



# An Interactive Web Application Helps Students Explore Water Balance Concepts

John P. Gannon<sup>1\*</sup> and Kevin J. McGuire<sup>1,2</sup>

<sup>1</sup> Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, VA, United States, <sup>2</sup> Virginia Water Resources Research Center, Virginia Tech, Blacksburg, VA, United States

The concept of a water balance is a foundational topic in hydrology classrooms. While understanding and applying this concept is crucial to the introduction of more advanced topics, students often struggle to develop a thorough understanding of the relationships between components, assumptions, and limitations of a water balance. To aid students in developing a working understanding of a water balance, we developed a web application that runs a one dimensional Thornthwaite-type water balance at any of thousands of NOAA climate stations across the continental United States using the local soil-water storage capacity at the station location. Within the app, students can manipulate the soil-water storage capacity, latitude, temperature, and precipitation to better understand how it works and explore scenarios of land use, extreme weather, and climate change. The application is free and will run on any device that can open an internet browser window (laptops, chromebooks, smartphones, etc). Here we present the details of the model, functionality of the application, and link to several ready-made classroom activities. Finally, results from student surveys in two hydrology classrooms show that students may learn water balance concepts more effectively than traditional methods such as spreadsheet computations.

**Keywords:** water balance, water budget, web app, teaching, hydrology

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### \*Correspondence:

John P. Gannon  
jpgannon@vt.edu

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## INTRODUCTION

A water balance of a soil pedon or watershed is a core concept in many introductory hydrology and hydrogeology courses and texts (e.g., Hendriks, 2010; Fitts, 2013; Hornberger et al., 2014; Dingman, 2015; Bedient et al., 2019; Davie and Quinn, 2019; Hiscock and Bense, 2021). It is a useful and powerful context through which to discuss core hydrology concepts like soil water storage, groundwater recharge, potential and actual evapotranspiration, and runoff. Additionally, the conceptual model of a water balance can then be used to examine the impacts of change on a hydrologic system, such as development, land use conversion, or climate change.

The ability to explain hydrologic concepts and explore impacts to a hydrologic system, however, is predicated on having a solid understanding of how a water balance works and how it responds to changing inputs or parameters that describe the system. This is often a challenge for students who are learning hydrology for the first time. While activities like hand calculations and water balance spreadsheets are helpful, students can spend more time and energy learning how to perform the calculations or manipulate a spreadsheet or graph a variable than working to understand the concepts behind the water

balance. Furthermore, we found hand calculations and spreadsheet-based activities were even more difficult to run effectively after the shift to online learning in the COVID-19 pandemic. In the online environment, it was challenging to provide adequate troubleshooting and help to students having trouble. This was especially problematic in introductory classes where effective use of spreadsheets is not a learning goal, but a conceptual understanding of a water balance was an important fundamental learning goal. For these reasons, we saw the need to create a way for students to explore a water balance in a variety of ways, both graphically and with tabular data, without having to perform calculations or work with a spreadsheet.

Importantly, we also wanted to create a way to introduce students to the water balance that maintained the active learning approach of traditional hand calculations or spreadsheets. Active learning, where students do not simply sit and listen to an instructor, has been shown again and again to be an effective pedagogical practice (Freeman et al., 2014) and one that can reduce achievement gaps between advantaged and disadvantaged groups (Haak et al., 2011). It was also a goal to develop something that would foster inquiry-based learning. Inquiry-based practices promote learning by inviting students to ask their own questions and then work to develop answers (Bransford et al., 2000). This is a powerful technique, but especially for an online-based activity, we felt students needed to be able to explore concepts without getting overwhelmed or encumbered by technical errors or procedural confusion.

