Responses to the Reviewer Comments and Description of Manuscript Changes

(Referee comments in black; Responses in blue; Changes in the manuscript in red (page/line number refer to the marked-up-document))

First, we would like to thank both reviewers for their fair and very valuable comments. In the following, we have addressed each reviewer comments in detail and have indicated how we have altered and updated the manuscript accordingly.
We hope that we have addressed all comments sufficiently, and we are looking forward to your feedback and your decision.
When giving details to changes and updates in the manuscript the first page and line numbers refer to the submitted document, the second to the updated version.

Comments by Referee #1:

1. *This paper presents a method for interactively teaching students about the unit hydrograph. The approach taken is simple, involving the students passing balls along defined flow pathways so that the result at the "catchment outlet" can be observed. It is a simple, low-cost method of demonstrating a simple case of "unit hydrograph".*
   Reply: We thank the referee for this statement, as it was exactly our intension to develop such a simple, easy to implement and cheap experiment suitable for demonstration within a lecture.
   Changes: - None -

2. *Given the time needed to run each "experiment", I feel that a hybrid approach would be better, where the idea is introduced using a simple participatory demonstration as described here, but more detailed experiments are done through computer simulation. This is particularly the case when the time needed for a single experiment (including discussion) is between 30 and 90 minutes (page 9, line 4-5). 90 minutes is a considerable break in a 3 hour lecture, and suggests a more efficient method might be needed.*
   Reply a): We fully agree with the reviewer that it is also necessary to have additional exercises (e.g. in the computer lab), where students do explicit calculations applying the unit-hydrograph concept. We also do that in our program within the course "Exercises in Hydrology". The course is conducted separately, but organized in close cooperation. The lecture theatre experiment (as introduced in the paper) is a visceral aid that gives an additional visualization and participatory demonstration. The main goal is therefore to stimulate student interests and to help them in their scientific learning. The positive effect of experimental demonstrations on deeper understanding and learning has been found by a number of authors (e.g. Roberts et al., 2005, Savec et al., 2005).
   Changes a): We have include a separate paragraph addressing this topic and referring to these references in the revised version of the manuscript (page 3, line 16-21).
   Reply b): Concerning the time of the experiment – we wrote 30-90min in the submitted manuscript –, we could repeat the experiment and, with the help of 2 student assistants, we were able to include the basic demonstration within a 15-20min time slot. When this time slot is well set, it is an ideal

interruption of a 3h lecture.
In the manuscript, we additionally describe variants of the experiment that can, but do not need to be performed. These variants are only described in case there is more time available.
Changes b): We have made these points clearer in the revised version of the manuscript (page 9, line 22-24).

3. *The real question here is: how many such experiments are needed in order to provide a suitable improvement in student understanding? Can a combination of participatory and computer examples achieve the same effect in less time?*
   This is a very interesting question and depending on some funding, there might be a good chance over the next years to tackle this question. In general, a longer-term educational experiment would be required to answer this question thoroughly. The experiment will use some kind of split group approach and then analyze the exam/learning results for these different settings. As we have received the teaching award of our university for this experiment in the last year, our educational department had approached us in order to discuss such a long-term study to examine the effect. We apologize to admit that currently an answer to this question is out of scope.
   Changes: In order to address this issue, we have slightly extended our discussion and added a paragraph on the need for such a longer-term investigation in the discussion (page 10, line 13-17), we also added a short paragraph giving some literature review on the effect of experimental demonstrations on the learning process (page 3, lines 24 - 27).

4. *The paper gives a reasonable review of the history of the unit hydrograph. I consider that the authors are incorrect in saying that the effective rainfall is homogeneously distributed over the catchment (page 4, lines 2-3). This is not necessarily the case. What the UH concept considers is that the spatial distribution of effective rainfall doesn't change between events. It can be non-homogeneously distributed. This can be due to spatial variations in rainfall (e.g. due to topographic effects), or due to spatial variations in the fraction of rainfall that is converted into effective rainfall (e.g. due to topography, soils, vegetation). Considering the effective rainfall to be homogeneously distributed across the catchment is a simple case, but not really the requirement of the unit hydrograph concept.*
   We fully agree on this comment. The assumption of a uniform "effective precipitation" however is very often made in many textbooks as a requirement (e.g. Maniak, 2016, p350).
   Changes: We deleted our statement about the requirement of homogeneous precipitation (page 4, line 4-5) and we added a sentence on the spatial distribution of precipitation at page 4, line 16-18.

5. *I think papers like this do have a place in HESS - but this paper needs a little more work in order to be of publishable quality.*
   We hope our comments and suggested adaptations will sufficiently address the comments made by Referee #1.

Literature:

Maniak, U.: Hydrologie und Wasserwirtschaft, eine Einführung für Ingenieure, 7.Aufl., Springer Vieweg, 2016

Roberts, J. R., Hagedorn, E., Dillenburg, P., Patrick, M., and Herman,T.: Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course, Biochem. Mol. Biol. Edu., 33, 105–110, 2005.

