7. GIS DATA AND HYDROLOGIC MODELING

We recommend the applications of GIS data models and hydrologic simulation models as the essential tool to help make salinity management decisions, formulate policies and implement regulations.

Models are simplified representations of real systems. There are different kinds of computer models that are typically used to apply effectively quantitative information to: (1) simulate and predict past and future conditions, (2) test system dynamics and response, (3) optimize critical parameters, and (4) estimate the range of possible outcomes with statistical descriptions.

Three kinds of models applicable to the investigation of the salinity impairment issue in the Central Valley are identified:

1. Data models used by Geographic Information System (GIS) application and spatial information analysis.

2. Hydrological models that simulate water flow and mass transport on the surface (surface water) and in the subsurface (unsaturated zone and ground water). These models typically make use of numerical analysis techniques, such as finite-difference and finite element methods in conjunction with stochastic approach.

3. Economic and management models used for cost-benefit analysis and economic forecast. They may include linear or non-linear optimization processes.

The latter kind is the subject of a concurrent study conducted by the University of California, Davis sponsored by the Central Valley Regional Water Quality Control Board, and therefore, it is not covered by this report.

7.1 GIS Data Models

GIS data models organize data into data structures so that model users can display and analyze the data according to predetermined sets of conditions and to show relationships and correlations among different parameters and data sets. GIS data sets normally contain spatial coordinates so that numerical or quantitative data can be displayed and analyzed as a function of location and space.

GIS data models also provide linkages among separate databases and the user interface. For example, the linkages can enable users to analyze and model water quality across different water quality databases at selected spatial and temporal resolutions.

ArcGIS (ESRI Corporation, Redlands, California; Figure 7.1) has the standard geographic information system modeling packages that we recommend and is most commonly used. It is the industrial standard that provides the flexibility for exchange of data and uses the widely acceptable data file formats. In addition, it has build-in spatial analytical tools and spatial statistical extensions that will greatly enhance the water quality modeling process. Special hydrologic application modules have also been developed.

A proposed example of application is summarized in Figure 7.2. We strongly recommend further development of this kind of GIS based data model for salinity data application and management.

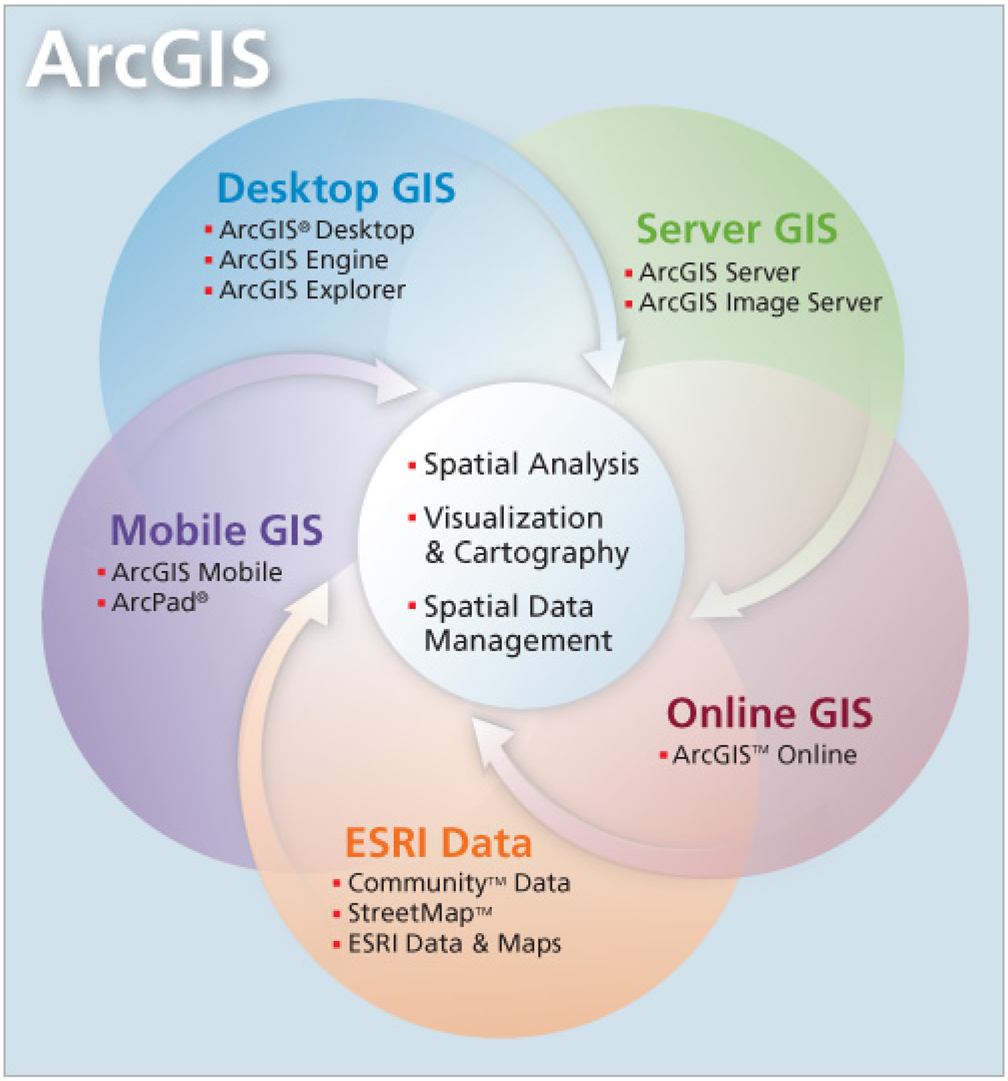

Figure 7.1 ArcGIS software packages (from ESRI Corp.)

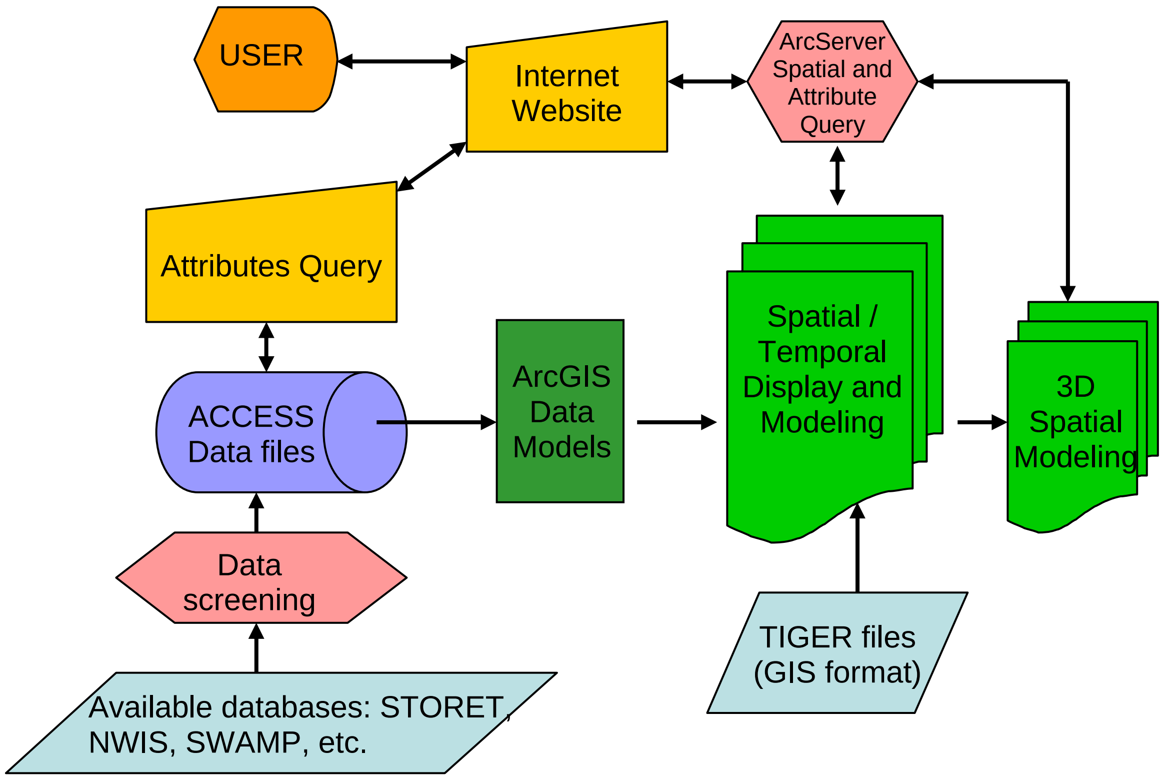

Figure 7.2 Recommended GIS Model Application

7.2 Hydrological Models and Numerical Simulations

Hydrological models include surface water models and groundwater models. These models typically calculate water flow and mass balance by solving numerically the hydrodynamic flow equation and the continuity equation of water flow through porous media.