Interactive web applications are one way to provide students with an inquiry-based learning experience that may aid their understanding of course concepts without overburdening them with the operational aspects of the calculations involved. These web applications are growing in popularity. They can be developed using common scientific coding languages (R, Python, Matlab) and hosting them continues to become easier and less expensive. In fact, the Consortium for the Advancement of Hydrologic Sciences, Inc. (CUAHSI) has resources for hosting several types of web applications (more info at: [www.cuahsi.org/education/](http://www.cuahsi.org/education/)). Furthermore, multiple studies found web applications benefit student learning (e.g., Hagtvedt et al., 2007; Azman and Esteb, 2016). There is such strong evidence for enhanced learning with web applications that the American Statistical Association recommends their use in statistics instruction (Franklin et al., 2007).

For these reasons, we developed a web-application that allows students to explore and better understand the water balance. The flexibility of a web application allowed us to add functionality that would be cumbersome, if not impossible, in a spreadsheet or by-hand activity in a hydrology classroom. Students can easily manipulate inputs and parameters in the water balance and load data from thousands of sites across the contiguous United States, choosing from two periods of monthly climate normals (1981–2010, 1991–2020) (Arguez et al., 2012). This allows for exploration of a variety of concepts at a range of levels of complexity, from an early activity in an introductory class to an upper level undergraduate hydrology or hydrogeology course.

In the following sections, we explain in detail how the app calculates a water balance and what data is used. We then explain

the functionality of the app and results from a survey of students who used the app in an in-class activity. Finally, we provide information about how to access several ready-to-use activities and an instructional video about using the app.

## METHOD: WATER BALANCE MODEL

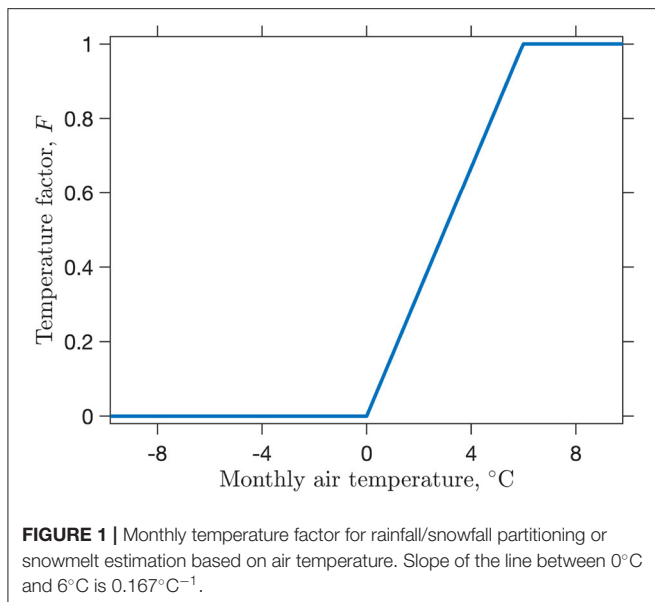
The app runs a Thornthwaite-type monthly water balance model following the approach described by Dunne and Leopold (1978) and Dingman (2015). Thornthwaite-type monthly water-balance models (Thornthwaite and Mather, 1955, 1957; Dunne and Leopold, 1978; Black, 2007), are lumped conceptual models that estimate climatic average or continuous hydrologic budgets (Dingman, 2015). Thornthwaite-type models have been applied to variety of settings (e.g., Alley, 1985; Willmott et al., 1985; Steenhuis and Van der Molen, 1986; McCabe and Markstrom, 2007; Westenbroek et al., 2010) and have proven to be useful tools in water resource assessment (e.g., Taylor et al., 2006; Tillman et al., 2017). Inputs for these models typically consist of monthly values of precipitation and temperature for a watershed or region of interest. Here we use mean monthly values to represent the climatic average. Thornthwaite-type models typically have a single parameter, the soil-water storage capacity,  $S_C$ , or the available water storage of the soil in the watershed.  $S_C$  is defined as:

