Interactive Hydrological Modelling and Simulation on Client-Side Web Systems: An Educational Case Study

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Abstract:
Computational hydrological models and simulations are fundamental pieces of the workflow of contemporary hydroscience research, education, and professional engineering activities. In support of hydrological modelling efforts, web-enabled tools for data processing, storage, computation, and visualization have proliferated. Most of these efforts rely on server resources for computation and data tasks, and client-side resources for visualization. However, continued advancements of in-browser, client-side compute performance present an opportunity to further leverage client-side resources. Towards this end, we present an operational rainfall-runoff model and simulation engine running entirely on the client-side using the JavaScript programming language. To demonstrate potential uses, we also present an easy-to-use in-browser interface designed for hydroscience education. Although the use case presented here is self-contained, the core technologies can extend to leverage multi-core processing on single machines and parallelization capabilities of multiple clients or JavaScript enabled servers. These possibilities suggest client-side hydrologic simulation can play a central role in a dynamic, interconnected ecosystem of web-ready hydrologic tools.

Keywords: client-side simulation, hydrological modelling, web-based simulation, hydrology

Highlights:
- We present HLM-Web, a simulation engine for rainfall-runoff modelling in JavaScript.
- The simulation engine runs full scale, physically based rainfall-runoff models.
- All computations are performed on the client-side within the browser.
- HLM-Web is demonstrated with a use case for hydroscience education.
- Use case facilitates hydrologic education and research "sandboxing".

Software
Name: HLM-Web
Developer: Gregory Ewing, Hydroinformatics Lab, University of Iowa
Contact Information: gregory-ewing@uiowa.edu
Year Available: 2022
Hardware Required: Any device with a browser
Software Required: Device with ECMA Script (i.e., JavaScript,) interpreter (e.g., a web browser.)
Availability and Cost: Open source, Free.
URL: https://github.com/uihilab/HLM-Web

1. Introduction

Computational models allow scientists and engineers to simulate the complex relationships that exist in real world systems. In water resources, computational hydrological models are fundamental pieces of the workflow of contemporary research, education, and professional practice. These models are used to support a broad range of tasks, including engineering design (e.g. Gironás *et al.*, 2010; US Army Corps of Engineers, 2018), flood forecasting (e.g. Beven *et al.*, 1984; Krajewski *et al.*, 2017), flood inundation mapping (Li & Demir, 2022), sedimentation forecasting (Xu *et al.*, 2019), water quality research (Jha *et al.*, 2007), and water resources management (Sulis & Sechi, 2013), among others.

From a practical perspective, using physically-based models present many challenges. Data appropriateness, preparation, scale, sparsity, and errors are significant obstacles that prohibit the use and confidence of models. Users must also contend with learning a standalone graphical user interface – or lack thereof – to access and deploy the modelling software. Likewise, the coupled challenge of access to computational resources, and the expertise to manage them, can be a significant burden to run a model fit for its intended purpose. These difficulties set a high training level threshold that stakeholders must meet if they want to use these tools and models. Finally, challenges of model reputation, adoption among stakeholders, and lack of benchmark datasets (Ebert-Uphoff *et al.*, 2017) for comparative analysis present limitations to the reproducibility and impact of model findings.

Many of these practical challenges are associated with desktop-based, or off-line, modelling workflows. In response, hydroscience computational architectures have advanced alongside cyber and computing technologies. The most recent advances fall within Web-Based Simulation (WBS) or the use of the Internet to separate modeling tasks among networked machines. A key criterion of WBS is that a web browser plays an active role in modelling and simulation sub-tasks, such as for simulation, visualization, data storage, or documentation (Byrne *et al.*, 2010).

Arguably, the two primary goals of WBS are simulation and visualization. In a client-server model, either of these tasks can be completed locally, in a browser on the client's local machine, or remotely, on a server. There are numerous examples of server-side simulation for hydrology and water resources studies, such as streamflow forecasting (Castronova *et al.*, 2013), ecosystems services (Feng *et al.*, 2011), hydrology and climate change (Goodall *et al.*, 2013; Zhang *et al.*, 2019), watershed management (Demir & Beck, 2009), mountainous snow-water resources (Wu *et al.*, 2018), environmental decision support (Sun, 2013), and urban watershed hydrology (Zeng *et al.*, 2021).

Likewise, there are equally many examples of client-side implementations of data exploration and visualization tools ranging from pure client-side architectures (Jadidoleslam *et al.*, 2020; Walker *et al.*, 2020) to architectures that offer client-side visualizations and some server-side data analytics (Booth *et al.*, 2011; Brendel *et al.*, 2019; Rottler *et al.*, 2021). Further, other efforts have sought to integrate server-side computation and data storage with client-side visualization to support web-based hydrologic workflows (Peckham *et al.*, 2013; Delipetrev *et al.*, 2014; Swain *et al.*, 2015; 2016; Yildirim and Demir 2021). Taken together, these efforts demonstrate a focus on, and the viability of, modelling as a web-service for hydrologic applications. Notably, this design places computation and simulation predominantly on server resources.

Client-side simulation, however, should not be ruled out as a viable option as it offers many usability advantages. First, all modern browsers comply with the ECMAScript specification (ECMA International,

2021), i.e. JavaScript, meaning that JavaScript code is interoperable across any browser on any device, no matter the browser or machine. Second, recent advances in JavaScript interpreters have resulted in significant increases in compute speeds, with one-to-one tests showing JavaScript performance on the order of magnitude of C++ code (Hinkelmann, 2019). When considering a computationally intensive task, JavaScript no longer holds a severe performance disadvantage, while still maintaining its usability and interoperability advantages as a native web language.

Client-side compute resources have been used to perform various computational tasks, including modelling, in environmental and water resources applications. Prior to the cross-browser standardization of JavaScript, Java language applets were used to perform client-side tasks, such as calculations for decision support tools in watershed management (Voinov and Costanza 1999; Mustajoki *et al.,* 2004). More recent examples show the potential to leverage client-side compute resources for much of a WBS workflow. A client-side simulation engine was implemented to calculate BOD and DO along a river reach (Walker & Chapra, 2014). The simulation engine was complemented by client-side visualization and a user interface which allowed for rapid iteration of simulation inputs. The same authors also implemented a client-side version of the ABCD Water Balance model to simulate streamflow at a daily scale (Walker, 2014). In another example, a web-based analysis and scenario tool for eutrophication of inland waters performs all necessary computations in the web browser (Strömbäck *et al.,* 2019). The authors, however, report that they simplified the original model to make the browser implementation more performant. Finally, a numerical engine has been developed to simulate tsunami wave generation and propagation, and its visualization, as a JavaScript-WebGL library (Galaz *et al.,* 2022). The simulation engine was tightly coupled with other web elements, data sources, and sensors to support a web platform for public education and tsunami awareness.

Environmental web applications have demonstrated the potential to leverage client-side computational resources for flood mitigation (Alabbad *et al.,* 2022), well forecasting (Sit *et al.,* 2021), sedimentation forecasting (Xu *et al.*, 2019), and decision support systems (Ewing & Demir, 2021). Furthermore, other client-side tools have been developed for hydrological studies focusing on participatory decision support (Teague *et al.,* 2021), watershed delineation (Sit *et al.,* 2019), and flood map generation (Hu & Demir, 2021). Taken together, an ecosystem of web-ready, hydrologic tools has emerged in the last decade. Implementing a hydrological model in JavaScript, the lingua franca of the web, provides many opportunities for extensions in this dynamic, interconnected ecosystem.

In this paper we demonstrate the capability of client-side technologies to perform hydrological modelling via a JavaScript-based simulation engine for full scale, physically based rainfall-runoff models. Further, to demonstrate potential uses, we also present a fast and interactive in-browser interface designed for hydroscience education. We show that coupling client-side simulation and an in-browser user interface can advance education and greatly reduce the entry threshold needed to operate and apply hydrological models. In the Materials and Methods section, we detail the hydrological model used, a previous implementation of the same model in the C Programming Language, and then the current implementation of the model in the JavaScript language. In the Results section, we first detail the benchmarking and time performance of the new implementation. We then detail the client-side model and simulation engine as part of an educational use case. In the Discussion section, we examine further the performance and discuss the benefits of client-side simulation for research, education, and operation. We conclude with a look to future work and the general benefits to client-side computation for water and environmental modelling.

2. Materials and Methods

In this section we first describe the hydrological model, the Hillslope Link Model (HLM), implemented in JavaScript. Next, we describe the original implementation of HLM in the C programming language. Finally, we describe the current methodology to implement the hydrological model as a native client-side simulation engine.

