GeoStudio Example File

Understanding the Surface Water Balance

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Introduction

Land-climate interaction (LCI) analysis is a critical part of soil cover design and mine closure planning. The global objective of the analysis is to understand the moisture dynamics within the cover system and to 'close the water balance'. Closing the water balance implies that the various fluxes incident on the ground surface can be resolved; that is, mass balance can be verified by ensuring that the 'ins' equal the 'outs'. In the case of the SEEP/W LCI boundary condition, the components of a surface water balance include rainfall, snowmelt, actual evaporation, and runoff. This example demonstrates how to interpret the surface water balance for a simple hillslope problem.

Background

The water flux boundary condition required to solve the water transfer equation can be calculated from a mass balance equation at the ground surface, which is given by:

$$(q_P + q_M)cos\alpha + q_E + q_R = q_I \qquad \text{Equation 1}$$

where subscripts on the water fluxes (q) indicate rainfall (P), snowmelt (M), infiltration (I), evaporation (E) and runoff (R), and α is the slope angle. The evaporation and runoff fluxes are negative; that is, out of the domain. The total precipitation is the sum of the rainfall and snowmelt (P + M). The slope angle is included because precipitation is measured for a horizontal plane. The infiltration is deemed the residual of the surface mass balance equation and therefore forms the boundary condition of the water transfer equation. Transpiration does not appear in Equation 1 if root water uptake occurs entirely below the ground surface.

It is important to consider the following aspects of the land-climate-interaction boundary condition when verifying the surface mass balance:

1. Evaporative flux is set to zero during rainfall or snowmelt events, or if the ground temperature is below 0°C. During a rainfall event, the relative humidity at the ground approaches the relative humidity in the air, effectively shutting down evaporation. Evaporation does not occur when the ground is frozen or when snow is present.
2. Precipitation data in the input function is not tracked as rainfall unless the snow depth is zero and the air temperature is above 0°C. The snow depth function should reflect the precipitation which occurred on these days. As such, the input precipitation function need not contain the precipitation that was recorded as snow water equivalent.
3. Snowmelt, which is controlled by the snow depth function (i.e. not the precipitation function), only occurs if the air temperature is above 0°C and the snow depth is decreasing.

Numerical Experiment

The model domain comprises a small-scale hillslope with an angle of 14°. The domain is intentionally small to simplify verification of the surface water balance. The initial pore-water pressure condition is defined using a water table located just below ground near the toe of slope. The upper boundary is modeled using the land-climate interaction (LCI) boundary condition. All of the analyses include liquid water transfer, which is the default physics for SEEP/W, and isothermal vapor flow.

