cost flow through the network that satisfies mass balance and all link flow upper bounds.

We begin with an initial solution for the integer flow vector, dual price vector pair as *(x,p)* = *(0,0)*. Notice that this solution satisfies the complementary slackness conditions, but violates feasibility since node surpluses $g_i \neq 0$.



ITERATION #1

ARC	x_{ij}	u_{ij}	s_i	s_j	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	0	2	3	2	5	0	0	3	2	INACT
(1,3)	0	2	3	-1	1	0	0	3	-1	INACT
(2,3)	0	3	2	-1	4	0	0	2	-1	INACT
(2,4)	0	1	2	-4	2	0	0	2	-4	INACT
(3,2)	0	2	-1	2	3	0	0	-1	2	INACT
(3,4)	0	5	-1	-4	0	0	0	-1	-4	BAL

Dual Objective Function = 0 + 0 = **0**

Step

0. $L = \{1\};\ S = \{0\}$

1. Select $i \in L - S$; $S = S \cup \{i\}$

2. $$y' = \sum_{active} u_{ji} - \sum_{active\ or\ balanced} u_{ij} + \sum_{i \in S} s_i$$

$$= 0 - 0 + 3 > 0$$

4. No x_{ij} adjustment is made at this iteration, since this is only done for balanced arcs; calculate:

$$\gamma = \min \begin{cases} 0 - 0 + 5 \\ 0 - 0 + 1 \end{cases} = 1 \quad [\textit{for}\ \text{arc}(1,3)]$$

ITERATION #2

ARC	x_{ij}	u_{ij}	s_i	s_j	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	0	2	3	2	5	1	0	3	2	INACT
(1,3)	0	2	3	-1	1	1	0	3	-1	BAL
(2,3)	0	3	2	-1	4	0	0	2	-1	INACT
(2,4)	0	1	2	-4	2	0	0	2	-4	INACT
(3,2)	0	2	-1	2	3	0	0	-1	2	INACT
(3,4)	0	5	-1	-4	0	0	0	-1	-4	BAL

Dual Objective Function = 0 + 3 = 3

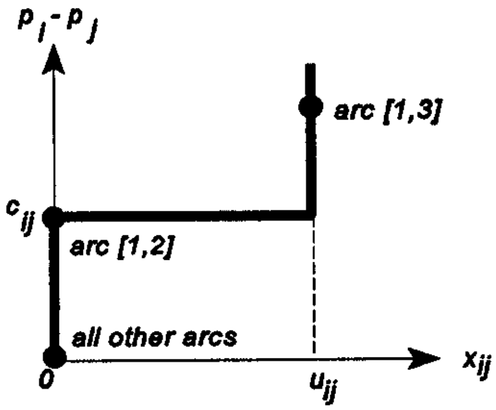
Step

0. $L = \{1\}$; $S = \{\phi\}$

1. Select $i \in L - S$; $S = \{1\}$

2. $y' = -2 + 3 = 1 > 0$

4. Link [1,3] is balanced--
   set $x_{13} = 2$
   $\gamma = 0 - 1 + 5 = 4$
   (for link [1,2]);
   therefore, $p_1 = 1 + 4 = 5$



ITERATION #3

ARC	x_{ij}	u_{ij}	s_i	s_j	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	0	2	3	2	5	5	0	1	2	BAL
(1,3)	2	2	3	-1	1	5	0	1	1	ACT
(2,3)	0	3	2	-1	4	0	0	2	1	INACT
(2,4)	0	1	2	-4	2	0	0	2	-4	INACT
(3,2)	0	2	-1	2	3	0	0	1	2	INACT
(3,4)	0	5	-1	0	0	0	0	1	-4	BAL

Dual Objective Function = 2 + 5 = 7

Step

0. $L = \{1\}$; $g_1 > 0$
[Note: node 1 is still selected, even though g_2 is a greater value]

1. $S = \{1\}$

2. $y' = -\sum_{\text{active or bal}} u_{ij} + \sum_{i \in S} s_i = -4 + 3 < 0$

$L = L + \{j\}$
$L = \{1,2\}$: outflow link *and* balanced *and* $x_{ij} < u_{ij}$
Check if $g_2 \geq 0$ [yes!]
RETURN TO Step 1:

1. $S = \{1\}$; $L = \{1,2\}$
Select $i \in L - S$; $i = 2$;
$S = \{1,2\}$

2. $y' = \sum_{i \in S} s_i = 5 > 0$

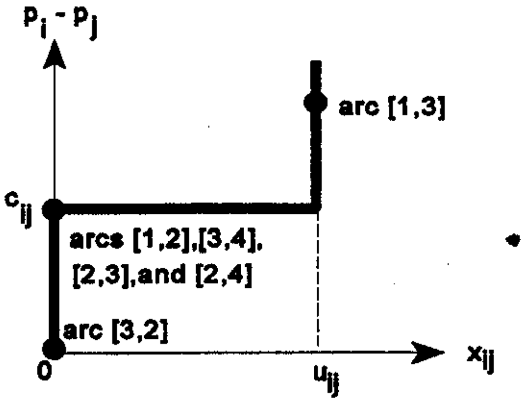
4. $\gamma = \min \{[p_j + c_{ij} - p_i]$ for arcs $[2,3], [2,4]\}$
$= \min \{4,2\} = 2$
Therefore, $p_1 = 5 + 2 = 7$; $p_2 = 0 + 2 = 2$

ITERATION #4

ARC	x_{ij}	u_{ij}	s_i	s_j	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	0	2	3	2	5	7	2	1	2	BAL
(1,3)	2	2	3	-1	1	7	0	1	1	ACT
(2,3)	0	3	2	-1	4	2	0	2	1	INACT
(2,4)	0	1	2	-4	2	2	0	2	-4	BAL
(3,2)	0	2	-1	2	3	0	2	1	2	INACT
(3,4)	0	5	-1	-4	0	0	0	1	-4	BAL

Dual Objective Function = 2 + 7 + 4 = 13

Step



0. L={1}; keep selecting node 1 since $g_1 > 0$

1. S={1}

2. $y' = (-2 -2) + 3 = -1 < 0$
   L = L + {j}
   L = {1,2}
   Check if $g_j \geq 0$ [Yes!]
   RETURN to Step 1

1. S = {1,2}; L = {1,2}

2. $y' = -2 - 1 + 5 = 2 > 0$

4. Does $x_{ij} = u_{ij}$ for all balanced arcs OUT? Yes!--arc [2,4]
   Therefore, set $x_{24} = 1$
   $\gamma = \min \{[p_j + c_{ij} - p_i]$
   for arc [2,3]} = 2
   Therefore $p_1 = 7 + 2 = 9$; $p_2 = 2 + 2 = 4$

ITERATION #5

ARC	x_{ij}	u_{ij}	s_i	s_j	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	0	2	3	2	5	9	4	1	1	BAL
(1,3)	2	2	3	-1	1	9	0	1	1	ACT
(2,3)	0	3	2	-1	4	4	0	1	1	BAL
(2,4)	1	1	2	-4	2	4	0	1	-3	ACT
(3,2)	0	2	-1	2	3	0	4	1	1	INACT
(3,4)	0	5	-1	-4	0	0	0	1	-3	BAL

Dual Objective Function = $2 + 2 + 9 \cdot 1 + 4 \cdot 1 = 17$

Step

0. L={1}; $g_1 > 0$

1. S={1}

2. $$y' = -\sum_{\text{active or balanced}} u_{ij} + \sum_{i \in S} s_i = (-2\ -2) + 3 = -1 < 0$$

   L = L + {j} with label (1,2)

L = {1,2}
Check if $g_2 > 0$; Yes!
RETURN to Step 1

1. S = {1,2}; L = {1,2}
2. $$y' = -\sum_{active/balanced\ OUT} u_{ij} + \sum_{i \in S} s_i = (-2-3-1)+5 = -1 < 0$$

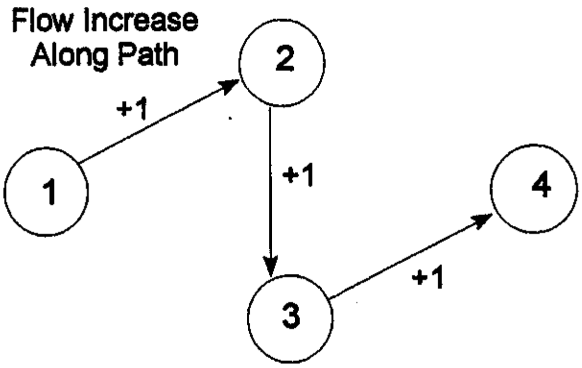
L = L + {j} with label (2,3)
L = {1,2, 3}
Check if $g_3 > 0$; Yes!
RETURN to Step 1

1. S = {1,2}; L = {1,2, 3}
   Select i ∈ L - S = 3
2. $$y' = -\sum_{active/balanced\ OUT} u_{ij} + \sum_{i \in S} s_i = (-1-5)+(3+2-1) = -1 < 0$$

L = L + {j} with label (3,4)
L = {1,2,3,4}
Check if $g_4 = < 0$; Yes! = -3; GOTO Step 3: Flow Augmentation

3. Path of flow augmentation P is 1-2-3-4
   [all forward arcs] ; so $P^+ = P$

$$\gamma = \min \begin{cases} \cdot 1 \quad [g_1] \\ \cdot -(-4)\ [- \\ \cdot 2\ [u_{12} - x_1 \\ \cdot 3\ [u_{23} - x \\ \cdot 5\ [u_{34} - x_3 \end{cases}$$



ITERATION #6

ARC	x_{ij}	u_{ij}	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	1	2	5	9	4	0	1	BAL
(1,3)	2	2	1	9	0	0	1	ACT
(2,3)	1	3	4	4	0	1	1	BAL
(2,4)	1	1	2	4	0	1	-2	ACT
(3,2)	0	2	3	0	4	1	1	INACT
(3,4)	1	5	0	0	0	1	-2	BAL

Dual Objective Function = 5 + 2 + 4 + 2 + 4 = 17

Step

0. L = {2}; S = {ϕ } ; node k = 2

1. S = {2}; i = 2
2. $y' = -\sum_{active/balanced\ OUT} u_{ij} + \sum_{i \in S} s_i = (-3 - 1) + 2 < 0$

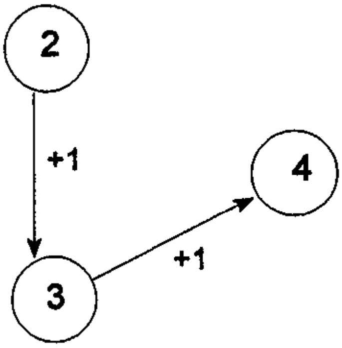
   L = L + {j} ; add node 1 [label (1,2)] and node 3 [label (2,3)]
   L = {1,2, 3} ; check $g_1 = 0$ and $g_3 = 1$ [both ≥ 0]
   RETURN to Step 1

1. set L - S = {1,3}
   Select node i = 3
   Therefore: S = {2,3}
2. $y' = \sum_{active\ IN} u_{ji} - \sum_{active/balanced\ OUT} u_{ij} + \sum_{i \in S} s_i = 2 - 5 + (2 + 1) = -2 < 0$

   L = L + {j} ; add node 4
   Check $g_4 = -2 < 0$; GOTO Step 3: Flow Augmentation

3. $\delta = \min\{1\ [g_2], 2\ [-g_4],$
   $4\ [u_{34} - x_{34}],$
   $2\ [u_{23} - x_{23}]$
   $= +1$

Flow Increase
Along Path



Path P: 2-3-4
All forward arcs--
Therefore, $P_+ = P$

ITERATION #7

ARC	x_{ij}	u_{ij}	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	1	2	5	9	4	0	0	BAL
(1,3)	2	2	1	9	0	0	1	ACT
(2,3)	2	3	4	4	0	0	1	BAL
(2,4)	1	1	2	4	0	0	-1	ACT
(3,2)	0	2	3	0	4	1	0	INACT
(3,4)	2	5	0	0	0	1	-1	BAL

Dual Objective Function = 5 + 2 + 8 + 2 = 17

Step

0. L = {3} ; S = {0} ; node k = 3

1. S = {3} ; node i=3

2. $y' = \sum_{active\ IN} u_{ji} - \sum_{active/balanced\ OUT} u_{ij} + \sum_{i \in S} s_i = +2 - 5 - 1 = -4 < 0$

   L = L + {j} ; add node 2 [label (2,3)] and node 4 [label (3,4)]
   L = (2,3,4}
   Check $g_2 = 0$; $g_4 = -1$ [both ≤ 0]

4. Path $P^+ = 3\text{-}4$; Path $P^- = 2\text{-}3$
   node k = 3 ; node j = 4
   $\delta = \min \{1\ [g_3],\ 1\ [-g_4],\ 3\ [u_{34} - x_{34}]\} = 1$

FINAL SOLUTION

ARC	x_{ij}	u_{ij}	c_{ij}	p_i	p_j	g_i	g_j	STATE
(1,2)	**1**	2	5	**9**	4	0	0	BAL
(1,3)	**2**	2	1	9	0	0	0	ACT
(2,3)	**2**	3	4	**4**	0	0	0	BAL
(2,4)	**1**	1	2	4	0	0	0	ACT
(3,2)	**0**	2	3	**0**	4	0	0	INACT
(3,4)	**3**	5	0	0	**0**	0	0	BAL

Notice that $g_i = 0$ for all nodes. Therefore, *dual objective* = *primal objective* and all complementary slackness conditions are satisfied.

APPENDIX B

PREPARING MODFLOW FILES USING IDRISI

B.1 Overview

A number of computer models have been developed to simulate complex groundwater stream-aquifer conjunctive use problems. One of the most widely used is the USGS Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) developed by McDonald and Harbaugh (1988). Groundwater flow is simulated using a block-centered finite difference approach. Layers can be simulated as confined, unconfined, or a combination of confined and unconfined. Flows associated with external stresses, such as wells, areal recharge, evapotranspiration, drains, and streams, can also be simulated.

B.2 Background

The movement of groundwater of constant density through saturated porous earth material can be described by the following partial differential equation:

$$\frac{\partial}{\partial X}(Kh\frac{\partial H}{\partial X}) + \frac{\partial}{\partial Y}(Kh\frac{\partial H}{\partial Y}) + Q = S\frac{\partial H}{\partial t}$$

where:

K = hydraulic conductivity or permeability
h = saturated thickness of aquifer
H = potential, referred to as an established datum
S = storage coefficient or effective porosity (specific yield)
Q = net groundwater withdrawal per unit area
X,Y= space dimensions
t = time dimensions

Specific yield is defined as the ratio of water that will drain freely from a volume of soil to the soil volume itself. For alluvial aquifers the value is about 0.2. Permeability or hydraulic conductivity is a velocity term expressed in $L^3/t/L^2$, or L/t. Transmissivity is a flow term used to better describe the characteristics of an aquifer and is equal to the average permeability times the saturated thickness of the aquifer.