2.1. Hillslope Link Model

The nature of how rainfall is transformed on and through the landscape to generate runoff and streamflow is a complex physical process, and accurate estimation of this process is important for flood forecasting, disaster relief, engineering design, etc. To address these needs, mathematical models to estimate runoff generation from rainfall have proliferated. One such model is the Hillslope-Link Model (HLM) (Mantilla, 2022). HLM uses the concept of landscape decomposition into just two elements: hillslopes and channel links. Hillslopes are irregular-shaped polygons where the conversion of rainfall to runoff takes place. This process depends on the hillslope attributes such as size, shape, slope, exposure, soil type and land use. Each hillslope is uniquely associated with a channel link. A hillslope's runoff, both surface and subsurface, drains to the corresponding link and the links make the river network. Runoff that finds its way to the channel is transported downstream and aggregated as the small streams come together to form larger ones that then become rivers; first small then larger. Channel links also have certain attributes that control water transport. These include length, slope, roughness, as well as other aspects of hydraulic geometry (e.g., channel cross sectional shape). The typical size of a hillslope is on the order of 0.01 km^2 and the typical length of a link is on the order of 0.1 km.

The construction of the modeling domain (also called "hydrofabric",) requires use of digital topography data, better known as Digital Elevation Model (DEM). Such data are widely available at very high spatial resolution, as high or higher than 10 m. From the DEM data one can extract the drainage (river) network and its basic attributes and the associated outline of the hillslopes with some of the key attributes (Mantilla & Gupta, 2005). From other available public sources, such as land surveys, one can obtain the information regarding land use and soil types as well as the geometry of the channel cross-sections.

Mathematically, the physical processes involved in runoff generation and transport can be described as a set of ordinary differential equations. There is a good deal of flexibility on how detailed of a description is desired. For example, a simple model can be based on constant runoff coefficient (fractions of rainfall) and constant channel velocity. This results in a linear system of equations and thus is easy to solve. A more realistic description could be based on a non-linear concept of storage at a hillslope and non-linear channel velocity. The resulting system requires a numerical algorithm to solve. Please refer to Appendix 2 in Supplemental Material for a description of the mathematical formulations of the constant and variable runoff models. Likewise, formulation of both the constant and variable runoff models can also be found in (Small & Debionne, 2016).

HLM has several attractive properties. First, it respects the scaling (fractal) properties of real river networks (e.g., Horton laws). This allows the model to mimic the correct temporal response for a given size upstream drainage area. Second, it avoids the challenge of properly estimating the lateral fluxes necessary for other regular grid-based models. Each hillslope drains to one channel link and there is no other "communication" between the adjacent hillslopes (this is true ignoring the saturated groundwater contribution to streamflow).

Third, as we just briefly discussed above, the model structure (hydrofabric,) and the mathematical description of the physical process are independent. This allows for a consistent study of the importance of different models of certain processes. Four, the numerical solvers of ordinary differential equation are much more efficient and easier to implement. The model structure is also amenable to parallelization. Note that the computations of runoff at the hillslopes are independent from each other and that it is the transport of water in the river network that is coupled but in a rather weak way (computations at a link require availability of streamflow at the two nodes upstream). Five, the model does not require intensive calibration. With a reasonable selection of the parameters, which all have some physical interpretation, the model demonstrates an acceptable level of skill out-of-the-box.

2.2. High Performance Computing (HPC) Implementation

Note that HLM framework is the mathematical model by which to describe the physical, hydrological processes. To solve these equations, i.e., simulate the rainfall-runoff response of a network, a numerical solver is required. One advantage of the HLM framework is that its river network has a directed graph topology, such that the solution at a hillslope only requires information at the hillslope itself and its direct "parents." Because of this structure, a numerical solution to the rainfall-runoff response at each hillslope-link can be found asynchronously. One such numerical solver has been developed to solve systems of ODEs linked by a directed tree structure, as in the case of the HLM river network topology (Small *et al.,* 2013). This solver was written in the C programming language and uses an adaptive step size Runge-Kutta method with dense output interpolant capabilities. The authors also present a network partitioning scheme and scheduler routine which enables distributed and parallel workflows to support massive simulations with HPC resources. A version of this implementation provides operational hydrologic forecasts for the entire domain of Iowa (Krajewski *et al.,* 2017), and is also used for research applications (e.g. Jadidoleslam *et al.*, 2019). Currently, it supports a variety of input and output types such as from databases, binaries, text files, and hierarchical data formats.

2.3. Client-side Implementation

This section details the methodology of the client-side (i.e., JavaScript) web application for simulating the rainfall-runoff response of a river network using the HLM family of models. First, we chose to use HLM because of its flexibility to describe varying levels of complexity in the physical processes; it is open source and well-documented; it has proven its performance in advanced operational forecasting and research applications; and, finally, we have significant experience with it.

To develop HLM-Web as a JavaScript application we used the object-oriented programming paradigm. As stated previously, DEM data are processed to generate discrete hillslope-link sections with distinct physical properties, such as channel length, area of hillslope, and total upstream area. As such, the hillslope-link unit was used as the basis for the object model. Each hillslope link object contains object methods and properties. In general, these methods and properties can be categorized into three groups: physical attributes, model structure (equations), and numerical solver. All necessary properties and methods are added at object instantiation, but can also be altered prior to simulation execution.

Physical attributes of the hillslope link object are either direct inputs from the discretization of the river network to be simulated or were calculated using both the hillslope-specific physical attributes and global variables that apply for all hillslope link objects. Refer to Appendix 2 in Supplemental Material for

definition and use of the physical attributes in the model equations. Refer to the HLM-Web Educational Hydrology Tool section for more information about setting global variables.

HLM-Web uses The Runge-Kutta method (4th order) as a numerical solver. This method is used with an adaptive step size routine that compares the truncation errors of derivative approximations to user-defined error thresholds to adapt the step size of the integration (Press *et al.,* 1986). Further, a dense-output interpolation scheme was used in the solver (Hairer *et al.,* 1993). Dense output schemes allow for higher-order interpolation between step sizes. This is an important feature of the solver because the integration at a hillslope-link requires the discharge from upstream links as an input. Due to the adaptive step size routine, it is unlikely that the upstream links will have a solution at the exact time required for the downstream link. As such, the dense method is used to interpolate the discharge from upstream links as necessary to solve for a hillslope-link.

At each hillslope link, the hydrologic model is described as a set of ordinary differential equations. These equations vary depending on the model (i.e., constant versus variable runoff.) See Appendix 2 in Supplemental Material for a mathematical comparison between the constant and variable runoff models. At the instantiation of a Link object a function is assigned to the object as a method (dydt.) No matter the internal structure of the derivatives themselves, the method takes the same inputs: an array, Y, of states of the link; the current simulation time, t; and an array, f, for the forcing (evaporation, precipitation, etc.,) at the current simulation time. The function returns the calculated derivates in an array of equal length to that of array Y.

A complete HLM-Web simulation work cycle can be found below in Figure 1. On initiation of a simulation, the numerical solver configuration data is accessed from the setup file and used, along with the parametric, forcing, and model data, to instantiate the links to be solved. Next, a Link object is instantiated for every hillslope-link in the simulation, the order of their solution is collected, and then it used to step all links to the end of the simulation time. The procedure to step the solution at a link forward in time is an iterative process. First, the subroutine estimates the solution at a step forward in time. If the estimated truncation error is too large for the solution, a smaller step size is calculated and then used to advance the solution. This procedure is done until the solution for the link has reached the end of simulation time.

The order by which the Link objects will be stepped can be generated on the fly using the function (getOrder,) or supplied in an input file. Our current methodology is to provide an input file where the order of hillslopes to be processed is generated by a post-order traversal listing of link ids from a depth first search of the river network as a directed graph. Because solving a link only requires information from the link itself and the link(s) immediately upstream of it, all data held in the upstream link objects can be scrubbed once the simulation of the downstream link is complete. Thus, the post-order traversal is a memory-efficient order by which to solve for the links. Only simulation data from preselected links are stored after they are used for the solution of links immediately downstream. Once all link objects have stepped to the end of simulation time, the simulation runtime is reported. Simulation results can be exported as comma separated values or viewed in a figure within the browser window.

