2019

Lecture 1: Stochastic Hydrology

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Lecture 1: What is stochastic hydrology?

Julianne Quinn
Engineering Systems and Environment

What is stochastic hydrology?

Stochastic:

of a random variable with a probability distribution

Derived from the Greek word *Stochos*, meaning

(1) to shoot (an arrow) at a target;

(2) to guess or conjecture (the target)

"Stochastic methods thus aim at predicting the value of some variable at non-observed times or at non-observed locations, while also stating how uncertain we are when making these predictions"

Bierkens, M. F., & van Geer, F. C. (2007). Stochastic hydrology.

What is stochastic hydrology?

Hydrology:

A science dealing with the properties, distribution, and circulation of water on and below the earth's surface and in the atmosphere

Stocha

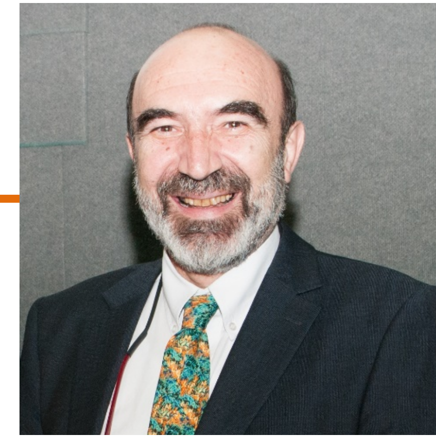
Study

predict ... or in

those predictions

So are all problems in hydrology stochastic? When should we apply deterministic vs. stochastic hydrology?

Deterministic vs. stochastic hydrology

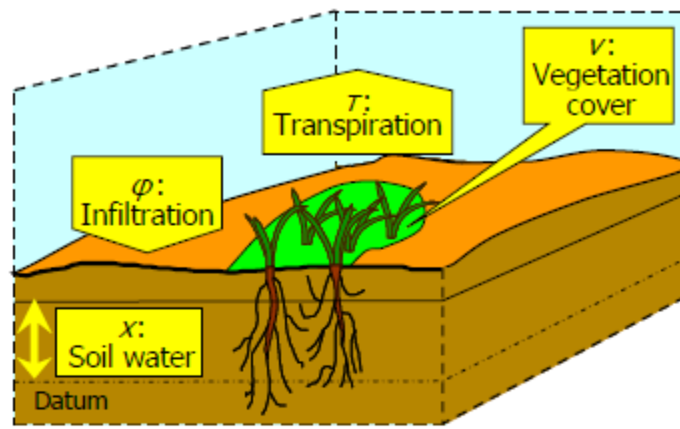


Consider the following toy problem:

$$x_t = \min(x_{t-1} + \varphi\Delta t - T v_t \Delta t, \alpha)$$

$$v_t = \frac{\max\left(1 + \left(\frac{x_{t-1}}{\beta}\right)^3, 1\right) v_{t-1}}{\max\left(1 + \left(\frac{x_{t-1}}{\beta}\right)^3, 1\right) + \left(\frac{x_{t-1}}{\beta}\right)^3 v_{t-1}}$$

x: depth of soil water (mm)
v: land cover vegetation fraction (-)
φ: infiltration rate (mm/s)
T: transpiration rate (mm/s)
α: maximum soil depth (mm)
β: (mm)
t: time (s)



Koutsoyiannis, D. (2010). HESS Opinions "A random walk on water." *Hydrology and Earth System Sciences*, *14*(3), 585-601.

Deterministic vs. stochastic hydrology

Imagine we know this system deterministically. We know this is the only governing relationship, we know all the parameters (φ, T, α and β), and we have no observation error in x and v.

However, our observation is only accurate to 1% precision. What happens if we perturb our initial observations of x and v by ±1%?

