Author Responses to Referees

The referee response is given in italic purple text, whereas the author responses as a list of changes are given in non-italic text under each referee response. In the edited paper, major additions to the text are indicated in a blue color and line or page numbers are also provided in the responses below. Revisions have been made to the paper structure along with an associated editing of content to address the referee responses. A version of the manuscript showing differences is also attached to this response file.

Anonymous Referee #1

Overall, this is a very interesting paper that explains the planning and execution of a circuit building and calibration activity in an advanced undergraduate hydrology class. I think the information that is presented will be of interest to other educators teaching hydrology and climatology classes. The author does a good job of providing details on all aspects of the activity and how the activity was received by the students.

Thank you for these comments and for your recommendations.

I think the paper would benefit from clearly identifying what the questions and/or objectives of the study are and restructuring the methods and results to separate out conceptual and technical information, as well as ensuring that results are not presented in the Methods section. For example, the information on different types of systems in section 2.1 Background could be integrated into the Introduction section to provide a rationale for the study. A lot of this information seems out of place in the Materials and Methods section.

- The objectives of the study are now listed in point form in the Introduction section of the paper (pg. 5).
- The background information previously in Section 2.1 has now been moved to the Introduction section (Section 1).
- The information in the materials and methods section has been restructured to separate conceptual and technical information.

As well, throughout the paper, very short paragraphs (2-3 sentences) are used (e.g. L248-57). While I can see the benefit of this in some places, I think the overall flow of the paper is hampered with this approach. For example, in section 2.3, the focus of the paragraphs jump around quite a bit (technical information about the calibrations, student feedback). Overall, I recommend the author try to integrate some of these shorter paragraphs together under common themes.

- The shorter paragraphs have been combined into larger paragraphs for presentation throughout the paper and some paragraphs have been eliminated or restructured, as necessary. Lines L248-57 in the original draft have been removed and replaced in an associated discussion (see the second paragraph of Section 2.2).
- The manuscript has now been organized by common themes.
- This restructuring approach has also been implemented with respect to the suggestions given by Reviewer #2. Please see the response to Reviewer #2 for further information related to the restructuring changes used for this paper.

In the results and discussion section, the author should try to make clear links back to the research questions/objectives, i.e., try to make the different sections of the paper mirror each other.

- The results and discussion section (now Sections 4-5) indicate the objectives of the paper identified on pg. 5.

Specific Comments L53: I recommend changing 'will eventually' to 'may'.

- The wording has been changed as recommended (line 127).

L67: Unclear what 'threshold concepts' is referring to in this sentence.

- The sentence has been re-written for clarity (line 151-153).

L76-83: I recommend trying to tighten up this paragraph a bit as there is some repetition. For example, 'Before circuits are constructed: : :' and 'Prior to circuit construction: : :'.

- The repetition in this sentence has now been removed as recommended. Please see the first paragraph of Section 2.4.

The mention of HRUs, CRHM and SWAT seem unnecessary here. They do not further the explanation of systems in hydrology in any way. I recommend removing these or rewording to make it clear why this information is useful for understanding hydrological systems.

- For clarity and presentation, references to these models have been removed from the paper (Section 3) and Figure 4 updated.

L210-4: This paragraph seems out of place here since below the actual details of the activity are explained.

- The paragraph has been removed from the paper for clarity and to reduce repetition.

L225: I recommend presenting the methods sequentially. This paragraph describes what happened before the activity started, so present it first.

- This paragraph has now been written and the information moved to Section 2.4.

L231-2: Was this based on written feedback? Or just the verbal feedback?

- This is a verbal response during the class activity. Please see Section 4.2 for an updated version of these lines. All verbal responses during the class circuit activity are given in Section 4.2, whereas feedback collected after the class circuit activity is discussed in Section 5.

L258-266 and L280-4: This seems like information that should be in the Results and/or Discussion section.

- This information has been moved to Section 5.1.

L297-305: Section 2.4 is really a result of the study. I recommend moving it into section 3.

- The information in Section 2.4 has now been moved to Section 4.3 of the updated paper and paragraphs combined for presentation.

L308-24: Section 2.5 seems more suitable for a Discussion section.

- The information in Section 2.5 has now been moved to Section 4.4.

L412-414: Instead of using the trends plot, I recommend providing quotes from the students. Otherwise the reader is left to guess the context for each of these words.

- Quotes from the students are now provided in Table 3 and the quotes are analyzed by a discussion (pg. 17).
- The trends plot allows for five re-occurring words to be quantitatively identified in the text and the associated discussion is supplemented by Table 3.
- The student responses were checked before Table 3 was created. A transcribing error for Student #7 was fixed before Table 3 was inserted into the document and Figure 11 was updated. The update of Figure 11 does not change the analysis presented in the text of this paper or the analysis given on pp. 16-17. All quotes from the students are also available for download (Section 7).

L425-35: I'm not sure that the overall course survey feedback is relevant here as it's really the circuit building/calibrating activity that is being discussed.

- For clarity, the overall course survey feedback discussion was removed from the paper.

L456-7: While good to hear, I don't think that feedback on the instructor for a single course is relevant here. I recommend that the author just focus on student feedback related to the circuit activities.

- The instructor feedback has been removed from the paper so that the paper is focused on student feedback related to circuit activities.

L562: I'm not sure that the inclusion of information on the 3D watersheds is helpful in this paper since the focus is really on the circuit building.

- The information on 3D printed watersheds has now been removed from the paper to better focus the paper on the student activity. Figure 4 in the revised paper has also been accordingly updated along with the Abstract.

L574-620: I recommend trying to shorten the Conclusions. There is information in here that could be placed back in the Discussion (e.g., recommendations for future classes).

The Conclusion section has been shortened and some information (recommendations for future classes) has been placed in the discussion sections of the paper. Please see Section 6 and the end of Section 5.1.

Figure 3: I suggest choosing just one of these photos.

One of these photos of the class activity has been retained in the edited version of the paper (please see Figure 6 in the edited version of the document).

Referee #2 – Nilay Dogulu

It was a great pleasure to review this manuscript. However, I agree with the Editor that there is an overwhelming focus on the technical details. There must be an equal focus, e.g. on aspects related to hydrology education and overall (methodological) design of the activity, to balance out such skewness. In my report, there are some suggestions for mainly the Introduction and Conclusion parts to address this issue. There is a good potential in this manuscript, and I look forward to the revised version.

Nilay, thank you for your comments and recommendations. I have addressed your suggestions and a response to each suggestion is given below. The manuscript has been restructured as per the suggested outline.

The manuscript by N. J. Kinar shares the experiences gained from a class activity held in a fourth year Hydrology class offered at the University of Saskatchewan. The activity is aimed at synthesizing hydrological process knowledge from a systems approach perspective. Inputting the collected data by the low-cost instrumentation using electronic circuits design, students were asked to build a hydrological model for gaining insights into mathematical modelling in environmental sciences.

First and foremost, I would like to thank N. J. Kinar for his motivation to invest in designing innovative activities for advancing hydrology teaching in line with growing technology opportunities. I believe that this work sets a good example on how small efforts like designing such class activities during early years of hydrology education (i.e. postgraduate level) can prove valuable in shaping the future minds that are able to connect the dots in trying to solve today's (and future's) increasingly complex and growing environmental problems in the most efficient and plausible manner.

The suggestions that you have given help to support and indicate the arguments presented in this paper.

In general, the manuscript conveys a good quality content and is well-written. There are, however, a number of opportunities to make it more successful. Repetition of information is the biggest issue that prevails throughout the manuscript. Paragraphs with only a few sentences are very common (it is not disturbing me as it makes the reading easier), in some parts not really necessary though. Merging (e.g. last two paragraphs in Sec 3.3) or creating a bullet point list (e.g. "the students found that" in P9) can be considered.

- The repetition of information has been minimized throughout the document.
- The last two paragraphs in Section 3.3 of the first draft have been merged (pp. 16-17).
- A bullet-point list starting with "the students found that" has been added to the paper (pg. 14).

The Title reads fine. It is long but comprehensively highlights the paper's scope to the potential targeted audience. Abstract and Short Summary is written in a concise manner and include key information about the paper. Supplementary Material provides the required background knowledge on the electronics and some practical considerations, as well as explains in detail the three circuits (Water Detection Circuit, Relative Humidity (RH)/Air Temperature Circuit, Pyranometer Circuit) whose descriptive schematics are available via figshare for downloading.

- Thank you for these comments.

Introduction: It can definitely benefit from drawing a wider picture for setting the background in relation to fundamental links to practical considerations. For details, please see my comment on P2 L33 under "Specific Comments".

- The detailed comment has now been implemented in the revised version of the paper as per the blue text given in the revised document Section 1.

Research Question & Objectives: Not mentioned at all. Please add a paragraph stating the objective of this manuscript. Obviously, one objective is to share experiences (i.e. challenges, tips and resources), and another is to highlight the benefits of integrating simple hands-on exercises (using simple technology) into teaching curriculum to enhance active learning in geo- and environmental sciences, particularly in hydrology education.

- These objectives have now been added into this manuscript in the Introduction section of the manuscript (Section 1, bottom of pg. 5).

Materials and Methods (Section 2): I don't think that this title is appropriate. This section is overloaded and mixed, needs to be revised. A new outline with properly structured sections (subsections) which enable the reader to follow the manuscript with much less confusion is a must.

Methodology: Open a new section please. A workflow diagram would be really helpful here. It should depict different stages involved in every main phase of this class activity (i.e. pre-, during- and after). A brief summary should be added explaining which methods/tools/etc. are considered/used in each before describing each step in detail in subsections.

Results (Section 3): The subsections "3.1 Manufacturing Defects" and "3.2 Choice of Configuration" don't seem to fit well in here. These shall be moved to a new section titled "Electronic Circuits". "3.3 Open-Ended Feedback" and "SLEQ Feedback" form the core of this part. Instead of "Results", this section can be titled such that it tells the reader now is time to read the feedback by the course participants. Section 4 "Discussion" should be combined in this section too.

- The "Materials and Methods" section has now been replaced with the "Methodology" section of the paper (Section 2), and the outline restructured as recommended.
- A workflow diagram has been added as Figure 1 and the workflow diagram described with a summary at the beginning of Section 2.

Outline: Thus, my new outline suggestion is:

1. Introduction
2. Methodology
Be more specific about stages of the class activity (i.e. pre-, during- and after).
    a. Course (activity) proposal and acceptance
    b. Technical setup material purchase
    c. Preparation of handouts, guidance material for students
    d. Implementation of the activity

e. FAQ

f. …
g. Design, Analysis and Collection of Written Feedback
3. Systems Approach and Hydrological Modelling
Try to create two or three subsections on the text provided in "2.1 Background". Be careful not to overlap with the Introduction part. In other words, avoid repetition.
4. Electronic Circuits
a. Theory and Construction
b. Classroom Application
It is too long as a whole, but some paragraphs are very short. Try to create sub-subsections to clearly present various aspects presented in Sec 2.3.
Manufacturing defects and choice of configuration shall be mentioned here.
c. Example Applications for Electronic Circuits
d. Modelling with Electronic Circuit Data
5. Feedback
a. Open-Ended Feedback
b. SLEQ Feedback
c. Feedback Loops (i.e. Sec 4 Discussion)
6. Conclusion

- The manuscript outline has been re-structured as suggested.

Conclusion: Overall not so good. I especially liked the paragraphs on P19 (L598-620). However, these are essentially the summary of feedback from the students. My suggestion is to relocate this into (new) Section 5 "Feedback". P18 L587-591 should be in the Methodology.

- The paragraphs summarizing feedback from the students have been relocated into the Feedback section (pg. 16).
- P18 L587-591 in the first draft has been moved to the Methodology section (Section 2.5).

Conclusion can be concise. It is more important to adopt a more general perspective into the scope and purpose of the study rather than sharing (again) various details of the activity. See also my comment on the Introduction. This (conclusion) is the part where the author can take the floor to convince the reader that hydrology education needs improvements which incorporate innovative class activities into teaching strategies adopted by the lecturers (and invite more lecturers to embrace this strategy). A discussion on the importance of teaching aspect of a "professorship" position can be given too. (e.g. a call for universities to accommodate such needs by distinguishing explicitly between "lecturer" and "researcher" positions. And that courses should be designed by a joint team so that well-defined teaching strategies supported with innovative and fitting class activities can be formulated addressing the needs of students and in line with emerging topics & technologies in hydrology.)

- The conclusion has now been updated to show that hydrology education should be improved utilizing relevant classroom activities, as per these suggestions (Section 6, pg. 22)

Specific comments

P2 L33. The connection to the previous paragraph can be strengthened in the following manner: First, set the scene by mentioning that geography and environmental science teaching (recommended to) involve(s) different components, i.e.: introduction of conceptual theory, examples of how theories are implemented in real life applications and relevance to address societal challenges (addressed by the United Nations Sustainable Development Goals, UN SDGs), class activities to consolidate information to knowledge for achieving efficient learning of students. Then it is safe to bring forward the latter (class activities) and explain further. Paragraph 1 (in the current version of the manuscript) fits into here. Also, it will be good to include some comments on how such activities encourage development of a diverse set of skills, as well as if (by training future's professionals) and how such skills contribute to Multi-, Inter-, Trans- disciplinary research and practice.

Secondly, provide a brief overview on the progress and needs of hydrology education (see the list of suggested reading). Give some examples of class activities from the hydrology literature.
Thirdly, highlight the importance of data for science and teaching: The essential ingredient for geography and environmental sciences is data. Data collection is the backbone of advances in geosciences (thus teaching). In hydrological sciences education, water data (discharge and/or water level) collection is traditionally covered in many hydrology courses, however in rather a traditional way (e.g. in terms of measurement techniques) and often with a limited scope within a short duration. Maybe merge Paragraph 3 into this section. I recommend citing Tauro et al. (2017) to give an overview on the efforts to advance hydrological sciences through innovative measurement techniques. Also, the need for such efforts in view of not only providing support to financially disadvantaged countries but also harnessing the power of harmony in unity (e.g. WMO HydroHub).

Lastly, explain how electronic circuits are used for data collection purposes in hydrology and meteorology. Paragraph 2 fits into here, followed by Paragraph 4, 5 and 6.

- The paper has been updated as per these suggestions regarding structure and content (Section 1). Thank you for the detail presented in this specific comment and for the references.

P2 L59-63. How is the open source electronics movement linked to the Open & FAIR data? Briefly mention.

- The paragraph at the top of pg. 5 has been updated to mention the link between Open & FAIR data. Please see the blue text.

P3 L70. Before Paragraph 7, please state the research objective (and associated questions). L74-75 are the objectives of the course taught, not the manuscript's.

- These objectives have now been added into this manuscript in the Introduction section of the manuscript (Section 1, bottom of pg. 5).

P3 L76-93. Paragraph 8-9-10 should be moved to Section 2 "Materials and Methods" (Sec 2.3 in particular) as they describe several aspects related to pre-, during- and after the class activity (i.e. electronic circuit construction).

- This text has now been moved to Section 2.5, edited and re-written for clarity.

P18 L587-591. Better if moved to Section 2 “Materials and Methods” (before subsections, a general summary can be given supported with a diagram showing all the stages).

- Please see Section 2.5 and Section 2.
- As suggested, a workflow diagram was added to Section 2 as Figure 1.

P19 (Code and Data Availability). Thanks for your dedication to Open Science and FAIR Data.

- Thanks for this comment. Open Source and FAIR data are necessary for advancement of hydrology as a science.

P20 (Author contribution). Is there really a need to specify all tasks individually? Maybe one sentence is enough? E.g. All tasks (conceptualization, methodology, software, ….) are contributed by N. K.

- No, there is not a need to specify all tasks individually and the author contribution text has been updated as suggested.

