GEO-MODSIM: SPATIAL DECISION SUPPORT SYSTEM FOR RIVER BASIN MANAGEMENT

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presented at:
2007 ESRI International User Conference
San Diego Convention Center
San Diego, California
June 18-22, 2007

ABSTRACT: The MODSIM river basin management model has been extended to GEO-MODSIM for integration with GIS for spatial data base management, analysis, and display. GEO-MODSIM is a custom ArcMap extension that provides the foundation for integrated river basin management. Numerous geodatabase layers are loaded and processed in GEO-MODSIM, including topography, political divisions, hydrography, irrigated fields, soil maps, land use, field measurements, and satellite imagery. Spatial-temporal data bases are also loaded such as NEXRAD precipitation data, water rights, gauging station records, diversions, pumping wells, and monitored surface water locations. These base GIS layers are processed to delineate watersheds, generate geometric networks, and create hydro-networks. Formatted data sets are created for executing external spatially distributed network flow optimization models, groundwater models and water quality models directly from the ArcMap interface. GEO-MODSIM is applied to the Lower Arkansas River basin, Colorado for salinity management and the Imperial Irrigation District, California for water conservation analysis.

KEY WORDS: Conjunctive use, Decision support systems, Geographic information systems, Geometric networks, Network analysis, River basin management, Water quality modeling, Water rights

INTRODUCTION

MODSIM 8.0 (Labadie, 2005) is a generalized river basin network flow model designed to aid stakeholders in developing a *shared vision* of planning and management goals, while gaining a better understanding of the need for coordinated operations in complex river basin systems that may impact multiple jurisdictional entities. MODSIM provides for integrated evaluation of hydrologic, environmental, and institutional/legal impacts as related to alternative development and management scenarios, including conjunctive use of surface water and groundwater resources. Although the MODSIM graphical user interface (GUI) allows display of background maps for network creation, it lacks capabilities for geo-referencing of network objects to real-world coordinate systems and incorporation of geographic information system (GIS) capabilities. GEO-MODSIM has been developed as an extension of MODSIM 8.0 for creating and analyzing georeferenced river basin networks inside ArcGIS™ 9 (ESRI, Inc.). GEO-MODSIM allows full utilization of the available spatial data processing, display and analysis tools in ArcGIS in conjunction with the powerful MODSIM model functionality.

The custom GEO-MODSIM Data Model is applied to developing georeferenced MODSIM networks by creation of an ESRI geometric network in ArcGIS using imported feature classes such as National Hydrologic Dataset (NHD) stream and canal layers, reservoirs, gauging stations, diversion structures, and wells. Various tools programmed under the MS .NET Framework utilize ESRI ArcObjects to develop a MODSIM compatible georeferenced network of river basin features from the geometric network that can be directly loaded into the MODSIM GUI within which users can then perform all data import, processing, network simulation, and display of scenario results. Alternatively, custom GEO-MODSIM forms and controls allow data processing, model execution, and output display to be performed entirely within the ArcMap, which essentially serves as the GUI for MODSIM. This allows full exploitation of all spatial data processing and display functionality in ArcGIS for development of MODSIM datasets, and establishes GEO-MODSIM as a spatial decision support system for river basin management.

Features and capabilities of GEO-MODSIM are described, followed by presentation of two case studies demonstrating these capabilities. The first case study applies GEO-MODSIM to the irrigated stream-aquifer system of the Lower Arkansas River basin in Colorado for development of salinity management strategies under complex water rights and interstate compact agreements. For the second case study, GEO-MODSIM is used to assess water conservation programs for the large and complex Imperial Irrigation District (IID) water delivery system in support of the IID/SDCWA Water Transfer Agreement that could provide significant additional water supplies to San Diego County from the Colorado River.

GEO-MODSIM STRUCTURE AND USAGE

River Basin Networks Built from Geometric Networks

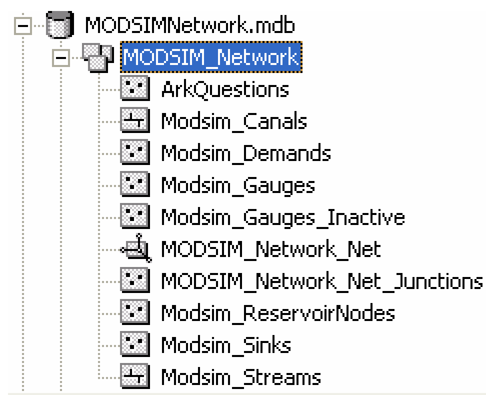


Figure 1. GEO-MODSIM Data Model.

The topology and infrastructure of a river basin network is represented using ArcGIS geometric networks. The geometric network contains the geometry and location of edges and junctions, along with connectivity information between edges and junctions and rules of behavior (e.g., which edge classes can be connected to a particular junction class). The geometric network is assembled from a custom GEO-MODSIM Data Model designed to accommodate MODSIM features in a geographic environment (Figure 1). System edges in the geometric network are based on the USGS National Hydrography Dataset (NHD), which is a comprehensive set of digital spatial data containing information on surface water features such as lakes, ponds, streams, rivers, canals, drains, springs and wells. The NHD data are filtered to an adequate degree of detail, with streams then separated from canals and drainages and imported into the Modsim_Streams and Modsim_Canals elements of the Geo-MODSIM Data Model. Reservoir nodes are created into the Modsim_ReservoirNodes feature class based on locations of water bodies in the NHD layer and linked to the appropriate streams and canals. Demand Nodes are connected to canal edges close to the diversion points. The NHD digitized direction provides a reasonable initial estimate of flow direction in the geometric network, although manual editing is sometimes required in the drainage system.

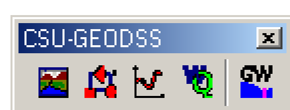


Figure 2 shows a geometric network based on the GEO-MODSIM Data Model as displayed in the ArcMap interface. Once the geometric network is loaded into ArcMap, the toolbar for the GEO-MODSIM Extension is accessed from the *Tools* > *Customize* > *Toolbars* tab by selecting the CSU-GEODSS toolbar. Clicking the GEODSS-MODSIM Dialog icon  in the toolbar opens the GEO-MODSIM GUI in ArcMap. All the functionality

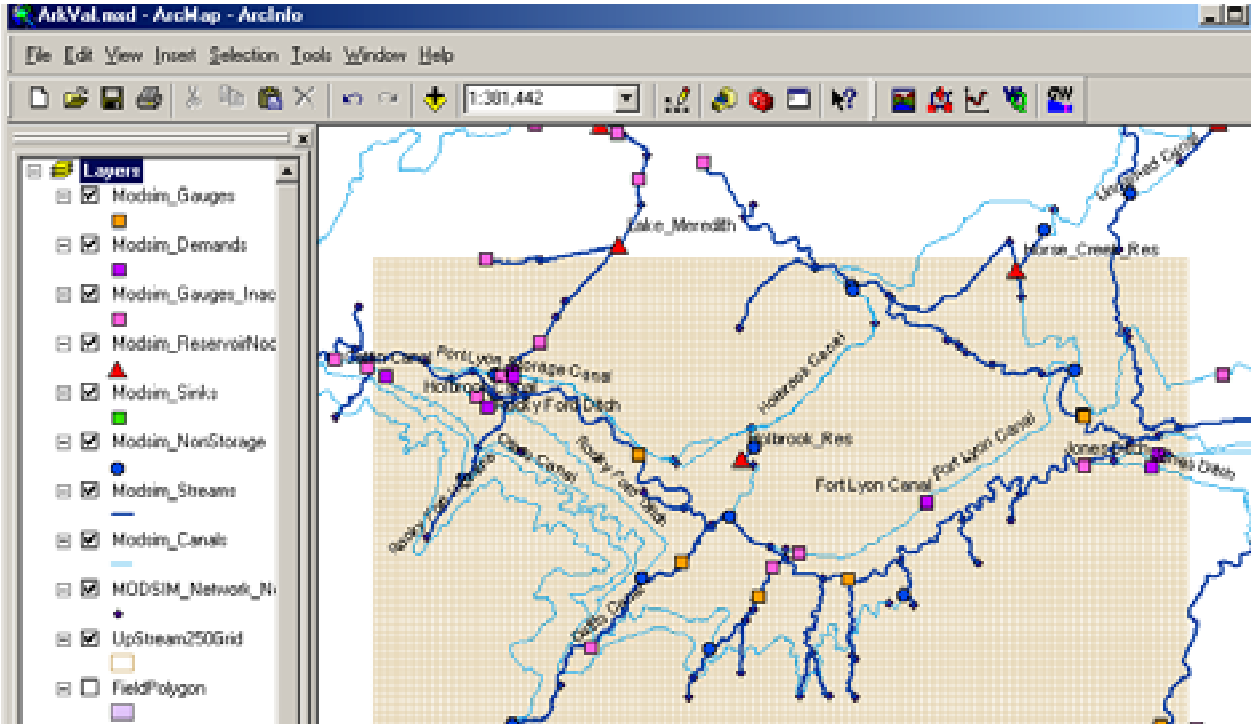


Figure 2. Example geometric network based on the GEO-MODSIM Data Model.

for connecting ArcGIS and MODSIM is available in this custom dialog which docks into the ArcMap work space, providing a convenient means of capturing the objects and characteristics of the geometric network and transforming them into a MODSIM network flow model (Figure 3). New MODSIM networks can be generated from this dialog, or existing networks updated based on changes in the geometric network. The network is saved in the MODSIM *.xy file format to accommodate storage of MODSIM specific data. Synchronization between the geometric network and MODSIM networks is automatically maintained, while providing access to general MODSIM user dialogs, run options and customized tools for spatial/temporal data pre-processing.

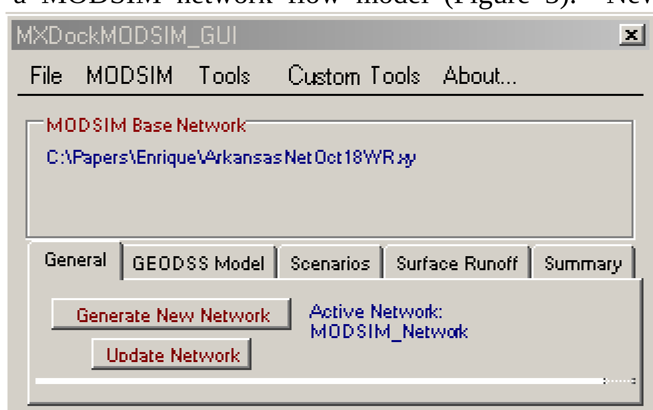


Figure 3. GEO-MODSIM GUI displayed in ArcMap.

