Representing time variant water storage and mixing schemes in isotope tracer-aided hydrologic simulation

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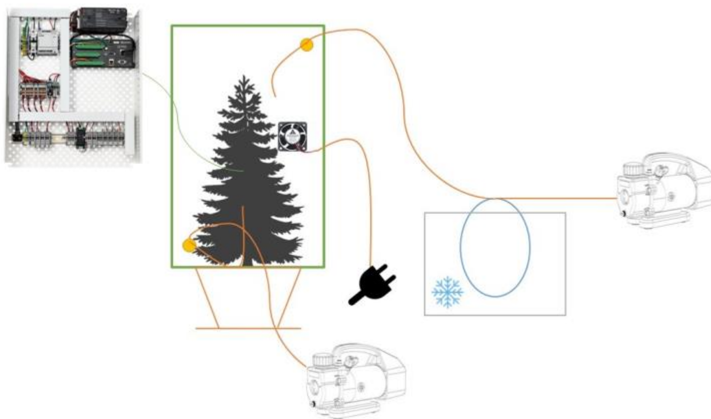

Abstract

Hydrologic models are often used to predict flooding risk driven by land surface features and meteorology. These models can be useful in estimating the consequences of the intersection of two ongoing events in the Catskill region: increased precipitation extremes and the rapid dieback of Eastern hemlock, a foundation tree species. However, simulation of transpiration in these models tends to be erroneous, with storage of water in the plants emerging as a cumbersome process to simulate. In order to improve the fidelity of modeled plant hydraulics, it is important to avoid errors originating from the simplification of the storage of water within plants. Research has found that simulating tree water storage improves model calibration. We investigate water storage in four common conifers as captured by StorAge Selection (SAS) functions generated via a machine learning-based model. We generate model inputs through stable water isotope-tracer based experiments conducted in both growth chamber and field site settings, examining how key environmental variables drive changes in SAS functions. We integrate the SAS framework, enhanced by our experimental data, into a hydrologic model, and assess whether model performance is improved. Finally, we utilize this model to simulate hydrological impact of hemlock loss under different climate scenarios.

Three Summary Points of Interest

- Project utilizes a novel methodology not previously applied to the study of plant transpiration.
- Project aims to significantly improve hydrologic prediction by testing the enhancement of a key characteristic of land surface models.
- Project may potentially increase the accuracy of flood prediction, especially as it relates to the loss of the foundation tree species Eastern hemlock, in the Northeastern U.S. under different climate scenarios.

Keywords
Hydrology, Hydrologic Modeling, Plant Hydraulics, Transpiration, Transit Time Theory, StorAge Selection Functions, Riverine Flooding, Conifers, Eastern hemlock

Introduction and Background

Riverine flooding is a critical problem within the Hudson River basin and the Catskill region.[1,2] Further, the frequency and intensity of extreme precipitation across the Northeast U.S. have been increasing.[3,4,5] Research indicates that changes to the tree species composition of regional forests, particularly the ongoing rapid dieback of Eastern hemlock due to the spread of the invasive insect Hemlock Woolly Adelgid, could increase flooding risk to downstream communities.[6,7]

Hydrologic simulation models serve as useful tools to estimate how extreme precipitation will drive flooding while accounting for surface features such as vegetation. Still, many popular models simplify complicated but important aspects of plant hydraulics.[8] Hence, sub-daily land surface modeling of transpiration tends to be erroneous,[9,10] with storage and mixing of water in the plant stem emerging as a particularly cumbersome process to simulate.[11,12]

In order to further improve the fidelity of modeled water flow through the earth surface, and therefore to more accurately predict the potential for floods originating in forested catchments, it is important to eschew errors that may originate from the simplification of the storage and mixing of water within plants. Research has found that simulating water storage in trees improved the calibration of a tracer-aided model, relative to the assumption of no storage.[13] While both uniform and piston flow representations of mixing during storage outperformed the no storage scenario, the researchers estimated that actual mixing is likely some time-variant composite of these extreme schemes.