$$S_C = (\theta_{fc} - \theta_{pwp}) \cdot Z_r, \quad (1)$$

where  $\theta_{fc}$  is the field capacity,  $\theta_{pwp}$  is the plant permanent wilting point, and  $Z_r$  is the depth of the root zone (often assumed as 1 m). The difference between  $\theta_{fc}$  and  $\theta_{pwp}$  is the (plant) available water capacity, which is expressed as a fraction of total volume of soil ( $\text{cm}^3$  of water per  $\text{cm}^3$  of soil) and is the water available for transpiration. The average available water capacity (i.e.,  $\theta_{fc} - \theta_{pwp}$ ) for watersheds in this app is the Available Water Storage measure for the upper 100 cm of soil from the Natural Resource Conservation Service (NRCS) gNATSGO (Gridded National Soil Survey Geographic Database) database (Soil Survey Staff, 2020). Runoff estimation is not included in this version of the water balance in the model. Instead, runoff can be considered part of the surplus water term. Runoff values can be separately estimated from the monthly water surplus and/or by applying a direct runoff coefficient as a fraction of monthly precipitation (e.g., see McCabe and Wolock, 2011).

Monthly precipitation,  $P$ , is partitioned into rainfall,  $RAIN$ , and snowfall,  $SNOW$ , using a factor,  $F$ , that is multiplied by total monthly precipitation to determine the amount of rainfall in that month. If monthly air temperature is below  $0^\circ\text{C}$ , precipitation is considered snowfall and  $F$  is zero. If the monthly air temperature is above  $0^\circ\text{C}$ , but below  $6^\circ\text{C}$ ,  $F$  is computed based on the linear temperature relationship shown in **Figure 1** and the rainfall fraction of the precipitation is  $0 \leq F \leq 1$  (Dingman, 2015). Therefore,  $RAIN = F \cdot P$  and  $SNOW = (1 - F) \cdot P$ .

The factor,  $F$ , is also used to estimate monthly snowmelt following a degree-day or temperature-index approach. Here,  $F$  is multiplied by the sum of the snow water equivalent on the ground,  $PACK$ , for the previous month and the current month's



snowfall, *SNOW*, to estimate snowmelt, *MELT*. The result is the amount of snow that will melt and be considered part of water input to the soil, *W*. Water input, *W*, to the soil storage is therefore the sum of rainfall and snowmelt. The snowpack at the end of month is then computed following Dingman (2015) as the proportion of precipitation that fell as snow and contributed to that month's snowpack, plus the previous month's snowpack that did not melt.

Potential evapotranspiration, *PET*, in this model is calculated using the Thornthwaite (1948) equation; however, other approaches that use air temperature (e.g., Hamon, 1961) could be used as well. The model assumes that if monthly water input exceeds monthly *PET*, then actual evapotranspiration, *ET*, takes place at the *PET* rate and the soil-water storage, *S*, increases or, if it is already at soil-water storage capacity (*S<sub>C</sub>*), it remains constant. The Thornthwaite (1948) equation for *PET* depends on monthly temperature and latitude, which is used to account for the varying number of days per month and hours of daylight (Criddle, 1958). When water input for a month is less than *PET*, *ET* is equal to the sum of water input and the amount of soil-water that can be removed from the soil storage for month *i* depending on the following exponential drainage function (Alley, 1984):

$$S_i = -S_{i-1} \cdot \left[ 1 - \exp\left(-\frac{PET_i - W_i}{S_C}\right) \right] - S_{i-1}. \quad (2)$$

The app provides a table of monthly values (e.g., **Table 1**) and five graphs for any given location defined by a NOAA observing station location. The graphs display monthly water inputs to the soil-water storage that are divided into snowmelt and rainfall contributions, soil-water and snowpack storage, monthly temperature, and the snow and rain monthly fractions of precipitation. **Table 1** is the monthly water balance output

for Blacksburg, Virginia, at 37.2 °N latitude. The onset of snow inputs and snowpack occur in December and the snowpack reaches its peak in February, and melts in March. For the months when there is adequate supply of soil-water storage for the evaporative demand (October–May), *ET* is equal to *PET*. Recharge of the soil-storage begins in October and reaches its capacity the following month. The depletion of soil-water storage begins in June and continues into September as the evaporative demand is satisfied by removing water from the soil-water storage, *S*. The average monthly water surplus ( $W - ET - \Delta S$ ), i.e., water available for recharge and runoff, are the monthly inputs that are in excess of monthly *ET* and soil-water storage changes.