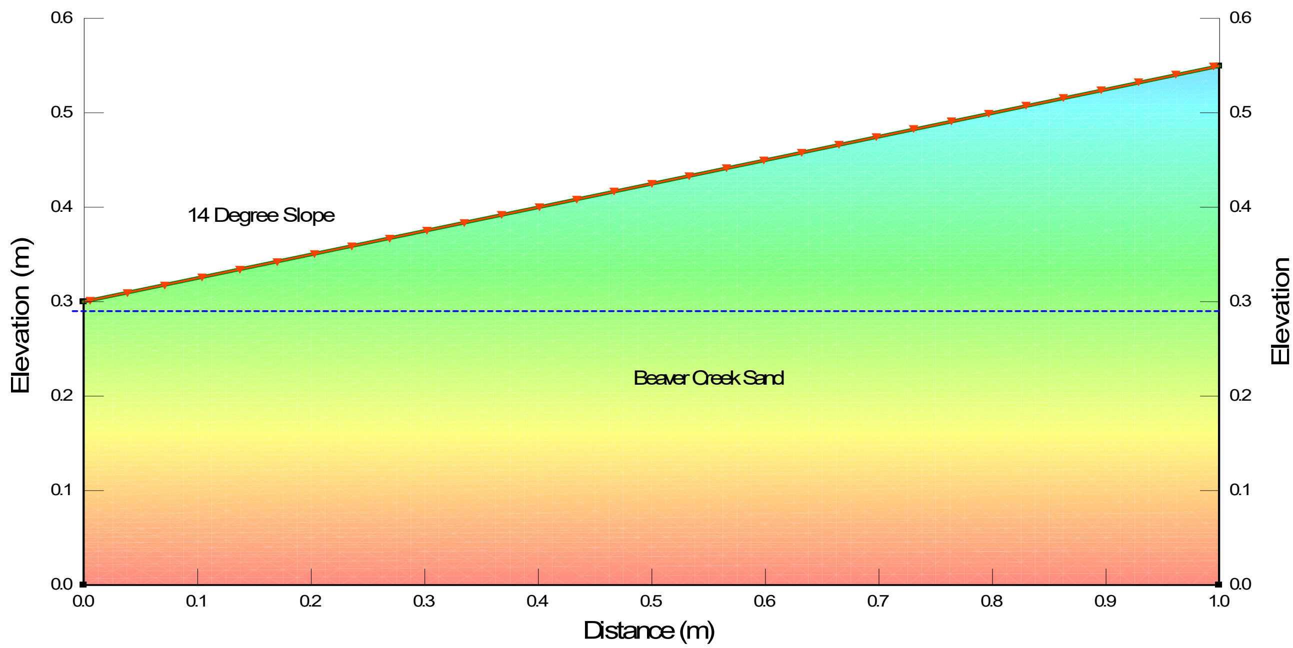

Figure 1. Model geometry and initial conditions.

Figure 2 presents the analysis tree for the GeoStudio project. There are seven analyses in the file, with the first five forming a Parent-Child relationship. The first sequence of analyses (1) includes the following climate conditions:

a. Day 0 to 1: 7 mm/day of evaporative flux;
b. Day 1 to 2: 5 mm/day of rainfall flux;
c. Day 2 to 3: 7 mm/day of evaporative flux;
d. Day 3 to 4: 5 mm/day rainfall with 1 mm/day snowmelt and 7 mm/day evaporation; and,

e. Day 4 to 5: 20 mm/day rainfall with 7 mm/day evaporation.

The LCI boundary condition for each Case can be examined in the associated reader project file. The LCI boundary condition for Analyses 1d and 1e is configured to demonstrate the conditions mentioned above; namely that (1) snowmelt is considered if the air temperature is above freezing and the snow depth is decreasing (1d); and, evaporation is zeroed during a rainfall event (1e).

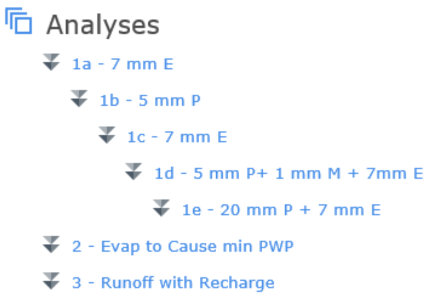

Figure 2. Analysis Tree for the GeoStudio Project.

The evaporative flux for Case 2 is set to 20 mm/day such that the minimum pore-water pressure is reached over the time step. The minimum pore-water pressure is a boundary condition option for the LCI (Figure 3) that can either be calculated automatically or user-defined. In this case, the minimum pore-water pressure has been set to -300,000 kPa. If the evaporative flux over a time step causes the pore-water pressure to drop below the minimum, the step is resolved with the minimum pore-water pressure applied as the boundary condition.

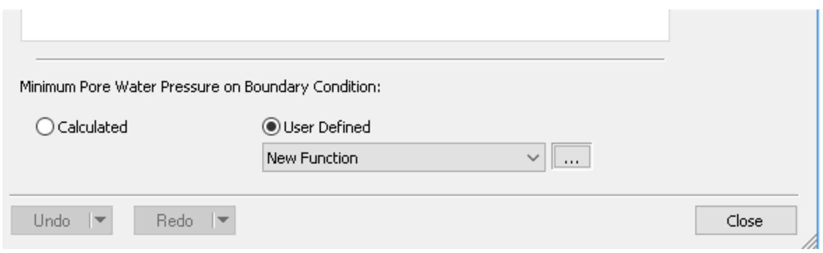

Figure 3. Minimum pore-water pressure option for the LCI boundary.

Case 3 is a 1D analysis conducted on the right vertical edge of the 2D domain. The rainfall flux is set to 500 mm/day. This value was selected to cause the water table to rise to the ground surface and runoff to therefore be calculated.

