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Thirsty Earth: A Game-Based Approach to Interdisciplinary Water Resources Education

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Abstract. The sustainable management of water resources requires cooperative institutions, whose development is rarely included in often overloaded engineering education curricula. To address this gap, we developed *Thirsty Earth*, an open-access online multi-player game designed to introduce key concepts in water governance through experiential learning. The game can be integrated into standard water management and hydrology classes as part of interactive teaching modules. In *Thirsty Earth*, students assume the roles of farmers in rural communities, making annual decisions about crop selection and irrigation methods to maximize agricultural profits under uncertain climate conditions. Through gameplay, they encounter critical trade-offs associated with environmental uncertainty, cooperation over shared infrastructure, and the depletion of common-pool water resources, which are central to contemporary water management. Students can address these issues by purchasing and sharing reliable information on resource use and crafting institutional rules to regulate behavior. The game's dual versions, which include a simplified spreadsheet-based implementation and an advanced web-based interface, offer flexibility to promote active learning in diverse educational contexts.

1 Introduction

Interdisciplinary problem-solving is a critical skill for addressing today's complex social and environmental challenges, particularly in the context of water resources (see, e.g., Muller et al., 2024). Despite its importance, it remains inadequately incorporated into college STEM (science, technology, engineering, and mathematics) curricula. The importance of interdisciplinary education is gaining recognition in official educational standards. For instance, the Accreditation Board for Engineering and Technology (ABET) requires engineering programs in the United States to ensure that students can "function on multidisciplinary teams" and "understand the impact of engineering solutions in a global, economic, environmental, and societal context" (ABET (2017), pp. 4-5). In response, colleges and universities are increasingly introducing dedicated interdisciplinary programs, but the integration of these programs into existing engineering curricula has encountered significant organizational and cultural challenges (see Bacon et al., 2011; Richter and Paretti, 2009; Gantogtokh and Quinlan, 2017). Given the time constraints of already demanding engineering schedules, alternative approaches are needed to allow for students to gain lit-

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eracy (though not necessarily specialized expertize) in congruent disciplines in a way that seamlessly integrates into current engineering curricula.

Experiential learning through educational games offers a promising approach to address interdisciplinary challenges. This paradigm emphasizes hands-on, interactive experiences that engage higher-order cognitive skills such as analyzing, evaluating, and creating (Adams, 2015). Increasingly integrated into college education, these games facilitate a deeper understanding of knowledge across disciplines while enhancing students' motivation and capacity for learning (Gouveia et al., 2011). Water resources management, as a relatable, yet complex, engineering challenge with immediate real-world connections and strong interdisciplinary interactions, is particularly well-suited to this approach. Numerous educational games focused on water resources have been developed over the past few decades (see review in Aubert et al., 2018). Computer-based games, in particular, stand out for their ability to engage users' attention and evoke emotional responses, both of which enhance learning outcomes (Argasiński and Węgrzyn, 2019). Their scalability and suitability for remote teaching also make them an increasingly valuable tool in modern education, as highlighted during the COVID-19 pandemic.

Educational computer games on water resources broadly fall into two categories. The first category focuses on decision-making under technical constraints. Examples include optimization challenges such as water use decisions under uncertainty (Asplund et al., 2019), resource conservation (Kocher et al., 2019), climate change adaptation (Warren, 2016), and water resources allocation (Australian Broadcasting Corporation, 2008; Craven et al., 2017). These games effectively highlight technical trade-offs and resource optimization challenges and have been successfully used to stimulate negotiation among real stakeholders by presenting simulated scenarios. However, these are inherently single-player games that process the decisions of a single entity. While these decisions might emerge from a negotiation process among multiple players collaborating as a team (Craven et al., 2017), the interactions and stakeholder dynamics they represent are not internalized within the game itself, which does not explicitly simulate the complex dynamics and incentives that arise from real-world stakeholder interactions. As a result, these games are not optimal for providing interdisciplinary literacy to students, as they do not allow players to embody specific roles and experience the complex dynamics and incentives of stakeholder negotiations.