## RESULTS: APP IMPLEMENTATION AND FEATURES

The water balance app is a Shiny web application (<https://shiny.rstudio.com/>) and is hosted by CUAHSI. The web application can be run on any common internet browser on a computer, tablet, smartphone, or chromebook. Use of the app is free and does not require the user to download any special software. Source code for the app can be found at <https://github.com/jpgannon/Water-Balance-App>.

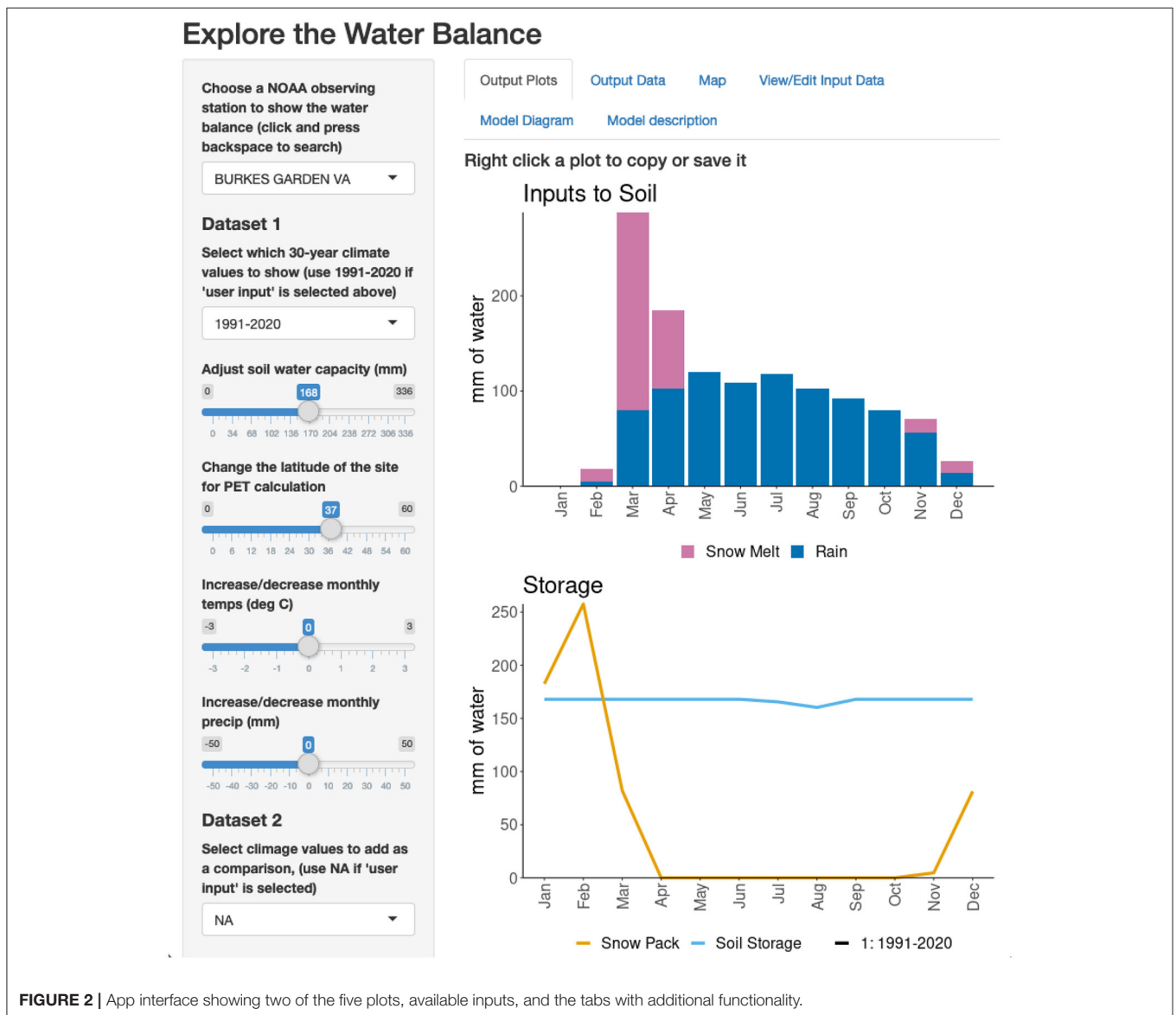
The app, shown in **Figure 2** has six tabs which support a variety of functions. The landing page for the app is the “Output Plots” tab. Here students see five plots rendered from the results of the water balance function: soil inputs, soil storage, soil output, temperature, and precipitation. The plots will resize if the user changes the size of their browser window, and they can copy and paste the plots or save them by right-clicking on them. This facilitates saving the plots for activity write-ups. The plots will update automatically if the user makes changes to any of the settings on the left side of the app.