P20 (Acknowledgements). Thanks for being so elaborate and honest.
P21 (References). Quite a comprehensive list, impressive. Properly cited, incorporated well into the text.

- Thank you for these comments.

Minor Edits

P1 L14. “systems science, models in hydrology, and calibration” > “systems science, modelling in hydrology, and model calibration”

- This line has now been updated in the Abstract.

P3 L71. Abbreviation (USask) can be used for the “University of Saskatchewan” in the remaining part.

- The abbreviation has been added throughout the text and the change is indicated in a blue color.

P4 L115&122, P5 L160. Students in the Advanced Hydrology > Just say “students”.

- This has been updated; please see Section 3.1.

P7 L213&L222, P12 L430, P17 L529… The name of the course “Advanced Hydrology class” doesn’t need to be indicated every single time.

- The course name has been removed throughout the document and reference is only made to the “class” rather than “Advanced Hydrology class.”

P13-15 L405-470. The texts quoted should be written in Italic.

- All of the quoted texts are now written in italic and indicated in a blue color (Section 5.2).

P18 L578. Add in parenthesis the English translation of "tawāw".

- Due to restructuring of the Conclusion to not share again the details of the activity as suggested, this translation is now only provided on pg. 13.

P18 L581. allowed for > allowed

- Due to restructuring of the conclusion, the words "allowed for" have now been removed.

P18 L584. Instead of "hydrology", use "technology".

P18 L586. Reformulate the sentence, maybe better as follows: "This paper provides explanations on Circuit theory and relevant concepts for classroom implementation and replication."

- Due to restructuring of the paper and the removal of repeated information, these sentences have been removed.

Introducing Electronic Circuits and Hydrological Models to Postsecondary Physical Geography and Environmental Science Students: Systems Science, Circuit Theory, Construction and Calibration

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Abstract. A classroom activity involving the construction, calibration and testing of electronic circuits was introduced to an advanced hydrology class at the postsecondary level. Two circuits were constructed by students: (1) a water detection circuit; and (2) a hybrid relative humidity (RH)/air temperature sensor and pyranometer. ~~Along with 3D printing of watersheds, the~~The circuits motivated concepts of systems science, ~~models~~modelling in hydrology, and model calibration. Students used the circuits to collect data useful for providing inputs to mathematical models of hydrological processes. Each student was given the opportunity to create a custom hydrological model within the context of the class. This is an example of constructivist teaching where students engage in the creation of meaningful knowledge and the instructor serves as a facilitator to assist students in the achievement of a goal. Analysis of student-provided feedback showed that the circuit activity motivated, engaged, and facilitated learning. Students also found the activity to be a novel and enjoyable experience. The theory of circuit operation and calibration is provided along with a complete bill of materials (BOM) and design files for replication of this activity in other postsecondary classrooms. Student suggestions for improvement of the circuit activity are presented along with additional applications.

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1~~.~~ Introduction

~~Geography and environmental science students are often exposed to~~ Due to the increasing need for interdisciplinary approaches in hydrology (Vogel et al., 2015), teaching of this subject at the post-secondary level should utilize a synthesis of techniques that involve the introduction of concepts and theories with an emphasis on real-world applications (Seibert et al., 2013; Van Loon, 2019). To maximize societal gain, these applications can address United Nations Sustainable Development Goals (SDGs) to encourage environmental stewardship, human equality, and a basic standard of living while preserving the functionality of planetary systems that sustain life (Crespo et al., 2017; Filho et al., 2019; Kopnina, 2018). Closely associated with the use of real-world applications for teaching hydrology to Geography and environmental science students are class activities (Yli-Panula et al., 2019) intended to provide experiential learning opportunities (Healey and Jenkins, 2000; Ives-Dewey, 2009) such as the use of data and computer programs for analysis of spatial phenomena (Bowlick et al.,

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2017), field trips (Krakowka, 2012; Lai, 1999; Schiappa and Smith, 2019), fieldwork (Elkins and Elkins, 2007; Mol et al., 2019; Ramdas, 2019), case studies (Hofmann and Svobodová, 2017) and guest lectures (Graham et al., 2017; Hovorka and Wolf, 2019). Experiential activities encourage critical thinking related to the environment (Hofreiter et al., 2007); increase an appreciation of landscapes and physical land surface processes (Karvánková et al., 2017); introduce role models that provide examples of career paths available for graduates (Solem et al., 2019); heighten an appreciation of sustainable practices (Robinson, 2019; Yli-Panula et al., 2019); and equip students with skills that improve marketability after graduation (Spronken-Smith, 2019). These activities diversify the skillset of students and thereby contribute to the training of future professionals equipped to address societal challenges related to water security and ecosystem management. Skill diversification allows for these professionals to contribute to: multidisciplinary problem solving where research teams from different branches of academia are required to search for solutions (Scholten et al., 2007); interdisciplinary activities involving a combination of knowledge approaches within a field of inquiry (Cosens et al., 2011); and transdisciplinary synthesis where new fields of inquiry are created by the combination of disciplines (Krueger et al., 2016). Multidisciplinary problem solving is required for conservation (Dick et al., 2017) and water security (UNESCO, 2019) due to the complexity and heterogeneity of environmental systems at a number of scales and the need for social issues to also be addressed in context with these systems. Interdisciplinary activities are often encountered in hydrology due to water resources management related to civil engineering, groundwater extraction, and water use, necessitating the consideration of non-stationarity and human activity as integrated within the hydrologic cycle (Vogel et al., 2015). Transdisciplinary synthesis is required for the production of water knowledge between stakeholders, governments and academics to find innovative solutions to water issues that have been influenced by the philosophies and methodologies of traditional fields of inquiry (Krueger et al., 2016) and can involve data collected using techniques traditionally associated with different disciplines (Rohde et al., 2019).

Formal hydrology education began in the 20th century when academic institutions started to offer hydrology courses. Initially, the course content was focused more on the understanding of general hydrological processes. Over time, the curriculum became more quantitative with the use of mathematical models and applications integrating social and economic issues. This trend continues, along with an increasing emphasis on conducting research related to teaching and learning to better develop a student-centred "constructivist" teaching approach where students engage in meaningful and creative activities and the instructor acts in an interactive fashion to help students with the creation of knowledge (Ruddell and Wagener, 2015). Students thereby assume an active role in the learning process and do not passively receive knowledge from the instructor, textbooks, and lecture notes (Klein and Merritt, 1994). A constructivist teaching approach is of increasing importance in a digital era where information is easily accessible from the Internet and the role of the instructor becomes more of a facilitator of learning responsible for encouraging critical thinking and creative problem-solving in a cross-disciplinary fashion that often involves student-led research activities (Ruddell and Wagener, 2015). Effective hydrology education requires knowledge synthesis to encourage progress in the hydrological sciences (Wagener et al., 2007). However, hydrology students often have a diversity of academic backgrounds and aptitudes that create challenges related to

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the training of students with strong competencies in mathematics, physics, sociology, psychology, and fieldwork required for research and for finding solutions to cross-disciplinary hydrological problems (Seibert et al., 2013). To heighten student interest and increase the applicability of geographic place within the context of a hydrology class, homework and class assignments should be relevant to individual students and grounded in experiential reality related to local hydrological processes (Van Loon, 2019). Moreover, classroom activities should integrate new developments in hydrology and associated technological advances to better prepare students for working on environmental challenges over the course of a career, thereby mitigating a well-known issue in the field of hydrology where application of scientific advances are often not applied in an operational context. In addition, the practice and teaching of hydrology is often extensively associated with Western cultural perspectives that do not take into consideration the viewpoints and practices of local and regional cultures; instructors should therefore endeavour to represent ideas and conceptualizations from these cultures in active teaching practice (Ruddell and Wagener, 2015).

Instructors have formulated novel class activities to address the needs of hydrology education. For example, Kingston et al. (2012) describe a student activity involving the collection of GPS data using mobile computing devices and DVD technology used to implement a virtual tour of a weather station field site. Students processed the self-collected GPS data using a GIS system and the DVD also provided multiple choice questions for student self-assessment of comprehension. Van Loon (2019) developed assignments where students select a river for analysis. The students then subsequently completed homework tasks and formulated a poster presentation related to the associated hydrology of the area. Lyon et al. (2013) created a field course where students were able to propose, implement and document a self-directed program of data collection and analysis to characterize the ecohydrology of a Mediterranean location in Greece. To teach challenges related to sharing of water resources and associated conflicts, Seibert and Vis (2012) developed the "Irrigania" computer game to simulate "tragedy-of-the-commons" scenarios related to water use and farming between individual farmers and villages, whereas Hoekstra (2012) and colleagues developed the "River Basin Game" and the "Globalization of Water Role Play" game to teach elements of water management at regional and global scales. The use of simulation games in the classroom complements traditional methods of teaching and allows for experiential learning (Rusca et al., 2012). For all these class activities, students reported a greater satisfaction with respect to the learning experience and the development of skills useful for the solution of real-world problems. These activities are also good examples of a constructivist teaching approach.

Hydrology as a quantitative science requires data for characterizing hydrological processes and associated phenomena. The development of innovative technologies for distributed spatial and high-temporal resolution data collection in association with the archiving and analysis of large datasets is essential for driving advances related to the understanding and modelling of hydrological processes (Tauro et al., 2018). Projects such as the WMO HydroHub (https://hydrohub.wmo.int/en/home) and EnviroDIY (https://www.envirodiy.org/) allow for sharing of devices, data and measurement projects between scientific collaborators and stakeholders, thereby supporting United Nations SDGs, and this is particularly useful for developing countries with sparse data collection networks where data availability is required for water management and climate change mitigation (Dixon et al., 2020). In a similar fashion, data availability is an essential

component of hydrological education at the post-secondary level and necessary for advancing the science of water education (Ruddell and Wagener, 2015).

However, in the context of a traditional hydrology course, datasets such as water level, velocity and associated discharge are often collected from streams using standard field techniques such as wading rods and current flow meters. These example datasets are not extensive and are therefore limited in a spatial and temporal fashion, particularly when students are briefly taken to a field site for a data collection opportunity. Student experimentation with data collection instruments only occurs during the time of the field trip and the students do not borrow instrumentation for private experimentation. This can be considered as a lack of data availability for curiosity-driven learning experiences and construed as a type of data scarcity. Moreover, plots of actual data collected at field sites are not the same as synthetic curves in textbooks and therefore students should be exposed to the collection of actual data. Data often requires imputation, averaging or filtering prior to providing inputs for hydrological models (Gao et al., 2018) and some hydrology textbooks do not present this in a clear fashion. Students who have worked with actual data appreciate the nuances and challenges of datasets (Lim et al., 2020) and are better prepared for graduate school research and environmental science jobs (Hovorka and Wolf, 2019).

Electronic circuits are deployed at field sites to autonomously collect data (Hund et al., 2016; Navarro-Serrano et al., 2019; Wickert et al., 2019) and are used to provide inputs to mathematical models for hydrological prediction and forecasting (Lavers et al., 2020). When visiting geographic locations equipped with electronic instrumentation, students often appreciate the presence of meteorological stations that collect precipitation, solar radiation, heat and energy balance data. These stations can provide data useful for class assignments. The stations may have also been used for the creation of figures in research papers and lectures that the students have read and utilized. Consequently, students are aware of the need for electronic instrumentation to measure hydrological processes.

~~Plots of actual data collected at field sites are not the same as synthetic curves in textbooks~~ Despite~~. Data often requires imputation, averaging or filtering prior to providing inputs for hydrological models (Gao et al., 2018) and some hydrology textbooks do not present this in a clear fashion. Students who have worked with actual data appreciate the nuances and challenges of datasets (Lim et al., 2020) and are better prepared for graduate school research and environmental science jobs (Hovorka and Wolf, 2019).~~

~~However, despite~~ working with data collected by electronic circuits at field sites, students at the postsecondary level are often not exposed to how these circuits are calibrated or why these circuits work. Calibration is important for circuit operation where an output is corrected for accuracy (Kouider et al., 2003) or related to a physical quantity. A classic example of calibration involves pyranometers to measure solar radiation from the sun: an output voltage is related to a solar radiation flux (Faiman et al., 1992; Kim et al., 2018; Norris, 1973). In addition, hydrological models are often calibrated to select the best model parameters to represent a physical reality (Gupta et al., 1998; Singh and Bárdossy, 2012). Circuit calibration and hydrological calibration can be considered as similar processes since both require the discovery of a transfer function that relates a set of inputs to outputs. Since students ~~will eventually~~may be required to calibrate hydrological

models or electronic circuits as environmental science professionals, students should have the opportunity to learn these important skills in the classroom. When an environmental sensing circuit fails to operate as expected, students should understand that re-calibration is required or that the circuit is not collecting valid data. Moreover, understanding circuit operation may motivate students to eventually develop novel and interesting environmental monitoring circuits, thereby encouraging the development of innovative sensors that help to provide better insight into environmental phenomena.

The open source electronics movement has reduced the cost of monitoring environmental phenomena, democratizing the use of instrumentation and providing non-proprietary methods for data collection that do not require the use of expensive software licenses for data access and programming (Pearce, 2013). ~~Two examples include the use of the Arduino platform to create low-cost dataloggers (Hund et al., 2016; Wickert et al., 2019) and the use of standalone miniature self-contained logging sensors (Lundquist and Lott, 2008; Navarro-Serrano et al., 2019). The introduction of custom electronic circuits in a hydrology class in lieu of commercial devices exposes students to the idea that instrumentation can be developed locally without a high cost of acquisition. Given the opportunity, students can build and test circuits used for environmental measurement. This opportunity can be viewed as empowering and enriches the educational experience by introducing threshold concepts that allow students to move beyond the nuanced idea of electronic environmental measurement circuits as black boxes, thereby allowing for~~This electronics movement is also associated with the concept of Open Data (Borgesius et al., 2015) and FAIR (Findable, Accessible, Interoperable, and Reusable) data (Mons et al., 2017) since the hardware and software of the instrumentation used to collect observations can be easily analysed due to availability of schematic diagrams and design files, thereby allowing for an unprecedented understanding of file formats, metadata produced during a data sampling process, and device operation that provides insight into the accuracy and precision of the sampling procedure. More specifically, using the FAIR acronym, the data is Findable due to the potential for automated upload to online databases; Accessible since file formatting is known and the data is available for download; Interoperable since the data can thereby be utilized with other datasets; and Reusable to be employed in the context of more than one study in a fashion that also encourages replication of experiments. Examples of systems built on open source technology that utilize these principles include 4ONSE (4 times Open and Non-Conventional technology for Sensing the Environment) (Sudantha et al., 2018) and the ODM2 Data Sharing Portal (Horsburgh et al., 2019) designed for interoperability with open source hardware. Electronics designs using elements of open source technologies often include the use of the Arduino platform to create low-cost dataloggers (Hund et al., 2016; Wickert et al., 2019). The introduction of custom electronic circuits in a hydrology class in lieu of commercial devices exposes students to the idea that instrumentation can be developed locally without a high cost of acquisition. Given the opportunity, students can build and test circuits used for environmental measurement. This opportunity can be viewed as empowering and enriches the educational experience by allowing students to move beyond the nuanced idea of electronic environmental measurement circuits as black boxes, thereby enabling a better understanding of how these devices are constructed and calibrated.

~~This~~The objectives of this paper ~~describes~~are to:

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- Share the circuit ~~theory, construction~~, calibration, and data analysis experiences ~~of including~~ challenges, tips and resources ~~of~~ the 2019 Advanced Hydrology (GEOG 427) class in the Department of Geography and Planning at the University of Saskatchewan~~. GEOG 427 is a final-year (4th year) undergraduate class that is taken by Environmental Science major, Physical Geography major and Hydrology minor students. Some graduate students will also audit the class as a refresher course on hydrological processes.~~ (USask). The goal of the class is to introduce students to instrumentation, mathematical models, and hydrological processes~~. A secondary goal as discussed in this paper is to introduce~~, along with concepts of systems theory and critical thinking skills.

