Description of IWFM

Name: Integrated Water Flow Model (IWFM)

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Availability of Technical Support: Information about IWFM, including source code and documentation downloads, training material and contact information can be obtained from http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/.

Main Features and Capabilities:

- The following hydrologic processes can be simulated by IWFM:
  - Groundwater elevations (piezometric) in a multi-layer aquifer system that may include a combination of confined and unconfined layers and the vertical flows between these layers;
  - Stream flows and stream-aquifer interactions;
  - Lake storages and lake-aquifer interactions;
  - Surface runoff due to infiltration excess of rainfall and agricultural return flow;
  - Soil moisture accounting in the root zone as affected by to rainfall, applied irrigation water, evapotranspiration, and deep percolation.
- In addition to the hydrologic processes listed above, the effect of tile drains, pumping/injection wells and subsidence on the groundwater storage as well as the effect of stream diversions and bypasses on the stream flows can be simulated.
- Hydrologic runoff processes are modeled at a regional scale.
- Simulation time step is specified by the user.
- The depth-integrated groundwater equation is solved using the Galerkin finite element method.
- The distribution of four land use types (agricultural with specified crops, urban, native and riparian vegetation) over the model domain dictate the evapotranspiration, surface runoff and infiltration characteristics as well as the demand for agricultural and urban water supply. The infiltrated water is routed vertically through root zone and vadose zone to compute the recharge to the groundwater.
- Stream diversions and groundwater pumping can be specified and distributed to meet agricultural and urban water requirements. They can also be adjusted dynamically to balance supply and demands.
- The entire model area can be divided into smaller sub-regions for the grouping and reporting of the simulation results.
- Groundwater, stream and tile drain hydrographs, and boundary node flows at locations specified by the user as well as vertical flows among aquifer layers can be printed out during the simulation.
- Detailed groundwater budget for zones specified by the user can be printed.
- IWFM is written in mixed Fortran 77 and FORTRAN 95 languages. Features of FORTRAN 95 such as dynamic array dimensioning and pointer arrays increase the

portability and applicability of IWFM. The full source code is available for download in case recoding is necessary.

Applications:

- The following known IWFM applications are either in the calibration phase:
  - C2VSIM (California Central Valley SIMulation Model; approximately 20,000 sq. miles in size; simulation period 1922 – 2003);
  - WESTSIM (Western San Joaquin Basin; 2400 sq. miles; simulation period 1970 – 2000);
  - Application to Milton-Freewater area in the Walla Walla Basin on the Oregon-Washington border (approximately 320 sq. kilometers in size; details can be found at http://web.engr.oregonstate.edu/~petridea/);
  - Application to California Solano County;
  - Application to Butte Basin.
- The following known IWFM applications are in initial phase of development (i.e. construction of conceptual model, data collection, input file generation, etc.):
  - Application to Merced River Basin;

Calibration / Validation / Sensitivity Analysis: As mentioned above, several projects are in calibration and validation phase. Among the applications listed above, C2VSIM is being calibrated using PEST (Parameter ESTimation program), an automated calibration software. Specific information as to the calibration and validation methods used in other projects listed above is not available since these projects are performed by other agencies/consulting companies. A formal sensitivity analysis of simulation results against input parameters of IWFM has not yet been performed.

Peer Review: Peer review of IWFM has not been performed yet. It is estimated that a peer review process may be started sometime in 2006. In the meantime, technical papers about specific methods used in IWFM are being written by staff and submitted to peer-reviewed journals.

Anatomy of IWFM:

- **Conceptual Model:**

The objective of IWFM is to model the hydrologic runoff processes, interactions between these processes, agricultural and urban water requirements, and the effect of natural runoff processes and agricultural/urban activities on each other. As a planning tool, it allows the user to adjust the water supply automatically to meet the computed agricultural and urban water demands. Conceptually, there are multiple levels of complexity in IWFM. These complexity levels, from the simplest to the more sophisticated, are as follows:

