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A Three-Part Activity to Draw Out the Importance of System Interconnectedness in Engineering Analysis

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Abstract

Engineering analysis requires knowledge of system interconnectedness to provide adequate engineering judgment towards a design issue. However, core technical courses in engineering often provide limited opportunities for students to practice this kind of integrative thinking. The courses are typically taught in a traditional manner, leaving little room for students to explore broader system interactions or societal implications of engineering solutions. Therefore, the goal of this work was to design a class activity that engaged students in applying engineering analysis within a complex, real-world context. A three-part activity was implemented in a third year Fluid Mechanics course. This investigation examines how students consider external factors, in addition to engineering analysis, when forming their opinions and perceptions of the role of hydroelectric power in the declining flow rates of the Colorado River. Students are asked to submit their initial opinions, which are grouped as a percentage of responsibility, expressed as one of 0%, 25%, 50%, 75%, and 100%, that hydroelectric power has towards the declining Colorado River flow rates. The students are provided with an overview of the issue and take an initial survey from hearing general arguments from the instructor on both sides of the issue. They then perform an energy water intensity factor (EWIF) calculation and research the social, technical, environmental, economic, and political (STEEP) aspects of the issue, enabling them to formulate a new opinion on the issue. Finally, students are randomly grouped into teams of three for each of the above percentages to justify their assigned position during an in-class debate. After the debate, students take a second survey to express their final opinion on the topic. This paper delves into the evolution of student opinions over the various stages of the activity to explore how their understanding developed through exposure to multiple perspectives and analytical tasks. The findings highlight how engaging with quantitative (EWIF) and qualitative (STEEP) analyses influences students' recognition of system interconnectedness and enhances their ability to exercise sound engineering judgment.

I. Introduction

Engineers have a crucial role in shaping sustainable infrastructure and systems that support modern society, and their choices have a profound impact on the environment, society, and economy [1]. Climate change, water scarcity, energy transitions, and resource management are examples of modern engineering issues that go beyond strict technical bounds [2,3].

To address these socio-technical challenges, engineers must be trained to apply system thinking; but current educational practices often fall short of cultivating such skills. Even when confronted with real-world problems, many students concentrate narrowly on discrete calculations, limiting their capacity to account for sustainability and the interdependencies across systems [2]. Moreover, sustainability is often viewed as a peripheral or abstract idea rather than as an essential framework for engineering judgment [3]. It is challenging to establish stand-alone sustainability courses due to such limited curricular space [4]. As a result, students who possess strong technical proficiency may lack the ability to integrate sustainability into their engineering judgment. Sustainability education encourages students to move beyond rote memorization and consider the wider consequences of their engineering decisions.

In response to the growing imperative to prepare engineers for sustainability-oriented decision-making, engineering programs worldwide have increasingly incorporated sustainability education. One prominent effort supporting this shift is the **Engineering for One Planet (EOP)** framework, developed through a multi-stakeholder process led by the Lemelson Foundation and VentureWell, with input from over 100 academic, industry, and nonprofit partners [5, 6]. The EOP framework provides structured guidance for integrating sustainability within existing engineering curricula by delineating a suite of targeted learning outcomes centered on systems thinking and responsible decision-making. By incorporating these principles within traditional coursework, educators can foster a sustainability mindset that is environmentally responsible, socially just, and economically viable. Furthermore, challenges exist in adding sustainability modules in required engineering courses since limited class periods are available to achieve learning objectives, but the structure of EOP and its alignment with ABET aids faculty in identifying opportunities to include sustainability concepts into their courses.

Evidence from the literature shows the successful integration of EOP principles into undergraduate engineering curricula [7]. For example, Jayasinghe et al. describe EOP integration in a second-year Engineering Design course at the University of Calgary, where students engaged in collaborative projects addressing complex, open-ended sustainability challenges aligned with the UN Sustainable Development Goals [8]. These projects required students to apply technical skills alongside sustainability tools such as design for repairability, reuse, and disassembly, while mapping interconnected system components and considering diverse stakeholder perspectives. Reflections from the first iteration of the Calgary program indicated that EOP principles created a positive learning environment, fostering critical thinking, creativity, systems reasoning, and sustainability mindsets. Similarly, Kwaczala et al. reported that embedding EOP principles in undergraduate projects improved students' ability to reason across system boundaries, evaluate trade-offs, and make defensible decisions in complex, real-world scenarios [9]. Building on these insights, Western New England University also successfully mapped sustainability modules to EOP learning objectives across the four-year engineering curriculum, combining course-based instruction with experiential, hands-on projects. However, much of the existing work has focused on project-based or design-oriented contexts, with comparatively limited attention given to the integration of EOP principles within instructional activities centered on contested or debated sustainability topics.

One area of work less explored is the integration of sustainability concepts into topics that are currently under debate within the industry. We posit that the use of debatable sustainability-related topics while simultaneously analyzing a traditional engineering issue draws out new insights related to EOP goals since a deeper level of thinking is required by the students to defend a position, pointing to a higher level of learning (the "Evaluation" level in Bloom's Taxonomy [10]) than rote memorization or even analysis.