Savec, V. F., Vrtacnik, M., and Gilbert, J. K.: Evaluating the educational value of molecular structure representations, in: Visualisation in Science Education, edited by: Gilbert, J. K., Springer, 269–300, 2005.

Comments by Referee #2

1. *This paper presents a creative method of teaching the Unit Hydrograph, a fundamental concept in hydrology, in an interactive and non-lecture format. This would be a good addition to HESS as more and more instructors hope to incorporate nontraditional and active methods of teaching STEM concepts to suit different types of learning styles. While the demonstration may not be feasible in some cases, this paper presents one option of teaching the UH concept and could be the basis of different modifications to suit individual classroom needs.*
   We thank the referee for this statement!

2. *One general concern I had was that the authors cited "strong difficulties in students' perceptions of the UH' as the motivation for using the active demonstration. However, I could not find what specifically the previous concerns were and if they were actually addressed/reflected in the final evaluations after the demonstration. I believe summarizing some of these learning difficulties and how the demonstration overcomes them would help convince other readers to try this method, especially if they are encountering the same issues with their students.*
   One major difficulty we observed in the exams of years before was a general lack of understanding of the UH-principles. Namely, that the unit hydrograph represents a transfer function that describes the "generation" of a hydrograph given a unit of effective precipitation in a catchment. We first included (for the case of a uniform distribution of effective precipitation) an interpretation of the UH as a distribution of travel times (similar to time-area histograms). It seemed not sufficient as still a large number of students were not able to formulate the functioning and interpretation of an UH properly. Our impression was, that with the introduction of our experiment understanding has improved (also many students now use the experiment as an example to explain the UH). However, given the large variation of students' backgrounds and capabilities from year to year, I would not dare to express any direct and sole effect of the experiment quantitatively.
   Change: We added a paragraph to detail some of the difficulties (page 3, lines 16-21), and extended the conclusions as described under Rev.#1, comment 3.

3. *The organization of the paper as well as the figures are of good quality; the only concern regarding the writing pertains to some awkward phrasing and some typographic errors (see technical corrections in supplement).*
   See below.
   Change: - see specific comments -

Specific Comments

P2, Line 14 – This section starts at a nice review for the UH; however the Zoch and Clark references here are inserted without much description and are vague. If you want to use them as using 'similar concepts', I would suggest you provide more details.

As the introduction into the UH is already quite long, we prefer to not extend the description, and rather to delete that sentence.

Change: we deleted that that statement, in order to not extend the intro further and deleted the two citations from the list of references.

P2, Line 19-21 – You should cite what you say here

Given the infiltration process as one of the processes that control effective precipitation, and given the non-linearity in the soil hydraulic properties, we do think it is obvious that this process is non-linear. We believe that additional explanation are not necessary in the text and also do not think it is necessary to have a citation for this fact. Nevertheless, we are happy to provide a reference, if required by the editor.

Change: - None -

P2, Line 25 – Different conditions such as?

We will add them. Examples are: soil moisture, climate.

Change: we added (soil moisture conditions and climate) as explicit examples for different conditions (page 2, line 26).

P2, Line 33 – I believe that the MHM model in the Samaniego paper does *not* explicitly use the UH concept as a routing method as it summarizes different grid cells through the regionalization process, then upscales to larger spatial scales and is not necessarily constrained to the UH assumptions/limitations. Perhaps double check the use of this citation.

The mHM uses a simple triangular UH to convolute runoff that is produced in each cell to represent spatially variable runoff production. The routing between cells in the catchment however is done differently. Therefore we would like to keep this citation of a current mesoscale hydrological model making use of the UH concept.

Change: We explicitly stated the concrete use of the UH concept within mHM. We also deleted the reference Michel et al. 2003 as it primarily referring to an analysis of storage related formulations of catchment behavior.

P3, Line 12-13 – Could you elaborate a bit more here? Understanding how the students struggle here would help the reader understand how the activity improves their understanding

See answer to comment 1

Change: as described under comment 1 (page 3, lines 16-21)

Figure 1 – The figure illustrates the concept fairly well. I would choose colours/patterns that contrast more. Also make sure that the final version does not have blurry text

Change: Figure 1 has been adapted so that pattern contrast more.

Technical Corrections

P1, Line 12 – Unit-hydrograph and unit hydrograph are used interchangeably throughout the text and title. You should pick one and be consistent with it (consistently changed to “unit hydrograph”)

P1, Line 13 – ‘up-to-date’ is awkward, perhaps use ‘to date’ or ‘to this day’ (changed to “to this day”)

P1, Line 15 – topic addressed in most of the (engineering) hydrology…(rephrased)

P1, Line 19 - experiment involving an active student….(rephrased)

P2, Line 10 – A step further has been the first attempt of a spatially distributed…First section is awkwardly phrased. (rephrased)

P2, Line 18 – Check that your references don’t have the brackets {} for next submission. They also appear later on. (changed to “(.)” throughout the whole manuscript.)