  - Simulation of groundwater system only where all sources/sinks are computed external to IWFM and entered as input data;
  - Simulation of stream flows, lake storages and their interaction with the aquifer system;
  - Simulation of surface runoff (direct runoff of rainfall infiltration excess and/or return flow of irrigation water), infiltration, evapotranspiration, soil moisture in

the root zone, and vertical movement of soil moisture through the root and vadose zones to become recharge to the saturated groundwater system;
  - Simulation of the effect of tile drainage, subsurface irrigation, and the usage of pumping and stream diversions as agricultural/urban water supply on the hydrologic runoff processes (groundwater elevations, stream flows, lake storages, soil moisture in the root and vadose zones);
  - Simulation of agricultural and urban water demands and the automated adjustment of water supply (stream diversions and groundwater pumping) to meet these demands.
- **Theoretical Model:**

IWFM is a water resources planning and management model that simulates groundwater, surface water, groundwater-surface water interaction, as well as other components of the hydrologic system (Figure 1). Preserving the non-linear aspects of the surface and subsurface flow processes and the interactions among them is an important aspect of IWFM.

In the core of IWFM lies the simulation of regional groundwater elevations. IWFM utilizes a quasi-three dimensional model to simulate the groundwater elevations. Depth-integrated, non-linear groundwater equation is used to model the horizontal flow in each aquifer layer. The vertical flows among aquifer layers are simulated by an approximate method.

In natural hydrological systems the regional groundwater interacts with other components of the hydrologic cycle. As precipitation falls on the ground surface, it infiltrates into the soil at a rate that is dictated by the soil type, ground cover and antecedent soil moisture conditions. The moisture in the top soil moves downward as well as it is taken out of the soil by vegetation through the process of evapotranspiration. The downward-moving soil moisture travels through the unsaturated zone of the soil before it replenishes the groundwater. IWFM uses the SCS method to simulate the infiltration and surface runoff. The evapotranspiration is simulated based on the methods described in the FAO Irrigation and Drainage Paper 56 (Allen et al., 1998). The vertical movement of the soil moisture through the root zone and vadose zones is modeled using a simplified conservation equation (Schroeder et al., 1994)

If the infiltration capacity of the soil is less than the precipitation rate, the portion of the precipitation that is in excess of infiltration becomes surface runoff and contributes to streams and large bodies of water such as lakes. In wet periods, streams act as water sources for the aquifer system whereas in dry periods they drain water away from the aquifer. Similarly, large bodies of water, such as lakes, affect the groundwater heads during wet and dry periods. IWFM models groundwater heads, stream flows and lake storage simultaneously as well as other components of the hydrological cycle discussed above in order to simulate the interactions between these hydrological components accurately. In IWFM, groundwater pumping and recharge can be specified in two ways: well pumping/recharge and element pumping/recharge. Ideally, the specific details (location, pumping rates, etc) of each well that is operated in the modeled area are specified and the effect of each well on the groundwater elevations is simulated. However, in areas where thousands of wells are operated (e.g. Central Valley of California) and the specific information for each well is not available, IWFM allows the