In contrast, role-playing computer games emphasize negotiation and conflict resolution, providing a nuanced portrayal of stakeholder dynamics in water resource management. These games simulate diverse contexts, including managing a reservoir command area (Rusca et al., 2012), an irrigation district (Hirsch, 2010), a floodplain (Den Haan et al., 2020), or a transboundary river basin (Douven et al., 2014), as well as scenarios like virtual water trade (Hoekstra, 2012) and mitigating water-related hazards (Teague et al., 2021). By immersing players in these realistic scenarios, these games can foster interdisciplinary literacy by allowing students to experience some of the key dynamics of water governance. However, the emphasis on capturing the complexity of real-world stakeholder interactions can come at the expense of didactic focus in terms of a structured approach to break down specific, tractable issues that would help students systematically identify problems and develop potential solutions. Balancing realism to reflect the intricacies of real-world challenges with accessibility to ensure pedagogical effectiveness has long been a core challenge educational games in water resources (see e.g., Hoekstra, 2012).

In this context, the farmer irrigation problem stands out as a relevant water management challenge where the trade-off between realism and pedagogy can be effectively addressed. In recent games focusing on the problem (e.g., Seibert and Vis,

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2012; Ewen and Seibert, 2016; Hoekstra, 2012; Fund, 2019), players usually take on the role of farmers who periodically decide how much cropland to irrigate to maximize profits. This scenario captures specific challenges in water management (such as navigating environmental uncertainty, managing resource depletion, and addressing the risks of free-riding on common-pool resources) that are governed by environmental processes commonly taught in hydrology and water management courses (precipitation, evapotranspiration, groundwater flows). At the same time, they integrate key stakeholder dynamics and misaligned incentives that exemplify the broader challenge of governing common-pool resources. Solutions require coordination beyond individual decisions, relying on rules, enforcement, and governance systems that bridge technical expertise in hydrology with insights from the social sciences. Educational games built around this scenario offer a platform for students to engage directly with these dynamics, fostering interdisciplinary literacy without requiring extensive theoretical knowledge of social sciences.

Three recent games have adopted this logic: the *River Basin Game*, developed by Arjen Hoekstra at the University of Twente (Hoekstra, 2012); *Irrigania*, developed by Jan Seibert et al. at the University of Zürich (Seibert and Vis, 2012; Ewen and Seibert, 2016); and the *Groundwater Game*, developed by UN-IGRAC (Fund, 2019) (see Table 1). All three games include a computer interface that collects players' water use decisions and simulates their consequences on shared water resources using realistic representations of key hydrological processes. They effectively allow players to experience the incentives and consequences of a tragedy of the commons associated with irrigation water use, where private profits and communal costs drive overuse and resource depletion (see Section 2). However, they stop short of providing systematic tools for students to design solutions to address these challenges.

Here, we present *Thirsty Earth*, a web-based irrigation water use game designed to support interdisciplinary water resources education. The game distinguishes itself from its predecessors in two important ways. First, it emphasizes accessibility and playability. The full version (v1) of the game leverages a specialized multi-player game engine (boardgame.io) to deliver attractive 2D graphics and improved game flow, while the light version (v0) of the game is implemented entirely in Google Sheets and Forms, ensuring ease of adoption with minimal learning requirements for instructors. Second, *Thirsty Earth* goes beyond illustrating the *tragedy of the commons* by enabling students to design institutional arrangements to address this issue. Inspired by Ostrom's eight principles for sustainable common-pool resource governance (see Section 2 and Table 2), the game challenges students to not only set consumption caps and penalties (as in the *Groundwater Game* (Fund, 2019)), but also to create mechanisms for enforcing those rules. Specifically, students can purchase bits of reliable information (e.g., on the state of the resource or on players' decisions) to design and implement enforcement mechanisms using a standardized institutional 'grammar' (Table 3). This approach introduces STEM students to the interdisciplinary aspects of institutional design, bridging technical problem-solving with insights from the social sciences to address critical governance challenges effectively.

The rest of the article is organized as follows. Section 2 provides background on tragedies of the commons as they arise in the farmer irrigation problem, and institutional design principles to address them. Sections 3 and 4 describe the two current versions of *Thirsty Earth*, in terms of their game principles (Section 3), and gameplay and software implementation (Section 4). Section 5 discusses the possible integration of both versions of the game into teaching curricula, and Section 6 concludes with informal feedback from seven years of teaching implementations.