The finite-difference method and the finite-element method are the numerical analysis techniques commonly used to solve the partial differential equations in the spatial and temporal domains. Other less common variations but more robust techniques, such as the integral element method, are also used. Each method has its own advantages and disadvantages. For example, integral element method produces better mass balance than finite element method. Detailed descriptions of numerical methodology are beyond the scope of this work.

The spatial domain of simulation in hydrological models can be one-, two-, or three-dimensional depending on conceptualization and simplification. To satisfactorily track the movement of salt and to ensure mass balance, three-dimensional models are definitely required and recommended.

Two different possible scales of modeling studies are recognized:

1. Farm or regional scale
2. Valley-wide scale (covering either the San Joaquin Valley or the Central Valley) models.

7.2.1 Farm or Regional Scale Hydrologic Models

Farm or regional scale models cover a farm or farmlands within a hydrologic basin or a sub-basin unit (e.g. an irrigation district). They track the salt balance within a farm or a sub-basin unit taking into accounts of input parameters, such as, crop types, evapotranspiration, climate, inflow and runoff, precipitation and infiltration, surface water- ground water interaction, groundwater pumping, geometry and distribution of geological materials and their hydrological parameters (for example, porosity, storage, hydraulic conductivity and unsaturated properties of soil types). These models can be applied to study the outcomes of different farm operations and practices, and used for "what-if" scenario analysis in the farm or regional scale. Based on the results of model simulations, optimized salinity management practices can be then determined.

Currently, the most comprehensive model specifically developed for this purpose is the FARM process (FMP) model developed for the U.S. Geological Survey (Schmid, et al, 2006). The current user guide and data requirements are provided by the USGS at http://pubs.usgs.gov/tm/2006/tm6A17/.

The current release of the FARM process model is based on MODFLOW-2000 (MF2K), a tried-and-true finite-difference three-dimensional groundwater stimulation model developed by the U.S. Geological Survey and it is widely available. Summary information for the latest version of MODFLOW-2005 from the USGS is included in Section 7.4.1 of this chapter.

A related MODFLOW based model has been applied successfully to study farm drainage in areas in the San Joaquin Valley (Brush, et al, 2006). We believe that with further developments, the FARM process model would be useful to study on farm salt balance and can be used for on-farm salinity management applications. However, the FARM process model needs further development and refinement into order to be tailored specifically for salinity studies.

We recognize some of the apparent weaknesses of the FARM process model (MF2K based) as follows*:

(1) The model is originally developed to handle water balance of an open system. It was not designed to specifically handle the mass balance and transport of solutes (dissolved salt). Very often, numerical models based on either finite-difference or finite-element methods "leak" if mass balance is not enforced at each time step.

(2) The original model based on MF2K mainly solves the water flow equation but not the mass transport equation, which accounts for the both advection and dispersion processes. However, an additional Ground Water Transport (GWT) module is being linked to provide the solute transport functionality applicable for salinity management. (Please see additional information in Section 7.4.3).

(3) The FMP model does not model in detail hydrogeochemical reactions and processes, such as precipitation and dissolution, sorption and retardation, dissociation and degradation. These are the common processes which control salt accumulation and transport. An additional equilibrium geochemical module with simplified reaction kinetic feature can be developed and included.

(4) The FARM model is based on MODFLOW-2000. While it does take into account of surface water ground water interaction, it is not equipped to fully simulate the unsaturated zone flow and transport processes (e.g. solve Richards equation) in detail. A module based on HYDRUS2D developed by USDA Salinity Laboratory has been used to simulate the evapotranspiration process in

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* The discussion in this section (7.2.1) is solely based on the current official release of information by the U.S.G.S. for the FMP model. USGS has updated and upgraded the Farm Process (FMP) environment with additional functionalities and software packages based on the latest version of MODFLOW-2005. The additional pre-published information on the ongoing work is included in Section 7.4.3. This information was kindly provided by Steven P. Phillips of USGS whose assistance and comments are greatly appreciated.

the root zone in two dimensions. Nevertheless, an Unsaturated Zone Flow UZF package has been developed for MODFLOW-2005.

Based on the currently available information, we therefore recommend the development of a salinity specific model based on the FARM process model and MODFLOW platform. We recommend that the salinity specific model should include the following functionalities, some of which may have already been recognized and additional work may be under development or already completed. (Please see also Section 7.4.3).

- A coupled three-dimensional solute transport module with a robust mass balance routine. A sequential solution at each time step would be desirable.
- A coupled unsaturated flow module. (The Unsaturated Zone Flow (UZF) package has been developed for MODFLOW-2005).
- An additional equilibrium geochemical reaction module for ionic compounds (salt). It should include thermodynamic data for salts and model simple reaction kinetic effects.
- Necessary user-friendly GUI that links to GIS application.

7.2.2 Valley-Wide Hydrologic Model

The California Department of Water Resources has developed groundwater-surface water models covering the entire Central Valley. The C2VSIM (California Central Valley Groundwater-Surface Water Simulation Model) was developed based on IWFM (Integrated Water Flow Model, formerly known as IGSM2) (Brush, et al, 2007). It is a three-dimensional finite element groundwater flow model coupled with a one-dimensional land surface, stream flow, lake flow and vertical unsaturated-zone flow process. The groundwater flow process can simulate groundwater pumping or injection, farm drainage, and land subsidence. The land-surface process takes into account of crop types, soil properties, land use, precipitation, and evapotranspiration. The surface water process also simulates stream flow, groundwater-surface water interactions, inflow and runoff. Similar to the FARM process model, it also calculates water balance. It can be used to assess the impacts of different scenarios as a result of different human activities (e.g. development) and other natural changes (e.g. global warming).

DWR's C2VSIM model has similar limitations as the USGS's FARM process model, although they are intended to be used for different purposes. While C2VSIM does couple unsaturated-saturated flows, it is primarily a water flow model and thus it does not address solute transport or hydrogeochemical processes. These processes are important factors controlling salt movement. Therefore, we have similar recommendations for its future developments for salinity specific studies.

7.2.3 State-Wide Water Conveyance Model

The California Department of Water Resources has also developed a state-wide water conveyance model (CALSIM) which simulates water flow and storage operations of the water resource systems of the entire state, covering both the federal Central Valley Project (CVP) and the California State Water Project (SWP). Based on mass balance and hydraulic principles, the model simulates flow through aqueducts, canals, river channels, reservoirs, and pumping plants. It can be used for scenario analyses or as an optimization tool to evaluate operational alternatives in terms of water quantity. However, although the model balances water quantities, it is not a hydrological model and does not account for subsurface flow, storage in groundwater basins, or the dynamic interaction between ground and surface waters. Nevertheless, since the water transfer probably accounts for the largest amount of salt movement in the state, it would be very desirable to develop a water quality module coupled to CALSIM to simulate the movement of dissolved salt through the water conveyance systems. A limited amount of water quality data are available (please see Chapter 3 of this report) and could be used as model inputs or used for model calibration.

The overview of CALSIM (an excerpt from the CALSIM manual) is included at the end of this chapter (section 7.4.4).