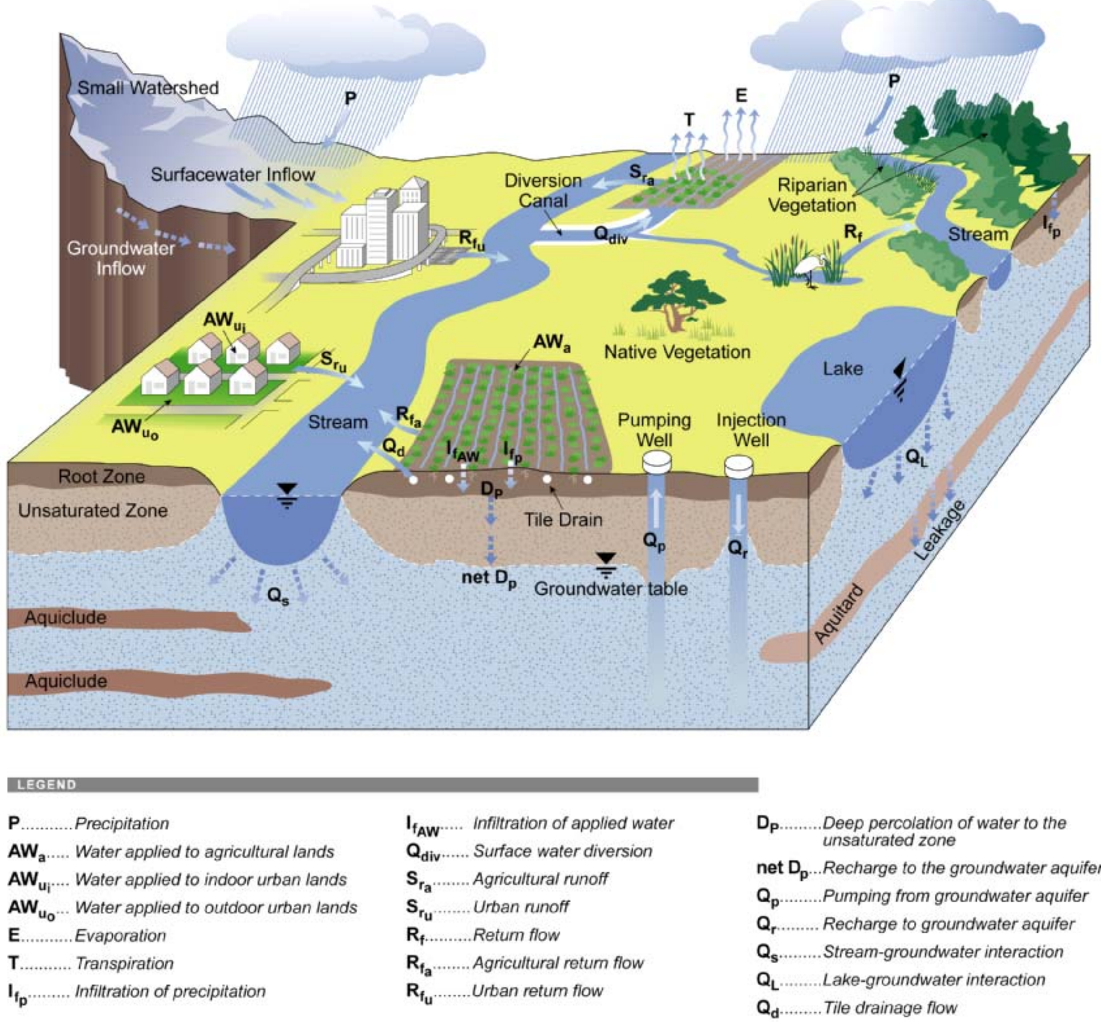

Figure 1 Hydrologic processes modeled in IWFM

option of element pumping where the user specifies a lumped amount of pumping for particular elements of the finite element mesh. The lumped amount of pumping can alternatively be distributed among several elements based on the relative agricultural and urban areas within each element.

The allocation of surface water diversions and pumping to agricultural and urban lands is determined by defining the fraction of the specified diversion and pumping that is intended for irrigation purposes, and designating the remaining portion for urban use. Once stream flows are simulated, actual surface water diversions are computed based on the available stream flows, and applied to agricultural and urban areas according to user specified fractions to meet the appropriate demands. Similar to surface water diversions, groundwater pumping can also be distributed among agricultural and urban lands with respect to predefined fractions.

An important task in water resources planning studies is to find answers to questions such as if there is enough water supply in the modeled area to meet the agricultural and urban water demand, and how to operate the pumping and diversion facilities in order to minimize the discrepancy between the supply and demand. In order to achieve this task, the functionality to adjust the surface water diversions and/or pumping automatically has been included in IWFM.

The user can choose some or all of the diversions, pumping or both to be adjusted by IWFM in order to meet the agricultural and urban water demand, or to minimize the surplus supply amounts. It should be noted at this point that IWFM does not incorporate optimization techniques in adjusting the water supply. Instead, it tries to distribute the discrepancy between the supply and demand among adjusted diversions or pumping as equally as possible without considering any operation rules. Thus, the resulting diversion and pumping amounts after the adjustment may not be the optimum management of the water resources in terms of financial, environmental and legal constraints. However, these results may help the user to identify hot spots of the modeled region such as streams and pumping locations that may be utilized when there is a shortage of supply, or diversion and pumping locations that constantly fail to produce required amounts of water supply.