On the left panel, the user has several options. The first dropdown allows the user to select one of several thousand NOAA climate monitoring sites by either scrolling through the available options or typing to search. Next, the climate normal period can be switched between 1991–2020 and 1981–2010. The next slider down automatically starts at the soil water capacity of the site, which is the Available Water Storage measure for 100 cm of soil from the Natural Resource Conservation Service (NRCS) gNATSGO database (Soil Survey Staff, 2020). Moving this slider will change the water holding capacity in the model. The latitude slider similarly updates depending on the site chosen, and if moved, changes the latitude in the *PET* calculation in the model. The following two sliders, precipitation and temperature, always start at zero. If the user moves these sliders, they will add or subtract the value of the slider from each monthly value for the site chosen. For example if the temperature slider was moved to +1, it would add 1°C to the temperature data for each month at the site. Finally, if the user selects a climate normal period in the dropdown at the bottom of the column, those data will be added as a separate dataset to the plots. This can be used to compare the two climate normals, or if the user selects the same climate normal period for both, they can more clearly see how the water

**TABLE 1** | Output of Thornthwaite-type monthly water balance for Blacksburg, VA.

	P	T	F	RAIN	SNOW	PACK	MELT	W	PET	W - PET	S	ΔS	ET	W-ET-Δs
Jan	78.2	-0.3	0	0	78.2	130.3	0	0	0	0	140	0	0	0
Feb	71.4	1.2	0.2	14.5	56.8	149.0	38.1	52.7	2.6	50.1	140	0	2.6	50.1
Mar	92.5	5.3	0.9	82.2	10.3	17.7	141.6	224	19.3	204	140	0	19.3	204
Apr	88.4	10.4	1	88.4	0	0	17.7	106	46.5	59.6	140	0	46.5	59.6
May	110.0	15.2	1	110	0	0	0	110	82.2	27.8	140	0	82.2	27.8
Jun	101.6	19.8	1	102	0	0	0	102	114	-12.7	128	-12.1	114	0
Jul	108.2	21.8	1	108	0	0	0	108	130	-22.1	109	-18.6	127	0
Aug	91.2	21.1	1	91.2	0	0	0	91.2	118	-26.7	90.3	-19.0	110	0
Sep	78.7	17.3	1	78.7	0	0	0	78.7	81.8	-3.0	88.4	-1.9	80.7	0
Oct	70.6	11.3	1	70.6	0	0	0	70.6	45.1	25.5	114	25.5	45.1	0
Nov	72.9	6.3	1	72.9	0	0	0	72.9	19.3	53.6	140	26.1	19.3	27.5
Dec	74.9	1.0	0.2	12.5	62.4	52.0	10.4	22.9	2.0	20.9	140	0	2.0	20.9
Annual	1039		831	208		208	1039	661				648	390	

Temperatures, *T*, in °C, water-balance terms in mm. *S<sub>C</sub>* = 140 mm.



**FIGURE 2** | App interface showing two of the five plots, available inputs, and the tabs with additional functionality.

budget changes when they manipulate the sliders, as the second dataset is unaffected by user inputs.