7.3 Additional Data Requirements for Model Applications

Apart from the water quality data sources indentified in the previous chapters, hydrologic models require additional hydrogeological input parameters, such as hydrologic properties of soils and aquifers, geometry and distribution of geological layers, initial and boundary conditions, and mineralogical and geochemical descriptions. These additional data are most likely more difficult to obtain. Case in point, to simulate water flow of the entire Central Valley, a hydrogeology model (an accurate description of sedimentary layers) for the entire Central Valley is needed. Such information can only be obtained from thousands of well logs kept by DWR. Because the well log information is proprietary under state law, these data are unavailable unless the State Water Board can make special arrangements or obtain special permission to access the necessary data sources.

7.4. Model Information

7.4.1 Summary Information on MODFLOW (latest version, from USGS)

U.S. Geological Survey (USGS) modflow(1)

NOTE: Any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

NAME

modflow - Modular three-dimensional finite-difference ground-water model

ABSTRACT

MODFLOW is a three-dimensional finite-difference ground-water model that was first published in 1984. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model. Harbaugh (2005) documents a general update to MODFLOW, which is called MODFLOW-2005 in order to distinguish it from earlier versions.

MODFLOW-2005 simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block.

In addition to simulating ground-water flow, the scope of MODFLOW-2005 has been expanded to incorporate related capabilities such as solute transport and ground-water management; however, this distribution incorporates only the ground-water flow parts of MODFLOW.

METHOD

The ground-water flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform. In plan view the blocks are made from a grid of mutually perpendicular lines that may be variably spaced. Model layers can have varying thickness. A flow equation is written for each block, called a cell. Several solvers are provided for solving the resulting matrix problem; the user can choose the best solver for the particular problem. Flow-rate and cumulative-volume balances from each type of inflow and outflow are computed for each time step.

HISTORY

MODFLOW-2005 Version 1.5 4/28/2008 - Updated SFR, UZF, and LAK Packages to the versions used in the GSFLOW coupled ground-water and surface-water model. Also added the capability to use different damping factors in the PCG Package for transient and steady-state stress periods. Added option "DDREFERENCE" to the Output Control Files, which was an option implemented in MODFLOW-2000. Also fixed several miscellaneous problems. All of the changes are documented in the release.txt file.

MODFLOW-2005 Version 1.4 11/2/2007 - Added SWT Package, added adaptive damping to GMG, and fixed minor problems (see release.txt file).

MODFLOW-2005 Version 1.3.01 8/2/2007 - Checks added to prevent using HUF with UZF Package or the unsaturated flow part of SFR Package.

MODFLOW-2005 Version 1.3 8/1/2007 - Fixed several minor problems (see release.txt file).

MODFLOW-2005 Version 1.2.01 10/24/2006 - Fixed bug in SFR.

MODFLOW-2005 Version 1.2 10/16/2006 - SFR, LAK, UZF, and GAG packages were added.

MODFLOW-2005 Version 1.1 05/18/2006 - DRT, ETS, RES, and SUB packages were added. Observations (OBS Process) as implemented in MODFLOW-2000 were also added.

MODFLOW-2005 Version 1.0 01/15/2006 - Initial release.

DATA REQUIREMENTS

In order to use MODFLOW, initial conditions, hydraulic properties, and stresses must be specified for every model cell in the finite-difference grid. Input data are read from files.

SYSTEM REQUIREMENTS

MODFLOW-2005 is written primarily in Fortran 90. Only the GMG solver package is written in C. The code has been used on UNIX-based computers and personal computers running various forms of the Microsoft Windows operating system.

FUNTIONALITY

This version of MODFLOW includes the following functionality that is documented in Harbaugh (2005).

BAS -- Basic Package
BCF -- Block-Centered Flow Package
LPF -- Layer-Property Flow Package
HFB -- Horizontal Flow Barrier Package
CHD -- Time-Variant Specified-Head Option
RIV -- River Package
DRN -- Drain Package
WEL -- Well Package
GHB -- General Head Boundary Package
RCH -- Recharge Package
EVT -- Evapotranspiration Package
SIP -- Strongly Implicit Procedure Package
PCG -- Preconditioned Conjugate Gradient Package
DE4 -- Direct solver

The following functionality is also included. This functionality is documented in separate reports for use in earlier versions of MODFLOW. Conversion of this functionality to work with MODFLOW-2005 is documented in separate files that are provided with the MODFLOW-2005 distribution.

STR -- Streamflow-Routing Package
FHB -- Flow and Head Boundary Package
IBS -- Interbed Storage Package
GMG -- Geometric MultiGrid Solver Package
HUF -- Hydrogeologic-Unit Flow Package
MNW -- Multi-Node Well Package
ETS -- Evapotranspiration with a Segmented Function Package
DRT -- Drains with Return Flow Package
RES -- Reservoir Package
SUB -- Subsidence Package
OBS -- Observation Process
SFR -- Streamflow-Routing Package
LAK -- Lake Package
UZF -- Unsaturated Zone Package
GAG -- Gage Package
SWT -- Subsidence and Aquifer-System Compaction Package

DOCUMENTATION

The basic documentation for MODFLOW-2005 is contained in:

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16, variously p.

The STR Package is documented in:

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

The FHB Package is documented in:

Leake, S.A., and Lilly, M.R., 1997, Documentation of a computer program (FHB1) for assignment of transient specified-flow and specified-head boundaries in applications of the modular finite- difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 97-571, 50 p.

The IBS Package is documented in:

Leake, S.A. and Prudic, D.E., 1991, Documentation of a computer program to simulate aquifer-system compaction using the modular

finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chapter A2, 68 p.

The GMG Package is documented in:

Wilson, J.D. and Naff, R.L., 2004, The U.S. Geological Survey modular ground-water model -- GMG linear equation solver package documentation: U.S. Geological Survey Open-File Report 2004-1261, 47 p.

The HUF Package is documented in:

Anderman, E.R., and Hill, M.C., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- Documentation of the Hydrogeologic-Unit Flow (HUF) Package: U.S. Geological Survey Open-File Report 00-342, 89 p.

Anderman, E.R., Kipp, K.L., Hill, M.C., Valstar, Johan, and Neupauer, R.M., 2002, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- Documentation of the Model-Layer Variable-Direction Horizontal Anisotropy (LVDA) capability of the Hydrogeologic-Unit Flow (HUF) Package: U.S. Geological Survey Open-File Report 02-409, 60 p.

Anderman, E.R., and Hill, M.C., 2003, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- Three additions to the Hydrogeologic-Unit Flow (HUF) Package: Alternative storage for the uppermost active cells, Flows in hydrogeologic units, and the Hydraulic-conductivity depth-dependence (KDEP) capability:U.S. Geological Survey Open-File Report 03-347, 36 p.

The MNW Package is documented in:

Halford, K.J. and Hanson, R.T., 2002, User guide for the drawdown-limited, multi-node well (MNW) package for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, versions MODFLOW-96 and MODFLOW-2000: U.S. Geological Survey Open-File Report 02-293, 33 p.

The DRT and ETS Packages are documented in:

Banta, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- documentation of packages for simulating evapotranspiration with a segmented function (ETS1) and drains with return flow (DRT1): U.S. Geological Survey Open-File Report 00-466, 127 p.

The RES Package is documented in:

Fenske, J.P., Leake, S.A., and Prudic, D.E., 1996, Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 96-364, 51 p.

The SUB Package is documented in:

Hoffmann, Jorn, Leake, S.A., Galloway, D.L., and Wilson, A.M., 2003, MODFLOW-2000 ground-water model -- User guide to the Subsidence and Aquifer-System Compaction (SUB) Package: U.S. Geological Survey Open-File Report 03-233, 46 p.

The OBS Process is documented in:

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to the Observation, Sensitivity, and Parameter-Estimation Processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 209 p.

The SFR Package is documented in:

Prudic, D.E., Konikow, L.F., and Banta, E.R., A new Streamflow-Routing (SFR1) Package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open File Report 2004-1042, 95 p.

Niswonger, R.G., and Prudic, D.E., 2005, Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams -- a modification to SFR1: U.S. Geological Techniques and Methods Book 6, Chapter A13, 47 p.

The UZF Package is documented in:

Niswonger, R.G., Prudic, D.E., and Regan, R.S., 2006, Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005: U.S. Geological Techniques and Methods Book 6, Chapter A19, 62 p.

