GIS AND CONJUNCTIVE USE FOR IRRIGATED AGRICULTURE

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ABSTRACT

A microcomputer based geographic information (GIS) is presented for decision support in conjunctive use of groundwater and surface water for irrigated agriculture. A powerful, yet low-cost, raster GIS for PC's called IDRISI is utilized for preparing and processing grid-based spatial data for MODRSP, a modified version of the USGS 3D finite-difference groundwater model, MODFLOW. Spatially distributed stream-aquifer response coefficients are generated and then used within a generalized river basin network model called MODSIM. The GIS is also used for displaying and analyzing results of conjunctive use schemes. Integration of GIS, MODFLOW, and MODSIM allows analysis of conjunctive use plans with consideration of decreed flow and storage rights, river calls, exchanges, trades, and plans for augmentation. The hydrologic components include: reservoir seepage, irrigation infiltration, groundwater pumping, channel losses, return flows, river depletion flows due to pumping, and aquifer storage. Capabilities of the decision support system are demonstrated on a 70 mile section of the Lower South Platte River, Colorado.

INTRODUCTION

Water has always been the key to the success of agriculture in the West. In a state such as Colorado, where 75% of the water is used for agriculture, the importance of meeting the water needs of irrigated agriculture in quantity and quality will remain a major issue in the 1990's. Faced with the prospect of increased competition for available water from a growing urban sector and a moratorium on new large-scale water projects, irrigated agriculture will have to depend on effective management of currently available resources.

Because of the complexities involved in river basin management, computer based models are finding increasing acceptance as tools to assist water users and water managers in developing improved basin wide and regional strategies. In the western U.S., these efforts are complicated by the administrative and legal constraints dictated by water right issues and the interdependence of surface and groundwater users. Some of the areas where computer based models have been identified as having high potential for providing better decision support include daily water administration, drought contingency planning, voluntary basin wide management, groundwater exchange program evaluation, recharge and augmentation project management, and regional scale modeling to resolve conflicts between urban and agricultural water users (Caulfield et al, 1987).

To support this modeling effort, a microcomputer based river basin decision support system (DSS) has been developed for improved conjunctive use management of

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groundwater and surface water for irrigated agriculture under appropriation water rights doctrine. A finite difference groundwater flow model (MODRSP) has been linked with a river basin network model (MODSIM) using database management (DBMS) and geographical information system (GIS) technology.

DSS STRUCTURE AND FEATURES

The DSS has been structured around decision support system theory. Decision Support System (DSS) can be defined as " an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems" (Sprague and Carlson, 1982). DSS software should have three sets of technical capabilities (Sprague, 1980):

1. Database management software (DBMS)
2. Model base management software (MBMS)
3. Software for managing the interface between the user and the system, the dialogue generation and management software (DGMS).

The DSS has been designed to model long term river basin planning activities, daily river administration, and river management options such as groundwater augmentation. Groundwater modeling of stream-aquifer return flows is done using response coefficients which can be calculated from numerical or analytical methods. Groundwater management is accomplished using a network simulation model which is able to represent even the most complex river basin systems. The DSS can operate in a microcomputer environment and incorporates commercial, non-proprietary, or supported public domain software. Geographical information (GIS) and data base management (DBMS) system technology is used to process data available from sources such as public domain databases, published maps, or digital maps. The ability to incorporate appropriation water rights, to model stream-aquifer events, and to allocate river basin water resources according to user specified operational rules and demand priorities provides the user with a powerful river basin modeling tool.

The components of DSS are presented in Figure 1.

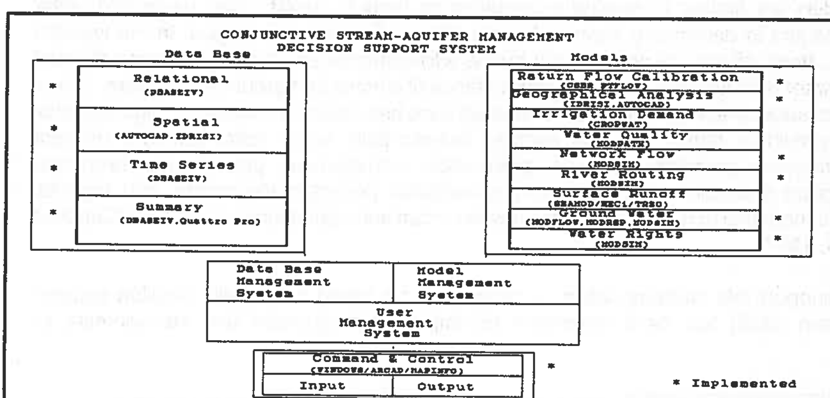


Fig 1: Conjunctive Stream-Aquifer Management Decision Support System

The database component is supported using DbaseIV, a data base management package that can be used to create, organize, and access a database; and Quattro Pro, a spreadsheet package with graphics and database support.