P2, Line 28 – Principal idea, not principle (changed)

P2, Line 30 – In other words, (changed)

P2, Line 36 -in any of the academic hydrology courses at the (BSc and MSc); I would say undergraduate and graduate level as they can be different in institutions or countries, e.g. BASc, B.Eng., etc. (changed accordingly.)

P4, Line 1 – We would like to point out here, that the UH… (changed)

P4, Line 3 – a spatially explicit (changed)

P4, Line 8 - Units for runoff are given normalized by …(changed to “Units for runoff are provided as catchment area specific runoff in …”

P4, Line 14 – 90 min (changed)

P5, Line 21 – The sampling of the water packages and along is carried out with… (corrected to “The sampling of the water packages (balls) and along the “main stream channel” is carried out …”)

P7, Line 16 - …by a yellow ball (first event from Figure 1) (Captions for figure 1 are rephrased)

P7, Line 20 - many of the recent (changed to “While such an analysis is presented in recent hydrology textbooks ..”)

P7, Line 29 – (e.g. steep areas close to …. You need to close the parenthesis somewhere (done)

P9, Line 12 – Confucius (sorry we used the German spelling; we changed the name to Confucius)

Demonstrating the “Unit Hydrograph” and flow routing processes involving active student participation – A university lecture experiment

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Abstract

The unit ~~-~~hydrograph (UH) has been one of the most widely employed hydrological modelling techniques to predict rainfall-runoff behavior of hydrological catchments, and is still used to this day~~up-to-date~~. Its concept is based on the idea that a unit of effective precipitation per time unit (e.g. mmh^{-1}) will always lead to a specific catchment response in runoff. Given its relevance, the UH is an important topic that is addressed in most ~~of the~~ (engineering) hydrology courses at all academic levels. While the principles of the UH seem to be simple and easy to understand, teaching experiences in the past suggest strong difficulties in students’ perception of the UH theory and application.

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In order to facilitate a deeper students’ understanding of the theory and application of the UH, we developed a simple and cheap lecture theatre experiment which involved~~ing an~~ active student participation. The seating of the students in the lecture theatre represented the “hydrological catchment” in its size and form. A set of plastic balls, prepared with a piece of magnetic strip to be tacked to any white/black board, each represented a unit amount of effective precipitation. The balls are evenly distributed over the lecture theatre and routed by some given rules down the catchment to the “catchment outlet”, where the resulting hydrograph is monitored and illustrated at the black/white board.

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The experiment allowed an illustration of the underlying principles of the UH, including stationarity, linearity and superposition of the generated runoff and subsequent routing. In addition, some variations of the experimental setup extended the UH-concept to demonstrate the impact of elevation, different runoff regimes and non-uniform precipitation events on the resulting hydrograph.

In summary, our own experience in the classroom, a first set of student exams, as well as student feedback and formal evaluation suggest that the integration of such an experiment deepened the learning experience by active participation. The experiment also initialized a more experienced based discussion of the theory and assumptions behind the UH. Finally, the experiment was a welcome break within a 3-hour lecture setting, and great fun to prepare and run.

1 Introduction

1.1 *Background*

The prediction of catchment rainfall-runoff behavior is an important prerequisite of any effective flood risk and water resources management practice. Rainfall-runoff modelling has a long history with a starting point that can been dated back more than 150 years to the work of Mulvaney (1851) and even further (see e.g. Biswas et al., 1970). He first introduced a simple linear relationship between peak discharge and maximum catchment average rainfall intensity that is dependent on catchment size and an empirical coefficient that effectively represents all other catchment characteristics (Beven, 2012). It is known as the *rational method* in engineering hydrology, and with modification is still used today (e.g. Hromadka, 1994; Plate, 1988).

~~A step further has been~~ T~~t~~he first attempt to develop ~~of~~ a spatially distributed hydrological model can be attributed ~~by~~ to Ross (1921). In his approach, the catchment was split up into zones of equal travel times to the catchment outlet, and runoff production is calculated for each area, dependent on the antecedent conditions and rainfall rates. The resulting time-area diagrams represent the delays for runoff from each part of the catchment. ~~Similar concepts have been introduced by e.g. Zoch (1934) or Clark (1945) and are still included in current distributed hydrological model systems.~~

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While it has been long known that flow velocities change in a nonlinear way with flow rate or flow depth, the Ross-approach relies on the assumption of linearity in routing the runoff to the catchment outlet. This violation however, has been shown less critical compared to the problem of estimating the effective rainfall for each event (Beven, 2012). The effective precipitation is thereby the part of the total precipitation contributing to runoff during an event. The estimation of this proportion is generally a nonlinear process depending on the antecedent catchment conditions, including soil moisture and interception storage conditions, possible snow cover, as well as rainfall intensities. Common approaches to calculate effective precipitation are the *constant loss rate* (ϕ-index) method, the *constant proportion* method, or infiltration based methods as suggested by Horton (1933).

