A Spreadsheet Approach to the Hydrological Cycle

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ABSTRACT
I have devised a spreadsheet approach that is designed to help students better understand the terrestrial or “basin” hydrological cycle. Students are assigned problems to create spreadsheets accounting for the flux in and out of the major surface and subsurface “reservoirs.” The effects of hydroclimatic variation upon runoff are tested in the spreadsheet model. The assignment is given to upper-level undergraduates and graduate students in order to promote proficiency in the use of the spreadsheet, a potentially important tool in the geoscience curriculum.

Keywords: Education – computer assisted; engineering and environmental geology; hydrogeology and hydrology; miscellaneous and mathematical geology.

Introduction
The spreadsheet is becoming increasingly popular; however, it is not yet universally used as a tool for course assignments. The spreadsheet not only serves as a time-saving means of producing errorless calculations; it can also facilitate a better understanding of various geological, environmental and hydrological processes. Perhaps the most appealing aspect of using a spreadsheet is that it allows the student to readily find answers to his or her “what if” questions. I have observed that both undergraduate and graduate students are becoming progressively more proficient with the spreadsheet. However, there is a clear need for instructors to assign more spreadsheet problems in order to enhance these programming skills.

To meet this need, I have developed a simple spreadsheet assignment that can be used to promote better understanding of the various components of the terrestrial part of the hydrological cycle – particularly those involving subsurface and surface-water interactions. An additional objective of the assignment is to stimulate thinking regarding the effects of climate change on the hydrological cycle and water resources. I give the exercise to my undergraduate/graduate (400/600) level Hydrogeology course as a homework assignment.

Background
(presented as an introduction to the assignment)

Hydrological Cycle and Budgets: The hydrological cycle is a scheme employed to account for the flux of water from the oceans, to the atmosphere, to the hydrosphere (the earth’s surface and shallow subsurface), and then back to the oceans. An estimated 1 x 10^17 kilograms of water are transferred through the terrestrial or continental portion of the hydrological cycle annually (Chaahine, 1992).

The hydrological cycle can be stated in the form of a budget or water balance as follows:

\[ \text{INFLUX} = \text{OUTFLUX} \quad \text{or} \quad [\text{Equation 1}] \]

Precipitation = Evapotranspiration + Infiltration + Runoff.

This is a steady-state equation in that no water is accumulated or lost. The sum total of the global water budget remains constant. This is a good first-order approximation for the global cycle; however, it fails to account for important relationships between infiltration and runoff. After all, a great deal of streamflow is accounted for by water that has already infiltrated the earth’s surface. How else could a stream flow on a perennial basis? We will return to this problem in our assignment.

A second, and more general, equation accounts for the input or output of water to and from “storage” \[ \pm \Delta S \] (that is, water held within some storage “reservoir” such as rocks, soil, lakes or the oceans). This equation is stated as follows:

\[ \sum \text{INFLUX} - \sum \text{OUTFLUX} = \pm \Delta \text{STORAGE} \quad . \quad [\text{Equation 2}] \]

The hydrological cycle is typically shown as a series of interrelated “reservoirs” with “flux” rates (mass/time, length/time, or volume/time) between each reservoir. Engineers call these “pot-and-pipeline” diagrams (Figure 1).

Residence Time: The mass of water within a reservoir divided by the flux in or out of the reservoir is known as the “residence time.” This can be thought of as the average period of time a water molecule spends within a reservoir. For example, the total mass of water within the terrestrial atmosphere is 4.5 x 10^15 kg. The flux rate is 107 x 10^15 kg/yr (Chaahine, 1992). The residence time is computed as follow:

\[ \text{Residence Time} = \frac{4.5 \times 10^{15} \text{kg}}{1.07 \times 10^{15} \text{kg/yr}} = 4.2 \times 10^{-2} \text{yr} = 15 \text{days}. \]

The shorter the residence time the more that particular reservoir is sensitive to perturbations within the hydrological cycle (for example, droughts) and pollution. In other words, low-residence time reservoirs are not “buffered” very well with respect to change.