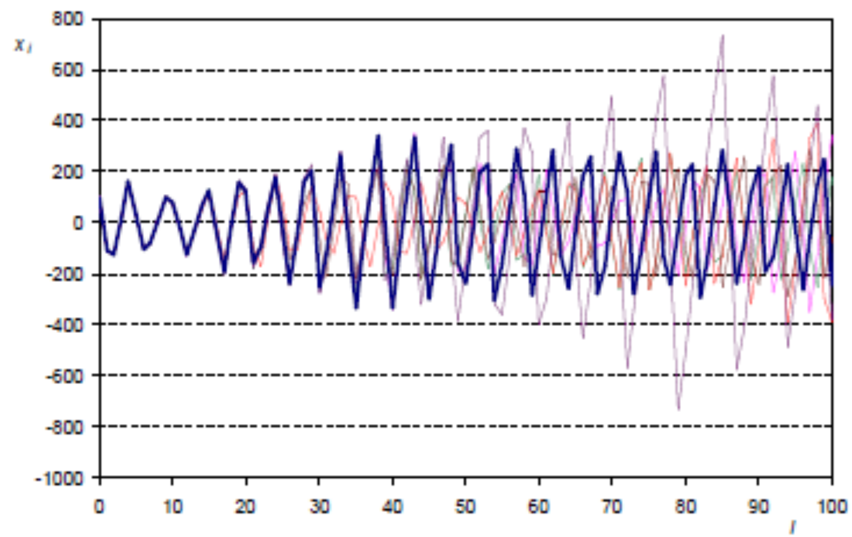


Fig. 5. Evolution of soil water x as in Fig. 4 but with uncertainty in initial conditions: bold blue line corresponds to initial conditions s_0=100 mm, v_0=0.30 and the other five lines represent initial conditions slightly (<1%) different.

Deterministic vs. stochastic hydrology

Even in this deterministic system, there is great uncertainty!

Even if we know the mechanistic hydrological processes and how to parameterize them (which we often don't!), there will always be errors due to imperfect observations and precision.

The goal of this course is to learn how to model this random component with stochastic hydrologic methods.

How could we model uncertainty in this system?

Run simulations under:

- Different initial conditions around our best estimate
- Different parameter values around our best estimate (if they're unknown, which they usually are)

Use simulated results to estimate probability distribution of x_t and v_t at every time step

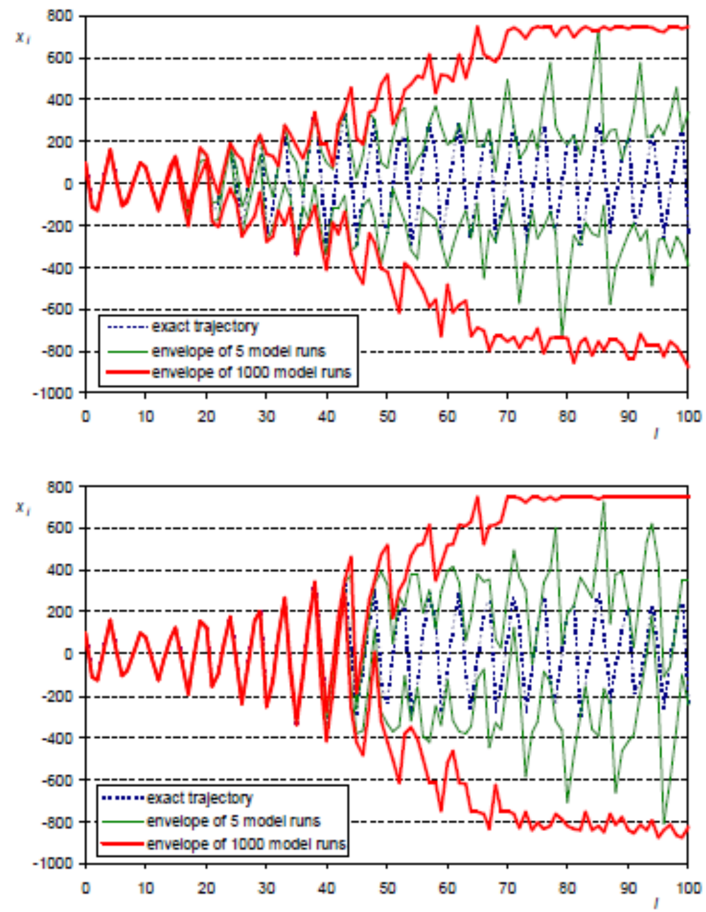


Fig. 6. Stream tube representation of the evolution of soil water x (with initial conditions as in Fig. 4 and 1% uncertainty) in a deterministic setting using envelope curves constructed by 5 or 1000 simulation runs: (upper) when only x_0 is observed; (lower) when x_0 to x_{30} are observed.

Course Objectives

The goals of this course are two-fold:

1) to learn the importance of modeling uncertainty in hydrologic process, and
2) to learn methods to do so!

Applications:

Flood frequency analysis

Drought frequency analysis

Predictions in ungauged basins

Time series analysis

Flood frequency analysis

How do we fit this distribution?