- To assess and highlight the benefits of integrating hands-on exercises utilizing simple technology into the hydrology post-secondary teaching curriculum to enhance learning using electronic circuits that allow students to experiment with instrumentation used for environmental data collection.

2 Methodology

A workflow diagram (Fig. 1) shows the stages involved in the class activity coincident with each of the sections of this paper. The stages are classified into time periods related to pre-activity, during-activity, and after-activity tasks. The activity was first proposed for departmental approval (Section 2.1) before circuit design, setup, and purchase of materials (Section 2.2). Then, technical references and circuit theory as discussed in the Supplement were prepared for student use (Section 2.3). Implementation of the activity (Section 2.4) was explicitly planned before circuit activity kits were given to the students; this planning involved a framework for collection of written feedback that includes the use of a conceptual model of learner-instructor feedback loops (Section 2.5). Section 3 discusses a systems approach associated with hydrological modelling concepts covered in class. The systems approach is also exemplified by electronic circuits as collections of sub-systems. Section 4 describes the circuit activity as conducted in the class, indicating: the theory, construction, and circuit operation (Section 4.1); elements of classroom application (Section 4.2); and example applications for the electronic circuits identified by the students (Section 4.3), including the use of mathematical models (Section 4.4). After the activity, student open-ended feedback (Section 5.1) and closed-ended questions (Section 5.2) were analysed using the framework established in Section 2.5 to identify conceptual feedback loops (Section 5.3). Based on this classroom activity, conclusions were identified (Section 6) indicating that there is a need for improvement of post-secondary hydrological education using innovative strategies and institutional support. The flowchart also indicates that there is a potential for possible implementation of the activity in other classrooms.

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2.1 Course Activity Proposal and Acceptance

The course activities were proposed to the Department of Geography and Planning at USask six months before the start of the class in September. The activity proposal indicated the need for the course activities to include components necessary for teaching hydrology as summarized in Section 1 of this paper. Three months before the start of the class, the activities were approved along with a budget used to procure required materials.

2.2 Technical Setup and Material Purchase

Printed Circuit Boards (PCBs) were produced from digital design files designed specifically for this activity (cf. Section 7 and the Supplement). PCBs are designed using layout software utilizing layers in a similar fashion to a GIS system (Fig. 2). Although it is possible for an instructor to manufacture a class set of PCBs utilizing chemical processes and manual drilling (Andrade, 1965), this is a labour-intense process that is prone to human error and therefore it was easier and cheaper to purchase PCBs from a "board house" supplier that created a batch of custom PCBs using automated manufacturing methods for a relatively low cost. PCBs can take weeks to months to arrive based on the supplier and the "turn time" associated with an order that affects the overall cost of the PCBs.

Circuit components including the PCBs are provided to the students individually bagged and labelled for the water detection sensor and the RH/air temperature and pyranometer sensors (Fig. 3a). Each individual bag is marked with a PCB designator corresponding to a component or components on the circuit board. The designator is also marked on the circuit board using "silkscreen" lettering by the PCB board house supplier as specified by the design files. The use of designators allows students to expeditiously populate components on the PCB without the use of an associated placement diagram. There are three kits in total: a base kit with a microcontroller and power supply components that are common to the project, whereas a choice can be made related to which of the other kits to populate for a system used to measure RH/air temperature and a pyranometer sensor to measure solar radiation. Five toolboxes of battery-operated soldering irons, pliers, scissors, tape, screwdrivers and IC pin straightener tools were also provided to a maximum of 20 people allowing for approximately four students per group. The number of kits were limited due to cost and the initial size of the class (18 students).

The purchasing of materials for this activity required a month of preparation time since the components had to be obtained from an electronics supplier in larger quantities; individual plastic bags and a labelling machine were obtained from a packaging supply company; and most hand tools were sourced locally. Working with another person, the instructor had to allocate approximately one hour of setup time for the assembly of a single student kit. Although some electronic suppliers will provide components individually bagged as a kit if a bill-of-materials (BOM) is provided, the cost of a "kitting service" is often not justifiable if a small number of kits are required for a classroom activity.

The kits and additional components were placed in containers on a cart for transportation to the classroom (Fig. 3b). A dedicated lab was not required for this classroom activity since the instructor provided all required materials. Bags of

additional components as well as additional tools, soldering irons and batteries were also provided in another container to ensure that damaged or lost components could be replaced during the activity. Moreover, additional tools ensured that students could more efficiently work together if some students required more time to use a tool during the construction process.

2.3 Preparation of Handouts and Guidance Material for Students

To provide background circuit theory for the instructor and interested students, reference books are recommended. Horowitz and Hill (2015) serves as an excellent starting point for learning electronic circuit design. Holdsworth and Woods (2002) is a good reference for logic gates. Williams (2014) provides an overview on how to program an Atmel AVR microcontroller. Similar books are also available for other microcontroller architectures. De Vinck (2017) offers a complete course on how to solder electronic circuits.

The schematics, circuit board design files and BOM are available as an electronic download associated with this paper (Section 7). All design files are licensed under the CERN Open Hardware Licence (OHL). Technical details related to circuit operation and calibration are explained in the Supplement. These details are provided for context and to provide students and instructors with background information so that the circuits are not perceived as black box systems with inputs and outputs. Context related to calibration is also important to guide students and instructors in the implementation of this activity. The schematics and calibration information are provided by the instructor to students as a printed handout or as a digital download from a class materials website or content management system (CMS).

2.4 Implementation of the Activity

Before circuits are constructed, the class is initially introduced to actual data collected from field sites ~~representative of hydrological processes. Prior to circuit construction, circuit theory is explained during class lectures. The students construct circuits in class and~~ . This actual data includes temperature, Relative Humidity and pyranometer observations intended to show similarities to the data collected by circuits constructed in class. The students are responsible for calibration of these circuits ~~before data collection.~~. For a final class assignment, students are given the option to use ~~these~~the circuits to collect and analyse data to provide inputs for a hydrological model. The assignment is open-ended in that each student is responsible for constructing a simple hydrological model ~~that can be~~ driven by data collected from the circuits that students constructed in class. In this manner, students learn about how the circuit operates and how a hydrological model is assembled from different equations with associated assumptions coupled together to provide ~~a~~ numerical ~~output~~outputs.

Students are provided with PowerPoint slides and a lecture on circuit construction. Students are also told that the circuit construction activity contributes to a 4% overall participation grade in the class. This participation grade was also assessed throughout the term based on attendance and class participation and was not primarily associated with the circuit

activity. The circuit construction activity is introduced as a type of "game" or "puzzle" comprised of matching components to designators on the circuit board and soldering the components in a correct place. This is a form of "gamified learning" that can improve the enjoyment of an educational activity (Subhash and Cudney, 2018).

~~For replication of the circuit activity in other postsecondary classes, this paper describes the educational trajectory of how the class learned about hydrological processes, circuit theory, construction, calibration and data analysis during the Winter Term of 2019 at the University of Saskatchewan. The design files and bill of materials (BOM) used to create the circuits are provided under a permissive open hardware license, allowing for replication of this activity in other classrooms. For pedagogical purposes, hydrological model applications are described that students or instructors can use for facilitating this activity.~~

~~Each student in the class is given the opportunity to create electronic circuits and keep the circuits after the class is over. This provides memories of the class and allows for the circuits to be used by the students for other personal self-learning activities outside of the classroom. Written open-ended feedback provided by the students and course feedback collected by the University of Saskatchewan was used to quantify the pedagogical use of circuits in a hydrology classroom.~~

~~2 Materials and Methods~~

~~2.1 Background~~

~~At the beginning of the term, students~~Everyone in the classroom working on circuits must wear safety glasses to prevent eye damage from flying debris when component leads are trimmed after soldering; this also prevents injury from particulate matter during the soldering process. Students are also told about the possible hazards of soldering prior to the activity. Safe soldering techniques are demonstrated so that no injuries associated with burns or scratches occur during the circuit construction.

The activity was implemented so that students can help each other construct the circuits and formulate novel methods for circuit calibration and application. Students bend, insert and solder components into holes on printed circuit boards (PCBs). Students are encouraged to work together on the associated calibration and modelling assignment, although each student is responsible for submitting an individual write-up. This is a form of cooperative learning that is known to enhance retention and engage students (Slavin, 1980).

Students are given handheld temperature, RH, and solar radiation flux meters to serve as calibration references. These handheld devices are commercially available and are listed in a downloadable BOM associated with this paper. Calibration depends on the type of sensor populated by each student on the PCB (temperature/RH or pyranometer).
For handheld commercial meters that reported light outputs in lumens or lux, students use an appropriate conversion factor to obtain a solar radiation flux in units of $\mathrm{W\,m^{-2}}$. Further details on calibration are given in the Supplement.

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2.5 Design, Analysis and Collection of Written Feedback

Student-provided feedback was used to assess the efficacy of this activity for teaching hydrology at the postsecondary level. The Narciss (2013) and Hattie and Timperley (2007) models provided a conceptual framework for the collection and analysis of feedback associated with this activity. The Wilson et al. (2014, p.76) framework was used to indicate that the circuit activity can motivate student interest.

The conceptual framework used for the design of written student feedback related to this class activity is outlined by Narciss (2013) as the interactive tutoring feedback model (ITF-model). The ITF-model incorporates ideas of systems theory and constructivist teaching. These two ideas are also utilized within the context of the student activity described in this paper. Narciss (2013) considers both the learner and the instructor as control systems within three feedback loops. One feedback loop is internalized by the learner and is related to student satisfaction, knowledge creation and retention, whereas another feedback loop is used by the instructor to adjust the class activities to achieve external competency standards and maximize learning associated with instructor and department-specified goals. The third feedback loop links the instructor and student systems together. The purpose of each conceptual feedback loop is to establish equilibrium in each system with respect to a setpoint that represents a goal or a level of competency. In this paper, the three feedback loops are identified as learner (L), instructor (I), and learner-instructor (L-I) to identify the system domains where these feedback loops operate.

Quantification of learning is to understand how these feedback loops are operating. To quantify each of the three feedback loops identified by Narciss (2013), the Hattie and Timperley (2007) model is used to construct questions. According to Hattie and Timperley (2007), feedback questions are associated with four levels. These four levels are associated with each of the feedback loops in the list below. Although all feedback loops are interrelated, each of the levels have been matched to the feedback loop that is mostly indicative of the level:

1. Task Level, associated with how well the task is performed in relation to an external standard (L-I and I).
2. Process Level, related to how learners perceive the tools and techniques of a task (L, L-I, and I).
3. Self-Regulation Level, indicating a self-assessment of how well a student performs the task (L).
4. Self Level, related to the change in self-worth of a student engaging in the task (L).

Open-ended feedback allows for all the task levels and functioning of the conceptual feedback loops to be assessed. This is because open-ended feedback solicits responses without imposing a more rigid structure associated with specific task-based questions (Ballou, 2008). Students in the class were voluntarily asked to provide open-ended written feedback on the circuit activity for assessing quality of classroom instruction (Davis, 2009, p.461–463). An open-ended feedback sheet was handed out in class. Eleven students returned the open-ended feedback sheet. The question asked at the top of this sheet was "Using the space below, please provide your thoughts and feedback on the circuit activity." The students signed a permission consent to indicate acceptance associated with using the feedback in a published paper.

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Class feedback in a more structured format involving rating questions and written feedback was also solicited by the College of Arts and Science at USask as the Student Learning Experience Questionnaire (SLEQ). Data from the end-of-term SLEQ was collected using the *blue* experience management feedback system (provided by *explorance*, https://explorance.com/products/blue/) in accordance with policies established by USask. This automated feedback system aggregates and anonymizes responses. All responses from students are voluntary and eleven students in the class completed this online survey. The SLEQ questionnaire allowed for all four task levels to be assessed.

It is not possible to determine whether the same students also completed the in-class open-ended written feedback sheet. Responses could not be matched to individual students. The SLEQ data is also provided as an associated download for this paper. The class instructor personalized some of the questions asked by the SLEQ survey. Along with standardized closed-ended questions asked by the Department of Geography and Planning and the College of Arts and Science at USask, these personalized open-ended questions helped to address the efficacity of teaching and learning associated with this circuit activity. The questions below are classified to indicate the targeted task level. The questions cover all four task levels to assess the three conceptual feedback loops.

1. What are your thoughts about the building, construction, and calibration of electronic circuits in this class? (Process, Self-Regulation)
2. Do you think that calibration of circuits and understanding how circuits work are important learning experiences for environmental scientists? Why or why not? (Task, Process, Self-Regulation, Self)
3. After taking this class, how do you perceive systems theory as being important in environmental science? (Task, Process)
4. What did you learn about critical thinking in the class related to the use of electronic circuits, models and hydrological processes? (Task, Process, Self-Regulation)

To identify trends and similarities in the feedback, the Voyant web-based tool (https://voyant-tools.org/) was used for quantitative text analysis (Rockwell and Sinclair, 2016). Student feedback responses are provided as a download associated with this paper. The responses were transcribed and anonymized without modification of grammar or sentence structure since this maintains context and intent.

3 Systems Approach and Hydrological Modelling

3.1 Hydrology as a Systems Science

Students in the class are initially introduced to the concept of hydrology as a systems science. A systems thinking approach is important in geographic education since this enhances understanding of spatial relationships and interconnections between processes (Cox et al., 2019a, 2019b). At the postsecondary level, systems thinking is a key component of courses designed for sustainable development competencies (Schuler et al., 2018). A system can be

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represented as a collection of entities that have attributes and an internal state (Hieronymi, 2013). The boundaries of the system are often demarcated as a type of control volume and visually represented by lines on a diagram (Fig. ~~1a~~4a). A system can have inputs and outputs. Sub-systems can be combined to form a larger system by coupling the outputs from one sub-system to the inputs of another sub-system. Examples of well-known systems with inputs and outputs include a vehicle, plumbing in a building, a computer~~,~~ and a smartphone as circuits, and the human body. Students tend to understand examples couched in experiential reality (Oliveira and Brown, 2016) and therefore these system concepts have the potential to be more easily understood when presented to the class. Hydrological processes can also be represented as systems. A watershed is construed as consisting of basins and sub-basins that respectively correspond to systems and sub-systems with inputs and outputs (Zävoianu, 1985, p.9–25) (Fig. ~~1b~~4b). The sub-systems are coupled together by linkages indicative of water flowpaths associated with processes such as runoff, infiltration, evapotranspiration, sublimation, snowmelt, groundwater flow, and river discharge. ~~Hydrologists have represented sub-systems in hydrological models as Hydrologic Response Units (HRUs) (Fig. 1c); examples include the Cold Regions Hydrological Model (CRHM) (Pomeroy et al., 2007), and the Soil and Water Assessment Tool (SWAT) (Gassman et al., 2007).~~ The summation of inputs and outputs along with an appropriate positive and negative convention is the basic idea associated with the computation of a water balance using these sub-systems (Berghuijs et al., 2014).

3.2 Hydrological Modelling

Students ~~in the Advanced Hydrology class~~ learn about three different types of hydrological simulation models in the context of the class: physical, mathematical and analog (Dingman, 2015, p.597). A physical model is a representation of the world at a different scale; examples include tabletop watersheds, sprinkler plots and hydraulic structures with inputs and outputs of water. Mathematical models have state variables and transfer functions that represent equations coupled together to form inputs and outputs. Analog models nominally use concepts from electrical engineering and circuit theory to represent hydrological phenomena such as groundwater flow and evapotranspiration and ~~also~~ have inputs and outputs. Described in this fashion, the three types of models are considered as systems.