The Basin Hydrological Cycle: The basic unit of landmass used to account for water on the continents is known as the “watershed” or the land area between two watershed divides. The hydrological budget for a basin can be accounted for by the

Sample Calculation: Convert 2.5 inches/year rainfall to cubic meters per day and then gallons per day given a basin area of 100 square miles.

\[
\frac{2.5 \text{in}}{\text{year}} \times \frac{100 \text{mi}^2}{\text{year}} \times \frac{1 \text{ft}^3}{12 \text{in}} \times \frac{(5.280 \text{ ft})}{(1 \text{mi})} \\
(3.048 \text{m})^3 \times \frac{1 \text{year}}{365.25 \text{ days}} \times \frac{450 \times 10^3 \text{m}^3}{1 \text{ day}}
\]

\[
264 \text{ gallons} = 119 \times 10^3 \text{ gal per day}
\]

Assignment

Part 1 (Scenario 1): The objective of this assignment is to devise and implement a spreadsheet solution for the basin hydrological cycle shown in Figure 1. The input to your model will consist of the hypothetical “percentage fluxes” to and from the various components or “pots.” We also assume a net influx of 50 inches of rainfall per year and a basin area of 100 square miles. The primary output will consist of the total runoff generated from these inputs. Follow these steps and answer the related questions.

a) Set up a spreadsheet program and calculate the total ET. Your answer should be given in inches per year, cubic meters per day, gallons per day, and cubic feet per second. [Hint: These will all be columns in your spreadsheet. Build your conversion factors into the spreadsheet.]

b) Do the same for runoff.

c) In order to complete “a” and “b” you must calculate all fluxes for all reservoirs shown on Figure 1.

d) From your spreadsheet calculations, compare the difference between precipitation rates and the sum of ET and runoff.

e) Let us assume the average person consumes 200 gallons of water per day. Given the total runoff, how many people can this basin support?

f) Calculate the volume of the ground water reservoir, assuming a basin area of 100 mi², a porosity of 25% and a saturated thickness of 10 meters. Given the calculated rate of ground-water recharge, calculate the residence time of groundwater in this hypothetical basin.

g) Are ground water and surface water divides necessarily the same for a given watershed? Explain.

## Table 1. Spreadsheet Solution to “Scenario 1.”

<table>
<thead>
<tr>
<th>RESERVOIRS Flux sources</th>
<th>% Flux</th>
<th>Basin Area (mi²)</th>
<th>Inches per year</th>
<th>Cubic meters per day</th>
<th>Gallons per day</th>
<th>Cubic feet per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTERCEPTION precip.</td>
<td>0.05</td>
<td>100</td>
<td>2.50</td>
<td>4.50E+04</td>
<td>1.19E+07</td>
<td>1.84E+01</td>
</tr>
<tr>
<td>OVERLAND FLOW precip.</td>
<td>0.10</td>
<td>100</td>
<td>5.00</td>
<td>9.01E+04</td>
<td>2.38E+07</td>
<td>3.68E+01</td>
</tr>
<tr>
<td>INFILTRATION precip.</td>
<td>0.85</td>
<td>100</td>
<td>42.50</td>
<td>7.66E+05</td>
<td>2.02E+08</td>
<td>3.13E+02</td>
</tr>
<tr>
<td>UNSATD. SOIL MOISTURE infiltration</td>
<td>1.00</td>
<td>100</td>
<td>42.50</td>
<td>7.66E+05</td>
<td>2.02E+08</td>
<td>3.13E+02</td>
</tr>
<tr>
<td>G.W. RECHARGE unsatd. s.m.</td>
<td>0.40</td>
<td>100</td>
<td>17.00</td>
<td>3.06E+05</td>
<td>8.08E+07</td>
<td>1.25E+02</td>
</tr>
<tr>
<td>SATURATED GROUND WATER g.w. recharge</td>
<td>1.00</td>
<td>100</td>
<td>17.00</td>
<td>3.06E+05</td>
<td>8.08E+07</td>
<td>1.25E+02</td>
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<tr>
<td>ET.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>1.84E+01</td>
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<tr>
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<td>1.25E+02</td>
</tr>
<tr>
<td>satd. g.w.</td>
<td>0.05</td>
<td>100</td>
<td>0.85</td>
<td>1.53E+04</td>
<td>4.04E+07</td>
<td>6.25E+01</td>
</tr>
<tr>
<td>TOTAL ET</td>
<td></td>
<td>100</td>
<td>20.35</td>
<td>3.67E+05</td>
<td>9.68E+07</td>
<td>1.50E+02</td>
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<tr>
<td>BASEFLOW satd. g.w.</td>
<td>0.95</td>
<td>100</td>
<td>16.15</td>
<td>2.91E+05</td>
<td>7.68E+07</td>
<td>1.19E+02</td>
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<tr>
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<td>0.20</td>
<td>100</td>
<td>8.50</td>
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<td>4.04E+07</td>
<td>6.25E+01</td>
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<tr>
<td>OVERLAND FLOW precip.</td>
<td>0.10</td>
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<td>5.00</td>
<td>9.01E+04</td>
<td>2.38E+07</td>
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<td>7.68E+07</td>
<td>1.19E+02</td>
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<td>1.53E+05</td>
<td>4.04E+07</td>
<td>6.25E+01</td>
</tr>
<tr>
<td>overland</td>
<td></td>
<td>100</td>
<td>5.00</td>
<td>9.01E+04</td>
<td>2.38E+07</td>
<td>3.68E+01</td>
</tr>
<tr>
<td>TOTAL RUNOFF</td>
<td></td>
<td>100</td>
<td>29.65</td>
<td>5.34E+05</td>
<td>1.41E+08</td>
<td>2.18E+02</td>
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</tbody>
</table>