A general flowchart of IWFM is given in Figure 2.

- **Numerical Model:**

IWFM uses several numerical methods to solve the conservation equations that govern different components of the hydrological system. The non-linear conservation equation that governs the groundwater flow at each aquifer layer is discretized spatially using Galerkin finite element method. Fully-implicit finite difference method is used to discretize the same equation in the time domain. The resulting set of non-linear algebraic equations is coupled with the stream flow conservation equation at each stream node and lake conservation equation at each lake node. The final set of non-linear equations is linearized using Newton-Raphson iterative method. This procedure results in a matrix equation with a non-symmetric coefficient matrix. IWFM offers several choices to solve the matrix equation iteratively. The two methods that are included so far in IWFM are the point successive over-relaxation method and the generalized pre-conditioned conjugate gradient method.discretize the same equation in the time domain. The resulting set of non-linear algebraic equations is coupled with the stream flow conservation equation at each stream node and lake conservation equation

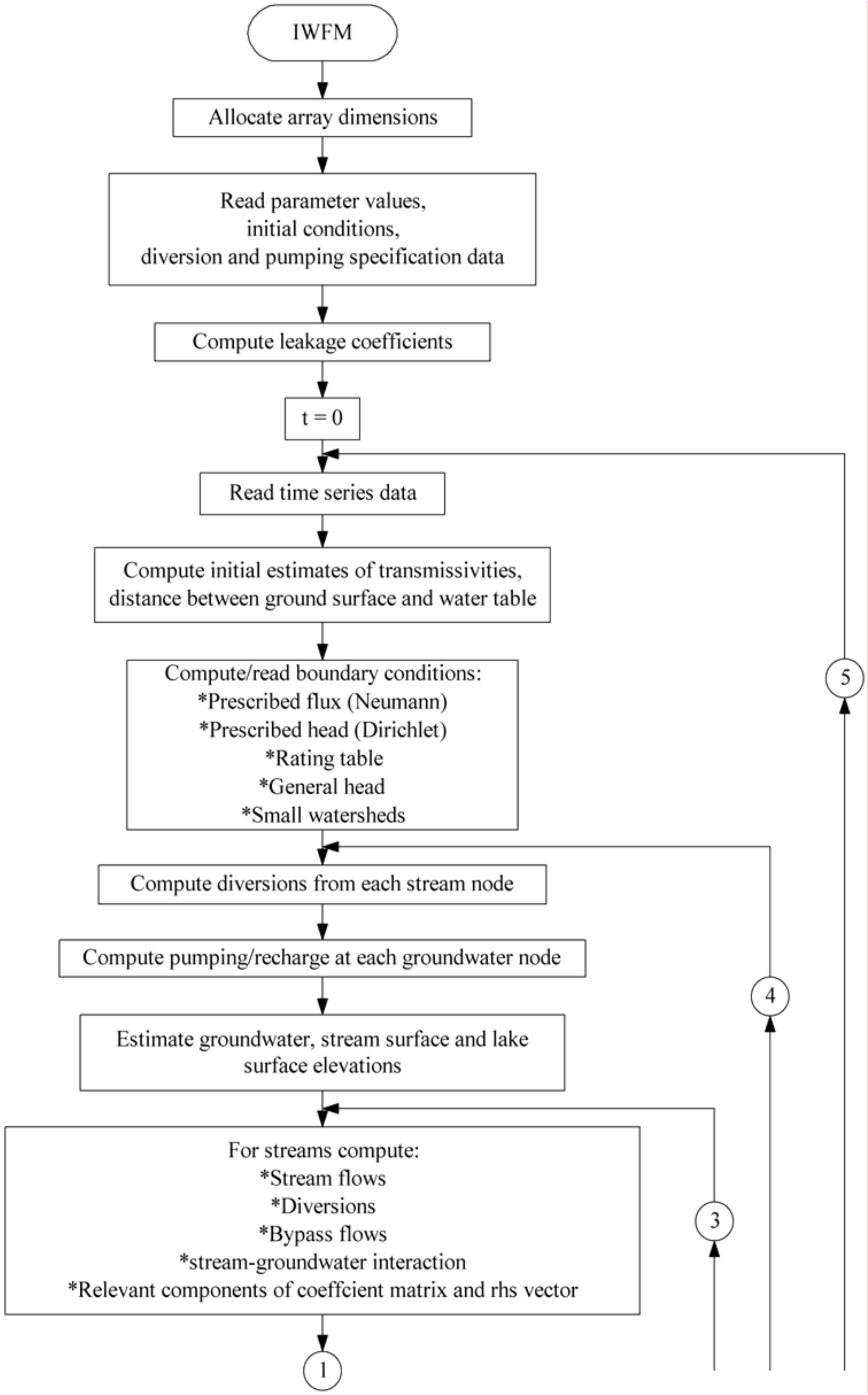

Figure 2 General flowchart of IWFM *(continued on next page)*

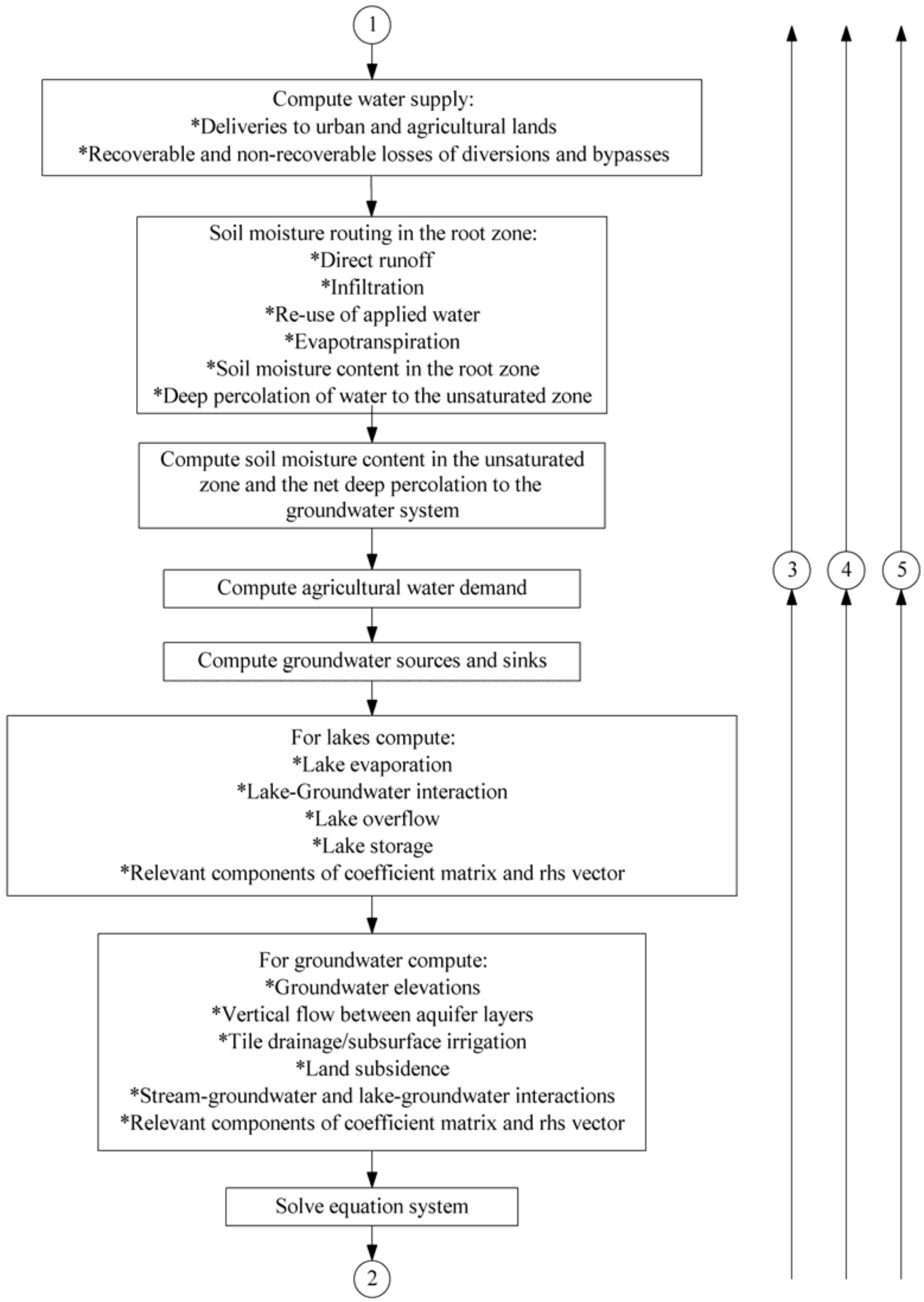

Figure 2 General flowchart of IWFM *(continued)*

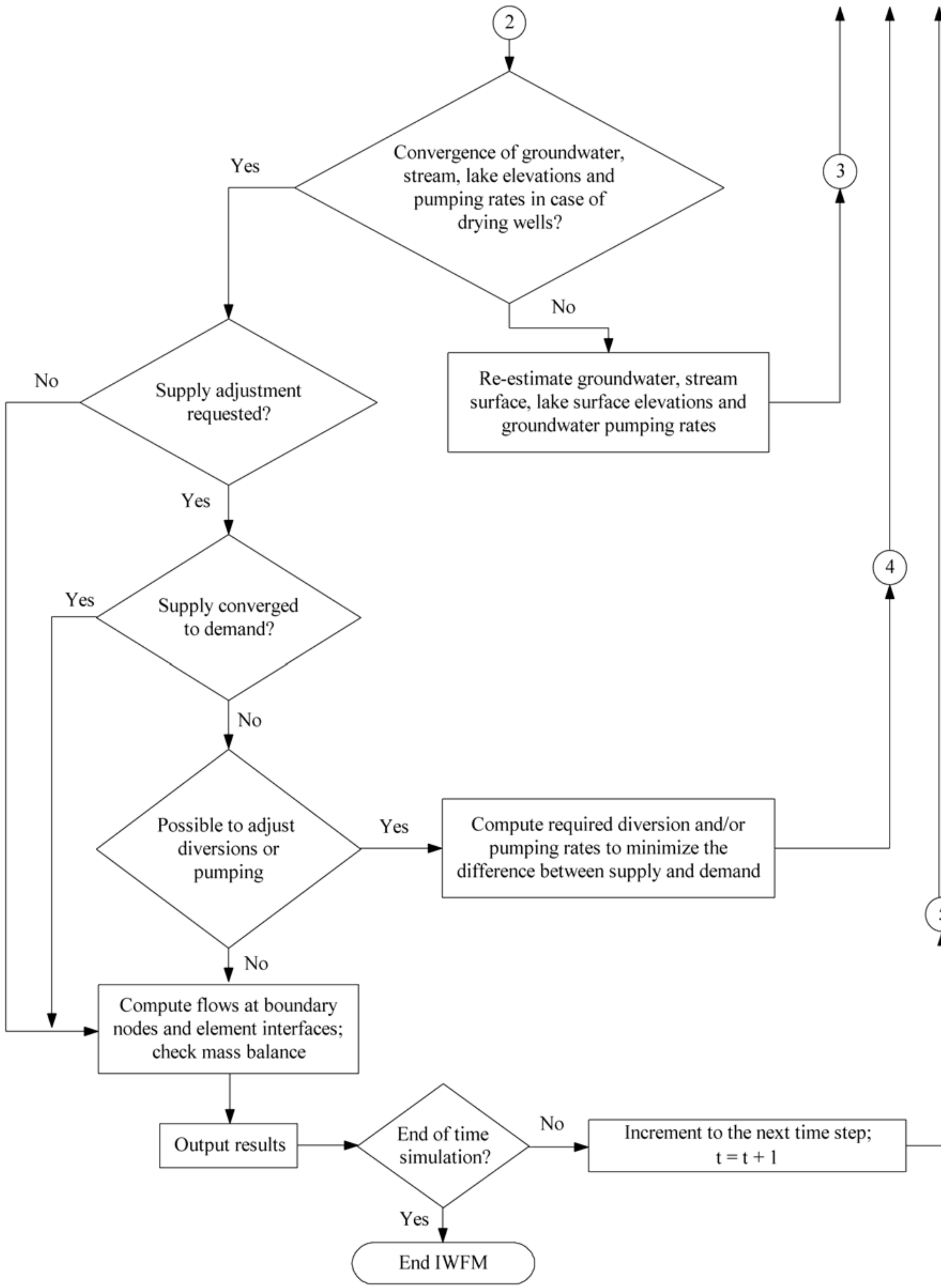

Figure 2 General flowchart of IWFM *(continued)*

at each lake node. The final set of non-linear equations is linearized using Newton-Raphson iterative method. This procedure results in a matrix equation with a non-symmetric coefficient matrix. IWFM offers several choices to solve the matrix equation iteratively. The two methods that are included so far in IWFM are the point successive over-relaxation method and the generalized pre-conditioned conjugate gradient method.

The non-linear conservation equation that governs the vertical movement of soil moisture in root and vadose zones is solved iteratively using Newton-Raphson method.

- **Input and Output Data:**

IWFM is comprised of four programs including the pre-processor, simulation model and two post-processor (Figure 3). These programs must be run sequentially and the binary output generated from one program must be transferred to the next before running the next program.

The Pre-processor program reads in the time-independent data and processes it to be used in the Simulation. The element configuration data, spatial location of all nodes, stratigraphic information on the aquifer layers and soil characteristics at each element