GEO-MODSIM Functionality

As an extension of MODSIM, GEO-MODSIM networks include all the essential functionality for comprehensive water resources modeling and river basin management. Figure 4 summarizes the important river basin features and infrastructure that can be integrated into GEO-MODSIM networks, including dynamic, time-lagged stream-aquifer interaction for conjunctive use modeling. Complex management criteria incorporated into GEO-MODSIM include water right decrees, costs and benefits of water use, reservoir operation rules, shortage rules for water allocation during drought conditions, energy production targets from hydropower, storage ownership accounting, instream flow requirements for environmental/ecological protection, flood control rules, and dynamic streamflow routing. MODSIM simulates water allocation mechanisms in a river basin through sequential solution a minimum cost network flow optimization problem. The objective function and constraints are automatically formulated

Icon	Functionality	Data Requirements
Reservoir [Operations]	▪ Main-stem and offstream reservoir operations ▪ Flood control, conservation pools; dead storage ▪ Zones for storage balancing in multi-reservoir systems	▪ Elevation-area-capacity tables ▪ Maximum, minimum, initial storage ▪ Reservoir storage guidecurves ▪ Reservoir balance tables ▪ Hydraulic outlet capacity tables ▪ Net evaporation loss; seepage ▪ Inflow forecasts (if available)
Reservoir [Hydropower]	▪ High-head hydropower ▪ Run-of-river hydropower [0 storage] ▪ On-peak, secondary and firm energy ▪ Pumped storage	▪ Nonlinear efficiency tables as functions of head and discharge ▪ Tailwater-discharge tables ▪ Powerplant capacity ▪ Load factors for pumped storage
StorageRight Reservoir	▪ Storage right accounts ▪ Storage ownership maintenance ▪ Water banking and service contracts	▪ Storage right users ▪ Group ownerships
NonStorage	▪ Watershed runoff ▪ Tributary inflow ▪ Flow confluence and diversion ▪ Groundwater return flows ▪ Stream depletion from pumping	▪ Imported inflow time series data ▪ Execution of external rainfall-runoff models through custom code
Demand	▪ Consumptive demand ▪ Groundwater pumping ▪ Stream-aquifer modeling with Glover model or USGS stream depletion factor (sdf) method	▪ Import of demand time series data ▪ External consumptive use models ▪ Demands/priorities conditioned on hydrologic state ▪ Water use efficiency (time variable) ▪ Aquifer parameters; pumping capacity
Flowthru	▪ Instream flow requirements environmental, ecological or navigation purposes ▪ Nonconsumptive demands ▪ Gaging station for model calibration	▪ Time series of instream flow requirements ▪ Flow-through demands and priorities vary with hydrologic conditions ▪ Measured flow data for calibration
NetworkSink	▪ River basin outlet (multiple outlets for several basins allowed)	
Link	▪ Channel losses ▪ Maximum and Minimum Flow	▪ Time series of maximum capacities ▪ Link costs and benefits
MultiLink	▪ Represent nonlinear discharge-channel loss functions ▪ Nonlinear cost-discharge functions ▪ Multiple water sources and rights	▪ Time series of maximum capacities ▪ Link costs and benefits
Routing Link	▪ Streamflow and channel routing	▪ Muskingum method coefficients ▪ User defined lag coefficients

Figure 4. MODSIM functionality and features.

in the GEO-MODSIM interface and solved with the highly efficient Lagrangian relaxation algorithm RELAX-IV (Bertsekas and Tseng, 1994), which is up to two orders of magnitude faster than the revised simplex method of linear programming. Although GEO-MODSIM is primarily a simulation model, the network flow optimization provides an efficient means of assuring allocation of flows in a river basin in accordance with specified water rights and other priority rankings, including economic valuation.

GEO-MODSIM Customization

Several river basin management models such as MIKE BASIN (DHI Water & Environment, 2006) offer internal rainfall-runoff, water quality, and groundwater flow models within their software packages. In addition to these modules, WEAP (Stockholm Environmental Institute-Boston; Yates et al., 2005) includes consumptive use, demand forecasting, and economic valuation modules. These modules are generally simplified for ease-of-use, whereas many users will often have their own, more accurate models already calibrated to their system. Rather than including simplified, internal modules, GEO-MODSIM is designed to provide powerful customization capabilities allowing users to attach their own preferred modules. The Custom Code Editor shown in Figure 5 is accessed in the MODSIM GUI for preparation of customized code in the Visual Basic.NET or C#.NET languages that are compiled with MODSIM in the Microsoft .NET Framework. The .NET CLR produces executable code as opposed to other applications requiring scripts to be prepared in an interpreted language such as PERL or JAVASCRIPT with poorer runtime performance. The Custom Code Editor guides users in the preparation of customized code, allowing interfacing with MODSIM at any desired strategic locations, including data input, execution at the beginning of any time step, processing at intermediate iterations, and model output. Access to all key variables and object classes in MODSIM is provided, allowing customization for any complex river basin operational and modeling constructs without reprogramming and recompiling the MODSIM source code.

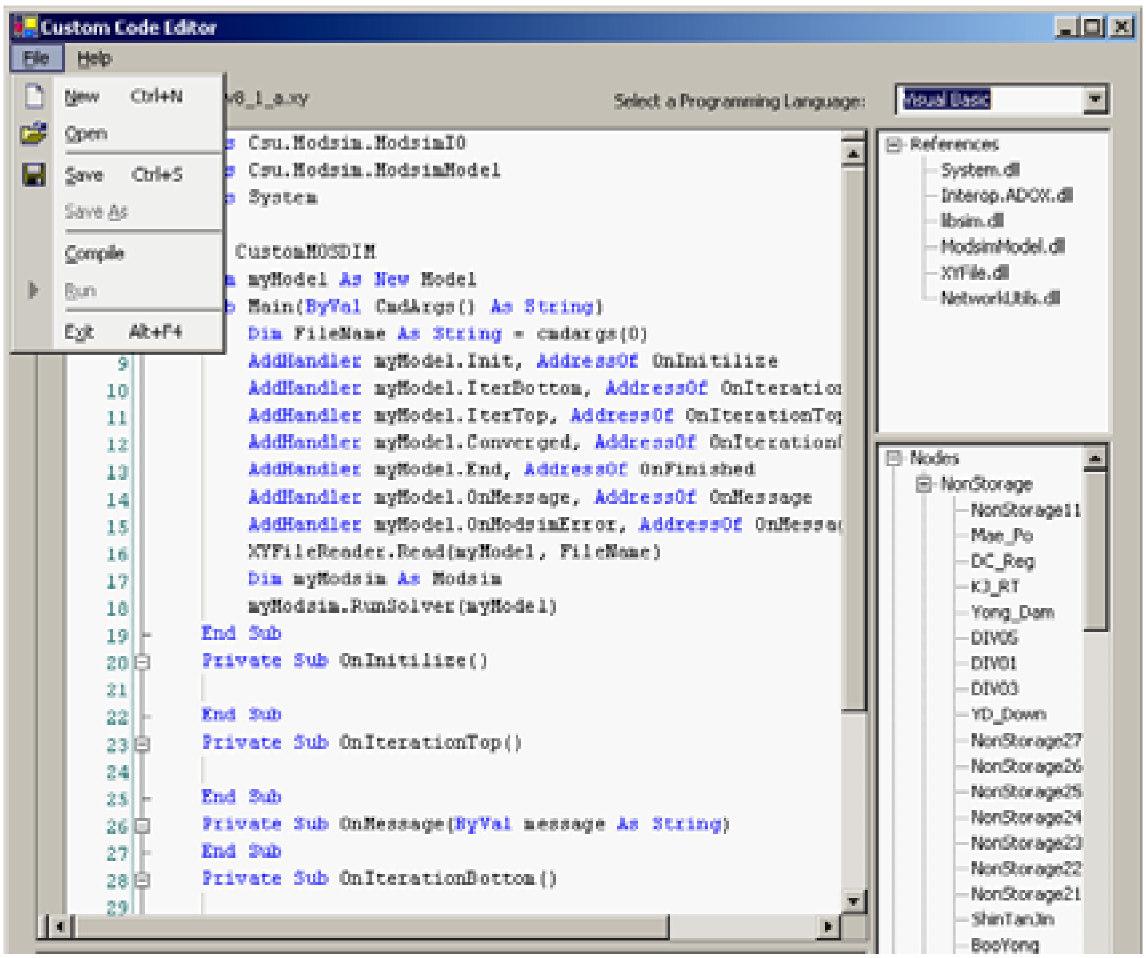


Figure 5. Custom Code Editor in MODSIM.

Assigning River Basin Feature Attributes in ArcMap

Once the MODSIM network is generated, clicking the MODSIM tab in the GEO-MODSIM GUI opens forms for setting MODSIM network properties, selecting variables for output display, activating various MODSIM Extensions such as the Water Rights Extension and the Storage Rights Extension; importing water rights data, and specifying cost and priority structures governing water allocation in the basin (Figure 6).

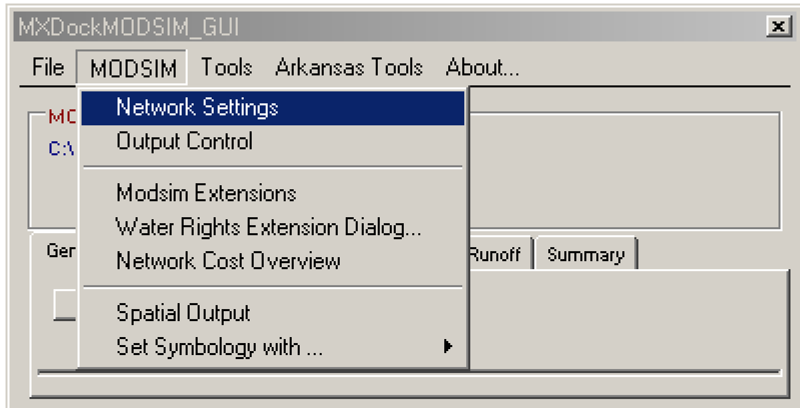
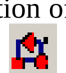


Figure 6. MODSIM network settings displayed in ArcMap.

MODSIM user dialogs can be opened in the ArcMap interface using GEO-MODSIM for import and editing of necessary data for the network objects. ESRI ArcObjects provide access to events triggered in ArcMap that allow association of the MODSIM object oriented database with the georeferenced features.

The Select Features button  in the GEO-MODSIM toolbar opens access to the MODSIM dialog for any network object. Users can click on any network feature in the ArcMap display to open a dialog that permits entry and editing of all pertinent data for that feature (Figure 7). The GUI then saves the data in MODSIM format. By incorporating MODSIM dialogs in this way, GEO-MODSIM affords the same functionality as the stand-alone MODSIM interface, but with the added capabilities of GIS.