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	Groundwater Game Fund (2019)	River Basin Game Hoekstra (2012)	Irrigania Seibert and Vis (2012)	Thirsty Earth v0 This paper	Thirsty Earth v1 This paper
Play Options					
Fallow (Fixed Wages)					x
Rainfed (Env. Uncertainty)			x		x
Surface Irrig. (Common Pool)			x		x
Grndwater Irrig. (CP & Depletion)	x	x	x	x	x
Consumption caps and penalty	x				x
Monitoring and enforcement					x
Platform	LAN and Win executable	MS Excel	Server (html)	Google Sheets	Server (boardgame io)
Input/Output	Textboxes on Mobile App	Paper sheets	Textboxes on browser	Google Forms	2D graphics

Table 1. Educational games focusing on the farmer Irrigation problem

2 The farmer irrigation problem as a case of common-pool governance

2.1 Common-pool resources (CPR)

Consider the stylized case of two farmers who have recently acquired neighboring parcels of land that share a common aquifer. Both need irrigation for their crops and must decide whether to invest in high-capacity (H) or low-capacity (L) irrigation equipment. This decision involves substantial sunk costs that lock them into their chosen capacity for a long time. Importantly, the two farmers do not know each other and cannot coordinate their decisions, leaving each to act independently based on their own expectations and incentives. If both farmers choose H, they each earn \$2 per unit of profit from their irrigated crops. However, pumping from the shared aquifer increases groundwater depth, leading to higher energy costs, which grow quadratically with the volume of water extracted (Mullen et al., 2022; Müller et al., 2017). In contrast, if both farmers choose L, they extract less water, avoiding significant increases in pumping costs, and each earns \$3 in profit due to a better balance between costs and crop production benefits. If one farmer selects H while the other opts for L, the H farmer can produce more crops with lower average pumping costs due to reduced aquifer depletion from the L farmer's restraint, resulting in a profit of \$4. Conversely, the L farmer suffers reduced crop yields without the full associated cost savings, earning only \$1.

The payoff matrix for this scenario is represented in Figure 1. Clearly, the optimal outcome (henceforth referred to as *First Best*) is for both farmers to select L. This option maximizes total welfare, generating the highest combined profit for both farmers. It also happens to maximize individual profit, as each farmer would prefer earning \$3 over any other possible outcome. However, when deciding which option to choose, a rational farmer will evaluate their best course of action *in response to the other farmer's choice*. In the payoff matrix shown in Figure 1, if Farmer B chooses H, the best response for Farmer A is to also choose H (\$2 vs. \$1). If Farmer B instead chooses L, the best response for Farmer A remains to choose H (\$4 vs. \$3). The same reasoning applies to Farmer B in response to Farmer A's choices, making H the dominant strategy for both farmers, regardless of the other's decision. This leads to a situation known in game theory as a *Nash Equilibrium*, where both farmers rationally

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select H as a best response to either of the other farmer's possible choices. In this example, this best response equilibrium causes the farmers to choose H despite their mutual best interest being for both to select L. It causes profit losses for both farmers and prematurely depletes the resource in a situation that is akin to the *tragedy of the commons* famously described by Hardin (1968) in the context of overgrazed pastures.

This stylized example is extremely simplified. It neglects important factors such as environmental variability (Roche et al., 2020), groundwater flows (Müller et al., 2017; Brozović et al., 2010), differences in payoffs between farmers (Mullen et al., 2022), and the actual depletion of the shared resource (Provencher and Burt, 1993; Rubio and Casino, 2003), all of which have been shown to amplify misaligned incentives in the farmer irrigation problem. The example also mistakenly equates welfare maximization to the raw maximization of irrigation profits, which disregards important environmental, ecosystem, and social impacts that arise as opportunity costs to using the water for irrigation. It also assumes a single-shot game with no communication or coordination between the players, which is unrealistic (Sahu and McLaughlin, 2021; Ristić and Madani, 2019). Despite these simplifications, the example effectively illustrates the fundamental commitment problem that arises when players generate private profits while externalizing part of the cost of their actions onto others (here in the form of increased pumping costs due to falling groundwater levels). In this situation, nobody can credibly commit to restricting their pumping to levels that all know to be both collectively and individually optimal. Even if both farmers genuinely wish to act responsibly, neither can trust with certainty that the other will to do the same, leading to a situation where individual optimization does not aggregate into a collectively optimal outcome (hence the 'tragedy'). These characteristics are emblematic of many contemporary water resource challenges beyond irrigation, including those related to climate change adaptation (Roche et al., 2020) and mitigation (Madani, 2013; Paavola, 2011), multipurpose reservoir management (Madani and Lund, 2012), transboundary aquifers (Penny et al., 2022b; Mullen et al., 2022; Müller et al., 2017) and rivers (Ansink and Ruijs, 2008), or household-level sanitation (Penny et al., 2022a).

