frontiers

Supplementary Material

Table S1: Description of the modules examined in the current study

Module title	Short description	Authentic task
Development of Design Storms	This module is intended to promote the development of relevant technical skills, such as using the Alternating Block Method, to develop a design storm hyetograph at a site in Louisiana.	Students develop a design storm hyetograph that is then used in a successive module to determine infiltration and runoff.
Quantifying Runoff Generation	This module includes determining soil properties, and calculating the infiltration and runoff depths using the Green-Ampt method. Students will use HEC-HMS to construct precipitation, infiltration and runoff time series.	Students calculate the infiltration and runoff depths using the Green Ampt Method, then compare those results with those derived from HEC-HMS.
Developing Storm Inflow and Outflow Hydrographs	Using the results from the previous module, students use fundamental methods to calculate parameters to create inflow and outflow hydrographs, use HEC-HMS to create the hydrographs, and compare those results.	Ultimately students are tasked with designing a storm detention basin and analyzing various benefits to flood protection using different design parameters in the reservoir.
Culvert Design using HEC-RAS	This module uses a case study set in Louisiana. After a brief tutorial, students construct a hydraulic model and conduct a steady state simulation in an open channel using HEC-RAS modeling software.	Students use HEC-RAS to model the channel and design culverts for 2, 10, 50, and 100-year design storms.
Hydrologic Droughts and Drying Rivers	Students are introduced to hydrologic indices and indicators used by the federal government regarding drought and low flow conditions in streams or rivers. Then the students use flow duration curves to assess long-term change associated with river regulation.	The culminating authentic task is to synthesize the information produced from earlier sections into a case study of a drying stream or river to educate stakeholders about water stewardship.
Introduction to Floodplain Analysis	The students perform a floodplain analysis, which is the first step in determining the depth of floodwaters and to determine the size and width of the floodplains.	Students will apply their new skills to assess a case study set in Darlington, WI, a town that experienced significant flooding in the spring of 2019.
Snow and Climate	This module provides students with learning activities and tools needed to develop a basic knowledge of snow processes and complete a report for the hypothetical client.	The high cognitive demand task is based on the snow energy balance that will project the long-term and seasonal snowmelt timing and volume.
Remote Sensing Applications in Hydrology	This module guides students through the fundamentals of remote sensing while also taking advantage of existing online resources and tools for the visualization and analysis of satellite observations (e.g., NASA's Soil Moisture Active Passive and MATLAB online).	Students examine a case study set in areas that were affected by Hurricane Maria (2017) and use their skills to visualize remote sensing data, detect temporal trends, interpret satellite images, and assess errors and uncertainties in a remote sensing product.

Data Science in Earth and Environmental Sciences	This module caters to a range of learners whose coding (R or Python) expertise ranges from beginner to expert. The capstone project guides students in proposing their own earth and environmental science problem using the tools introduced in prior sections.	This module has two authentic activities: first, the analysis of driving factors behind a wildfire, and second, an analysis of hydrocarbon production's impact on groundwater quality.
Physical Hydrology	Students are exposed to the engineering professional software TOPMODEL, which is a physically-based, distributed watershed model that simulates hydrologic fluxes of water through a watershed.	Students will retrieve and evaluate hydrologic data to support a quantitative interpretation of hydrologic processes, describe sources of uncertainty, quantify and model hydrologic processes and apply and interpret the results from their analysis to answer relevant questions faced by professionals.
Evapotranspiration	Module contains a broad overview of evapotranspiration at a level that is appropriate for advanced undergraduates or graduate students in hydrology and covers topics such as water budgets, and measurements, parameters, and estimation methods related to evapotranspiration and potential evapotranspiration.	Students participate in a role-playing scenario wherein they are engineering consultants hired by a corn growers association to help reduce their crop's water footprint, save on production costs and help alleviate the urgent threat of groundwater exhaustion of the aquifer.
Groundwater Flow	Topics include analyzing well hydrographs, determining hydraulic gradients, analyzing potentiometric surface maps, calculating Darcy velocity, and calculating flow and transport.	Students access and interpret well data, apply it to determine hydraulic gradient in an aquifer and calculate groundwater flow direction, travel time, and flux.
Fluid Mechanics: Bernoulli's Equation	The Bernoulli Equation is a foundational topic for many engineering subdisciplines. This module guides the learner through the development of Bernoulli's Equation, then combines it with the Continuity Equation and the Q-A-V relationship to allow students further authentic applications.	The culminating assignment for this module asks students to design, demonstrate, and film an experiment to demonstrate Bernoulli's equation using commonplace situations and materials.
What's in Your Water? Assessing Groundwater Chemistry and Suitability	The module provides an in-depth overview of the factors that govern groundwater chemistry, while equipping students with the tools to describe data through classic graphical tools.	The students will complete a case study wherein they are tasked with evaluating the groundwater quality data to determine the 'natural' factors that affect groundwater composition in wells and to assess the suitability of water for drinking and irrigation.
Frequency Analysis in Hydrology	Concepts learned in this module are demonstrated through a case study using data from a USGS stream gage. Topics covered include probability versus statistics, random variables, probability functions, the normal distribution, as well as descriptive statistics, outliers, and data visualization.	Given USGS stream gage peak flow, the student will perform a flood frequency analysis to choose a culvert design for John's Creek in Virginia that can carry the required design flood and is both safe and economical for the town.