Results and Discussion

Case 1: Climate Sequence

Figure 4 presents the surface water balance components for Case 1. The evaporative flux from Day 0 to 1 is 7 mm/day (- 0.007 $m^3/day/m^2$). Evaporation flux is normal to the ground surface, so the cumulative volume is calculated by multiplying the flux by the surface area of the ground surface and the duration:

$$-\ 0.007\frac{m^3/d}{m^2}\left(\frac{1\ m^2}{cos\alpha}\right)1d = -\ 0.00721\ m^3$$

Rainfall occurs from Day 1 to 2 at a rate of 0.005 $m^3/day/m^2$. Rainfall and snowmelt, as defined by the precipitation and snow depth functions, are incident on a horizontal plane. The rainfall flux that is applied to the domain is calculated from Equation 1. The cumulative volume of rainfall over the sloping ground surface is:

$$0.005\frac{m^3/d}{m^2}cos\alpha\left(\frac{1\ m^2}{cos\alpha}\right)1d = \ 0.005\ m^3$$

Evaporation then occurs from Day 2 to 3.

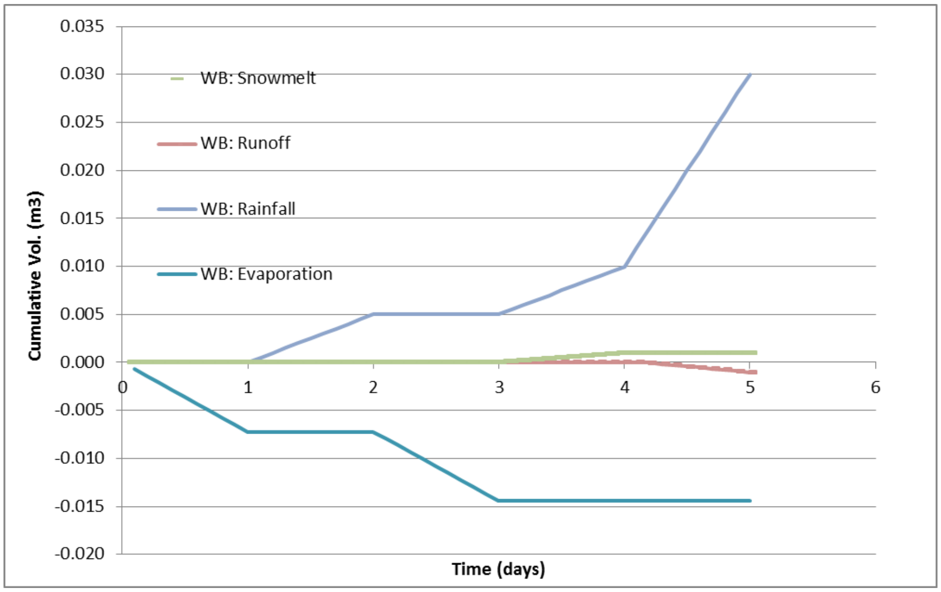

Figure 4. Surface water balance components for Case 1.

A total of 0.001 m^3 of snowmelt is recorded from Day 3 to 4. Rainfall also accumulates between Day 3 and 4.0, despite the presence of snowpack, because the air temperature is above zero. This represents a rain-on-snow event. The anticipated rainfall volume is therefore calculated as:

$$0.005\frac{m^3/d}{m^2}cos\alpha\left(\frac{1\ m^2}{cos\alpha}\right)1.0d = \ 0.005\ m^3$$

From Day 4 to Day 5, the rainfall accumulates at 0.02 m^3/day/m^2; that is, 20 mm/day. The lowest and next lowest nodes form part of the seepage face at the end of Day 4.2 and 4.3, respectively. Rainfall is recorded as runoff if it occurs on the seepage face. Calculation of runoff requires consideration of contributing area associated with each node. The horizontal distance between the nodes of an element is 0.025 m. The contributing area apportioned to a node from a single element is calculated as:

$$\frac{0.025}{2.0\ (cos\alpha)}m^2 = \frac{0.0125}{cos\alpha}m^2$$

The second highest node is associated with 2 elements. Runoff from the time of initiation – that is, Day 4.1 and 4.2 and the lowest and next lowest nodes, respectively – to the end of the analysis is calculated as:

$$-\ 0.02\frac{m^3/d}{m^2}cos\alpha\left(\frac{0.0125}{cos\alpha}\ m^2\right)(5-4.1)d + \ -\ 0.02\frac{m^3/d}{m^2}cos\alpha\left(\frac{0.025}{cos\alpha}\ m^2\right)(5-4.2)d = \ -\ 0.000625\ m^3$$