~~To provide an example of hydrological systems science, students in the Advanced Hydrology class were given an assignment to create watersheds from a raster digital elevation model (DEM) by applying watershed delineation algorithms in a geographic information system (GIS). For this class, the Free and Open Source (FOSS) software QGIS (https://qgis.org/) was used since it is freely available for all students without the need to pay for a software license. The digital elevation model (DEM) datasets corresponding to each student watershed were subjected to an algorithm (Modi et al., 2015) consisting of a series of calculations used to produce a stereolithography file (Fig. 1d shows a computer graphics rendering). The stereolithography file was then sent to a 3D printer for creation of a plastic version of the watershed (Fig. 1e). Students were able to view the 3D printer operating during a lab tour. Each student could take home a 3D printed watershed by the end of the term. The assignment demonstrates the use of mathematical models used to convert a DEM file~~

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into a physical model that is a representation of the watershed land surface at a different scale. The watershed is printed using a 3D printer that is also a system comprised of sub-systems. The required processing algorithms consist of mathematical models as sub-systems combined to together to produce an output from the DEM raster input data. The watershed delineation algorithms track water flow paths over a landscape and there are inflows and outflows representative of water flow between raster cells in a domain (Haag et al., 2018).

Analog models are often implemented as mathematical models with equations evaluated using a computer program in lieu of building actual circuits (Ménard et al., 2014) (Fig. 2a5a). Actual circuits were constructed in the past consisting of elements such as resistors and capacitors (Sander, 1976; Shen, 1965; Skibitzke, 1960) (Fig. 2b5b,c) since computation resources were more limited in the 20th century and building of a circuit allowed for current or voltage to be measured and easily related to the magnitude of a hydrological process.

By conceptualizing hydrological models as systems with inputs and outputs, students can learn how to construct a mathematical model by combining equations along with assumptions in a similar fashion to a circuit, where circuit elements are combined to provide a set of outputs given inputs (Kang, 2016). The practice of assembling a circuit provides students with an experiential example of how sub-systems are combined to form a system.

A similar process also occurs when combining equations to compose a hydrological model. If equations are conceptualized as sub-systems with assumptions, students may find it easier to select equations, combine equations together, and understand how the inputs affect the outputs. This process is useful to learn since it is often performed by graduate students and hydrology research professionals who model hydrological phenomena using mathematics and associated computer programs to produce predictions and forecasts related to phenomena such as drought (Mishra and Singh, 2011), flooding (Teng et al., 2017), geotechnical slope stability (Fawaz, 2014) and avalanche activity (Morin et al., 2020).

Students are given the opportunity to propose their own mathematical models for use with electronic circuits in lieu of everyone in the class being obligated to complete the same assignment. This is in line with the concept of constructivist teaching and learning, where students engage in meaningful and creative activities and the instructor acts in an interactive fashion to help students with the creation of knowledge This is in line with the concept of constructivist teaching and learning. Moreover, allowing students to be creative enhances(Klein and Merritt, 1994). Students thereby assume an active role in the learning process and do not passively receive knowledge from the instructor, textbooks, and lecture notes. Moreover, allowing students to be creative can enhance geographic learning (Yli-Panula et al., 2019). Applied to an environmental science classroom, this instructional method can increase class exam scores and student satisfaction ratings (Lord, 1999).

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~~2.2~~4 Electronic ~~Circuit~~Circuits

4.1 Theory ~~and,~~ Construction and Circuit Operation

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~~Students in~~Since the ~~Advanced Hydrology~~ class is not an engineering course, students do not design circuits since there is not enough time in one term to learn circuit design and PCB layout. The creativity aspect of the course in line with constructivist and experiential learning is associated with the use of the circuits to collect data utilized as inputs to student-proposed mathematical models. However, circuit theory and associated circuit operation (as described in the Supplement) is provided by the instructor for learning context and relevance.

Students were given the opportunity to assemble (Fig. ~~3~~6) and take home two circuits: a water detection circuit (Fig. ~~4~~7) and a circuit with a relative humidity (RH)/air temperature sensor as well as a photodiode with a diffuser that is calibrated as a pyranometer to measure shortwave radiation (Fig. ~~5).~~ 8). The water detection sensor as the first project (Fig. 7) provides students with an opportunity to learn some basic circuit theory and construction skills. This first project is deliberately kept simple. This is because students learn best in a formal teaching environment where skills and concepts are presented in a fashion progressing from simpler to more complicated formulations (Davis, 2009, p.280–281).

~~The~~Since the second circuit (Fig. ~~5~~8) can ~~also~~ be constructed in three configurations using either or both RH/air and pyranometer sensors. ~~This~~, this allows the students to choose which configuration would be most useful for collection of data for ~~an assignment that asks students to formulate their own~~the formulation of hydrological models. A microcontroller is used as a control system. The temperature, relative humidity and calibrated solar flux is displayed on an LCD display driven by the microcontroller. (Fig. 8b, c). This allows for the data to be easily read in lieu of utilizing other instrumentation such as a voltmeter. To acknowledge the ancestors of the land on which ~~the University of Saskatchewan~~USask is built and to contribute to Indigenous reconciliation in Canada (Castleden et al., 2017), the LCD display shows "Welcome" and "tawāw": words in English and Cree indicating that the device is ready for operation (Fig. 8a). ~~.~~ The Cree word tawāw can be literally translated as "come in, you're welcome; there's room" (Wolvengrey, 2001, p.218) and allows students to view words other than English that are normally displayed on most ~~LCD displays~~LCDs. The letter ā with a macron (overbar) had to be uploaded to the LCD display memory since the default LCD character set did not support this special character used for the Cree Roman Orthography.

~~Circuit components are provided to the students individually bagged and labelled for the water detection sensor and the RH/air temperature and pyranometer sensors. There are three bags for the RH/air temperature sensor; all students constructing this circuit need to populate the "base" kit, whereas a choice can be made concerning which of the other kits to populate. Toolboxes are provided with solder, battery operated soldering irons and various hand tools for construction (Fig. 6a). The kits and additional components were placed in containers on a cart for transportation to the classroom (Fig. 6b). A dedicated lab was not required for this activity since the instructor provided all required materials.~~

Students bend, insert and solder components into holes on printed circuit boards (PCBs). Each individual bag is marked with a PCB designator corresponding to a component (or components) on the circuit board. The designator is also marked on the circuit board. This allows students to expeditiously populate components on the PCB without the use of an associated placement diagram. PCBs are designed using layout software (Fig. 7) and further details are given in the Supplement.

Since the Advanced Hydrology class is not an engineering course, students do not design circuits since there is not enough time to learn basic concepts of electrical theory and printed circuit board layout. The creativity aspect of the course in line with constructivist and experiential learning is associated with the use of the circuits to collect data utilized as inputs to student-proposed mathematical models. Circuit theory is described to provide learning context and relevance, so the circuits are not merely considered as black-box systems with inputs and outputs. Relevance is important to motivate learning (Kember et al., 2008) and students are provided with basic circuit theory that can be used for electronics associated with dataloggers and measurement devices.

To provide background circuit theory for the instructor and interested students, a few reference books can be recommended. Horowitz and Hill (2015) serves as an excellent starting point for learning electronic circuit design. Holdsworth and Woods (2002) is a good reference for logic gates. Williams (2014) provides an overview on how to program an Atmel AVR microcontroller. Similar books are also available for other microcontroller architectures. De Vinck (2017) offers a complete course on how to solder electronic circuits. These books are selected to provide reference texts for the student activity described in this paper.

The schematics, circuit board design files and bill of materials (BOM) are available as an electronic download associated with this paper. All design files are licensed under the CERN Open Hardware Licence (OHL).

Technical details related to circuit operation and calibration are explained in the Supplement. These details are provided for context and to provide students and instructors with background information so that the circuits are not perceived as black-box systems with inputs and outputs. Context related to calibration is also important to guide students and instructors in the implementation of this activity.

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4.2.3 Classroom Application

Verbal feedback from students during the circuit activity can be used to assess some common advantages and disadvantages associated with classroom application. The observations listed in this section might not be universally applicable to all groups of students but have been derived from the personal experiences of the instructor of the Advanced Hydrology class.

Everyone in the classroom working on circuits had to wear safety glasses. This prevented eye damage from flying debris when component leads were trimmed after soldering and prevented injury from particulate matter during the soldering process. No soldering injuries associated with burns or scratches occurred during this activity.

Working together, the students were able to help each other construct the circuits and formulate novel methods for circuit calibration and application. Students were also encouraged to work together on the associated calibration and

modelling assignment, although each student was responsible for submitting an individual assignment. This is a form of cooperative learning that is known to enhance retention and engage students (Slavin, 1980).Construction of the water detection sensor took approximately 1.5 hours as the maximum class time and one Advanced Hydrology class was allocated for this activity. Construction of the RH/air temperature circuit took approximately 4 classes for a total time of 6 hours. Out of this total time, three classes (4.5 hours) had to be allocated for construction, and one class (1.5 hours) for debugging of soldering errors associated with construction.

Before the activity started, students were provided with PowerPoint slides and a lecture on circuit construction. Students were told that this activity would count towards a 4% overall participation grade in the class. This participation grade was also assessed throughout the term based on attendance and class participation and was not primarily associated with the circuit activity. The circuit construction activity was introduced as a type of "game" or "puzzle" comprised of matching components to designators on the circuit board and soldering the components in a correct place. This is a form of "gamified learning" that positively improves the enjoyment of an educational activity (Subhash and Cudney, 2018).

Students who had soldered in the past verbally indicated during the activity that they found the circuits easier to construct than students who had not worked with soldering tools and techniques. Students who had previous experience were thereby paired with students who had less experience. This practice reducesreduced tension and preventsprevented students from feeling excluded. Indeed, three students verbally indicated to the instructor that they liked the idea of circuit construction, but they did not feel competent to successfully construct the circuits. The instructor alleviated the concerns of these students by assisting all students in the classroom over the duration of the activity. The idea of an instructor as a facilitator is in line with the philosophy of constructivist teaching (Klein and Merritt, 1994; Lord, 1999). everyone in the classroom during the activity.

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Five kits of battery-operated soldering irons, pliers, scissors, tape, screwdrivers and IC pin straightener tools were provided to a maximum of 18 students allowing for approximately three to four students per group. The number of kits were limited due to cost and not all the 18 students showed up for the circuit construction activity. However, the finite number of kitsThe finite number of tools allowed students to work together. While one student soldered a component, the other students in the group were able to observe the soldering process and learn from each other. Students were able to help each other students with part placement and orientation. This process emphasizes the importance of using battery-operated soldering irons since students canwere able to quickly exchange and share irons without the disadvantage of having to deal with cords and power cables. The disadvantage is thatHowever, a number of additional AA batteries had to be kept in the classroom for facilitating this activity since the batteries in each soldering iron lasted for approximately 45 minutes of continuous operation and had to be changed in-class to allow the students to continue working on the circuit for the total class time of 1.5 hours.

Students were able to match designators on the PCB to designators written on a label affixed to the outside of each individually bagged component in the kit. Kits with individually bagged components thereby helped to expedite the class activity.

~~A container with additional electronics parts and an extra soldering iron was useful. The additional parts accommodated students who had lost a part. Moreover, the additional soldering iron could be~~ used ~~by the instructor to demonstrate soldering or by a student who wanted to work more quickly.~~

~~During the circuit construction process, students were asked to identify concepts of systems and sub-systems associated with collections of components on the circuit board; this practice reiterated concepts taught in class. The idea of an analog model associated with resistors and capacitors was also addressed to enhance student comprehension associated with modelling evapotranspiration and water flow processes.~~

~~Verbal feedback was provided by students during and after the activity. One student indicated that the circuits should have datalogging capabilities. As a response, the instructor replied that these capabilities will be added in an updated version of the circuit. Students also remarked that the plastic jumpers used to set calibration coefficients were challenging to insert and remove. This is a disadvantage associated with the budgetary cost of each circuit.~~

~~One student recommended via written feedback that the PCB should have feet. Conventional plastic feet elevate the PCB above a surface and provide a convenient platform to situate the circuit while it is being operated. To engage students, the instructor used a 3D printer to create a class set of "feet" with toes that can be glued on the bottom of the PCB (Fig. 8a). Figure 8b is an example of a student standing next to a PCB with "feet." Injecting humour into a classroom situation is known to increase retention while engaging students by heightening interest and attentiveness (Korobkin, 1988).~~

~~Students were given~~ the handheld temperature, RH~~,~~ and solar radiation flux meters ~~to serve as calibration references. These handheld devices are commercially available and are listed in the downloadable BOM associated with this paper. Calibration proceeded based on the types of sensor populated by each student on the PCB (temperature/RH or pyranometer).~~ for circuit validation and calibration. For meters that reported light outputs in lumens or lux, students used an appropriate conversion factor to obtain a solar radiation flux in units of $W\,m^{-2}$. Some students took the ~~PCB~~circuit and hand-held light meters outside to measure solar radiation flux from the sun as an outdoor calibration procedure (Fig. 9a), whereas others used an indoor calibration procedure utilizing smartphone LED flashlights (Fig. 9b, c). This was a novel development not anticipated by the instructor. Alternately, some students used radiation flux data from a nearby meteorological station for sensor calibration.

Figure 9b and Fig. 9c show students engaged in the smartphone LED flashlight calibration procedure. The light intensity of the LED flashlight was measured using ~~the~~a handheld light meter. The voltage output of the pyranometer circuit was then determined using the LED flashlight. An associated calibration coefficient was subsequently obtained using ~~the~~ techniques identified in the Supplement. The coefficient was refined using further experiments conducted at an outdoor location.

~~The~~From this calibration procedure, the students found that ~~pyranometer:~~

- Pyranometer calibration did not work well at an indoor location such as in the atrium of the Agriculture Building at ~~the University of Saskatchewan.~~USask. Despite the presence of many windows in this

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location, sunlight that enters the building interior is directional and strongly diffused by metal and glass reflecting surfaces and is therefore not an accurate representation of solar radiation associated with a hemispherical sky. Pyranometers calibrated in this indoor environment did not provide an approximate representation of radiation flux at an outdoor location.

- Due to the inexpensive cost of the photodiode used for the pyranometer, ~~the students found that~~ calibration coefficients did not approximately coincide between PCBs due to manufacturing tolerances. Calibration coefficients could exhibit order of magnitude differences. Students realized that all photodiodes were not alike, and that calibration is important for this application.
- ~~The students found that temperature~~Temperature and RH as reported by the circuit (Fig. ~~5b~~8b) agreed to within ±1 ℃ and ±3% RH. This is approximately the same as the accuracy reported by the AM2320 datasheet used for the circuit and includes differences due to temperature gradients and boundary layer effects near the PCB.
- For the pyranometer (Fig ~~5c), students found that~~8c), the average error ranged between approximately 3% to 35% compared to handheld light/radiation meters. The error was dependent on calibration and the position of the PCB relative to the sun. For more accurate measurements, the pyranometer sensor had to be positioned level to the ground to allow for an approximation of a hemispherical measurement of radiation.

~~2.4~~Some of the PCBs constructed by the students had manufacturing defects. Table 1 shows the estimated number of defects that had to be repaired before student PCBs worked successfully. Soldering joint defects were the most prevalent. Another common defect was related to some components not placed with the right orientation. Since PCB repair and re-work tools were not available in the classroom, the instructor repaired the PCBs outside of class time.