The LAK Package is documented in:

Merritt, M.L., and Konikow, L.F., 2000, Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model: Water-Resources Investigations Report 00-4167, 146 p.

The GAG Package is documented as part of the above SFR and LAK documentation.

The SWT Package is documented in:

Leake, S.A. and Galloway, D.L., 2007, MODFLOW ground-water model -- User guide to the Subsidence and Aquifer-System Compaction Package (SUB-WT) for water-table aquifers: U.S. Geological Survey Techniques and Methods 6-A23, 42 p.

CONTACTS

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(703) 648-5001
ogw_webmaster@usgs.gov

See http://water.usgs.gov/software/ordering_documentation.html

for information on ordering printed copies of USGS publications.

7.4.2 Summary Information on FARM process model
(From USGS, Techniques and Methods 6-A17, 2006)

There is a need to estimate dynamically integrated supply-and-demand components of irrigated agriculture as part of the simulation of surface-water and ground-water flow. To meet this need, a computer program called the Farm Process (FMP1) was developed for the U.S. Geological Survey three-dimensional finite-difference modular ground-water flow model, MODFLOW- 2000 (MF2K). The FMP1 allows MF2K users to simulate conjunctive use of surface- and ground water for irrigated agriculture for historical and future simulations, water-rights issues and operational decisions, nondrought and drought scenarios. By dynamically integrating farm delivery requirement, surface- and ground-water delivery, as well as irrigation-return flow, the FMP1 allows for the estimation of supplemental well pumpage. While farm delivery requirement and irrigation return flow are simulated by the FMP1, the surface-water delivery to the farm can be simulated optionally by coupling the FMP1 with the Streamflow Routing Package (SFR1) and the farm well pumping can be simulated optionally by coupling the FMP1 to the Multi-Node Well (MNW) Package. In addition, semi-routed deliveries can be specified that are associated with points of diversion in the SFR1 stream network. Nonrouted surface-water deliveries can be specified independently of any stream network. The FMP1 maintains a dual mass balance of a farm budget and as part of the ground-water budget.

Irrigation demand, supply, and return flow are in part subject to head-dependent sources and sinks such as evapotranspiration from ground water and leakage between the conveyance system and the aquifer. Farm well discharge and farm net recharge are source/sink terms in the FMP1, which depend on transpiration uptake from ground water and other head dependent consumptive use components. For heads rising above the bottom of the root zone, the actual transpiration is taken to vary proportionally with the depth of the active root zone, which can be restricted by anoxia or wilting. Depths corresponding to anoxia- or wilting-related pressure heads within the root zone are found using analytical solutions of a vertical pseudo steady-state pressure- head distribution over the depth of the total root zone (Consumptive Use Concept 1). Alternatively, a simpler, conceptual model is available, which defines how consumptive use (CU) components vary with changing head (CU Concept 2).

Subtracting the ground water and precipitation transpiration components from the total transpiration yields a transpiratory irrigation requirement for each cell. The total farm delivery requirement (TFDR) then is determined as cumulative transpiratory and evaporative irrigation requirements of all farm cells and increased sufficiently to compensate for inefficient use from irrigation with respect to plant consumption. The TFDR subsequently is satisfied with surface- and ground-water delivery, respectively constrained by allotments, water rights, or maximum capacities.

Five economic and noneconomic drought response policies can be applied optionally, if the potential supply of surface water and ground water is insufficient to meet the crop demand: acreage-optimization with or without a water conservation pool, deficit irrigation with or without water-stacking, and zero policy.

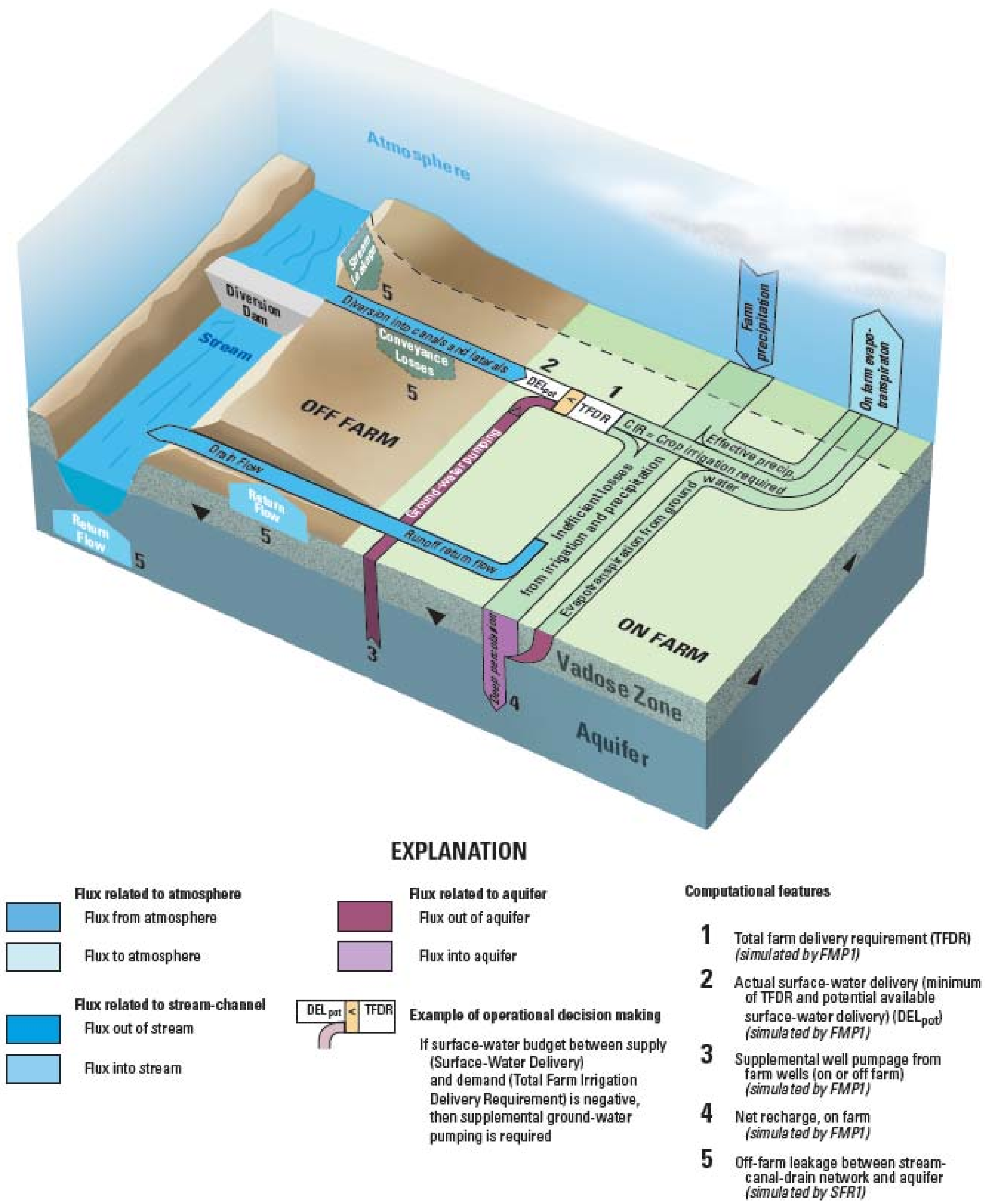


Figure 3. Flow chart of the flow of water into and out of the farm budget as simulated by the FMP1.

Figure 7.3: Taken from USGS, Techniques and Methods 6-A17, 2006.