The second tab at the top of the app is titled “output data” this tab shows all the output from the water balance model. This can be used to explore more quantitative differences between outputs, such as PET and AET. The data can also be downloaded using a download button at the bottom. This produces a comma-separated value (CSV) of the model output, which a user could then use to create their own visualizations, perhaps for an upper-level class or for custom figures for a lecture.

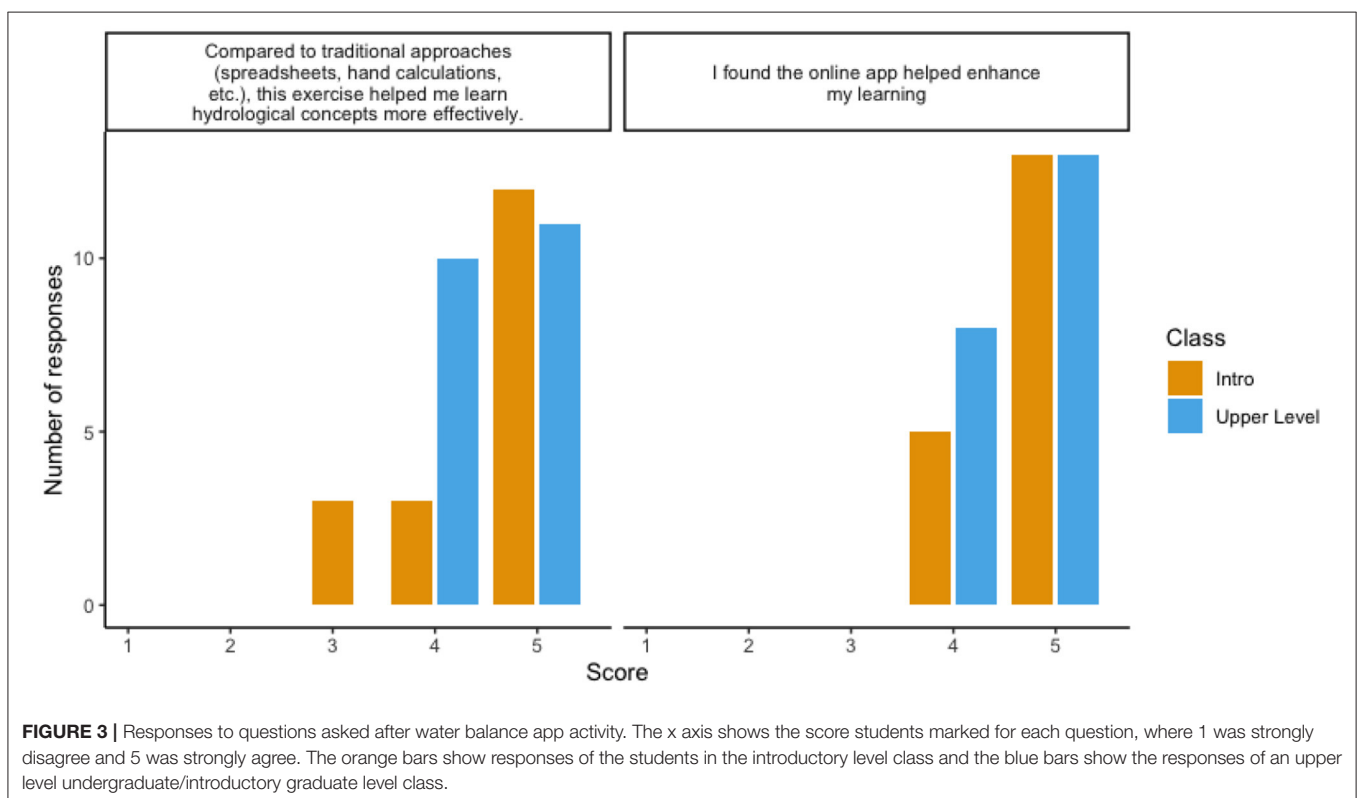
The third tab is the map tab. Here the user can zoom and pan around the contiguous US and see all available places for which they can calculate the water balance. If the user clicks a marker, that site will be selected in the left panel. If the user selects a site using the drop-down menu in the first tab, it will be highlighted on the map in the map tab.