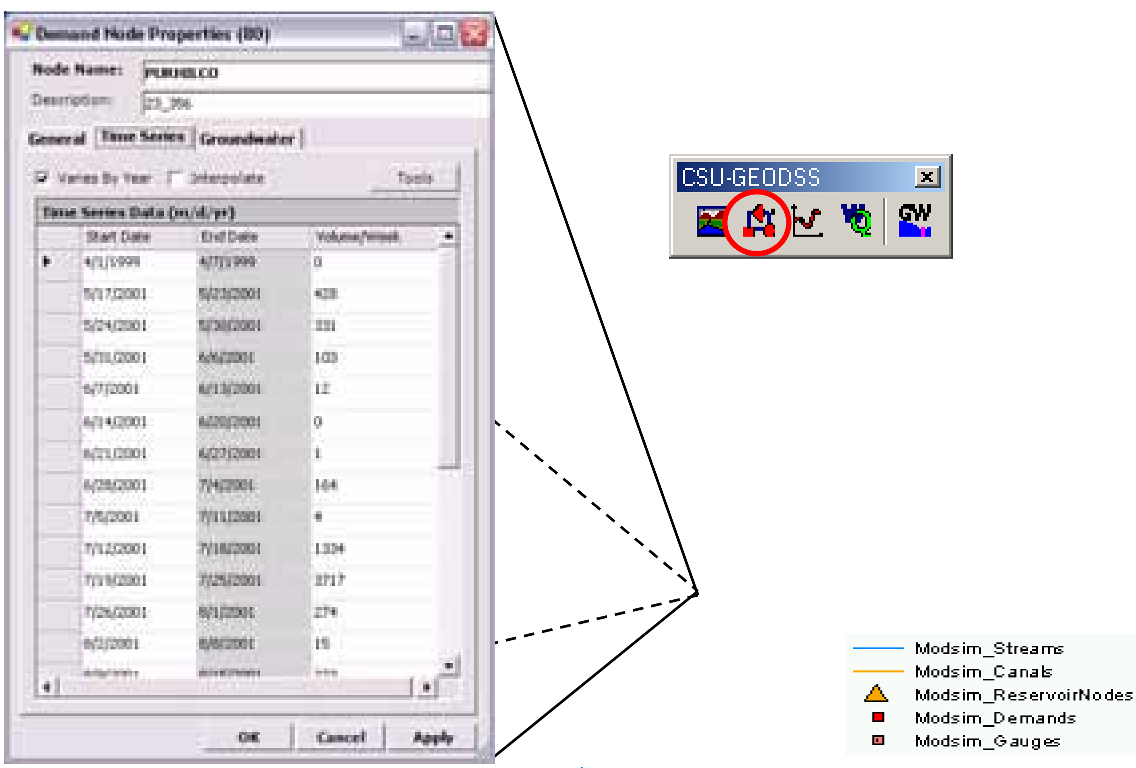


Figure 7. Georeferenced data input via MODSIM forms in ArcMap.

Time Series Data

The Populate Time Series Tool (Figure 8) opens the Import TimeSeries dialog (Figure 9) for importing time series data from database management systems. Supported DBMS software include MS Access, MS Excel, and *.CSV ASCII files. This tool processes measured data from various agencies, including diversion records, pumping records, and reservoir contents, with the time series data processed in the correct model time step and units. The processed time series are automatically incorporated into the corresponding MODSIM objects in the ArcMap display.

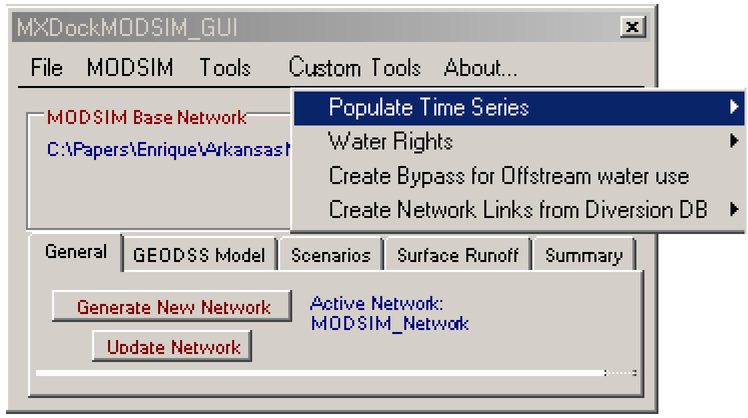


Figure 8. Time series data import tool in ArcMap.

Water Rights Data Base

The Water Rights Extension Dialog menu item in the GEO-MODSIM GUI opens the Water Rights–Priorities utility for processing large numbers of water rights and transactions and locating them in a MODSIM network at georeferenced sites (Figure 10). Most States record original water rights in a database management system, as well as modifications in decrees. Water rights can be abandoned, change diversion location and amounts, have alternate points of diversion, and change original appropriation dates State Admin numbers are used to logically analyze all water right records and assign them to links connected to the corresponding demand node. The utility is easily modified to accommodate various State water right database formats.

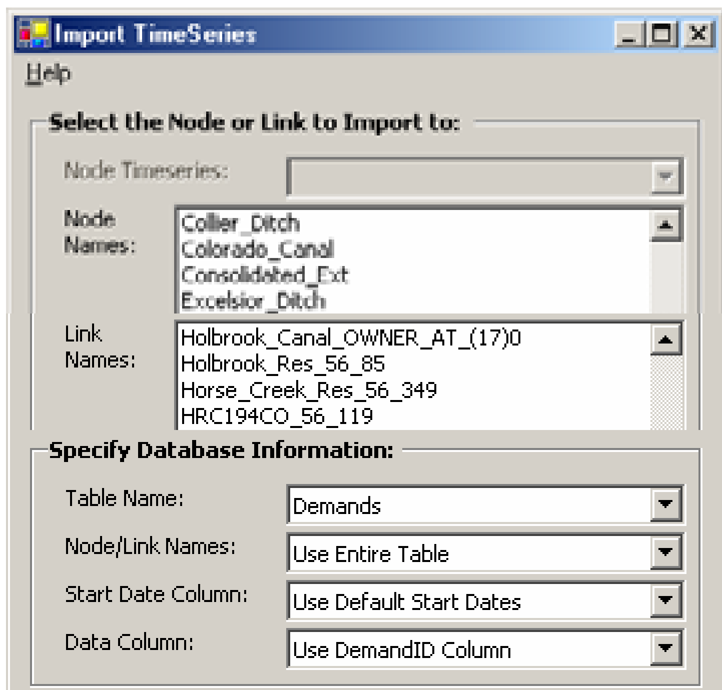
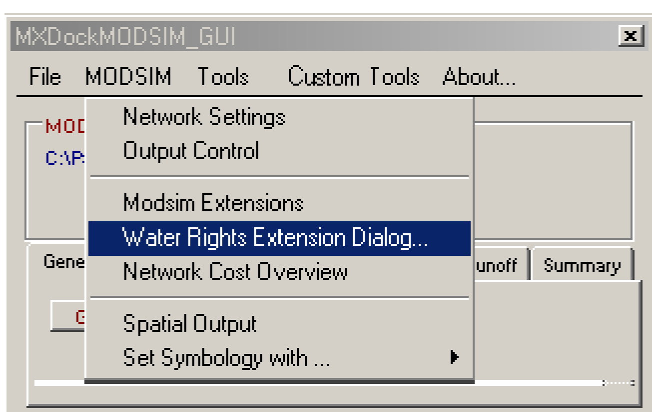


Figure 9. Access to database management systems with Import TimeSeries Dialog.



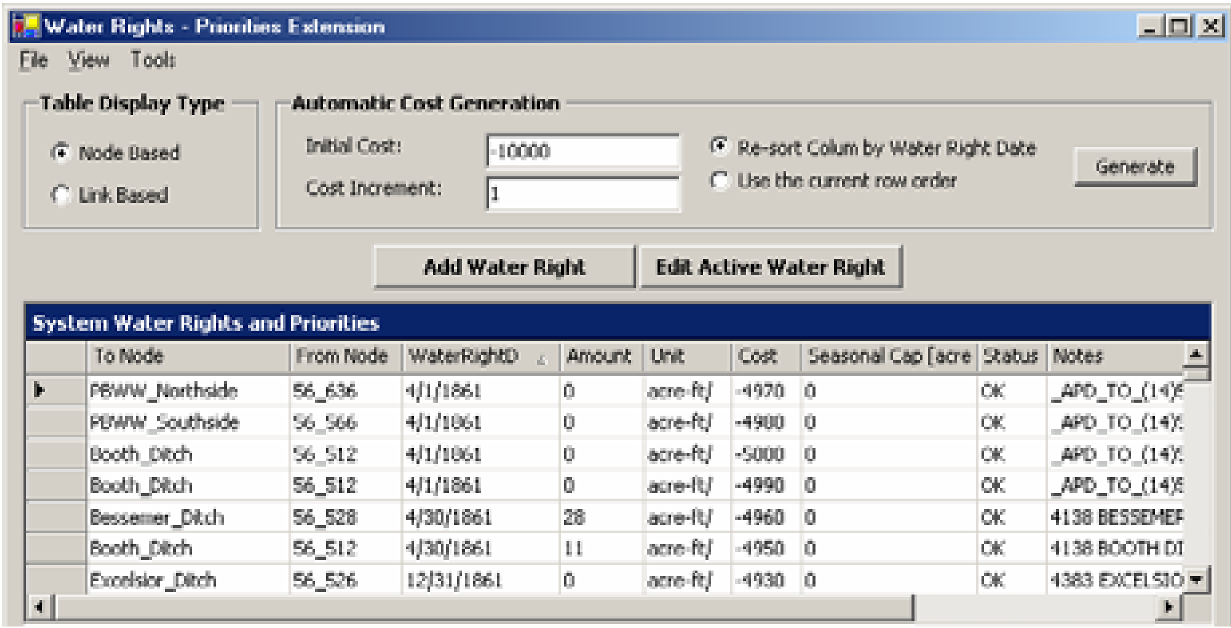


Figure 10. MODSIM Water Rights Extension User

MODSIM Execution from ArcMap

MODSIM networks can be directly executed from the GEO-MODSIM GUI in ArcMap in either Calibration Mode or Management Mode. Calibration Mode automatically calculates unknown river reach gains and losses such that calculated flows at gauging station locations match the imported times series of historical measured flows at that location and measured reservoir storage levels agree with historical data. These estimated gains and losses can then be utilized for executing MODSIM networks in Management Mode where the impacts of various water allocation priorities and reservoir operation policies can be simulated.