2.2 Features of long-enduring CPR institutions

The type of market failure illustrated in the stylized example has been alternatively described as a *prisoner's dilemma* (Ostrom, 1990), a *tragedy of the commons* (Hardin, 1968), or a *collective action free-rider problem* (Olson Jr, 1971), and it arises across a wide range of goods beyond water resources. These goods, referred to as common-pool resources, are defined by two key characteristics: they are rivalrous, meaning that one user's consumption reduces the availability for others, and they are non-excludable, meaning that it is difficult or impossible to prevent access to users who do not adhere to established rules. Such goods defy governance by traditional institutions: centralized authorities often lack the localized information necessary to allocate resources effectively (e.g., pumping costs determined by local hydrogeologic conditions in groundwater management), while markets struggle to establish and enforce property rights. Yet, in her seminal book Governing the Commons (Ostrom, 1990), Nobel Laureate Elinor Ostrom famously argued that alternative approaches to governance must have been historically effective in managing common-pool resources, otherwise these resources would have been depleted long ago. Ostrom studied traditional institutions that had evolved over centuries to manage such resources sustainably, reasoning that only effective institutions could persist, as those that failed would collapse along with the resources they governed. Her analysis spanned

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diverse contexts, from Swiss alpine pastures and Japanese forestry to Spanish and Philippine irrigation systems. Through this work, she identified eight principles shared by successful institutions (Table 2). These principles are hallmarks of systems capable of sustainably managing common-pool resources. To address the diversity of institutional arrangements and their contexts, Crawford and Ostrom (1995) also developed a coherent framework, often referred to as institutional grammar, to codify and analyze the structures underlying these governance systems (Table 3).

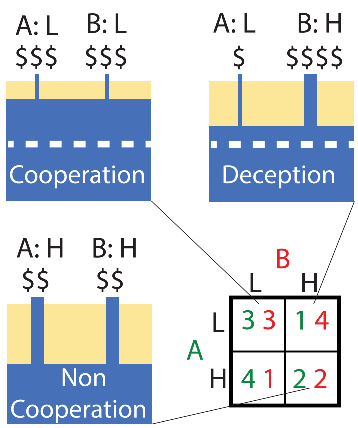

Figure 1. Stylized example of Prisoners' Dilemma game applied to the farmer irrigation problem. The matrix at the bottom right indicates payoffs for farmers A and B under various combinations of choices of high (H) and low (L) capacity irrigation equipment, which are represented in the schematic graphs. 'Cooperation' outcome is the First Best outcome that maximizes both individual (3) and collective (6) payoffs. 'Non cooperation' is the Nash Equilibrium outcome that arises from a best response strategy by both farmers.

3 Thirsty Earth: Game principles

Thirsty Earth is a multi-player web-based game designed to introduce university students in STEM fields to common-pool governance challenges that lie at the heart of many water resources management issues. Through gameplay, students experience the misaligned incentives that arise from the consumption of irrigation water as a common-pool resource and its ensuing premature depletion. They are also equipped with tools to address these issues through institutional design using Ostrom's design principles and ADICO grammar (Section 2) as a framework. In that process, students must navigate the complexities of collaboratively creating these institutions within a consensual, deliberative process. In the game, students take on the role of farmers who make annual irrigation decisions with the goal of maximizing agricultural profits over a set number of rounds. The game simulates the externalized costs that are characteristic of common-pool resources in a multi-player environment; water use decisions by individual farmers increase the current and future costs for everyone. To replicate the coordination challenges that often arise in the real world, the game is structured so that the costs in any given period depend on the total water consumption of *all* farmers during that period. Crucially, this information is not known until all players have made