A finite difference model such as MODFLOW replaces the continuous system described by the groundwater equation with a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points. This leads to a system of simultaneous linear algebraic difference equations. Important in the solution of the finite difference equations is proper simulation of the model boundary conditions. MODFLOW model allows specification of three types of boundary conditions:

- no flow
- constant head
- under flow (i.e., constant head gradient)

Typical data requirements for a finite difference model include:

- boundary conditions
- water levels
- aquifer characteristics
- well recharge and discharge
- surface hydrography
- recharge and ET considerations

B.3 Procedure

The following example serve to illustrate how to take groundwater and related data that have been digitized into IDRISI vector format, rasterize the data, perform required data manipulation, and output results for use in the USGS groundwater model, MODFLOW. Output from MODFLOW model will then be read back into IDRISI for presentation purposes. This example focuses on developing two input data files used by MODFLOW: a boundary data file and a transmissivity data file. After executing MODFLOW, aquifer water levels will then be read back into IDRISI. The finite difference network to be modeled is shown in Figure B.1.

Step 1: Load Data Files

The following files should be loaded into the IDRISI exercise directory:

IDRISI Files:

well.vec	[project well locations]
trans.vec	[transmissivity contour map]
aquifer.vec	[aquifer boundaries]
stream.vec	[stream location map]
head.img	[head water levels output from MODFLOW]

MODFLOW Files:

modflow.exe	[executable MODFLOW program]
unit1.dat	[basic package input file]
unit11.dat	[block-centered flow package input file]
unit12.dat	[well package input file]
unit19.dat	[strongly implicit procedure input file]
unit22.dat	[output control input file]
bound.dat	[boundary file from IDRISI]
trans.dat	[transmissivity file from IDRISI]

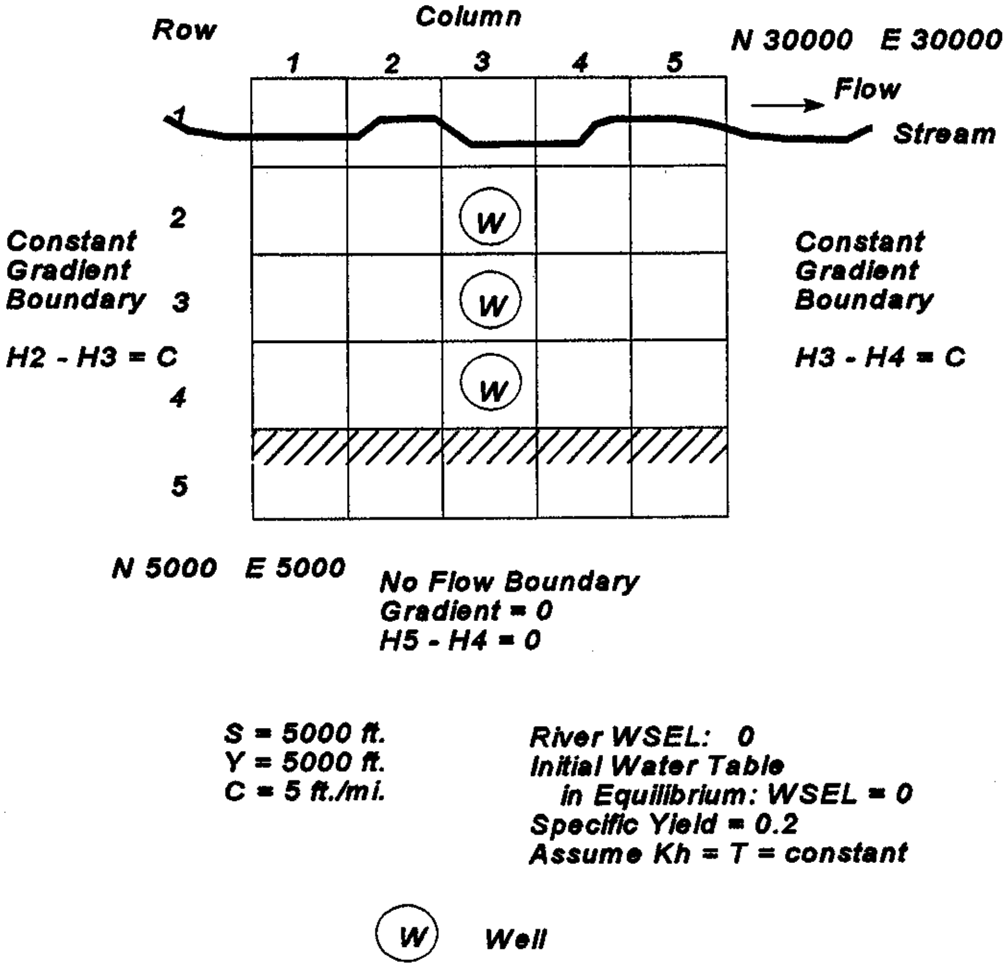


Figure B.1. Example Illustrating Data Preparation for Finite Difference Groundwater Flow Model Using GIS

Step 2: Create Document Files

Four vector files have been digitized for use in IDRISI:

well.vec
trans.vec
aquifer.vecs
stream.vec

These files all have integer attribute values and are in ASCII format. The x-y coordinates were digitized in "feet" units in a plane coordinate reference system with 1 unit equal to 1 foot.

For this problem assume we have a study area which spans the following map coordinates in feet:

N 5000 E 5000
N 5000 E 30000
N 30000 E 30000
N 30000 E 5000

Proper vector document files are required before the hdata can be used by IDRISI. When making these document files, it is important that the raster grid is the same size for all files. The maximum and minimum coordinate values should be entered directly and should correspond to the study area map coordinates listed above.

min x = 5000
max x = 30000
min y = 5000
max y = 30000

Use the **DOCUMENT** command in IDRISI to make the proper vector document header files. Note the object type for each of the files, respectivey:

well	[point coverage]
aquifer	[polygon coverage]
stream	[line coverage]
trans	[line coverage]

Step 3: Plot Vector Files

Data in the vector files may be displayed on the screen using the IDRISI **PLOT** command. To overlay and view each of the vector files on the screen at the same time, it is necessary to create a script file. The **EDIT** command is used to create the file PLOT.scr , which is composed of the following lines:

```
f u 3 aquifer
f u 5 stream
f u 6 well
f i 0 trans
r w 5000 30000 5000 30000 0
```

The **PLOT** command can now be used to load and display the vector files on the screen by entering the name of the script file PLOT when prompted for a file to load.

Step 4: Convert Vector Files to Raster Files

For the purpose of this example, it is only necessary to convert the aquifer, stream, and trans files to raster format.

(a) A raster file is first created using **INITIAL** that can be used to receive the transformed vector data. Each vector file requires its own raster or image file. The **INITIAL** command also creates the proper image DOCUMENT header file.

Image files are created with the following names and titles:

AQUIFER1 [aquifer raster file]
STREAM1 [stream raster file]
TRANS1 [transmissivity contour file]

All image files used for vector conversion **must** be created in binary format.

To verify whether the original vector data is in integer, real, or byte format, the vector files can be directly viewed using **EDIT** or the **DESCRIBE** command can be used to view the vector document header file. It is important to remember that the data format specification is for the attribute values, and not for the x,y coordinate points.

All image files will have the same number of rows, columns and x and y cell dimensions. This should correspond to the layout of the finite difference network, with rows and columns equal to 5. In this example, the plane coordinate reference system is used with a unit distance of "1". As before, maximum and minimum coordinate values should be set as follows:

min x = 5000
max x = 30000
min y = 5000
max y = 30000

Assign "0" as the initial value for all cells for the AQUIFER1 and STREAM1 image output files. Since it is possible that a "0" transmissivity value can occur outside the aquifer, a value of "-999" should be assigned as the initial value for the TRANS1 image output file. None of the files have a requirement for a special unit value.

(b) IDRISI includes three modules for vector to raster conversion:

POINTRAS [for point conversion]
LINERAS [for line conversion]
POLYRAS [for polygon conversion]

The aquifer, stream, and trans vector files are converted to raster format using the raster image target files created using the **INITIAL** command in Step (a) above. If there is uncertainty as to which vector to raster conversion module should be used, the object type of a vector file can be examined using the **DESCRIBE** command.

(c) After the conversion process has been completed, the resulting image files can be viewed on the screen using the **COLOR** command.

View the AQUIFER1.img file using **COLOR**. After the image has been displayed on the screen, enter the letter "V" on the keyboard. A prompt then requests a file name, which should be typed in as **STREAM** from the keyboard. In response to the prompt "Enter Color Code:" type in **5**. The well and transmissivity vector files can now be easily overlain.

Step 5: Development of Finite Difference Grid Boundary File

The boundary file required for input into MODFLOW for this example should have the following format:

```
-1 -1 -1 -1 -1
 0  1  1  1  0
 0  1  1  1  0
 0  1  1  1  0
 0  0  0  0  0
```

where:

-1 : constant head boundary (stream location)
0 : no flow boundary (aquifer boundary)
1 : variable head and variable flow

Each value corresponds to a row and column in the finite difference model grid network. This can be compared to the network shown in Handout 5.

To develop this boundary file, raster image files AQUIFER1 and STREAM1, along with a combination of IDRISI **OVERLAY, RECLASS, UPDATE**, and **INITIAL** commands, are used:

(a) The AQUIFER1 image file was initially used to define the extent of the aquifer and the variable head and variable flow cells. The aquifer cells have an attribute value of "3". This can be checked by using the **COLOR** command and pressing the letter "c", and then clicking the left mouse button on any cell. Note that the file must be in unpacked binary format for this to work.

The aquifer cells can now be converted to a value of "1" , corresponding to the variable head and variable flow designations required by MODFLOW. The **RECLASS** command can be used to change all cell values from "3" to "1". The output file can be named AQUIFER2, and no designation of unit values is required.

Since this example includes constant outflow and inflow along the eastern and western boundaries, these conditions can be simulated through the use of external source terms and no-flow cells. Therefore, the east and west boundaries should be defined as no-flow conditions using a cell attribute value of "0". The **UPDATE** command can be applied to the AQUIFER2 image file for this purpose. It is important to note that the column and row numbers in IDRISI always begin with "0" not "1".

The **COLOR** command can now be used to display the modified aquifer file on the screen and the results checked results using **VIEW**.

(b) The process to assigning values of "-1" to cells representing the stream requires several steps since the **RECLASS** command does not allow the user to directly assign a "-1" value.

The **RECLASS** command is first applied to STREAM1, with "1" reassigned to the stream attribute value of "5". The new output file can be named STREAM2.

Next, the **INITIAL** command is used to create a new image file similar to the procedure outlined in Step 4(a), with the exception that "-1" is assigned as the initial attribute value for all cells. This output image file can be named IDENT.

Using the **OVERLAY** command and the **MULTIPLY** option, a new file called STREAM3 is created from the STREAM2 and IDENT image files. This results in a new file with stream cells assigned an attribute value of "-1", which can be checked using the **VIEW** command.

(c) In order to complete the final raster boundary file, the AQUIFER2 image file must be overlain with the STREAM3 image file using the **OVERLAY COVER** option. The resulting output file is named BOUND.

(d) The **VIEW** command displays the BOUND image file with a field width of "3" and "0" decimal places. Starting with row "0", results can be compared with the BOUND.dat file used as input to MODFLOW.

Step 6: Development of MODFLOW Transmissivity Input File

The **COLOR** command can now be used to display the TRANS1 image file on the screen. Note that the raster file is still a contour file. IDRISI provides a special command, **INTERCON**, to interpolate a raster Digital Elevation Model (DEM) from a set of digitized contours using linear interpolation between contours.

INTERCON is now executed using the TRANS1 image file. Notice that the background value is "-999". For our example, the corner transmissivity values in ft^2/day:

NW: 15
NE: 15
SW: 0
SE: 0

The resulting output image file can be named TRANS2.

The **VIEW** command is now used to display the TRANS2 image file with a field width of "6" and "2" decimal places. Starting with row "0", results can be compared with the TRANS.dat file used as input to MODFLOW.

Step 7: Execute Program MODFLOW

The number of input data files required for use with MODFLOW depends on which modules the user requires to simulate a groundwater flow problem. For purposes of this example, a total of seven files are needed. Five of these files are defined as input files in the *Basic Package Input File* as part of the IUNIT variable element table. These carry the unitxx.dat name and include:

unit1.dat	[Basic package input file]
unit11.dat	[Block-centered flow package input file]
unit12.dat	[Well package input file]
unit19.dat	[Strongly implicit procedure input file]
unit22.dat	[Output control input file]

The finite difference groundwater model can now be executed by typing at the DOS prompt:

```
MODFLOW
```

The user is then prompted for two files:

```
unit24
unit23
```

Two types of files have been developed through IDRISI:

for unit 24, type: `BOUND.dat` [boundary file]
for unit 23, type: `TRANS.dat` [transmissivity file]

These two files will be listed by MODFLOW in the output files MODFLOW.out and HEAD.out. The output results of course reflect the fact that these input files have been created to simulate only two stress periods and one time period.

Step 8: Display of MODFLOW Output in IDRISI

Output from MODFLOW for water levels in the aquifer after the end of simulation of stress period 1 have been transferred to IDRISI image format and saved in the file named HEAD.img. To use this file, a document header must be created. The **DOCUMENT** command in IDRISI is used to assign the title of "MODFLOW OUTPUT: HEAD LEVELS". The file is an ASCII real number file with 5 rows, 5 columns, and maximum and minimum x-y coordinates as defined previously. The results can be viewed using **VIEW** or **ORTHO**.