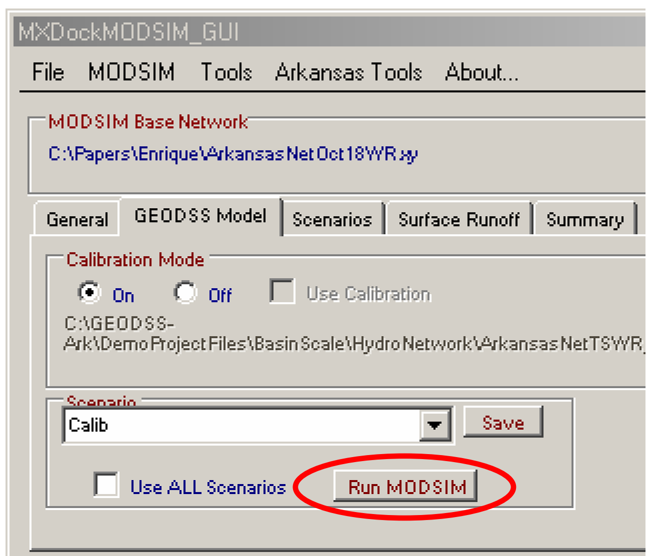
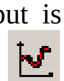


Figure 11. Execution of MODSIM from ArcMap interface.

GEO-MODSIM Output Display and Scenarios Analysis

MODSIM model output is also georeferenced with access available by simply clicking the Display MODSIM Output icon  on the GEO-MODSIM toolbar in ArcMap and selecting any desired network feature in the ArcMap display (Figure 12). The results display contains a comprehensive summary of the variables modeled in each time step including flow, link losses, routed network flows, water demands and shortages, groundwater variables, reservoir storage, storage right accounting, and many others. Output options include extensive statistical analysis and plots of flow duration or exceedance probability curves from Monte Carlo analysis. Scenario Analysis tools allow comparison of the performance of several

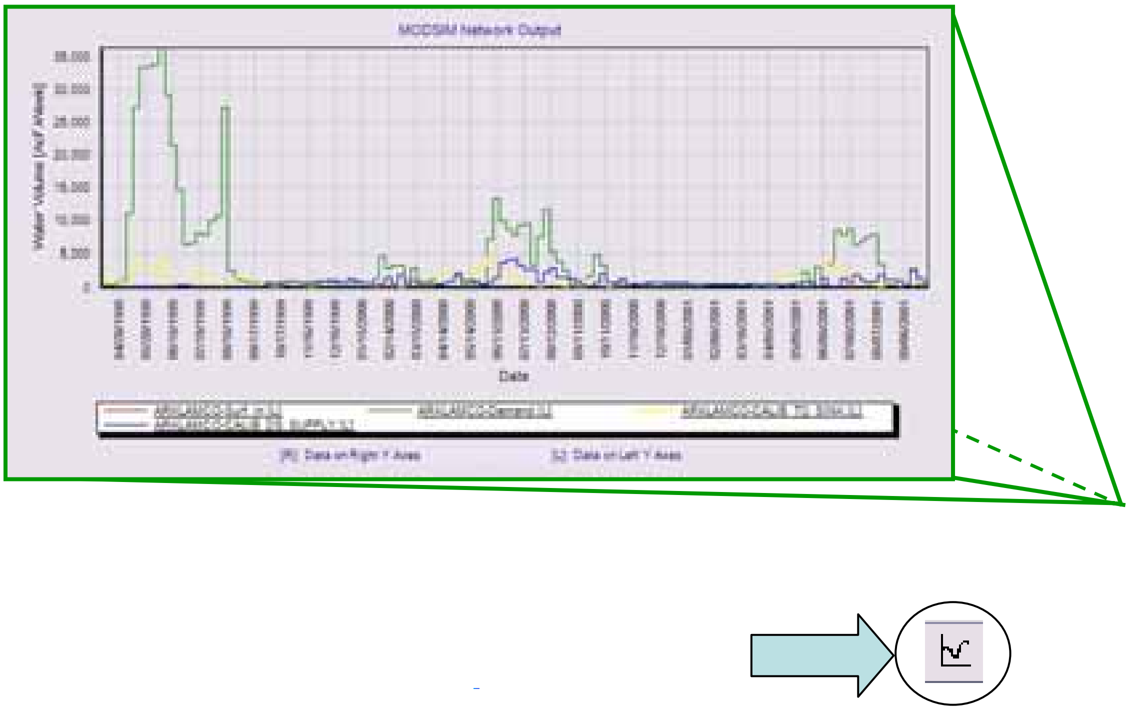


Figure 12. Georeferenced MODSIM output results displayed in ArcMap.

management scenarios for any selected output variable. As shown in Figure 13, a tool has been developed in ESRI ArcObjects where users may play an animated movie of MODSIM simulation results in the ArcMap display, with dynamically varying sizes and colors of MODSIM nodes and links reflecting flow and storage magnitudes occurring during the simulation.

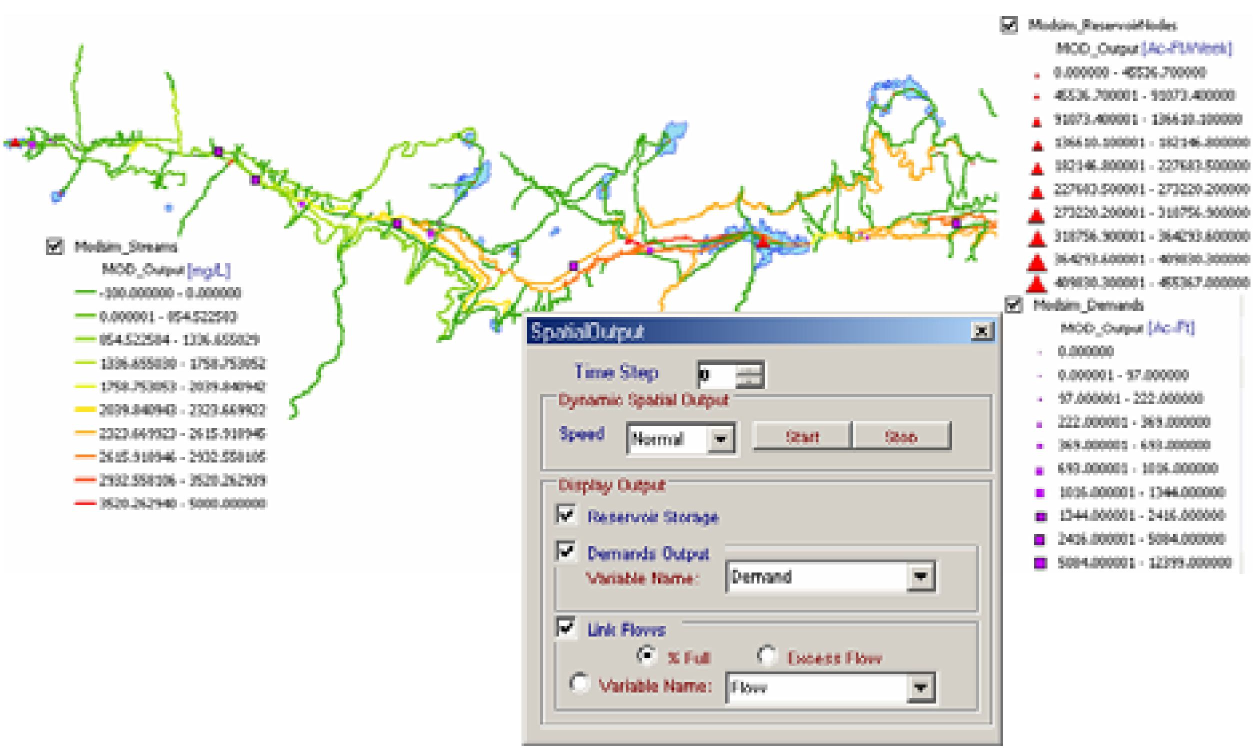


Figure 13. Dynamic, animated display of MODSIM simulation results in ArcMap.

APPLICATION TO THE LOWER ARKANSAS RIVER BASIN, COLORADO

Waterlogging and Salinization

The Lower Arkansas River Valley in Colorado (Figure 14) is currently experiencing the damaging effects of waterlogging from shallow water tables, excessive salt buildup, and high selenium (Se) concentrations, both on the land and in the river ecosystem. Innovative methods for solving these problems are needed to insure sustainability of the Valley's productive agricultural base, preservation and revitalization of its rural communities, and enhancement of the overall river environment. Since 1999, Colorado State University (CSU) has conducted studies to develop insight into current water-related problems in the Lower Arkansas River Valley and to identify promising solution strategies for consideration by water managers and stakeholders. Extensive field data and modeling tools have been developed and incorporated into a decision-making framework based on GEO-MODSIM that is focused on: (1) maximizing the net economic benefits of agricultural production by reducing salinity and waterlogging; (2) minimizing salt concentrations in the river at key locations, including the Colorado-Kansas state line; (3) maximizing salvaged water by reducing non-beneficial consumptive use from high water tables under fallow and naturally-vegetated alluvial lands, and (4) providing tradeoff information relating expected economic net benefits and salinity reduction to expected costs of implementing alternative water management strategies, with consideration of budgetary constraints.

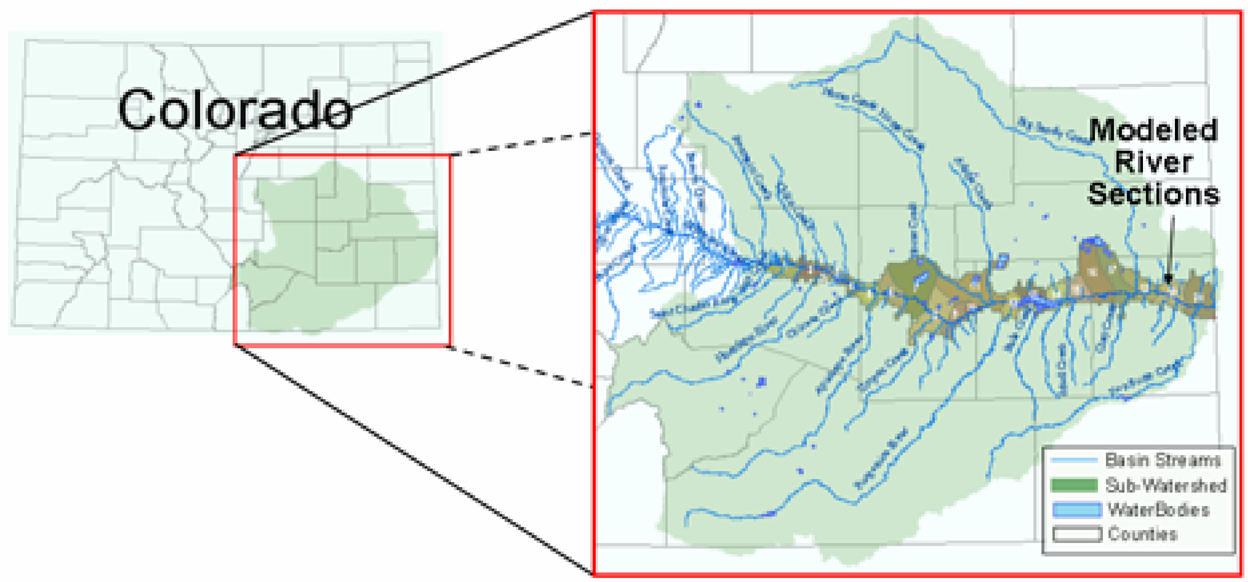


Figure 14. Location map of study regions in the Lower Arkansas River basin, Colorado.