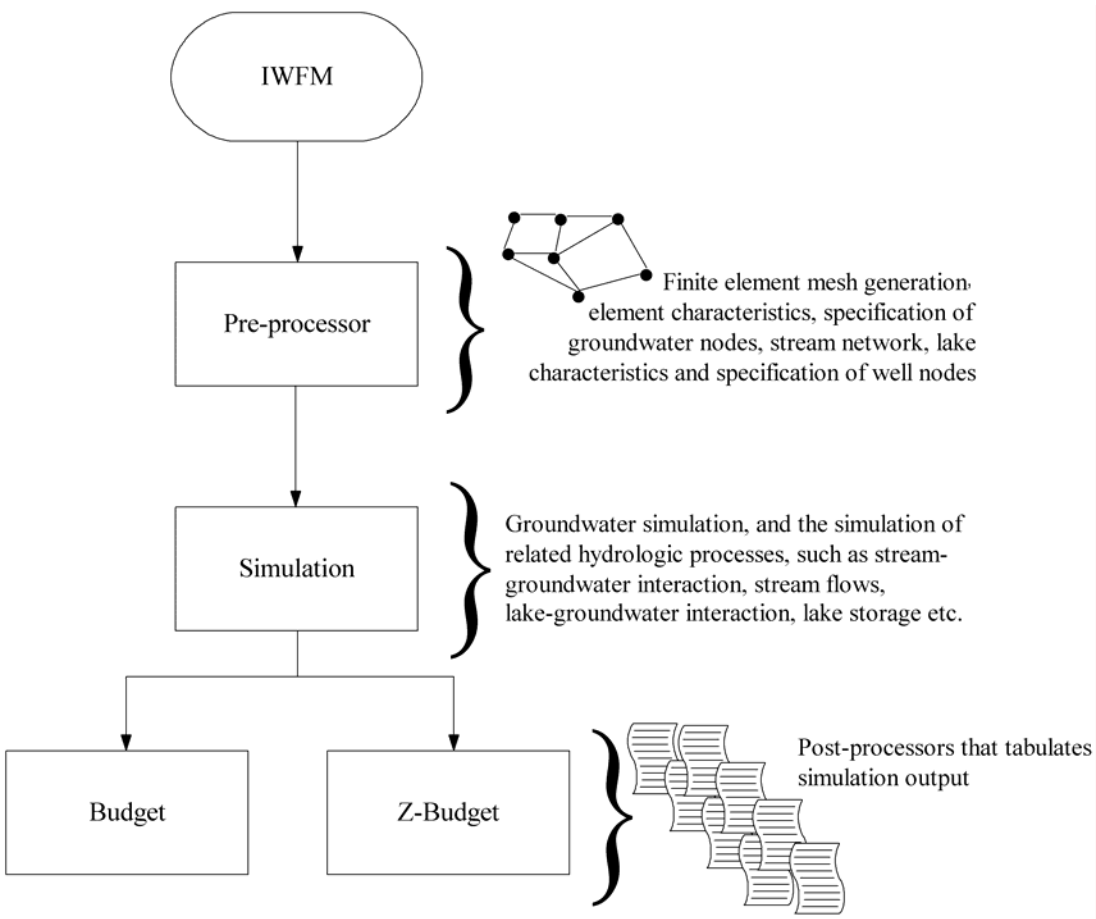

Figure 3 IWFM program structure

are the data that are required for all applications. If included in the simulation, stream and lake configuration information, and well location and characteristics are also required. Pre-processor processes these input data and generates a binary file that will be used in the Simulation.

The required input data for the Simulation part also depends on the processes included in the model. The hydraulic properties of the aquifer layers, and the boundary and initial conditions for the groundwater system are required input data for all applications. Depending on the components to be modeled, the following is a list of the required input data:

- Hydraulic properties of root and vadose zones;
- Stream bed hydraulic properties;
- Stream inflows at upstream nodes;
- Lake bed hydraulic properties;
- Time series data for the distribution of four land use types (agricultural, urban, native vegetation and riparian vegetation) over the model domain;
- Time series data for the acreages for individual agricultural crops;
- Time series precipitation data;
- Evapotranspiration data for each crop type;
- Location and elevation of tile drains, hydraulic properties of the interface material between tile drains and the aquifer;
- Specifications for urban water use (indoors vs. outdoors usage);
- Urban water demand;
- Data for the computation of agricultural demand (rooting depths, minimum soil moisture requirements and irrigation efficiencies);
- Pumping data and specifications (distribution of pumping vertically among aquifer layers and horizontally among elements);
- Stream diversions and specifications (diversion and delivery locations, recoverable and non-recoverable losses, etc);
- Irrigation fractions for pumping and stream diversions.

The following is a list of optional output data for Simulation:

- Binary output data (groundwater budget, stream budget, lake budget, land and water use budget, root zone moisture budget, stream diversion and delivery details) to be used by the Budget and Z-Budget programs, post-processors to IWFM;