Although most students constructed a hybrid RH/temperature/pyranometer circuit, no student chose to only construct a pyranometer (Table 2). Two students constructed a PCB with only a RH/air temperature sensor and did not populate the pyranometer components. For the RH/air temperature and pyranometer circuit, four classes were required to construct the circuit and students that did not attend the class on one day could attend on another day to work on circuit construction. The students that did not construct a PCB were either absent from class during circuit construction or auditing the class. All students who constructed a water detection circuit were also present for the construction of the hybrid RH/temperature/pyranometer circuit.

~~4.~~3 Example Applications for Electronic Circuits

Students identified novel applications that were not discussed by the instructor. One student expressed an interest to use the water detection circuit to determine if seasonal water levels exceeded a certain height in wetlands~~; this indicated~~,

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indicating whether water could be exchanged between two nearby ponds. Another student suggested that the RH/air temperature circuit and pyranometer could be used in lieu of more expensive micrometeorological handheld instruments to collect measurements at a field site during fieldwork. The wetness detection sensor can be used as a groundwater dipper (Fulford and Clayton, 2015) to determine the level of the water surface in a groundwater well. The sensor would be waterproofed and fastened on the end of a wire for lowering down an observation well. The piezoelectric buzzer ~~provides~~would provide audible feedback when the water sensor reaches the position of the water surface. The distance to the water surface ~~is read from~~can be determined using a series of graduated markings on the wire.

~~2.5~~4.4 Modelling with Electronic Circuit Data

This section briefly summarizes possible models for classroom application. Students can use some of these models for a class assignment. Examples listed in this section were utilized, identified, or considered by students in the ~~Advanced Hydrology~~ class, but other example applications might also be suitable based on regional geography if this activity is to be replicated at another location. Students are graded on how assumptions are provided in the assignment, since each equation coupled together to form a hydrological model is ~~implicitly~~ associated with assumptions. The students are also graded on how they interpret the model outputs. Students justify if the outputs are physically reasonable based on a literature search or on theoretical calculations providing insight into the magnitude or frequency of hydrological processes.

The RH/air temperature circuit can be used to obtain daily mean air temperature. The mean air temperature is related to snowpack temperature or snowmelt using an empirical degree-day or similar relationship for cold regions where snow is prevalent (Fontaine et al., 2002). Relative humidity and air temperature can also be related to transpiration processes (Clum, 1926; Mahajan et al., 2008). If the pyranometer circuit is used to measure incoming shortwave radiation from the sun, outgoing shortwave radiation can be estimated using an assumed albedo (Oke, 1992, p.86). The longwave radiation can be obtained from a semi-empirical (Sicart et al., 2006) or physical model (Viúdez-Mora et al., 2015). If sensible and latent heat fluxes are modelled or measured along with appropriate assumptions (Essery, 1997; Marks et al., 2008), the energy required for snowmelt and the resulting change in Snow Water Equivalent (SWE) can be calculated (Pomeroy and Brun, 2001, p.92).

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~~2.6 Design, Analysis and Collection of Written~~ 5 Feedback

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5.1 Open-Ended Feedback

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Out of the 15 students who completed the in-class circuit activities, 11 students submitted an open-ended feedback sheet, indicating that four students completing the activity chose to not provide in-class feedback or were absent from class. ~~The conceptual framework used for the design of written student feedback related to this class activity is outlined by Narciss (2013) as the interactive tutoring feedback model (ITF model). The ITF model incorporates ideas of systems theory and constructivist teaching. These two ideas are also utilized within the context of the student activity described in this paper.Narciss (2013) considers both the learner and the instructor as control systems within three feedback loops. One feedback loop is internalized by the learner and is related to student satisfaction, knowledge creation and retention, whereas another feedback loop is used by the instructor to adjust the class activities to achieve external competency standards and maximize learning associated with instructor and department specified goals. The third feedback loop links the instructor and student systems together.The purpose of each conceptual feedback loop is to establish equilibrium in each system with respect to a setpoint that represents a goal or a level of competency. In this paper, the three feedback loops are identified as learner (L), instructor (I), and learner-instructor (L-I) to identify the system domains where these feedback loops operate.~~

~~Quantification of learning is to understand how these feedback loops are operating. To quantify each of the three feedback loops identified by Narciss (2013), the Hattie and Timperley (2007) model is used to construct questions. According to Hattie and Timperley (2007), feedback questions are associated with four levels. These four levels are associated with each of the feedback loops in the list below. Although all feedback loops are interrelated, each of the levels have been matched to the feedback loop that is mostly indicative of the level:~~

~~1. Task Level, associated with how well the task is performed in relation to an external standard (L-I and I).~~
~~2.1. Process Level, related to how learners perceive the tools and techniques of a task (L, L-I, and I).~~
~~3.1. Self-Regulation Level, indicating a self-assessment of how well a student performs the task (L).~~
~~4.1. Self Level, related to the change in self-worth of a student engaging in the task (L).~~

~~Open-ended feedback allows for all the task levels and functioning of the conceptual feedback loops to be assessed. This is because open-ended feedback solicits responses without imposing a more rigid structure associated with specific task based questions (Ballou, 2008). Students in the class were voluntarily asked to provide open-ended written feedback on the circuit activity for assessing quality of classroom instruction (Davis, 2009, p.461–463). An open-ended feedback sheet was handed out in class. Eleven students returned the open-ended feedback sheet. The question asked at the top of this sheet was "Using the space below, please provide your thoughts and feedback on the circuit activity." The students signed a permission consent to indicate acceptance associated with using the feedback in a published paper.~~

Class feedback in a more structured format involving rating questions and written feedback was also solicited by the College of Arts and Science at the University of Saskatchewan as the Student Learning Experience Questionnaire (SLEQ). Data from the end-of-term SLEQ was collected using the *blue* experience management feedback system (provided by *explorance*, https://explorance.com/products/blue/) in accordance with policies established by the University of Saskatchewan. This automated feedback system aggregates and anonymizes responses. All responses from students are voluntary and eleven students in the class completed this online survey. The SLEQ questionnaire allowed for all four task levels to be assessed.

It is not possible to determine whether the same students also completed the in-class open-ended written feedback sheet. Responses could not be matched to individual students. The SLEQ data is also provided as an associated download for this paper. The class instructor personalized some of the questions asked by the SLEQ survey. Along with standardized closed-ended questions asked by the Department of Geography and Planning and the College of Arts and Science at the University of Saskatchewan, these personalized open-ended questions helped to address the efficacity of teaching and learning associated with this circuit activity. The questions below are classified to indicate the targeted task level. The questions cover all four task levels to assess the three conceptual feedback loops.

1. What are your thoughts about the building, construction, and calibration of electronic circuits in this class? (Process, Self-Regulation)
2. Do you think that calibration of circuits and understanding how circuits work are important learning experiences for environmental scientists? Why or why not? (Task, Process, Self-Regulation, Self)
3. After taking this class, how do you perceive systems theory as being important in environmental science? (Task, Process)
4. What did you learn about critical thinking in the class related to the use of electronic circuits, models and hydrological processes? (Task, Process, Self-Regulation)

To identify trends and similarities in the feedback, the Voyant web-based tool (https://voyant-tools.org/) was used for quantitative text analysis (Rockwell and Sinclair, 2016). Student feedback responses are provided as a download associated with this paper. The responses were transcribed and anonymized without modification of grammar or sentence structure since this maintains context and intent.

3. Results

3.1 Manufacturing Defects

Some of the PCBs constructed by the students had manufacturing defects. Table 1 shows the estimated number of defects that had to be repaired before student PCBs worked successfully. Soldering joint defects were the most prevalent.

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~~Another common defect was related to some components not placed with the right orientation. Since PCB repair and re-work tools were not available in the classroom, the instructor repaired the PCBs outside of class time.~~

~~3.2 Choice of Configuration~~

~~Although most students constructed a hybrid RH/temperature/pyranometer circuit, no students chose to only construct a pyranometer (Table 2). Two students constructed a PCB with only a RH/air temperature sensor and did not populate the pyranometer components. For the RH/air temperature and pyranometer circuit, students had four classes to construct the circuit and students that did not attend the class on one day could attend on another day to work on circuit construction. The students that did not construct a PCB were either absent from class during circuit construction or auditing the class. All students who constructed a water detection circuit were also present for the construction of the hybrid RH/temperature/pyranometer circuit.~~

~~3.3 Open-Ended Feedback~~

~~Out of the 15 students who completed the in-class circuit activities, 11 students submitted an open-ended feedback sheet, indicating that four students completing the activity chose to not provide in-class feedback or were absent from class.~~ ~~Feedback~~Written feedback was mostly positive and indicated that students found the learning experience to be an enjoyable, informative, beneficial, and novel opportunity (Table 3). Three students indicated changes should be made to the activity: (1) more soldering irons required per group and the calibration process should be explained in a more in-depth fashion; (2) feet should be provided so that the PCB can be situated on a table; and (3) the activity took too long.

As indicated by Student #2, additional soldering irons should be provided to allow students to work more quickly, but this is dependent on the class budget and number of batteries available. Although battery-operated soldering irons are beneficial for allowing students to work freely without cords and cables, a permanent teaching lab for hydrological circuits would benefit from the use of AC-powered soldering irons to reduce the number of batteries required for this activity. The feedback response also suggests that the calibration process should be clearly explained in the context of systems theory and mathematical modelling, so the instructor should be willing to address this concept in an in-depth fashion by extensive demonstrations, lectures or videos shared with the students to further enhance comprehension.

Since a student in the class recommended via written feedback that the PCB should have “feet” (Student #3) the instructor considered providing some feet for students who would like to glue the feet on the bottom of the PCB. Conventional plastic feet elevate the PCB above a surface and provide a convenient platform to situate the circuit while it is being operated. To engage students, the instructor used a 3D printer to create a class set of “feet” with toes that can be glued on the bottom of the PCB (Fig. 10a). Figure 10b is an example of a student standing next to a PCB with “feet.” Injecting

humour into a classroom situation is known to increase retention while engaging students by heightening interest and attentiveness (Korobkin, 1988).

~~. Three students indicated changes should be made to the activity: (1) more soldering irons required per group and the calibration process should be explained in a more in-depth fashion; (2) feet should be provided so that the PCB can be situated on a table; and (3) the activity took too long.~~

One caveat addressed by student feedback was the time required for this activity (Student #7). Since the class did not have a lab section, classroom lecture time had to be used for this circuit-building activity, reducing the time for lectures and other activities. Future circuit construction activities should therefore be conducted in the context of a scheduled lab to allow class time to be effectively utilized for questions, problem-solving activities, and lectures.

The trends plot from the Voyant software (Fig. ~~10a~~11a) shows that there are five re-occurring words in the open-ended student feedback~~:~~ (Table 3): circuit, activity, building, fun and class. This demonstrates that students recognized the experiential aspects of the circuit building activity that occurred in class, and ~~that~~ the activity was fun. Fig. ~~10b~~11b shows that most links in the student feedback are associated with the following words: building, activity, and circuit. Although the word "fun" is linked with "circuit" and "activity" the figure demonstrates that most feedback was focused on the circuit construction. The linkages between the rest of the words indicate that the kits allowed for the incorporation of a unique activity into the class that gave an opportunity for students to experience the building of a circuit~~.~~ and experiment with the circuit for data collection. This interpretation is further supported by the associated mandala plot (Fig. ~~10c~~11c) that shows most students found the circuit activity to be "great" and "fun" although "experience" and "opportunity" are also a part of the responses. The word "learning" ~~only~~or "learnt" shows up in the responses of ~~two~~four students (Student 1, 3, 5, 11) indicating that this was not explicitly identified by most students as a goal of the activity; however, the learning process and engagement of students is implicitly demonstrated by the responses.

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~~**3.4 SLEQ Feedback**~~

Students identified that the circuit activity provided a useful insight into calibration and operation of electronic devices utilized for fieldwork (Student #1) and that it was "*cool to be able to have your own circuit*" for the collection of actual data (Student #4). Student #5 identified the process of circuit building as a "*great learning experience*" but indicated that technical aspects of the building process were unrelated to hydrological processes. However, Student #10 indicated that the activity was "*…a great way to incorporate Hydrological Modelling and circuit building*" and Student #11 indicated that the circuit activity "*…allowed us to make correlations between what we learnt in class and apply it to an activity.*" Student #6 indicated that the circuit building activity "*helped me to understand how these sensors work*" and mentioned that the skills developed in class would have future use. Student #8 indicated that the circuit activity provided an incentive for students to attend class, whereas Student #9 found that the circuit activity was unique, useful, engaging, and enjoyable.

Although the circuit activity was primarily intended to teach systems theory in hydrology and to allow students to collect data for use with mathematical models of hydrological phenomena while providing a background to the use of electronic circuits for environmental monitoring, there is a possibility to further develop this activity. As suggested by verbal feedback from students after the activity, the circuits should be modified to log data to flash memory (such as SD cards), thereby enabling automated collection of data. Students also verbally indicated that the plastic jumpers used to set calibration coefficients were challenging to insert and remove. Moreover, at least two students remarked that the PCBs should be waterproofed to allow for usage in wet environments such as at a field site location. Although increasing the complexity and cost of the circuit construction activity, these changes would be worthwhile additions to a circuit used for teaching purposes. Since environmental scientists and hydrologists often utilize electronic circuits in conjunction with dataloggers, circuit design could also be introduced to advanced undergraduates and graduate students in the context of a separate class at the undergraduate level. This class would enable students to propose, design and test their own electronic circuits, thereby encouraging innovation and allowing students to develop important skills useful for the collection of data in the context of graduate work and environmental consulting.

5.2 SLEQ Feedback

The SLEQ feedback closed-ended questions allowed for a quantitative analysis of student responses submitted directly to the university. The feedback was not submitted to the instructor and was processed using a third-party web survey service in accordance with university policies. Using "*A great deal*" or "*mostly*" as rankings, the respondents indicated that the ~~Advanced Hydrology~~ class provided a "*deeper understanding of the subject matter*" and in this regard, the class responses associated with number of students per ranking scored slightly higher than other classes offered by the department and college at the same 4th year level. Also, in the same fashion, the respondents found the class to be "*intellectually stimulating*" and once again the scores are slightly higher compared to other classes. Most respondents indicated that the instructor "*created an environment that contributed to my learning*" and that the class projects and assignments improved understanding and provided opportunities to "*demonstrate an understanding of the course material*." The quality of learning in the class was rated as "*Excellent*" or "*Very good*" by all respondents.

Although the class did not have a separate lab section, the SLEQ feedback form also asked the students questions related to the quality of experiential learning in the context of a lab that includes the circuit activities. Once again using "*A great deal*" or "*mostly*" rankings, students found that the instructor created a conducive learning environment. Similar rankings were also given by most respondents for the question regarding an improvement of understanding related to the course objectives, but one student gave a response to this question as slightly lower with a "*Moderately*" ranking. Although most respondents indicated that the course lab circuit activity provided transferable skills for other courses with a "*A great deal*" or "*mostly*" rankings, two students provided a lower ranking at the "*Moderately*" level. The quality of learning experience in the lab component associated with the circuit construction was ranked "*Excellent*" or "*Very good*" by most

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respondents, although one respondent indicated that the experience was "*Good*." For these questions, the rankings either coincided with or exceeded the rankings associated with other classes at the department and college level.

The cirrus representation of words (Fig. ~~11a~~12a) from the SLEQ responses shows that words occurring with a greater frequency are larger and positioned near the centre of the figure. The words "*good*", "*learning*", "*circuit*", "*class*", and "*building*" occurred at a higher frequency in the responses. Words that occurred at a slightly lower frequency but still predominant in the responses include "*models*", "*use*", "*different*", "*helpful*", "*systems*" and "*thought*." Words that appeared with lower frequency included "*assumptions*" and "*calibration*." The links plot (Fig. ~~11b~~12b) shows that in the student SLEQ responses, the words "*building*", "*great*" and "*class*" had the most linkages to other words. Words with the least linkages include "*good*", "*electronic*", "*different*" and "*mathematical*."