Alternative conjunctive groundwater and surface water management strategies evaluated with GEO-MODSIM include: (1) reduction of recharge from field irrigation, reduction in canal seepage; (2) improved subsurface drainage options; (3) altered groundwater pumping patterns in exchange with surface water applications or to effect improved drainage; (4) releases from new reservoir storage accounts to offset impacts of reduced irrigation diversions to comply with the Arkansas River Compact; altered rates and quality of inflows from tributaries; (5) optional water exchange agreements within the basin; and (6) short-term leasing of water by individual ditch companies to municipalities. Major accomplishments in this study and findings to date can be found in a summary technical report by Gates et al. (2006). GEO-MODSIM is applied to finding the best alternatives, or combination of alternatives, that can achieve the stated goals.

Basin-Scale Modeling with GEO-MODSIM

GEO-MODSIM is incorporated into a spatial decision support system designed to assist in the assessment of water management options across the entire river basin from Pueblo Reservoir to the Colorado-Kansas state line. The customization capabilities of GEO-MODSIM are exploited to integrate geographic information systems (ArcGIS), surface and groundwater quantity and quality models, and artificial neural networks (ANN) into a robust tool for conjunctive surface and groundwater modeling and conjunctive management decision support (Figure 15).

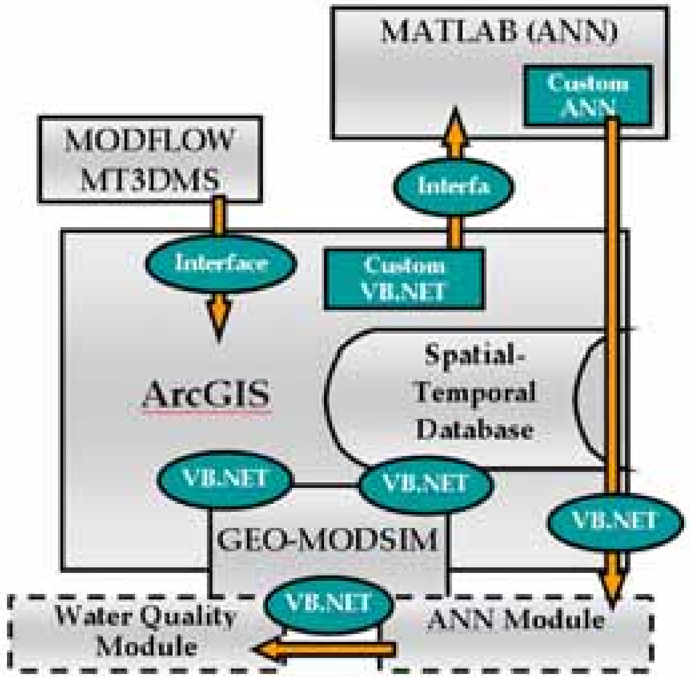


Figure 15. Spatial decision support system integrating GEO-MODSIM with water quality module and ANN for stream-aquifer modeling.

As shown in Figure 16, the MODSIM network for the entire Lower Arkansas River basin in Colorado is created from a geometric network integrating NHD feature classes for reservoirs, rivers, tributaries, canals, diversions, demands, and gauging stations by applying the GEO-MODSIM Data Model. Using the aforementioned tools, attribute data for all river basin feature classes are imported in ArcMap, along with tools for importing time series data on tributary inflows, flow gauging station records,

Figure 16. MODSIM network for the Lower Arkansas River basin created from ESRI geometric network and GEO-MODSIM Data Model.

meteorological data, and recorded reservoir levels that automatically assign the time series data to the appropriate river basin feature. The Water Rights Extension not only imports all relevant water rights data, but creates physical links conveying flows for each water right to the appropriate decree-holder. Various calibration tools are applied to estimating unmeasured river reach gains and losses using historical gauging station records.

Stream-Aquifer Interaction

An innovative methodology developed by Triana et al. (2003) trains an artificial neural network (ANN) using data sets generated from the Groundwater Modeling System (GMS) (Brigham Young University, 1999) which links the MODFLOW finite-difference groundwater flow model (Harbaugh et al., 2000) and the MT3DMS (Zheng and Wang, 1999) contaminant transport model. Stream-aquifer response relationships from irrigation return flows and streamflow depletion from groundwater pumping are captured by the ANN and linked to GEO-MODSIM using the customization capabilities available through the MS .NET Framework. GEO-MODSIM can also be directly integrated with the MODFLOW numerical groundwater flow model using a new GIS-based tool that provides a seamless linkage of the surface water and groundwater flow models. Shown in Figure 17 is the GEO-MODFLOW tool for overlaying a GEO-MODSIM surface water network on MODFLOW grids in the ArcMap interface for calculating return flows to selected GEO-MODSIM links.

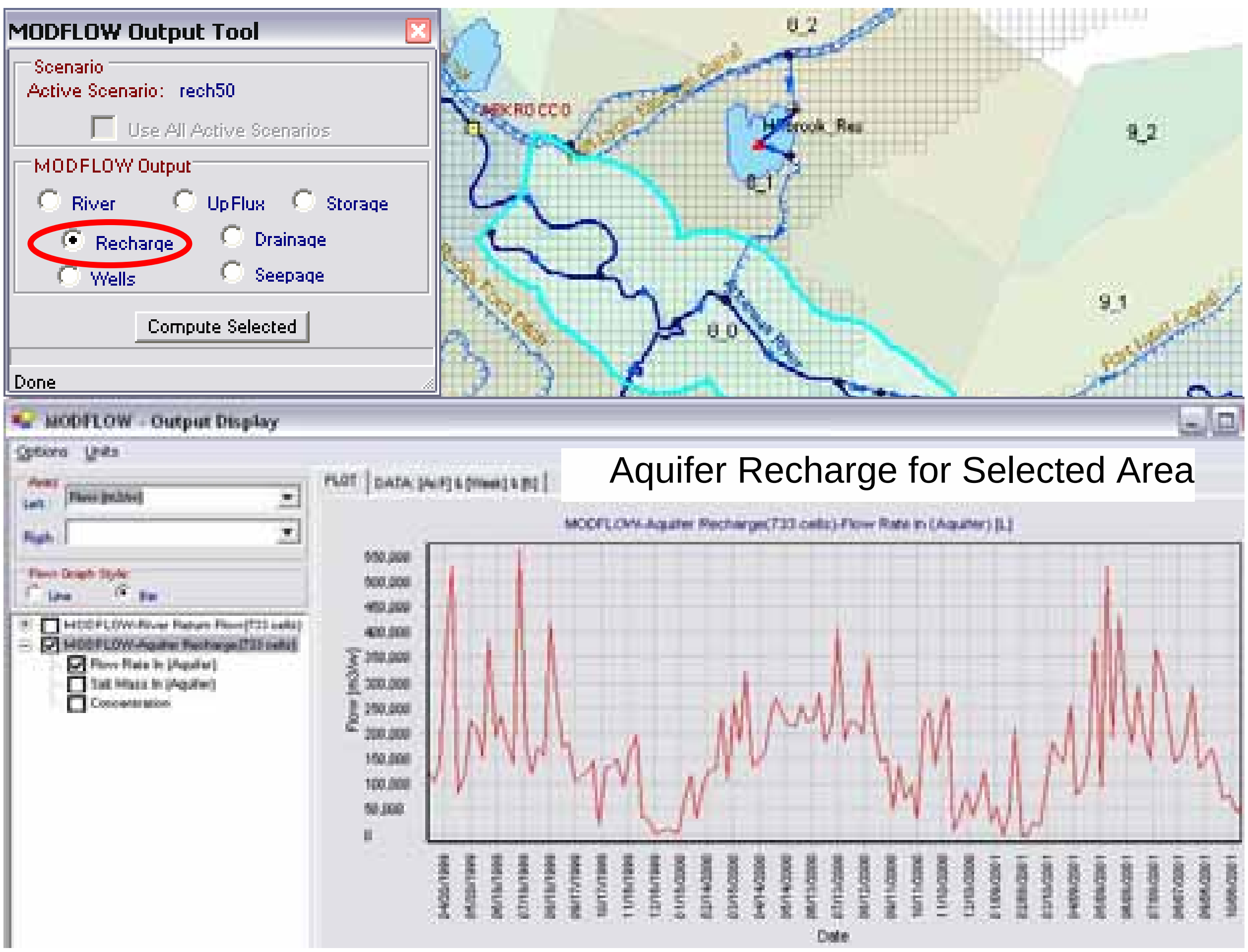


Figure 17. GEO-MODFLOW tool in ArcMap for integrating MODFLOW output with the GEO-MODSIM surface water network.

Water Quality Tools in GEO-MODSIM

Custom tools in ArcMap have been developed for importing and processing both intermittent and regular water quality samples in a river basin. Specific conductance data are imported as total dissolved solids (TDS) using a user selected conversion equation and visualized in the ArcMap environment through user dialogs activated by the water quality modeling tool (WQM)  in the GEO-MODSIM toolbar. A variety of regression equations can be selected for *filling in* missing or sporadic TDS concentration data by estimating flow vs. concentration relationships (Q and C relations). Minimum and maximum TDS concentration ranges can be selected by users or automatically calculated for nodes with water quality data in the surrounding area. A semi-automatic calibration procedure then allows adjustment of concentrations at upstream nodes with missing concentration data such that measured calculations at downstream nodes in the river are matched as closely as possible. The WQM features an efficient georeferenced network tracing algorithm that allows navigation throughout the network from upstream to downstream for computing changes in water quality constituents while having access to user data, MODSIM flows, and GIS-spatial data. GEO-MODSIM is coupled with the WQM and the ANN module at run time to provide conjunctive surface and groundwater salt mass routing throughout the modeled basin. Combined with simulated flow results, the user is capable of monitoring solute concentrations throughout the river system.

