# *Supplement of:*
# Teaching hydrological modelling: Illustrating model structure uncertainty with a ready-to-use teaching module

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## S.1 Survey Outline

In order to get a clearer picture on if and how uncertainty is currently taught to students in the field of Earth- and Environmental Sciences a quick survey on "Teaching Uncertainty in Hydrological Modelling" was conducted via the survey software surveymonkey.com. The main questions we wanted to answer were:

1. How commonly is uncertainty in hydrological modelling part of the teaching curriculum in water resources (related) courses?

2. Are data uncertainty, parameter uncertainty and model structure uncertainty equally often covered in the curriculum?

3. Which tools are being used to teach hydrological modelling and, specifically, how often are modelling exercises part of the curriculum?

We wanted to design the survey as short as possible in order to get many participants to take the time to answer it. We hoped that a large number of participants would allow a broad general overview on the topic. The survey was distributed via twitter, different e-mail lists and by explicitly searching for and contacting different hydrology institutes and water research related faculties. Additionally, a flyer to the survey was passed out during AGU 2019. We were able to collect 101 answers in approximately 6 months (the survey was open between 18.09.2019 and 06.03.2020). The survey had between eight and eleven questions depending on the path the participants took through the survey (see Figure S1) and took approximately three minutes to answer.

In the following section the survey questions and answer possibilities are listed with the number of responses in blue. Note that different paths through the survey were possible depending on which answers were given, resulting in consecutive questions occasionally having a different number of respondents. Due to the way the survey tool works, certain questions needed to be duplicated to let them be part of different paths. The different survey paths and their corresponding questions can be seen in Figure S1 displaying a flow diagram of the survey with its introductory text.

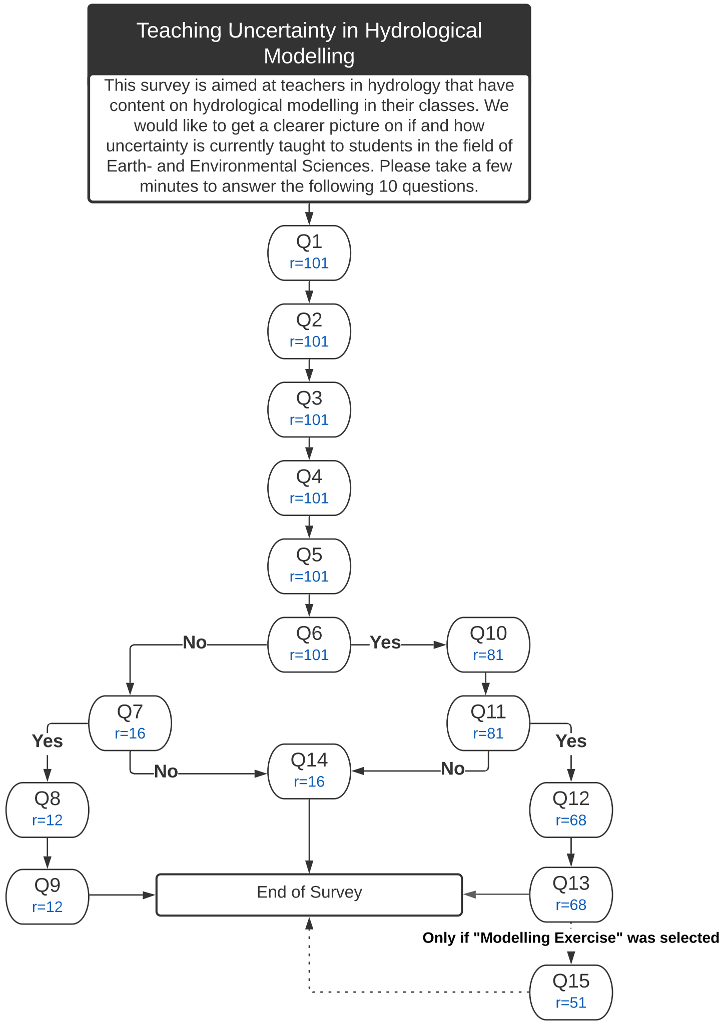


**Figure S1.** Flow diagram of the survey showing different question paths and the introductory text. The number of responses each question received is given in blue.