The fourth tab allows the user to view or edit the input data for the model. When a site is chosen, its data populates this table. If the user double clicks on any value, they can enter a new value in its place, and the app will recalculate the water balance with the new data. This could be used to simulate a large flood or a drought, for instance. This tab has the additional functionality of allowing the user to put in a custom dataset from somewhere not included in the available data. If the user selects “User Input”, the first option in the dropdown menu for sites on the left panel, the view or edit input data becomes all zeros. The user can then enter their own temperature and precipitation values and use the sliders to change the available soil water capacity and latitude of the site.

Finally, the fourth and fifth tabs of the app offer a diagram of the model used, and a detailed description of the functionality of the app and the Thornthwaite soil water balance.

## DISCUSSION: EFFICACY IN A CLASSROOM ENVIRONMENT

We used the app to introduce the water balance in two classes at Virginia Tech. One class was an introductory watershed hydrology class taught in the department of Forest Resources and Environmental Conservation and the other was an upper level undergraduate/introductory graduate level hydrology methods class taught in the Biological Systems Engineering department. The introductory class had around 60 students and the advanced class about 20. Both classes were taught in-person. After a short slideshow presentation introducing the water balance and a demonstration of the functionality of the app, students were provided with an activity. Both the lecture introduction and activity are included in the resources linked below. In both cases, these were individual activities in an in-person class. However, the application and included activities are likewise suitable for group-based activities and virtual or hybrid modalities, as no specific computing resources are required. After the activity, we asked the students to respond with how much they agreed with two statements to help determine if the students felt the app helped them understand the water balance, and if they enjoyed it more than previous activities using other methods,



such as spreadsheets or hand calculations. The exact statements posed were:

“Compared to traditional approaches (spreadsheets, hand calculations, etc.), this exercise helped me learn hydrological concepts more effectively.”

“I found the online app helped enhance my learning.”

Students responded to each of the statements on a scale of 1–5 where 1 was “strongly disagree”, 3 was “agree”, and 5 was “strongly agree.” **Figure 3** shows that students uniformly agreed that the app enhanced their learning and that the exercise helped them understand the material more effectively than a spreadsheet or hand calculation. For both courses, the most frequent response was “strongly agree” for both questions.

While the student response was positive, there are some drawbacks to using this web application as a sole replacement for other types of activities, depending on the learning goals for the class. For instance, exploring the app alone would not be appropriate if the topic is introduced in a class with the dual purpose of developing a conceptual understanding of the water balance and developing/practicing spreadsheet skills, graphing, unit conversion, or basic budget calculations. However, this app can also be used to facilitate these more advanced activities. For example, students could use the app to explore water balance concepts across the US and then export the data for a site of their choosing as a comma separated values (csv) file *via* the “output data” tab to perform further analysis by hand or in a spreadsheet program.

## READY-TO-USE ACTIVITIES

To facilitate use of this app in hydrology and earth science classrooms, we created three activities that can be used in a classroom after a short introduction to the water balance and the app. The questions addressed in these activities are as follows:

1. What controls how water is partitioned in a water balance?
2. What controls the amount of actual evapotranspiration at a site?

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3. What is the difference between a water limited and energy limited system?
4. How can climate change affect the water balance?

The complete activities are available *via* CUAHSI's hydroshare, along with Powerpoint slides that introduce the water balance, a link to a video showing how to use the app, and a link to the app itself (<https://www.hydroshare.org/resource/0ecadff374aa4a2b84e41f146d39f48c/>).

## CONCLUSIONS

The water balance is a crucial concept for students of hydrology to understand thoroughly, but is often confusing due to numerous interactions between parameters. Common methods used to explore the water balance can leave students bogged down in calculations or spreadsheet operations, taking away from their opportunity to become more comfortable with the core concepts. Interactive web-applications offer a solution, as they are a platform-agnostic and easy to use way for students to explore hydrologic concepts in the classroom.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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