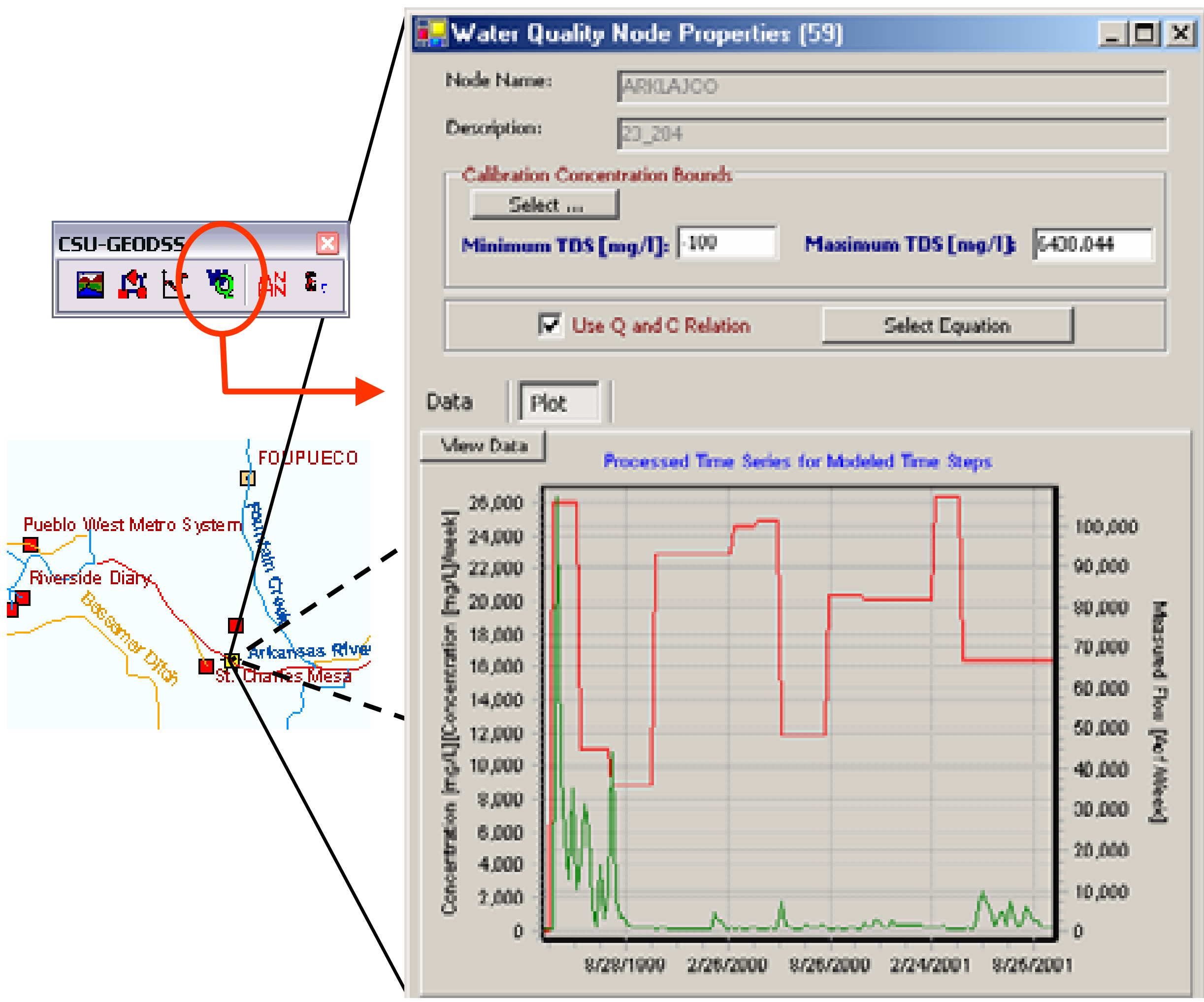


Figure 18. Access to water quality tools from GEO-MODSIM toolbar

Optimal Conjunctive Management Strategies

GEO-MODSIM, as integrated with the groundwater and water quality modules, is being applied to investigating impacts of alternative conjunctive management strategies, including increased irrigation efficiency and reduction in canal seepage. These strategies result in reductions in soil water salinity and waterlogging with consequent increases in crop yield and reduced return flows to the river. Salt loadings and Se concentrations in return flows are markedly reduced under these strategies, thereby enhancing river water quality. However, associated changes in rates and timing of canal diversions and return flows alter the patterns of river flows available for downstream diversion, in-stream use, and discharge into Kansas. GEO-MODSIM and associated tools are being applied to development of strategies for offsetting these impacts by establishing new accounts in existing on-stream and off-stream reservoirs to store water volumes resulting from reduced canal diversions and optimizing the timing of releases that would adequately preserve historical river flow patterns in compliance with Colorado water law and the Arkansas River Compact. Other strategies include altering groundwater pumping patterns to facilitate efficient irrigation practices in exchange for use of surface water rights; altered rates and quality of inflows from Fountain Creek (primarily composed of drainage and stormwater runoff from the city of Colorado Springs) upstream of the study area; optional water exchange agreements within the basin; and short-term leasing of water by individual ditch companies or collective entities such as the recently proposed *super ditch*.

A *Scenario Manager* is implemented in the GEO-MODSIM GUI for compiling utilities for scenario management and analysis (Figure 19). The *Scenario Manager* endows the user with tools to simulate the implementation of these management options at the basin scale. Scenario preferences are loaded and stored for ease of access and repeatability. The tools allow graphical comparison of quantity and quality modeling results from multiple scenarios within the ArcMap interface.

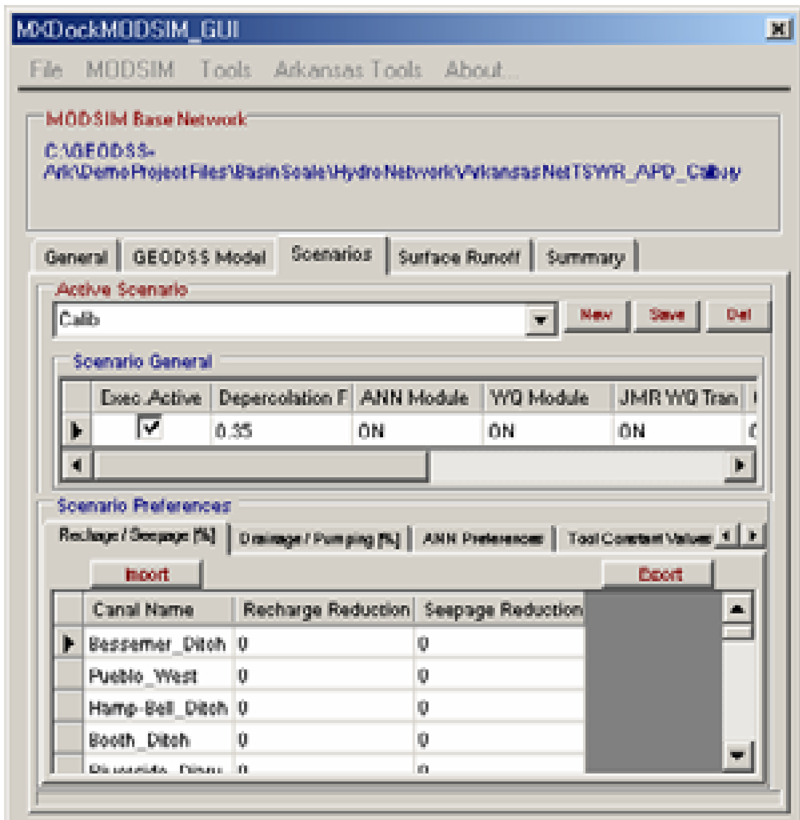


Figure 19. Scenario manager accessed in GEO-MODSIM GUI.

APPLICATION TO THE IMPERIAL IRRIGATION DISTRICT WATER TRANSFER AGREEMENT

Development of IID Water Delivery Network

GEO-MODSIM is being applied to analysis of the water transfer agreement between the Imperial Irrigation District (IID) and the San Diego Water County Water Authority in Southern California, as described by Miller et al. (2005). Over 3.7 billion m^3 of Colorado River flow is diverted annually to the world's largest irrigation canal, the All American Canal, which supplies the IID. Since IID farmers receive the great majority of these flows, GEO-MODSIM is applied to identifying opportunities for water conservation in the IID that can generate up to 370 million m^3 per year of transferable flow to the large urban areas of Southern California. The IID includes over 2000 km^2 of irrigated farmland served by 2736 km of canals and laterals distributing flow to 5300 farm delivery gates. The high efficiency of the GEO-MODSIM solver allows fully integrated modeling of the IID network, comprising over 10,000 nodes and links. In addition to conservation planning, MODSIM is also being configured to provide daily, and possibly hourly, real-time regulation guidance for automated control of gates in the IID system.

As illustrated in Figure 20, modeling the complex, large-scale water delivery system of the Imperial Irrigation District begins with the design and implementation of an ArcGIS (ESRI, Inc.) Data Model. Georeferenced objects are created that embrace the data required for application of GEO-MODSIM within the ArcMap interface. A key feature of this application is that all MODSIM-related data are stored in the ArcGIS geo-database, allowing all data editing to be directly performed in ArcMap.