- Specific hydrographs (boundary flux, tile drain, groundwater elevations and stream flow) at user-specified locations;
- Groundwater elevations at all finite element nodes.

One of the post-processors, Budget, uses the binary files generated by the Simulation and prints out the water budget for specific components of model at user-defined intervals for all model regions that were identified in Pre-processor. Z-Budget is another post-processor that prints out detailed water budget for the aquifer system for a group of finite elements (different from the model regions that the Budget program uses) specified by the user.

- **Data Management:**
  IWFM uses flat files for the input and output of the data. Other than internal processing of input data for use during the simulation, it does not offer any specialized data management tools. A GIS (Geographical Information System) based graphical user-interface is being developed. This user-interface will offer tools to generate, manipulate and visualize the input and output data.
- **Software:**
  IWFM is written in mixed Fortran 77 / FORTRAN 95 language. The source code has been compiled using Compaq Visual Fortran® v6.6c. A few extensions to the standard FORTRAN language that is specific to the Compaq® compiler have been implemented.

Availability of source code:

The source code is developed to cover many possibilities that may arise in different applications so that users should not need to modify and re-compile the source code. However, the interested users can download the source code at http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/. IWFM is licensed under the terms of the GNU General Public License as published by the Free Software Foundation.

References:

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. 1998. *Crop evapotranspiration: guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56, Rome.

Schroeder, P. R., Dozier, T. S., Zappi, P. A., McEnroe, B. M., Sjostrom, J. W., and Peton, R. L. 1994*. The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3, EPA/600/R-94/168b*, U.S. Environmental Protection Agency Office of Research and Development, Washington, DC.