This study contains a three-part activity to explore the different points of view on an active debate in the sustainability community. The topic is the drying up of the Colorado River, and how much of the responsibility for its flow reduction is attributable to hydroelectric power production via the Hoover Dam. The reason for the debate in industry is that it is unclear as to how much water consumption should be attributed to hydroelectric power production. The commonly used metric for this is the energy water intensity factor (EWIF), defined as the amount of water used (in L) per electric power produced (in kWh). The factors attributed to the calculation of the EWIF primarily include surface water evaporated, which in the case of hydroelectric power is due to the increased surface area of bodies of water (Lake Mead in this case) produced by the presence of dams.

Calculated values of the EWIF for hydroelectric power generation are much more dependent on location than other electric generation fuels per Peer et al. [11], even showing a water surplus in the northeastern U.S., with a massive water cost in the southwestern U.S. Therefore, at face value the large EWIF associated with hydroelectric power in the southwestern U.S. suggests that the use of hydroelectric power in this region is a principal cause of the region's water scarcity problem.

The primary goal of this study is to examine how a scaffolded, three-part instructional activity influences engineering students' sustainability-related engineering judgment in the form of a demonstrated systems thinking outcome, with a secondary goal in examining their final positions on a complex socio-technical issue. This work investigates how engaging students in sequential exposure to contrasting viewpoints, independent quantitative analysis, systems-level exploration, and structured debate support the development and refinement of students' ability to justify sustainability-related decisions. The students should be able to justify engineering decisions using technical evidence, external system considerations, and assumptions. While changes in students' attributed responsibility positions provide insight into shifts in perspective, the focus of this study is also on understanding how students' reasoning evolves as they integrate quantitative analysis with broader social, environmental, economic, and political contexts when formulating engineering judgments. This work therefore improves environmental engineering education within mechanical engineering students by enabling the students to consider both technical and non-technical aspects in decisions related to environmental sustainability issues.

II. Methods – Classroom Activity

The full picture of the causes of the drying up of the Colorado River, however, requires an entire social, technological, environmental, economic, and political (STEEP) analysis of these causes. The activity for the course was therefore developed to ingrain the STEEP mindset for the students to create broader understanding of these causes rather than merely reducing the complex situation to a single parameter. This goal was accomplished through the use of three activities:

(1) an introductory presentation that provides two extreme points of view, (2) an independent homework assignment that delved deeper into the calculation of EWIF and the STEEP factors affecting the water scarcity problem, and (3) an in-class debate to provide alternative points of view, enabling students to develop their own final opinion on the issue. These three activities span Bloom's taxonomy, with the first activity focusing on knowledge, the second on synthesis, and the third on evaluation.

The activity was therefore created with the inquiry question "*How does introducing these three parts of the activity impact students' view of the importance of system interconnectedness and STEEP factors in formulating engineering judgement*?" The specific learning outcome associated with evaluating this inquiry question is demonstrated systems thinking ability. The question uncovers how the use of these activities affects student's ability to recognize interconnectedness of different systems.

The progression of student viewpoints is captured in three ways:

- Part 1 (introductory presentation): Students were provided with a link to a short survey at the end of the presentation to obtain their initial impression, captured as the percentage of responsibility (R) of the drying up of the Colorado River that is attributed to hydroelectric power, expressed as one of $\{0\%, 25\%, 50\%, 75\%, 100\%\}$.
- Part 2 (homework assignment): Students provide evidence of in-depth research of the issue through calculations of the EWIF value and exploration of STEEP analysis. The students also provide an updated value of R.
- Part 3 (after in-class debate): Students completed a second survey after the debate with their final value of R and a justification for the chosen value.

The activity was integrated into half-hour portions of two lectures in an undergraduate junior-level mechanical engineering fluid mechanics course section containing 32 students within a four-year university. The integration occurred in lectures 7 and 11 out of 25 total lectures. To accommodate this activity, some lecture material was recorded and posted for students to study offline. The activity was performed after the course coverage of fluid statics was completed since the activity is considered an extension of analysis of fluid dam structures towards their impact on the surrounding environment.

A. Part 1: Introductory Presentation and Survey

The first presentation, delivered via PowerPoint, introduced the class to two fictitious students who are debating on whether hydroelectric power is good for the environment. One student (Bob) fully believes that the answer is "yes", whereas the other student (Judy) fully believes that the answer is "no". Bob and Judy present their arguments based on various aspects (carbon footprint, potential for flooding, and disruption of fish population) and cite examples. Judy also mentions evaporative water loss as a major detriment to hydroelectric power, citing the decline in water in Lake Mead on the Colorado River. The class was then told that evaporative water loss is the focus of the three-part activity.

The class was then introduced to the concept of the energy-water intensity factor (EWIF), how it is calculated, and the ongoing debate on how much of the EWIF should be attributed to hydroelectric power, considering that Lake Mead is also used for drinking water and recreation. The students were finally informed of external factors (e.g., water rights, reduced snowpack, and megadrought) that could also influence the loss of flow in the Colorado River.

