GROUNDWATER ANALYSIS TOOL: A COMPONENT OF THE WATER RESOURCES DECISION SUPPORT SYSTEM FOR THE GILA RIVER INDIAN COMMUNITY

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ABSTRACT

The Gila River Indian Community's Water Resources Decision Support System (WRDSS) provides an operations and planning tool for managing a multi-source water supply to sustain the Community in their tribal homeland. The Gila River Indian Community Water Right Settlement Act of 2003 provides water from nine sources, including imported surface water supplemented with groundwater. These sources are needed to meet multiple water supply needs including agricultural use by the Gila River Indian Community. The expansion of irrigated agriculture, importation of surface water, and increased groundwater withdrawal within the Reservation will change the long-term groundwater balance – in terms of both quantity and quality. Managing and protecting the groundwater resource for multiple purposes within the framework of the Community's water resource management goals, objectives, and economic constraints is a key component for long-term water supply sustainability.

The Groundwater Analysis (GWA) is one of three components of the WRDSS. It is linked to an Overall Water Resources Analysis (OWRA) module, which manages the conjunctive use of surface water and groundwater supplies, via an Interface Manager (IM) component. The GWA is a modeling tool based on an analytical model for unsaturated flow and salt transport in the vadose zone, the numerical groundwater flow model (MODFLOW), and a numerical solute transport model (MT3D) for salt transport in groundwater. The GWA is used to evaluate aquifer yield and water quality constraints in response to meeting water supply demand specified by the OWRA. It also provides a management tool to forecast potential impacts and assess management strategies for long term sustainability of the groundwater resource.

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INTRODUCTION

A water resources management plan was developed to manage the conjunctive use and long term sustainability of surface water and groundwater resources available to the Gila River Indian Community (GRIC). The Central Arizona Project Settlement Act entitles the GRIC to 653,500 acre-feet of water per year to meet agricultural and non-agricultural (municipal, industrial, environmental, and recreational) water supply needs into the future. This quantity will be provided by a combination of imported surface water sources and groundwater withdrawal on the Reservation to cover any annual shortfalls. Meeting the objectives of the GRIC, including irrigation supply to approximately 146,000 acres of crop land, will require careful development and management of the Reservation's groundwater resource.

A water resource planning tool, referred to as the Water Resources Decision Support System (WRDSS, Bliesner et. al., 2004), provides a framework for both operational (short-term) and strategic (long-term) water supply analyses. The WRDSS integrates the various water sources, water demands, and associated economics by interfacing separate surface water and groundwater model components that address both water quantity and quality. The WRDSS consists of three model components: Overall Water Resources Analysis (OWRA); Interface Manager (IM); and the Groundwater Analysis (GWA). This paper discusses the design and function of the groundwater analysis (GWA) and how it relates to the other WRDSS components. The OWRA and IM are described in an accompanying paper by Westfall et. al., 2006, included in these proceedings.

GROUNDWATER ANALYSIS (GWA) COMPONENT

GWA Elements

The GWA is a modeling tool designed to evaluate the effects of pumping and irrigation on the groundwater quality and quantity. The GWA model is based on a detailed assessment of hydrogeologic and water quality conditions within and surrounding the Reservation. This hydrogeologic assessment was a key first step in developing a predictive model representative of the physical system. The GWA consists of three principal elements that together "represent" the physical system:

1. An analytical model describes unsaturated flow and salt transport in the vadose zone (unsaturated zone above the water table);
2. A numerical hydraulic model (MODFLOW) describes saturated groundwater flow; and,
3. A numerical mass transport model (MT3D) describes salt movement in the saturated zone.

A schematic of the GWA elements, general linkage, and flow of information, including the exchange of model inputs and outputs with the OWRA, is presented in Figure 1. The GWA is supported by a groundwater database, developed in Microsoft Access, which serves as a repository for historical, baseline, and future hydraulic and water quality data. The groundwater database will also store all input and output data related to predictive model runs, as an integral part of the modeling tool. The primary inputs from OWRA include recharge, and associated salt (total dissolved solids) concentration. For a water supply demand simulation, the OWRA also specifies a groundwater quantity and water quality requirement to meet that demand. GWA output to the OWRA is pumping lift (cost) and water quality of the groundwater supply based on the well configuration selected to meet the specified demand.