How do we account for uncertainty in that fit?

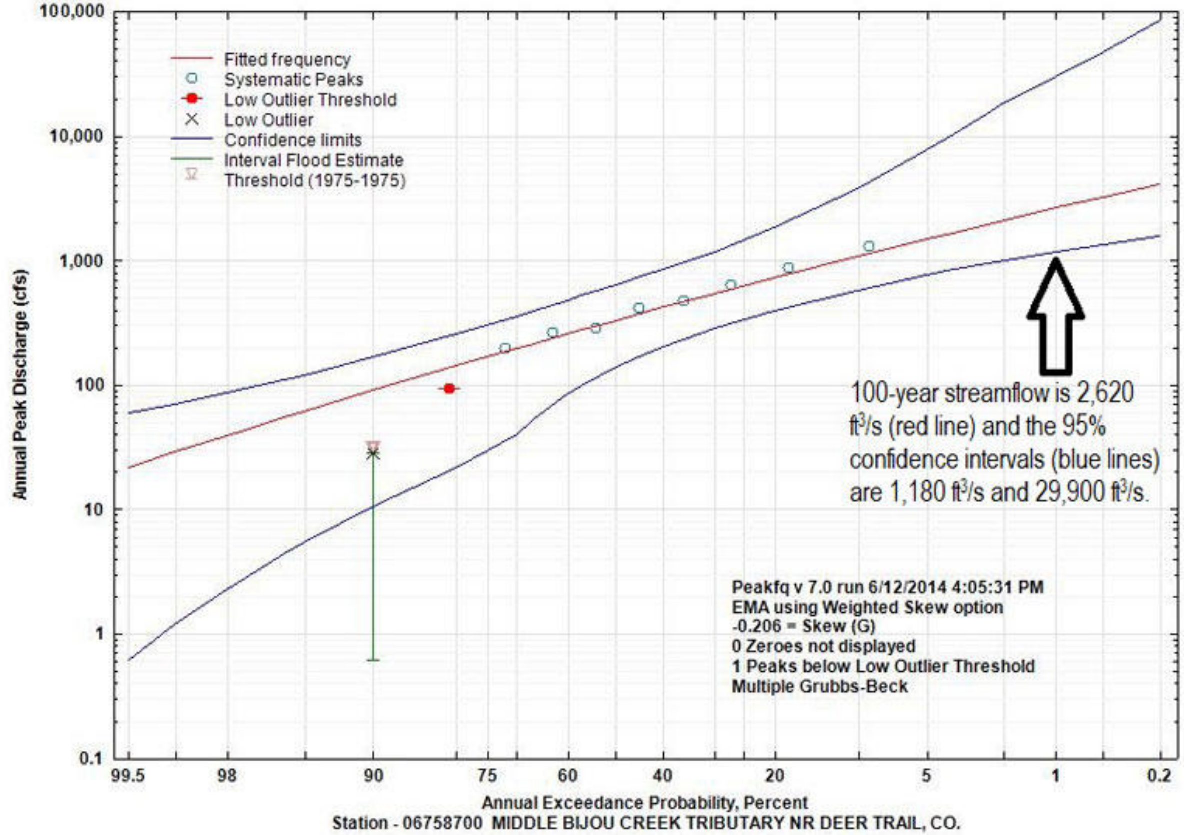
Figure 2-1. Illustration of transformation for traditional expected annual damage computation

USACE. (1996). Risk-Based Analysis for Flood Damage Reduction Studies.

Flood frequency analysis

Why is it important?
What is it used for?

- Sizing levees, dams, culverts, storm drains, …
- Operating dams
- Floodplain mapping



Flood frequency analysis: Historical information

What about known severe flood events that occurred before the gauged record?

Can we include that information in our flood frequency analysis? How?