The initial anonymous survey, delivered via Google Forms, contains only two questions. The first question is a consent to participate, and the second is a declaration of the percentage of responsibility of the drying up of the Colorado River attributed to the hydroelectric power (one of 0%, 25%, 50%, 75%, and 100%).

B. Part II: Homework Assignment

Students were provided two weeks to complete the assignment, receiving five bonus percentage points on their second class test if they completed all aspects of the activity. The assignment begins by collecting information (e.g., Lake Mead surface area, average Hoover Dam power output, and average air temperature and relative humidity for Las Vegas) and performing prescribed calculations to determine the evaporative water loss rate from the lake compared to the power output from the dam, thereby enabling calculation of the EWIF. The students then compare the calculated EWIF value to that prescribed to hydroelectric power in the southwestern U.S. from literature. This comparison is a key assessment for the students to think critically, which is a desired outcome from the EOP.

The second aspect of the assignment involves a social, technological, environmental, economic, and political (STEEP) exploration of the various external factors that affect the drying of the Colorado River. The students were encouraged to use artificial intelligence (A.I.) tools to aid in this exploration.

The final part of the assignment requires the students to update their opinion on the percentage of responsibility for the drying of the Colorado River attributed to hydroelectric power (one of 0%, 25%, 50%, 75%, 100%) based on their findings, and then writing a short (up to one-page) essay justifying their position.

C. Part III: In-Class Debate

The in-class debate was held shortly after the due date for the homework assignment to ensure that the activity was still fresh in the students' minds. Students were first provided with information about proper debate etiquette, and then the rules for the debate were indicated:

- Randomly created groups of three students were assigned independent of the students' choices of percentage group in the initial survey or homework assignment. This approach was used to force the students to defend a position that they did not necessarily agree with. Since five groups were created (one each for 0%, 25%, 50%, 75%, and 100%), then a total of 15 students were placed into these groups, with the remaining students as observers of the debate.

- Student groups were provided with three minutes to formulate their positions on the topic and to elect a group speaker representative.
- Each group was then provided with two minutes to present their position.
- All groups were then provided with three minutes to formulate a rebuttal argument.
- Each group was then provided with one minute to present their rebuttal argument.

The students then filled out a second survey in Google Forms to finalize their position on the topic through choosing a group (one of 0%, 25%, 50%, 75%, and 100%) and by providing a short (one page equivalent) essay explaining their choice. The students were provided with one week to complete the form. The purpose of the survey is intended to capture changes in student beliefs by understanding others' perspectives.

D. Analysis

The results from each of the three parts were analyzed in two ways:

1. A descriptive analysis of the student responses was performed to assess (1) the students' ability to reflect the core EOP principles of critical thinking and interconnected systems within their engineering judgement, and (2) the evolution of chosen percentage group with the introduction of deeper analysis in successive parts of the activity. The assessment of critical thinking through the homework assignment was achieved through (1) examining the discrepancy of their calculated EWIF value and the published value from literature, and (2) providing an appropriate justification of their chosen percentage group. The assessment of interconnectedness/systems thinking was done through examining (1) the thoroughness of STEEP analysis on factors influencing the drying up of the Colorado River, and (2) the identification of external factors affecting the chosen percentage group.

2. To better understand how students developed their engineering judgments within a complex socio-technical system, a qualitative thematic analysis was conducted using NVivo 15.

The analysis examined students' written responses to the prompt:

"Use your findings from Part II to formulate a position on how much the Hoover Dam contributes to water scarcity on the Colorado River. Specifically, what percentage of the river's water scarcity can be attributed to hydroelectric power?"

This task required students to combine their quantitative EWIF calculations with qualitative STEEP analyses to justify a specific percentage. Their responses provided insight into how they reasoned system boundaries, relationships, resource flows, and engineering responsibility within a complex socio-technical context.

Following Braun and Clarke's six-step framework for qualitative analysis, an inductive thematic approach was applied [13]. A purposive sample of 15 student submissions was chosen for detailed coding to capture the full range of responsibility attributions and reasoning strategies present across the cohort.

The analysis revealed four key themes reflecting Meadows' systems thinking framework: System Boundary Framing, Resource Flow and Consumption, Interconnected Causality, and Mental Models of Engineering Judgment [14]. These themes helped to explain how students conceptualized responsibility within the broader Colorado River system.

Ultimately, the goal of the analysis was to explore *how* students constructed their sense of responsibility for hydroelectric power's role in water scarcity, rather than whether their percentage estimates were correct. It examined how they justified their reasoning by defining system boundaries, distinguishing between consumptive and non-consumptive water uses, integrating both quantitative and qualitative evidence, and expressing engineering judgment while navigating physical, institutional, and environmental constraints. This integrated approach provides a nuanced understanding of how engagement with both quantitative and qualitative analytical frameworks shapes students' reasoning about system interconnectedness and engineering judgment.

III. Results

A. Evolution of Students' Positions

31 out of 32 students agreed to the consent to participate in the initial survey, and the results are provided in Table 1. The results indicate no absolute (0% or 100%) identification or dissolution of responsibility to hydroelectric power, undoubtedly due to the presence of facts supporting both sides of the argument. The data skew towards less responsibility (25%) due to the external factors mentioned in the course, with fewer concrete reasons assigning responsibility to power production.