GIS and spatial analysis is supported through several different software packages. IDRISI is a grid based geographic analysis system, developed at Clark University, that is designed to provide inexpensive access to computer-assisted geographic analysis technology. AUTOCAD is a general purpose computer aided design (CAD) program that can be used to prepare a variety of two dimensional drawings and three dimensional models. SURFER is a powerful and flexible tool for creating contour or surface plots of three dimensional data. The USGS General Cartographic Transformation Package (GCTP) is the standard computer software used by the National Mapping Division for map projection computations.

The modeling component is supported by several well documented and recognized water resource models. MODSIM is a river basin network simulation model developed at Colorado State University. MODFLOW is the USGS Modular Three-Dimensional Finite-Difference Groundwater Flow Model. MODRSP, developed at Arizona State University, is a modification of the USGS MODFLOW finite difference model that can be used to calculate drawdown, velocity, storage losses, and capture response functions for multi-aquifer groundwater flow systems. PTFLOW is a USBR river water balance program that can be used to calculate reach gains and losses between stream gages given diversion and inflow data.

A user interface was designed to run under a DOS operating system using WINDOWS, a graphical environment that allows users to run more than one application at a time. It also allows users to access the virtual memory capabilities of the Intel 80386/486 processor, allowing WINDOWS applications to use more memory than is available. The desktop mapping software, MAPINFO, was used to integrate database information with maps. The application language, MAPBASIC, was used to customize MAPINFO to create custom applications, perform sophisticated geographic SQL queries, and create custom menus and dialogue boxes.

INVENTORY OF DATA RESOURCES

An inventory of data resources was carried out as part of the DSS development process. Although a number of the data sets reviewed are unique to Colorado, most of the data required to support the DSS 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 US Geological Survey (USGS) is quite extensive. USGS Ground Water Site Survey Database (GWSI) includes data on depth of well, ground surface elevation at well, specific capacity, transmissivity, well location, pumping capacity, seasonal water levels, and well use. Published groundwater maps which show hydrogeologic characteristics such as well location, bedrock configuration, aquifer delineation, water table contours, saturated thickness, and transmissivity are available for many major aquifers (Hurr, Schneider, and others, 1972). Digital Line Graphs (DLG) providing digital representation of cartographic information such as hypsography (contours), hydrography (water), vegetative surface cover, boundaries, survey control markers, transportation, manmade features, and U.S. Public Land Survey System (township, range, section) are available for most areas. Land Use and Land

Cover (LULC) data can 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. LANDSAT provides satellite photos. Digital Elevation Model (DEM) data is elevation data interpolated from USGS maps. Northern Great Plains AVHRR Data Set is NOAA-9 Advanced Very High Resolution Radiometer (AVHRR) data which is 1 kilometer grid data for bands 1-5 afternoon satellite coverage that has normalized difference vegetative index images.

Another source of data is the Colorado Division of Water Resources. Typical databases include: 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 Water Commissioners.

Cross section data for tributaries and streams at road crossings is available from the Bridge Division of the Colorado Department of Transportation.

US 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.

The National Oceanic and Atmospheric Administration maintains: 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.

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 accurate map data with related geographic information and population statistics. The TIGER files include digitized data on hydrography, roads, and political boundaries.

The US 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

Bureau of Land Management has been tasked with preparing the Coordinate Conversion Database that will allow conversion of Public Land Survey data to Latitude-Longitude coordinates; however this is still not available for eastern Colorado.

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, 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 ammounts for the Bijou Irrigation Company. Project Maps have also been prepared on well and recharge locations.

ROLE OF GIS IN THE MODELING PROCESS

Geographic Information Systems (GIS) provide a number of capabilities 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, Taylor, French, 1985; Goulter and Forest, 1987) include the ability to display and graphically summarize data input and output, to improve data input and editing, to provide an effective interface between models and modelers and models and data bases, and to improve the comprehension of spatial and time varying information. The DSS integrates several GIS and spatial analysis tools and software packages such as AUTOCAD (CADCAM,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. Figure 2 shows steps used to extract digital map data from U.S. Bureau of Census TIGER files (Bureau of the Census, 1989).