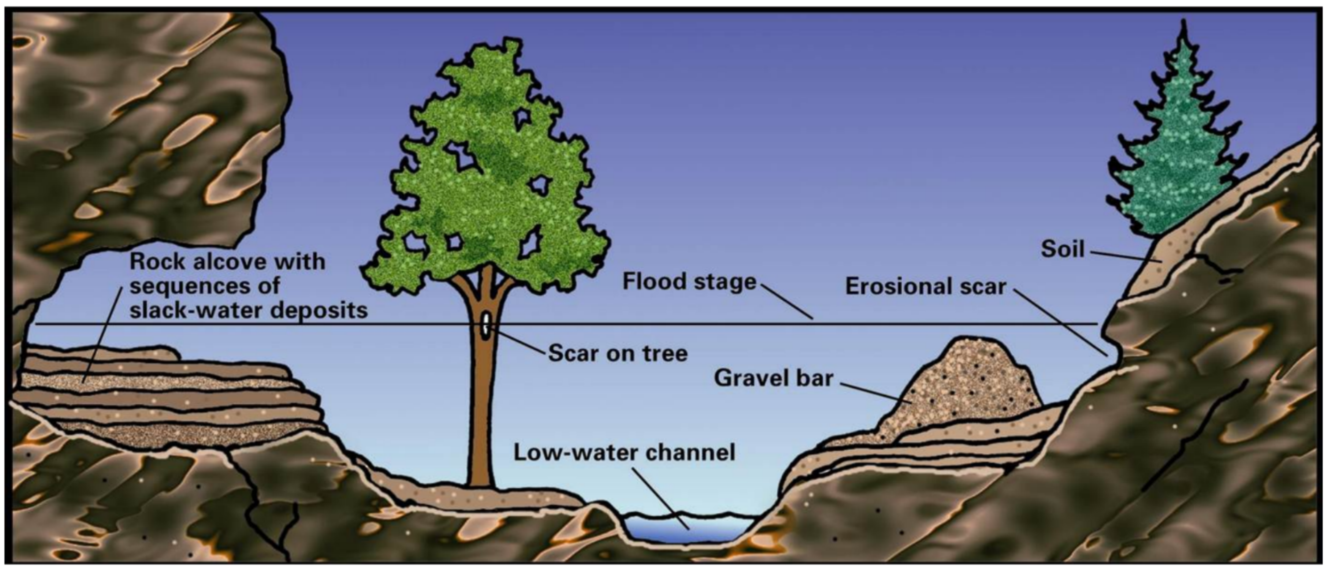
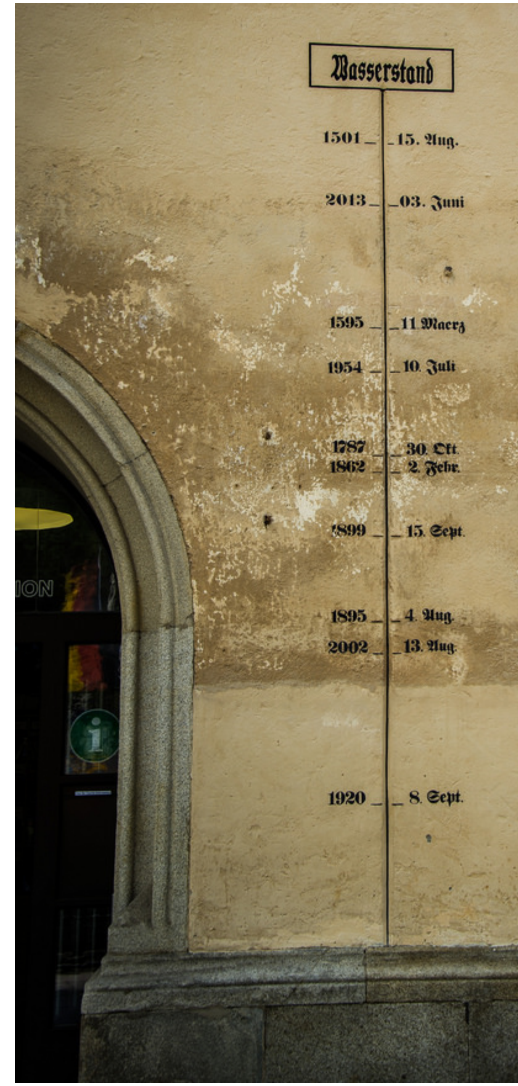


Figure 7. Diagram of a section showing typical paleoflood features used as paleostage indicators (from Jarrett and England, 2002).



Drought frequency analysis

What drought characteristics do we want to characterize?