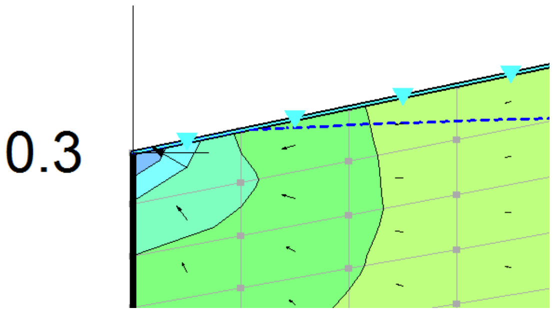

Figure 5. Location of seepage face.

Figure 6 presents the net infiltration and the 'calculated surface water balance' obtained by moving all terms in Equation 1 to the same side. The net infiltration decreases due to evaporation from Day 0 to 1, increases from Day 1 to Day 2 as a result of rainfall, decreases due to evaporation from Day 2 to 3, and increases from Day 3 to 4 as a result of snowmelt and rain-on-snow. The net infiltration increases starting at Day 4 but then flattens out at Day 4.2 despite the continued rainfall.

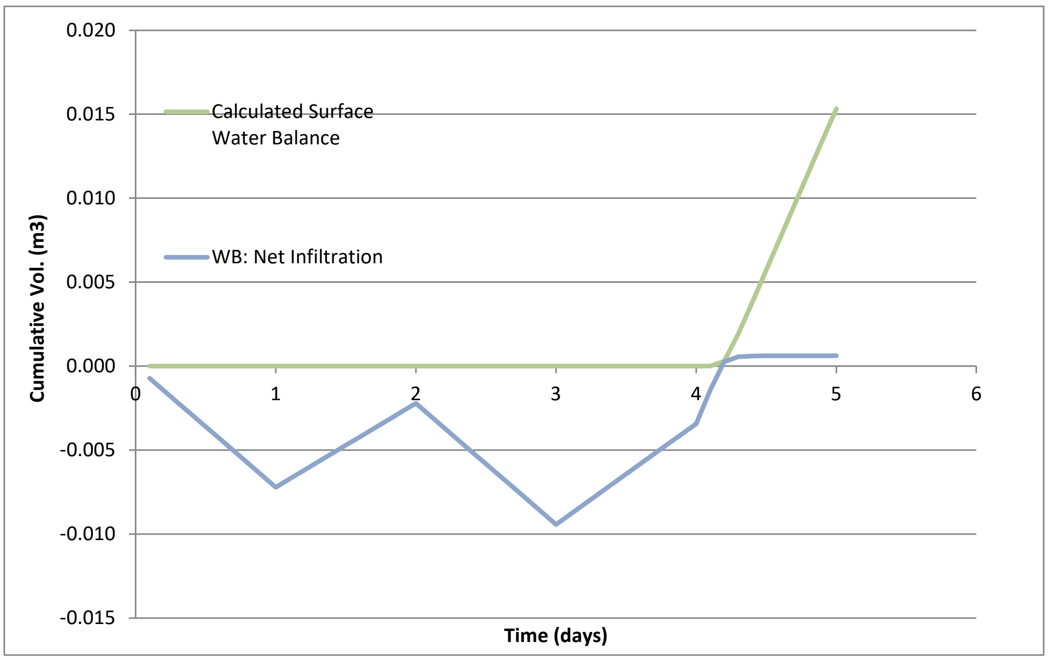

Figure 6. Net infiltration and calculated water balance for the analysis.