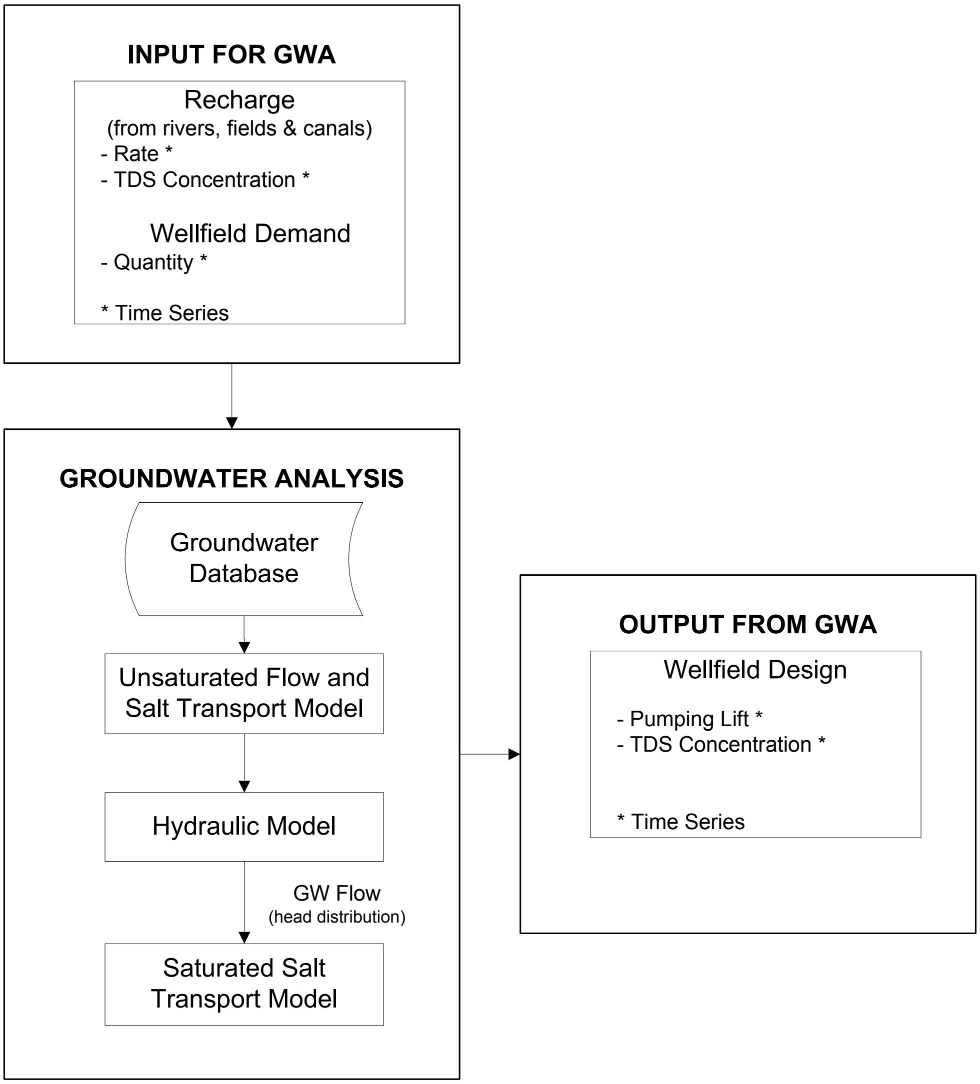

Figure 1. GWA Model Elements

Unsaturated Flow and Salt Transport: The GWA uses an analytical approach to compute the time-lag for irrigation water and associated dissolved salts, which are applied at the ground surface, to reach the groundwater table. This time-lag calculation is computed outside of the numerical MODFLOW model utilizing an analytical "spreadsheet" model which is easily and directly incorporated into the GWA.

The analytical approach is based on the advection dispersion equation (e.g., Hillel, 1998) to estimate the time-lag for salt breakthrough at the water table in response to irrigation return flow below the root zone. Groundwater flow in the unsaturated zone is governed by Darcy's law, with hydraulic conductivity and hydraulic head expressed as functions of moisture content. Salt transport in the unsaturated zone is governed by the advection dispersion equation, with groundwater velocity and dispersion coefficients also expressed as functions of moisture content. The van Genuchten equation (Tindall and Kunkel, 1999), which is widely used in agricultural applications, is used to describe the relationship between soil moisture content and hydraulic conductivity.

Input parameter requirements for computing the vertical salt movement in the unsaturated zone with respect to depth and time include: the average irrigation return flow, saturated hydraulic conductivity (vadose zone), depth to groundwater, salt concentration in the return flow (below the root zone), soil dispersivity, and soil characteristic curves to describe the relationship between moisture content and hydraulic conductivity.