- Intensity
- Duration
- Frequency

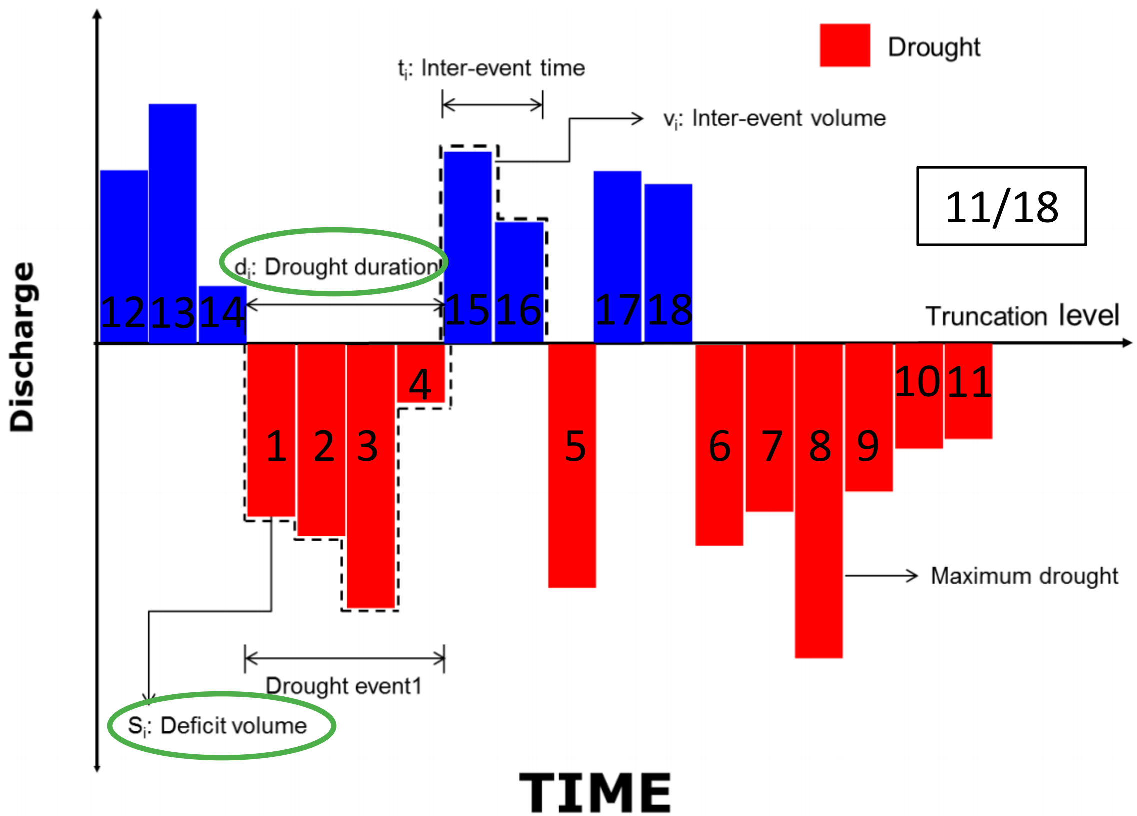


Figure 2. Definition sketch of a general drought event.

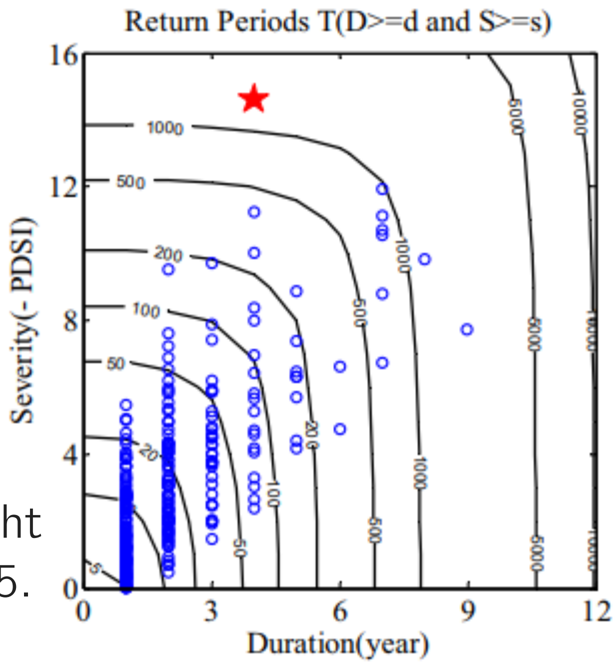
Sung, J. H., & Chung, E. S. (2014). Development of streamflow drought severity–duration–frequency curves using the threshold level method. *Hydrology and Earth System Sciences*, *18*(9), 3341-3351.

Drought frequency analysis

Can we characterize all simultaneously? How?

Kwon and Lall (2016) found the 2012-2015 drought in CA to be the most severe historically despite its short 4-yr duration.