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Design principles of long-enduring Common-pool resources (CPR) institutions	
1	**Clearly Defined Boundaries**: Individuals or households who have rights to withdraw resource units from the CPR must be dearly defined, as must the boundaries of the CPR itself.
2	**Congruence Between Appropriation and Provision Rules**: Appropriation rules restricting time, place, technology, and/or quantity of resource units are related to local conditions and to provision rules requiring labor, material, and/or money.
3	**Collective Choice Arrangements**: Most individuals affected by the operational rules can participate in modifying the operational rules.
4	**Monitoring**: Monitors, who actively audit CPR conditions and user behavior, are accountable to the users and/or are users themselves.
5	**Graduated Sanctions**: Appropriators who violate the rules will likely receive graduated sanctions (depending on the severity and context of the offense) by other users, officials accountable to users, or both.
6	**Conflict-Resolution Mechanisms**: Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials.
7	**Minimal Recognition of Rights to Organize**: The rights of appropriators to self-organize and make their own rules are not challenged by external authorities.
8	**Nested Enterprises**: For CPR's that are parts of larger systems, the appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.

Table 2. Ostrom's Design Principles, from Ostrom (1990)

ADICO format for institutional statement	
A	**ATTRIBUTES**: To whom the institutional statement applies? (e.g., 18 years of age, female, college-educated, 1-year experience, or a specific position, such as employee or supervisor).
D	**DEONTIC**: What does the institutional statement entail? (permission – 'may', obligation – 'must' (obliged), prohibition – 'must not', etc.)
I	**AIM**: What is the institutional statement focusing on? (e.g., 'use of water for irrigation from the shared aquifer').
C	**CONDITIONS**: When, where, how, and to what extent the AIM is permitted, obligatory, or forbidden? (e.g., 'Annual use of water for irrigation shall not exceed 10 million cubic meters per farmer').
O	**OR ELSE**: What are the sanctions to be imposed for not following a rule?

Table 3. Institutional grammar, adapted from Crawford and Ostrom (1995)

their decisions, meaning that individual players have to decide how much water to use without knowing the exact costs that their choices will incur. This information barrier makes it challenging for players to commit to any predetermined level of

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consumption and makes the need for an effective enforcement mechanism (i.e. institutions) clear to the players. These key features are shared by the two versions of the game, although the types and complexity of the decisions vary.

3.1 Light Version (v0)

The light version (v0) of the game has a setting that is comparable to the *River Basin Game* (Hoekstra, 2012). Students decide how much water to withdraw each year from a shared aquifer, which is recharged annually and experiences losses to natural discharge. Each unit of water withdrawn generates a fixed revenue for the player, but costs increase incrementally with the total volume withdrawn by all players that year (the first unit costs C_0, the second unit $C_0 + 1$, and so on, see Supplementary S1). This structure is designed to simulate the increasing pumping costs associated with declining groundwater levels, where the cost of the first unit of water each year depends on the state of groundwater storage. Groundwater levels, in turn, are determined by historical withdrawals, recharge, and discharge fluxes. Recharge is constant and set to be proportional to the number of players in the game, while discharge is proportional to the amount of water stored in the aquifer during a given year (i.e. the aquifer behaves like a linear reservoir). Through this setup, students experience the overuse incentives characteristic of common-pool resources, which arise due to communal costs and coordination challenges. The game also demonstrates how these effects are exacerbated by the 'memory effect' of depletable resources, where excessive consumption can impact communal costs far into the future. The four solution concepts addressing these effects (*Nash Equilibrium* and *First Best*, under myopic and steady state conditions) are derived for the game's default parameters and presented in Supplementary S1.

3.2 Full Version (v1)

The full version (v1) of the game is similar to *Irrigania* (Seibert and Vis, 2012) in that each student manages nine fields and must decide whether and how to irrigate. The three irrigation options are designed to illustrate fundamental challenges in agricultural water management:

- **Rainfed (no irrigation)** fields incur no costs and can yield high profits in good years, but are subject to climate uncertainty. This uncertainty is simulated in the game through randomly drawn 'good' or 'bad' years. The game can simulate climate change by allowing the probability and expected returns in good and bad years to change over the course of the game.
- **Surface water irrigation** mitigates environmental uncertainty by ensuring a predetermined unit revenue for each irrigated field. However, its cost increases proportionally with the total number of fields (across all players within a village) relying on surface water irrigation in a given year. This cost structure simulates the maintenance costs of shared surface irrigation infrastructure (e.g., canals, reservoirs, see Yu et al., 2015) and differs from *Irrigania*, where the revenue (not the costs) of surface water irrigation are affected by the number of participants. A distinguishing feature of surface irrigation is the absence of a 'memory effect', meaning that costs in any given period are independent of historical use.
- **Groundwater irrigation**, in contrast, has a memory effect, with costs influenced by the cumulative use of the shared resource by all players within the same village across all previous periods. Like in the Light version (v0) of *Thirsty*

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Earth, groundwater levels are subject to natural recharge and discharge, meaning that the effects of overuse in earlier periods diminish over time. The recharge rate, which determines the time scale of this memory effect, can be adjusted as a game parameter.