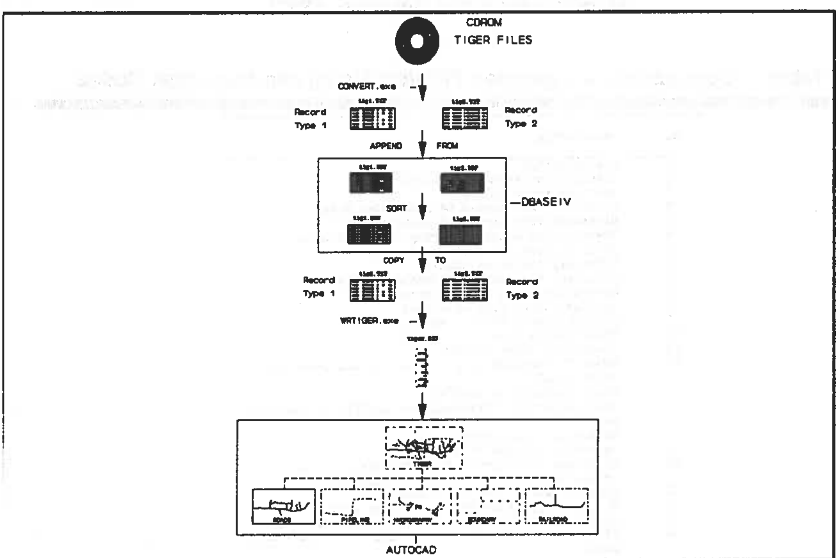


Fig 2: Procedures Used to Import TIGER Files into AUTOCAD

STREAM-AQUIFER MODELS

The various hydrologic conditions usually considered in stream-aquifer management models are listed in Table 1 and graphically presented in Figure 3.

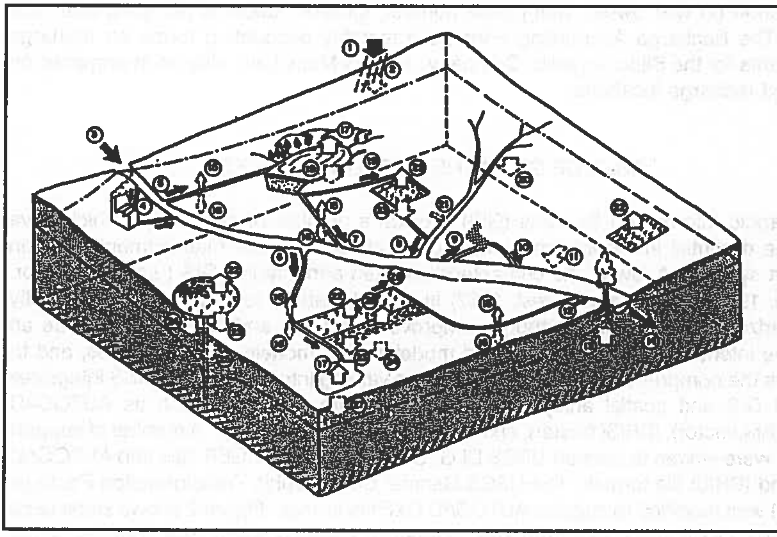


Fig 3: Representation of the Stream-Aquifer System (Morel-Seytoux and Restrepo, 1987)

Table 1: Correspondence Between Physical Model and Numerical Codes

No.	Description
1	Precipitation
2	Infiltration from precipitation
3	Upstream river inflow
4	Diversion from stream to industrial area
5	Diversion from stream to reservoir
6	Diversion to canal supplying irrigated land
7	Spillway from reservoir to stream
8	Tributary inflow to stream
9	Diversion from stream to municipal area
10	Return flow from city to stream
11	Aquifer return flow to stream
12	Surface return flow to stream
13	Phreatophyte loss
14	Downstream river outflow
15	Canal evaporation (e.g., diversion and reservoir spill canal)
16	Canal recharge to aquifer
17	Evaporation from reservoir and artificial recharge area
18	Reservoir recharge to aquifer
19	Reservoir release to supply area
20	Tributary recharge to aquifer (stream not in hydraulic connection with the aquifer)
21	Aquifer return flow to tributary
22	Evapotranspiration from cultivated area
23	Infiltration from irrigated area
24	Effective infiltration from irrigated or bare soil area
25	Aquifer withdrawal by pumping well
26	Evaporation from bare soil
27	Area of artificial recharge to aquifer
28	Surface drainage from irrigated field