Recharge is input into the groundwater flow model, likewise, the salt concentrations computed using this analytical method are input as a source term into the saturated salt transport model, described below. The hydraulic time lag (e.g., recharge of irrigation return flow) will approach zero as "piston" flow develops, however the salt time lag remains a function of depth to the groundwater table.

Saturated Flow: The groundwater flow model was developed using the numerical code MODFLOW (Harbaugh, et. al. 1996), an industry standard for modeling groundwater flow in saturated porous media. MODFLOW is used as a predictive tool to forecast and evaluate aquifer response to varying water resource management demands and conditions, at multiple spatial and temporal scales (e.g., pumping induced well field response versus long-term changes in groundwater conditions across the Reservation). Groundwater Vistas™ (Environmental Simulations, Inc., 2004) was used as a graphic interface to facilitate model input, output, sensitivity analysis, and calibration.

The "footprint" of the flow model extends beyond the Reservation boundary to incorporate the influence of off-reservation pumping and to address natural hydrogeologic boundaries. The total area included in the flow model is over 2000 square miles. The model is constructed by subdividing the area into a horizontal grid (1 square mile cells) with vertical layers, based on the principal hydrostratigraphic units encountered on the Reservation. To facilitate local scale analysis, the hydrostratigraphic units were further subdivided into a total of eight vertical layers to provide improved flow simulation of pumping effects, aquifer characteristics, and vertical hydraulic gradients. The level of vertical layer discretization is also critical in evaluating water quality changes associated with salt loading using the solute transport analysis, discussed below. MODFLOW performs water balance calculations on each of the "blocks" based on head changes imposed by stresses placed on the groundwater system (e.g. recharge or well pumping).

The flow model outputs head values for each cell. Pumping levels at wellfields are further evaluated in a spreadsheet outside of MODFLOW using the analytical Thiem correction (Anderson and Woessner, 1992). MODFLOW calculates the groundwater level across an entire grid cell, which underestimates pumping lift because of spatial averaging. The correction is applied to provide a more accurate determination of pumping lift for output to the OWRA. The amount of correction is related to the size of the cell, the type of aquifer material, and the pumping rate.

<u>Salt Transport in the Saturated Zone:</u> In addition to evaluating groundwater flow, the GWA is designed to track the accumulation of salts, evaluate changes in groundwater quality on the Reservation, and predict the water quality of groundwater supply from on-Reservation wells. Salt transport within the saturated zone is evaluated using the numerical solute transport model MT3D (Zheng, 1990) with flow conditions specified by output from MODFLOW. The output from MODFLOW includes a groundwater head (equipotential) file, a cell-by-cell flow file specifying volumetric inputs and outputs for each cell, and an input file for MT3D.

Understanding the vertical movement of salt and resultant water quality impact in the aquifer system, is critically important in assessing the long term sustainability of the Reservations groundwater resource. The flow model was designed with eight vertical layers to facilitate tracking the movement of salt through the aquifer system. The transport simulation generally uses average or steady-state groundwater velocities to reduce the computational timeframe, however transport simulations can also be made for transient groundwater flow conditions.

Design Flexibility to Address Multiple Spatial and Temporal Scales

A key attribute of the GWA is the flexibility to address groundwater quantity and quality issues at multiple spatial and temporal scales. The WRDSS was developed to provide a tool to evaluate both operational (e.g. forecasting the quantity and quality of a well field supply to meet irrigation demand) as well as the strategic planning (e.g. assess sustainable groundwater yield and storage across the Reservation) objectives of the GRIC. To provide this functionality, the GWA uses a model grid scaling tool to provide improved resolution to support both flow and salt transport simulations at multiple spatial scales while preserving a reasonable simulation run time. GWA simulations can also be run using different computational timesteps, to address varying time scales.

Variable Spatial Scale: The regional flow model employs a grid cell size of 640 acres, and covers an area approximately 4 times the size of the Reservation. The extent of the regional model was based on lateral model boundaries largely defined by 'no-flow' bedrock contacts. The regional model was adapted for more local scale analysis (e.g. at the Reservation-scale and wellfield-scale) using Telescopic Mesh Refinement, or 'TMR.' The graphical user interface for the numerical modeling, Groundwater Vistas™ , largely automates TMR, including processing the results of the larger hydraulic model to set the smaller hydraulic model boundary conditions. TMR is first employed for Reservation-scale analysis using grid cells of 160 acres in size. TMR is also employed using the results of the Reservation-scale model for more detailed analysis to simulate a particular wellfield-scale with 40-acre or smaller grid cells.