## S.2 Survey questions and answers

**Q1** On which level do you teach? - 101 responses

- Undergraduate Level (BSc) - 30
- Graduate Level (MSc) - 28
- Under- and Graduate Level (BSc & MSc) - 40
- Other (please specify) - 3

Specifications of "Other" were: PhD; Public stakeholders in FRM; TX groundwater conservation district.

**Q2** In which field do you teach? - 101 responses

- Hydrology - 50
- Water Resources and Management - 21
- Civil or Environmental Engineering - 21
- Geography - 5
- Other (please specify) - 4

Specifications of "Other" were: Hydrology and Geology; Environmental Modelling; Hydrogeology; Urban Drainage.

**Q3** Where do you teach? - 101 responses

- Europe - 52
- North America - 20
- South America - 5
- Africa - 8
- Asia - 8
- Australia - 6
- Other (please specify) - 2

Specifications of "Other" were: Globally; Both - South America and Europe.

**Q4** How long have you been teaching a course with hydrological modelling content? - 101 responses

- < 2 years - 35
- < 5 years - 24
- < 10 years - 14
- > 10 years - 28

**Q5** What percentage of your total lecture time do you spend on hydrological modelling compared to all other class content? - 101 responses

- state a number between 0 and 100 - The average of all given answers is 44.36 %, but answers vary between 1 and 100 %.

**Q6** Does your class include exercises on hydrological modelling? - 101 responses

– Yes - 84

– No - 17

– Other (please specify) - 0

**Q7** If there is no exercise on hydrological modelling, is uncertainty in hydrological modelling part of your course? - 16 responses - 1 skipped answer

– Yes - 13

– No - 3

**Q8** Please state which sources of uncertainty you are discussing in your hydrological modelling class. Select all options that apply. - 12 responses - 1 skipped answer

– Input Uncertainty - 11

– Model Parameter Uncertainty - 10

– Model Structural Uncertainty - 8

– Uncertainty as Overarching Term - 5

– None - 0

– Other (please specify) - 1

Specifications of "Other" were: initial conditions uncertainty.

**Q9** Which tools do you use to communicate uncertainty in hydrological modelling? Select all options that apply. - 12 responses

– Slides & Graphics - 10

– Papers - 5

– Books/Book Chapters - 1

– Other Reading Material - 1

– Case Studies - 6

– Active Discussion - 7

– Other (please specify) - 1

Specifications of "Other" were: serious gaming.

**Q10** Which tools do you use to teach hydrological modelling? Please use the "other" option if you wish to specify the tools and/or models you use. Select all options that apply. - 81 responses - 3 skipped answers

- Thought Experiments - 22
- Pen & Paper Exercises - 37
- Labratory Setup - 11
- Computer Exercises - 76
- Other (please specify) - 10

Specifications of "Other" were: Interactive activities such as discussion, presentation of case studies by students, attendance to scientific conferences at the international level; Multimodel exercises, Decision enactments; HEC-HMS; Virtual Reality; Structured group discussion; Literature review assignments on modelling (written and presentation). Actually teach an environmental modelling course with content that is equally applicable to hydrological modelling and other fields.; Lectures; field course - including relationships between field work (to derive parameters) and hydrologic modelling; Hbv- light, building small models with Matlab code; IWG-HW.

**Q11** Is uncertainty in hydrological modelling part of your course? - 81 responses

- Yes - 68
- No - 13

**Q12** Please state which sources of uncertainty you are discussing in your hydrological modelling class. Select all options that apply. - 68 responses

- Input Uncertainty - 57
- Model Parameter Uncertainty - 60
- Model Structural Uncertainty - 45
- Uncertainty as Overarching Term - 39
- None - 0
- Other (please specify) - 6

Specifications of "Other" were: Formulation of hydrological models in a stochastic physically based framework therefore integrating uncertainty assessment with model identification, estimation and application; Model predictive uncertainty; Scenario uncertainty; Propagation of uncertainty; Forecast uncertainty; Cascade of uncertainties in decision making.