The stream-aquifer modeling process has traditionally been viewed as a saturated groundwater flow problem (Pinder, 1988). Several of the more common modeling methods include:

* Channel Water Balance (Schafer, 1979; Wright,1980). This method uses multiple linear regression based on water balance equations to determine time and spatially variant return flow coefficients.
* Glover's Analytical Solution (Glover, 1978; Labadie, et al, 1983). The linear form of the Boussinesq partial differential equation for one dimensional groundwater flow is used to generate sets of response coefficients for different groundwater flow processes.
* Stream Depletion Factor Method (Jenkins, 1968; Moulder and Jenkins, 1969; Taylor and Luckey, 1972; and Hurr, Schneider, and others, 1972; Warner, Sunada, and Hartwell, 1986). The Glover equation is solved graphically; dimensionless curves and tables are developed to compute the rate and volume of stream depletion by wells. Regional groundwater numerical models have been used to develop SDF factor contour maps.
* Finite Difference Numerical Model (McDonald and Harbaugh, 1988). The partial differential equation for groundwater movement in a heterogeneous and anisotropic medium is solved using a finite difference method. This method uses a finite set of discrete points or grids to represent the system and replaces the partial differential equations with terms calculated from the differences in potentiometric head at these grid points. The result is a system of simultaneous linear difference equations.
* Discrete Kernel/Response Function Approach (Maddock, 1972; Morel-Seytoux and Restrepo, 1987; Maddock and Lacher, 1991). Linear system theory is applied to the groundwater flow equation. The response of the groundwater system due to external excitation such as pumping, recharge, or infiltration at any point or 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.

The DSS allows a user to model stream-aquifer interaction using the discrete kernel/response function approach, the Glover equations, or predefined SDF values.

GENERATING STREAM-AQUIFER RESPONSE COEFFICIENTS

The DSS uses MODRSP (Maddock and Lacher,1991) to generate numerical stream-aquifer response coefficients. MODRSP,a modification of the USGS MODFLOW finite difference model (McDonald and Harbough,1988), can be used to calculate drawdown, velocity, storage losses, and capture response functions for multi-aquifer groundwater flow systems. Capture response functions can be generated for stream-aquifer leakance, reduction of evapotranspiration losses, leakance from adjacent aquifers, flows to and from prescribed head boundaries and increases in natural recharge or discharge form head dependent boundaries. (Maddock and Lacher,1991A).

The procedures required to generate spatially distributed stream-aquifer response coefficients for use in a stream-aquifer management model are shown in Figure 4.

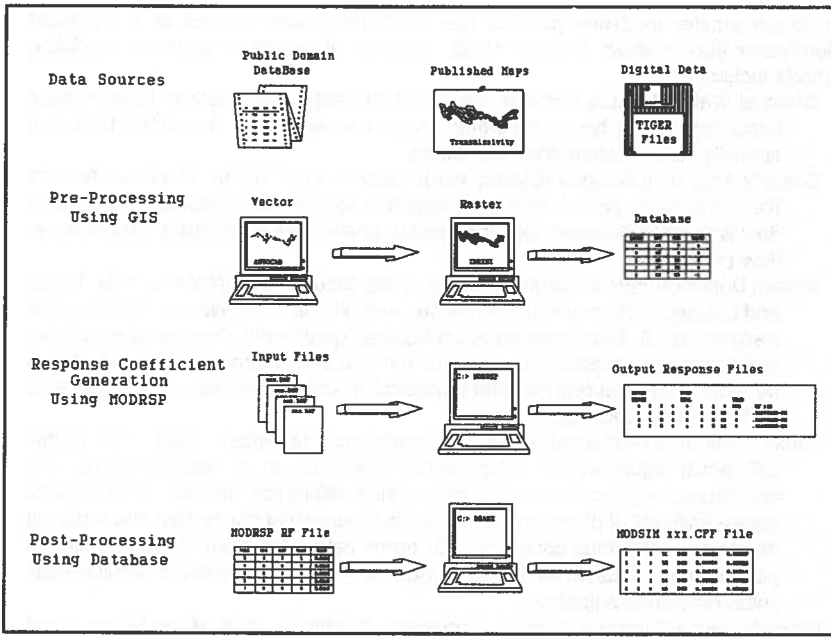


Fig 4: Using MODRSP to Create Response Coefficients

Data Preprocessing for MODRSP

GIS and DBMS procedures were used to prepare aquifer transmissivity, boundary, well, and river reach input data files used by MODRSP. Figure 5 illustrates procedures used to prepare boundary files.