The written feedback provided with the SLEQ survey indicates that students perceived the instructor as accessible, willing to help facilitate the circuit activity and to assist students with learning. Students also indicated that the circuit construction class experience was novel and unique, but in a similar fashion to the the open-ended feedback, some respondents indicated that it took longer than expected, indicating that a dedicated lab section might be useful to hold in conjunction with the class. The student feedback indicates the novelty of the activity. In the words of one student, "*I never thought I would be building a circuit within my university journey, but I am happy to have experienced it.*" All respondents agreed that calibration and learning about how circuits work is an important educational experience for environmental scientists. Most respondents indicated that they found systems theory to be important, although one student indicated "*…still confused by it, I think it is good knowledge to know.*" Most respondents also indicated that they enjoyed the activity and one student indicated that "*I would recommend continuing the activity in upcoming classes, as it is something unlike any other class.*". Some students also commented on the exploratory nature of the course and the emphasis on not having a right or wrong answer when students had to develop their own mathematical models. In the words of one student, "*I had to develop more critical thinking skills as the assignments didn't really have any exact right answer.*" whereas another student commented that "*circuit building, 'story telling' with mathematical equations, building and organizing models, systems and sub-systems*" were skills developed in the context of the course.

5.3 Feedback Loops

This section identifies the feedback loops and the Hattie and Timperley (2007) levels associated with the feedback. The feedback loop model is related to the Wilson et al. (2014, p.76)

~~4. Discussion~~

~~The discussion of this activity identifies the feedback loops and the Hattie and Timperley (2007) levels associated with the feedback. This demonstrates the efficacity of the research question design to guide the discussion.~~

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~~**I Feedback Loop**: Soldering joint defects were observed by the instructor as most prevalent during PCB construction since many students in the class had not previously used soldering irons to construct electronic circuits. Component orientation was another common mistake since most students were not familiar with polarity and pin indicator marks used in electronics assembly. These mistakes and others~~framework for motivating student interest in the classroom.

I Feedback Loop: Defects listed in Table 1 could have been mitigated by having the students watch a video demonstrating circuit assembly from a first-person perspective (Fiorella et al., 2017). Although the instructor walked around the classroom and demonstrated soldering and assembly skills during the circuit construction activity, students learned skills from a third-person perspective. These instructor demonstrations may have been less effective than if a first-person perspective video was used in a pedagogical fashion. The act of the instructor repairing the PCBs outside of class time agrees with the philosophy of constructivist teaching where the teacher acts as a facilitator of learning.

Before beginning the activity, the instructor had a preconceived notion that most students in the class would construct a RH/temperature circuit and that only a small number of students would choose to also populate the parts for a RH/temperature/pyranometer circuit. This unfounded thought was based on the idea that most students will choose a simpler project to reduce required effort and maximize gain. But as identified by Inzlicht (2018) as the "Paradox of Effort," more effort expended when completing a task can serve to increase the perceived cognitive value of the task, despite physical activity being costly in terms of physiological energy use.

L Feedback Loop, Self and Self-Regulation Levels: Psychological studies of student motivation in higher education show that students are willing to attempt tasks based on an intrinsic motivation that varies between individuals and a classroom environment cultivated by the instructor where students feel a sense of belonging and interest in performing the activity (Nupke, 2012). Other common factors for motivation that may have played a role include novelty of the activity as per self-determination theory (González-Cutre et al., 2016); a participation grade to serve as an incentive for class participation (Czekanski and Wolf, 2013); the possible usefulness of the circuit in a class assignment as necessary for completion of the course; and a ~~possible~~ perception that participating less in the activity would not provide an experience justifying the monetary cost of taking the class, particularly since the circuit was a tangible item as a type of "self-gift" taken home after construction. A "self-gift" may boost self-esteem and encourage an individual to recognize "specialness" (Mick and Demoss, 1990). Moreover, the construction of the circuit is an achievement and taking home a tangible and functioning ~~PCB~~circuit can be construed as a type of badge or acknowledgement. Badges function as awards, increasing social self-worth, and thereby serve as incentives for behaviour (Ling et al., 2005).

L and L-I Feedback Loops, Process and Self-Regulation Levels: Similar wording was used by the respondents who completed the instructor-provided and open-ended sections of the SLEQ evaluations, indicating that both feedback forms served as reasonable assessments of the class and circuit activity. However, since the open-ended feedback form was given directly to the instructor, students used this form to provide more implementation-based suggestions for improving the circuit activity than the SLEQ evaluation that served to provide a final assessment of class feedback at the end of the term. The SLEQ evaluation was also the most anonymous. These anonymous types of feedback forms make it more likely that the

students will provide a less-biased assessment of the class (Stone et al., 1977), although complete anonymity may not always be reliable nor accurate due to lessened accountability (Lelkes et al., 2012). Therefore, both the instructor-provided feedback and SLEQ evaluation can be used together to obtain a more comprehensive understanding of how the students assessed the circuit activity.

L Feedback Loop, Process and Self Levels: The open-ended feedback shows that the students provided responses indicating that the circuit construction activity was grounded in experiential reality; to the students, this was a "hands-on" activity that was also fun. Most student respondents did not use the word "learning" in the open-ended feedback solicited by the instructor, although this word appears in the SLEQ evaluation responses, suggesting that students identified the activities ~~are~~as more enjoyable than classic lecture-based forms of learning and that the learning process was implicit in the circuit building activities.

L Feedback Loop and Self Level: Class activities involving unique experiential opportunities engages students, increases comprehension and facilitates learning (Gavillet, 2018). An element of enjoyment as "fun" for adult learners also heightens appreciation of the class and the associated subject material, increases retention of concepts, and leaves students with a positive and enjoyable experience of the learning process (Lucardie, 2014). The results thereby show that the use of circuits served to bring these elements into the context of the ~~Advanced Hydrology~~ class.

Process and Self Levels: The SLEQ feedback standardized questions quantitatively showed that students in the ~~Advanced Hydrology~~ class perceived the educational experiences as leading to a better understanding of the subject area; to the students, these experiences were engaging and perceived to be intellectually beneficial. The instructor of the class was identified as facilitating learning and acting as a consultant for the student learning experience. These results underscore the efficacity of the constructivist teaching philosophy used for the class and emphasizes how this philosophy engages students and facilitates learning. Since the standardized question scores for the ~~Advanced Hydrology~~ class tend to exceed the average scores at the college or departmental level, this indicates the usefulness of these techniques for teaching hydrology at the university level.

Despite the emphasis on circuit construction, analysis of written SLEQ feedback from the students in the class also identified that a "different" learning experience was offered in a fashion that is helpful for thinking about models and systems as conceptualizations of hydrological processes. Associated with the use of models were two related ideas of assumptions and calibration. Although these ideas are often used with mathematical models, the student responses did not show a strong association with mathematics (~~cf.~~ Fig. ~~11b~~11 and Fig 12). This is important since the students learned concepts in class related to identification and analysis of models and systems. The use of mathematics was de-emphasized in favour of concepts, although the students used mathematics to propose hydrological models. De-emphasizing mathematics and focusing class lectures on concepts may have reduced any possible math anxiety present in students at the postsecondary level (Núñez-Peña et al., 2013), thereby allowing students to focus on gaining an understanding of hydrological and environmental processes within the context of the class.

Self Level: The open-ended feedback (Table 3) did not provide any results related to the "gamified learning" aspects of circuit construction. There is a possibility that the idea of circuit construction as a game or puzzle enhanced student enjoyment of class activities, but since no questions were provided on the feedback forms explicitly addressing this concept, it is possible to only conjecture that the idea was beneficial to help facilitate the activity. Further classroom implementation and analysis would be required to quantitatively assess the benefits of gamified learning to teach hydrology. Computer, particularly since computer games have been used to teach water resource management (D'Artista and Hellweger, 2007; Seibert and Vis, 2012) indicating, and further analysis may indicate the possible benefits of involving hydrology students in gamified learning opportunities. The constructivist teaching philosophy associated with this course was also demonstrated by the open-ended nature of the assignments where students were given the opportunity to propose models of environmental phenomena. Allowing students to create knowledge helps to prepare students for future graduate and consulting work in hydrology and environmental science where mathematical modelling skills are necessary. The positive nature of the student feedback suggests that the circuit activity heightened interest in class subject matter and engaged students. Out of the total number of 18 students in the class, only three students did not participate in the circuit construction activities, indicating that 83% of students showed up for class and engaged in the activity.

All Levels: Wilson et al. (2014, p.76) (2014, p.76) indicate that techniques for motivating student interest in the higher education classroom involves "suspense, novelty, ambiguity, incongruity, or discovery." These terms can be used as a framework to analyse the student circuit activity and associated ideas related to systems and models in hydrology. The use of circuit construction is suspenseful since in a similar fashion to a puzzle, students assemble the circuit and after a successful assembly, the circuit can be turned on and data displayed on an LCD display. Also associated with this idea is the notion introduced by the instructor as the circuit assembly serving as a type of "game" that is implicitly a puzzle. The 3D printed watersheds and circuit construction activities areactivity is a novel additionsaddition to thea hydrology class. This statement is supported by student feedback, where some students indicated that they had not constructed a PCB and electronic circuit in the context of a class at the postsecondary level. Ambiguity and incongruity are associated with the novelty of the circuit construction activity. Since many students had not constructed a PCB and electronic circuit, mistakes were made with respect to soldering and the placement of components. However, these mistakes can serve as useful learning opportunities where students are better prepared for future situations when an experiment does not work as expected (Glagovich and Swierczynski, 2004). Discovery was evident in the classroom since the students had the opportunity to formulate novel models of hydrological phenomena and to use a self-constructed circuit to collect data. These activities engaged students and allowed students to develop creative ways of thinking and learning.

Discovery was evident in the Advanced Hydrology classroom since the students had the opportunity to formulate novel models of hydrological phenomena and to use a self-constructed circuit to collect data. This engaged students and allowed students to develop creative ways of thinking and learning.

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~~5. Conclusions~~

~~A custom electronic circuit was developed specifically for the Advanced Hydrology class.~~ 6 Conclusion

~~The circuit was used to introduce concepts of systems theory in hydrology and environmental science as well as models in hydrology. The use of Cree and English on the LCD display acknowledged the ancestors of the land on which the class was taught and contributed to the reconciliation and Indigenization efforts of the University of Saskatchewan. The activity also taught students the Cree word tawāw, introducing the students to a word in an Indigenous language.~~

~~After circuit~~ construction~~, students were given the opportunity to use the circuit to collect data useful for application of a hydrological model that was proposed and tested in the context of a student assignment. The assignment was open-ended and allowed for students to creatively examine concepts associated with assumptions~~ and modelling ~~of hydrological processes. These~~ activities ~~engaged students, increased relevance of the subject material, and allowed for the development of important skills related to electronics and modelling that can be useful for graduate work or application in the context of a job related to environmental science and hydrology. Introducing the circuit construction as a type of "game" or "puzzle" may have enhanced enjoyment, but there are no quantitative results in the feedback to support this hypothesis.~~

~~Circuit theory and explanation of concepts are provided~~described~~ in this paper for classroom implementation and replication. Student provided feedback served to assess the efficacity of this activity for teaching hydrology at the postsecondary level. The Voyant software tools provided a means for graphical visualization and analysis of the feedback. The Narciss (2013) and Hattie and Timperley (2007) models provided a conceptual framework for the collection and analysis of feedback associated with this activity. The Wilson et al. (2014, p.76) framework was used to indicate that the circuit activity can motivate student interest.~~

~~The circuit construction and modelling activities~~ supported the implementation of constructivist teaching in ~~the Advanced Hydrology classroom, where students are the constructors of~~ a post-secondary undergraduate hydrology class. In the context of this activity, students constructed knowledge ~~rather than~~ and did not serve as passive consumers of facts and ~~material~~materials provided by the instructor for rote memorization. The instructor also served in the role of a facilitator to support student learning. This motivated students to attempt the circuit construction task and heightened interest in the activity. Given the engagement of ~~the~~ students ~~in this class,~~by the circuit activity, similar constructivist teaching and innovative class activities should be more widely applied in hydrology classrooms at the ~~higher education~~post-secondary level to improve the student experience ~~and~~ enhance learning~~.~~

~~For future implementations of this activity, student feedback indicated that some aspects should be modified. As indicated by one student, additional soldering irons should be provided to allow students to work more quickly, but this is dependent on the class budget and number of batteries available. Although battery-operated soldering irons are beneficial for allowing students to work freely without cords and cables, a permanent teaching lab for hydrological circuits would benefit from the use of AC-powered soldering irons to reduce the number of batteries required for this activity. Student~~

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~~feedback also suggests that the calibration process should be clearly explained in the context of systems theory and mathematical modelling, so the instructor should be willing to address this concept in an in-depth fashion by extensive demonstrations, lectures or videos shared with the students to enhance comprehension.~~

~~One caveat addressed by student feedback was the time required for this activity. Since the Advanced Hydrology class did not have a lab section, classroom lecture time had to be used for this circuit-building activity, reducing the time for lectures and other activities. We therefore recommend that future circuit construction activities should be conducted in the context of a scheduled lab to allow class time to be effectively utilized for questions, ,~~ encourage experimentation with electronic circuits for data collection, and allow for student-led creative problem-solving ~~activities, and lectures.~~

~~Although the circuit activity was primarily intended to teach systems theory in hydrology and to allow students to collect data for use with mathematical models of hydrological phenomena, there is a possibility to further develop this activity. As suggested by verbal feedback from students in the class, the circuits should be modified to log data to flash memory (such as SD cards),~~ approaches to address educational challenges while subsequently training a new generation of scientists capable of applying knowledge from multiple disciplines to address societal challenges related to water. The lack of constructivist teaching and associated class activities at many educational institutions indicates the need for good teaching practices in hydrology at the postsecondary level. There is a need for universities to explicitly distinguish between a "lecturer" and a "researcher" to ensure specialization in teaching and thereby ~~enabling automated collection of data. Although increasing the complexity and cost of the circuit construction activity, this would be a worthwhile addition to a circuit used for pedagogical purposes.~~improve the student experience. Moreover, the ~~PCBs should be waterproofed to allow for usage in wet environments such as at a field site location.~~design of courses by a joint team of teachers and researchers in hydrology can ensure the use of well-founded teaching strategies conducted in relation with innovative classroom activities to meet the needs of students, and to also encourage the application of new methods, technologies, and developments in the hydrological sciences to meet SDGs and provide the foundation for a better collective future for the planet and for humanity.

~~Since environmental scientists and hydrologists often utilize electronic circuits in conjunction with dataloggers, circuit design could also be introduced to advanced undergraduates and graduate students in the context of a separate class at the undergraduate level. This class would enable students to propose, design and test their own electronic circuits, thereby encouraging innovation and allowing students to develop important skills useful for the collection of data in the context of graduate work and environmental consulting.~~

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~~6.~~7 Code and Data Availability

The microcontroller code, data, bill-of-materials (BOM) and associated circuit design files for replicating this activity are available as a link from Github (https://github.com/nkinar/Introducing-Electronic-Circuits) or Figshare

(https://doi.org/10.6084/m9.figshare.12410588). This download also includes figures created by the Voyant software and anonymized student responses.

~~7.~~8 Author Contribution

All tasks (Conceptualization, ~~N.K.;~~ methodology, ~~N.K.;~~ software, ~~N.K.;~~ validation, ~~N.K.;~~ formal analysis, ~~N.K.;~~ investigation, ~~N.K.;~~ resources, ~~N.K.;~~ data curation, ~~N.K.;~~ writing—original draft preparation, ~~N.K.;~~ writing—review and editing, ~~N.K.;~~ visualization, ~~N.K.;~~ supervision, ~~N.K.;~~ project administration, ~~N.K.;~~ funding acquisition~~, N.K~~) are contributed by N. K. Additional contributions to this paper are listed in the Acknowledgements section below.