7.4.3 Current Developments and Upgrades of the FARM Process and MODFLOW Models†

Farm Process Model Upgrades

FMP Upgrades -- Completed:

(1) The upgrade of the Farm Process (FMP) environment for MODFLOW-2005 (FMP-MF2K5) has been completed. During that process, interconnected flow-terms between FMP and SFR and MNW had to be declared differently in MF2K5 than in MF2K. FMP2 uses shared parameters that are declared externally to FMP2 by FORTRAN "MODULES" of the other packages. That is, the nature of the updated link is that SFR and MNW do not have to deal with any FMP parameters. However, the FMP had to be reformatted by changing SFR and MNW parameters from arguments lists of FMP subroutines to parameters in the "only"-list associated with a particular "use"-command that refers to SFR or MNW modules. Notice, while in general this could be done simply by invoking MODULE parameters by the "use"-command, FMP2 follows the "MF2K5" system of parameter accounting by the "only" list, which utilized only parameters that are actually used in FMP2. Further, a few global SFR variables that were considered not of "global" relevance anymore, were declared by the SFR authors now as local variables. This needed to be reverted, as FMP depends on these global variables.

(2) A new link to the UZF package has been established and tested in a simple example model. The FMP yields for every model cell a rate of percolation beyond the root zone. This rate can be used to define a temporally variable infiltration boundary of the deeper unsaturated zone below the root zone. The UZF package then simulates a wetting front of a wave generated from an infiltration rate dynamically passed on to the UZF by the FMP. This allows both the simulation of delayed recharge and of rejected excess infiltration to runoff generated from farms. The new link allows the simultaneous simulation of instant recharge for farms without a UZF link and of UZF-simulated recharge for farms whose spatial extent coincides with UZF arrays of infiltration areas. For these areas, percolation out of the root zone simulated by FMP is taken to be the infiltration rate into a deeper vadose zone. When simulating demands driven by transpiration and evaporation, FMP benefits from its separation of evapotranspiration into the two components and their different conceptualizations, which include different extinction depths. Therefore, when linking FMP and UZF, transpiration and evaporation of crops are still simulated by the FMP and not processed as UZF-specified evapotranspiration. Recharge and lumped evapotranspiration from UZF-specified infiltration may still be simulated by the UZF in infiltration areas, where no FMP farms coincide.

(3) Changes in one delivery component simulated by one package (e.g., routed surface-water by SFR or ground-water pumpage by MNW) will dynamically affect the other as well as farm related flow rates and changes in overland and subsurface return flows. MF2K5-FMP2 has a new subroutine that allows the automatic adjustment of head and

† Pre-published information is provided by Steven P. Phillips of USGS.

residual closure criteria to allow convergence of MNW-pumping to FMP-pumping requirements. In addition, the user has to option to recompute interdependent flow rates at the end of time step loop.

FMP Upgrades -- In Progress:
Although a simple example model has been constructed to test the link between UZF and FMP, a more sophisticated model is being developed at the moment. Aside from the UZF link, several new features of FMP2 need to be demonstrated simultaneously, such as uptake of certain plants from saturated conditions (ex. rice), matrix of efficiencies by farm and by crop type, non-irrigated vegetation, code internal calculation of potential crop evapotranspiration by specified reference ET and crop coefficients, semi-routed return flows to specified reaches of the stream network, restrictions on farm-well pumping, where no irrigation requirement exists, and a physical budget of farm inflows and outflows. To demonstrate the delayed recharge by the UZF-link and the uptake from saturated conditions, the new example model has to accommodate in different areas of the model both a deeper unsaturated zone and water levels close or above ground surface.

FMP Upgrades -- Still To Come This Year:
The upgraded and updated version of MF2K5-FMP2 yet has to be documented and published optionally either in a new FMP2 user guide (TWRI series) or in a professional journal article. The publication will document these new linkages and will provide a new example problem to highlight the use of the linkages to features in the SFR7, MNW7, and UZF1 packages. A new version of the code will be released on the USGS web site along with a copy of this report, guidance on compilation of source code, and EXCEL spreadsheet templates for pre-processing crop data and post-processing model results.
We expect this task to be completed by the end of August 2008.

<u>Current Developments of the Farm Process Model Applicable to Salinity Management</u>

Salinity Management and Simulation of Solute Transport in Areas of Irrigated Agriculture using the FARM PROCESS for MODFLOW (Approach):

The following discusses modifications and additions to the Farm Process (FMP) and to the Ground-Water Transport Process (GWT) that are necessary to allow the simulation of solute transport to and from farms within a MODFLOW-FMP-GWT model.

Task 1: Calculation of Solute Concentration within and out of the Root Zone (FMP)

Modifications and/or additions to the FMP include the calculation of solute concentrations within and out of the root zone and of irrigation water supply. Additions to the Farm Process might either be implemented within the Farm Process code (expanded FMP) or eventually lead to a new, separate module. The general approach would underlie assumptions, such as instantaneous flows and instantaneous mixing, uniform solute concentration across the root zone, and no change in soil water storage. A steady state approach would calculate the mixing of solute loads into and out of a reference root zone volume while assuming no changes in solute mass. A more complex approach would be to allow a transient mass balance of solute mass into and out of a root zone volume.

Task 2: Update of Salt Build-Up & Salinity dependent Evapotranspiration in Root Zone (FMP)

The expanded FMP (or an additional new package linked to it) will solve for the concentration in the root zone. At the current stage of the FMP, FMP-internal analytical solutions approximate numerical solutions of the Richards equation by HYDRUS2D (Simunek et al., 1999) for a vertical steady-state pressure-head distribution over the depth of the total root zone. This approximation simulates the reduction of transpiration proportionally to the reduction of the root zone by changes in the zones of anoxia and wilting. The simulation of actual transpiration and evaporation in the FMP depends on the following parameters (crop type and associated stress response functions, soil type and associated soil-water constitutive functions, root zone depth, capillary fringe, potential transpiration, and potential evaporation).

The analytical solution could be expanded to a dependency of calculated transpiration and evaporation on an updated value of solute concentration in the root zone (for each time step or even for each iteration). Previous non-salinity dependent solutions where derived from transient soil column model runs with HYDRUS2D, which also allows for solute dependent solutions. In the present version of FMP, analytical solutions where derived for only three soil types representative for most soil types of the US soil taxonomy system (sandy loam, silt, silty clay). When expanding analytical solutions to salinity dependent solutions of transpiration and evaporation, we may consider the derivation for additional soil types. Salinity dependent analytical solutions will simulated a reduction in transpiration and/or a complete cessation of crop growth.

Task 3: Calculation of Solute Concentration of Irrigation Water Supply and Return Flow (FMP)

The solute load in irrigation deliveries consists of different components associated with different water types (non-routed deliveries, routed deliveries, ground-water deliveries). Solute concentrations of non-routed deliveries (e.g., water transfers via pipeline) will have to be specified by the user as new data input into the expanded FMP.

A link between the Ground-Water Transport Process (GWT) and the Streamflow Routing Package (SFR) already yields updated values of solute concentration in each stream reach. Therefore, concentrations associated with routed diversions that alter concentrations in root zones of Farm-Process farms can be provided by a link to the SFR package. Conversely, solute loads associated with runoff that stems from inefficient losses (or excess irrigation returnflow) will alter the concentrations in drains, which can be simulated by tributary stream segments in an SFR stream-canal-drain network. The solute load associated with returnflow will be calculated in the expanded FMP and passed on to the SFR package, where it contributes to the solute mixing in a “drain.”

Concentrations of groundwater well pumping can be simulated by an already existing link between the FMP and the Multi-Node Well package (MNW) and by a link between the MNW and the GWT. This allows GWT to use solute concentrations for respective aquifer nodes in order to calculate a mixed concentration for the net-pumping of a MNW-well. Alternatively, in an expanded FMP, FMP-embedded farm wells need to receive a solute source with a concentration from a particular screened aquifer that is simulated by the GWT. Lastly, a mixing scheme will be developed in an expanded FMP for all FMP- and MNW-simulated wells contributing to a particular farm.

Task 4: Calculation of solute loads between the root zone and the aquifer (GWT)

In GWT, source/sink terms of the solute transport equation would have to be expanded by loads associated with the following terms:

- Upward capillary rise due to evapotranspiration;
- Downward deep percolation out of the root zone;
- Farm-well pumping rate;
- Farm-well injection rate.

The latter term will only be necessary when simulating Aquifer-Storage-and-Recovery Systems (ASRs) by injecting excess water-transfer deliveries (with known solute concentration) into injection wells of a “virtual farm,” which represents an ASR.