B.4 MODFLOW Output File: MODFLOW.OUT

```
                   U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER MODEL

SAMPLE----1 LAYER, 5 ROWS, 5 COLUMNS; STEADY STATE; CONSTANT HEADS ROW 1,       LAYER 1;  WELLS
   1 LAYERS         5 ROWS         5 COLUMNS
  2 STRESS PERIOD(S) IN SIMULATION
MODEL TIME UNIT IS SECONDS
I/O UNITS:
ELEMENT OF IUNIT:  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
        I/O UNIT: 11 12  0  0  0  0  0  0 19  0  0 22  0  0  0  0  0  0  0  0  0  0  0  0
BAS1 -- BASIC MODEL PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT  1
ARRAYS RHS AND BUFF WILL SHARE MEMORY.
START HEAD WILL BE SAVED
     239 ELEMENTS IN X ARRAY ARE USED BY BAS
     239 ELEMENTS OF X ARRAY USED OUT OF   30000
BCF1 -- BLOCK-CENTERED FLOW PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 11
TRANSIENT SIMULATION
CONSTANT HEAD CELL-BY-CELL FLOWS WILL BE PRINTED
     LAYER  AQUIFER TYPE
     ------------------
        1         0
      26 ELEMENTS IN X ARRAY ARE USED BY BCF
     265 ELEMENTS OF X ARRAY USED OUT OF   30000
WEL1 -- WELL PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM 12
MAXIMUM OF    9 WELLS
      36 ELEMENTS IN X ARRAY ARE USED FOR WELLS
     301 ELEMENTS OF X ARRAY USED OUT OF   30000
SIP1 -- STRONGLY IMPLICIT PROCEDURE SOLUTION PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 19
MAXIMUM OF  50 ITERATIONS ALLOWED FOR CLOSURE
 5 ITERATION PARAMETERS
     305 ELEMENTS IN X ARRAY ARE USED BY SIP
     606 ELEMENTS OF X ARRAY USED OUT OF   30000
1SAMPLE----1 LAYER, 5 ROWS, 5 COLUMNS; STEADY STATE; CONSTANT HEADS ROW 1,       LAYER 1;  WELLS

                                                BOUNDARY ARRAY FOR LAYER  1 WILL BE READ ON UNIT 24 USING FORMAT: (5I3)
-----------------------------------------------------------------------------------
        1   2   3   4   5
 ............................
   1   -1  -1  -1  -1  -1
   2    0   1   1   1   0
   3    0   1   1   1   0
   4    0   1   1   1   0
   5    0   0   0   0   0
```

```
AQUIFER HEAD WILL BE SET TO  999.99     AT ALL NO-FLOW NODES (IBOUND=0).
                                                                      INITIAL HEAD =   .0000000     FOR LAYER  1
HEAD PRINT FORMAT IS FORMAT NUMBER  10    DRAWDOWN PRINT FORMAT IS FORMAT NUMBER  10
HEADS WILL BE SAVED ON UNIT 45    DRAWDOWNS WILL BE SAVED ON UNIT  0
OUTPUT CONTROL IS SPECIFIED EVERY TIME STEP
                                                        COLUMN TO ROW ANISOTROPY =   1.000000
                                                                            DELR =   5000.000
                                                                            DELC =   5000.000
                                                           PRIMARY STORAGE COEF =   .2000000     FOR LAYER  1

          TRANSMIS.  ALONG  ROWS  FOR  LAYER   1  WILL  BE  READ  ON  UNIT  23  USING  FORMAT:  (5F6.2)
--------------------------------------------------------------------------------------------
         1       2       3       4       5
.................................................
  1   15.00   15.00   15.00   15.00   15.00
  2   13.00   12.50   12.50   12.50   13.00
  3   10.00   10.00   10.00   10.00   10.00
  4    5.00    5.00    5.00    5.00    5.00
  5     .00     .00     .00     .00     .00


                                                            SOLUTION BY THE STRONGLY IMPLICIT PROCEDURE
                                                            -------------------------------------------
                                                    MAXIMUM ITERATIONS ALLOWED FOR CLOSURE =       50
                                                                   ACCELERATION PARAMETER =     1.0000
                                                        HEAD CHANGE CRITERION FOR CLOSURE =    .10000E-02
                                                        SIP HEAD CHANGE PRINTOUT INTERVAL =        1

   5 ITERATION PARAMETERS CALCULATED FROM SPECIFIED WSEED =  .00100000 :
           .0000000E+00    .8221720E+00    .9683772E+00    .9943766E+00    .9990000E+00

1                                                      STRESS PERIOD NO.    1, LENGTH =   2592000.
                                                       ---------------------------------------------
                                                      NUMBER OF TIME STEPS =      1

                                                        MULTIPLIER FOR DELT =     1.000

                                                     INITIAL TIME STEP SIZE =   2592000.
            9 WELLS
```

```
                                                     LAYER    ROW    COL    STRESS RATE   WELL NO.
                                                     ----------------------------------------------
                                                       1       2      2       .12000E-01      1
                                                       1       2      4      -.12000E-01      2
                                                       1       3      2       .60000E-02      3
                                                       1       3      4      -.60000E-02      4
                                                       1       4      2       .50000E-02      5
                                                       1       4      4      -.50000E-02      6
                                                       1       2      3      -1.0000          7
                                                       1       3      3       .00000          8
                                                       1       4      3       .00000          9
3 ITERATIONS FOR TIME STEP   1 IN STRESS

PERIOD  1
 MAXIMUM HEAD CHANGE FOR EACH ITERATION:
  HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL
 ------------------------------------------------------------------------------------------------------
   -.2602E-01 (  1,  2,  3)  -.8198E-02 (  1,  4,  2)  -.5231E-03 (  1,  4,  3)

 HEAD/DRAWDOWN PRINTOUT FLAG = 1     TOTAL BUDGET PRINTOUT FLAG = 1     CELL-BY-CELL FLOW TERM FLAG = 1
 OUTPUT FLAGS FOR ALL LAYERS ARE THE SAME:

   HEAD    DRAWDOWN  HEAD  DRAWDOWN
 PRINTOUT  PRINTOUT  SAVE    SAVE
 --------------------------------
    1         1        1       0

    CONSTANT HEAD   PERIOD  1   STEP  1   LAYER  1   ROW   1   COL   1   RATE    .0000000
    CONSTANT HEAD   PERIOD  1   STEP  1   LAYER  1   ROW   1   COL   2   RATE    .1700408
    CONSTANT HEAD   PERIOD  1   STEP  1   LAYER  1   ROW   1   COL   3   RATE    .3973679
    CONSTANT HEAD   PERIOD  1   STEP  1   LAYER  1   ROW   1   COL   4   RATE    .1820737
    CONSTANT HEAD   PERIOD  1   STEP  1   LAYER  1   ROW   1   COL   5   RATE    .0000000


1                     HEAD IN LAYER  1 AT END OF TIME STEP  1 IN STRESS PERIOD  1
                ---------------------------------------------------------------------
          1     2     3     4     5
 ..................................
   1   .000  .000  .000  .000  .000
   2  ***** -.012 -.029 -.013 *****
   3  ***** -.012 -.017 -.013 *****
   4  ***** -.010 -.012 -.011 *****
   5  ***** ***** ***** ***** *****


 HEAD WILL BE SAVED ON UNIT 45 AT END OF TIME STEP  1, STRESS PERIOD  1
```

```
1                DRAWDOWN IN LAYER  1 AT END OF TIME STEP  1 IN STRESS PERIOD  1
            ---------------------------------------------------------------------

          1     2     3     4     5
 ...................................
  1   .000  .000  .000  .000  .000
  2  *****  .012  .029  .013 *****
  3  *****  .012  .017  .013 *****
  4  *****  .010  .012  .011 *****
  5  ***** ***** ***** ***** *****

                            VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  1 IN STRESS PERIOD  1
                            ---------------------------------------------------------------------------

                   CUMULATIVE VOLUMES      L**3                                    RATES FOR THIS TIME STEP      L**3/T
                   ------------------                                              ------------------------

                         IN:                                                             IN:
                         ---                                                             ---
                           STORAGE =    .64927E+06                                         STORAGE =    .25049
                     CONSTANT HEAD =    .19427E+07                                   CONSTANT HEAD =    .74948
                             WELLS =    59616.                                               WELLS =    .23000E-01
                          TOTAL IN =    .26515E+07                                        TOTAL IN =    1.0230
                        OUT:                                                            OUT:
                        ----                                                            ----
                           STORAGE =    .00000                                             STORAGE =    .00000
                     CONSTANT HEAD =    .00000                                       CONSTANT HEAD =    .00000
                             WELLS =    .26516E+07                                           WELLS =    1.0230
                         TOTAL OUT =    .26516E+07                                       TOTAL OUT =    1.0230
                          IN - OUT =   -75.250                                            IN - OUT =   -.28968E-04
                PERCENT DISCREPANCY =                .00                        PERCENT DISCREPANCY =                .00



          TIME SUMMARY AT END OF TIME STEP  1 IN STRESS PERIOD  1
                                SECONDS      MINUTES       HOURS          DAYS          YEARS
                             --------------------------------------------------------------------
       TIME STEP LENGTH       .259200E+07   43200.0      720.000       30.0000       .821355E-01
     STRESS PERIOD TIME       .259200E+07   43200.0      720.000       30.0000       .821355E-01
  TOTAL SIMULATION TIME       .259200E+07   43200.0      720.000       30.0000       .821355E-01


11                                            STRESS PERIOD NO.   2, LENGTH =   2592000.
                                             ----------------------------------------------
```

```
                                                 NUMBER OF TIME STEPS =     1

                                                  MULTIPLIER FOR DELT =     1.000

                                               INITIAL TIME STEP SIZE =   2592000.

         6 WELLS
                                             LAYER     ROW     COL     STRESS RATE   WELL NO.
                                             ---------------------------------------------
                                               1        2       2       .12000E-01       1
                                               1        2       4      -.12000E-01       2
                                               1        3       2       .60000E-02       3
                                               1        3       4      -.60000E-02       4
                                               1        4       2       .50000E-02       5
                                               1        4       4      -.50000E-02       6

    3 ITERATIONS FOR TIME STEP   1 IN STRESS PERIOD  2

 MAXIMUM HEAD CHANGE FOR EACH ITERATION:
  HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL
 -------------------------------------------------------------------------------------------------------------
   .2309E-01 (  1,  2,  3)   .6258E-02 (  1,  3,  2)   .4044E-03 (  1,  4,  3)

 HEAD/DRAWDOWN PRINTOUT FLAG = 1     TOTAL BUDGET PRINTOUT FLAG = 1     CELL-BY-CELL FLOW TERM FLAG = 1
 REUSING PREVIOUS VALUES OF IOFLG
    CONSTANT HEAD   PERIOD  2   STEP  1   LAYER  1   ROW   1   COL   1   RATE    .0000000
    CONSTANT HEAD   PERIOD  2   STEP  1   LAYER  1   ROW   1   COL   2   RATE    .4226673E-01
    CONSTANT HEAD   PERIOD  2   STEP  1   LAYER  1   ROW   1   COL   3   RATE    .5654003E-01
    CONSTANT HEAD   PERIOD  2   STEP  1   LAYER  1   ROW   1   COL   4   RATE    .5598900E-01
    CONSTANT HEAD   PERIOD  2   STEP  1   LAYER  1   ROW   1   COL   5   RATE    .0000000
1                     HEAD IN LAYER  1 AT END OF TIME STEP  1 IN STRESS PERIOD  2
              -----------------------------------------------------------------------

        1     2     3     4     5
 .....................................
   1   .000  .000  .000  .000  .000
   2  ***** -.003 -.004 -.004 *****
   3  ***** -.005 -.006 -.006 *****
   4  ***** -.006 -.007 -.008 *****
   5  ***** ***** ***** ***** *****



 HEAD WILL BE SAVED ON UNIT 45 AT END OF TIME STEP  1, STRESS PERIOD  2
1                   DRAWDOWN IN LAYER  1 AT END OF TIME STEP  1 IN STRESS PERIOD  2
              -----------------------------------------------------------------------

        1     2     3     4     5
```

```
......................................
  1   .000  .000  .000  .000  .000
  2  *****  .003  .004  .004 *****
  3  *****  .005  .006  .006 *****
  4  *****  .006  .007  .008 *****
  5  ***** ***** ***** ***** *****

                          VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  1 IN STRESS PERIOD  2
                          ------------------------------------------------------------------------------
                  CUMULATIVE VOLUMES      L**3                               RATES FOR THIS TIME STEP      L**3/T
                  ------------------                                         ------------------------
                        IN:                                                         IN:
                        ---                                                         ---
                          STORAGE =    .64927E+06                                     STORAGE =    .00000
                    CONSTANT HEAD =    .23439E+07                               CONSTANT HEAD =    .15480
                            WELLS =    .11923E+06                                       WELLS =    .23000E-01
                         TOTAL IN =    .31124E+07                                    TOTAL IN =    .17780

                       OUT:                                                        OUT:
                       ----                                                        ----
                          STORAGE =    .40032E+06                                     STORAGE =    .15444
                    CONSTANT HEAD =    .00000                                   CONSTANT HEAD =    .00000
                            WELLS =    .27112E+07                                       WELLS =    .23000E-01
                        TOTAL OUT =    .31116E+07                                   TOTAL OUT =    .17744
                         IN - OUT =    835.25                                        IN - OUT =    .35121E-03
             PERCENT DISCREPANCY =                  .03                   PERCENT DISCREPANCY =                  .20



         TIME SUMMARY AT END OF TIME STEP  1 IN STRESS PERIOD  2
                                     SECONDS      MINUTES        HOURS          DAYS           YEARS
                                 ----------------------------------------------------------------------
      TIME STEP LENGTH            .259200E+07    43200.0       720.000        30.0000        .821355E-01
    STRESS PERIOD TIME            .259200E+07    43200.0       720.000        30.0000        .821355E-01
 TOTAL SIMULATION TIME            .518400E+07    86400.0       1440.00        60.0000        .164271
1
```

B.5 MODFLOW Input Files

BASIC PACKAGE INPUT FILE: UNIT1.DAT

```
SAMPLE----1 LAYER, 5 ROWS, 5 COLUMNS; STEADY STATE; CONSTANT HEADS ROW 1,
LAYER 1;  WELLS
         1         5         5         2         1
 11 12  0  0  0  0  0  0 19  0  0 22
         0         1     IAPART,ISTRT
         1         1(5I3)                        3    IBOUND-1
    999.99
         0        0.                                  HEAD-1
  2592000.         1        1.     PERLEN,NSTP,TSMULT PERIOD-1
  2592000.         1        1.     PERLEN,NSTP,TSMULT PERIOD-2
```

IBOUND ARRAY VALUES READ FROM UNIT 24: BOUND.DAT

```
 -1 -1 -1 -1 -1
  0  1  1  1  0
  0  1  1  1  0
  0  1  1  1  0
  0  0  0  0  0
```

BLOCK-CENTERED FLOW PACKAGE INPUT FILE: UNIT11.DAT

```
         0        -1      ISS,IBCFBD
 0
         0        1.                                  TRPY
         0     5000.                                  DELR
         0     5000.                                  DELC
         0       .2                                   SY-1
        23        1.(5F6.2)                      4    T-1
```

TRAN ARRAY VALUES FOR TRANSMISSIVITY READ FROM UNIT 23: TRANS.DAT

```
 15.00 15.00 15.00 15.00 15.00                       ROW 1
 13.00 12.50 12.50 12.50 13.00                       ROW 2
 10.00 10.00 10.00 10.00 10.00                       ROW 3
  5.00  5.00  5.00  5.00  5.00                       ROW 4
   .00   .00   .00   .00   .00                       ROW 5
```

WELL PACKAGE INPUT FILE: UNIT12.DAT

```
9         0      MXWELL,IWELBD
9                ITMP (NWELLS) STRESS PERIOD 1
1         2          2      +.012
1         2          4      -.012
1         3          2      +.006
1         3          4      -.006
1         4          2      +.005
1         4          4      -.005
1         2          3        -1.
1         3          3         0.
1         4          3         0.
6                ITMP (NWELLS) STRESS PERIOD 2 (No pumping)
1         2          2      +.012
1         2          4      -.012
1         3          2      +.006
1         3          4      -.006
1         4          2      +.005
1         4          4      -.005
```

STRONGLY IMPLICIT PROCEDURE PACKAGE INPUT FILE: UNIT19.DAT

```
50        5         MXITER,NPARM
1.     .001          0       .001          1 ACCL,ERR,IPCALC,WSEED
```

OUTPUT CONTROL INPUT FILE: UNIT22.DAT

```
10       10        45
 0        1         1         1
 1        1         1
-1        1         1         1
-1        1         1         1
```

APPENDIX C

GENERATING STREAM-AQUIFER COEFFICIENTS USING MODRSP

C.1 Introduction

This appendix presents the detailed procedures required to generate spatially distributed stream-aquifer response coefficients for use in a stream-aquifer management model using MODRSP (Maddock and Lacher,1991). The procedure is described graphically in Figure 5.5 of Chapter 5.