Execution of MODRSP

MODRSP is written in 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. Figure 6 shows the input and output files required for MODRSP. A well documented user manual is available for MODRSP (Maddock and Lacher,1991)

Data Postprocessing for MODRSP

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 before they can be used in a stream-aquifer management model. This is done using database procedures.

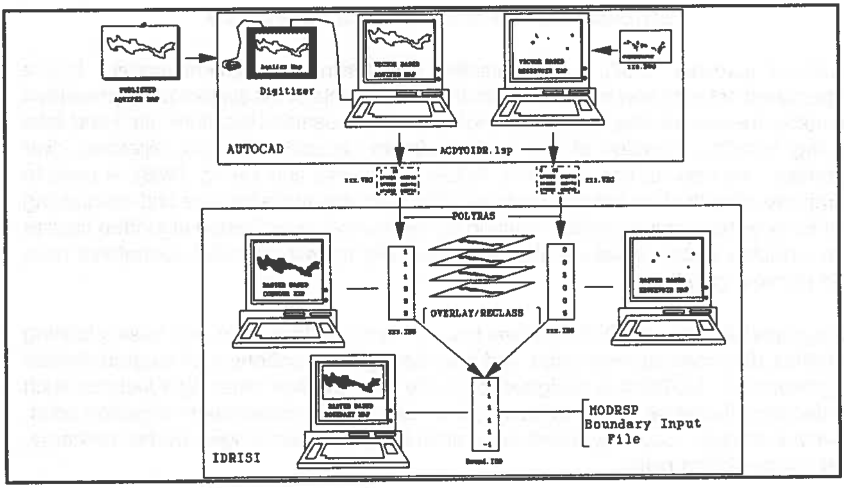


Fig 5: MODRSP Boundary File

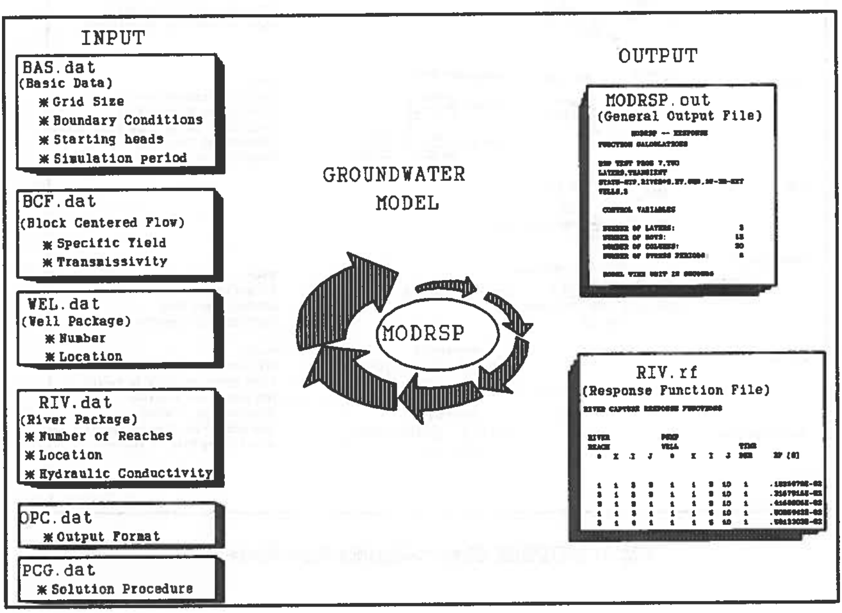
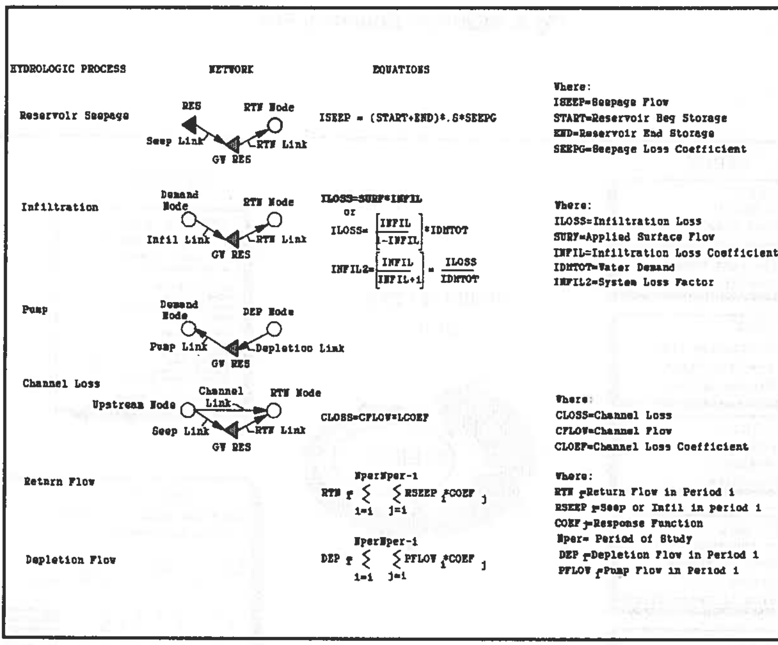