Table S2 Concepts and skills of modules evaluated in the study

Concepts	Skills
Development of Design Storms	
• Flash Floods • Return Period • Storm Duration • Hydrographs • Hyetographs • Design Storm • Intensity-Duration-Frequency (IDF) curve • Depth-Duration- Frequency (DDF) • Alternating Block Method • Probability Density Function (PDF) • Cumulative Distribution Function (CDF)	• Construct an Intensity-Duration- Frequency (IDF) curve • Construct a Depth-Duration- Frequency (DDF) curve • Use the Alternating Block method to develop a design storm hyetograph
Quantifying Runoff Generation	
• Soil porosity • Soil moisture content • Retention • Infiltration methods • Green-Ampt Method • Runoff • Hydrograph • Hyetograph • Darcy's Law • Hydraulic conductivity • Curve Number	• Quantify design storm runoff • Quantify design storm infiltration depths • Identify the soil properties of a watershed • Apply the Green-Ampt method to calculate infiltration depth • Apply the Green-Ampt method to calculate runoff depths • Determine the soil class of a watershed using the NRCS's SSURGO database • Use HEC-HMS to construct precipitation, runoff, and infiltration time-series distributions
Developing Storm Inflow and Outflow Hydrographs	
• Flash flooding • SCS Unit Hydrograph • Storm Hydrographs • Level Pool Routing	• Design a detention basin to provide flood protection using HEC-HMS • Construct a storm hyetograph using HEC-HMS • Construct a storm hydrograph using HEC-HMS
Culvert Design using HEC-RAS	
• Open Channel flow • Hydraulic structures • Steady-state flow	• Build a culvert structure using HEC-RAS • Analyze a culvert structure using HEC-RAS • Delineate a watershed • Conduct a steady-state simulation in HEC-RAS • Interpret output data in the form of graphs, figures, and tables
Hydrologic Droughts and Drying Rivers	
• Types of droughts • Frequency, magnitude, and duration of droughts • Drought indices • Flow regimes • Flow duration curves • Human impacts on streamflow • Eco deficits and eco surplus	• Download USGS streamflow data • Calculate drought indices using streamflow data • Interpret and develop flow duration curves • Create graphics showing changes in low flows • Create a presentation on changes in river flows