They estimated the conditional return period of such a severe event, given its 4-yr duration at 21,580 [11,719–41,957] years!



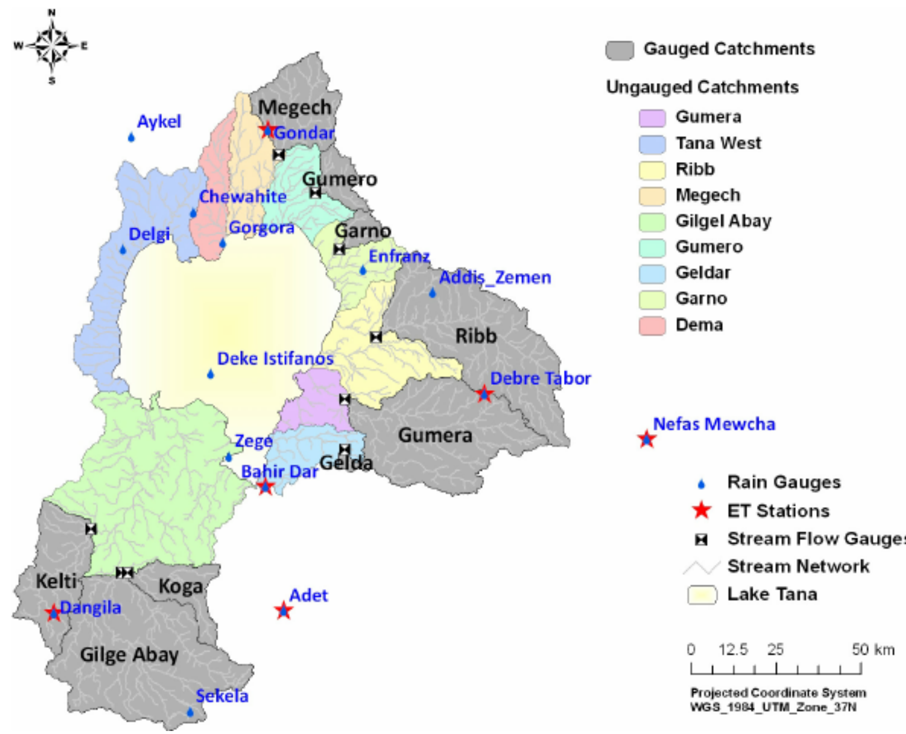
Kwon, H. H., & Lall, U. (2016). A copula-based nonstationary frequency analysis for the 2012–2015 drought in California. *Water Resources Research*, *52*(7), 5662-5675.

Predictions in ungauged basins (PUB)

How do we size water infrastructure in basins without gauged records? (or with limited records)

Can we use information on basin characteristics and nearby gauges to estimate flood and drought statistics?

How do we quantify the uncertainty in those estimates?

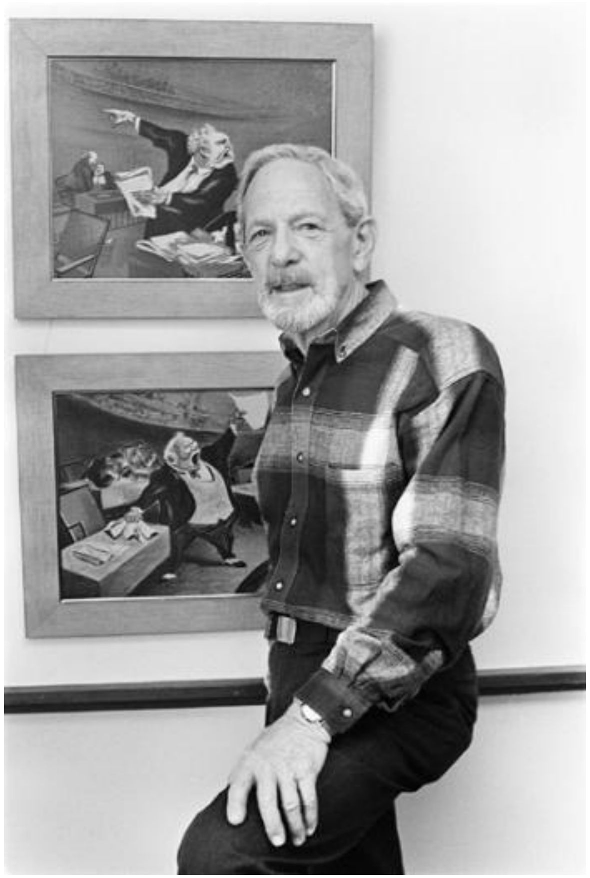


Rientjes, T. H. M., Perera, B. U. J., Haile, A. T., Reggiani, P., & Muthuwatta, L. P. (2011). Regionalisation for lake level simulation–the case of Lake Tana in the Upper Blue Nile, Ethiopia. *Hydrology and Earth System Sciences*, *15*(4), 1167-1183.