It is important to note that this workflow is essentially the same, whether the core HLM-Web simulation engine is used alone or with a graphical user interface (such as the educational user interface presented in Results.) Input data can either be edited within the files prior to the browser parsing them or after.
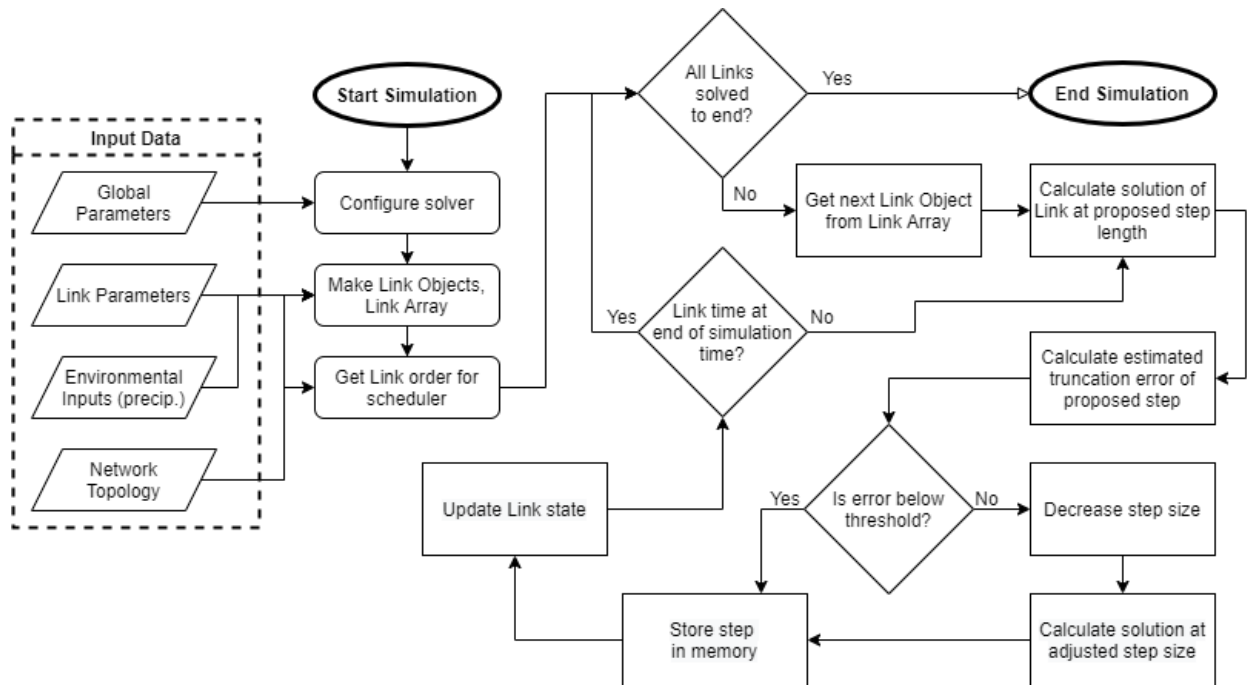

Figure 1. Complete workflow diagram of an HLM-Web simulation.

3. Results

In this section we present and detail two case studies of the HLM-Web simulation engine. First, we illustrate that HLM-Web reproduces simulation results with adequate time performance as compared to the C Programming Language implementation. Next, we illustrate how HLM-Web's simulation engine can be integrated with other web technologies to create an interactive educational tool to support hydrology education.

3.1. Simulation Benchmark and Time Performance

Several benchmarking tests are provided with HLM's C Programming Language implementation (Iowa Flood Center (IFC), 2018) and are discussed in detail in the project's documentation (Small & Debionne, 2016). Two such benchmarking tests use the constant and variable runoff models, respectively. These two benchmarking simulations were used to demonstrate HLM-Web's ability to reproduce results generated using the C Programming Language implementation. Simulation results show that the model outputs are completely coincident (Figure 2.) These results show that simulation results from the HLM-Web (JavaScript,) simulation engine are concordant with the C Programming Language version of the model. Thus, we have successfully implemented the solver and properly constructed each model.

Next, simulation runtime performance between the two implementations was compared. Simulations for river networks of varying size and constant simulation length of 24 hours were performed (Figure 3.) To provide equal comparison all simulations were performed on a Dell XPS 9560 with an Intel(R) Core (TM) i7-7700HQ CPU @ 2.80GHz. Google's Chrome browser, with the V8 JavaScript interpreter, was used for

the client-side simulation runs. Parallel processing was not used with the C code runs. The constant runoff hillslope formulation was used.
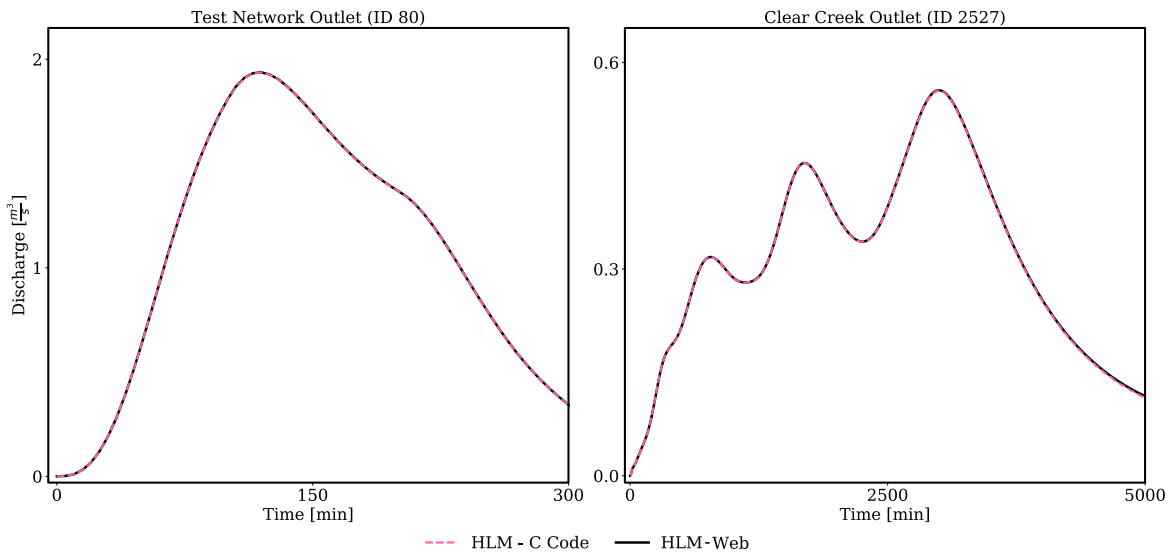

Figure 2. Benchmarking tests for the implementation of the HLM-Web compared to the C Programming Language implementation of HLM. The Test network (left) compares results of the JavaScript and C code implementations of the Constant Runoff Model at the network's outlet. Clear Creek (right) compares results of the Variable Runoff Model at its outlet.
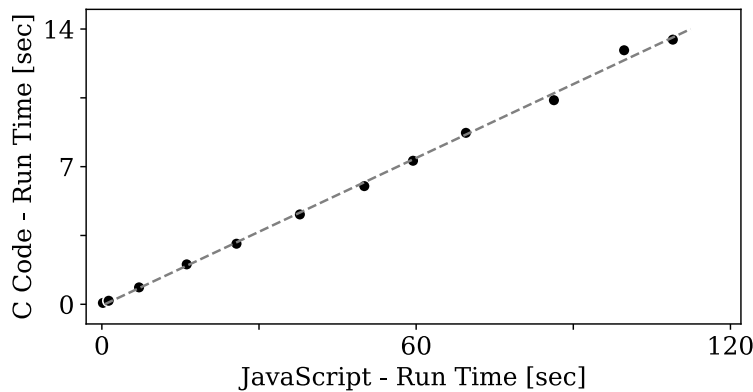

Figure 3. Simulation run time, in seconds, for JavaScript and C Programming Language implementations of the Hillslope Link Model. Simulations of river networks of increasing size and uniform rainfall forcing were used in both languages. All simulation runs simulate a 24-hour period. At the end of each simulation run, the simulation software reports the length of the simulation in seconds. Simulation results are plotted with a linear regression line fitted to the data. The slope of the line is 8.0, $R^2 = 0.99$, and n = 12.

3.2. HLM-Web Educational Hydrology Tool

The second demonstration of the HLM-Web simulation engine is an interactive educational tool to teach hydrology. Though models are fundamental to various professional workflows, there are many challenges to a model's successful integration into hydroscience curricula. First, the educational focus in hydroscience curricula is (or should be,) on core hydroscience concepts and not a particular vocational tool, such as a

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model. Equally, there is no single model (i.e., vocational tool,) that is universally used professionally, which would justify its instruction over all others, always.