The results show that students' positions shifted most substantially after engaging in independent quantitative and systems-level analysis, with comparatively smaller changes following the in-class debate. Table 1 summarizes the distribution of student responses across the three stages of the activity, reported as the percentage of responsibility attributed to hydroelectric power for the drying of the Colorado River. After the introductory presentation (Part I), student responses were distributed across the 25%, 50%, and 75% responsibility categories, with no students selecting the extreme positions of 0% or 100%. The largest proportion of students (14 of 31) selected 25%, followed by 12 students selecting 50% and 6 students selecting 75%. This distribution indicates that students entered the activity with varied perspectives while generally avoiding absolute attribution of responsibility.

Following completion of the homework assignment (Part II), a clear shift in student positions was observed. The number of students selecting 25% responsibility increased from 14 to 21, while selections of 50% and 75% responsibility decreased from 18 to four. In addition, six students selected 0% responsibility for the first time. This redistribution coincided with students' engagement in quantitative calculations of the energy–water intensity factor (EWIF) and a structured exploration of external social, technological, environmental, economic, and political (STEEP) factors affecting water scarcity in the Colorado River Basin.

After the in-class debate (Part III), the overall distribution of responses remained similar to that observed after Part II. The 25% responsibility category continued to represent the majority of student responses, increasing slightly to 25 of 32 students, with only minor redistribution among the remaining categories. Compared to the transition from Part I to Part II, the magnitude of change in student positions from Part II to Part III was relatively small.

These results indicate that the largest shifts in attributed responsibility occurred following students' independent engagement with quantitative and systems-level analysis, while the in-class debate primarily served to refine or reinforce existing positions rather than produce substantial changes.

Table 1: Tally of Survey Results for Various Parts of Activity

Score	**Number of Students After First Part of Activity**	**Number of Students After Second Part of Activity**	**Number of Students After Third Part of Activity**
1 (0%)	0 (0%)	6 (19%)	2 (6%)
2 (25%)	14 (45%)	21 (68%)	25 (78%)
3 (50%)	11 (35%)	3 (10%)	3 (9%)
4 (75%)	6 (19%)	1 (3%)	2 (6%)
5 (100%)	0 (0%)	0 (0%)	0 (0%)
Totals:	**31[*] (100%)**	**31[**] (100%)**	**32[***] (100%)**

[*]One student indicated in the first survey that they did not want to participate in that portion of the study. Their response is not provided in the table.
[*]All students indicated that they wanted to participate in the study, but one student did not perform the homework assignment.
[*]All students indicated that they wanted to participate in the study.

The Qualitative analysis supports this trend and claims that students perceived their views as evolving primarily during the homework assignment. Engagement with quantitative EWIF calculations and STEEP systems analysis prompted many students to reassess responsibility attribution and consider the interconnectedness of social, environmental, technological, economic, and political factors. These reflections suggest that the homework facilitated deeper consideration of system complexity and engineering responsibility, providing the main driver for shifts in student positions.

B. Evidence of Systems Thinking and STEEP Integration

The results indicate that most students incorporated systems-level considerations into their reasoning after the homework assignment, though the depth and completeness of STEEP integration varied across students. Evidence of students' systems thinking emerged most clearly in the homework assignment, where students were required to explore social, technological, environmental, economic, and political (STEEP) factors contributing to the drying of the Colorado River and to integrate these considerations into their justification of attributed responsibility. Table 2 summarizes student performance across multiple dimensions related to systems thinking and engineering reasoning.

Of the 31 students who completed the homework assignment, 20 demonstrated sufficient evidence (as evidenced by providing at least one cause – not impact – of water loss related to for each of the STEEP areas) of systems thinking through a STEEP analysis that addressed multiple external factors influencing water scarcity. These students identified factors such as agricultural water consumption, climate change, water rights and policy constraints, population growth, and competing societal uses of water resources. In contrast, 11 students did not demonstrate sufficient STEEP integration. Common limitations included focusing on the impacts of water scarcity rather than its causes, or addressing only one or two STEEP dimensions rather than considering the broader system.

Additional evidence of systems thinking was observed in students' written justifications for their chosen percentage of responsibility attributed to hydroelectric power. While 28 of 31 students provided sound, evidence-based justification for their selected position, slightly fewer students (26 of 31) explicitly incorporated external, non-technical factors into their reasoning. The remaining students justified their positions primarily through technical or literature-based arguments without connecting those arguments to broader social, environmental, or political systems. For example, two students cited studies reporting a specific percentage of water loss attributable to Lake Mead evaporation but did not engage with additional system-level contributors to water scarcity.

These findings suggest that while most students moved beyond single-parameter explanations and demonstrated emerging systems thinking, the extent to which students fully integrate all STEEP dimensions varied. This variation highlights differences in how students conceptualized interconnected systems when formulating sustainability-related engineering judgments.