StorAge Selection (SAS) theory offers a set of mathematically robust methods to better understand water storage in watersheds.[14,15,16,17] We propose that this framework can be applied to better understand the movement of water through plants as well, and that the integration of SAS-based schemes within physically based models will improve their performance, serving as the next step in the representation of plant traits and prediction of riverine flooding in this context. Our research explores the following questions as applied to four conifer species in both growth chamber and field study site settings:

1. Are different plant species best characterized by different SAS functional forms?
2. Are SAS functions relating plant water storage and transpiration nonstationary? If so, are nonstationary effects in SAS form driven by the following factors:
    a. volumetric inflow rate?
    b. change in storage volume as a result of plant growth?
    c. relative humidity and temperature?
    d. changes in flow paths as a result of sub daily shift between transpiration and reverse flow?
3. Is ecohydrological model performance improved when SAS form is set explicitly as a function of the key variables driving nonstationary effects?

Results & Discussion

This project is still in preparation. While we were able to finish the first of two phases of a growth chamber-based experiment in 2020, COVID-19 related delays prevented us from completing the field component. We are preparing to wrap up all necessary field work in 2021 and expect to have results to present later this year and early 2020. In the appendices, we present some figures depicting transpiration patterns at our field site, generated with data logged during the operating period of the field experiment utilizing sap flux sensors, the purchase of which was facilitated with funding from the NYS WRI. We also present figures generated by isotopic analysis of some key water samples that demonstrate our growth chamber-based experimental apparatus is valid for studying transpiration patterns.

Policy Implications

This research has two immediate applications. First, this work will support efforts to derive accurate economic appraisals of forest management within the Catskill region. Despite the myriad environmental consequences of losing forest tree species diversity,[18] presenting a convincing economic argument for forest conservation remains a challenge.[19] Our proposal will help in the development of a regional flood hazard assessment of Eastern hemlock loss which could be used by forest managers, landowners, and other agency users such as the NYC DEP to address biodiversity loss and flooding risk. Second, this research will contribute to a fundamental improvement in simulation model structure that are used to predict and evaluate surface hydrology. Most popular existing models incorporate a simplified representation of plant water storage, which is a barrier to their use in forest conservation decision making.

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Methods

Growth chamber

In 2020, we conducted a growth chamber-based experiment collecting data to understand sub-daily transpiration patterns of four conifer species: Eastern hemlock, balsam fir, white pine, and white spruce. Plants of height 0.3m – 1m were placed in gas exchange chambers, a deuterium tracer was applied to the soil, and soil evaporation was suppressed so that the only outflow of tracer was through plant use. Transpiration was routed out with vacuum pumps, condensed in dry ice, and a sample was collected every two hours for a period of 30 hours, and then again at the same frequency for periods of 6 hours on the two following days. Transpiration flux rate was logged with a LiCor Photosynthesis system. The pairing of deuterium concentration and transpiration volume data, along with some plant dimensional specifics are used to fit SAS curves with a machine learning based-model called MESAS.[16] This first experimental phase aimed to isolate the effect of plant species and size, and as such climate conditions were fixed. This experiment will be repeated in the spring of 2021 with varied climate conditions to tease out other drivers of transpiration changes.

Field Study

In 2021, a field site adaptation of our growth chamber study will be conducted. The gas exchange bag-based apparatus described above will be deployed on Eastern hemlock and white pine trees of heights 2.5m – 3 m. This difference in size will enable us to scale our data up and identify allometric scaling relationships of SAS distribution shape to plant size that model users can rely on to scale up their existing without having to empirically gather new data. Methodologically, the growth chamber experiment will be repeated with some key additions. Sap flux sensors and dendrometers will be used to estimate plant stem storage and also to have a high-resolution log of transpiration flux.[20,21] Soil moisture sensors and a rain gauge will be used to monitor any change in the soil water reservoir.

Modeling

We will utilize a machine-learning based model, MESAS, to fit dynamic SAS functions that mathematically represent transpiration patterns to each of our four species. We will then integrate these functions explicitly into a land surface model, and carry out simulations of different case studies of Eastern hemlock loss at various catchments across the Catskill region, identified as hydrologically important by the NYC DEP.