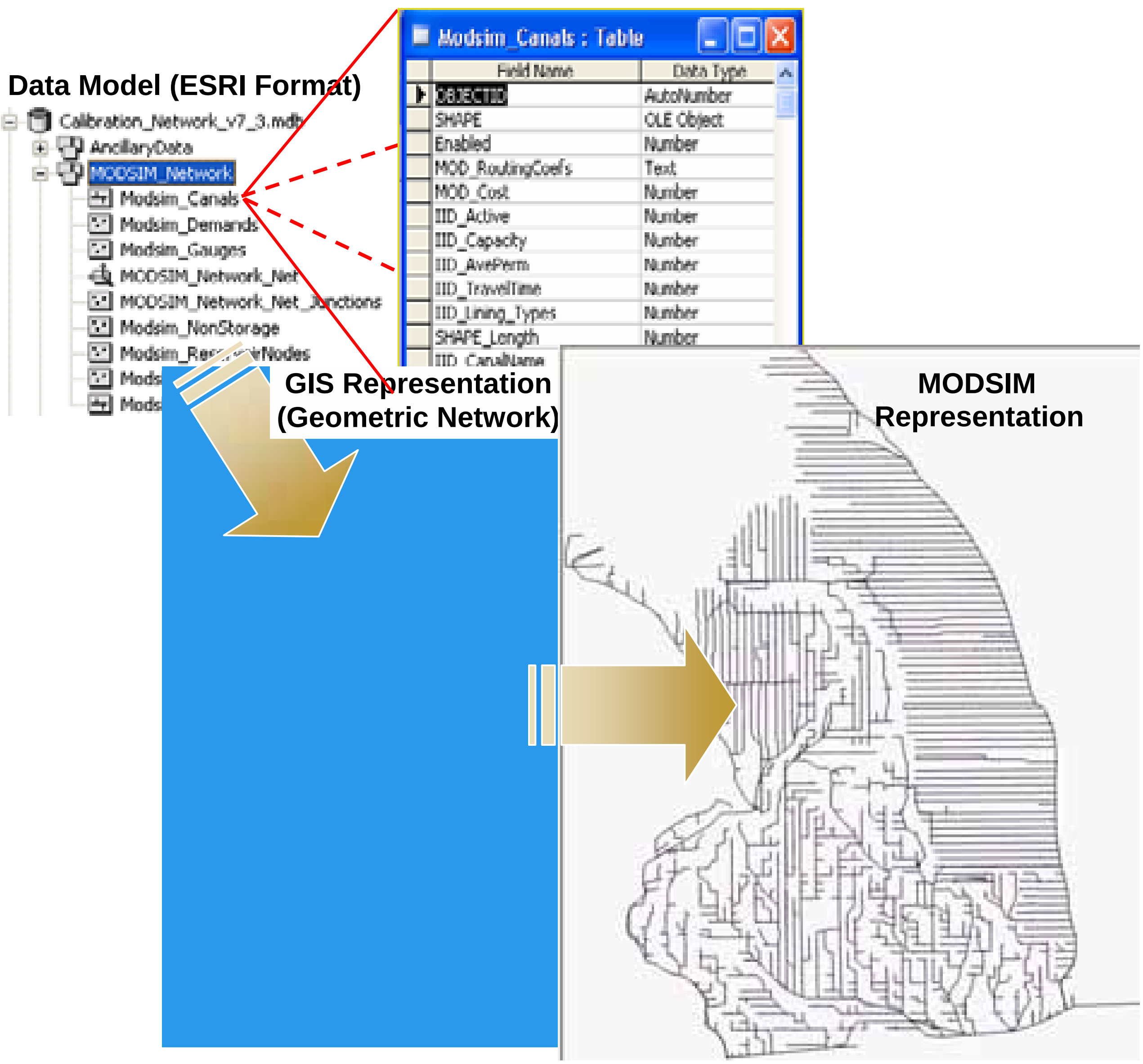


Figure 20. Generation of MODSIM network from Geometric Network developed from GEO-MODSIM Data Model.

Three-Pass Computational Scheme

A *three-pass* computational scheme has been designed and implemented to accurately simulate important structural and operational elements of the IID network (Figure 21). The three-pass scheme is performed sequentially, with each subsequent network building on computations from the previous pass. The network is automatically transformed and loaded with data for each of the three passes used to simulate IID system operations using a custom GEO-MODSIM dialog as shown in Figure 22.

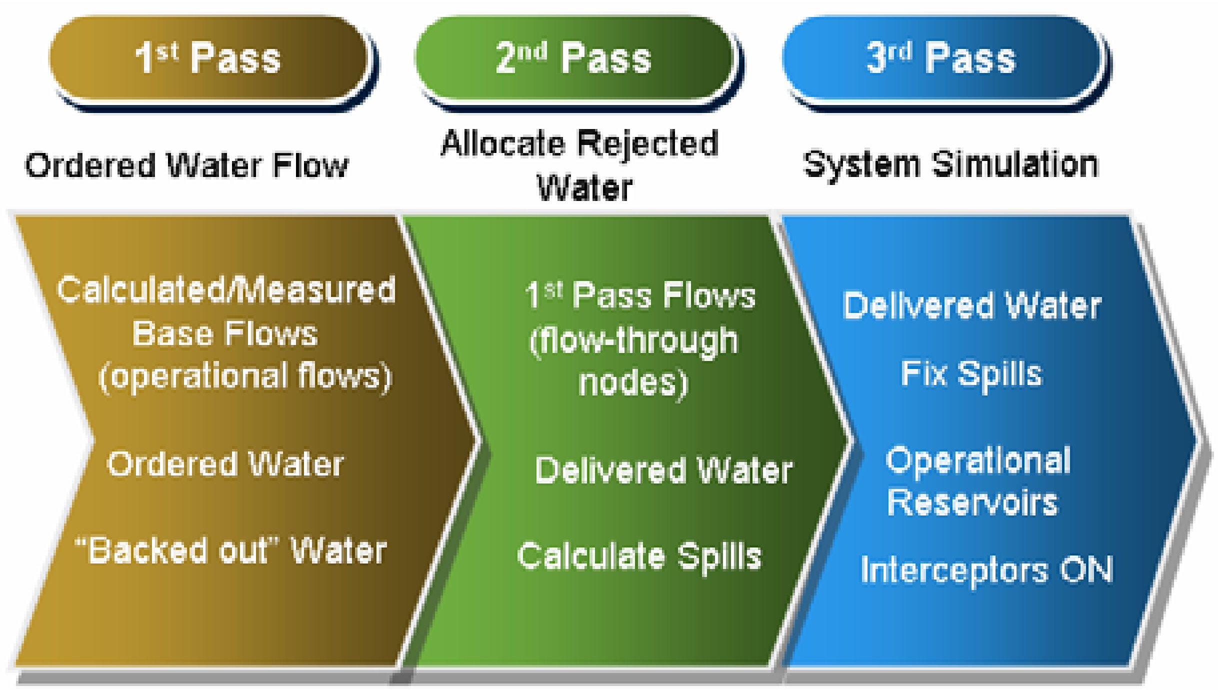


Figure 21. Three-pass computational scheme for accurate simulation of required water deliveries in the IID network.

Several obstacles needed to be overcome for accurate modeling of the IID water delivery system in GEO-MODSIM. Computer hardware and software resources were exhausted when attempting to simulate the large-scale IID system in daily time steps over several years. Run times improved significantly with computer upgrades to dual core Xeon processors and 2GB of DRAM memory. Software for post-processing results from GEO-MODSIM runs were designed to take advantage of multi-threading technologies that improve computational efficiency. The use of carefully designed object types in the GIS data model (i.e., canal interfaces, terminal interfaces, reservoir interfaces, reservoir bypass links, etc.) facilitated the implementation of network transformations and changing priority structures in the three-pass computational scheme. Implementation of relief valves is a valuable part of the automation process to programmatically deal with interface data and spill base flow inconsistencies. These inconsistencies occur when flows through a terminal interface cannot be used by any downstream demand and terminate in a spill node with a base flow set to a lower amount than the excess water. Computer memory leakage created by combining MS COM-based and .NET-based technologies were discovered and researched, with methods implemented to avoid or at least minimize these inconsistencies. Restrictions in the size of the MODSIM database output files (2GB per database) were found to be a serious limitation. Automatic Output Control methods were implemented to reduce the enormous output files produced from daily network simulations over several years by including only selected output variables.

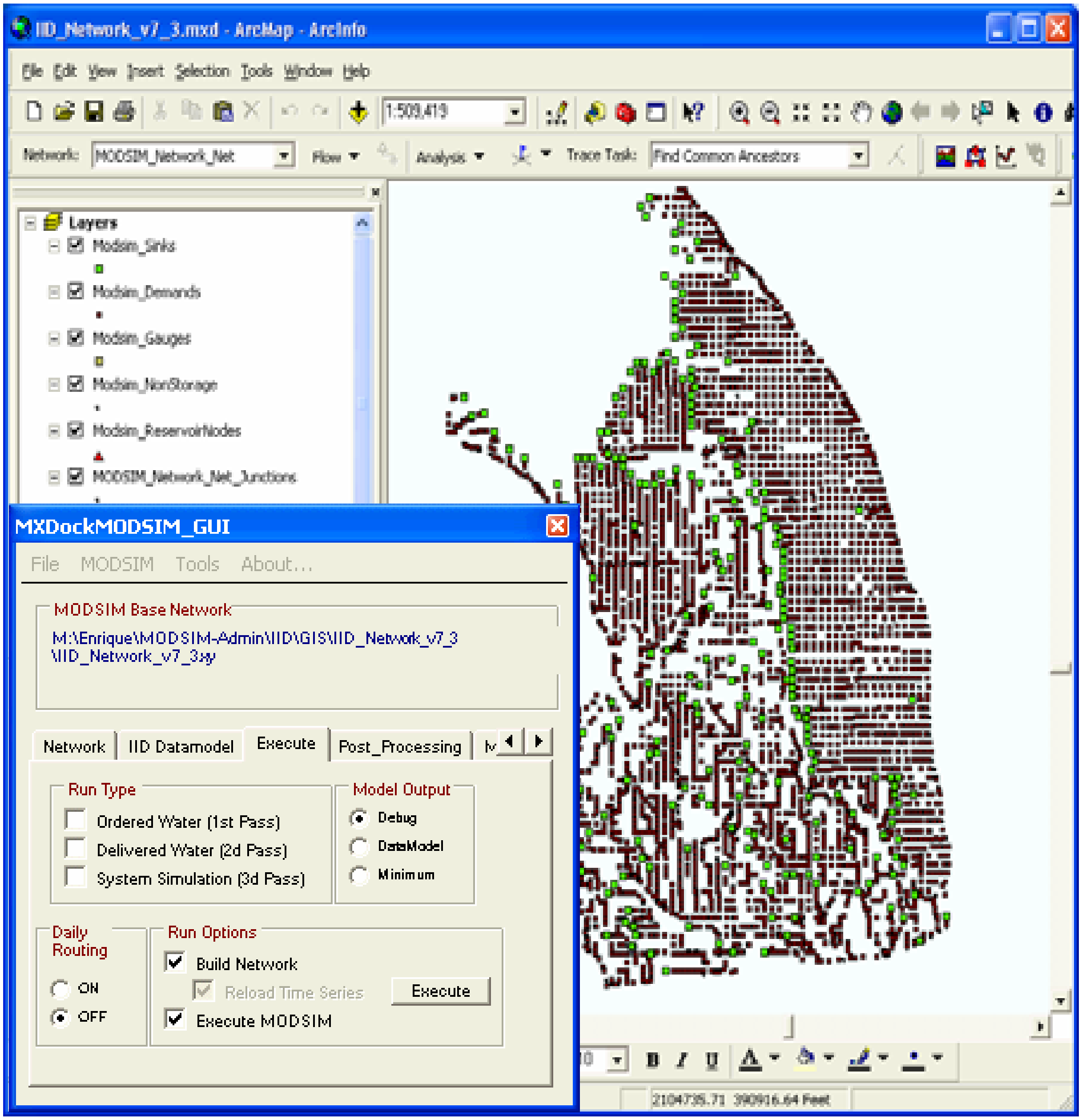


Figure 22. Implementation of three-pass computational scheme in the GEO-MODSIM GUI in ArcMap.