C.2 Data Preprocessing for MODRSP

The GIS and DBMS procedures used to prepare aquifer transmissivity, boundary, well, and river reach input data files used by MODRSP are presented below.

C.2.1 Aquifer Transmissivity

This example assumes that transmissivity data are available from published contour maps.

- Use AUTOCAD to digitize the transmissivity contour map using the **PLINE** command.
- Assign contour transmissivity values to each contour "polyline" using the **THICK** command.
- Draw in system boundary.
- Extend all open contour lines to the system boundary.
- If necessary, use GTCP to transform coordinates into UTM.
- Run the AUTOLISP program ACDTOIDR.lsp, which creates an IDRISI vector file with each contour polyline assigned with transmissivity as the attribute.
- Use the IDRISI **DOCUMENT V** command to create the header file for the new transmissivity vector file, and use the system boundary as the file coordinate limits.
- Prepare a blank raster file using the IDRISI command **INITIAL** for use with **LINERAS**. The grid size should correspond to the grid and cell size to be used by MODRSP. This must be defined as a binary file.
- Convert the IDRISI vector file to a raster file using **LINERAS**.
- Use the IDRISI **INTERCON** command to interpolate between the contour line values and assign transmissivity values to each raster grid.
- Use **OVERLAY** to convert transmissivity values to units to be used by MODRSP.
- Use **OVERLAY** with a rasterized aquifer boundary file and the transmissivity file to assign zero to all transmissivities outside the defined aquifer boundary.
- Use **CONVERT** to create an ASCII IDRISI image file of the final transmissivity raster file, and save this file for use with MODRSP.

C.2.2 Boundary File

The groundwater system boundary data required for use by MODRSP requires that each finite grid be assigned a boundary value:

No flow: 0
Constant head: -1
Underflow: +1

This requires that a raster based aquifer file be developed that indicates which cells are inside the aquifer (+1) and which are outside the aquifer (0). This file can then be combined with a raster file indicating the aquifer cells that are reservoirs, ponds, or perennial streams. For this example, it is assumed that the source of the aquifer boundary is a published map and the hydrography data are available from TIGER files transferred to AUTOCAD.

- Use AUTOCAD to digitize in aquifer boundary as a polyline.
- Assign an attribute value to the boundary line using the command THICK.
- Run the AUTOLISP program ACDTOIDR.lsp to create an IDRISI vector file of the aquifer boundary.
- Read in hydrography data from TIGER files into AUTOCAD. THAW all layers with ponds, reservoirs, and perennial streams. Assign an attribute value different from that used for the aquifer boundary using the command THICK.
- Run the AUTOLISP program ACDTOIDR.lsp to create an IDRISI vector file of the constant head boundary data.
- Use the IDRISI DOCUMENT V command to make vector header files for the aquifer boundary and constant head boundary lines. Use the system boundary as the coordinate limits.
- Use INITIAL to prepare blank binary raster image files for both boundary vector files. Grid size and number of rows and columns should correspond to the MODRSP finite grid system.
- Use POLYRAS to rasterize the two vector boundary files.
- The constant head grid locations must be assigned a negative value. This requires several steps. Create an equivalent size raster file with an initial value of -1 using INITIAL. Use OVERLAY with the MULTIPLY option to create a new constant head raster file with negative values.
- Use OVERLAY with the COVER command to create a single file with constant head grids having negative value attributes, normal aquifer cells with positive value attributes, and no flow cells with a zero value attribute.
- Use CONVERT to make an ASCII image file. This file can be used directly by MODRSP as the groundwater system boundary file.

C.2.3 Well File

The MODRSP Well file is used to identify the location of each cell in the finite difference model for which response coefficients are to be generated. In the groundwater management model, these grid related response coefficients can be used to represent a single well, several wells located within the grid, or combined with response coefficients developed for other grids to model return flows from a recharge source, reservoir seepage, or channel loss. GIS and DBMS techniques are well suited for generating and managing this type of information. For this example, it is assumed that well or recharge locations are available in published maps, and non-geographical related data are available in separate databases. The Well File used by MODRSP requires the number of wells and their row/column locations. The process for identifying row/column grid locations for a single well is different than for a reservoir or a channel.

- Use AUTOCAD to digitize in well data from a map as POINT data.
- Use the GCTP transform package to convert well point data to UTM, if required.
- Use AUTOCAD (Autodesk, Inc, 1990) database related functions to create attributes, insert them into a drawing, and extract data:
  - ATTDEF [defines attribute format]
    ATTDISP [displays drawing attribute]
    ATTEDIT [edits attribute values]
    ATTEXT [extracts attribute data]
  - Define an attribute with three attribute tags:
    Type: Well
    Well_no: Consecutive reference number
    Name: Unique name for linking with external database
  - Link attribute to a block using the BLOCK command.
  - Use the INSERT command to recall the attribute block and assign it to each well location point. Fill in attribute tags with proper data. A short AUTOLISP program can be written to automate the process.
  - Prepare an attribute template file with an ASCII text editor that includes the block name, type, well-no, name, and location.
  - Extract attribute data, along with location, as an SDF (space delimited) file using ATTEXT.
- Import the well SDF file into DBASEIV.
- Using the following formulas calculate the equivalent finite difference grid row and column values from the x and y location fields.

$$\text{Column no.} = INT\left[\frac{X_{val} - X_{\min}}{X_{unit}}\right] + 1$$

and

$$\text{Row no.} = INT\left[\frac{Y_{\max} - Y_{val}}{Y_{unit}}\right] + 1$$

where

INT = integer value
X_{val}, Y_{val} = well location x and y values
X_{min}, Y_{max} = system boundary limits
X_{unit}, Y_{unit} = grid dimension

if Column no. > $\text{Column}_{\max}$, then Column no. = $\text{Column}_{\max}$;
if Row no. > $\text{Row}_{\max}$, then Row no. = $\text{Row}_{\max}$.

- Create another calculated field with the equivalent finite difference grid cell number using the following equation:

$$\text{Location Array}(\text{cell no.}) = (\text{Row no.} \times Col_{max}) - (Col_{max} - \text{Col no.})$$

- Create a database boundary file from the IDRISI ASCII boundary image file. This is accomplished by importing the boundary file to DBASEIV, adding a field called CELL, and filling the CELL field with REC_NO( ) using the DBASE REPLACE ALL command.
- Use the boundary file to extract only those cell locations in the well database that are within the aquifer boundary.
- Create a new field in the extracted well database file called LAYER and fill this field with values of 1, which represent Layer 1 in the aquifer.
- Modify the database structure so that the LAYER, ROW, and COLUMN fields are all integers with 10 places.
- Create an ASCII text file from the well database file that includes the LAYER, ROW, and COLUMN fields.
- Use an ASCII text editor to add a single header line to the ASCII well file which registers the number of wells in the data file. This file can be used as the well data file in MODRSP.

C.2.4 Reservoir File

- Read in data to AUTOCAD from TIGER files, or use AUTOCAD to digitize as polylines from published maps.
- Use the GTCP program to convert coordinates to UTM.
- Assign each reservoir a separate consecutive attribute value using the THICK command.
- Use the AUTOLISP program ACDTOIDR.lsp to create an IDRISI vector file.
- Use DOCUMENT V to make the appropriate header file setting the coordinate limits to those of the groundwater system.
- Create a blank binary raster file with grid size and row/column numbers equivalent to that required for MODRSP.
- Convert the reservoir IDRISI vector file to an IDRISI raster file using POLYRAS. If the reservoir polygon covers over 50 percent of a grid, the attribute corresponding to the reservoir attribute value will be assigned to the raster grid cell.
- Eliminate all reservoir grid cells outside the aquifer by using OVERLAY and MULTIPLY on the aquifer boundary IDRISI raster file. Use RECLASS to set all aquifer cells to 1 and non-aquifer cells to zero in the IDRISI aquifer boundary file, if necessary, prior to performing the overlay.
- Use CONVERT to create an ASCII file from the binary reservoir raster image file.
- Import the reservoir image file into DBASEIV.
- Create a new field called CELL.
- Use REPLACE ALL to fill this field with the RECNO() for each record.
- Use QUERY to extract only those records having a non-zero attribute value.
- Create calculated ROW and COLUMN fields using the following:

```
if $\text{INT(Cell no./Col}_{max}) = \text{Cell no./Col}_{max}$
    then: $\text{Row no.} = \text{Cell no./Col}_{max}$
else
    $\text{Row no.} = \text{INTCell no./Col}_{max}) + 1$
    $\text{Col no.} = \text{Cell no.} - ((\text{Row no.} - 1) \times \text{Col}_{max}$
```

- Create a new field in the reservoir database file called LAYER. Fill this field with values of 1, representing Layer 1 in the aquifer.
- Modify the database structure so that the LAYER, ROW, and COLUMN fields are all integers with 10 places.
- Create an ASCII text file from the reservoir database file that includes the LAYER, ROW, and COLUMN fields.
- Use an ASCII text editor to add a single header line to the ASCII reservoir file which registers the number of records in the data file. This file can be used as a Well Data File in MODRSP.

C.2.5 Channel

The preparation of a Well Data File for canals, drains, etc., as represented by a line source, is the same as for a reservoir, except that the IDRISI LINERAS command is utilized instead of POLYRAS to rasterize the channel vector file. Note that it is important that each channel or canal reach being modeled in the groundwater management model is assigned its own attribute value.

C.2.6 River File

The MODRSP River Data File provides the number of river segments and the unit number directing the program where to write the response function output file. Each grid containing a river cell must be identified by Layer, Row, and Column. A streambed conductance must also be assigned to each river cell. A series of time based response coefficients are generated at each river cell location as a result of unit pumping at each cell listed in the Well File . Since a river reach may constitute more than one grid cell, it is generally necessary to combine response coefficients from several grid cells for use in a groundwater management model. Therefore, it is necessary to identify which grid cells are associated with each river reach. The assignment of streambed conductance to each cell also requires external data manipulation and calculation. GIS and DBMS techniques are well suited for generating and managing this type of information. For this example, it is assumed that river and stream hydrography data are available from TIGER files. River conductance is expressed as a function of stream width, aquifer saturated thickness, grid reach length, and aquifer transmissivity. Stream width data are available from cross-section surveys; and saturated thickness and transmissivity data from published maps.

Reach Number/Reach Length

- Use AUTOCAD to view river and stream hydrography imported from TIGER files.
- Use GTCP to convert coordinates to UTM.
- Edit the AUTOCAD river and stream files so that each stream or river is represented by a single continuous polyline.

- Locate and use the BREAK command to separate the river or stream into reach segments required for use in the groundwater management model.
- Use the PEDIT and WIDTH commands to assign a consecutive attribute value to each reach number.
- Modify the VECBRKW.lsp file using a standard ASCII text editor. Change the xmin, xmax, ymin, ymax, yunit, xunit values to match the groundwater system coordinates and grid cell sizes under study.
- Run the AUTOLISP program VECBRKW.lsp. This divides each river and stream line segment into a grid cell line segment and creates an ASCII script file.
- Load the script file into a new AUTOCAD layer.
- Run the AUTOLISP program VECDIST.lsp. This creates an ASCII text file which contains x1,y1,x2,y2, and the stream attribute number for each grid.
- Load this file into the QUATTRO PRO file ACDPRNIN.wq1 using /TOOLS IMPORT for comma delimited ascii text.
- Fill in the proper values for Xmax, Xmin, Ymin, Ymax, Row#, Col#, Xunit, and Yunit.
- Copy the equations for X1, Y1, COL, ROW, and CELL to all rows containing the grid data. The actual x, y, row, column, and cell values for each set of grid data are calculated, with reach numbers under the UNIT column and reach lengths under the DIST column.
- Create another column labeled REC, and use /EDIT FILL to place consecutive record values starting with 1.
- Use /TOOLS EXTRACT VALUES commands to create an xxx.DBF file with the following columns: REC, COL, ROW, CELL, UNIT, and DIST.

Width

- Follow the same procedures described above for assigning reach numbers, except use PEDIT and WIDTH command to assign a bed width attribute values to each reach segment.
- Modify the VECBRKW.lsp file using a standard ASCII text editor. Change the xmin, xmax, ymin, ymax, yunit, xunit values to match the groundwater system coordinates and grid cell sizes under study.
- Run the AUTOLISP program VECBRKW.lsp. This divides each river and stream line segment into a grid cell line segment, and creates an ASCII script file.
- Load the script file into a new AUTOCAD layer.
- Run the AUTOLISP program VECWDTH.lsp. This creates an ASCII text file which contains the same column values as the reach attribute file, except the distance column is absent.
- Load this file into the QUATTRO PRO file ACDPRNIN.wq1 using /TOOLS IMPORT as a comma delimited ascii text.
- Follow the same procedures described previously for the reach/distance calculation. Eliminate the DIST column and rename the UNIT column as WIDTH.
- Extract the REC and WIDTH columns to a xxx.dbf file.
- Join the WIDTH column to the REACH/DIST database linking on the REC field.

Saturated Thickness

This example assumes a published contour map as the source of saturated thickness data.

- Use AUTOCAD to digitize in saturated thickness contour map using PLINE command.
- Assign contour saturated thickness values to each contour "polyline" using THICK.
- Draw in system boundary.
- Extend all open contour lines to the system boundary.
- If necessary use GTCP to transform coordinates into UTM.
- Run the Autolisp program ACDTOIDR.lsp. This will create an IDRISI vector file with each contour polyline assigned saturated thickness as the attribute.
- Use the IDRISI DOCUMENT V command to make the header file for the new saturated thickness vector file. Use the system boundary as the file coordinate limits.
- Prepare a blank raster file using INITIAL for use with LINERAS. The grid size should correspond to the grid and cell size to be used by MODRSP. This must be defined as a binary file.
- Convert the IDRISI vector file to a raster file using LINERAS.
- Use the IDRISI INTERCON command to interpolate between the contour line values and assign saturated thickness values to each raster grid.
- Use OVERLAY to convert saturated thickness values to units to be used by MODRSP.
- Use OVERLAY with a rasterized aquifer boundary file and the saturated thickness file to assign zero to all cells outside the defined aquifer boundary.
- Use CONVERT to make an ASCII IDRISI image file of the final saturated thickness raster file.

River Conductance

- Import the IDRISI transmissivity and IDRISI saturated thickness files into DBASEIV.
- Add a CELL field to the transmissivity and saturated thickness files using MODIFY STRUCTURE and REPLACE ALL with RECNO().
- Use the QUERY command to add transmissivity and saturated thickness fields to the REACH/DIST/WIDTH dbase file, and link on CELL.
- Calculate the new field COND using the following equation based on the method of flow nets:

$$Conductance = \frac{T}{e} L \left(\frac{W_p + 2e}{e + 10Wp} \right)$$

where

T = transmissivity of the aquifer underlying the reach

e = average saturated thickness of the aquifer along the reach

L = length of reach

W_p = wetted perimeter of stream equal to width of reach

- Create a LAYER field and REPLACE ALL with 1.
- MODIFY STRUCTURE so that LAYER, ROW, and COLUMN fields have 10-digits and no decimals, and COND has 10-digits and 5 decimal places.