Fig 6: MODRSP

STREAM-AQUIFER MODELING USING MODSIM

MODSIM (Labadie, 1987) is an interactive river basin management model. It is a capacitated network flow model in which the components of the system are represented as nodes (reservoirs, diversion points, points of inflow, demand locations, etc.) and links having specified direction of flow and maximum capacities (canals, pipelines, river reaches). An optimization algorithm, RELAX (Bertsekas and Tseng, 1988), is used to iteratively solve the flow network problem while satisfying mass balance and maintaining link flows within required limits. Solution by the network optimization algorithm insures that available system flows are allocated according to user specified operational rules and demand priorities.

An updated version of MODSIM allows the user to model long term river basin planning activities, daily river administration, and river management options such as groundwater augmentation. MODSIM is designed to handle appropriation water right features such as decreed diversions, direct release from a reservoir to a downstream diversion point, reservoir storage accounts, diversions at alternate points, exchanges, trades, recharge, and augmentation plans.



$$RTN_i = \sum_{i=1}^{Nper} \sum_{j=1}^{Nper-i} RSEEP_i * COEF_j$$

$$DEP_i = \sum_{i=1}^{Nper} \sum_{j=1}^{Nper-i} PFLOW_i * COEF_j$$

Fig 7: MODSIM Stream-Aquifer Functions

The Stream-Aquifer module within MODSIM allows the user to consider reservoir seepage, irrigation infiltration, pumping, channel losses, return flows, river depletion flows due to pumping, and aquifer storage as shown in Figure 7.

Other features which can be modeled include, overbank storage, channel routing, and divided flows. Stream-Aquifer return/depletion flows are simulated using response coefficients calculated using one dimensional equations developed by Glover (1974), McWhorter (1972), and Maasland (1959). Groundwater response coefficients estimated from other methods such as the SDF method, the 3-D groundwater finite difference model MODRSP (Maddock and Lacher, 1991), or the discrete kernel generator, GENSAM (Morel-Seytoux and Restrepo, 1987) can be read in as external data files. 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 8.