**Q13** Which tools do you use to communicate uncertainty in hydrological modelling? Select all options that apply. - 68 responses

- Slides & Graphics - 53
- Papers - 40
- Books/Book Chapters - 21
- Other Reading Material - 10

- Case Studies - 33
- Active Discussion - 44
- Modelling Exercise - 58
- Other (please specify) - 4

Specifications of "Other" were: Open tutorial web pages published in my website. Open videos of all my lectures published on You Tube; Information Theory Approach, Non-linear dynamics, Chaos, Fractals (stochastic), self-similar processes; Blackboard; A model sensitivity of SWMM is part of the homework.

**Q14** Why is uncertainty not part of your course? Select all options that apply. - 16 responses

- Covered in another course - 1
- Not enough time to cover it - 13
- No good teaching materials available - 5
- Other (please specify) - 2

Specifications of "Other" were: I wish it was! Just didn't get around to it. Was not in the textbook I used; Bachelor students first need to grasp the concepts of modelling before introducing uncertainty.

**Q15** Please give a short description of the modelling exercises you use to teach uncertainty to your students. Are you differentiating different sources of uncertainty? - 51 responses - 7 skipped answers

- Participants had the possibility to give a text based answer.

The text based answers can be found in Section S.4.

### S.3 Main Results

Figures S2 and S3 provide an overview of the main results of each survey question. The text based answers to survey question 15 can be found in Section S.4. Note the different possible answer paths and their corresponding questions depicted in Figure S1. Based on these survey results, the answers to the 3 main questions stated in Section S.1 can be summarized as follows. Because the main focus of this survey is generating insight on the use of exercises in teaching modeling uncertainty, answers are split into a group that uses exercises and a group that does not.

#### General characteristics of respondents

Respondents teach at the undergraduate and graduate level in approximately equal numbers (Figure S2 - Q1). They refer to their field as "Hydrology" in nearly half of cases, with "Water Resources and Management" and "Civil/Environmental Engineering" appearing in 20% of cases each (Figure S2 - Q2). "Geography" and "Other" make up the remainder. Approximately half of respondents are based in Europe, with 20% being based in North America. Between 5 and 10% of respondents are based in each of South America, Africa, Asia and Australia (Figure S2 - Q3). Slightly more than a third of respondents is relatively new to teaching (<2 years experience) and more than a quarter are very experienced teachers (>10 years; Figure S2 - Q4).

**How commonly is hydrologic modelling uncertainty taught?**

On average the researchers and lecturers that took the survey spend about 44% of their lecture time on teaching hydrological modelling, but this can be as little as 1% or as high as 100%. Figure S2 - Q5 shows a histogram with a bin size of ten percent indicating that 68% of teachers spent less and 32% spent more than half their lecture time on teaching hydrological modelling. Modelling exercises are used by 83% of respondents (Figure S2 - Q6), and in approximately four-fifths of those cases uncertainty is part of the curriculum (Figure S3 - Q11). Those not using any modelling exercises nevertheless teach uncertainty in hydrological modelling in 81% of the cases (Figure S3 - Q7). If modelling uncertainty is not covered in class, the most common reason is lack of time with lack of good materials coming second. Just 6% stated the topic would be covered in another course (Figure S3 - Q14).

**Are data, parameter and structure uncertainty equally commonly taught?**

The focus on the different sources of uncertainty varies between both groups. Those not using exercises have a slightly stronger focus on teaching input uncertainty (92% compared to 83% parameter uncertainty and 67% structural uncertainty; Figure S3 - Q8) while those using modelling exercises focus sightly more on parameter uncertainty (88% compared to 84% input uncertainty and 66% structural uncertainty; Figure S3 - Q12). Model structural uncertainty is the least taught source of uncertainty, not appearing in the curriculum in a third of all cases.

**How is uncertainty in modelling taught and, specifically, how often are exercises used?**

The most used tools to teach uncertainty in the groups with and without exercises are slides and graphics as well as active discussion (Figures S3 - Q9 and Q13). The group conducting exercises uses computer exercises in 94% of cases (Figure S3 - Q10) and uses these to communicate modelling uncertainty in 85% of cases. Question 15 reveals a wide variety in the modelling exercises used to teach uncertainty. Notable examples include a combination of fieldwork to obtain observations and modelling based on the fieldwork; exercises to combine calibration, sensitivity analysis and uncertainty analysis; and exercises to trial different model parametrizations.


