SCWA Exh. 104
P. 1 7 3

APPLIED GROUNDWATER MODELING

Simulation of Flow and Advective Transport

Second Edition

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SCWA Exh. 104 ; p 2 of 3

and management problems potentially will be questioned in the legal arena where using an industry standard code is expected.

Regardless of the code selected, the following questions should be asked: (1) Has the accuracy of the code been checked (verified) against analytical solutions and/or a verified numerical solution? (2) Does the code include a water budget computation? (3) Has the code been used in field studies and does it have a proven track record? (4) Does the code have a graphical user interface (GUI)? Each of these questions is discussed below.

3.6.1 Code Verification

Codes for groundwater flow are *verified* by comparing the numerical results with analytical solutions and sometimes with other numerical solutions. The purpose of code verification is to test that the numerical solution has been properly programmed (ASTM, 2008). The level of agreement of numerical results with an analytical solution depends on the choice of closure criteria, grid spacing, and time step. Example problems used in code verification are typically included in the user's manual.

3.6.2 Water Budget

Water budget calculations are standard features of most codes; the computed water budget helps the modeler assess the accuracy of the numerical solution and allows comparison with the field-based water budget, which is normally calculated as part of the conceptual model. The water budget computed by the code itemizes flows across boundaries, including the water table; to and from sources and sinks, including surface water bodies; and in transient simulations to and from storage (Fig. 3.12). Release of water from storage is counted as inflow and uptake is counted as outflow. Typically, cells or elements associated with specified head boundary nodes are not considered part of the problem domain for purposes of the water balance computation. For example, recharge applied to specified head nodes is considered captured by the specified head and is not included in the water balance computation. Likewise, flow between specified head nodes is not normally computed although flow between specified boundary heads and the active problem domain is included in the water budget (Fig. 3.12).

The governing equation for groundwater flow is derived using conservation of mass (i.e., water balance) and Darcy's law (Section 3.2). Hence, the numerical solution of the governing equation should conserve mass. Failure to conserve mass locally has been a criticism of the FE method (e.g., see Berger and Howington, 2002) but is unwarranted as is demonstrated by water budget calculations in modern FE codes. Water balance errors reported in early FE solutions arose from flawed methodology and are not inherent to the FE method; modern FE codes include procedures that compute a numerically accurate water budget. For example, the consistent boundary flux method is used in FEFLOW (Diersch, 2014, pp. 391–393).

The water budget should show that total inflow equals total outflow. Typically, the code computes the water budget error as the difference between inflow and outflow

SCWA Exh. 104
p. 3 of 3


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             VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    5 IN STRESS PERIOD   12
        --------------------------------------------------------------------------------------
    CUMULATIVE VOLUMES      L**3                          RATES FOR THIS TIME STEP      L**3/T
    ------------------                                    ------------------------

          IN:                                                   IN:
          ---                                                   ---
              STORAGE =   0.11099E+08                              STORAGE =    23927.
        CONSTANT HEAD =    330.70                            CONSTANT HEAD =    24.778
                WELLS =    0.0000                                    WELLS =    0.0000
             RECHARGE =   0.17021E+08                             RECHARGE =    21375.
             TOTAL IN =   0.28120E+08                             TOTAL IN =    45327.
         OUT:                                                  OUT:
         ----                                                  ----
              STORAGE =   0.68859E+07                              STORAGE =    0.0000
        CONSTANT HEAD =   0.13935E+08                        CONSTANT HEAD =    25326.
                WELLS =   0.73000E+07                                WELLS =    20000.
             RECHARGE =    0.0000                                 RECHARGE =    0.0000
            TOTAL OUT =   0.28121E+08                            TOTAL OUT =    45326.
             IN - OUT =   -250.00                                 IN - OUT =   0.81250
 PERCENT DISCREPANCY =            0.00             PERCENT DISCREPANCY =             0.00
```

Figure 3.12 Water budget for a transient problem calculated by MODFLOW showing the cumulative water budget in volumes of water (left-hand side of figure) and the water budget in volumetric rates (right-hand side of figure) for time step 5 in stress period 12. (See Section 7.6 for an explanation of stress periods.) The problem has two specified head boundaries (itemized as "constant head" in the budget) that represent surface water bodies; areal recharge from precipitation (itemized as "recharge"); and a pumping well (itemized as "wells"). Note that water is both entering and leaving the system through the specified head boundaries. Water enters the system as recharge and is removed through the pumping well. There is a change in storage listed under inflow, which means that there is a net removal of water from storage (i.e., water leaves storage and enters the system). The error in the cumulative water budget for this time step is 250 ft^3, which is less than 0.01% of the total inflow or outflow and thus the error (percent discrepancy) is listed as zero.

(Fig. 3.12). The water budget should be less than around 0.5% (ideally less than 0.1%; Konikow, 1978), but an error as high as 1% may be acceptable. A higher percent water budget error might mean that the solution has not converged because the closure criteria are set too high or the solution may not have converged within the maximum number of iterations allowed (Section 3.7). A large water budget error may reflect errors in input and/or model design or conceptualization, or may be an artifact of how the code simulates a head-dependent boundary (Box 4.5). The global water balance is typically itemized in model output; some solvers check the water balance locally during solution to meet a water balance closure criterion (Section 3.5). ZONEBUDGET (Harbaugh, 1990) for MODFLOW calculates the local water budget for user-specified zones in the problem domain, which can be helpful in analyzing local flows in the model.

3.6.3 Track Record

Ideally, a code applied to engineering or management problems should have a history of use and testing. For illustrative purposes in our text, we use MODFLOW and FEFLOW. The MODFLOW suite of codes is the most widely used set of groundwater codes in the world and the standard for litigation purposes in the United States. MODFLOW has been applied to numerous and diverse field problems and is the focus of a series of