Table 2: Assessment of Student Performance on Homework Assignment

	Critical Thinking: Explanation on EWIF Discrepancy	**Systems Thinking: Sufficient STEEP Analysis**	**Critical Thinking: Appropriate Justification of Choice of Percentage Group**	**Systems Thinking: Identification of External Factors in Justification of Choice**
Shows Sufficient Evidence	22 (71%)	20 (65%)	28 (90%)	26 (84%)
Does not Show Sufficient Evidence	9 (29%)	11 (35%)	3 (10%)	5 (16%)

To further explore the reasoning behind these patterns, a qualitative analysis of student reflections was conducted. Initial codes captured recurring concepts related to hydrologic processes, policy constraints, resource use, and decision-making rationales. These codes were then clustered into four higher-level qualitative themes aligned with systems thinking and engineering judgment constructs. Figure 1 illustrates the relationship between initial reflections (Codes) and the emergent qualitative themes used to organize the results.

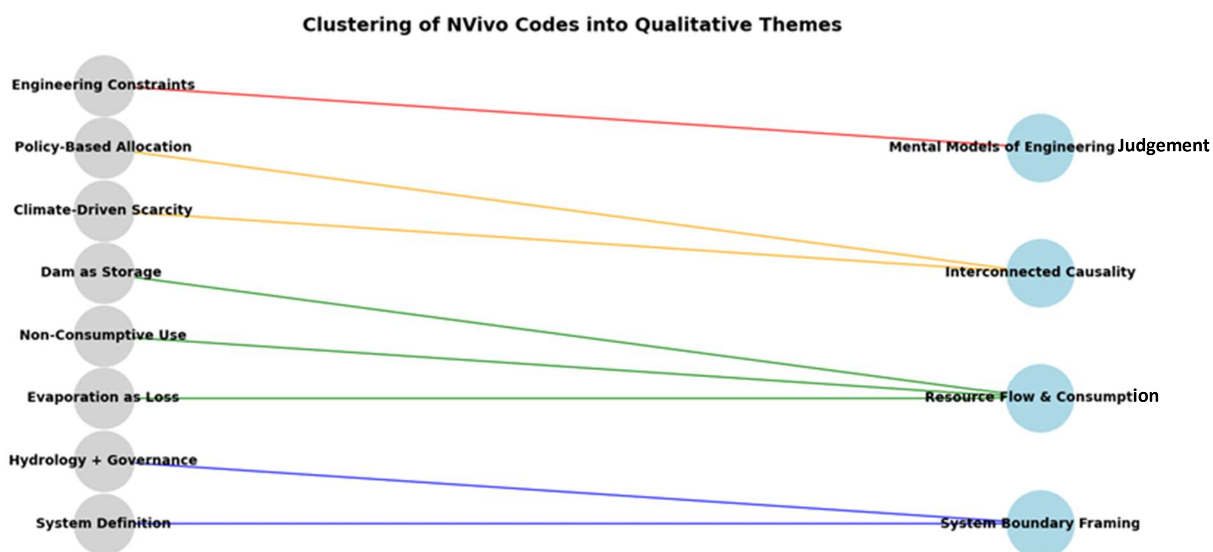

Figure 1: Qualitative Themes

While Table 2 indicates that most students engaged with multiple STEEP dimensions, it does not reveal how students defined system boundaries or connected resource flows to their responsibility judgments. Preliminary coding of written responses (Figure 2) showed that themes related to system definition and hydrology–governance interactions clustered under the broader construct of system boundary framing. To explore these patterns in depth, qualitative analysis focused specifically on how students operationalized systems thinking through system boundary framing and reasoning about resource flows. Table 3 summarizes these patterns, linking levels of responsibility attribution (0–75%) to corresponding approaches to defining system boundaries and interpreting resource flows.

Table 3: Patterns in System Boundary Framing and Resource Flow Reasoning

Attribution Level	System Boundary Framing	Resource Flow & Consumption Reasoning
0%	Clearly distinguishes hydropower from consumptive uses; dam framed as a pass-through infrastructure	Explicitly identifies hydropower as non-consumptive; evaporation attributed to storage and delivery, not power generation
25%	Expands boundary to include reservoir storage effects tied to dam existence	Recognizes evaporation as real loss but bounded relative to basin-wide use
50%	Boundary centered on dam–reservoir system with limited external comparison	Evaporation emphasized as major loss without proportional comparison to agriculture
75%	System boundary collapses around Hoover Dam as dominant cause	Treats evaporation as direct waste attributable to hydropower

Evidence of systems thinking emerged most clearly through students' STEEP analyses and written justifications, where students differed in how they defined system boundaries and reasoned about resource flows contributing to water scarcity in the Colorado River Basin. Some students conceptualized the Colorado River as a basin-wide socio-technical system that extended beyond the Hoover Dam to include multiple geographic regions, stakeholders, and long-term climatic influences. For example, one student emphasized the scale of the system by noting that

"the river serves about forty million people across seven U.S. states, many tribal nations, and Mexico."

In contrast, other students framed the system boundary more narrowly or temporally, situating current water scarcity primarily within long-term climatic variability. These students emphasized historical wet and dry periods or global climate trends, with limited integration of policy, infrastructure, or consumption patterns. Similarly, another student attributed scarcity largely to climate trends by noting that *“these warmer temperatures cause dryness in many different places, not just those with dams.”*

These responses reflect partial systems thinking in which only one or two STEEP dimensions were connected to the broader system.