If indeed a model is selected for classroom use, instructors face barriers to its successful educational application. Many barriers, if not all, stem from the most essential and precious resource: time. For example, data acquisition and preparation are fundamental modeling tasks. Yet, they can be the most time consuming. Various surveys of professionals across data science and scientific modeling disciplines show that data acquisition and data preparation account for a majority of the time spent on a modeling workflow (Anaconda, 2020; CrowdFlower, 2016; Jackson, 2014; Lohr, 2014). Further, using models often requires specific, standalone software and other Information Technology (IT) knowledge to operate. These technologies often have steep learning curves, especially for beginners. Learning and executing these parts of a model workflow take much more time than the time for computation and analysis of results, especially in the case of classroom examples. Thus, there is a tension for the instructor, between teaching the fundamentals of the subject matter and teaching the model workflow as a conduit to explore the subject matter; in short, teaching the science vs. teaching the tool. This reality describes the challenge to teach contemporary hydroscience topics in a manner which recognizes the state-of-the-science tools, without obscuring the subject fundamentals behind the technical/vocational knowledge of specific software or toolchains.

HLM's concept of the landscape decomposition and the resultant mathematical description are well suited for educational applications. In fact, one can organize an entire undergraduate engineering hydrology course using it. First, it is undisputable that the concept faithfully describes surface (including near subsurface or unsaturated zone) water flow in the environment. This facilitates subsequent discussion of the relevant physical processes of rainfall, evapotranspiration, infiltration, runoff, and open channel flow. Because the concept naturally covers a wide range of spatial and temporal scales, it provides background for discussion of space-time variability, land-atmosphere mass and energy exchange, the concept of storage and water balance, and water transport. As the model use requires data, this provides an opportunity to discuss different measurement and sensing technologies, from radar-rainfall to satellite-based soil moisture to in-situ techniques of water evaporation, infiltration, and flow. With the above elements in place, one can illustrate the key engineering practice methods of the rational method, curve number, unit hydrograph, and flood frequency estimation.

However, the current workflow for the C Programming Language implementation of the HLM model has many characteristics which prohibit its use as an educational tool. The first issue is that of access. This implementation is best suited for HPC environments, where the codebase, its dependencies, and the networked computing resources are maintained by IT professionals. Lack of access to HPC environments limits its use. The alternative to using an established HPC environment would require students to install and maintain a version – and all its dependencies – on one's personal machine. This also presents a significant burden to use. Second, this implementation lacks a graphical user interface. This requires users to alter input files manually, usually in a command line interface. Finally, the C Programming Language implementation lacks even a simple visualization tool. This means that the user would need to interpret simulation results in yet another software. Instructors cannot reasonably expect that students have the requisite knowledge of the supporting technologies required to use the current HLM workflow. Further,

they should not take time within a hydroscience course to teach them. Thus, the current C code implementation significantly limits any possibility of HLM's use in a classroom environment.

Toward the goal of making this model more accessible to educational applications, we extended the HLM-Web simulation engine with an easy-to-use user interface. Notably, all features of the educational tool are based on client-side technologies. The tool was developed with iterative feedback from course instructors with the objective that it would supplement the hydrology courses at the University of Iowa, Department of Civil and Environmental Engineering and University of Manitoba, Department of Civil Engineering.

In our design process we sought to clearly separate the model preparation subtasks, e.g., building a simulation "recipe". Each recipe subtask – domain selection, model selection, parameter selection, and rainfall input – has its own tab within the webpage (Figure *4*.) For model selection, users choose between five different river networks to simulate. These networks range in size of 10^1 to 10^4 km^2. Importantly, all input files required to simulate the river networks are already prepared for students. Users then choose between two mathematical models, the Constant Runoff Model, or the Variable Runoff Model, to describe the runoff generation and streamflow processes. Next, in the parameter selection tab, users have the option to alter global variables which are used in the model calculations. Parameter values are toggled via HTML slider inputs. Slider ranges are predefined by the course instructor and are based on a reasonable physical range of each parameter. Next, users define rainfall input for the simulation in the rainfall input tab. On this tab users select between three different rainfall event types: a single, constant event; a repeated, constant event; and a custom event. In a panel, users can track the current simulation recipe as it changes given inputs. Once the user has reviewed the simulation recipe, they can trigger the simulation execution. When the simulation is complete, the webpage automatically displays the visualization of the results.

Simulation results are shown at preselected hillslope links within the network. For this educational application, hillslope link results were selected for visualization by their approximate stream order with respect to the contributing area of the network outlet. Without needing to refresh the current webpage or navigate to a new page, users can easily change the simulation setup and run the simulation again. Simulation results (i.e., hydrographs,) and metadata can also be exported in comma separated values (CSV) format for further analysis and visualization.

4. Discussion
HLM-Web demonstrates that it is possible to implement a full-scale distributed rainfall-runoff model and simulation engine using only modern web standards. To the best of our knowledge, a full-scale hydrological model running completely as a client-side application has not yet been presented in the literature. Furthermore, we demonstrate that this technology can be applied to provide an accessible educational tool to the undergraduate hydroscience curriculum. In implementing a distributed rainfall-runoff model on the web, the technology becomes available for use alongside the many web-based applications that comprise the dynamic and interconnected ecosystem of web-ready hydrologic tools.

We begin this section with a brief discussion of benchmarking results. Next, we discuss the computational performance of HLM-Web and the potential strategies to improve it. Next, we discuss the benefits of client-

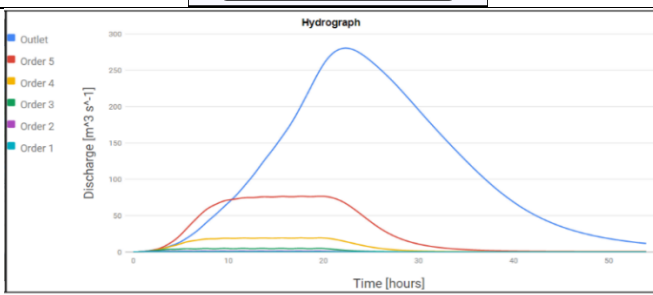|	
	Step 1. Select Domain: Choose one of five watersheds to simulate their runoff response (only three shown to the left.) Watersheds vary in size from $10 - 12{,}000$ km^2.
	Step 2. Select Model: Choose either the Constant Runoff or Variable Runoff – for how water is routed on the land surface and within the soil subsurface. (See Appendix 2 in Supplemental Material for mathematical details, equations, and descriptions of each.)
	Step 3. Set Model Parameters: Provide values for internal parameters of the hydrological model chosen in Step 2.
	Step 4. Define Rainfall: Define the rainfall forcing to be used in the simulation. Within Rainfall Forcing Generator, users can generate rainfall for a single event, repeated events, or for a custom event type. A repeated event is shown to the left, with the details of 25 mm per hour, lasting 60 minutes, repeating 10 times, with an interval of 60 minutes between intervals.
	Step 5. Review Simulation Recipe: After finishing building a simulation recipe, users will be prompted to review and then run their simulation. During review, if any errors or missing values are found, users will not be able to proceed to the simulation step without correction.
	Step 6. View & Analyze Results: Upon completion of simulation, the browser automatically will generate an interactive figure with hydrographs for pre-defined model elements. Users may also export these results to a CSV file format.

Figure 4. Step-by-step demonstration of the education webtool for hydrology courses using HLM-Web as simulation engine. The six-step process was designed with the consultation of hydrology instructors with the objective to simplify and streamline the modelling and simulation process.

side simulation via the strengths of our HLM-Web educational tool. Finally, we conclude with a discussion of how the technology may be leveraged beyond education in outreach, research, and operations.

Benchmark and Performance Results: Via the direct comparison of benchmark results provided in the HLM documentation (Figure 2), we show that the JavaScript-based HLM-Web provides identical results for both the constant and variable runoff models. This verifies two important criteria. The first, is that we have accurately formulated the mathematical models. The second is that we have demonstrated the ability of our numerical solver to return equivalent solutions to that of the solver of the current, operational version.

In comparing the time performance of the JavaScript implementation versus that of the C code implementation, we observe that the JavaScript implementation is slower by approximately a factor of 8 (Figure 3). The performance penalty is on the higher end of the current expectations of JavaScript interpreters being 2-10 times slower than C code (Hinkelmann, 2019).

The current performance leads us to ask two related questions. The first question is whether there are changes to the codebase that could bring the one-to-one performance closer to the expected upper limit of 2 times slower between JavaScript and C. Notably, our JavaScript code is not an exact replication of the C code. One difference between the two is in the data structures of the model elements. JavaScript is an object-oriented programming language, while C is not. Though the object-oriented paradigm of JavaScript allowed us to develop the application with "higher-level" data structures, the advantages of development with higher-level data structures may result in slower run times.

Another critical difference that may affect performance is the interconnection between memory management and the scheduler. In the C code, the user must specify how many previously computed timesteps are stored in an internal buffer for each link. The selection of the internal buffer size has implications on how the scheduler moves the solution forward at each link. It also allows the software to allocate a fixed amount of memory to the results for each link in the simulation. In comparison, the HLM-Web implementation has no limit to the number of steps stored in memory for each link, nor does it allocate a pre-computed amount of memory for link solutions at object instantiation. As a result, storing solutions during simulation runs requires dynamic allocation of memory and its associated performance penalty.