Another major difficulty with the Ross-approach was to decide which areas of the catchment would contribute to the different time zones, since there were almost no information on flow velocities and pathways in the different soil compartments (surface runoff, interflow) and on different environmental conditions (soil moisture, climate) available. The unit ~~-~~hydrograph (UH) method developed by Sherman (1932) tried to avoid these difficulties by representing the various time delays for runoff generated within the catchment by a stationary time distribution that has not necessarily any direct link to a particular location. The principal~~le~~ idea of the method is that assuming a linear routing procedure, this distribution could be normalized to represent the response to a unit of runoff production, or effective rainfall, generated over the catchment in one time step. In other words, the UH represents a discrete transfer function for effective rainfall to reach the basin outlet, lumped to the scale of the catchment. The UH has been one of the most widely employed hydrological modelling techniques to predict rainfall-runoff behavior of hydrological catchments, and is still used in current generations of hydrological forecasting systems (see e.g. Samaniego, 2010, who use a simple triangular UH to convolute runoff that is produced in each cell to represent spatially variable runoff production. The routing between cells in the catchment however is done differently.~~; Michel, 2003~~).

Formatiert: Englisch (Vereinigte Staaten)

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Given the importance of the UH in the historical development of rainfall-runoff models, and the fact that its basic principles are still included in current spatially distributed hydrological models, the UH is an important subject in any of the academic hydrology courses at the ~~B.Sc. and M.Sc.~~undergraduate and graduate level. The UH theory and principles include general concepts of catchment hydrology that form the foundation for further, more advanced topics and therefore need to be introduced in an understandable way.

1.2 Teaching Situation

The principles of runoff generation processes and the basic concepts for rainfall-runoff modelling are essential parts of the 3rd semester "Hydrology and Water Resources Management 1" course that is mandatory within the "Civil Engineering and Water Management (H033231)" program at the University of Natural Resources and Life Sciences (BOKU), Vienna. All students in the program have previously attended introductory courses in mathematics, physics, statistics, mechanics, hydraulics, and went through an introduction into hydrography and hydrometry. While in theory the previous knowledge seems to be more than sufficient and adequate to understand and grasp the central ideas behind the UH, exam results over the last years consistently and repeatedly demonstrated significant gaps in students' understanding. While the concept of "effective precipitation" contributing to catchment runoff did not seem to make any difficulties, it was in particular the interpretation of the UH within a hydrological system context and its use as a prediction tool that were identified as critical areas. This included the interpretation of the UH as a transfer function that describes the "generation" of a hydrograph given a unit of effective precipitation in a catchment. As a first attempt we included (for the case of a uniform distribution of effective precipitation) an interpretation of the UH as a distribution of travel times (similar to time-area histograms). It seemed not sufficient as still a large number of students were not able to formulate the functioning and interpretation of an UH properly.

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Therefore, ~~I~~in addition to the standard slide presentation of the theory, we decided in the winter-semester 2016/17 to additionally visualize the concept of the unit ~~-~~hydrograph, its underlying assumptions and the linear routing principles in a lecture theatre experiment. The main goal was to stimulate student interests and to help them in their scientific learning. The positive effect of experimental demonstrations on deeper understanding and learning has been found in a number of studies in a variety of natural sciences disciplines (e.g. Roberts et al., 2005, Savec et al., 2005).

In our experiment, students and the location they were sitting represented a hydrological catchment in the lecture theatre, and they were actively involved in routing an effective precipitation event to a fictive runoff gauge in the room. This gauge was "monitored" over time and the resulting runoff data was visualized in an illustrative way.

The setup of this experiment, the material required and its preparation as well as variants of the experiments and possible follow-up discussions to interpret these experiments will be described in some detail in the following.

2 Experimental Setup

2.1 The Unit Hydrograph (UH)

Summarizing the theory of the UH as briefly described in the previous section, three basic principles can be emphasized when transferring a unit of effective precipitation to the catchment outlet. These are: i) stationarity, ii) linearity, and iii) superposition. Stationarity of the UH concept assumes that a unit of effective precipitation will always generate the same hydrograph, independent of the time of the day/year and of the antecedent e.g. soil moisture conditions. Linearity in the routing process requires that any event with x units of effective precipitation will generate x-times as much predicted runoff in the hydrograph at the catchment outlet, having the same temporal distribution. The principle of superposition states that multiple consecutive effective precipitation events can be treated independently and predicted runoff in the hydrographs is superimposed by simply adding individual responses. An example unit hydrograph and these three fundamental principles are illustrated in Fig. 1.