Introduction to Floodplain Analysis	
• Watershed properties • Watershed delineation • Exceedance probability/return period • Probability distribution • Probability of occurrence • Frequency Analysis • Uniform flow • Critical flow • Gradually varied flow • Economic cost analysis • Floodplain analysis • The relationship between these main concepts	• Delineate a watershed • Determine watershed attributes from relevant data • Obtain relevant information for a watershed (i.e., streamflow) • Interpret relevant information for a watershed • Apply concepts of probability to hydrometric data • Perform a frequency analysis to determine the return period • Apply basic principles of open channel flow (i.e., Mannings equation, Froude number, etc) • Compute water surface profiles using the standard step method • Setup HEC-RAS to model a river reach • Perform a floodplain analysis to determine water levels • Identify sources of uncertainty in hydraulic models • Perform a basic cost analysis for alternative flood protection scenarios
Snow and Climate	
• Snow terminology • Snow measurement techniques • Model uncertainty • Model validation • Snow modeling • Climate modeling	• Navigate google colabs • Use jupyter notebooks • Find the difference in means • Perform data analysis • Perform climate assessment • Write a professional report
Remote Sensing Applications in Hydrology	
• Remote sensing definition • Electromagnetic spectrum • Geosynchronous and polar orbits • Digital images • Temporal and spatial resolution • Temporal trends • Significance tests • Image interpretation • Data validation and uncertainty assessment	• Define temporal and spatial characteristics of remote sensing observations • Recognize (daily, seasonal, climatological) cycles in a hydrologic variable • Apply linear regression to identify trends in a hydrological variable • Perform a significance test • Visualize and download satellite data • Interpret satellite images • Detect changes in hydrologic variables using visual interpretation and statistical analysis of satellite products • Quantify uncertainties and errors in remote sensing observations
Data Science in Earth and Environmental Sciences	
• Oil and gas production in Pennsylvania • Environmental impacts of oil and gas production	• Use cloud computing platform HydroShare JupyterHub

• Geospatial analysis • Kendall rank correlation • Heatmaps	• Execute Python codes in Jupyter Notebook • Publish data in an online data repository • Share data with others in a collaborative project via a data repository • Interpret geospatial analysis results • Read literature and summarize major findings
Physical Hydrology	
• Water balance • Residence time • Watershed delineation • Watershed characteristics • Basic hydrologic analysis • Flow duration curve • Runoff generation processes • Hydrologic modeling • Infiltration modeling • Hydraulic conductivity • Darcy's law • Topographic wetness index	• Use open-source software (e.g., HydroLearn, HydroShare, Jupyter Notebook) and programming tools (R and Python) to perform hydrologic analysis • Quantify uncertainty in components of the water cycle • Delineate a watershed • Determine watershed attributes from relevant data • Obtain relevant information for a watershed (e.g., precipitation, streamflow, area, etc.) • Perform basic hydrologic analysis for a watershed of interest (e.g., time series, annual and monthly flow statistics, flow duration curve, etc.) • Compute water balance using publicly available data • Derive hydrologic information using digital elevation models • Plot grain size distributions and determine soil texture • Quantify flow rate using Darcy's Law • Characterize and interpret basin soil properties • Calculate at-a-point infiltration and runoff using multiple models • Critically assess hydrologic data and model assumptions • Estimate areal average precipitation and associated uncertainty • Develop intensity – duration – frequency curves
Evapotranspiration	
• Evapotranspiration (ET) • Global Importance of ET • Potential Evapotranspiration (PET) • Crop Coefficients • Estimation methods for ET/PET • Pan evaporation • Eddy Covariance	• Conduct a water budget • Estimate PET based on Pan Evaporation • Estimate PET based on temperature/radiation • Estimate ET using Penman-Monteith equation • Identify measurements relevant to ET in FluxNet datasets • Select appropriate PET-estimation method for a given problem • Differentiate between Evaporation and Transpiration

	• Use the Google Earth Engine to calculate crop coefficients and/or identify how crop coefficients are expected to change seasonally.
Groundwater Flow	
• Well hydrographs • Potentiometric surfaces • Relationship between hydraulic conductivity and hydraulic gradient • Darcy's experiments • Groundwatershed divides • Groundwater model boundaries • Water budgets • Darcy velocity • Seepage velocity • Contaminant transport • Effective parameters • Groundwater-surface water interaction	• Access well data • Construct a well hydrograph • Interpret a well hydrograph • Calculate gradient • Calculate groundwater flux • Given hydraulic head, determine the direction of groundwater flow • Delineate a ground watershed • Draw a contour map of a potentiometric surface • List components of a water budget • Calculate groundwater velocity and travel time • Relate hydraulic gradient to contaminant flow patterns
Fluid Mechanics: Bernoulli's Equation	
• Streamlines • Bernoulli's equation – head form • Bernoulli's equation – pressure form • Total head • Continuity equation • Lift force • Hydraulic Grade Line • Obstruction flowmeters • Pitot tubes • Cavitation • Pressure breaks	• Write Bernoulli's equation for the flow of a liquid (head form) from memory. • Distinguish the key assumptions governing the use of Bernoulli's equation and their interpretations when applied to a real-world problem. • Convert between the pressure and head form of Bernoulli's equation. • Apply Bernoulli's equation to relate pressure and velocity to compute lift force for flat surfaces. • Solve for flow rate in a system using Bernoulli's equation in conjunction with the continuity equation for an obstruction flow meter. • Relate the volumetric flow rate, area, and velocity of flow between two points in a piping system using the continuity equation. • Evaluate a piping system by plotting the hydraulic grade line (HGL) and energy grade line (EGL) to determine required pressure breaks. • Solve for an unknown property value (pressure, velocity, or elevation) using Bernoulli's equation along a streamline. • Design and conduct an experiment demonstrating an application of Bernoulli's equation in the context of a commonplace situation from their own experience. • Communicate the results of their technical assessments in a professional and creative format using social media.