An additional performance bottleneck of the current scheduler is that it sequentially solves a Link object to the end of the simulation before beginning the solution of the next Link object. As stated in the Client-side Implementation section, the solver is an adaptive time step solver with a dense output method to interpolate solutions for upstream links between their computed timesteps. During the interpolant routine, a binary search algorithm is used to find the necessary solutions from the upstream link for interpolation. In practical terms, this means that for every interpolant routine run there is a binary search performed on an array. This array can be orders of magnitude larger than the default internal buffer size of 30 past timesteps held in memory used in the C code. This implies that for every dense interpolant calculated the search time is longer than in the C code implementation, which attributes to the performance difference.

The second question with respect to improving compute speeds is what can be done generally. This question is different than the first in the sense that improvement need not be compared one-to-one with the C implementation, but generally to itself. In this regard, two current web standards, Web Assembly and Web

Workers, offer means to improve compute speeds. First, Web Assembly is a standard which allows the execution of portable binary-code to be run on web pages (Haas *et al.,* 2017). In practical terms, leveraging this technology would allow for the entire simulation engine, or portions of it, to be run at speeds approaching native C code (Mozilla, 2013). Second, Web Worker technology allows JavaScript code to be executed in the background without blocking the function of the webpage it is running in (MDN, 2022). A characteristic feature of Web Worker technology is that it can more effectively use multi-core CPUs. Thus, another avenue to improve computational speeds is to parallelize the simulation task across a client's CPU cores via a Web Worker.

HLM-Web Educational Hydrology Tool: As we demonstrate with the educational use case, a client-side simulation workflow can mitigate some of the challenges of offline workflows for users. First, the client-side architecture of HLM-Web allows for interoperable, no install, no set up hydrological applications. This means that users can perform simulations on any device which has a browser, even on simple machines such as mobile phones or browser-only devices like Chromebooks. Likewise, when the HLW-Web simulation engine is combined with an easy-to-use web interface, modelling and simulation can be done without writing any code. Here, HLM-Web has a major advantage to other options available to educators. Although engineering students are expected to have some skill in programming, developing a full-scale model (code) within a single semester is clearly beyond their level of proficiency.

For users, the time and burden of data preparation and handling are all but eliminated with the HLM-Web educational tool. Likewise, the instructor can calibrate the amount of exposure to the data preparation and handling tasks needed without it being a critical lynchpin within a course. Taken together, HLM-Web and the easy-to-use web interface provides a "flat" learning curve for users to focus on hydrology. Instructors have used the tool for in-class demonstrations, homework, and final examinations. Concepts taught using the HLM-Web educational tool include simulating watershed response at a range of spatial scales, and in the process demonstrate the role of river network on flow aggregation; the role of rainfall intermittency on peak flow magnitude; the role of soil moisture as a system memory; unit hydrograph theory; and more. Please refer to Appendix 3 in supplemental materials where we provide sample problems which use the HLW-Web Educational Hydrology Tool.

Other Application Areas: There are many benefits to a distributed rainfall-runoff model implemented completely in modern, client-side web standards. While many of these benefits are exhibited in the educational tool presented here, they can also be leveraged in application areas such as operations, outreach, and research. First, a curated and simplified interface creates the scaffolding for rapid simulation without writing any code or manual alteration of inputs or parameterization. This can significantly lower barriers to time-sensitive use of simulation and models. For example, with improvements to compute speeds, either via more computational power or parallelization, HLM-Web could serve as a research sandbox to rapidly test different model formulations or parameter combinations.

The model application can also be coupled with online data products for seamless data preparation and integration. For example, the river network input data could be served to the browser dynamically based on latitude and longitude coordinates supplied via a map interface. Rainfall products, either historical or forecasts, could be queried from a web service (e.g. Seo *et al.,* 2019,) and served to the browser for direct integration with the simulation engine. These input data could then be used to generate custom forecasts

for a region of interest, or design flows for a proposed project. This streamflow data could then be used for dynamic flood inundation mapping. Further, the flood inundation maps could then be used directly as outputs or as inputs to generate real-time estimates of flood damage. A workflow such as described would provide value to first responders, disaster planning, and flood plain managers. The automated data preparation and integration opportunities could significantly improve some of modelling's most tedious and time-consuming tasks and, as such, increase the access to advanced modelling tools.

A client-side simulation engine also offers some advantages over WBS with server-side compute. First, because HLM-Web does not itself use any server-side compute, it can be hosted on a simple web host for static files. Static hosting presents a significant cost savings compared to a server environment running compute intensive tasks, such as simulation. A second advantage to using JavaScript and client-side architectures is that it is inherently open source because the server passes the written code to the browser and then interprets it on the client machine. This is in contrast with the server-side compute model, where users do not necessarily have access to the source code used. In this manner, the codebase is more available to inspection and development by the community. These advancements lower barriers to access and increases ease-of-use of rainfall-runoff modelling and simulation for a range of applications. In effect, it provides a wide range of stakeholders the means to use and engage in the subject matter within a self-contained, ubiquitous platform.

5. Conclusion

In this work we present HLM-Web, a simulation engine for distributed rainfall-runoff modelling in JavaScript, which can run full-scale, physically based models on the client side using a browser. We show that the simulation engine provides equivalent results compared to benchmarks from a previous implementation of the same model in the C Programming Language. We then demonstrate how the core simulation engine can integrate with an easy-to-use in-browser interface designed for hydroscience education.

Previous work in the literature has demonstrated the possibility of in-browser, client-side modeling with simplified models of environmental phenomena. This work moves the field beyond the current state-of-the-science and shows the potential benefits to simulation using native web technologies. Namely, these benefits are increased integration with other web-based tools for hydrological modelling, such as integration of the input data and results pipelines; the inherit open-source nature of JavaScript applications; the write once, run everywhere characteristic of JavaScript, allowing for users to always access the most current version of the software; and the potential application pipelines it can service in education, outreach, and research.

Future work will focus on improving computational performance of the simulation engine and extending its modeling capabilities. Overall performance can be improved through improvement on single machines – via better scheduler and memory management; converting all or part of the engine to Web Assembly; leveraging parallelization of simulations with Web Workers – and developing distributed (Agliamzanov *et al.,* 2020), peer-to-peer compute capabilities. Extending modeling capabilities entails incorporating other environmental processes alongside the hydrologic models presented here and streamlining input and output data with other web-ready hydrologic tools. Together, with the possible extensions, the current

implementation suggests that client-side hydrologic modeling and simulation can play a central role in a dynamic, interconnected ecosystem of web-ready hydrologic tools.

6. References

(Mozilla), K. V. (2013). Starting at the Sun: Dalvik vs. ASM.js vs. Native. Retrieved August 11, 2021, from https://blog.mozilla.org/javascript/2013/08/01/staring-at-the-sun-dalvik-vs-spidermonkey/

Agliamzanov, R., Sit, M., & Demir, I. (2020). Hydrology@Home: A distributed volunteer computing framework for hydrological research and applications. *Journal of Hydroinformatics*. https://doi.org/10.2166/hydro.2019.170

Alabbad, Y., Yildirim, E., & Demir, I. (2022). Flood mitigation data analytics and decision support framework: Iowa Middle Cedar Watershed case study. *Science of the Total Environment*, *814*, 152768. https://doi.org/10.1016/j.scitotenv.2021.152768

Anaconda. (2020). *2020 State of Data Science*. Anaconda Inc.

Beven, K. J., Kirkby, M. J., Schofield, N., & Tagg, A. F. (1984). Testing a physically-based flood forecasting model (TOPMODEL) for three U.K. catchments. *Journal of Hydrology*. https://doi.org/10.1016/0022-1694(84)90159-8

Booth, N. L., Everman, E. J., Kuo, I. L., Sprague, L., & Murphy, L. (2011). A Web-Based Decision Support System for Assessing Regional Water-Quality Conditions and Management Actions. *Journal of the American Water Resources Association*. https://doi.org/10.1111/j.1752-1688.2011.00573.x

Brendel, C. E., Dymond, R. L., & Aguilar, M. F. (2019). An interactive web app for retrieval, visualization, and analysis of hydrologic and meteorological time series data. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2019.03.003

Byrne, J., Heavey, C., & Byrne, P. (2010). A review of Web-based simulation and supporting tools. *Simulation Modelling Practice and Theory*, 253–276. https://doi.org/10.1016/j.simpat.2009.09.013

Castronova, A. M., Goodall, J. L., & Elag, M. M. (2013). Models as web services using the Open Geospatial Consortium (OGC) Web Processing Service (WPS) standard. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2012.11.010

CrowdFlower. (2016). *Data Science Report*. Retrieved from http://www2.cs.uh.edu/~ceick/UDM/CFDS16.pdf

Delipetrev, B., Jonoski, A., & Solomatine, D. P. (2014). Development of a web application for water resources based on open source software. *Computers and Geosciences*. https://doi.org/10.1016/j.cageo.2013.09.012

Demir, I., & Beck, M. B. (2009). GWIS: a prototype information system for Georgia watersheds. In *Proceedings of the 2009 Georgia Water Resources Conference: Regional Water Management Opportunities*. Athens, GA, USA.