Differences in resource flow and consumption reasoning further illustrate variation in systems thinking. Many students demonstrated nuanced understanding by distinguishing between consumptive and non-consumptive water uses and identifying evaporation from Lake Mead as the primary mechanism linking hydropower infrastructure to water loss. Some students quantified evaporation at the basin scale, such as one student who estimated that

“Lake Mead’s evaporation is estimated to make up about 10–15% of the basin’s consumptive water loss.”

Others linked physical resource flows directly to system performance metrics, stating that

“147 m^3 of water are lost per 1 MWh of electricity… evaporation is a huge factor when it comes to loss of water supply in Lake Mead.”

At the same time, several students emphasized that hydropower itself is non-consumptive, redirecting attention toward storage and allocation decisions rather than turbine operation. As one student explained,

“Hydropower is a non-consumptive use, meaning the same water that turns the turbines is released downstream for cities, farms, ecosystems, and treaty deliveries.”

Some responses, however, revealed difficulty reconciling these distinctions, with students alternately describing hydropower as both wasteful and non-consumptive without fully articulating the mediating role of evaporation.

Taken together, the quantitative and qualitative findings triangulate around the idea, while most students demonstrated emerging systems thinking by moving beyond single-factor explanations, the extent to which students integrated multiple STEEP dimensions, defined coherent system boundaries, and reasoned consistently about resource flows varied substantially across responses.

C. Engineering Judgement

The results show that most students were able to integrate quantitative analysis with qualitative reasoning to justify an engineering judgment, particularly when reconciling calculated results with uncertainty and external evidence.

Evidence of students’ engineering judgment was most apparent in their energy–water intensity factor (EWIF) calculations completed as part of the homework assignment. Figure 2 presents the distribution of EWIF values calculated by students, alongside the value reported in the literature by Peer et al [11]. While most student-calculated values were of the same order of magnitude as the reported value, a substantial spread was observed across submissions.

The variation in calculated EWIF values can be attributed to differences in assumptions related to heat transfer coefficients, reported climate data (e.g., average temperature and relative humidity), the Hoover Dam power output, and the Lake Mead surface area. Students employed a combination of standard equations, external data sources, and A.I. tools to perform psychrometric calculations, while following a common calculation procedure provided in the assignment. As a result, although the computational steps were consistent, differences in assumptions and data sources led to divergent numerical answers.

Nearly all student-calculated EWIF values (87%) exceeded the literature-reported value, prompting students to explicitly address this discrepancy in their written responses. As shown in Table 2, 22 of 31 students demonstrated sufficient evidence of critical thinking by providing a reasoned explanation for the discrepancy between their calculated values and the reported value. Alternative reasoning, however, may not be captured under the current criterion. Common justifications included recognition of the transient nature of temperature and humidity, the uncertainty in heat transfer coefficients, and changes in lake surface area over time.

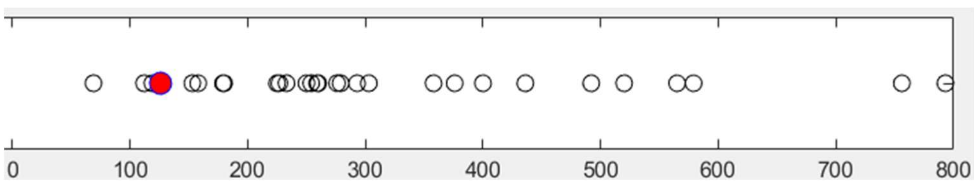

Figure 2: Collection of student calculations of EWIF. Value in red is the value of 126 L/kWh provided by Peer et al. [11]. Excluded is a single data point at 1.41 million L/kWh resulting from an erroneous calculation.

Building on the themes identified in the qualitative analysis, additional evidence of engineering judgment emerged in students' written justifications for their attributed percentages of responsibility. A large majority of students (28 of 31) provided appropriate, evidence-based rationales for their selected positions. While not all students explicitly incorporated external system factors, most demonstrated the ability to connect quantitative results, assumptions, and supporting evidence when defending their engineering judgments. One exception to this trend, for example, is a student who selected the 50% group did not provide equally compelling arguments supporting and opposing the notion that hydroelectric power is 50% responsible for water scarcity issues in the Colorado River. These findings suggest that the activity encouraged students to move beyond direct calculation toward interpretation, justification, and reconciliation of results within a broader engineering context.

Written reflection of students further highlighted meaningful variation in how they translated quantitative results into engineering judgments. Responsibility attributions corresponded closely with differences in how students conceptualized system causality and weighted quantitative evidence (Table 4). Students assigning lower responsibility percentages tended to adopt broader causal framing, balancing evaporation losses against basin-scale drivers, whereas higher attributions reflected narrower system boundaries and dominant reasoning. Student responses

(Figure 1) indicated that factors such as policy-based allocation, climate-driven scarcity, and engineering constraints contributed to the reasoning of interconnected causality and informed students' engineering judgments.