Model Calibration and Results Analysis

The challenges of calibrating GEO-MODSIM to measured flow and storage data throughout the IID network required development of customized tools in ArcMap for facilitating adjustment in model parameters and providing both time series displays and statistical results, as shown in Figure 23. Results analysis show reasonable matching of flows at control points throughout the system, with most discrepancies and differences in the results identified and explained. The calibrated network model is applied to determining minimum deliveries to IID from the All American Canal that satisfy all IID irrigation requirements, thereby determining the amount of transferable flow available. Dynamic, spatial visualization tools similar to those developed for GEO-MODSIM to the Arkansas Valley salinity

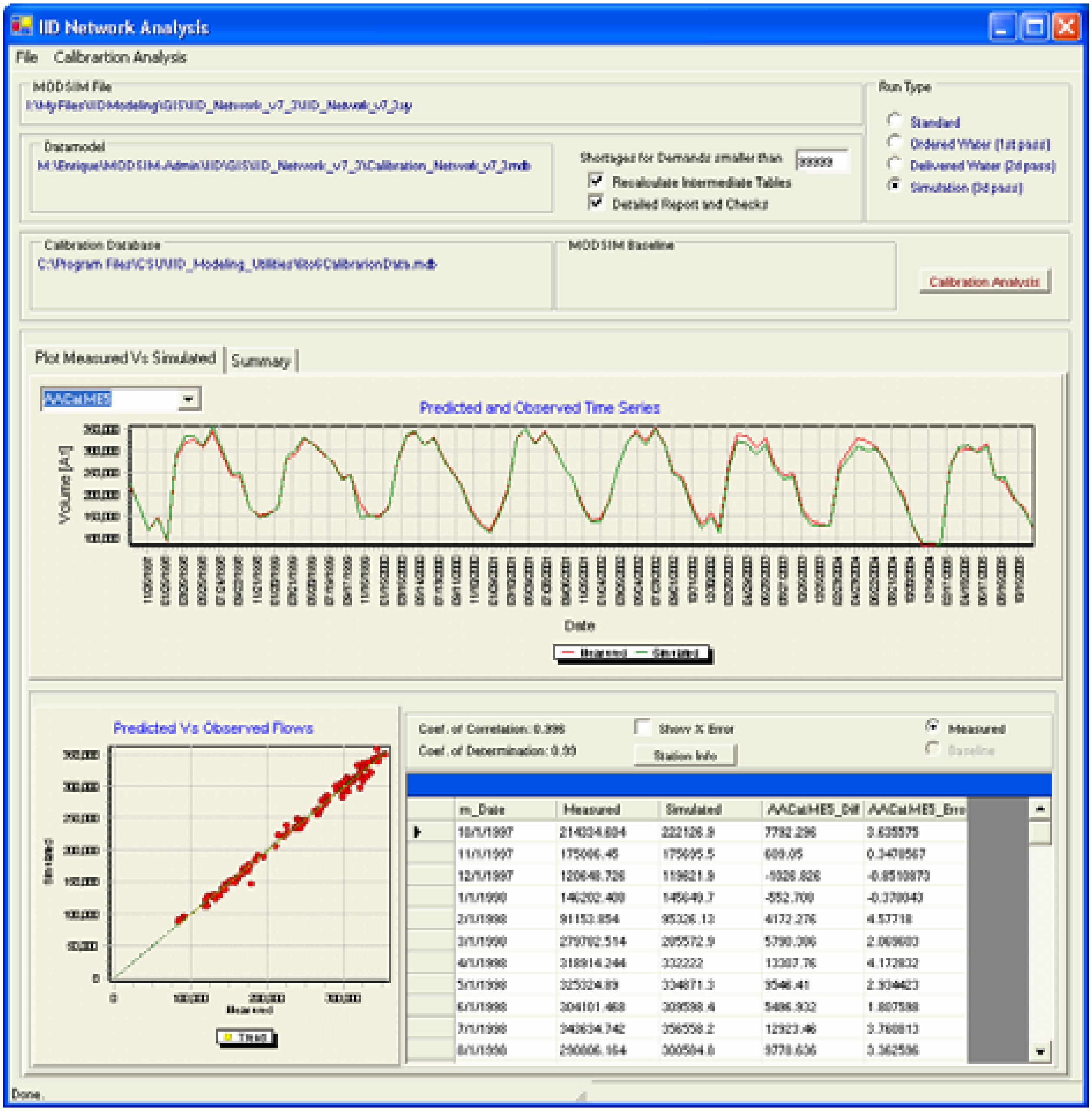


Figure 23. Customized calibration tools for analysis of the IID network.

management project provide animated simulations of flow and storage conditions throughout the network under optimum water distribution schemes, as seen in Figure 24.

CONCLUSIONS

A georeferenced version of MODSIM (GEO-MODSIM) is implemented to incorporate GIS functionality in the powerful modeling tools of MODSIM. GEO-MODSIM is developed as an extension in ArcGIS, thereby providing full access to GIS tools for creating network topology, importing and processing temporal-spatial data, and spatially pre-processing required model data. A spatial decision support system that incorporates GEO-MODSIM is applied for developing and evaluating salinity management

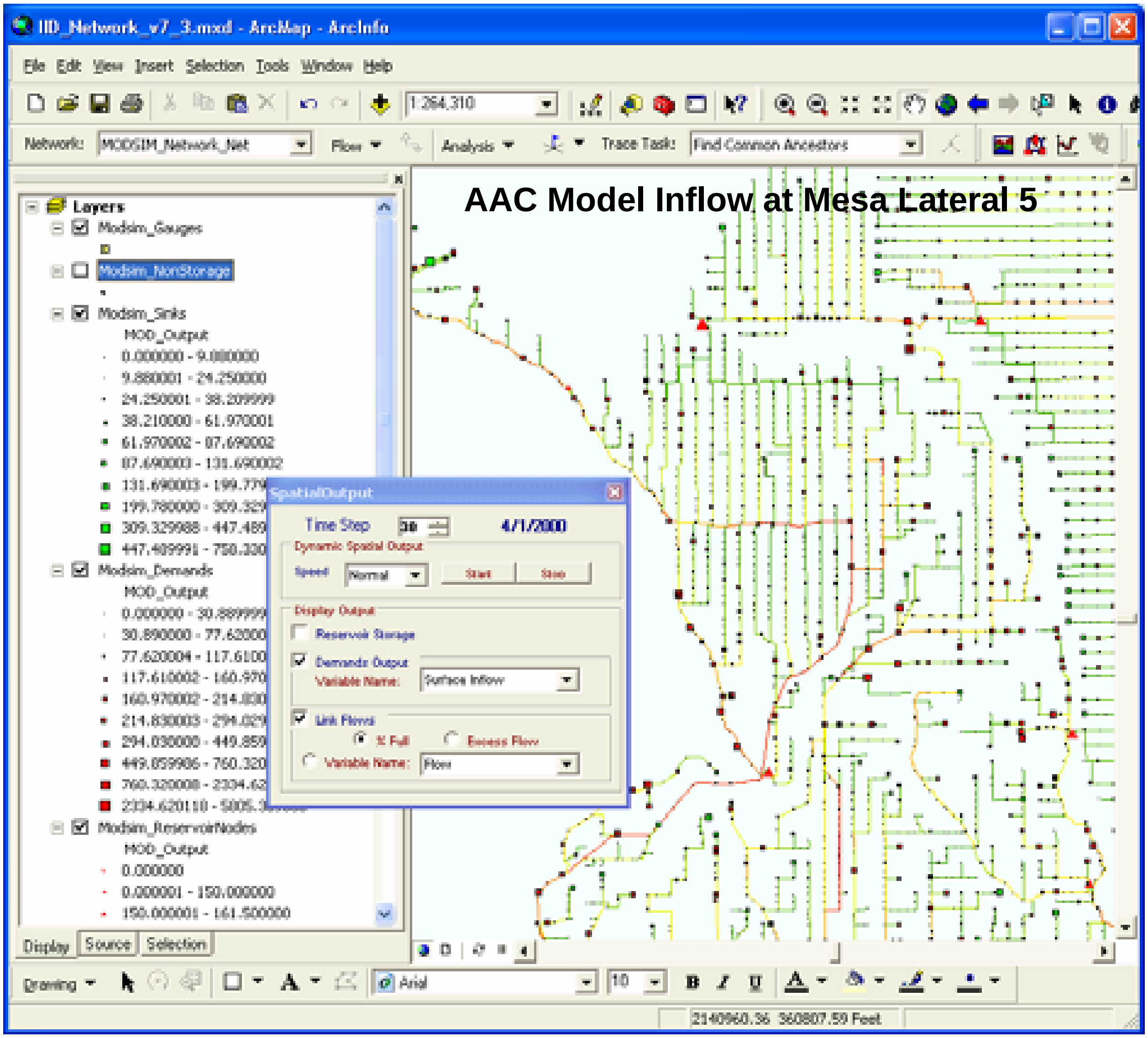


Figure 24. Dynamic spatial visualization tool for IID network.

strategies in the Lower Arkansas Valley, Colorado. GEO-MODSIM as integrated with water quality and groundwater modules makes full use of the MODSIM customization capability to accommodate specific features dealing with the Arkansas River Basin Modeling, but without requiring any modification or updating of the original MODSIM source code. Relational data in the spatial-temporal database allows access to and processing of time series data, water rights priorities and storage water activities, and inserting them directly into GEO-MODSIM. GEO-MODSIM is also applied to the large-scale water delivery system of the Imperial Irrigation District in support of the IID/SDCWA Water Transfer Agreement. The ability to automatically generate the large-scale, complex MODSIM network for the IID system from GIS layers already developed for IID proved to be essential to the success of this project. Again, the unique customization capabilities embodied in GEO-MODSIM allowed complex operational schemes to be effectively modeled in the IID network, along with the speed and efficiency of the MODSIM network optimization solver.

ACKNOWLEDGEMENTS

Funding support for this research has been provided by the U.S. Bureau of Reclamation (Eastern Colorado Area Office), U.S. Bureau of Reclamation (Roger Larson, Pacific Northwest Division), Colorado Agricultural Experiment Station, Colorado Water Resources Research Institute, Southeastern Colorado Water Conservancy District (James Broderick, General Manager), Lower Arkansas Valley Water Conservancy District (Jay Winner, General Manager), Imperial Irrigation District (John Eckhardt, Executive Program Manager), Keller-Bliesner Engineering, and Davids Engineering, Inc.. The authors are grateful to Timothy Gates, who has served as principal investigator for several of the projects applying GEO-MODSIM to the Lower Arkansas River Valley, and Andrew Keller, who has provided important guidance and direction for the Imperial Irrigation District study.

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