- Export LAYER, ROW, COLUMN, and COND fields to an SDF river text file.
- Use an ASCII text editor to add a single header line to the ASCII river file which registers the number of records in the data file and the unit number for the response coefficient output file. This file can be used as the river data file in MODRSP.

C.3 Execution of MODRSP

MODRSP is written in the FORTRAN programming language. Large model simulations (50,000 cells) can be run on a microcomputer by compiling MODRSP using Microsoft Fortran 5.1 and running under Microsoft Windows. A well documented user manual is available for MODRSP (Maddock and Lacher, 1991).

C.3.1 Input

To run MODRSP, the following input files must be prepared:

- basic data file (RBAS)
- block centered data file (RBCF)
- well package data file (RWEL)
- river package data file (RRIV)
- output format data file (OPC)
- solution procedure data file (PCG)
- boundary data file (bound.dat)
- transmissivity data file (trans.dat)

The basic data file (RBAS) is used to assign files and unit numbers for the packages to be used to run MODRSP.

```
UNIT# 1    2    3    4    5    6    7    8    9    10   11  12  13  14
      RBCF RWEL RDRW RVEL RSTO RRIV REVT RALK RCHB RGHB SIP SOR PCG OPC
```

Instead of reading boundary data in from the basic data file (RBAS), data can be read in from a separate data file. To read the boundary data file prepared using IDRISI, line 6 of the RBAS file is written:

```
         1         2         3         4         5
12345678901234567890123456789012345678901234567890
        25         1(I2)                        -1
     LOCAT   ICONST   FMTIN                   IPRN
       I10    I10      A20                     I10
```

where

LOCAT: indicates the location of the data which will be put in the array
ICONST: every element in the array is multiplied by this constant
FMTIN: format of records containing the array values; the format must be enclosed in parentheses; for data read in from an IDRISI image file, read a single record per line.
IPRN: flag for printing array

Instead of reading transmissivity data in from the block centered data file (RBCF), data can be read in from a separate data file. To read the transmissivity data file prepared using IDRISI, line 6 of the RBCF file is written:

```
         1         2         3         4         5
12345678901234567890123456789012345678901234567890
        26         1(I2)                        -1
     LOCAT     CONST  FMTIN                   IPRN
       I10     F10.0    A20                    I10
```

where

LOCAT: indicates the location of the data which will be put in the array
CONST: every element in the array is multiplied by this constant
FMTIN: format of records containing the array values; the format must be enclosed in parentheses; for data read in from an IDRISI image file, read a single record per line.
IPRN: flag for printing array

To run the program, type

```
MODRSP
```

After the command prompt, the screen clears, the title MODRSP appears, and the user is asked to supply the input and output file names for the various modules.

C.3.2 Output

The number of output files created by MODRSP depends on the packages being used. For this example, two output files are created: the main output file (MDRSP.out) and the river response file (RIV.RF). It is the river response file that contains the groundwater response coefficients.

C.4 Data Postprocessing for MODRSP

The coefficients produced by MODRSP represent groundwater flow responses over a user defined time period at a single river grid due to pumping of a unit discharge for a single period at a single well. These results must be summarized by river reach and by source before they can be used in a stream-aquifer management model. This can be a one, two, or three step process, depending on whether each record in the well data file represents a single well, a segment of channel reach, or reservoir, or if more than one well is located in a grid cell.

C.4.1 River Reach Summary

MODRSP determines the effects of well pumping on individual river reach grid cells. Usually, most reaches are composed of a number of grid cells. Data base concepts can be used to summarize MODRSP response coefficients by river reach.

- Use a text editor to eliminate the column titles from the river response output file.
- Import the response file to DBASEIV.

- Use the river data base file which identifies which MODRSP grids are associated with each river reach segment prepared during the preprocessing stage
- Use the QUERY mode to sum response coefficients by linking the two files on river reach record number and grouping by well number, river reach unit number, and time period.

C.4.2 Source Summary

In the case of reservoirs or channels where more than one cell grid is used to represent the reservoir or channel system, the response coefficients of several grids can be superimposed by the following procedure.

- Use the river reach summary response coefficient data base
- Use the reservoir or channel database file originally developed during the preprocessing stage.
- Use the query mode to sum response coefficients by linking the two files on well record number and grouping by well number, reservoir or channel reach unit number, and time period.

C.4.3 MODSIM Coefficient File

Add the field TYPE to the source summary or river reach summary data base file. The value for TYPE is assigned based on the source and use of the response coefficients:

1. Reservoir
2. Demand
3. Link

Use MODIFY STRUCTURE to set field widths as follows:

```
TYPE    : 2 digits
WELL_NO: 4 digits
UNIT    : 4 digits
PERIOD : 4 digits
RF      : 10 digits, 8 decimal places
```

Export the TYPE, WELL_NO, UNIT, PERIOD, and RF fields to an SDF ASCII text file.
Run MODCOEFF.exe to output a MODSIM compatible coefficient file.

APPENDIX D

CASE STUDY MODRSP FILES

D.1 Example Screen for Reading Input and Output File Names

```
                                  MODRSP

MAIN OUTPUT FILE (ODF)        ON UNIT 36    ASSIGN TO FORMATTED FILE: MDRSP.OUT
BAS                           ON UNIT 35    ASSIGN TO FORMATTED FILE: RBAS
BCF                           ON UNIT  2    ASSIGN TO FORMATTED FILE: RBCF
WEL                           ON UNIT  3    ASSIGN TO FORMATTED FILE: RWEL
RIV                           ON UNIT  9    ASSIGN TO FORMATTED FILE: RRIV
RIVER CAPTURE RF              ON UNIT 54    ASSIGN TO FORMATTED FILE: RIV.RF
BOUNDARY FILE                 ON UNIT 25    ASSIGN TO FORMATTED FILE: BOUND.DAT
TRANSMISSIVITY FILE           ON UNIT 26    ASSIGN TO FORMATTED FILE: TRANS.DAT
PCG                           ON UNIT 13    ASSIGN TO FORMATTED FILE: PCG
```

D.2 Basic Package Input File: 7BAS

```
SOUTH PLATTE
TEST PROBLEM
         1       140       370       120         1         1
  2  3  0  0  0  9  0  0  0  0  0  0 13  0
         0
        25         1(I2)                          -1
       10.
 2592000.         1       1.
 2592000.         1       1.
```

D.3 Block-Centered Flow Package Input File: 7BCF

```
         0         0
         0        1.

         0     1000.

         0     1000.
         0      0.16                              -1
        30        1.(F6.3)                        -1
```

D.4 Well Package Input File: Well.dat

```
      177        -1
         1        54       165
         1        54       167
         1        55       184
```

D.5 Well Package Input File: Drain.dat

```
      246          -1          0
        1          51        155
        1          52        156
```

D.6 Well Package Input File: Pond.dat

```
       25          -1
        1          63        152
        1          65        184
```

D.7 River Package Input File: River.dat

```
      889           0         54       0.00001
        1          10        343       0.54616
        1          10        344       0.16086
        1          11        343       1.02508
```

D.8 Precoditioned Conjugate Gradient Input File: PCG

```
       10          50          1
    0.001       0.001       0.97          0          0          0
```

D.9 Transmissivity Input File: TRANS2

```
 .000
 .000
 .000
 .000
 .000
```

D.10 Boundary Input File: BOUND2

```
0
0
0
0
0
0
```

D.11 River Response Output File: Riv.rf

```
2  18  11   1 .57943450
2  18  11   2 .04152328
2  18  11   3 .00717168
2  18  11   4 .00276704
```

APPENDIX E

MODSIM AUGMENTATION PLAN INPUT FILES

E.1 Control Data

Item	SDF Control File	MODRSP Control File
UNITS	English	English
PERIOD	Monthly	Monthly
MODE	Calibration	Calibration
GW COEF FILE	SPSDF.CFF	SPLAT.CFF
MAX PRIORITY	2450	2450
TITLE	BIJOU:SDF	BIJOU:MODRSP
TOTAL NODES	281	281
RESERVOIR NODES	8	8
SPILL NODES	8	8
DEMAND NODES	232	232
IMPORT NODES	0	0
LINKS	81	81
RIVER LINKS	0	0
TOTAL PERIODS	7	7
START PERIOD	1985	1985
FROM PERIOD	1	1
END PERIOD	7	7

E.2 ADATA File: Bijou.ada

Time series data for inflows (Type 1), demands (Type 2), and reservoir evaporation rates (Type 3)--partial data set of 50 out of 1314 records listed as an example:

TYPE	NODE	YEAR	MON1	MON2	MON3	MON4	MON5	MON6	MON7	MON8	MON9	MON10	MON11	MON12
2	47	1985	0	0	0	0	827	395	0	0	0	0	0	228
2	48	1985	0	0	0	0	313	149	0	0	0	0	0	78
2	49	1985	0	0	0	0	112	53	0	0	0	0	0	30
2	51	1985	0	0	0	0	246	117	0	0	0	0	0	72
2	52	1985	0	0	0	0	112	53	0	0	0	0	0	30
2	53	1985	0	0	0	0	336	160	0	0	0	0	0	90
2	54	1985	0	0	0	0	45	21	0	0	0	0	0	12
2	55	1985	0	0	0	0	89	43	0	0	0	0	0	24
2	56	1985	0	0	0	0	89	43	0	0	0	0	0	24
2	57	1985	0	0	0	0	45	21	0	0	0	0	0	12
2	62	1985	0	0	0	0	0	102	97	238	0	6	199	0
2	65	1985	0	0	0	0	252	95	255	170	32	0	352	242
2	69	1985	0	0	0	0	88	35	64	39	0	0	78	62
2	70	1985	0	0	0	0	34	14	25	15	0	0	30	24
2	71	1985	0	0	0	0	34	14	25	15	0	0	30	24
2	72	1985	0	0	0	0	54	22	39	24	0	0	48	38
2	73	1985	0	0	0	0	34	14	25	15	0	0	30	24
2	74	1985	0	0	0	0	7	80	275	508	1588	1138	122	815
2	75	1985	0	0	0	0	104	33	128	86	106	261	219	143
2	76	1985	0	0	0	0	51	16	62	42	51	127	106	70
2	77	1985	0	0	0	0	36	11	44	29	36	89	75	49
2	78	1985	0	0	0	0	18	6	22	15	18	45	37	25
2	79	1985	0	0	0	0	24	7	29	20	24	60	50	33
2	80	1985	0	0	0	0	18	6	22	15	18	45	37	25
2	81	1985	0	0	0	0	30	9	37	25	30	75	62	41
2	82	1985	0	0	0	0	18	6	22	15	18	45	37	25
2	83	1985	0	0	0	0	0	2	16	19	33	70	10	3
2	84	1985	0	0	0	0	0	0	55	92	50	174	47	10
2	88	1985	0	0	0	0	0	0	0	0	21	31	0	0
2	90	1985	0	0	0	0	0	0	9	0	0	23	0	0
2	94	1985	0	0	0	0	0	0	0	0	4	40	12	0
2	95	1985	0	0	0	0	0	0	0	11	57	284	0	0
2	97	1985	0	0	0	0	0	0	0	0	0	16	0	0
2	100	1985	0	0	0	0	0	0	29	0	11	23	14	9
2	101	1985	0	0	0	0	0	0	0	10	13	25	0	0
2	102	1985	0	0	0	0	0	0	0	36	47	88	2	0
2	103	1985	0	0	0	0	0	0	7	14	19	73	7	0
2	104	1985	0	0	0	0	0	0	0	0	60	47	7	0
2	105	1985	0	0	0	0	0	0	0	0	13	18	0	0
2	106	1985	0	0	0	0	0	0	7	21	0	30	3	0
2	107	1985	0	0	0	0	0	0	0	0	0	23	0	0
2	108	1985	0	0	0	0	0	0	0	0	70	63	5	0
2	109	1985	0	0	0	0	0	0	12	0	65	106	7	1
2	110	1985	0	0	0	0	0	2	9	14	16	31	7	2
2	112	1985	0	0	0	0	0	0	0	0	0	36	0	0
2	113	1985	0	0	0	0	0	0	0	5	76	223	0	1
2	115	1985	0	0	0	0	0	0	3	0	0	13	0	0
2	116	1985	0	0	0	0	0	0	0	19	25	46	1	0
2	119	1985	0	0	0	0	0	0	11	27	12	50	0	2
2	121	1985	0	0	0	0	0	0	0	0	0	47	0	7

E.3 Node Names: Nodes.dat (281 records)

```
Node   Name
================================
  1 KERSEY GAGE
  2 CROW CREEK INFLOW
  3 EMPIRE INLET
  4 RIVERSIDE INLET
  5 BOX ELDER CREEK INFLOW
  6 HARDIN INLET
  7 BIJOU INLET
  8 WELD CTY RESERVOIR
  9 CORONA INLET
 10 RIVERSIDE OUTLET
 11 LOST CREEK INFLOW
 12 JACKSON LAKE INLET
 13 WELDON VALLEY INLET
 14 KIOWA CREEK INFLOW
 15 JACKSON LAKE OUTLET
 16 FT. MORGAN CANAL INLET
 17 WELDONA GAGE
 18 WELDON VALLEY RETURN
 19 NARROWS RES INLET
 20 BIJOU CREEK INFLOW
 21 DUELL&SNYDER/UPPER PLATTE INLET
 22 BADGER CREEK INFLOW
 23 LOWER PLATTE & BEAVER CANAL INLET
 24 TREMONT INLET
 25 WILDCAT CREEK INFLOW
 26 GILL & STEVENS INLET
 27 SNYDER INLET
 28 TROWEL INLET
 29 BEAVER CREEK INFLOW
 30 NORTH STERLING INLET
 31 TETSEL DITCH
 32 PREWITT INLET
 33 BALZAC GAGE
 34 BOX ELDER CREEK TRIB
 35 LOST CREEK TRIB
 36 KIOWA CREEK TRIB
 37 BIJOU CREEK TRIB
 38 BADGER CREEK TRIB
 39 BEAVER CREEK TRIB
 40 CROW CREEK TRIB
 41 RIVERSIDE OUTLET
 42 JACKSON LAKE OUTLET
 43 WELDON VALLEY OUTLET
 44 WIDCAT CREEK TRIB
 45 LOST CK WEST INLET
 46 LOST CK EAST INLET
 47 BIJOU RCH #1
```