Ebert-Uphoff, I., Thompson, D. R., Demir, I., Gel, Y. R., Karpatne, A., Guereque, M., Kumar, V., Cabral-Cano, E., & Smyth, P. (2017). A vision for the development of benchmarks to bridge geoscience and data science. *17th International Workshop on Climate Informatics*. https://doi.org/10.5065/D6222SH7

Ewing, G., & Demir, I. (2021). An ethical decision-making framework with serious gaming: a smart water case study on flooding. *Journal of Hydroinformatics*, *23*(3), 466–482. https://doi.org/10.2166/hydro.2021.097

Feng, M., Liu, S., Euliss, N. H., Young, C., & Mushet, D. M. (2011). Prototyping an online wetland ecosystem services model using open model sharing standards. *Environmental Modelling and*

Software. https://doi.org/10.1016/j.envsoft.2010.10.008

Galaz, J., Cienfuegos, R., Echeverría, A., Pereira, S., Bertín, C., Prato, G., & Karich, J. C. (2022). Integrating tsunami simulations in web applications using BROWNI, an open source client-side GPU-powered tsunami simulation library. *Computers & Geosciences*, *159*(December 2021), 104976. https://doi.org/10.1016/j.cageo.2021.104976

Gironás, J., Roesner, L. A., Rossman, L. A., & Davis, J. (2010). A new applications manual for the Storm Water Management Model (SWMM). *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2009.11.009

Goodall, J. L., Saint, K. D., Ercan, M. B., Briley, L. J., Murphy, S., You, H., DeLuca, C., & Rood, R. B. (2013). Coupling climate and hydrological models: Interoperability through Web Services. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2013.03.019

Haas, A., Rossberg, A., Schuff, D. L., Titzer, B. L., Holman, M., Gohman, D., Wagner, L., Zakai, A., & Bastien, J. F. (2017). Bringing the web up to speed with WebAssembly. *ACM SIGPLAN Notices*, *52*(6), 185–200. https://doi.org/10.1145/3062341.3062363

Hairer, E., Nørsett, S. P., & Wanner, G. (1993). *Solving Ordinary Differential Equations I* (2nd ed., Vol. 8). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-78862-1

Hinkelmann, F. (2019). Speed, Speed, Speed: JavaScript vs C++ vs WebAssembly. In *International JavaScript Conference*. New York, NY, USA. Retrieved from https://youtu.be/aC_QLLilwso

Hu, A., & Demir, I. (2021). Real-time flood mapping on client-side web systems using hand model. *Hydrology*, *8*(2). https://doi.org/10.3390/hydrology8020065

International, E. (2021). ECMAScript 2021 Language Specification. Geneva: www.ecma-international.org. Retrieved from https://www.ecma-international.org/wp-content/uploads/ECMA-262_12th_edition_june_2021.pdf

Iowa Flood Center (IFC). (2018). Iowa-Flood-Center/asynch: A numerical library for solving differential equations with a tree structure. Emphasis is given to hillslope-link river basin models. Retrieved July 7, 2021, from https://github.com/Iowa-Flood-Center/asynch

Jackson, C. (2014). Average Time Spent on Each Step in the Simulation Process. Retrieved August 5, 2021, from https://www.lifecycleinsights.com/average-time-spent-on-each-step-in-the-simulation-process/

Jadidoleslam, N., Goska, R., Mantilla, R., & Krajewski, W. F. (2020). Hydrovise: A non-proprietary open-source software for hydrologic model and data visualization and evaluation. *Environmental Modelling and Software*, *134*, 104853. https://doi.org/10.1016/j.envsoft.2020.104853

Jadidoleslam, N., Mantilla, R., Krajewski, W. F., & Goska, R. (2019). Investigating the role of antecedent SMAP satellite soil moisture, radar rainfall and MODIS vegetation on runoff production in an agricultural region. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2019.124210

Krajewski, W. F., Ceynar, D., Demir, I., Goska, R., Kruger, A., Langel, C., Mantilla, R., Niemeier, J., Quintero, F., Seo, B., Small, S., Weber, L., & Young, N. C. (2017). Real-time flood forecasting and information system for the state of Iowa. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-D-15-00243.1

Li, Z., & Demir, I. (2022). A comprehensive web-based system for flood inundation map generation and comparative analysis based on height above nearest drainage. *Science of The Total Environment*, *828*, 154420. https://doi.org/10.1016/j.scitotenv.2022.154420

Lohr, S. (2014, April 17). For Big-Data Scientists, "Janitor Work" Is Key Hurdle to Insights. *New York Times*. Retrieved from https://www.nytimes.com/2014/08/18/technology/for-big-data-scientists-hurdle-to-insights-is-janitor-work.html

M. K. Jha, P. W. Gassman, & J. G. Arnold. (2007). Water Quality Modeling for the Raccoon River Watershed Using SWAT. *Transactions of the ASABE*, *50*(2), 479–493. https://doi.org/10.13031/2013.22660

Mantilla, R. (2022). The Hydrological Hillslope-Link Model for Space-Time Prediction of Streamflow: Insights and Applications at the Iowa Flood Center. In M. Astitha & E. Nikolopoulous (Eds.), *Extreme Weather Forecasting* (1st ed.). Elsevier. Retrieved from https://www.elsevier.com/books/extreme-weather-forecasting/astitha/978-0-12-820124-4

Mantilla, R., & Gupta, V. K. (2005). A GIS numerical framework to study the process basis of scaling statistics in river networks. *IEEE Geoscience and Remote Sensing Letters*. https://doi.org/10.1109/LGRS.2005.853571

MDN. (2022). Using Web Workers. Retrieved April 1, 2022, from https://developer.mozilla.org/en-US/docs/Web/API/Web_Workers_API

Mustajoki, J., Hämäläinen, R. P., & Marttunen, M. (2004). Participatory multicriteria decision analysis with Web-HIPRE: A case of lake regulation policy. *Environmental Modelling and Software*, *19*(6), 537–547. https://doi.org/10.1016/j.envsoft.2003.07.002

Peckham, S. D., Hutton, E. W. H., & Norris, B. (2013). A component-based approach to integrated modeling in the geosciences: The design of CSDMS. *Computers and Geosciences*. https://doi.org/10.1016/j.cageo.2012.04.002

Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. (1986). *Numerical Recipes - the Art of Scientific Computing* (1st ed.). New York: Cambridge University Press.

Rottler, E., Vormoor, K., Francke, T., & Bronstert, A. (2021). Hydro Explorer: An interactive web app to investigate changes in runoff timing and runoff seasonality all over the world. *River Research and Applications*. https://doi.org/10.1002/rra.3772

Seo, B. C., Keem, M., Hammond, R., Demir, I., & Krajewski, W. F. (2019). A pilot infrastructure for searching rainfall metadata and generating rainfall product using the big data of NEXRAD. *Environmental Modelling and Software*, *117*(December 2018), 69–75. https://doi.org/10.1016/j.envsoft.2019.03.008

Sit, M., Langel, R. J., Thompson, D., Cwiertny, D. M., & Demir, I. (2021). Web-based data analytics framework for well forecasting and groundwater quality. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.144121

Sit, M., Sermet, Y., & Demir, I. (2019). Optimized watershed delineation library for server-side and client-side web applications. *Open Geospatial Data, Software and Standards*, *4*(1). https://doi.org/10.1186/s40965-019-0068-9

Small, S. J., & Debionne, S. H. P. (2016). Built-in Models -- Asynch 1.0 documentation. Retrieved July 7, 2021, from https://asynch.readthedocs.io/en/latest/builtin_models.html

Small, S. J., Jay, L. O., Mantilla, R., Curtu, R., Cunha, L. K., Fonley, M., & Krajewski, W. F. (2013). An asynchronous solver for systems of ODEs linked by a directed tree structure. *Advances in Water Resources*, *53*, 23–32. https://doi.org/10.1016/j.advwatres.2012.10.011