We would like to point out here, that the UH concept per se does not explicitly link the runoff generation processes to any particular location. The UH rather represents a travel time distribution of a unit effective rainfall for a particular catchment.~~that is homogeneously distributed over the catchment~~. Being aware of this fact, we nevertheless chose a spatially explicit setting for illustrating the UH and its principles as well as runoff routing processes. While the UH theory does allow to consider spatially heterogeneous precipitation field that are stationary in time, the focus here is on uniformly distributed precipitation fields, as is often done in hydrology textbooks for simplicity (Maniak, 2016, p.350). ~~-~~The implementation into a lecture theatre experiment will be explained step-by-step in the next subsection.

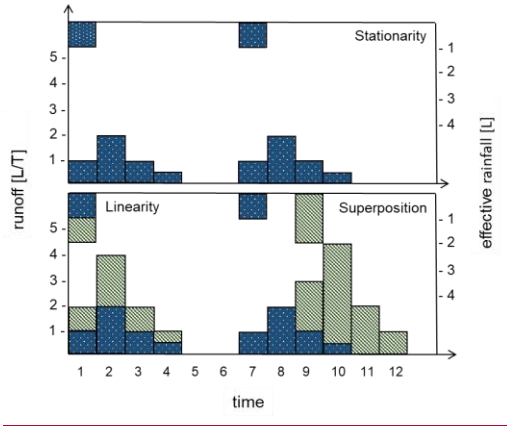


Figure 1: An example of a UH (upper left) and an illustration of the principles of stationarity (upper right), linearity (lower left), and superposition (lower right). Units for runoff are provided as catchment area specific runoff ~~given normalized by the catchment area~~ in length [L] per time [T].

Formatiert: Nicht Hervorheben

2.2 Lecture theatre experiment and teaching material

The following steps were implemented to realize an experimental illustration of the UH principle in a lecture theatre. The experiment took about 20-25 min including all instructions, explanations and some basic discussions. It will be shown later (section 2.3) that different variants of the experiments can be performed to focus on further aspects of catchment rainfall-runoff behaviour so that the experiment including discussions can be easily extended to 90 min. The experiment uses very simple and cheap materials that were easily available in any department store. Overall costs were in the range of €30,-.

Step 1 (ball preparation):

An effective precipitation of 1mm is realized using differently colored plastic balls. A short piece of magnetic stripe was glued to each ball so that they could be tacked to most of the lecture theatre and seminar room white/black boards. Figure 2 illustrates a prepared ball and its use at the white/black board.

Step 2 (defining the catchment):

The “size” and the “form” of the catchment is defined by the positioning/seating of the individual students in the lecture theatre. By considering a different number of students within the experiment and changing the seating positions, the catchment size and form can be varied in order to examine and illustrate the effect of variations in both on the resulting hydrograph. Figure 3 shows the lecture theatre setup – each student holding a plastic ball representing 1mm of effective precipitation received by the catchment.

One person - approximately in the center of the first row or a teaching assistant (see Fig.3, left, gauge) - is defined as the catchment outlet, thus receives all the effective precipitation (balls) that have been routed “down” the catchment (lecture theatre).

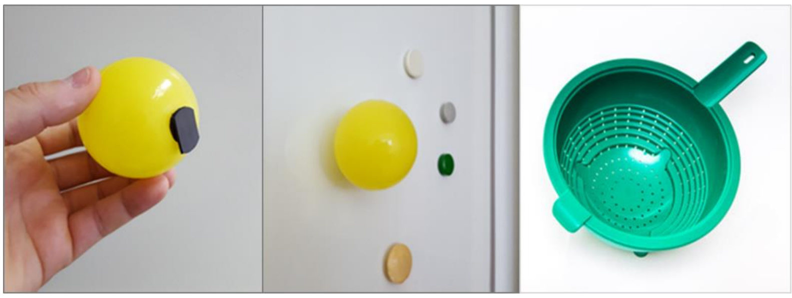


Figure 2: A piece of magnetic stripe glued to a plastic ball (left) that represents a unit amount (1mm) of effective rainfall, as well as generated specific runoff. It can be tacked to most of the classroom white/black boards (middle). The sieve is used to “collect” generated runoff during the routing procedure (right).

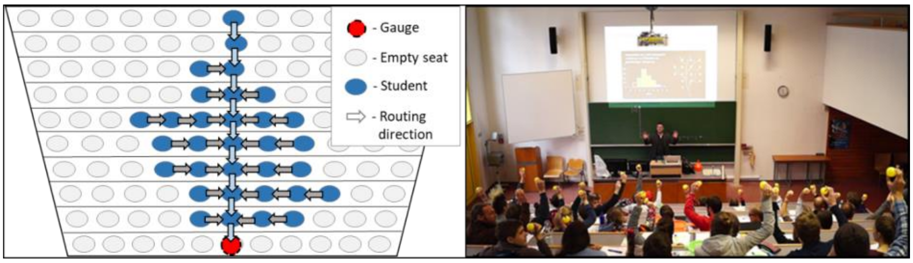


Figure 3: Catchment setup by 32 students in the original lecture theatre (right). The catchment/each student received an effective precipitation of 1mm represented by a plastic ball. A sketch of student seating, flow routing and the gauge (left). Blue flow arrows indicate the main stream channel within the catchment.