Outreach Comments

We plant to present our work at the Ecological Society of America Annual Meeting 2021, at the American Geophysical Union Fall Meeting 2021, and at the European Geosciences Union General Assembly 2022. Our modeling results will also be used by the New York State Hemlock Initiative and their partners (NYS DEC and NYC DEP) to target catchments in the Hudson Valley that are likely to contribute most significantly to downstream flooding, for biological control and treatment of the Hemlock Woolly Adelgid, an invasive insect that is driving hemlock loss across the Northeastern U.S.

Student Training

This project has trained three undergraduates: Miles McDonald, Olivia Pietz, and Bea Mace. The students have received a rounded education in setting up a field study location, field sampling, installing, using, and troubleshooting field instruments, extracting water samples from plant tissue and soil cores through the method of cryogenic vacuum distillation, analyzing stable water isotopes through a mass spectrometry-based approach, constructing gas exchange chambers, measuring transpiration and photosynthesis.

Publications/Presentations

We aim to generate at least 3 peer-reviewed publications from this work, currently in prep but expected to move to journal revision in early 2022.

Additional final reports related to water resource research are available at http://wri.cals.cornell.edu/news/research-reports

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Appendices

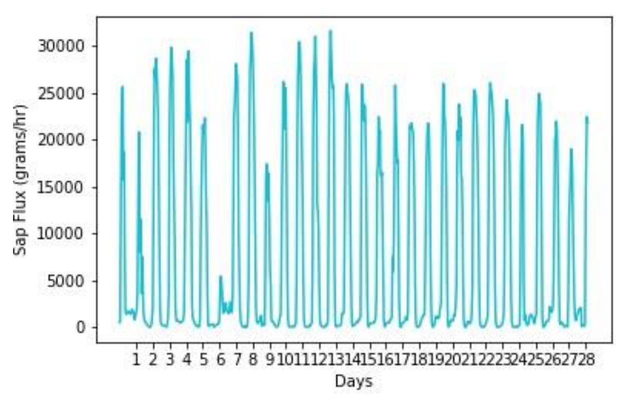

Fig 1: Daily sap flux data captured from one of eight sap flux sensors installed at field site over a month. Day and night oscillations in sap flow are evident.

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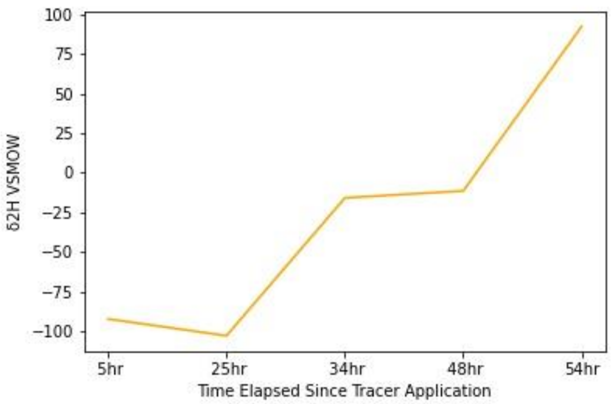

Fig 2: Test data of isotopic signature in transpiration collected from a single plant over a period of 54 hours following tracer application.

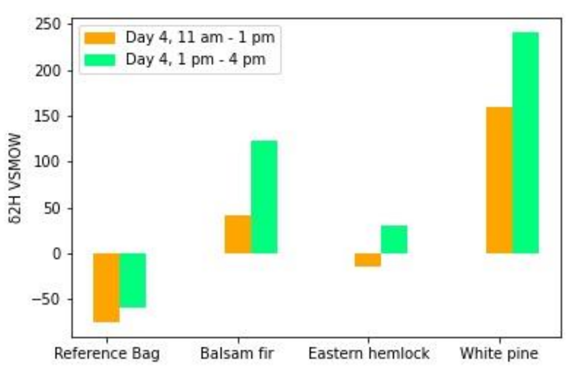

Fig 3: Test data of isotopic signature in transpired water from three plants and a reference. Water samples were collected on day 4 of sampling at times indicated.

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