Modifications to GWT will be accomplished through collaboration with its authors, Leonard Konikow and George Hornberger from the USGS in Reston, VA.

7.4.4 Summary Information on IWFM
(From DWR, Integrated Water Flow Model Theoretical Documentation, 2007)

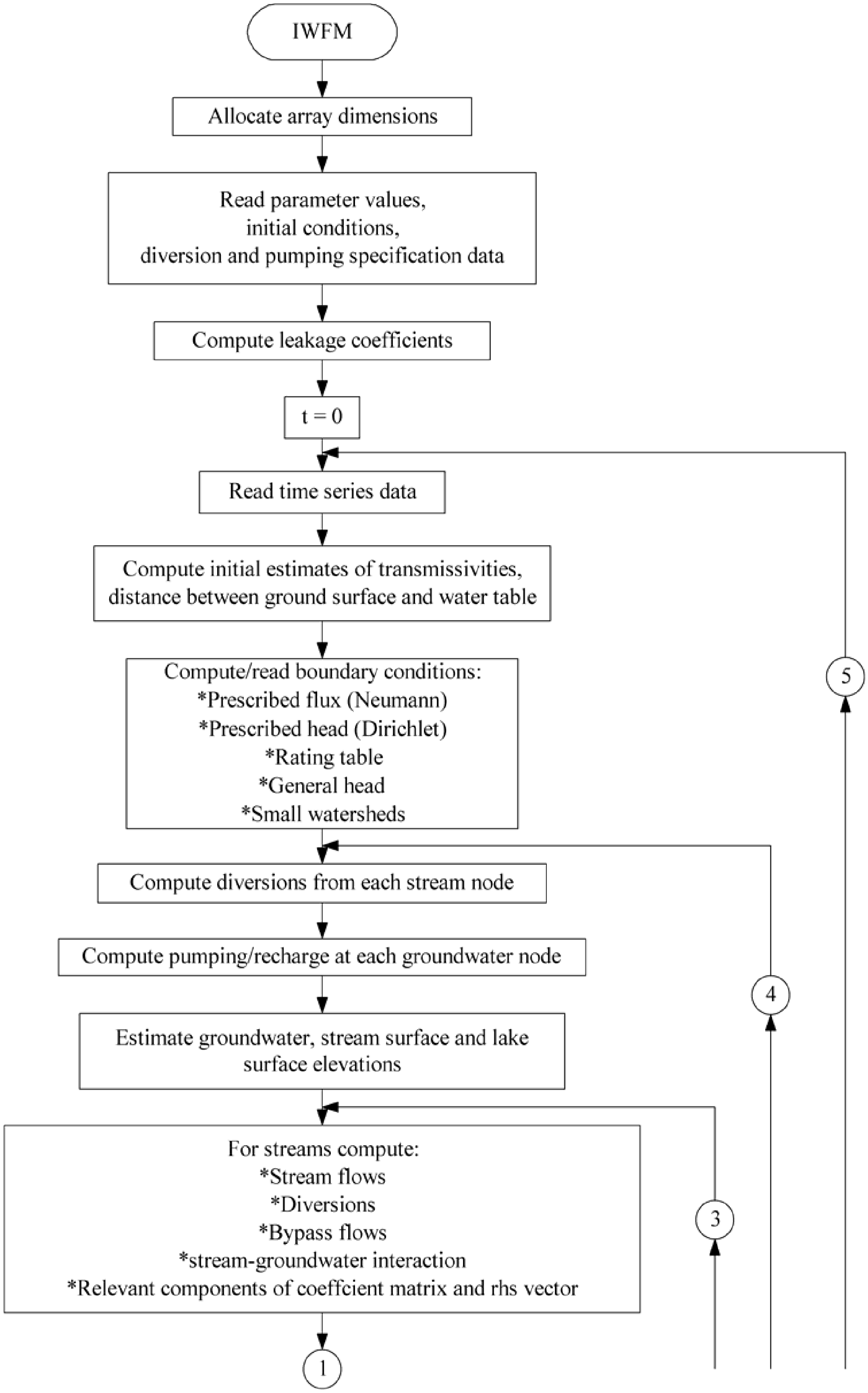
The Integrated Water Flow Model (IWFM) is a fully documented FORTRAN based computerized mathematical model that simulates ground water flow, stream flow, and surface water – ground water interactions. IWFM was developed by staff at the California Department of Water Resources (DWR). IWFM is GNU licensed software, and all the source codes, executables, documentation, and training material, are freely available on DWR’s website. The model was first released to the public by DWR in 2003 as IGSM2 (Integrated Groundwater-Surface water Model version 2). IGSM2 itself was a completely revised version, in theory and code, of IGSM which was originally developed in 1990 for a group of State and local agencies in California (including DWR).

<u>Summary of Current Model Features in IWFM</u>

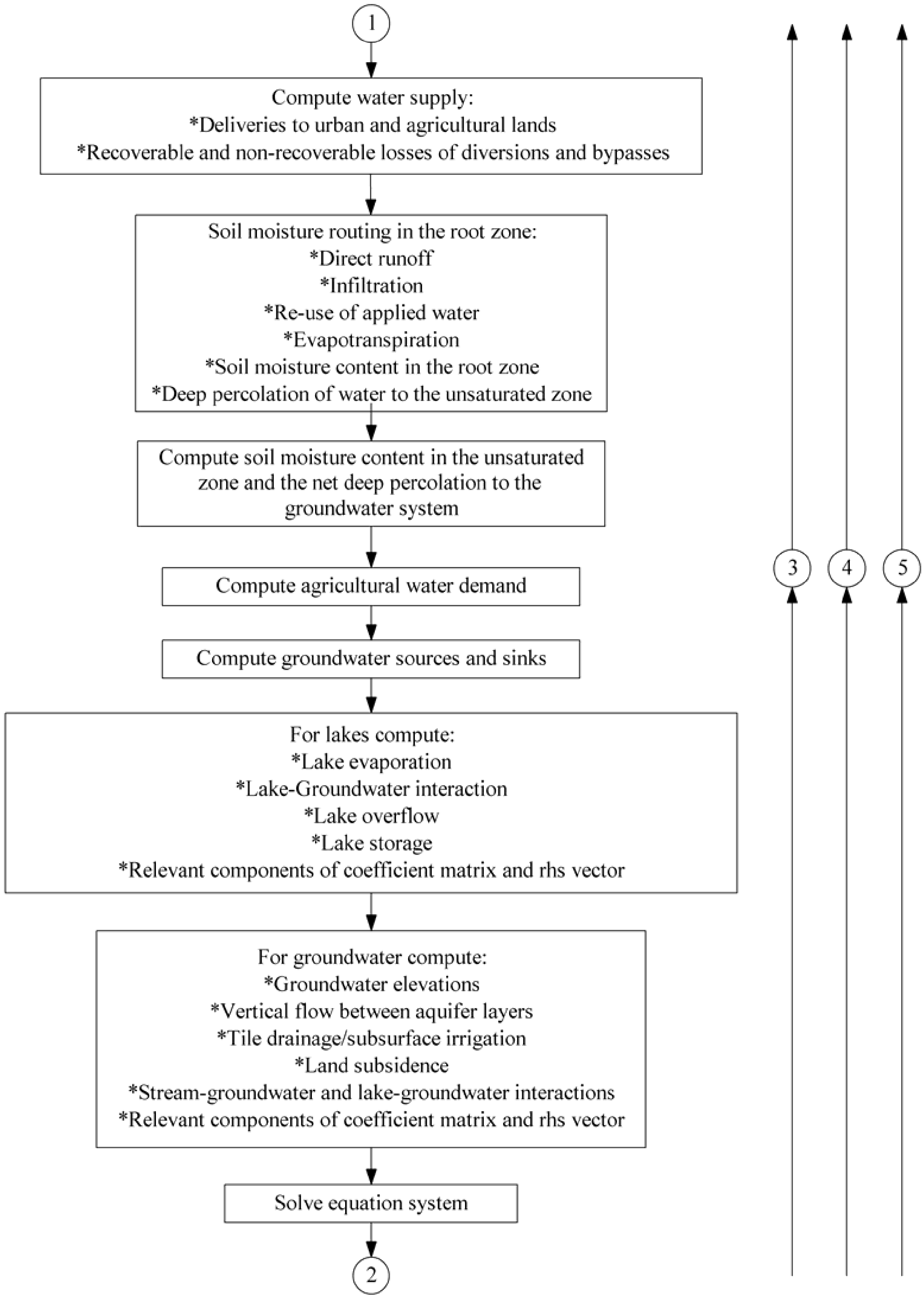
IWFM is a water resources management and planning model that simulates groundwater, surface water, groundwater-surface water interaction, as well as other components of the hydrologic system (Figure 1.1). Preserving the non-linear aspects of the surface and subsurface flow processes and the interactions among them is an important aspect of the current version of IWFM.
Simulation of groundwater elevations in a multi-layer aquifer system and the flows among the aquifer layers lies in the core of IWFM. Galerkin finite element method is