Step 3 (routing rules):

The routing of the effective precipitation within the catchment has to follow some rules in order to generate runoff. To mimic some real catchment behavior, each student has to transport her/his 1mm of effective precipitation water package towards the outlet. A simple routing scheme that is easy to explain and to execute is sketched in Fig. 3 (left) and proceeds as follows for each time step: i) vertical transport (blue arrows) of water packages of one position only along the main stream channel starting in the first row; the water packages in the gauge position are the measured runoff information for this time step; ii) horizontal transport (grey arrows) of one position towards the main stream channel in each row starting with the inside positions. The sampling of the water packages (balls) ~~and~~ along the “main stream channel” (middle column of the lecture theatre) is carried out with plastic sieves as the number of balls might exceed the number of balls that can be handled by hand (see Fig. 2, right).

Step 4 (hydrograph representation):

With each time step, a different number of water packages (balls) are collected/sampled at the catchment gauge. They represent the catchment hydrograph resulting from 1mm of effective precipitation homogeneously spread over the entire catchment. Given the routing scheme that has been chosen for this particular experiment, the hydrograph in Fig. 4 represents the corresponding UH of our lecture theatre catchment. The units of the y-axis are in length per time and dependent on the units chosen for the time steps and the effective precipitation (here 1 mm per ball).

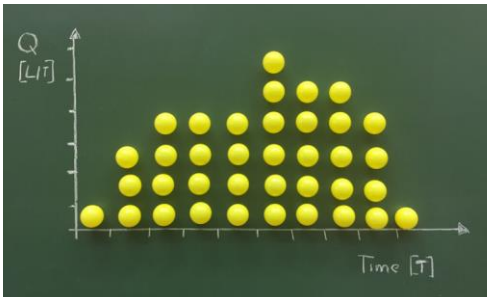


Figure 4: A lecture theatre catchment unit ~~-~~hydrograph resulting from 1mm effective precipitation (represented by a yellow plastic ball) homogeneously spread over the catchment.

3 Results and Discussion

The UH illustrated in Fig. 4 is the result of a specific lecture theatre setting including the form of the catchment defined by the positioning of the students in the lecture theatre (see Fig. 3) and the rules formulated to route the effective precipitation through the catchment. The basic experimental setup as described in section 2 can be extended in various ways to illustrate i) the basic principles behind the unit ~~-~~hydrograph, and ii) a number of additional factors that have a significant control on the generated hydrograph, such as the catchment terrain, the surface conditions and dominant runoff components, for example surface runoff or subsurface stormflow.

3.1 Illustration of unit hydrographs principles

The three principle underlying the UH are stationarity, linearity and superposition of runoff generated by different events (Fig. 1). The principle of stationarity is easily explained by simple repeating the experiment and thereby receiving the same hydrograph as result. Such a repetition might be not very exciting for the students, but experience shows us that a thought experiment is sufficient to foster understanding. The principle of linearity could be illustrated and discussed in two ways. First, given the initial experiment where each plastic ball represented a unit amount of effective precipitation (e.g. 1mm), this is simply redefined to twice the amount (e.g. 2mm) which exactly doubles the runoff generated in the hydrograph. Secondly, the experiment may be repeated with twice the number of balls per student, again resulting in a doubling of the runoff in the generated hydrograph. The second variant will obviously provide a more vivid illustration of the principle of linearity; however, it will require more resources in terms of number of balls and more experimental execution time, which might be more limiting given any lecture setting. The principle of superposition can be illustrated by considering two independent precipitation events, each producing e.g. 1mm of effective precipitation. The different precipitation events can be labeled by using differently colored balls (e.g. yellow and blue). While the first precipitation event will take place at the first time step, the second event will have a time delay of some steps. Figure 5 (right) shows the superposition of the two events (each 1mm of effective rainfall) and the resulting hydrograph.

As mentioned earlier, the unit hydrograph does not explicitly link any runoff generation to a specific location in the catchment. We here used an explicit setting to illustrate the principles of the UH – each explicit setting or form of a catchment and routing scheme will produce a specific hydrograph. The experiment in Fig. 5 provides a good opportunity to discuss this fact with the students. This point could be illustrated by designing a second but different experimental setting (form and/or routing scheme) that leads to the same hydrograph.