~~8.~~9 Competing Interests

The author declares that there is no conflict of interest.

~~9.~~10 Acknowledgements

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Permission was obtained to replicate Fig. ~~1a-c~~4a-b and Fig. ~~2a~~5a-c from other papers as identified in the figure captions. Thank you to John Wiley and Sons for providing the permission.

Ethics permission was obtained from the Department of Geography and Planning ~~at the University of Saskatchewan~~ and the ~~University of Saskatchewan~~ Research Ethics Board (REB~~).~~) at USask. Thank you to Department Head Dr. Alec Aitken and the REB for approving this activity to be conducted ~~for a class taught within the Department of Geography and Planning.~~. Ethics approval was granted by the REB as identification number BEH-2107.

Consent was obtained from ~~all~~ students who are visibly identifiable in images of the classroom activity and from all students who participated in the activity. Also, thank you to the ~~Advanced Hydrology Class of 2019~~ undergraduate and graduate students who participated in the activity (in alphabetical order): Kelby Brinley, Leah Clothier, Andrew Conan, Darin Duriez, Diane Eberle, Rebecca Kupchinski, Stefan Nenson, Danica Pittet, Mark Rambold, Jayvee Sadia, Maria Sanchez Garces, Nichole-Lynn Stoll, Ariel Thom, Josh Turtle and Michiel van Bemmelen. Another thank you is to be extended to ~~Advanced Hydrology~~ former student Maria Stamatinos and PhD student Eric Neil (Department of Soil Science,

College of Agriculture and Bioresources) who participated in ~~this~~the activity to build PCBs.~~ All of you helped to facilitate the activity. kinanāskomitin~~

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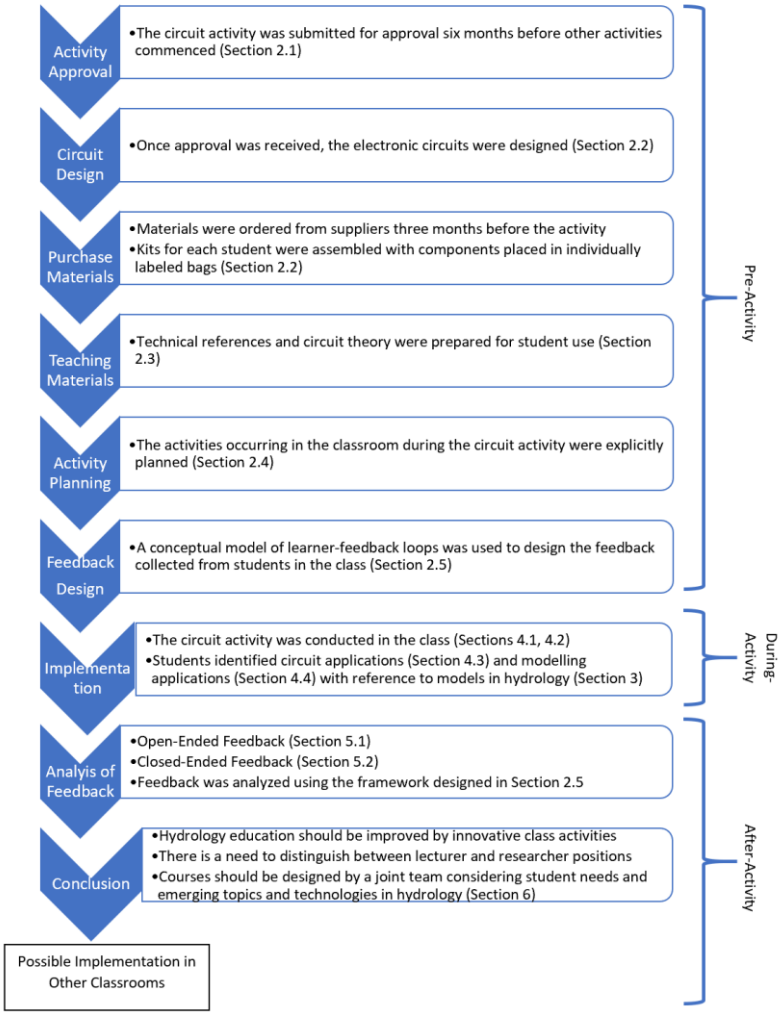

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Fig. 1. Workflow diagram showing stages of the class activity. A temporal classification of stages according to pre-activity, during-activity and post-activity is shown along with a brief description of each stage.

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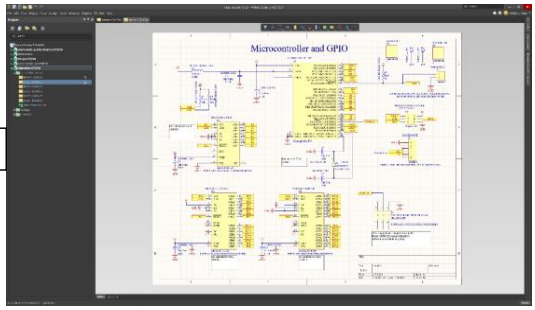

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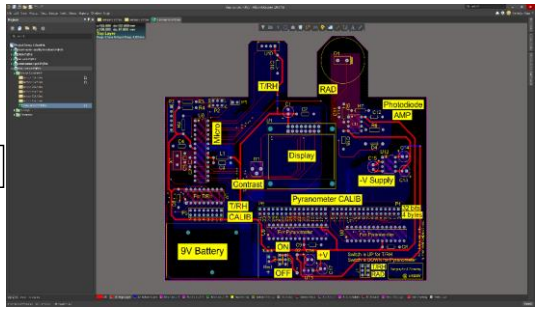

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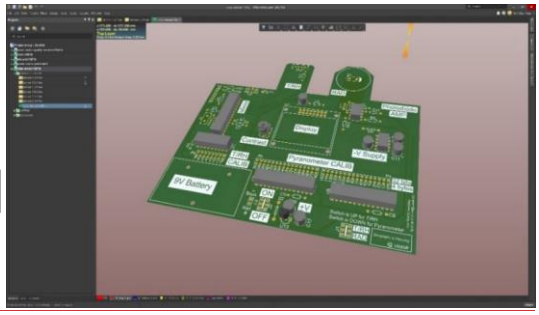

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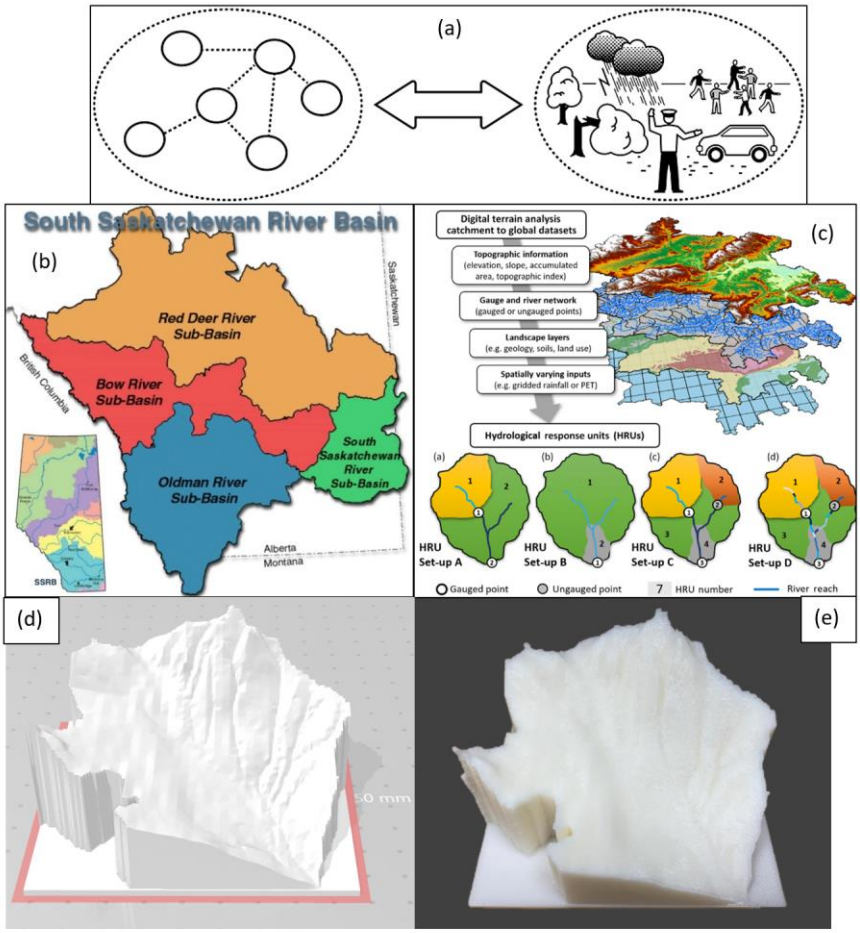

~~Fig. 12~~. (a) Electronic layout software showing a schematic page of the hybrid temperature, relative humidity, and solar radiation sensor. (b) Associated PCB with layers stacked in a similar fashion to a geographic information system (GIS). (c) 3D model of the PCB generated using the layout software.

(a)

(b)

Fig. 3. (a) The circuit components were individually bagged and labelled for student assembly. Also visible in this image is the battery-operated soldering iron used by students for soldering, a toolbox containing hand tools for assembly and a glue bottle used to glue on the diffuser to the circuit board to cover the photodiode for creation of a pyranometer to measure shortwave radiation from the sun. (b) Image showing containers used to transport the kits to a classroom.

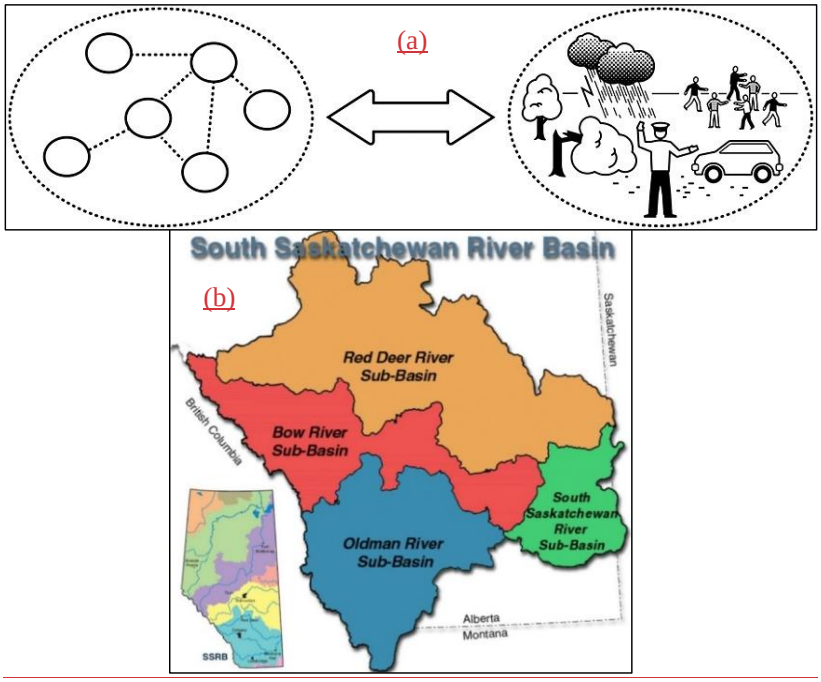

Fig. 4. (a) Demarcation of a system using control volumes and lines (Hieronymi, 2013). (b) Sub-basins used as an in-class example (Sauchyn et al., 2016). ~~(c) Fig. showing connectivity between HRUs (Coxon et al., 2019). (d) Example 3D rendering of a student watershed created from a digital elevation model (DEM). (e) 3D printed version of the same watershed. Figures 1a-c are provided under license by John Wiley and Sons.~~

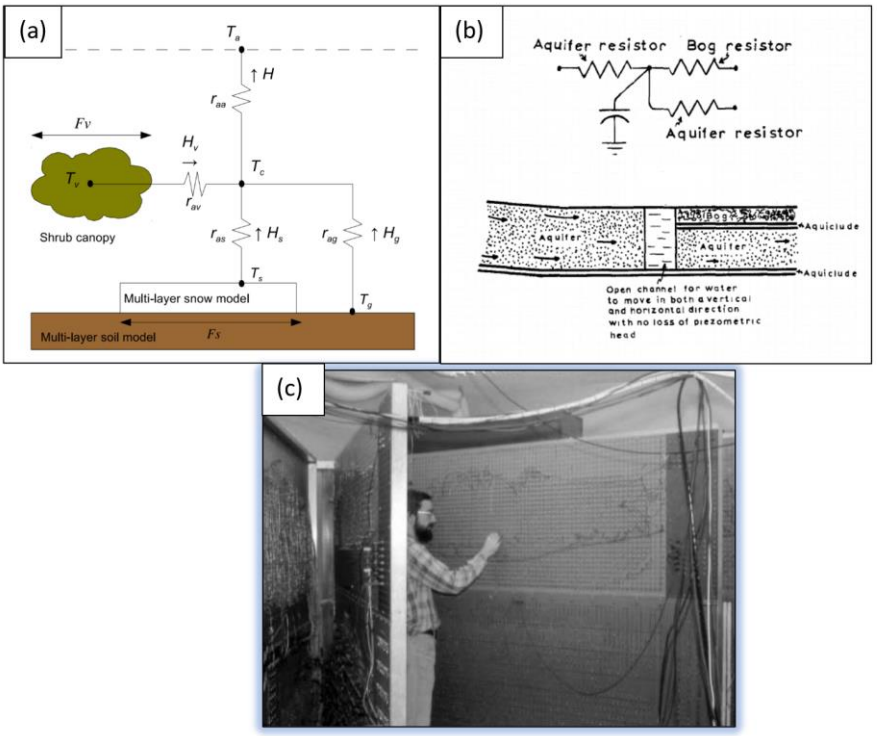

Fig. ~~2~~5. (a) Example of an analog model used for modelling heat exchange between snow, soil, a shrub canopy and the atmosphere at a sub-Arctic tundra site (Ménard et al., 2014). For a complete explanation of terms, please see Ménard et al. (2014). Visible on this circuit schematic are resistors connected to form a circuit. (b) Analog model used to represent the flow of water in a peat bog (Sander, 1976). Visible on this circuit schematic are resistors and capacitors. (c) Picture showing a large analog circuit in the 1970s used to model groundwater (Reilly, 2004). Figures 2a-c are provided under license by John Wiley and Sons.

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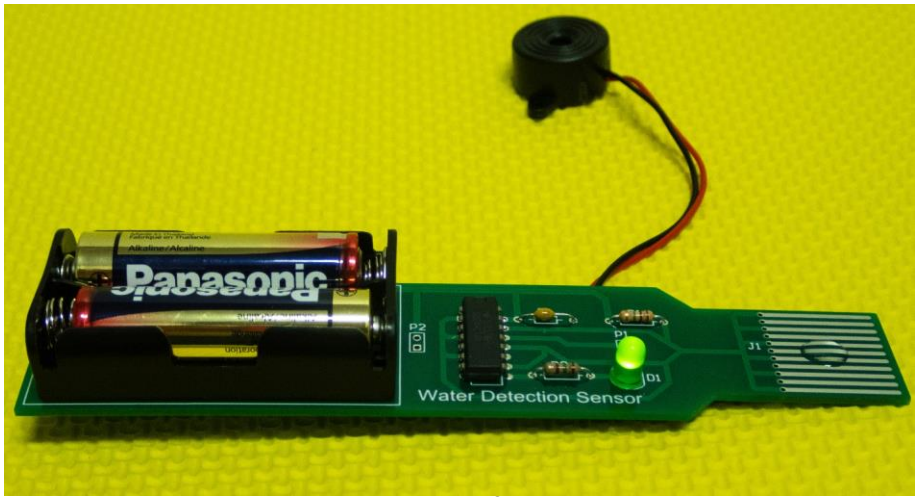
Fig. ~~3~~6. Example images of circuit assembly in the ~~Advanced Hydrology~~ class. The students are using battery-operated soldering irons to solder components to the PCB.