Time series analysis and synthetic generation

What if we want to simulate our system design, but only have a short record? How can we supplement that? How can we validate designs out-of-sample?

Idea pioneered by Thomas and Fiering (1962) through the Harvard Water Program, an interdisciplinary group started by Arthur Maass (right) in 1955 to revolutionize the country's water system design process.



Thomas, H.A. & Fearing, M. B. (1962). Mathematical synthesis of streamflow sequences for the analysis of river basins by simulation. In: *Design of Water-Resource Systems*. Cambridge, MA: Harvard University Press.

What about climate change? Land use change?

- Can we detect any trends in hydrologic characteristics?
- Maybe average annual flows. What about floods and droughts?
- What does theory suggest should happen?
- Can we model these changes?

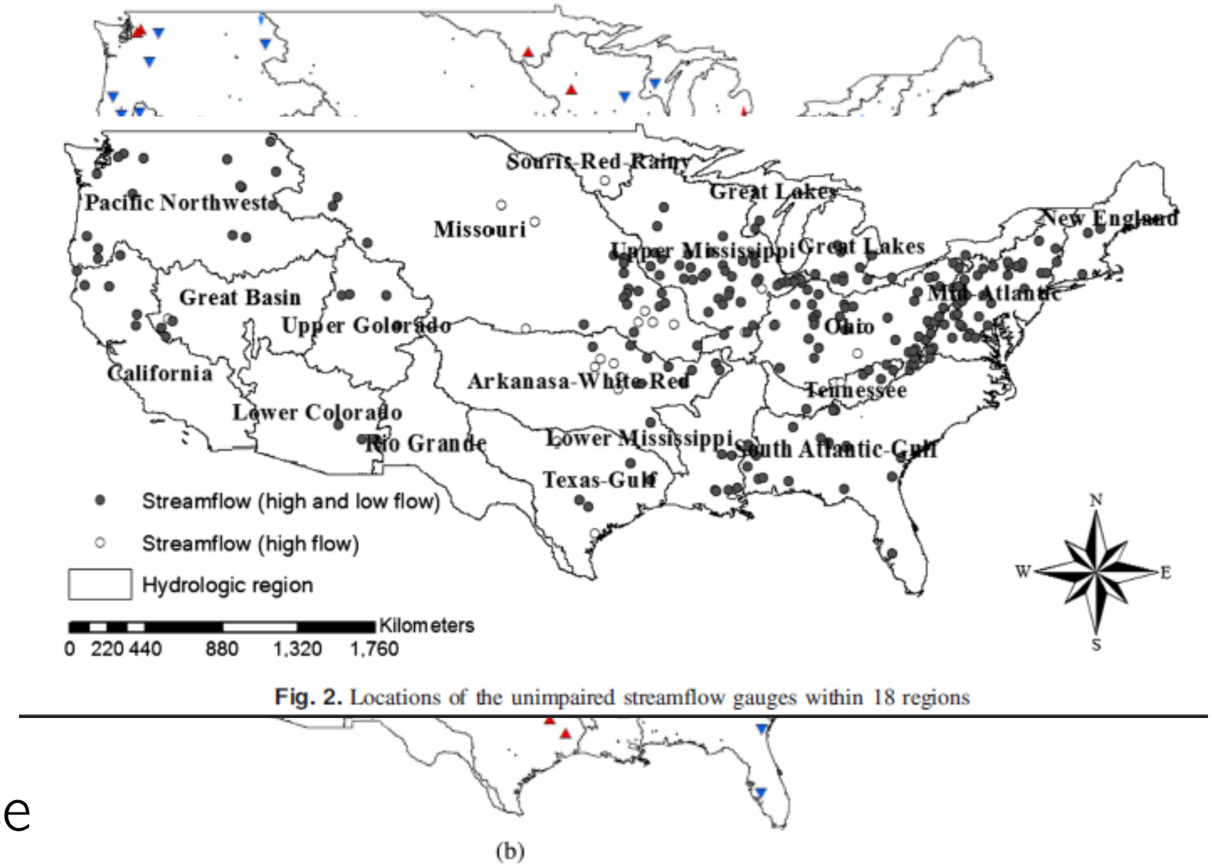


Fig. 2. Locations of the unimpaired streamflow gauges within 18 regions

Fig. 3. Results of the Mann-Kendall analysis: (a) high flow; (b) low flow

Ahn, K. H., & Palmer, R. N. (2015). Trend and variability in observed hydrological extremes in the United States. *Journal of Hydrologic Engineering*, *21*(2), 04015061.