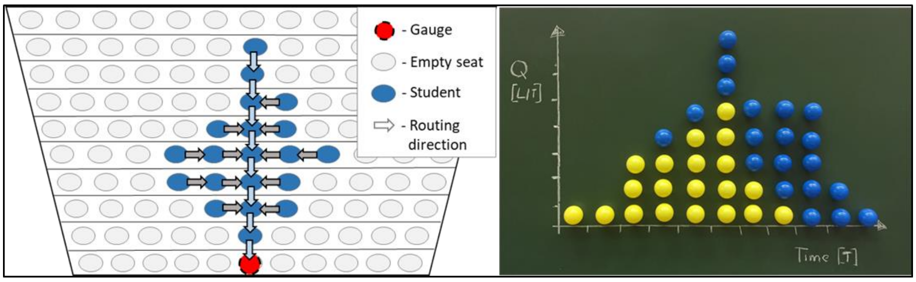


Figure 5: The superposition of two rainfall events, both producing an effective precipitation of 1mm. The first event is represented by ~~a~~ yellow balls, the second event which is delayed by 4 time steps is represented by ~~(first event) and a~~ blue balls~~(second event, delayed by 4 time steps)~~.~~,~~ ~~and~~ T~~t~~he resulting hydrograph is shown on the ~~(~~right~~)~~. The left figure illustrates the student seating and routing scheme applied in this experiment.

3.2 Analysis of factors controlling the unit ~~-~~hydrograph

One obvious factor to analyze is the form of the catchment and its impact on the dynamics of the hydrograph. While such an analysis is ~~given in many of the~~presented in recent hydrology textbooks (~~{~~e.g. ~~\~~Baumgartner et al., ~~1996~~ 1996; ~~#8160`, ~~, p.525f; ~~\~~Ward and Trimble, , 2003 ~~#8161`~~, p.126f)~~}~~, this effect is simply assessed by changing the seating positions of the students in the lecture theatre and repeating the experiment. Figure 6 illustrates the representation of different catchment forms by student seating in the lecturer theatre (top panel) and the resulting hydrographs (lower panel).

While the concept of the UH per-se does not require any linkage between the time delay of any runoff generated in the catchment to a particular location (see section 1), the lecture theatre experiment is well suited to additionally discuss any of the catchment properties that are related to the different forms of runoff processes in the catchment. In the standard routing scheme as introduced in section 2, no effect of differences in topography is considered in the routing scheme. In order to investigate the effects of topography, different areas with steep elevation gradients (e.g. steep areas close to the catchment boundaries, where the transport of water is enhanced) are demonstrated by allowing balls to “jump” over 2 positions, thus representing the increase in flow velocities due to increased potential gradients. Differences in the soil texture and resulting infiltration capacities might be represented similarly, indicating areas with more frequent surface runoff generation and quick flow conditions versus areas with more dominant subsurface or interflow flow regimes that deliver water more slowly towards the catchment outlet. In this way, different routing rules can be linked to different catchment properties and runoff/flow regimes, which can be used for critical discussion of the assumptions and underlying principles of the UH, as well as the possible effects in case those principles and assumptions are violated.

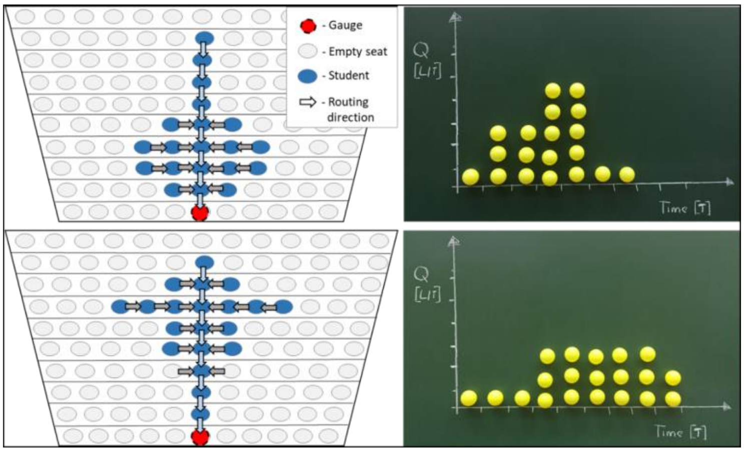


Figure 6: The effect of different catchment forms (same area/number of students, left) on the resulting hydrographs (right).

While beyond the underlying assumptions of the UH (spatially uniform effective precipitation), this lecture theatre experiment is well suited to additionally demonstrate the effect of spatially non-uniform precipitation and runoff generation processes, by limiting the distribution of plastic balls to only a subset of the students. Figure 7 illustrates the resulting hydrographs when only the lower half (left) or the upper half (right) of the catchment receive a unit amount of effective precipitation. The differences in the timing of the resulting hydrographs are clearly visible.