**Figure S2.** Results to questions 1 to 6 of the survey. Number of responses to each question is given in brackets. Note that Q5 shows a histogram with a bin size of 10 percent.


**Figure S3.** Results to questions 7 to 14 of the survey. Number of responses to each question is given in brackets. Q7 to Q9 were answered by respondents that do not conduct exercises on hydrological modelling while Q10 to Q13 describe the responses of the group that does conduct modelling exercises. Q14 was answered by those respondents that stated uncertainty was not part of their course in Q7 and Q11.

### S.4 Text based responses to question 15

The following is a list of answers to the question "Please give a short description of the modelling exercises you use to teach uncertainty to your students. Are you differentiating different sources of uncertainty?".

- Students are measuring discharge during an excursion and use afterwards in a seminar the hydrological model HYMOD to reproduce the observed discharge, together with given longterm data. They get to know all the measurement instruments (uncertainty discussed), the model structure (uncertainty discussed) and the model parameters (uncertainty discussed). On the gained results, they write a short 2 page thesis.
- The students design their own models for the same catchment. We talk about input uncertainty, but they experience parameter uncertainty during calibration of their own model and structural uncertainty in comparison with the results of their peers.
- The use of Monte Carlo approaches to the assessment of risk
- I teach environmental modeling at the senior level in an undergraduate engineering program. We model pollutants moving across various media including rivers and lakes. We introduce uncertainty through a simple dynamical system that is sensitive to initial conditions. We perform multiple runs with small initial perturbations and study the evolution of the errors as they grow with time until they reach a saturation level. We discuss uncertainty also when performing Mote-Carlo simulations of a recharging aquifer by perturbing the model parameters.
- The class is for Honours years (last year of BSc) and their first exposure to Hydrology, so it is through discussion of results and papers that this is done
- Monte Carlo, Manual calibration by different students, ...
- Rainfall-runoff modelling, groundwater modeling. I am assessing uncertainty in an integrated framework within the stochastic physically based modeling
- Parameter uncertainty of many different models. I consider different sources of uncertainty.
- Assessing different rainfall-runoff model structures (incl. their individual parameter uncertainty) on a range of catchments. Uncertainty quantification and attribution of a hydrologic model in much greater detail (incl. forcing and parameter uncertainty) using Global Sensitivity Analysis methods.
- My approach doesn’t fall into your traditional paradigm of uncertainty
- Students represent competing stakeholder groups. Use multimodel analysis to make uncertain forecasts as basis for negotiations. Use models to identify observations. Consider measurement, parameter, and structural uncertainty.

– Students build and implement two models from scratch as part of their learning experience. One is a physics/conceptual watershed-scale state-space rainfall-runoff model. The other is a dynamics systems model for any system of their choosing. Model development includes (1) perceptual-conceptual modeling, (2) mathematical modeling, (3) computational modeling (including numerical implementation), (4) model calibration and evaluation, (5) uncertainty-sensitivity analysis, and (6) model improvement. Students are encouraged to investigate all sources of uncertainty, and to think about models and data from an information theory perspective.

– Monte Carlo simulations of effect of uncertainty in hydrologic properties on the model results; model calibration demonstration that multiple parameter sets can achieve reasonable (or not) matches to uncertain data sets

– For example stochastic rainfall modeling, with uncertain structure and parameters. Also the transfer of such uncertainty to the other components of the hydrologic cycle.

– Primarily looking at how a random hydraulic conductivity field influences model estimates

– We use Rational method and Unit hydro graph method to check input uncertainty on runoff generation

– Calc different process algorithms in excel, play with parameters

– I discuss different uncertainties such as analytical uncertainties of input data (e.g., water table or tracer measurements) and how to propagate these uncertainties for parameters that depend on measured data.

– Creating synthetic rainfall and modifying parameters

– We discuss various sources of uncertainty, but for the computer modeling we mostly focus on parameter uncertainty. We use Excel for undergraduate and MATLAB for postgraduate courses.