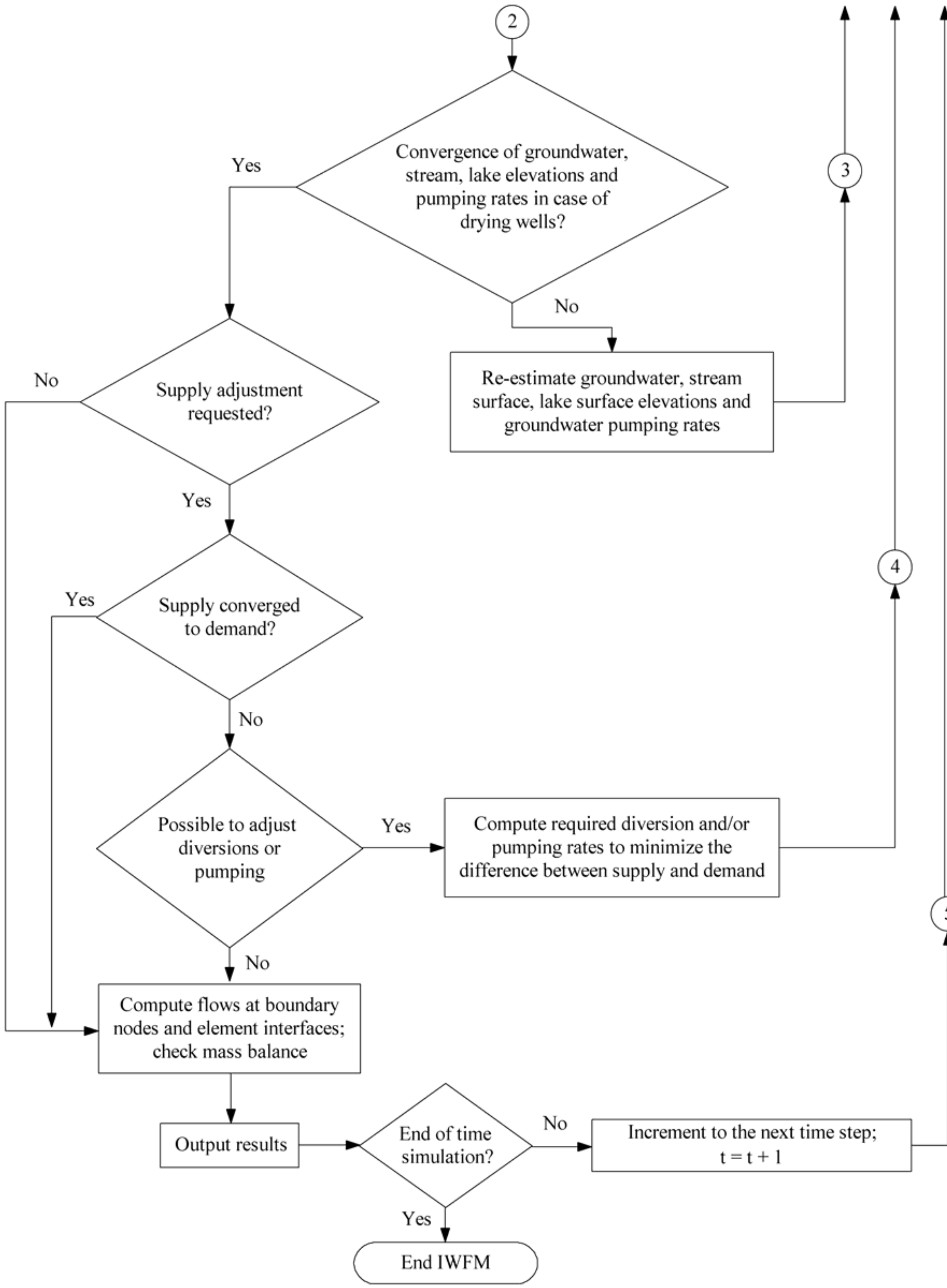
used to solve the conservation equation for the multi-layer aquifer system. Stream flows and lake storages are also modeled in IWFM. Their interaction with the aquifer

Figure 7.4: General Flowchart of IWFM
(Taken from DWR, 2007. See the 3 following pages)



IWFM
Allocate array dimensions
Read parameter values,
initial conditions,
diversion and pumping specification data
Compute leakage coefficients
t = 0
Read time series data
Compute initial estimates of transmissivities,
distance between ground surface and water table
Compute/read boundary conditions:
*Prescribed flux (Neumann)
*Prescribed head (Dirichlet)
*Rating table
*General head
*Small watersheds
Compute diversions from each stream node
Compute pumping/recharge at each groundwater node
Estimate groundwater, stream surface and lake
surface elevations
For streams compute:
*Stream flows
*Diversions
*Bypass flows
*stream-groundwater interaction
*Relevant components of coeffcient matrix and rhs vector
1
3
4
5


1
Compute water supply:
*Deliveries to urban and agricultural lands
*Recoverable and non-recoverable losses of diversions and bypasses
Soil moisture routing in the root zone:
*Direct runoff
*Infiltration
*Re-use of applied water
*Evapotranspiration
*Soil moisture content in the root zone
*Deep percolation of water to the unsaturated zone
Compute soil moisture content in the unsaturated zone and the net deep percolation to the groundwater system
Compute agricultural water demand
Compute groundwater sources and sinks
For lakes compute:
*Lake evaporation
*Lake-Groundwater interaction
*Lake overflow
*Lake storage
*Relevant components of coefficient matrix and rhs vector
For groundwater compute:
*Groundwater elevations
*Vertical flow between aquifer layers
*Tile drainage/subsurface irrigation
*Land subsidence
*Stream-groundwater and lake-groundwater interactions
*Relevant components of coefficient matrix and rhs vector
Solve equation system
2
3
4
5


2
Convergence of groundwater, stream, lake elevations and pumping rates in case of drying wells?
Yes
No
Re-estimate groundwater, stream surface, lake surface elevations and groundwater pumping rates
3
Supply adjustment requested?
No
Yes
Supply converged to demand?
Yes
No
Possible to adjust diversions or pumping
Yes
Compute required diversion and/or pumping rates to minimize the difference between supply and demand
4
No
Compute flows at boundary nodes and element interfaces; check mass balance
Output results
End of time simulation?
No
Increment to the next time step; t = t + 1
5
Yes
End IWFM

7.4.4 Summary Information on CALSIM
(Taken from CALSIM Draft Doc, 2000)

Introduction

The simulation of large, complex water resource systems for planning studies requires a flexible and efficient modeling tool to assist in the evaluation of rapidly changing alternatives. The California Department of Water Resources has developed a general-purpose water resources simulation model, CALSIM, that enables users to quickly develop system representations and specify operational criteria. CALSIM represents a fundamental change in the modeling approach used to simulate the operation of California's water resource systems, particularly the coordinated operation of the Federal Central Valley Project (CVP) and the California State Water Project (SWP). Model users now specify the system objectives and constraints as input to the model, rather than embedding the simulation goals and logic in thousands of lines of procedural code as is common in traditional simulation models. While CALSIM is not a prescriptive optimization model, it utilizes optimization techniques to efficiently route water through a network given user-defined priority weights. A linear programming (LP)/mixed integer linear programming (MILP) solver determines an optimal set of decisions for each time period given a set of weights and system constraints.