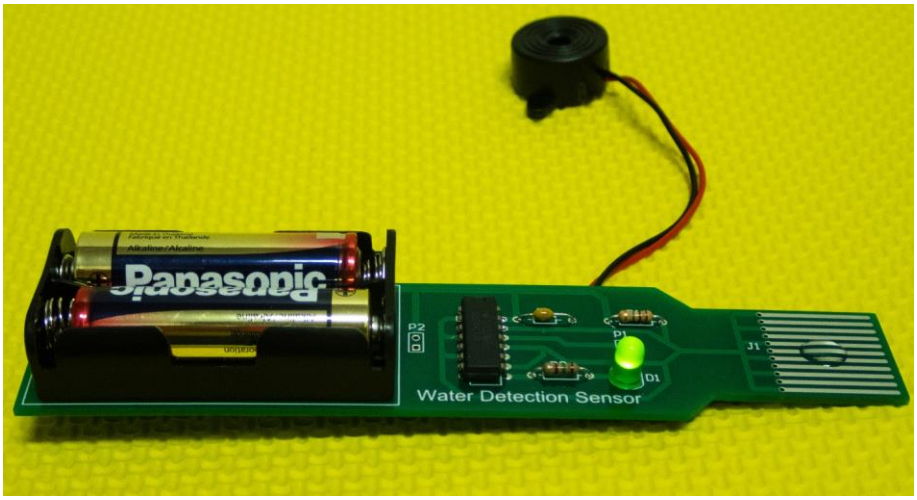


Fig. 47. Water detection PCB. A droplet of water turns on the light-emitting diode (LED) and an attached piezoelectric buzzer to provide visual and audible feedback.

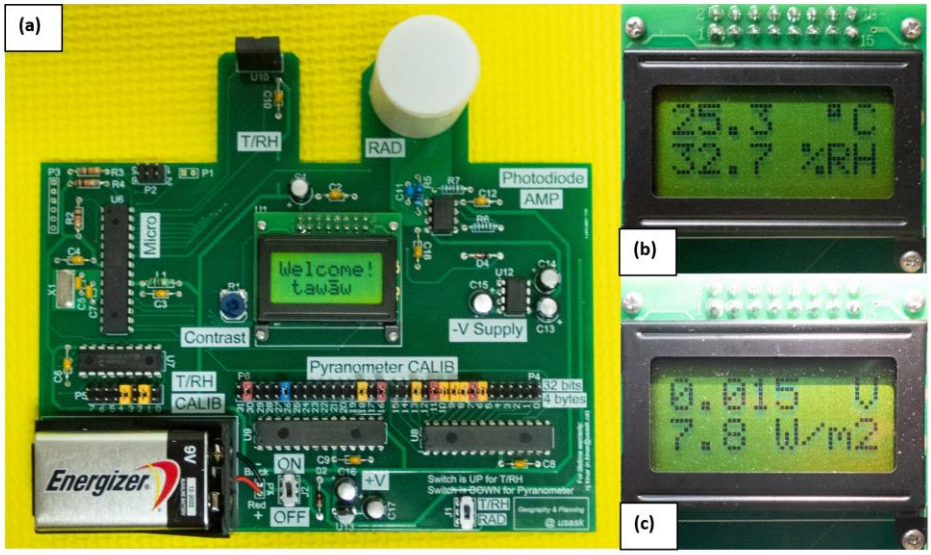


Fig. ~~58~~. (a) Hybrid temperature, relative humidity (RH) and solar radiation sensor. (b) LCD display showing calibrated temperature and relative humidity (RH) readout. (c) LCD display showing calibrated voltage output and radiation flux in $\mathrm{W\,m^{-2}}$. Calibration coefficients are set using removable plastic jumpers and the position of each calibration header is indicated by "CALIB" marked on the PCB silkscreen. The "T/RH" marking indicates the position of the temperature and RH sensor, whereas the "RAD" marking indicates the position of the pyranometer sensor comprised of a photodiode and an op-amp. The photodiode is covered with a piece of plastic pipe and a circular Teflon diffuser. This ensures that the photodiode has a cosine response to obtain a hemispherical measurement. Other markings indicate the positions of various PCB sub-systems, including a switch for setting the mode of circuit operation and a contrast adjustment potentiometer.

Fig. 9. Students engaged in calibration activities. (a) Outdoor calibration of temperature, RH and pyranometer devices using hand-held commercial sensors. Indoor calibration (b, c) with a smartphone flashlight and a hand-held solar radiation meter used as a standard for comparison.

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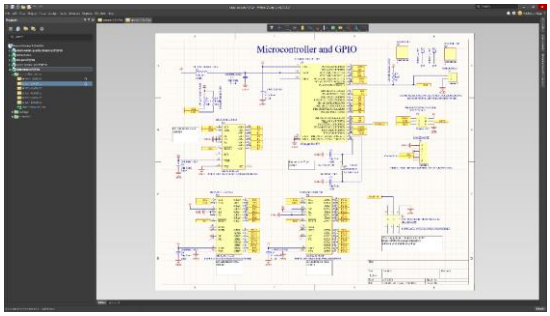

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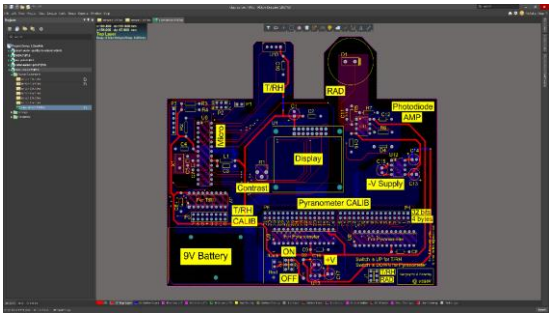

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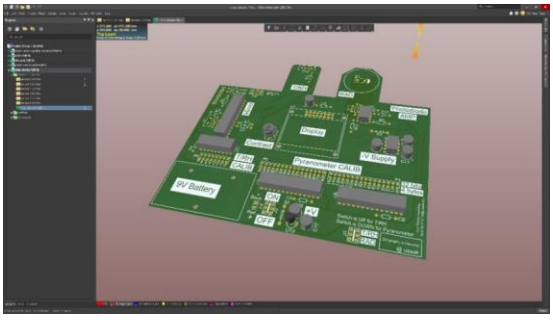

Fig. ~~7. (a) Layout software showing a schematic page of the hybrid temperature, relative humidity, and solar radiation sensor. (b) Associated circuit board with layers stacked in a similar fashion to a geographic information system (GIS). (c) 3D model of the circuit board generated using the layout software.~~

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Fig. 8. (a) Example of 3D printed "feet" to be glued on the bottom of a PCB. The 3D printed "foot" nearest the bottom of the image has a 3D printed "raft" that has not been removed. The "raft" is placed on the 3D printer build platform to ensure that the deposited plastic sticks to a substrate. (b) Student next to a PCB exhibiting "feet" glued on the bottom.

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~~**Fig. 9.** Students engaged in calibration activities. (a) Outdoor calibration of temperature, RH and pyranometer devices using hand-held commercial sensors. Indoor calibration (b, c) with a smartphone flashlight and a hand-held solar radiation meter used as a standard for comparison.~~

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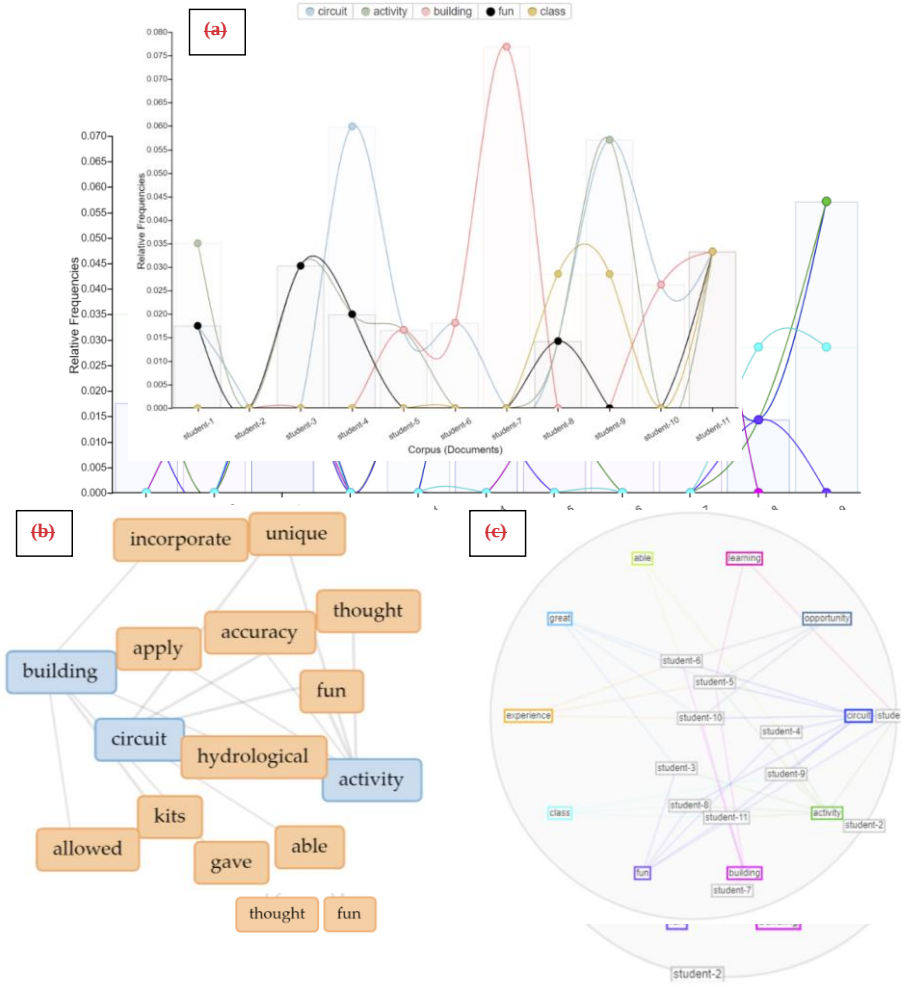

Fig. ~~10~~11. Text analysis for the open-ended class feedback using the Voyant software. (a) Trends plot showing words that occur most often with respect to student responses. The "Corpus" in the Voyant software refers to the student responses. (b) Links plot showing relationships between words over all responses. (c) Mandala plot indicating relationships between student responses and words.

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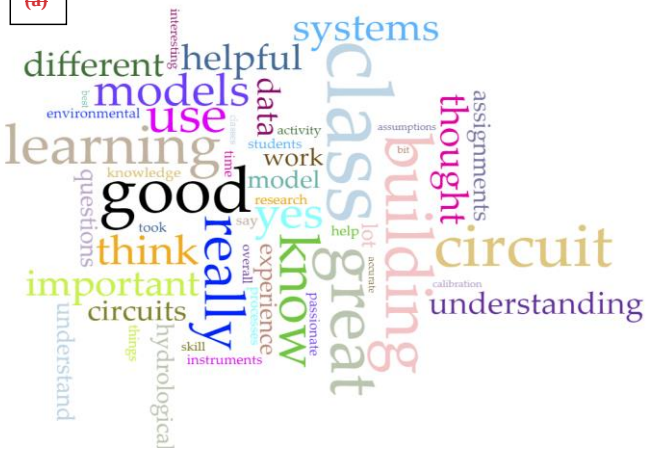
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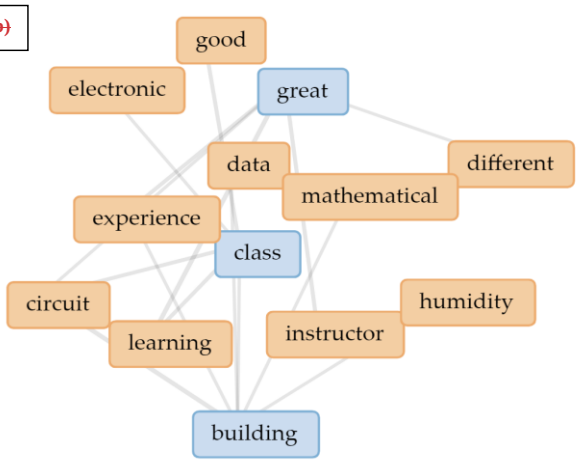
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Fig. ~~11~~12. Text analysis for the SLEQ class feedback. (a) Cirrus plot showing words with higher frequencies as larger and closer to the center of the Fig.. (b) Links plot showing relationships between words over all responses.

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Manufacturing Defect	Number of PCBs Affected
Soldering joints	9
Components placed with wrong orientation	5
Battery connections	3
Glue dripping on photodiode from diffuser	4
Battery holder breaking	3
Damaged PCB pads	1

Table 1. Estimated list of defects associated with PCBs created by the students.

PCB Configuration	Number of Students
Water detection circuit	12
Relative humidity (RH)/air temperature	15
Pyranometer	0
RH/Temperature/Pyranometer	13
Total Students in Class	18

Table 2. Number of students with completed circuit configurations.

1690

Student Number	Response
1	I thought the circuit activity was very informative. We spend our time learning concepts in other classes and not much time on the instruments being used. It's important to know the accuracy of the instrument. This activity helped with the understanding and mechanics of the tools we use in the field. It was also lots of fun.
2	In the future maybe 1 soldering iron per 2 people maybe go + explain the calibration process more thoroughly
3	The board needs feet so it will sit level on a table. The activity was fun and i learnt a lot. The practice soldering was also great. The calibration was an interesting task.
4	I thought that the circuit activity was fun. I have never built a circuit before & was a little nervous to, but this was a nice, easy introduction to it. It's cool to be able to have your own circuit that measures actual values useful to you that you built yourself.
5	The circuit activity was a very unique and beneficial experience! I have not had the opportunity to do something such as this in my previous studies, & I'm thankful for all the time Professor Kinar put into building these kits for us. Learning about the process used to build circuits, even unrelated to hydrological processes, has been a great learning experience!
6	Providing the opportunity for students to build and calibrate their own circuit boards is such a great hands on experience! Being able to be a part of the building process from A to Z really helped me to understand how these sensors work, and I will be able to use these skills in the future.
7	I liked how the building kits were organized and how every bag contained the necessary components I don't like how long the circuit building took overall, but it is how it is.
8	The circuit activity is a fun, educational, and hands-on way,

	of breaking up the class. It keeps students interested and gave them something they can take home and show for their work in the course. I also found that it encouraged attendance of the class. Professor Kinar, clearly a lot of work was put in on your behalf and explainations were very clear for the most part. Thank you!
9	The circuit activity was very unique. I found it very useful and I was more engaged in the class. The circuit activity did take multiple classes to complete but I still found it very enjoyable.
10	This exercise was a unique experience that I likely would not have had the opportunity to do if not a part of the Advanced Hydrology course. It was a great way to incorporate Hydrological Modelling and circuit building.
11	This exercise was very fun and gave us insight to circuit building. It allowed us to make correlations between what we learnt in class and apply it to an activity.

Table 3. Student open-ended feedback responses transcribed as written by the students. The student number in the first column of the table was only used for analysis and is not intended to covey a ranking of responses. Moreover, the student number cannot be used to identify a student in the class. The responses in the table above are also available for digital download (Section 7).