Strömbäck, L., Pers, C., Strömqvist, J., Lindström, G., & Gustavsson, J. (2019). A web based analysis and

scenario tool for eutrophication of inland waters for Sweden and Europe. *Environmental Modelling and Software*, *111*(November 2017), 259–267. https://doi.org/10.1016/j.envsoft.2018.07.012

Sulis, A., & Sechi, G. M. (2013). Comparison of generic simulation models for water resource systems. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2012.09.012

Sun, A. (2013). Enabling collaborative decision-making in watershed management using cloud-computing services. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2012.11.008

Swain, N. R., Christensen, S. D., Snow, A. D., Dolder, H., Espinoza-Dávalos, G., Goharian, E., Jones, N., Nelson, E., Ames, D., & Burian, S. J. (2016). A new open source platform for lowering the barrier for environmental web app development. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2016.08.003

Swain, N. R., Latu, K., Christensen, S. D., Jones, N. L., Nelson, E. J., Ames, D. P., & Williams, G. P. (2015). A review of open source software solutions for developing water resources web applications. *Environmental Modelling and Software*, *67*, 108–117. https://doi.org/10.1016/j.envsoft.2015.01.014

Teague, A., Sermet, Y., Demir, I., & Muste, M. (2021). A collaborative serious game for water resources planning and hazard mitigation. *International Journal of Disaster Risk Reduction*, *53*(November 2020), 101977. https://doi.org/10.1016/j.ijdrr.2020.101977

US Army Corps of Engineers. (2018). Hydrologic Modeling System HEC-HMS. User's Manual. Version 4.3. *Hydrologic Engineering Centre*.

Voinov, A., & Costanza, R. (1999). Watershed management and the Web. *Journal of Environmental Management*, *56*(4), 231–245. https://doi.org/10.1006/jema.1999.0281

Walker, J. D. (2014). ABCD Model. Retrieved March 30, 2022, from https://abcd.walkerenvres.com/

Walker, J. D., & Chapra, S. C. (2014). A client-side web application for interactive environmental simulation modeling. *Environmental Modelling and Software*, *55*, 49–60. https://doi.org/10.1016/j.envsoft.2014.01.023

Walker, J. D., Letcher, B. H., Rodgers, K. D., Muhlfeld, C. C., & D'angelo, V. S. (2020). An interactive data visualization framework for exploring geospatial environmental datasets and model predictions. *Water (Switzerland)*. https://doi.org/10.3390/w12102928

Wu, R., Scully-Allison, C., Rifat, M. H., Painumkal, J., Dascalu, S., & Harris, F. C. (2018). Virtual watershed system: A web-service-based software package for environmental modeling. *Advances in Science, Technology and Engineering Systems*, *3*(5), 382–393. https://doi.org/10.25046/aj030544

Xu, H., Demir, I., Koylu, C., & Muste, M. (2019). A web-based geovisual analytics platform for identifying potential contributors to culvert sedimentation. *Science of the Total Environment*, *692*, 806–817. https://doi.org/10.1016/j.scitotenv.2019.07.157

Xu, H., Muste, M., & Demir, I. (2019). Web-based geospatial platform for the analysis and forecasting of sedimentation at culverts. *Journal of Hydroinformatics*. https://doi.org/10.2166/hydro.2019.068

Yildirim, E., & Demir, I. (2021). An Integrated Flood Risk Assessment and Mitigation Framework: A Case Study for Middle Cedar River Basin, Iowa, US. *International Journal of Disaster Risk Reduction*, *56*(January), 102113. https://doi.org/10.1016/j.ijdrr.2021.102113

Zeng, Z., Yuan, X., Liang, J., & Li, Y. (2021). Designing and implementing an SWMM-based web

service framework to provide decision support for real-time urban stormwater management. *Environmental Modelling and Software*, *135*(September 2020), 104887. https://doi.org/10.1016/j.envsoft.2020.104887

Zhang, D., Fu, W., Lin, Q., & Chen, X. (2019). WOF-SWAT: A web-based open-source framework for investigating the hydrological impacts of climate change and human activities through online simulation and visualization of SWAT models. *ISPRS International Journal of Geo-Information*. https://doi.org/10.3390/ijgi8090368

Appendix

1.   Software Details
Name: HLM-Web
Developer: Gregory Ewing, Hydroinformatics Lab, University of Iowa
Contact Information: gregory-ewing@uiowa.edu
Year Available: 2022
Hardware Required: Any device with a browser
Software Required: Device with ECMA Script (i.e., JavaScript,) interpreter (e.g., a web browser.)
Availability and Cost: Open source, Free.
URL: https://github.com/uihilab/HLM-Web

2. Mathematical Formulations for the Constant and Variable Runoff Models of the Hillslope Link Hydrologic Model

$$\frac{dq}{dt} = \frac{1}{\tau}\left(\frac{q}{q_r}\right)^{\lambda_1}\left(-q + \left(q_{pc} + q_{sc}\right) \cdot (A_h/60.0)\right.$$
$$\left. + q_{in}(t)\right)$$

$$\frac{ds_p}{dt} = p(t) \cdot c_1 - q_{pc} - e_p$$

$$\frac{ds_s}{dt} = p(t) \cdot c_2 - q_{sc} - e_s$$

Where,

$$\frac{1}{\tau} = \frac{60 \cdot v_r \cdot (A/A_r)^{\lambda_2}}{(1-\lambda_1) \cdot L \cdot 10^{-3}}$$

$$c_1 = RC \cdot (0.001/60)$$

$$c_2 = (1 - RC) \cdot (0.001/60)$$

Figure 5 Mathematic and pictorial description of the constant runoff model implemented in HLM-Web.

$$\frac{dq}{dt} = \frac{1}{\tau}\left(\frac{q}{q_r}\right)^{\lambda_1}\left(-q + c_2 \cdot \left(q_{pc} + q_{sc}\right) + q_{in}(t)\right)$$

$$\frac{ds_p}{dt} = c_1 p(t) - q_{pc} - q_{pt} - e_p$$

$$\frac{ds_t}{dt} = q_{pt} - q_{ts} - e_t$$

$$\frac{ds_s}{dt} = q_{ts} - q_{sc} - e_s$$

$$\frac{ds_{precip}}{dt} = c_1 p(t)$$

$$\frac{dV_r}{dt} = q_{pc}$$

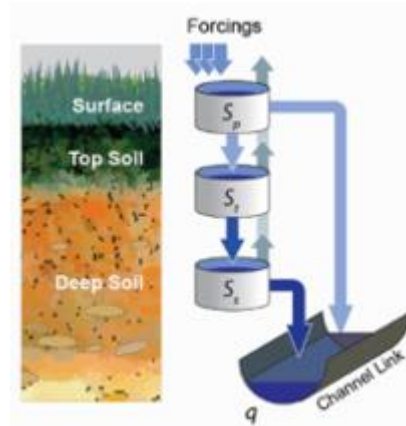$$\frac{dq_b}{dt} = \frac{v_B}{L}\left(A_h q_{sc} - 60 \cdot q_b + q_{b,in}(t)\right)$$

Figure 6 Mathematical (left) and pictorial (right) description of the variable runoff model.

Parameter	Description	Model
A	Total area draining into this link [km^2]	Both
L	Channel length of this link [km]	Both
A_h	Area of the hillslope of this link [km^2]	Both
v_r	Channel reference velocity [m/s]	Both
v_B	Channel baseflow velocity [m/s]	Variable Runoff Model
λ_1	Exponent of channel velocity discharge [-]	Both
λ_2	Exponent of channel velocity area [-]	Both
RC	Runoff coefficient [-]	Constant Runoff

Variable	Description	
q	Channel discharge of this link [m^3/s]	Both
s_p	Water ponded on hillslope surface [m]	-
s_s	Effective water depth in hillslope subsurface [m]	-
q_{pc}	Ponded, surface water to channel, flux [m/min]	-
q_{sc}	Subsurface water to channel, flux [m/min]	-
$p(t)$	Precipitation intensity [mm/hr]	-
e_p	Evaporative flux from ponded surface [m/min]	-
e_s	Evaporative flux from subsurface [m/min]	-

Table 1 Description of constants and variables used in the hydrologic models.

**3. Sample Problems which Use the HLM-Web Educational Hydrology Tool**

3.1. Sample Homework Assignment

1. Use the following URL to access the HLM-Web: A Web-based Modeling Framework for Hydrology Education: https://hydroinformatics.uiowa.edu/lab/hlmwebedu/. Make sure to refresh the page if you run into any problems. Explore the software and provide comments on its design: Is the user interface easy to use? Is the notation/documentation logical and intuitive? What did you learn from running the simulations? Any other comments are welcome.