Table 4: Interconnected Causality and Mental Models of Engineering Judgment Across Attribution Levels

Attribution Level	Interconnected Causality	Mental Model of Engineering Judgment
0%	Integrates climate change, agriculture, policy, tribal rights, and infrastructure as interacting drivers	Highly integrative judgment: responsibility allocated based on physical mechanisms and system purpose
25%	Connects evaporation, climate change, agriculture, and infrastructure constraints	Moderately integrative judgment; balances quantified losses with broader system drivers
50%	Partial linkage to social and technological factors, but limited interaction among them	Transitional judgment; recognizes complexity but weights single component heavily
75%	Cascading impacts asserted (ecosystems, economy) with minimal quantitative context	Low integrative judgment; dominant-cause reasoning with limited system differentiation

Note: No student selected 100% responsibility, reflecting awareness of multiple interacting drivers beyond Hoover Dam.

Building on the patterns shown in Table 4, Many students converged on a 25% attribution, framing it as a proportionate representation of responsibility within a complex system. For example, one student stated that

"a 25% attribution captures its proportional responsibility within a complex system," while another justified this choice by noting that hydropower *"is not the sole user of the lake."*

In contrast, other students assigned either minimal or dominant responsibility to hydropower, reflecting narrower causal reasoning. One student argued that

"the Hoover Dam is not responsible for how it's supplied water has been wasted and thus is 0% responsible for the water loss,"

while another asserted that *"75% of the water scarcity for the Colorado River can be attributed to hydroelectric power."*

These contrasting attributions illustrate differences in how students connected numerical estimates to system boundaries and causal mechanisms.

Evidence of interconnected causality further distinguished higher levels of engineering judgment. Many students explicitly link infrastructure operation, governance, climate change, and consumption patterns when forming their judgments. For example, one student wrote that

"the Colorado River Compact and the Central Arizona Project prioritize water deliveries for agriculture and cities, while climate change and prolonged drought intensify evaporation and reduce inflows."

Others emphasized that Hoover Dam operates within a broader causal network, noting that

"while the Hoover Dam's impact is smaller than these factors, it is a measurable part of the river's water-loss equation."

While most students demonstrated the ability to justify their decisions using evidence, assumptions, and contextual reasoning, a subset relied on isolated factors or unsupported numerical claims, suggesting surface-level quantitative engagement rather than fully integrated engineering judgment. Overall, these findings indicate that the activity supported students in moving beyond direct application of calculations toward interpretation, justification, and decision-making within a complex socio-technical system.

D. Role of the Debate

The results suggest that the in-class debate primarily served to reinforce and refine students' existing positions rather than substantially shifting the positions. All 32 students participated in the in-class debate and completed the post-debate survey. As shown in Table 1, the distribution of student responses following the debate closely resembled the distribution observed after completion of the homework assignment. The 25% responsibility category remained dominant, with only minor redistribution among the remaining categories. Compared to the shift observed between the introductory presentation and the homework assignment, the magnitude of change from the homework assignment to the post-debate survey was relatively small.

Although the debate did not result in large shifts in attributed responsibility, student responses indicate that it contributed to clarification and strengthening of existing viewpoints. Several students reported that the debate reinforced the positions they had developed during the homework assignment by exposing them to alternative arguments and perspectives that they had not previously considered. This suggests that the debate functioned as a reflective mechanism rather than a primary driver of opinion change.

To examine whether informal collaboration influenced student responses, the post-debate survey included a question regarding discussion with peers prior to selecting a final position. Most students (26 of 32) reported that their final selection did not involve collaboration, while six students indicated that some level of collaboration influenced their choice. Despite this, most students did not change their selected responsibility category following the debate, further supporting the observation that student positions had largely stabilized after the individual analysis conducted in the homework assignment. These findings indicate that while the in-class debate played a role in exposing students to alternative viewpoints and reinforcing reasoning, the most substantial development of student positions occurred prior to the debate through independent quantitative and systems-level analysis.

Building on these observations, the qualitative reflections illustrate how students integrated reasoning during the debate. During the in-class debate, students reported that exposure to alternative arguments and perspectives reinforced or clarified their positions. Students were able to combine quantitative results, assumptions, and evidence with broader socio-technical factors in their justifications. For example, many justified a 25% responsibility attribution by situating Hoover Dam within the larger Colorado River system, recognizing that hydroelectric power is only one of several interacting drivers of water scarcity. Other reflections highlighted the role of policy, climate, and infrastructure in shaping system outcomes. While the depth and coherence of justification varied, these patterns indicate that the debate functioned primarily as a reflective mechanism, supporting reasoning that had already been developed during the homework.

E. Other Notes

Nearly all students indicated the use of A.I. tools in the homework assignment. Surprisingly, most students used it for the EWIF calculations instead of identifying all STEEP factors. Some students focused their use on a subset of STEEP factors (e.g., only political factors). No students admitted to using A.I. to write their report justifying their choice of percentage group.