– Yes I am: model and input data uncertainty.

– We talk about different sources of uncertainty but in the modelling exercises use the GLUE method to investigate equifinality and parameter uncertainty.

– Comprehensive approach ranging from analysis of how uncertainty has been communicated, application of parameter estimation techniques, to scenario-based exercises. Fundamental idea is to understand the concept that results can change depending on the decisions made in an analysis, and this has a variety of consequences

– use same model with different equation options, e.g. Penman Montieth, Hargreaves and Samani etc. Look at changes in soil parameters and influence on stream flow. impact of rainfall measurements on modelling, nested gauges, radar satellite, diff temps and altitudes. Also look at stochastic flows vs actual, errors in gauges and networks.

– One-factor-at-a-time uncertainty analysis: Varying model parameters by -20%, -10%, 0%, +10%, +20% and then looking at different measures for Goodness of Fit of model results

- not explicitly; students are asked to consider uncertainty in the data, inputs, etc. when calibrating a model
- E.g. using SWAT-CUP mainly for parameter uncertainty and ensemble inputs for input uncertainty.
- Exercise is only on model parameter uncertainty. Students change model parameters, run the model, and look at the results
- yes
- Mainly through consideration of uncertainty in calibrated model parameter values and how these propagate through a model, and by comparing the performance of different model structures.
- Catchment modelling and broader system design problems using optimisation, sensitivity analysis, cross-validation, monte carlo experiments and GLUE and of which are either subject to uncertainty or characterise uncertainty.
- I use GLUE in the computer model simulations we do of hydrological processes
- We set up a hydrological model and discuss sources of uncertainty during each step of the model development.
- hydrological forecasts with ensemble forecasts as input; parameter equifinality in manual and automated parameter identification
- It is about input uncertainty using a normally distributed error model combined with an sensitivity analysis on calibrated parameters.
- GLUE & Top Model, SWAT-CUP, Error propagation, STD in regression parameter
- So far, i did not use modelling exercises
- Evaluate different model structures in different catchments including uncertainty analysis. Tools used are RRMT (Wagener et al., 2011, HESS) and SAFE (Pianosi et al., 2015, EM&S)
- I teach urban hydrology. As a course achievement, the students have to dimension a drainage network using EPA SWMM. Together with a Jupyter notebook, they are asked to perform a parameter sensitivity study acknowledging valid ranges for each parameter in runoff generation, runoff concentration, and in the hydrodynamic part of the model. Structural uncertainty is at least touched slightly, since they analyze differences in the hydrological response for two modeling approaches: the kinematic wave and the full dynamic model. However, this only discussed in brief, since the course on urban hydrology also involves other aspects of the topic such as processes, hydrologic design, blue and green infrastructure, and interdisciplinary approaches.
- ...
- Use different design floods for reservoir dimensioning

- HBV light model is used to simulate streamflow. In a guided exercise, students manually tweak selected parameters to see how the simulations change. We discuss Keith Beven's book Rainfall-Runoff Modelling: The Primer and discuss parameter equifinality. We use Monte-Carlo simulations to create different input parameter sets and test their effect on simulations. We also discuss the use of simulations of different climate models (precipitation and temperature) as input to HBV and the associated uncertainties.

- Uses Swat and Swat cup.

- HBV model combined with automatic calibration, sensitivity analysis, and uncertainty analysis

- Different lectures cover diagnostic methods to approach uncertainty quantification; we cover parameter and input uncertainty in greater depth, structural uncertainty we talk about but no exercises

- Teaching the difference between aleatoric and epistemic uncertainty. Tools to engrave uncertainty in model development and in deciding making

- We discuss epistemic, aleatory Uncertainty and ambiguity. Students design a case specific Uncertainty matrix, addressing uncertainties related to: input, parameters, model structure, context and decision processes. Students analyse input and parameter Uncertainty through model exercises

- I used SWAT for making students understand parameter uncertainty. Input data from different sources was used to assess input data related uncertainty.

- Calibration and dotty plots, Use three differently structured hydrological models

- Download and visualize climate projections or hydrological datasets and examine how they disagree with each other

- comparing own temperature measurements with station data (finding best matching station vs. nearest)