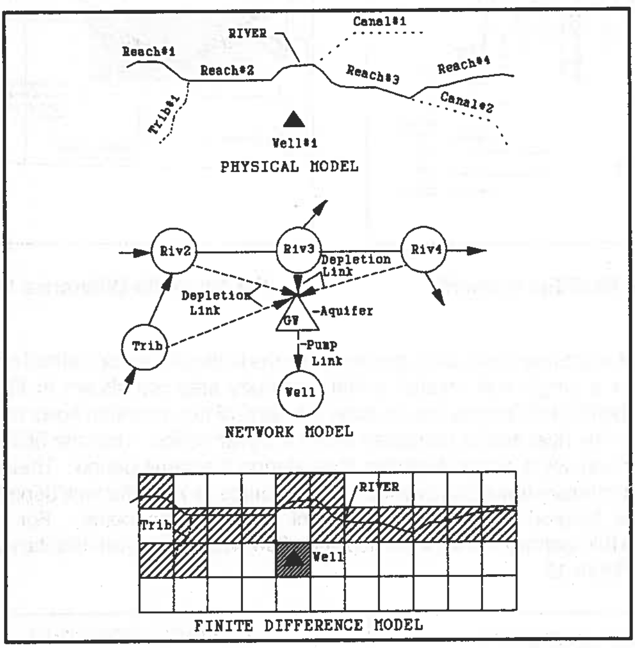


Fig 8: Stream-Aquifer Models

CASE STUDY

To demonstrate the capabilities of the DSS a reach along 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 was selected for study purposes. A river system network shown in Figure 9 was prepared which includes 9 reservoirs, 20 diversion points, 50 direct decree diversions, 30 storage decree diversions, and 9 recharge areas. Other network nodes were designated for exchanges, trades and alternate points of diversion. A groundwater grid network with 370 by 140 grids (1000 ft x 1000 ft cell) shown in Figure 10 was developed using GIS techniques. Spatially distributed stream-aquifer response coefficients were generated for the Bijou Irrigation Company augmentation plan (HRS 1983) which involves 200 wells and 32 recharge events. Conjunctive use management was demonstrated through monthly simulation of historical recharge and groundwater augmentation efforts for the Bijou augmentation plan. The consequences on daily river administrative of the South Platte River of various augmentation scenarios was then compared. An interactive graphical user interface was prepared for viewing the results of the study.

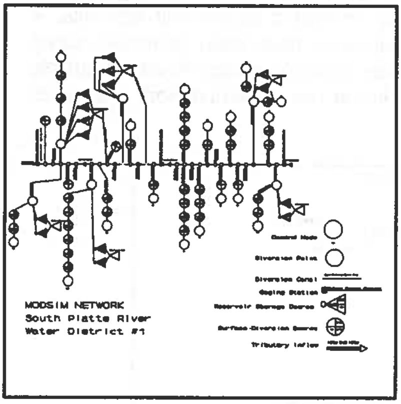


Fig 9: MODSIM Network

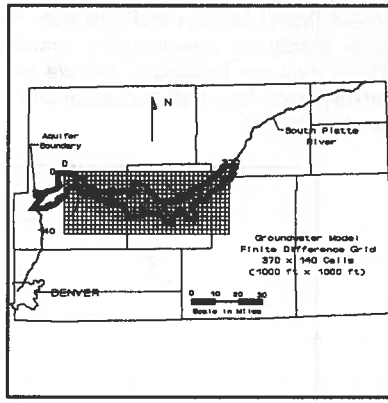


Fig 10: Finite Difference Grid

Comparison of response coefficients generated by the finite difference method and using SDF values for a single well located within the study area are shown in Figure 11. Results from the finite difference model show that 95% of the depletion flows to the well are drawn from the river and its tributaries within a 3 year period, while the SDF method accounted for only 68 % of the depletion flows during the same period. These results also show that tributary flows can provide a major source of water for well depletion and should not be ignored in the development of augmentation plans. For the well represented in this example 54 % of the depletion flow was drawn from tributary sources as shown in Figure 12.

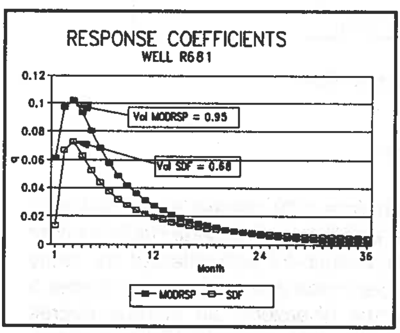


Fig 11: Comparing Response Coefficients

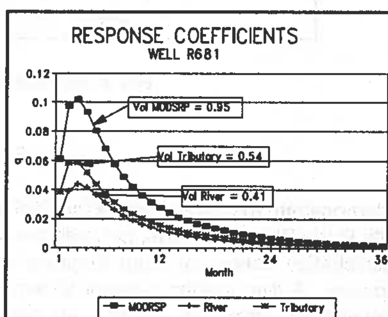


Fig 12: MODRSP Response Coefficients

CONCLUSIONS

A micro-computer based geographic information (GIS) is presented for decision support in conjunctive use of groundwater and surface water for irrigated agriculture. Spatially distributed stream-aquifer response coefficients are generated using the finite difference groundwater flow model, MODRSP, GIS and DBMS techniques. The river basin network simulation model, MODSIM, uses these coefficients to allocate return/depletion flows to any number of return/depletion flow nodes anywhere in the network. The use of MODSIM as a stream-aquifer management model was demonstrated by evaluating the effects of a major augmentation plan on daily river administration of a portion of the Lower South Platte River, Colorado.

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