<table>
<tr><td colspan="2">What’s in Your Water? Assessing Groundwater Chemistry and Suitability</td></tr>
<tr><td>• Unit conversions to represent appropriate concentration of groundwater
• Groundwater sampling procedures
• Physico-chemical parameters
• Major ion chemistry
• Charge balance calculation
• Hydrochemical facies
• Stiff diagram
• Piper trilinear diagram
• Gibbs diagram
• Determining drinking water quality using heavy metal pollution index
• Using indices to assess water quality suitable for irrigation</td><td>• Understand the basics of groundwater sampling
• Classify groundwater chemistry using physico-chemical parameters, major ions and trace elements
• Check quality of given dataset using charge balance calculation
• Represent major ions through Stiff diagram and identify hydrochemical facies
• Represent major ions through Piper trilinear diagram and identify hydrochemical facies
• Interpret geochemical origins of water chemistry through Gibbs diagram
• Assess suitability of water for drinking and irrigation purposes</td></tr>
<tr><td colspan="2">Effects of Urbanization on Stormwater Runoff</td></tr>
<tr><td>• Land Cover Maps & Classifications
• Hydrologic Soil Groups
• Infiltration
• Evapotranspiration
• Precipitation
• Stormwater Runoff
• Storm Hydrographs
• Peak Flows and Volumes
• SCS CN method
• Design Storms
• Surface Runoff
• Hydrologic modeling
• Low Impact Development
• The relationship between these main concepts</td><td>• Delineate a study area
• Estimate and map land cover changes of study area
• Interpret land cover classification
• Interpret and analyze the storm water runoff of the study area
• Estimate storm water runoff
• Develop a LID design
• Evaluate and interpret the LID designs
• Design long-term simulation</td></tr>
<tr><td colspan="2">Frequency Analysis in Hydrology</td></tr>
<tr><td>• Flood frequency analysis
• Low flow frequency analysis
• Descriptive Statistics
• Frequency Plot
• Probability axiom
• Random Variable
• Probability distribution
• Normal Distribution
• Sample and population and their difference
• Return Period
• Types of hydrologic data in flood frequency analysis
• Exceedance probability
• Non exceedance probability
• Data visualization
• Confidence interval</td><td>• Summarize a hydrologic dataset
• Apply a probability distribution to a hydrologic dataset
• Measure the fitness of a hydrologic dataset to a specific probability distribution
• Visualize a hydrologic dataset
• Apply transformation techniques to a hydrologic dataset
• Access hydrologic data for conducting frequency analyses
• Calculate exceedance and non-exceedance probabilities given a probability distribution
• Calculate the return period of a hydrologic event given the exceedance and non-exceedance probabilities
• Create and use probability plots
• Create and use frequency plots</td></tr>
</table>

	• Calculate confidence interval for a frequency plot • Select data of different durations for low-flow frequency analysis

Table S3: Details about universities that participated in the study

We used the most recent student population reports in conjunction with the rankings from the National Association for College Admission Counseling (CollegeData n.d.) to assign the university to a size range. We considered a university small if the student population is less than 5,000, medium for populations between 5,000 to 15,000, and large for populations greater than 15,000 students.

University	Size	US Region
A	Large	South
B	Large	Southwest
C	Small	Northeast
D	Medium	North
E	Large	Central
F	Large	Western
G	Large	Northeast
H	Large	Midwest
I	Large	Northeast
J	Medium	Northwest
K	Large	Northeast
L	Large	Central
M	Large	Southeast
N	Large	Southern
O	Large	Northeastern