The calculated water balance (from Equation 1) is zero until Day 4.2. At this point, a groundwater discharge zone develops, which is not accounted for in Equation 1. In contrast, the net infiltration considers the cumulative water volumes into and out of the domain at all nodes along the ground surface. At Day 4.2, the water recharging at nodes above the potential seepage face nearly equals the water discharging at nodes within the seepage face, causing the cumulative net infiltration plot to flat line. Zeroing the water balance from Day 4.2 to 5 would require an additional term in Equation 1: the discharge flux from the seepage face. Alternatively, the net infiltration graph could be generated using only nodes in the upslope recharge zone while the rainfall and runoff graphs would be generated using all nodes on the ground surface. The water balance will zero for most cases with a deep vadose zone, but this case was chosen specifically to demonstrate the effect of the phreatic surface rising to meet the ground surface.

Case 2: Minimum Pore-Water Pressure

Figure 7 presents the surface water balance components for Case 2, while Figure 8 presents the pore-water pressure at three locations along the ground surface. The application of the actual evaporation flux on each time step caused the pore-water pressure to drop below the user-input minimum. This triggers a boundary review and the time step is re-solved with the minimum pore-water pressure applied as the boundary condition. The final solution is then used to update the actual evaporation and net infiltration water balance components.

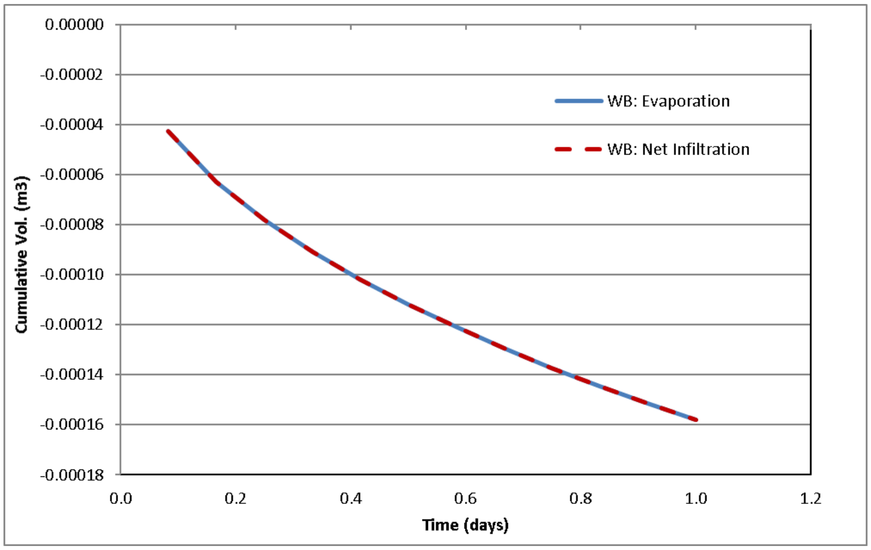

Figure 7. Surface water balance components for Case 2.

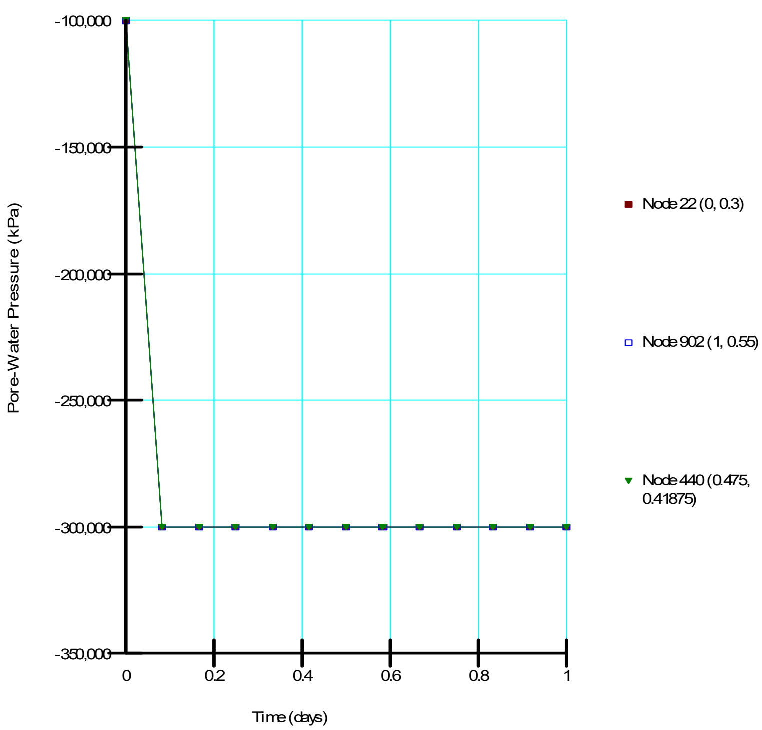

Figure 8. Pore-water pressure at three nodes along the ground surface.