The vast majority of students (31/32) indicated significant learning about sustainability issues in engineering from participating in the activity. Student feedback suggestions for changes for next year include:

- Enabling everyone to participate in the debate. This could be done using separate debates in small groups, by allowing audience members to ask questions, or by simply using small group discussions instead of debates.
- Assign debate groups prior to the HW assignment, so the students can be better prepared.
- Reduce the number of percentage groups.
- Introduce key equations in the HW assignment to minimize reliance on A.I.
- Provide specific data for EWIF calculations instead of relying on other sources
- Change some of the reporting requirements in justifying the chosen percentage group (e.g., provide three key reasons).
- Provide more quantitative data regarding the drying up of the river (e.g., annual flow rate)
- Break up the HW assignment into portions with different deadlines

The rationale by the students for primarily choosing the 25% group include:

- The evaporative losses from Lake Mead are minor compared to the water from the Colorado River that is consumed by agriculture.
- Climate change and a growing consumer base may be major contributors to the decline of water availability.
- Two students cited a study mentioning that 11% of water loss from the Colorado River was due to evaporation [12].
- Many students did not want to assign a 0% value, since such a value implies zero responsibility.

This three-part activity was introduced in a junior level Fluid Mechanics class, which has the opportunity cost of moving some material from a live lecture to a recorded online supplement. The choice of Fluid Mechanics for integration is merely for convenience of the instructor and can be instead implemented into several other engineering classes. However, the use of a sustainability-related activity provides a much-appreciated break for students from in-depth physics-related technical content.

The activity also aligns with the following ABET outcomes for Mechanical Engineering programs:

- *Outcome 2: an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors* and *Outcome 4: an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts*: The use of STEEP analysis enables engineering decisions based on a variety of factors.
- *Outcome 3: an ability to communicate effectively with a range of audiences*: The use of a classroom debate provides a unique opportunity to communicate a point of view orally since engineering courses rarely employ debating as a form of communication.
- *Outcome 6: an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions*: The activity involves using engineering judgement from both the EWIF and STEEP analyses to perform engineering judgement.
- *Outcome 7: an ability to acquire and apply new knowledge as needed, using appropriate learning strategies*: The homework assignment involves using A.I. tools to acquire information to enable students to perform engineering judgement.

IV. Limitations

While this study demonstrates positive impacts on students' understanding of system interconnectedness and engineering judgment, there are several limitations. First, the qualitative analysis was conducted on a subset of 15 students, and although responses across all responsibility percentages (0%-100%) were included, the results cannot be statistically applied to other cohorts.

Second, the study was conducted over a single semester in a single junior-level course, limiting the ability to examine long-term learning outcomes. Furthermore, the activity was implemented at one institution, and results may differ in other university contexts or with students at different academic levels. Notwithstanding these drawbacks, the study offers insightful information regarding how students explain system interconnectedness in an engineering simulation with a sustainability focus.

V. Conclusions and Future Work

This study involved three parts of a sustainability activity integrated into an existing junior-level fluid mechanics course. The assessment of the primary goals can be concluded as follows:

- The majority (22/31) of students showed critical thinking skills through explaining the discrepancy on their calculated EWIF and the accepted value from literature. A majority (28/31) also showed an appropriate justification for their choice of percentage group.
- The majority (20/31) of students demonstrated a systems thinking ability to perform a STEEP analysis on the various factors impacting the drying up of the Colorado River. The majority (26/31) also showed systems thinking in identifying external factors in justifying their chosen percentage group in the HW assignment.
- Analysis of post-debate reflections shows that students' responsibility attributions for Colorado River water scarcity ranged from 0% to 75%, reflecting different ideas about evaporation, hydropower, and other system factors. Engagement with EWIF calculations and STEEP analyses helped students' reasoning evolve, with many starting to see connections across the system, recognize how different parts affect each other, and use both technical data and contextual information to support their decisions. While the quality of reasoning varied, the activity helped students move beyond simple, single-factor explanations and encouraged them to consider assumptions and external system influences. Overall, the three-part activity helped students justify engineering decisions more clearly and develop system-level thinking, showing how their reasoning evolved from focusing only on calculations to considering the whole system.
- Nearly all (31/32) of the students indicated significant learning about sustainability issues through the use of the three-part activity, culminating in the debate.

An assessment of the secondary goals showed the following:

- The vast majority of students chose the 25% percentage group for assigning responsibility of the drying up of the Colorado River to hydroelectric power.
- The range of calculated EWIF values encompassed the value from literature but were generally higher than the value from literature. Possible reasons for this discrepancy are not considering a zero baseline evaporation rate, statistical uncertainties in heat transfer coefficient, and the oversimplification of the transient behavior of lake surface area and local weather conditions.

This study therefore successfully brought about the ability for students to garner understanding of sustainability issues related to a specific topic. Future implementations of this activity include possible modifications such as (1) the inclusion of all students in the debate activity, (2) a sliding scale for assigning percentages instead of discrete groups, and (3) providing the students with more guidance on the STEEP analysis, specifically examination of STEEP causes of the drying up of the river rather than effects. Furthermore, the sequence of activity components can be adjusted to examine how the chronological order of activity components influences learning and engagement.

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VI. Supplementary Materials

Course materials for the activity are available at 10.5281/zenodo.19609511.

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