The physical description of the system is expressed through a user-interface with tables outlining the system characteristics. The priority weights and basic constraints are also entered in the system tables. A new modeling language, Water Resources Engineering Simulation Language (WRESL), has been developed to serve as an interface between the user and the LP/MILP solver, time-series database, and relational database. Specialized operating criteria are expressed in WRESL. The WRESL expressions can be compartmentalized to provide for a highly organized arrangement of logical units and to serve as self-documenting modules. CALSIM is intended to replace the California Department of Water Resources' existing simulation model, DWRSIM, as well as PROSIM, another simulation model of the SWP/CVP system extensively used by the U.S. Bureau of Reclamation. However, the structure of the CALSIM engine is highly generic, such that the model can be applied to many other water resource systems.

CALSIM Overview

The CALSIM model has been designed to separate the physical and operational criteria from the actual process of determining the allocations of water to competing interests.
This separation of ***what*** are the goals of the system from ***how*** the problem is solved represents a fundamental change from traditional systems modeling. In traditional water systems modeling the *what* and *how* are intermingled when stepping through the formalized procedures of water allocation and often result in extremely complex code. Through the use of advanced computer science tools and a component-based structure CALSIM avoids requiring the user to specify procedures and allows for easy specification of system rules and constraints.

A graphical user interface has been developed for the defining the system configuration and basic constraints, as well as viewing the results of a simulation. The model user describes the physical system (reservoirs, channels, pumping plants, etc.), basic operational rules (flood-control diagrams, simple minimum flows, etc.), and priorities for allocating water to different uses entirely in through the user interface. A key component for specification of the specialized operational constraints is the WRESL language. The modeler describes specialized operational rules (delivery cutbacks, salinity-flow requirements, etc) entirely in WRESL statements. The statements are then assembled into WRESL files using a tree-structure for organization of related constraints. At run-time the WRESL statements are converted to generated Fortran90 code by a parser-interpreter program. The parser-interpreter has been developed by the use of the JavaCC parser generator and contains the entire WRESL language syntax. JavaCC, an advanced computer science tool based on the Java language, enables language syntax and functionality to be easily added or modified.

Once the WRESL statements have been converted to Fortran90 code, relational and time-series data are read from separate databases. CALSIM utilizes the HEC-DSS time-series data storage system developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center in Davis, California. Hydrologic data spanning a 73-year period are currently stored in this database. Relational data such as index-dependent flow standards and monthly flood control diagrams are stored in simple, text-based, relational tables.
WRESL statements, using SQL-type syntax, allow access to the relational and time-series data. Once the relational and time-series data are read from the databases, the entire problem is assembled into the proper format and passed to the solver. The MILP solver performs the necessary solution algorithms and returns the decision variable results to the time-series database. Diagnostic information from the solver is passed to the controlling user-interface and individual output files. The process involving the generated code, data access, and solver is repeated for each time period until the simulation is complete. The general flow of information is shown graphically in Fig. 1.

The model simulation and output viewing are performed through the CALSIM user interface. This interface is a Java-based application that allows the user to specify the files and criteria for simulation and provides access to time-series simulation results and input data. The CALSIM Study tab is used for defining the system and controlling the simulation. The CALSIM Output tab generates graphical plots, tables, and specialty reports. Mathematical operations may be performed on data records and saved for use in future studies. Several custom functions provide quick outputs of commonly used operations, such as aggregating all project deliveries and Delta exports. In addition, base and alternative studies may be compared directly from the CALSIM user-interface and statistics performed.

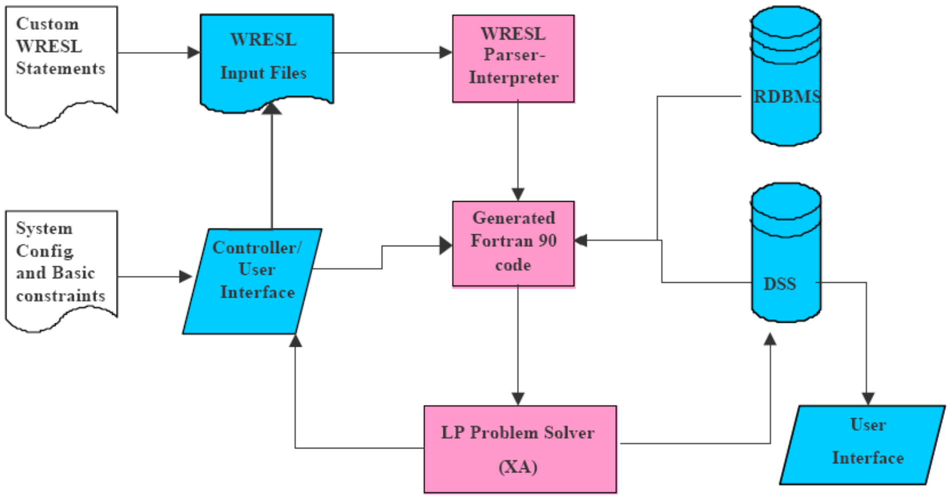


Fig. 1. CALSIM model structure and general flow of information.

Model Formulation

Model Network

The CALSIM model represents water resource systems, consisting of reservoirs and channels (natural and artificial), as a network of nodes and arcs. Nodes in the network may represent reservoirs, groundwater basins, junction points of two or more flows, or simply a point of interest on a channel. Arcs represent water flows between nodes, or out of the system, and may be inflows, channel flows, return flows, or diversions. An example network is shown in Figure 2.

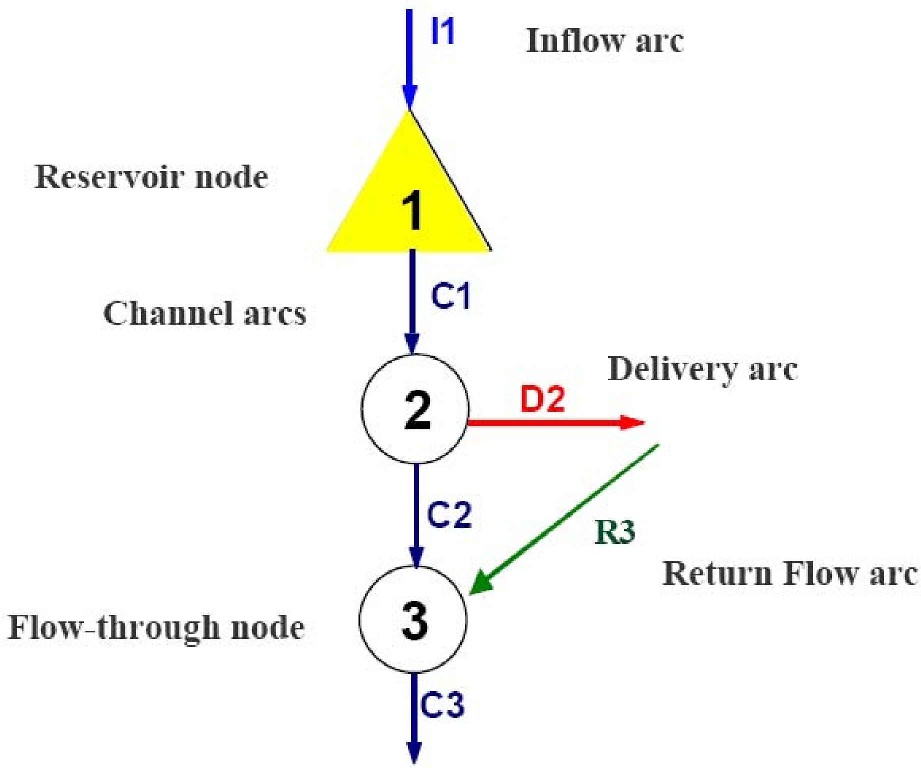


Figure 2. Example CALSIM network.