2. (a) Use the HLM-Web to compare the basin response to the same rainfall sequence for routing models with linear and non-linear channel velocity for all five basins. (b) Use the software to compare the response for uniform vs. highly variable rainfall with the same rain total. (c) Use the same rainfall uniform in time for all five basins and obtain the peak flow at the outlet. Plot the peaks for all five basins against basin drainage area. Use a logarithmic scale to make the plot.

3. Use HLM-Web: A Web-based Modeling Framework for Hydrology Education: https://hydroinformatics.uiowa.edu/lab/hlmwebedu/ to generate unit hydrographs for Muddy Creek and Clear Creek. Use the default parameter and the variable model options. Export the data. Generate an hourly rainfall sequence and apply the unit hydrograph method (Problem 2) and compare the response with one generate by HLM-Web for the same rainfall sequence.

4. Use the HLM-Web software for the following simulation. Provide rainfall as a single two-hour event with 5 inches per hour intensity. Try to simulate the effect of separating the rainfall into two one-hour events with the same intensity. Monitor the response at different scales (similar to that shown in the animation in Lecture 20, slide 15). Use Clear Creek or English River basin. For the first case (a single two-hour event) check the water balance at the outlet.

5. Using the HLM-Web software, design a simulation experiment that would mimic the effect of wet vs. dry initial conditions on peakflow simulation.

6. Use the following URL to access the HLM-Web: A Web-based Modeling Framework for Hydrology Education: https://hydroinformatics.uiowa.edu/lab/hlmwebedu/. Make sure to refresh the page if you run into any problems. (a) Use the HLM-Web to find (empirically) rainfall duration for reaching a steady-state response. Is it the same for the routing models with linear and non-linear channel velocity for all five basins? (b) Use the software to evaluate the effect of the antecedent soil moisture conditions on the peak response for all five basins. (c) Use the uniform rainfall in time for the larges basin and obtain the peak flow at all control points. Plot the peaks for all control points against their drainage area. Estimate the drainage area any way you want and check the estimates against the appropriate Horton Law. Use a logarithmic scale to make the plot.

3.2. Sample Lab Assignment

To make this assignment you just need excel and the Hillslope Link Model (HLM) web application (https://hydroinformatics.uiowa.edu/lab/hlmwebedu/.)

1. **(25%)** Using Muddy Creek, define a rainfall event that creates a plateau-shaped hydrograph (as the one shown in the figure) in the first two orders. Show your results in a figure with the results for both orders. Also, present the table that you used to define the rainfall event.
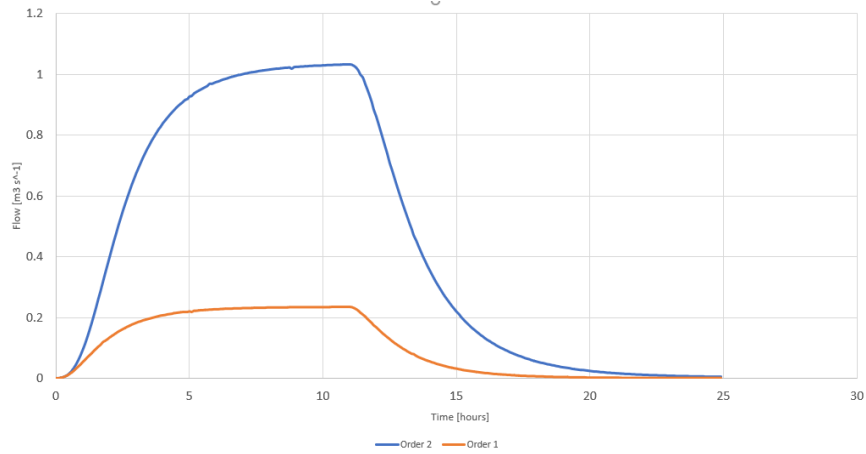
2. **(25%)** Using the same setup, change the rainfall pattern to remove the plateau shape. Show your updated results. The new rainfall pattern must keep the total volume of the first rainfall pattern.
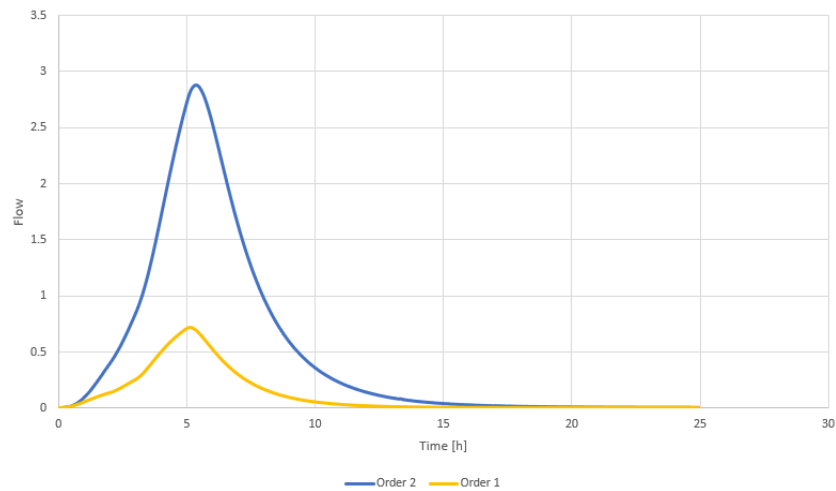
3. **(25%)** Using the same setup, change the rainfall pattern to obtain two separate hydrographs in the first two orders, and one single hydrograph at the outlet. Show your updated results. The new rainfall pattern must keep the total volume of the first rainfall pattern.

4. **(25%)** Using the Clear Creek watershed, generate a two-peak hydrograph until order 4. How different is the elapsed time between rainfall pulses of this case and the item 3 case?

Hydrograph
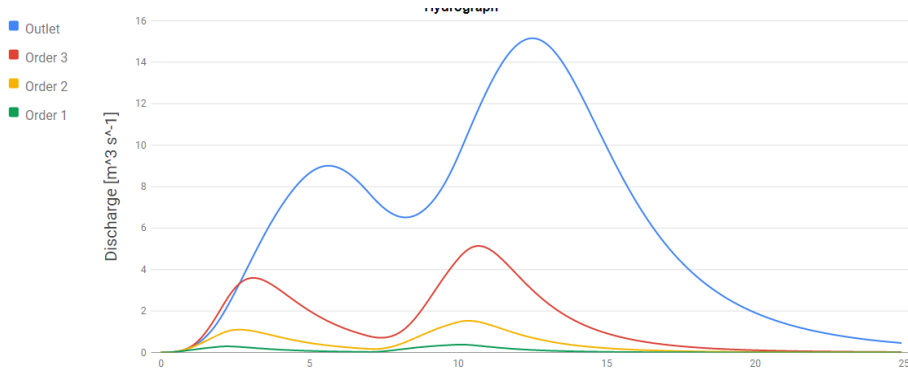
3.3. Sample Final Exam

This first group of questions is designed to test your understanding of definitions and basic concepts in the description of the hydrological cycle. Be precise in your definitions. No partial credit on these group of questions.

1. (20 points) Assume that the Dimensionless Unit Hydrograph for a 100 mi^2 basin can be approximated with a standard NRCS triangular hydrograph (Lecture 19, slide 6). The time to peak for an effective precipitation event of 1 inch has been estimated to be 10 hours.

    a. (3 points) Calculate the peak flow for the unit hydrograph
    b. (3 points) Calculate the total duration of the unit hydrograph (T_b)
    c. (3 points) Calculate the total runoff volume (in m^3) before the peak of the hydrograph
    d. (11 points) Calculate and plot the hydrograph (in m^3/s) that would result from an effective precipitation event with an hourly effective hyetograph given by (h_1, h_2, h_3, h_4, h_5, h_6, h_7) in **millimeters per hour**. Use the seven digits of your UM-Student-ID as the ordinates of the hyetograph (e.g. if your student ID is 7873525 then your precipitation intensities are h_1=7, h_2=8, h_3=7, h_4=3, h_5=5, h_6=2, and h_7=5 mm/hour)

2. (10 points) Use HLM-Web to calculate the hydrograph resulting from a "*customized precipitation event*" with intensities (h_1, h_2, h_3, h_4, h_5, h_6, h_7) described in the previous problem using the assumption of **constant flow velocity (v_r=1.0 m/s, l_1=0.0, and l_2=-0.0)** and **Runoff Coefficient of 1.0** for the outlet of Clear Creek basin (Note that HLM-Web expects precipitation time series in **millimeters per hour**). Compare the hydrograph with the one obtained from a "*single event*" that lasts 60 minutes with an intensity equal to the sum of the hyetograph, that is, $i = h_1+h_2+ h_3+h_4+h_5+h_6+h_7$ (mm/hour). Document your work using screenshots of the web interface.