4 Experience and Outlook

Our personal experience with the unit-hydrograph and runoff routing lecture theatre experiment, as well as the direct student feedback and the student evaluation was extremely positive and revealed the following key aspects:

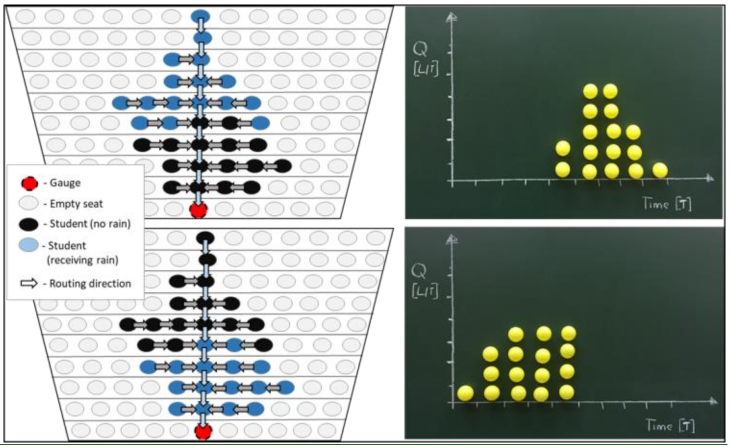
(1) The experiment was well suited to illustrate the concepts of the unit-hydrograph. The underlying principles such as stationarity, linearity and superposition, as well as the effect of different catchment form, catchment elevation, runoff mechanism and non-uniform precipitation events on the catchment hydrograph could be well demonstrated.

(2) The active participation of every student in the experiment allowed an intensive “active experience” of the UH and routing mechanism by being “one part of the catchment” and being “involved” in the transport of the water towards the catchment outlet. Student’s active participation in the experiment also highly supported an intensive discussion on the theoretical background of the unit-hydrograph. Assumptions such as the linearity of routing procedure could be questioned and discussed with regard to real catchment behaviour including the impact of antecedent soil moisture conditions on the runoff generation, and the non-linearity of flow depth – flow velocity relationship.

(3) For the basic experiment, a time slot of approximately 20-25min and the help of two student assistants was needed in the lecture. However, in case there is more time available the experiment and discussions can be easily extended to 90min and more by including some of the additional variants as illustrated in

section 3.2. ~~epending on the number of experiment , the time needed for a single experiment including the discussion will range between about 30 – 90 min~~. Given a 3-hour framework for our particular lecture, the experiment was a very welcome “active break” from the standard slide based lecturing. It refocussed students’ minds and attention.

(4) Actively participating in deriving the catchment rainfall-runoff relationship was fun, not only for the students, but also for everybody involved in the course teaching.

(5) 

(6) Figure 7: The effect of different spatial distributions of effective precipitation within the catchment on the resulting hydrograph. The student seating, the spatial distribution of effective precipitation and the routing scheme are indicated on the left, the hydrograph are illustrated on the right.

To summarize our experience with the integration of such a lecture theatre experiment into the course: We believe that overall a much deeper learning experience for the students could be achieved due to the visualization and active participation of the students. In order to quantify the impact of such experiments on the students learning process, a longer-term educational study using some kind of split group approach would be needed. While the education department of our university has expressed their interest in conducting such a study, we are currently not able to make a quantitative statement in that direction. Nevertheless, our subjective experience is well expressed by a statement of Confuc~~z~~ius (551-479 BC) saying that “I hear and I forget, I see and I remember, I do and I understand” and will encourage us to further extend the integration of experiments into lecture-based teaching.

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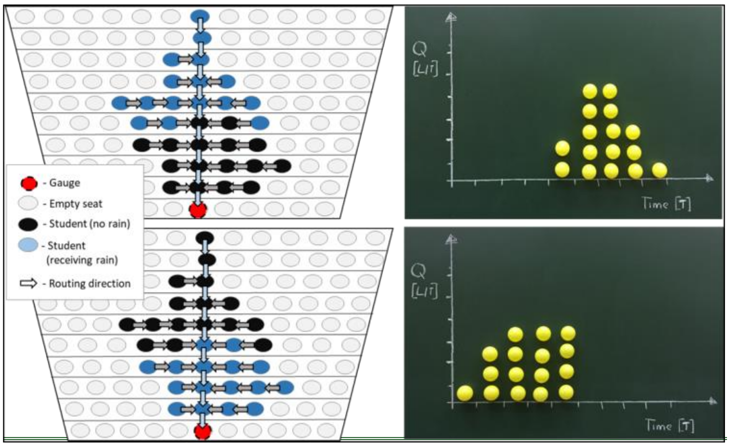

~~Figure 7: The effect of different spatial distributions of effective precipitation within the catchment on the resulting hydrograph. The student seating, the spatial distribution of effective precipitation and the routing scheme are indicated on the left, the hydrograph are illustrated on the right.~~

Data Availability. All required information and appropriate references are given in the text.

Author contributions. KS (PI) designed the experiment and run the lecture. RB (M.Sc. student) developed the teaching material. JW (PhD student), DK (PhD student), MH (Co-PI) as well as RB contributed to the development of the teaching experiment. All authors were involved in the manuscript and figure preparation.

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