The TMR methodology is also used to minimize computational errors typically encountered in groundwater transport simulations, particularly in error-prone regions such as in the vicinity of sharp salt concentration fronts. High resolution subgrids are used to focus the evaluation of salt transport specifically within the boundaries of the Reservation or to describe transport in the immediate vicinity of specific irrigation areas or well fields. To avoid long model run times, the spatial extent of the model must be reduced along with the grid cell size.

Variable Temporal Scale: For operational planning (e.g. irrigation scheduling), monthly timesteps are required to identify problems associated with meeting the demand with acceptable water quality and pumping lift. Irrigation forecasting, using model runs with monthly timesteps, may extend over 5 to 10 year planning horizon.

For strategic planning, evaluating resource management issues such as changes in aquifer storage and cumulative salt loading requires analysis over longer timeframes and consideration of both on- and off-Reservation impact to groundwater. To facilitate strategic planning of groundwater resource use, longer timesteps can be used. For instance, periods of steady groundwater development (from 1900 to 1975) were simulated with 40-year, 10-year, and 5-year timesteps. On the other hand, the period 1975 to 2002 was characterized by a period of relatively frequent episodic flooding events. These conditions were simulated using annual and monthly timesteps to more accurately represent changes in recharge conditions.

Functionality and Linkage to OWRA

A flowchart showing the GWA model operation and linkage to the OWRA is illustrated in Figure 2. At the beginning of an analysis run, an initial set of conditions and objectives/constraints is established by the OWRA. For example, water management objectives may include determining the optimum number of irrigated acres based on available surface water sources and sustainable groundwater pumping (quantity and quality). Related analysis may include assessing water costs, optimizing well field design, or enhancing aquifer storage. With initial conditions and objectives set, the OWRA provides the quantity and quality of recharge throughout the groundwater model domain and specifies groundwater pumping demand and associated water quality requirements by area (e.g. irrigation zone). Well field configurations are identified and the GWA run to assess feasibility and define a range of operating conditions. Intervening scenarios can then be extrapolated from the range of GWA results, thereby reducing the number of model iterations.

The first step in the GWA process is evaluating the time lag for recharge to percolate to the uppermost aquifer. MODFLOW is initiated after recharge from the first irrigation event reaches the groundwater table. If results indicate that the demand cannot be met with the initial well configuration, then well locations and pumping rates will be optimized until demand is met, or if not feasible, an alternative water demand is specified by the OWRA and the GWA iteration is repeated.

Once the demand is met, then the modeling process advances to predict water quality using MT3D. If MT3D output indicates salt concentrations in the groundwater discharge meets water quality criteria specified in the OWRA, then the model output will be exported back to the OWRA (via the IM) and the results stored in the groundwater database.

If MT3D output indicates that the groundwater will exceed water quality criteria specified in the OWRA, an optimization step will be performed for well locations and pumping rates within the GWA. The optimization loop will be performed until model results are acceptable or the demand, as specified, is deemed infeasible. In this case, alternate demand or salt criteria would be input into the OWRA and the GWA rerun.