Case 3: Run-off with Recharge

Figure 9 presents the water balance data for Case 3. The rainfall flux is 0.5 $m^3/day/m^2$, giving a cumulative rainfall of 0.5 m^3 over the elapsed time of 1 day. The application of such a large flux value caused the potential seepage face to trigger and re-set the pore-water pressure to zero. The resulting net infiltration was only 0.0329 m^3 and the runoff was - 0.469 m^3. The water balance for this analysis is zero: the net infiltration is apportioned between precipitation and runoff.

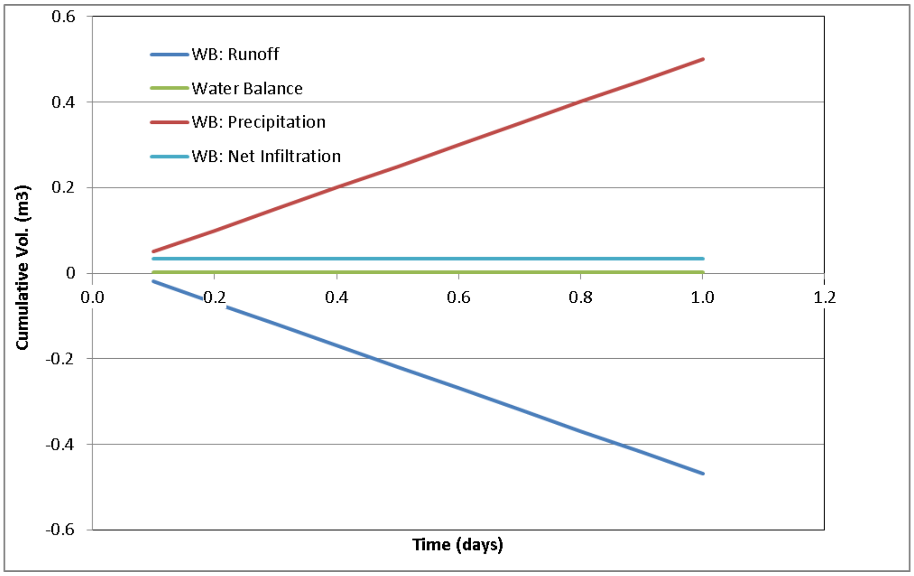

Figure 9. Surface water balance components for Case 3.

Summary and Conclusions

This example demonstrates how to interpret the water balance data for a land-climate interaction (LCI) analysis in SEEP/W. In order to understand the moisture dynamics in the near-surface, it is important to close the water balance. For most cases, this type of 'accounting' is fairly straightforward. The net infiltration at the ground surface is balanced by rainfall, evaporation, snowmelt and run-off. In a numerical analysis, however, there are a number of nuances that must be understood. First, the evaporation is set zero during a rainfall or snowmelt event or if the ground is frozen. Second, rainfall is not considered if the snow depth is non-zero unless the air temperature is above freezing.

The water balance equation does not account for interaction between the saturated groundwater flow system and the ground surface. Cases in which a groundwater discharge develops can render the water balance data meaningless because the net infiltration will include a portion of the ground surface that is not obeying the water balance equation. The cumulative rainfall and run-off data will be correct, but the water balance will not zero.

SEEP/W implements a minimum pore-water pressure limit on the LCI boundary condition to prevent over-drying during evaporation. Unfortunately, solving a time step using the minimum pore-water pressure, instead of the calculated actual evaporation, can cause some noise in the water balance calculations. This occurs because the evaporation component must be back-calculated using the liquid water flux normal to the surface. In contrast, the net infiltration is computed from the water rates at the nodes and is therefore an accurate value. These two values are not perfectly equal when the minimum pore-water pressure is applied.