STATUS OF COMPUTER PROGRAMS FOR SIMULATING LAND SUBSIDENCE WITH THE MODULAR FINITE-DIFFERENCE GROUND-WATER FLOW MODEL

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The Regional Aquifer-Systems Analysis (RASA) Program of the U.S. Geological Survey included studies of the Southwest Alluvial Basins in Arizona and New Mexico. Although land subsidence caused by ground-water pumpage occurs in this area, detailed analysis of land subsidence was beyond the scope of the Southwest Alluvial Basins RASA studies. Therefore, a follow-up RASA Subsidence-Modeling Study was initiated to develop improved methods of simulating aquifer-system compaction and land subsidence in models of ground-water flow. The purpose of this paper is to summarize the methods of simulating aquifer-system compaction that were developed by the Subsidence-Modeling Study.

The modular finite-difference ground-water flow model (MODFLOW) by McDonald and Harbaugh (1988) is widely used to simulate ground-water flow. MODFLOW was used for the Subsidence-Modeling Study because the modular structure of the computer program allows addition of new simulation capabilities in an organized way. In MODFLOW, simulation options are referred to as “packages.” The Subsidence-Modeling Study developed three packages for simulating aquifer-system compaction and land subsidence in MODFLOW. The first package is the Interbed-Storage Package, version 1, commonly referred to as IBS1. Similarly, the other two packages are referred to as IBS2 and IBS3. The name “Interbed Storage” refers to the ability of the packages to simulate storage changes and compaction in fine-grained interbeds within an aquifer; however, these packages also can be used to simulate compaction in extensive confining beds (for example, see Pool #1 abstract). All three packages are based on the theory of one-dimensional (vertical) consolidation developed by Terzaghi (1925). Each of the packages, however, uses a different set of simplifying assumptions and requires a different set of input arrays.

In the IBS1 package (Leake and Prudic, 1991), elastic and inelastic storage properties of compressible sediments are constant and head change is the stress that causes compaction. Delay in release of water from compressible interbeds is ignored. In the IBS2 package (Leake, 1990), storage properties also are constant and head change is the stress that causes compaction; however, IBS2 simulates the delay in release of water from compressible interbeds. For each model cell, IBS2 solves a one-dimensional equation to compute flow and compaction in an interbed of a representative or average thickness. Those results are extrapolated to compute compaction for the total thickness of interbeds in each cell. In the IBS3 package (Leake, 1991), compaction is computed as a function of effective stress, and elastic and inelastic specific storage can vary with changes in effective stress. The thickness of compressible sediments in an aquifer also can vary with changes in saturated thickness. The major assumptions for all three packages are outlined in table 1.

For confined aquifer systems in which geostatic load is constant and change in effective stress is small in relation to starting effective stress, use of the IBS1 package is appropriate. In some instances, the IBS1 package can be used in water-table aquifers by adjusting the elastic and inelastic storage coefficients to compensate for differences between magnitudes in change in head and change in effective stress. If an aquifer system includes thick interbeds for which delay in release of water cannot be ignored, the IBS2 package is the only package that can account for the delay. For unconfined aquifers or confined aquifers with varying geostatic load, the IBS3 package probably is the most appropriate. For comparison purposes, all three methods were applied to a model of ground-water flow in an alluvial basin in Arizona (Leake, 1992).

The amount of information needed to implement each package is related to the simplifying assumptions used for the package. The major arrays for all three packages are given in table 2. In addition to the arrays listed, all three packages read in a starting compaction array that allows continuation of a previous model run. Most of the information is read in as two-dimensional arrays for each model layer that includes compressible interbeds or a confining bed. The IBS1 package uses all four of the simplifying assumptions in table 1 but requires relatively few input arrays (table 2). Conversely, the IBS3 package uses only one of the assumptions in table 1 but requires many input arrays. In addition to the input arrays, IBS3 requires two additional arrays to store geostatic load and effective stress for which starting values are computed from input arrays.

Table 2. Assumptions for Interbed-Storage Packages IBS1, IBS2, and IBS3

	Assumption	IBS1	IBS2	IBS3
1.	A unit decrease in water level results in a unit increase in effective stress	✔	✔	
2.	A head change in coarse-grained aquifer materials in a model time step results in an equal head change in compressible interbeds	✔		✔
3.	Elastic and inelastic skeletal specific storages of compressible interbeds are constants	✔	✔	
4.	Total thickness of compressible interbeds is not a function of saturated thickness of the aquifer	✔	✔	

Table 3. Input arrays required for Interbed-Storage Packages IBS1, IBS2, and IBS3

Property or condition	Interbed-Storage Package		
	IBS1	IBS2	IBS3
Storage	1. Elastic storage coefficient 2. Inelastic storage coefficient	1. Elastic specific storage 2. Inelastic specific storage	1. Starting elastic specific storage 2. Starting inelastic specific storage
Hydraulic		3. Vertical hydraulic conductivity of interbeds	
Other	3. Starting preconsolidation head	4. Starting preconsolidation head 5. Starting head 6. Average interbed thickness 7. Number of interbeds	3. Starting preconsolidation stress 4. Elevation of land surface 5. Specific gravity of moist sediments 6. Specific gravity of saturated sediments 7. Void ratio 8. Starting total thickness of interbeds

The IBS1 package is formally documented for use inside and outside the U.S. Geological Survey (Leake and Prudic, 1991). The IBS2 and IBS3 packages were developed to study alternative methods of simulating land subsidence in ground-water flow models. The theoretical basis and mathematical development for these two packages are documented in Leake (1990) and Leake (1991); however, the computer programs are not formally documented. If either of these packages are needed for future land-subsidence studies, additional effort will be required to document the package prior to publication of the study results.