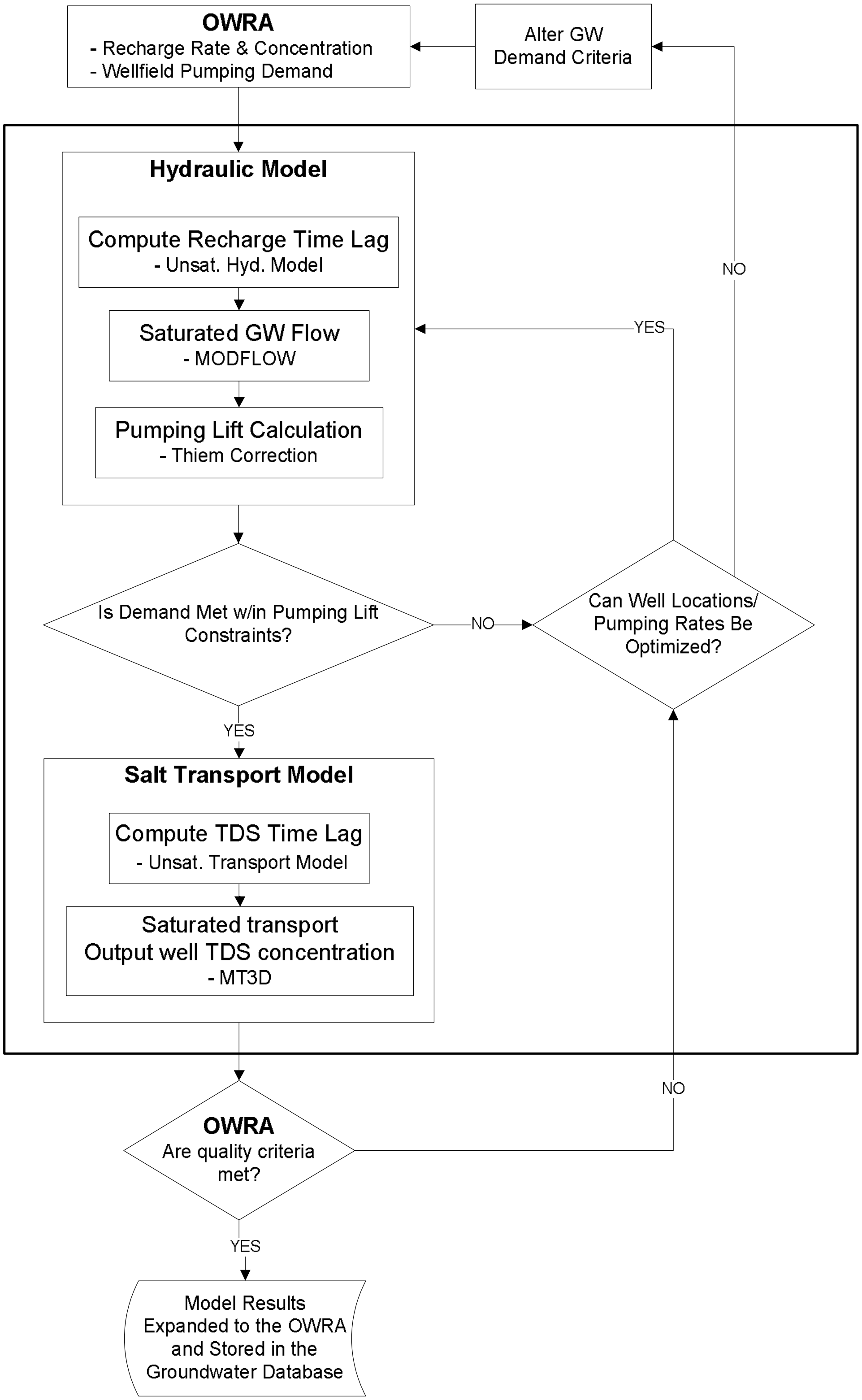

Figure 2. Iteration Sequence

SUMMARY

The GWA provides a modeling tool for evaluating changes in groundwater quantity and quality within the framework of the Gila River Indian Community Water Resources Decision Support System (WRDSS). A detailed assessment of hydrogeologic conditions within and surrounding the Reservation formed the conceptual framework for constructing the groundwater flow model. The GWA incorporates design flexibility to allow analysis at multiple spatial and temporal scales, to support the water resource management objectives of the GRIC.

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REFERENCES

Anderson, M. P. and Woessner, W.W., 1992, Applied groundwater modeling: simulation of flow and advective transport. San Diego, California: Academic Press, Inc.

Bliesner, R.D., Keller, A.A., Flynn, T.J., DeGrande, V., Sinclair, L., 2004, Gila River Indian Community – Managing a multi-source conjunctive use water supply for long-term sustainability, *in* Proceedings, Water Rights and Related Water Supply Issues, - Water Management Conference, p. 485-496.

Environmental Simulations, Inc. (ESI), 2004, Guide to using groundwater vistas, version 4.0.

Harbaugh, A. W. and McDonald, M. G., 1996, User's Documentation for MODFLOW-96, an update to the U. S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. U.S. Geological Survey. Open-File Report 96-485.

Hillel, D., 1998, Environmental Soil Physics: Fundamentals, applications, and environmental considerations, Academic Press.

Tindall, J.A. and Kunkel, J.R., 1999, Unsaturated zone hydrology for scientists and engineers, Prentice Hall.

Westfall, B.D., Keller, A.A., Bliesner, R.D., Flynn, T.J., Linstrom, S., 2006, Gila River Indian Community Water Resources Decision Support System – A Modeling System for Managing a Muli-Source Conjunctive Use Water Supply for Long-Term Sustainability, 2006 USCID Water Management Conference.

Zheng, C., 1990. MT3D: A modular three-dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems, Report to the USEPA, 170 pp.