Node	Name
48	BIJOU RCH #2
49	BIJOU RCH #3
50	MILLIRON INLET
51	BIJOU RCH #4
52	BIJOU RCH #5
53	BIJOU RCH #6
54	BIJOU RCH #7
55	BIJOU RCH #8
56	BIJOU RCH #9
57	BIJOU RCH #10
58	WEIMER INLET
59	BIJOU RCH #11
60	BIJOU RCH #12
61	BIJOU RCH #13
62	CHASE RES
63	LOST CRK WEST
64	LOST CRK EAST
65	WEINGART
66	WEINER
67	PUTNAM
68	MILLIRON DRAW
69	KIOWA RCH #1
70	KIOWA RCH #2
71	KIOWA RCH #3
72	KIOWA RCH #4
73	KIOWA RCH #5
74	BIJOU #2 RES
75	BIJOU CRK RCH #1
76	BIJOU CRK RCH #2
77	BIJOU CRK RCH #3
78	BIJOU CRK RCH #4
79	BIJOU CRK RCH #5
80	BIJOU CRK RCH #6
81	BIJOU CRK RCH #7
82	BIJOU CRK RCH #8
83	WELL1 013387
84	WELL2 013440F
85	WELL3 013442F
86	WELL4 013443F
87	WELL5 013444F
88	WELL6 0223R
89	WELL7 0396
90	WELL8 0405
91	WELL9 04235F
92	WELL10 04300F
93	WELL11 0554
94	WELL12 0555
95	WELL13 0591
96	WELL14 0593
97	WELL15 0858

```
Node    Name
================================
  98 WELL16 10013
  99 WELL17 10301
 100 WELL18 10303
 101 WELL19 10304
 102 WELL20 10305
 103 WELL21 10306
 104 WELL22 10358
 105 WELL23 10439
 106 WELL24 10574
 107 WELL25 10575
 108 WELL26 10576
 109 WELL27 10577
 110 WELL28 10582
 111 WELL29 10584-RF238
 112 WELL30 10585
 113 WELL31 10588
 114 WELL32 10805
 115 WELL33 10806
 116 WELL34 11015
 117 WELL35 11016
 118 WELL36 11121
 119 WELL37 11122
 120 WELL38 11345F
 121 WELL39 11483
 122 WELL40 11520
 123 WELL41 12077
 124 WELL42 12080
 125 WELL43 12339
 126 WELL44 12350
 127 WELL45 12351
 128 WELL46 12352
 129 WELL47 12355
 130 WELL48 12359
 131 WELL49 12360
 132 WELL50 12366
 133 WELL51 12369
 134 WELL52 12370
 135 WELL53 12371
 136 WELL54 12372
 137 WELL55 1251
 138 WELL56 1252
 139 WELL57 1262
 140 WELL58 12657
 141 WELL59 12659
 142 WELL60 1267
 143 WELL61 1289
 144 WELL62 13636
 145 WELL63 14336F
 146 WELL64 1434
 147 WELL65 14618
```

```
Node    Name
=================================
 148 WELL66 14619
 149 WELL67 14620
 150 WELL68 14643
 151 WELL69 1475(R74)
 152 WELL70 1476
 153 WELL71 15158(RF1039)
 154 WELL72 16112
 155 WELL73 1666
 156 WELL74 1675
 157 WELL75 1777
 158 WELL76 1778
 159 WELL77 1779
 160 WELL78 1780
 161 WELL79 1781
 162 WELL80 1782
 163 WELL81 1859
 164 WELL82 1941
 165 WELL83 1942
 166 WELL84 1945
 167 WELL85 1947
 168 WELL86 1968
 169 WELL87 1969
 170 WELL88 2019-1
 171 WELL89 2019-2
 172 WELL90 21216
 173 WELL91 22124F
 174 WELL92 2423F
 175 WELL93 3060
 176 WELL94 3838F
 177 WELL95 4202F
 178 WELL96 4203F
 179 WELL97 4204F
 180 WELL98 429
 181 WELL99 4418
 182 WELL100 4544F
 183 WELL101 4561
 184 WELL102 4743F
 185 WELL103 5367F
 186 WELL104 5711F
 187 WELL105 5858F
 188 WELL106 5870
 189 WELL107 5963
 190 WELL108 5995
 191 WELL109 6053F
 192 WELL110 6118
 193 WELL111 6120
 194 WELL112 6121
 195 WELL113 6181F
 196 WELL114 6250
 197 WELL115 6256
```

```
Node    Name
=================================
 198 WELL116 6333
 199 WELL117 6335F
 200 WELL118 6335F(10807F)
 201 WELL119 6337
 202 WELL120 6481
 203 WELL121 6482
 204 WELL122 6545F
 205 WELL123 6568
 206 WELL124 6663
 207 WELL125 6665
 208 WELL126 6666
 209 WELL127 6681
 210 WELL128 6685
 211 WELL129 6702
 212 WELL130 6853
 213 WELL131 6878F
 214 WELL132 6964
 215 WELL133 6968
 216 WELL134 6971
 217 WELL135 6976
 218 WELL136 6978
 219 WELL137 7032
 220 WELL138 7128
 221 WELL139 7132
 222 WELL140 7133
 223 WELL141 7134
 224 WELL142 7135
 225 WELL143 7137
 226 WELL144 7138
 227 WELL145 7139
 228 WELL146 7251
 229 WELL147 7333
 230 WELL148 7335
 231 WELL149 7336
 232 WELL150 762
 233 WELL151 8204
 234 WELL152 8209
 235 WELL153 8210
 236 WELL154 8290
 237 WELL155 8301
 238 WELL156 8313
 239 WELL157 8314
 240 WELL158 8315
 241 WELL159 8341
 242 WELL160 8341A
 243 WELL161 8342
 244 WELL162 8348
 245 WELL163 8350
 246 WELL164 8351
 247 WELL165 8352
```

```
Node    Name
===============================
 248 WELL166 8384
 249 WELL167 8419
 250 WELL168 8420
 251 WELL169 8422
 252 WELL170 8423
 253 WELL171 8431
 254 WELL172 8432
 255 WELL173 8476
 256 WELL174 8510
 257 WELL175 8512
 258 WELL176 8554
 259 WELL177 8638
 260 WELL178 8644
 261 WELL179 8648
 262 WELL180 8649
 263 WELL181 8650
 264 WELL182 8654
 265 WELL183 8843
 266 WELL184 9071F
 267 WELL185 R11524-01
 268 WELL186 R148(11212)
 269 WELL187 R15364
 270 WELL188 R15365
 271 WELL189 R218(7146)
 272 WELL190 R225(7126)
 273 WELL191 R260(1269)
 274 WELL192 R5913
 275 WELL193 R6687
 276 WELL194 R7174
 277 WELL195 R8289
 278 WELL196 RF634(11482)
 279 WELL197 RF671(6001)
 280 WELL198 RF681(8639)
 281 WELL199 RF802(8267)
```

E.4 Reservoir Data File: Res.dat (9 records)

```
NODE    CAP_MAX    CAP_MIN    CAP_BEG     PRIORITY  TARGET    SPL_PRI
   1     900000          0     900000           10       0          2
  33     900000          0          0           20       0          1
  34     900000          0     900000           30       0          3
  35     900000          0     900000           40       0          4
  36     900000          0     900000           50       0          5
  37     900000          0     900000           60       0          6
  38     900000          0     900000           70       0          7
  39     900000          0     900000           80       0          8
```

E.5 Demand Data File: Demand.dat (Partial listing - 50/232 records)

NODE	DEMAND	PRIORITY	TYPE	SEEPG	GW_RTN	PCAP	PCOST	SPYLD	TRANS	DIST	GW_DEPN
47	0	100		0.5	33			125	133.7	133.7	
48	0	110		0.5	33			350	133.7	133.7	
49	0	120		0.5	33			270	133.7	133.7	
51	0	130		0.5	33			750	133.7	133.7	
52	0	140		0.5	33			677	133.7	133.7	
53	0	150		0.5	33			1590	133.7	133.7	
54	0	160		0.5	33			3310	133.7	133.7	
55	0	170		0.5	33			4875	133.7	133.7	
56	0	180		0.5	33			5550	133.7	133.7	
57	0	190		0.5	33			5800	133.7	133.7	
59	0	200		0.5	33			5225	133.7	133.7	
60	0	210		0.5	33			4915	133.7	133.7	
61	0	220		0.5	33			7100	133.7	133.7	
62	0	230		0.5	33			7825	133.7	133.7	
63	0	240		0.5	33			30	133.7	133.7	
64	0	250		0.5	33			100	133.7	133.7	
65	0	260		0.5	33			5880	133.7	133.7	
66	0	270		0.5	33				133.7	133.7	
68	0	280		0.5	33			30	133.7	133.7	
69	0	290		0.5	33			750	133.7	133.7	
70	0	300		0.5	33			480	133.7	133.7	
71	0	310		0.5	33			270	133.7	133.7	
72	0	320		0.5	33			120	133.7	133.7	
73	0	330		0.5	33			30	133.7	133.7	
74	0	340		0.5	33			3310	133.7	133.7	
75	0	350		0.5	33			5070	133.7	133.7	
76	0	360		0.5	33			4320	133.7	133.7	
77	0	370		0.5	33			3630	133.7	133.7	
78	0	380		0.5	33			3000	133.7	133.7	
79	0	390		0.5	33			2430	133.7	133.7	
80	0	400		0.5	33			1920	133.7	133.7	
81	0	410		0.5	33			1470	133.7	133.7	
82	0	420		0.5	33			1080	133.7	133.7	
83	0	430				10000		1503	133.7	133.7	33
84	0	440				10000		1669	133.7	133.7	33
85	0	450				10000		1625	133.7	133.7	33
86	0	460				10000		389	133.7	133.7	33
87	0	470				10000		1394	133.7	133.7	33
88	0	480				10000		2470	133.7	133.7	33
89	0	490				10000		750	133.7	133.7	33
90	0	500				10000		851	133.7	133.7	33
91	0	510				10000		5532	133.7	133.7	33
92	0	520				10000		5046	133.7	133.7	33
93	0	530				10000		2934	133.7	133.7	33
94	0	540				10000		2664	133.7	133.7	33
95	0	550				10000		3273	133.7	133.7	33
96	0	560				10000		4315	133.7	133.7	33
97	0	570				10000		3014	133.7	133.7	33
98	0	580				10000		156	133.7	133.7	33
99	0	590				10000		2877	133.7	133.7	33

E.6 Link Data File: Link.dat (81 records)

LINK	NAME	BEG_NODE	END_NODE	MAX_CAP	MIN_CAP
1	SPLATTE_RCH1	1	2	10000	0
2	SPLATTE_RCH2	2	3	10000	0
3	SPLATTE_RCH3	3	4	10000	0
4	SPLATTE_RCH4	4	5	10000	0
5	SPLATTE_RCH5	5	6	10000	0
6	SPLATTE_RCH6	6	7	10000	0
7	SPLATTE_RCH7	7	8	10000	0
8	SPLATTE_RCH8	8	9	10000	0
9	SPLATTE_RCH9	9	10	10000	0
10	SPLATTE_RCH10	10	11	10000	0
11	SPLATTE_RCH11	11	12	10000	0
12	SPLATTE_RCH12	12	13	10000	0
13	SPLATTE_RCH13	13	14	10000	0
14	SPLATTE_RCH14	14	15	10000	0
15	SPLATTE_RCH15	15	16	10000	0
16	SPLATTE_RCH16	16	17	10000	0
17	SPLATTE_RCH17	17	18	10000	0
18	SPLATTE_RCH18	18	19	10000	0
19	SPLATTE_RCH19	19	20	10000	0
20	SPLATTE_RCH20	20	21	10000	0
21	SPLATTE_RCH21	21	22	10000	0
22	SPLATTE_RCH22	22	23	10000	0
23	SPLATTE_RCH23	23	24	10000	0
24	SPLATTE_RCH24	24	25	10000	0
25	SPLATTE_RCH25	25	26	10000	0
26	SPLATTE_RCH26	26	27	10000	0
27	SPLATTE_RCH27	27	28	10000	0
28	SPLATTE_RCH28	28	29	10000	0
29	SPLATTE_RCH29	29	30	10000	0
30	SPLATTE_RCH30	30	31	10000	0
31	SPLATTE_RCH31	31	32	10000	0
32	SPLATTE_RCH32	32	33	10000	0
33	CROW CREEK	40	2	10000	0
34	BOX ELDER CRK	34	5	10000	0
35	RIVERSIDE OUT	41	10	10000	0
36	LOST CREEK	35	11	10000	0
37	KIOWA CREEK	36	14	10000	0
38	JACKSON OUT	42	15	10000	0
39	WELDONA RTN	43	18	10000	0
40	BIJOU CREEK	37	20	10000	0
41	BADGER CREEK	38	22	10000	0
42	WILDCAT CREEK	44	25	10000	0
43	BEAVER CREEK	39	29	10000	0
44	BIJOU_RCH1A	7	45	0	0
45	BIJOU_RCH1B	45	46	0	0
46	BIJOU_RCH1C	46	47	0	0
47	BIJOU_RCH2	47	48	0	0
48	BIJOU_RCH3	48	49	0	0
49	BIJOU_RCH4A	49	50	0	0
50	BIJOU_RCH4B	50	51	0	0
51	BIJOU_RCH5	51	52	0	0
52	BIJOU_RCH6	52	53	0	0
53	BIJOU_RCH7	53	54	0	0
54	BIJOU_RCH8	54	55	0	0
55	BIJOU_RCH9	55	56	0	0
56	BIJOU_RCH10	56	57	0	0
57	BIJOU_RCH11A	57	58	0	0
58	BIJOU_RCH11B	58	59	0	0
59	BIJOU_RCH12	59	60	0	0
60	BIJOU_RCH13	60	61	0	0
61	CHASE	61	62	0	0
62	LOST CRK WEST	62	63	0	0

LINK	NAME	BEG_NODE	END_NODE	MAX_CAP	MIN_CAP
63	LOST CRK EAST	63	64	0	0
64	WEINGART	57	65	0	0
65	WEIMER	58	66	0	0
66	PUTMAN	47	67	0	0
67	MILLIRON DRAW	50	68	0	0
68	KIOWA_RCH1	51	69	0	0
69	KIOWA_RCH2	69	70	0	0
70	KIOWA_RCH3	70	71	0	0
71	KIOWA_RCH4	71	72	0	0
72	KIOWA_RCH5	72	73	0	0
73	BIJOU#2_RES	53	74	0	0
74	BIJOU_CRK1	74	75	0	0
75	BIJOU_CRK2	75	76	0	0
76	BIJOU_CRK3	76	77	0	0
77	BIJOU_CRK4	77	78	0	0
78	BIJOU_CRK5	78	79	0	0
79	BIJOU_CRK6	79	80	0	0
80	BIJOU_CRK7	80	81	0	0
81	BIJOU_CRK8	81	82	0	0