1The hypothetical percentage flux rates used are those given in Figure 1. Note also that the % flux in each box does not equal 1.0.

d) Compare and contrast the resulting ET and runoff rates derived for Scenarios 1 and 2.

c) By what percent did streamflow decline in Scenario 2?

e) Explain why either Equation 1 or Equation 2 is most relevant for the flux scheme shown on Figure 1. Which equation would be most relevant if only a total of 80% of the ground water recharge outfluxes through ET and baseflow? In other words account for the “missing” 20%.

### Spreadsheet Solution

A spreadsheet solution to the problem posed as “Scenario 1” is given in Table 1. I stress that the solution shown below is by no means unique nor is it likely the most efficient. However, it required less than a half hour to set up, run

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and check. A more sophisticated approach would involve the use of the Thornthwaite (1948) equation which relates evapotranspiration rates to mean monthly temperatures.

Acknowledgments
I thank the students of my Hydrogeology class for helping me to clarify some aspects of this exercise.

References

About the Author
Seth Rose is an associate professor in the Geology Department at Georgia State University. His current research interests involve the isotope chemistry of Piedmont watersheds and the fate of contaminants associated with acid mine drainage. He teaches courses in introductory geology, aqueous geochemistry and hydrogeology.

Letters

Student Evaluations
I have enjoyed reading your inside-the-front-cover editorials for many years; however, the latest (on teaching evaluations) really "hit the spot." I could not agree more!

Although class attendance has not been required at our institution for many years, I check attendance several times each semester, require students in my introductory classes to sign their test papers to show that they personally picked up their graded exams (and penalize those who do not pick them up because I believe that discussing the corrected exam is at least as important as taking it in the first place), ask for questions about the previous lecture before each new class period begins, stop frequently to answer any questions, and stay for a few minutes after class in case there are any questions at that time. Yet I routinely get student evaluations that fall below others in my department. In spite of the fact that I post my office phone number to students in my classes, invite them to call me at home if they have any problems, and require individuals who are doing poorly on exams or in their lab work to come to my office for a conference, as many as one-third of those same students give me the worst possible ratings for those evaluation questions that ask whether I am available to answer their questions.

Typical daily attendance in introductory classes is roughly 50%, and only a fraction of those who attend do so on a regular basis. How much value do evaluations given by students who only attend class occasionally really have? Frankly, I put little faith in student evaluations. How can someone who is present only half of the time on average determine that I am or am not teaching that course well?

Even in upper division and graduate level classes, attendance has become more erratic and many students hardly give a thought to coming late to class or not coming at all. They often seem oblivious to the distraction they cause when they arrive late and talk to the students sitting next to them to find out what they missed, or fail to understand the material you are discussing because they were not present when you started your lecture.

You noted that your early morning class seemed to be the worst, that in your early morning class you were rated among the worst 20% of all the instructors at UW-Parkside. I can sympathize with you. I have had the same experience.

Your editorial concluded with, "What seems to be a simple and straightforward method evaluating instruction turns out upon examination to be fatally flawed." The major flaws in student evaluations are that the majority of students are still immature and have no sound basis for judging the quality of instruction. They are more likely to judge instructors on the basis of how well they are doing in class and other factors that are not related to how thorough or technically correct the instruction was. It is much more revealing to find out what students who took your class ten or more years ago think today about how good a teacher you were. Of course, by that time the "bean counters" don't really care.

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