This course will try to cover all of that!

Week	Dates	Topic
1	1/15, 1/17	Introduction and statistics review
2	1/22, 1/24	
3	1/29, 1/31	
4	2/5, 2/7	
5	2/12, 2/14	
6	2/19, 2/21	
7	2/26, 2/28	
8	3/5, 3/7	
9	3/12, 3/14	
10	3/19, 3/21	
11	3/26, 3/28	
12	4/2, 4/4	
13	4/9, 4/11	
14	4/16, 4/18	
15	4/23, 4/25	
16	4/30	

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2	1/22, 1/24	Floods: Annual Maxima Series (AMS)
3	1/29, 1/31	Model Adequacy and Uncertainty
4	2/5, 2/7	Floods: Partial Duration Series (PDS)
5	2/12, 2/14	Floods: Historical information
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Floods

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6	2/19, 2/21	Droughts: Low flow estimation
7	2/26, 2/28	Fitting multivariate distributions
8	3/5, 3/7	Modeling dependency with copulas
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Floods

Droughts

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9	3/12, 3/14	--------------------- Spring break ---------------------	
10	3/19, 3/21	Review, Midterm	
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12	4/2, 4/4	Regression diagnostics	
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15	4/23, 4/25	Trend detection	
16	4/30	Project presentations	

Student Evaluation

Biweekly assignments will typically consist of 1 reading and 1 problem set. Problem sets will include written and coding components.

Assignments	30%

Readings should be done by the next class. Problem sets can be submitted in class of through Collab. Requests for extensions must be made before the day the assignment is due.

Students can work together but must submit their own work.

Office Hours will be right after class Tue and Thur from 2:00-3:30 in Olsson 102D.

Student Evaluation

The midterm will be the week after spring break with a review session the day before.

Assignments	30%
Midterm	30%

It will cover all material prior to spring break. There will be a written and coding component

Student Evaluation

Instead of a final exam, all students will do an individual final project.

Assignments	30%
Midterm	30%
Project	30%

The project must include at least one topic covered prior to the midterm and one topic covered after the midterm.

More details will be given later in the semester.

Student Evaluation

Students will be expected to participate in class discussions on the readings.

Assignments	30%
Midterm	30%
Project	30%
Participation	10%

Students will also be divided into groups that will each lead one lecture and discussion during the course of the semester.

Students can also earn bonus points on their participation grade by answering other students' questions on Piazza: https://piazza.com/class/jqmmg3pu8qg6la

All course communication will be through Piazza

Text Support

There is no mandatory book, but the following texts may be helpful (three of which are freely available online):

- Bierkens, M.F., & van Geer, F. C. (2007). Stochastic hydrology. http://www.earthsurfacehydrology.nl/wp-content/uploads/2012/01/Syllabus_Stochastic-Hydrology.pdf

- Loucks, D.P., & Van Beek, E. (2017). An Introduction to Probability, Statistics and Uncertainty. In: Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications. Springer, Cham. https://link.springer.com/chapter/10.1007/978-3-319-44234-1_6

- Stedinger, J.R., Vogel, R.M., Foufoula-Georgiou, E. (1993). Frequency Analysis of Extreme Events. In: Maidment, D.R. (Ed.) Handbook of Hydrology. (pp.18.1-18.66). New York: McGraw-Hill. https://engineering.tufts.edu/cee/people/vogel/documents/frequencyAnalysis.pdf

- Wilks, D.S. (2011). Statistical methods in the atmospheric sciences (3rd ed.). Oxford; Waltham, MA: Academic Press.

Programming Support

R, Python and Matlab may all be used for programming assignments in this course. Free online courses on these languages can be found on Coursera:

R: https://www.coursera.org/courses?query=R

Python: https://www.coursera.org/courses?query=python

Matlab: https://www.coursera.org/courses?query=MATLAB

Writing support (for the final project) is also available at the UVA Writing Center: https://virginia.mywconline.com/