E.7 Coefficient File Developed From MODRSP: SPLAT.cff
(Partial listing- 50/1079 records,5/89 fields)

```
 REC  FROM TO   TYPE     PER1
===================================
  1     47 33     1  0.53636610
  2     47  7     2  0.03102195
  3     47 10     2  0.14438130
  4     47 11     2  0.01065870
  5     47 12     2  0.01317517
  6     47 13     2  0.03215321
  7     47 14     2  0.00001510
  8     47 35     3  0.10303790
  9     48 33     1  0.31429420
 10     48 11     2  0.00000000
 11     48 12     2  0.00000287
 12     48 13     2  0.06543054
 13     48 14     2  0.02555172
 14     48 35     3  0.00000000
 15     48 36     3  0.00009090
 16     49 33     1  0.36024230
 17     49 13     2  0.00305342
 18     49 14     2  0.01998124
 19     49 36     3  0.00321241
 20     51 33     1  0.21155280
 21     51 13     2  0.00026886
 22     51 14     2  0.02015051
 23     51 15     2  0.00000000
 24     51 16     2  0.00000000
 25     51 36     3  0.13159960
 26     51 37     3  0.00000000
 27     52 33     1  0.22280620
 28     52 14     2  0.00036297
 29     52 15     2  0.00011321
 30     52 16     2  0.00027424
 31     52 17     2  0.00000000
 32     52 36     3  0.55826090
 33     52 37     3  0.00028512
 34     53 33     1  0.14946590
 35     53 14     2  0.00023619
 36     53 15     2  0.00046862
 37     53 16     2  0.00178601
 38     53 17     2  0.00012344
 39     53 18     2  0.00000000
 40     53 20     2  0.00000000
 41     53 36     3  0.05945479
 42     53 37     3  0.01826917
 43     54 33     1  0.11553850
 44     54 15     2  0.00000000
 45     54 16     2  0.00000000
 46     54 17     2  0.00000000
 47     54 36     3  0.00013715
 48     54 37     3  0.31816840
 49     55 33     1  0.10396390
 50     55 17     2  0.00000000
```

E.8 Return Data File: Rtn.dat
(Partial listing 50/1079 records)

```
  ITYPE INODE  TYPE2  INODETO
==============================
     2    47      1        7
     2    47      1       10
     2    47      1       11
     2    47      1       12
     2    47      1       13
     2    47      1       14
     2    47      1       35
     2    48      1       11
     2    48      1       12
     2    48      1       13
     2    48      1       14
     2    48      1       35
     2    48      1       36
     2    49      1       13
     2    49      1       14
     2    49      1       36
     2    51      1       13
     2    51      1       14
     2    51      1       15
     2    51      1       16
     2    51      1       36
     2    51      1       37
     2    52      1       14
     2    52      1       15
     2    52      1       16
     2    52      1       17
     2    52      1       36
     2    52      1       37
     2    53      1       14
     2    53      1       15
     2    53      1       16
     2    53      1       17
     2    53      1       18
     2    53      1       20
     2    53      1       36
     2    53      1       37
     2    54      1       15
     2    54      1       16
     2    54      1       17
     2    54      1       36
     2    54      1       37
     2    55      1       17
     2    55      1       36
     2    55      1       37
     2    56      1       22
     2    56      1       37
     2    57      1       20
     2    57      1       21
     2    57      1       22
     2    57      1       37
```

APPENDIX F

BIJOU IRRIGATION COMPANY AUGMENTATION PLAN WELL DATA

Item	Permit No.	SDF	Owner	Location
1	013387	1503	WEST GREELEY FARMS	SWNE 12-04-60
2	013440F	1669	COOPER LAND CO	NWNW 11-03-58 (S)
3	013442F	1625	COOPER LAND CO	NWNW 11-03-58 (N)
4	013443F	389	COOPER LAND CO	SWSE 01-03-58
5	013444F	1394	COOPER LAND CO	SESW 02-03-58
6	0223R	2470	MILLER DAVID	NESW 22-04-59
7	0396	750	MCCREERY ET AL	SWNE 02-03-58 (E)
8	0405	851	MCCREERY ET AL	SWNE 02-03-58 (W)
9	04235F	5532	NEB DAVE JR	SENW 21-03-58 (S)
10	04300F	5046	HOFF LESLIE	NWNE 19-03-58 (N)
11	0554	2934	LARRICK WM	SWSE 09-03-58
12	0555	2664	LARRICK WM	NWSE 09-03-58
13	0591	3273	FUERST POTATO GROWERS	SWSE 36-04-59
14	0593	4315	FUERST POTATO GROWERS	SWNE 35-04-59
15	0858	3014	SNODGRASS FARM	NWNW 15-03-58
16	10013	156	CHESTER ANSLEY ET AL	NWNW 28-04-61
17	10301	288	PROPP MELVIN	NWSE 07-03-58
18	10303	5384	WEIMER HAROLD	SWSE 13-03-59
19	10304	401	KEAGY LEONARD	NWNW 01-03-58
20	10305	549	KEAGY LEONARD	SWNW 01-03-58
21	10306	2011	AMEN HARRY J	SWNW 13-03-58
22	10358	4140	BOHL KENNETH	NWNW 25-03-58
23	10439	5650	RUPPEL PETE	SESW 13-03-59
24	10574	1756	HOFFNER ALEX	SWSE 03-03-58
25	10575	5640	FRITZLER GABRIEL	SWSW 29-04-58
26	10576	5640	TORMOHLEN MILTON	NWSW 32-03-57
27	10577	5399	3-T CATTLE COMPANY	SWSE 31-03-57
28	10582	1408	SCHLUNDT ALEX	NWNE 11-03-58
29	10584-RF238	2298	KROSKOB WILLIAM	SWNE 14-03-58 (W)
30	10585	5693	NEB DAVE JR	SENW 21-03-58 (N)
31	10588	537	BENDER THOMAS	SENW 14-04-60
32	10805	4655	EUFRACIO ROMERO	SWNE 13-03-59 (N)
33	10806	4722	EUFRECIO ROMERO	SWNE 13-03-59 (S)
34	11015	490	TOMKY DARWIN	SWSE 35-04-58
35	11016	1107	CHALK WINFORD	SESW 34-04-58
36	11121	1041	COOPER LAND CO	NWNW 12-03-58
37	11122	1263	COOPER LAND CO	SWNW 12-03-58
38	11345F	3232	MORGENTHALER LUELLA	SENW 28-04-59
39	11483	147	STEWART COMBS	NWNE 29-04-61
40	11520	110	KINGSBURY CK	SWSW 20-04-61
41	12077	2206	SAGEL ARTHUR	SWNW 09-03-58
42	12080	5390	NUKAYA BILL	SWSW 11-03-59
43	12339	2452	SHEPPARD ROBERT	SWSE 10-03-58
44	12350	2476	CHMELKA RICHARD	NWSW 20-03-57
45	12351	1783	BEAUPREZ ANTHONY TRUST	NWNE 31-04-58
46	12352	2382	HEITSCHMIDT WAYNE	SWSW 31-04-58
47	12355	5578	GROVES LARRY	SWNE 10-03-59
48	12359	270	SCHNEIDER HARLAN	SWNE 26-04-61
49	12360	4117	FISCUS ARNOLD	SWSW 29-03-57
50	12366	3630	RUSCH JOHN R JR	SWSW 24-03-58

Item	Permit No.	SDF	Owner	Location
51	12369	1353	BROOKS BARBARA	SWNE 03-03-58
52	12370	4736	SAGEL EDWARD	NWSW 18-03-58 (W)
53	12371	2435	SOUTHARD JOE	NWNW 31-04-58
54	12372	6176	TORMOHLEN MILTON	SWSW 32-03-57
55	1251	5704	MAROLF PERRY	SWNW 10-03-59
56	1252	5378	NEB DON	SWSE 03-03-59
57	1262	3443	REHKOP FRED	SWNW 29-03-57
58	12657	7560	WINDSHEIMER VERN	SENW 06-02-57
59	12659	6417	3-T CATTLE COMPANY	SESW 31-03-57
60	1267	2219	PEYTON WJ	SWNE 19-03-57
61	1289	1639	STALEY ROBERT	SWSW 12-03-58
62	13636	4621	STUMP CLARENCE	SESW 31-03-57
63	14336F	5201	HOFF LESLIE	NWNE 19-03-58 (S)
64	1434	46	FARMERS HOME ADMIN	SENE 19-04-61
65	14618	3080	GRAFF TURF	SWNE 36-04-59
66	14619	2239	YEAROUS HOWARD	NWSW 13-03-58
67	14620	4078	GRITZZFELD FARM	SESW 29-03-57
68	14643	3446	DILL DOUGLAS	SWSE 24-03-58
69	1475 (R74)	69	FARMERS HOME ADMINI	SWSE 19-04-61
70	1476	91	FARMERS HOME ADMIN	SESE 19-04-61
71	15158 (RF1039)	4673	SAGEL EDWARD	NWSW 18-03-58 (E)
72	16112	1125	BEAUPREZ ANTRUST	NWNW 32-04-58
73	1666	2226	KROSKOB WILLIAM	SWNE 14-03-58 (E)
74	1675	1983	WEITZEL GLENN	SWSE 11-03-58
75	1777	4107	LAUCK GEORGE	SWNW 17-03-58
76	1778	2889	BAUER ELMER	NWNE 15-03-58
77	1779	2884	BAUER ELMER	SWNE 15-03-58
78	1780	5396	EISENACH MARLIN	SWNE 21-03-58 (N)
79	1781	5733	EISENACH MARLIN	SWNE 21-03-58 (S)
80	1782	5359	NUKAYA BILL	NWSW 11-03-59
81	1859	1599	SNODGRASS FARMS	NWSE 13-03-58
82	1941	6252	WEIMER WILMA	SWNW 24-03-59 (N)
83	1942	6328	WEIMER WILMA	SWNW 24-03-59 (S)
84	1945	5192	ROGERS JOAN	SWNW 32-03-57
85	1947	6241	WACKER HENRY	SESE 31-03-57
86	1968	1960	THOMPSON JAMES	NENW 08-03-58
87	1969	3075	BURKHART R	SWSW 19-03-57
88	2019-1	4877	STEIN CHARLES	NWNW 20-03-58 (S)
89	2019-2	4863	STEIN CHARLES	NWNW 20-03-58 (N)
90	21216	5070	SIMMONS CE	NWSE 13-03-59
91	22124F	510	STARK HAROLD	SWSE 11-03-59
92	2423F	5125	PUETT FARMS	SESW 25-03-58
93	3060	5186	TRIPP JERRY	SWSW 02-03-59
94	3838F	604	BENDER THOMAS	NESW 14-04-60
95	4202F	6582	BILLINGS ESTATE	SESE 36-03-58 (N)
96	4203F	6750	BILLINGS ESTATE	SESE 36-03-58 (S)
97	4204F	5455	WEIMER DAVID	SWSE 13-03-59
98	429	2793	TIMCHUIA HELEN	SWSE 09-03-58
99	4418	171	SCHNEIDER HARLAN	NWNE 28-04-61
100	4544F	4032	FUERST POTATO GROWERS	SWNW 01-03-59
101	4561	2690	WATSON ALBERT	NWSE 14-03-58
102	4743F	2214	KRENING RJ	NWNE 24-03-58
103	5367F	557	CHRISTENSEN LARRY	SWSE 09-04-59
104	5711F	3983	SHORT FARM	SESE 29-03-57
105	5858F	1831	BECKER ALBERT	NENW 30-04-58
106	5870	2307	SHEPPARD DANIEL	SWSW 11-03-58
107	5963	5770	GROVES LARRY	SWSE 14-03-59
108	5995	5101	STARK HAROLD	SWSE 11-03-59
109	6053F	3749	BEAUPREZ OSCAR	NESE 12-03-59
110	6118	4284	STUMP CLARENCE	NWSE 25-03-58
111	6120	3360	KIRK DEAN I	SWNW 07-03-58 (E)
112	6121	3365	KIRK DEAN I	SWNW 07-03-58 (W)
113	6181F	2435	BLG ASSOC	SWNW 19-03-57
114	6250	2670	KOSMAN JACOB JR	NWSW 10-03-58

Item	Permit No.	SDF	Owner	Location
115	6256	2307		
116	6333	1503	WEST GREELEY FARMS	SWNW 18-04-59
117	6335F	936	LORENZINI DON	SESW 13-04-59
118	6335F(10807F)	936	USA (3-T)	NENW 24-04-59
119	6337	247	HART LEO C	SWNW 27-04-61
120	6481	5506	AMBROSE WE JR	SWNW 21-03-58
121	6482	5295	AMBROSE WE JR	NWNW 21-03-58
122	6545F	5291	NEB DON	SESE 03-03-59
123	6568	1167	MARICK CLAYTON	NENW 03-03-58
124	6663	4070	LIND DANIEL	SENW 17-03-58
125	6665	4485	SCHEIRMAN RUDY	NWSE 18-03-58(S)
126	6666	4552	SCHEIRMAN RUDY	NWSE 18-03-58(N)
127	6681	385	PUETT FARMS	SWNE 01-03-58
128	6685	1464	WUNSCH WILLIAM	NWSW 18-03-57
129	6702	903	SCHEIRMAN CONRAD	SWSW 01-03-58
130	6853	1220	MARICK ALLEN	NWNE 03-03-58
131	6878F	3646	RUSCH JOHN R JR	SESE 23-03-58
132	6964	2387	SCHLOLHAUER STEVE	NWSE 08-03-58
133	6968	1682	WHITE KENNETH	SWSE 18-03-57
134	6971	1273	NEILL DWIGHT	SWNW 18-03-57
135	6976	1794	SOUTHWORTH FARMS	NWSE 11-03-58
136	6978	1828	PEAVEY OTIS	SWSE 02-04-58
137	7032	1483	WEIMER ADAM SR	SWSE 19-04-58
138	7128	851	TOMKY DARWIN	SWNE 29-04-58
139	7132	2367	NANCY PUETT WALLEN	SWNW 10-03-58
140	7133	3955	PUETT FARMS	NENE 26-03-58
141	7134	2385	DILL DONALD	NWNW 14-03-58
142	7135	4437	BOHL KENNETH	NESW 25-03-58
143	7137	1604	WEIMER ADAM SR	SESW 19-04-58
144	7138	4320	NEB JOHN	SWNE 18-03-58
145	7139	772	ANDERSON ROBERT	SESW 01-03-58
146	7251	599	BENDER THOMAS	NWNE 14-04-60
147	7333	1080	FRIES HAROLD	SENE 18-03-57
148	7335	1773	CARLSON ROY H	SWSE 04-03-58
149	7336	1294	CARLSON ROY H	NWSE 04-03-58
150	762	864	CRUMLEY LH	SWNE 12-03-58
151	8204	39	YOCAM FLOYD W	SWNW 21-04-61
152	8209	5112	REHKOP DONALD	NWNE 20-03-58(S)
153	8210	5000	REHKOP DONALD	NWNE 20-03-58(N)
154	8290	4002	LARRICK WM	SWSE 30-03-57
155	8301	5126	3-T CATTLE COMPANY	NENE 31-03-57
156	8313	2659	FORT MORGAN LIVESTOCK	SESE 14-03-58
157	8314	4464	SCHREINER ADAM	NWSW 17-03-58(S)
158	8315	4345	SCHREINER ADAM	NWSW 17-03-58(N)
159	8341	2317	LIND DAN	NWSW 09-03-58
160	8341A	303	MCARTHUR LP	NENE 16-03-58
161	8342	3027	MCARTHUR LP	NENE 16-03-58
162	8348	1942	WUNSCH WILLIAM	SWSW 18-03-57
163	8350	3413	COOPER LAND CO	NWNW 30-03-57
164	8351	3228	GELROTH HERMAN	SESE 24-03-57
165	8352	1805	WEIMER ADAM SR	SWNE 30-04-58
166	8384	931	SOUTHARD JACK	SWSW 07-03-57
167	8419	2015	CARLSON ROY H	NWNE 09-03-58
168	8420	1720	GRAHAM RALPH B	NWSW 03-03-58
169	8422	4514	LIND DAVE JR	SWNW 18-03-58(N)
170	8423	4520	LIND DAVE JR	SWNW 18-03-58(S)
171	8431	2538	COLUMBIA CHARLES	SENE 07-03-58
172	8432	2472	COLUMBIA CHARLES	SWNW 08-03-58
173	8476	5188	SAUER ELDON ET AL	NENW 14-03-59
174	8510	2601	BURKHART RICHARD	NWSE 19-03-57
175	8512	2768	MORGAN BOYER	SWSW 20-03-57
176	8554	2646	BLG ASSOC	NESW 19-03-57
177	8638	728	BENDER DAVID	SWSW 12-04-60
178	8644	4090	COMM BANK STERL	SWNE 25-03-58

Item	Permit No.	SDF	Owner	Location
179	8648	1210	PRINTZ CARL	SWNW 02-03-58(S)
180	8649	1080	PRINTZ CARL	SWNW 02-03-58(N)
181	8650	3115	HAEKER ROBERT	NWNW 24-03-57
182	8654	1470	MORI BROS INC	SESW 12-03-58
183	8843	1349	STALEY RONALD	SWSW 04-03-58
184	9071F	4671	FUERST POTATO GROWERS	NWSE 35-04-59
185	R11524-01	3000	SCHOTT ANN	NWNE 30-03-57
186	R148(11212)	245	PETERSON VIOLET	SWNW 26-04-61
187	R15364	140	RUMSEY TRUST	SESE 23-04-61
188	R15365	250	RUMSEY TRUST	SENE 27-04-61
189	R218(7146)	685	FRITZLER GABRIEL	SWSE 29-04-58
190	R225(7126)	1563	EPSTEIN ROSE	SWNE 13-03-58
191	R260(1269)	2799	RUSCH JOHN RANDAL	NENE 23-03-58
192	R5913	3038	GUNTHER KATHERINE	SWNE 29-03-57(N)
193	R6687	1259	BECKER ALBERT	SWNW 29-04-58
194	R7174	2922	GUNTHER KATHERINE	SWNE 29-03-57(S)
195	R8289	4083	WEBER EDWARD	SENW 17-03-58
196	RF634(11482)	120	STEWART COMBS	SWSE 20-04-61
197	RF671(6001)	872	BENDER DAVID	SESE 12-04-60
198	RF681(8639)	373	EHRLICH GREG	SWNW 12-04-60
199	RF802(8267)	936	JENSEN DONALD	NWSE 13-4-59

APPENDIX G

BIJOU AUGMENTATION PLAN ACCOUNTS

G.1 Net Return Flow Calculations: Using SDF Coefficient Values

NODE	YEAR	MON	GWIN	GWOUT	Net
33	1985	1	0	0	0
33	1985	2	0	0	0
33	1985	3	0	0	0
33	1985	4	0	0	0
33	1985	5	0	159	159
33	1985	6	16	264	248
33	1985	7	34	249	215
33	1985	8	12	199	187
33	1985	9	12	163	151
33	1985	10	71	132	61
33	1985	11	81	141	60
33	1985	12	101	174	73
33	1986	1	100	187	87
33	1986	2	103	160	57
33	1986	3	99	142	43
33	1986	4	94	132	38
33	1986	5	87	144	57
33	1986	6	85	181	96
33	1986	7	87	199	112
33	1986	8	83	215	132
33	1986	9	85	208	123
33	1986	10	112	198	86
33	1986	11	139	206	67
33	1986	12	156	224	68
33	1987	1	179	225	46
33	1987	2	181	225	44
33	1987	3	178	218	40
33	1987	4	172	214	42
33	1987	5	169	321	152
33	1987	6	173	397	224
33	1987	7	162	412	250
33	1987	8	154	412	258
33	1987	9	159	362	203
33	1987	10	170	327	157
33	1987	11	182	360	178
33	1987	12	181	346	165
33	1988	1	179	343	164
33	1988	2	167	342	175
33	1988	3	149	333	184
33	1988	4	145	316	171
33	1988	5	133	350	217
33	1988	6	133	474	341
33	1988	7	116	519	403
33	1988	8	114	531	417
33	1988	9	130	476	346
33	1988	10	162	441	279

```
 NODE YEAR MON GWIN GWOUT Net
=============================
  33 1988  11  180    417 237
  33 1988  12  190    396 206
  33 1989   1  186    382 196
  33 1989   2  184    366 182
  33 1989   3  171    389 218
  33 1989   4  159    425 266
  33 1989   5  148    547 399
  33 1989   6  145    489 344
  33 1989   7  141    447 306
  33 1989   8  144    451 307
  33 1989   9  155    407 252
  33 1989  10  176    388 212
  33 1989  11  184    561 377
  33 1989  12  198    519 321
  33 1990   1  188    471 283
  33 1990   2  179    431 252
  33 1990   3  168    408 240
  33 1990   4  154    385 231
  33 1990   5  146    572 426
  33 1990   6  140    601 461
  33 1990   7  133    531 398
  33 1990   8  130    600 470
  33 1990   9  131    494 363
  33 1990  10  139    454 315
  33 1990  11  169    589 420
  33 1990  12  192    612 420
  33 1991   1  190    487 297
  33 1991   2  187    437 250
  33 1991   3  180    409 229
  33 1991   4  168    412 244
  33 1991   5  158    594 436
  33 1991   6  154    540 386
  33 1991   7  151    507 356
  33 1991   8  166    589 423
  33 1991   9  191    526 335
  33 1991  10  206    491 285
  33 1991  11  223    657 434
  33 1991  12  226    738 512
```

G.2 Net Return Flow Calculations: Using MODRSP Coefficient Values

				REC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
MON	NET	DEPL	RTN	Node	7	10	11	12	13	14	15	16	17	18	20	21	22	35	36	37	38
1	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	881	0	881		26	119	9	11	47	20	2	1	0	0	0	0	0	85	293	268	0
6	717	24	741		19	101	9	14	74	30	2	1	0	0	0	0	-1	70	206	167	25
7	709	119	828		6	42	4	11	61	33	1	3	1	0	0	0	-2	29	205	309	6
8	592	144	736		4	21	2	8	57	28	1	3	-1	0	0	-1	-10	17	145	259	59
9	204	537	741		2	11	2	6	49	20	0	-1	-3	0	0	-2	-20	12	17	347	-236
10	86	1016	102		2	7	1	5	7	17	0	-6	-10	-1	-2	-6	-42	10	-72	549	-373
11	547	712	259		1	4	0	3	5	18	-1	-8	-9	-2	-3	-7	-54	8	127	547	-82
12	664	560	224		7	35	2	5	10	19	-1	-10	-3	-2	-5	-4	-57	29	165	509	-35
13	506	447	953		2	14	1	5	19	18	-1	-9	4	-3	-5	-3	-55	13	158	372	-24
14	362	363	725		1	7	1	4	19	11	0	-7	11	-1	-5	-3	-57	9	36	359	-23
15	239	303	542		1	3	0	3	20	9	0	-4	20	-1	-5	-1	-55	6	19	244	-20
16	151	258	409		0	2	0	3	17	6	0	-3	21	0	-3	0	-47	5	15	151	-16
17	427	222	649		0	1	0	3	33	22	1	-1	26	1	-2	0	-41	5	235	161	-17
18	1009	230	239		0	1	0	2	40	31	1	2	27	1	-2	0	-39	3	224	741	-23
19	1181	272	453		0	0	0	2	33	28	1	3	32	1	0	0	-37	3	163	956	-4
20	1091	480	571		0	0	0	1	29	29	1	4	35	2	1	-1	-37	33	138	909	-53
21	466	872	338		0	0	0	0	25	21	0	3	33	2	0	-4	-52	4	-15	637	-188
22	457	907	364		0	0	0	0	16	19	0	-3	30	3	-1	-5	-73	2	-24	603	-110
23	449	1084	533		0	0	0	0	10	18	0	-8	27	2	-2	-6	-96	2	127	608	-233
24	533	811	344		0	0	0	0	11	19	2	-9	34	1	-5	-5	-98	1	221	408	-47
25	353	627	980		0	0	0	0	9	11	1	-11	45	2	-5	-1	-93	0	75	326	-6
26	266	513	779		0	0	0	0	7	8	0	-8	51	5	-4	0	-84	0	20	275	-4
27	220	442	662		0	0	0	0	7	7	0	-5	53	5	-2	0	-85	0	13	231	-4
28	342	356	698		0	0	0	0	4	3	0	-1	58	4	-1	0	-76	0	15	337	-1
29	946	307	253		0	1	1	1	25	25	2	1	54	6	2	0	-66	119	351	428	-4
30	1155	299	454		0	1	1	1	33	33	2	0	56	6	3	0	-59	138	245	666	29
31	1301	239	540		0	1	1	1	29	31	1	5	59	5	4	0	-52	128	205	834	49
32	1151	265	416		0	0	0	0	21	26	1	10	60	5	7	0	-39	95	175	807	-17
33	809	459	268		0	0	0	-3	7	20	0	10	54	6	7	-1	-43	8	67	751	-74
34	849	479	328		0	0	0	-4	-2	16	0	7	52	4	5	-3	-48	1	42	803	-24
35	684	584	268		0	0	0	-3	12	17	2	5	48	3	-1	-3	-48	41	231	465	-61
36	813	444	257		0	0	0	-3	-9	13	2	3	51	5	-1	-4	-47	1	179	616	7
37	696	354	050		0	0	0	-3	0	17	1	3	55	6	-1	-1	-42	0	195	453	13
38	510	292	802		0	0	0	0	5	16	0	5	56	6	1	0	-41	-1	67	386	10
39	443	233	676		0	0	0	0	3	14	0	7	58	6	4	0	-33	0	48	326	10
40	365	188	553		0	0	0	0	5	11	0	4	57	5	7	0	-24	0	37	255	8
41	746	146	892		0	0	0	0	13	18	1	8	57	5	8	0	-18	79	203	364	8
42	1536	152	688		0	1	1	1	23	41	4	9	57	5	7	0	-12	146	586	652	15
43	1480	141	621		0	0	0	1	32	52	4	10	59	7	7	0	-10	82	552	676	8
44	1111	523	634		0	0	0	-1	25	49	2	14	54	6	7	-1	-13	80	366	714	-191
45	633	650	283		0	0	0	-4	6	41	0	12	48	4	6	-5	-26	6	131	562	-148
46	143	940	083		0	0	0	-5	13	32	0	2	41	4	2	-8	-46	-1	77	274	-216
47	-62	1017	955		0	0	0	-5	16	29	-2	-2	39	1	-1	-10	-63	-2	53	190	-273
48	-63	781	718		0	0	0	-3	15	23	-1	-7	39	1	-1	-7	-67	-3	34	73	-129
49	-1	610	609		0	0	0	-3	12	16	-1	-7	41	2	2	-5	-65	-3	28	79	-73
50	28	507	535		0	0	0	-1	-9	12	0	-4	43	3	3	-2	-62	-2	26	74	-53
51	322	404	726		0	0	0	0	4	25	2	0	47	3	4	0	-55	-1	240	96	-43
52	365	338	703		0	0	0	0	22	33	2	2	50	4	4	0	-44	27	213	87	-35
53	700	272	972		0	1	1	1	33	46	3	1	47	3	6	0	-33	115	374	133	-31
54	473	269	742		0	0	0	0	30	39	1	0	45	3	6	0	-28	7	119	288	-37
55	228	393	621		0	0	0	0	16	33	0	3	43	3	5	0	-24	2	52	191	-96
56	156	556	712		0	0	0	0	2	30	1	2	39	3	5	0	-20	11	152	85	-154
57	-288	906	618		0	0	0	-1	13	23	0	0	26	3	4	-2	-30	1	-27	0	-272

MON	NET	DEPL	RTN	Node	7	10	11	12	13	14	15	16	17	18	20	21	22	35	36	37	38
58	-547	954	407		0	0	0	-2	20	17	0	-6	18	2	-1	-3	-43	0	-42	-203	-264
59	191	886	077		0	1	1	0	-8	31	2	-8	9	0	-4	-4	-52	126	341	-71	-173
60	496	674	170		0	0	0	-1	0	42	4	-9	11	0	-4	-3	-56	8	436	129	-61
61	168	527	695		0	0	0	0	5	29	1	-6	12	0	-4	0	-57	2	82	132	-28
62	27	422	449		0	0	0	0	5	23	0	-6	16	0	-3	0	-57	1	37	32	-21
63	-18	347	329		0	0	0	0	5	17	0	-7	14	0	-2	0	-54	0	26	-1	-16
64	-12	284	272		0	0	0	0	4	14	0	-5	15	-1	1	0	-47	0	20	-1	-12
65	1318	228	546		0	0	1	1	39	53	5	-1	16	-1	2	0	-40	106	758	389	-10
66	1197	203	400		0	0	1	0	47	56	6	2	17	0	2	0	-31	97	424	578	-2
67	918	266	184		0	0	0	0	39	48	3	6	22	1	2	0	-25	17	135	723	-53
68	665	726	391		0	0	0	0	27	44	2	6	18	0	2	-1	-26	60	201	603	-271
69	726	555	281		0	0	0	0	20	30	1	3	18	-1	-2	-4	-37	5	56	678	-41
70	463	693	156		0	0	0	0	15	23	1	2	17	-1	-5	-4	-45	1	29	566	-136
71	288	878	166		0	0	0	-1	-1	28	3	-4	19	-1	-8	-4	-60	81	305	166	-235
72	248	679	927		0	0	1	-1	10	18	2	-7	26	-1	-10	0	-65	102	165	117	-89
73	223	548	771		0	0	0	0	-7	11	0	-2	29	-1	-7	-1	-66	7	42	270	-52
74	219	445	664		0	0	0	0	-6	7	0	1	39	-1	-5	0	-59	2	30	250	-39
75	146	371	517		0	0	0	0	-4	6	0	1	44	0	-2	0	-54	1	26	160	-32
76	385	304	689		0	0	1	0	7	14	0	3	44	1	2	0	-42	89	80	208	-22
77	1388	246	634		0	1	1	1	33	42	3	5	47	1	4	0	-35	142	536	624	-17
78	1125	230	355		0	0	0	1	31	42	1	5	47	2	5	0	-31	30	190	816	-14
79	1075	327	402		0	0	0	0	19	37	0	9	53	4	6	0	-27	4	103	973	-106
80	1238	668	906		0	0	0	-1	11	49	4	10	56	4	6	-1	-30	72	517	776	-213
81	560	852	412		0	0	0	-3	36	36	1	8	51	5	1	-3	-43	5	109	630	-201
82	385	911	296		0	0	0	-3	41	31	0	4	50	5	-6	-5	-54	0	37	522	-155
83	735	1038	773		0	1	1	-1	42	39	4	1	53	3	-6	-6	-58	136	457	430	-277
84	887	771	658		0	1	1	0	29	34	5	0	56	3	-10	-7	-60	139	500	355	-101