The profit functions and solution concepts (*Nash Equilibrium* and *First Best*) associated with each irrigation option are given in Supplementary S2, along with a default parametrization selected to optimize the learning experience by enhancing the distinctive features of each option.

Unlike *Irrigania*, students can also decide whether and what to plant on each field. Instead of the default crop, players may choose to leave a field fallow to secure a fixed wage (representing outside work). This wage is stable, unaffected by environmental uncertainty or the decisions of other players, but is lower in expectation than any crop option. In contrast, players may choose to plant a higher-value crop, which doubles both the revenue and costs for that field. That option effectively increases a player's potential productivity, allowing them to simulate up to 18 fields if all nine are dedicated to high-value crops. This dynamic setup allows students to explore trade-offs between risk, cooperation, and resource sustainability through agricultural decision-making within the framework of shared resource constraints. The game also provides flexibility for instructors to progressively activate choice options, enabling students to focus on individual trade-offs. For example, deactivating all irrigation options allows students to manage risk and environmental uncertainty (choosing between rainfed crops and a fixed outside wage) without the influence of common-pool overuse incentives or resource depletion. This flexibility makes the game an effective tool for integration into a broader curriculum on water resources management (see Section 5).

3.3 Private vs Public Information

The distinction between private and public information is a unique feature of both versions of the game that sets them apart from their predecessors. This aspect is central to the game's ability to simulate institutional design. In the default mode of both versions, students have access to limited information to guide their decisions. Specifically, they are provided with the initial costs of both irrigation options, the historical sequence of 'good' and 'bad' years in prior periods, and the average profit across all players from the previous period as a benchmark for evaluating their performance relative to the group. However, information about the specific actions of other players remains private. This information asymmetry introduces coordination and commitment challenges that are at the core of the *tragedy of the commons* (see Section 2). The game allows students to address these challenges by designing institutions around certain types of information that they might collectively decide to make public.

- In the Light version (v0), the water use decision of one randomly selected player can be revealed to the group after each period.
- In the Full version (v1), players can collectively decide before the game to purchase one or more of the 22 available "information bits" listed in Table 3. These bits, which are accessible to all players in all periods of the game, provide details about player decisions, outcomes, or resource dynamics.

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This framework enables students to experiment with how shared information can be used to create and enforce regulations on water usage. The process is further enriched through an institutional design workshop, where players collaboratively design rules based on the selected information to address coordination and enforcement challenges effectively (Section 5).

Table 4. List of information bits available for players to purchase when designing institutions.

Purchasable information bits	
1	Average number of fields irrigated with groundwater per player this year in our village
2	Average number of fields irrigated with surface water per player this year in our village
3	Average number of rainfed fields per player this year in our village
4	Average number of fields left fallow per player this year in our village
5	Average number of fields with high value crops per player this year in our village
6	Probability of next year being a good year given this year's rain type
7	Average unit groundwater cost in the village this year
8	Average unit surface water cost in the village this year
9	Average profits in the village this year
10	ID of player with the highest net profit this year
11	Maximum net profit this year
12	ID of player using the most groundwater this year
13	Maximum groundwater used by a single player this year
14	ID of player using the most surface water this year
15	Maximum surface water used by a single player this year
16	Randomly show a player's number and groundwater usage this year
17	Randomly show a player's number and surface water usage this year
18	Randomly show a player's number and rain water usage this year
19	Randomly show a player's number and their number of fields left fallow this year
20	ID of player with the maximum number of high value crops this year
21	Maximum number of fields with high value crops for a single player this year
22	Average groundwater recharge amount

4 Thirsty Earth: Gameplay and software implementation

4.1 Light Version (v0)

The light version of *Thirsty Earth* (v0) is entirely programmed within the Google Sheets environment to maximize portability, accessibility (for both instructors and students), and adaptability, making it ideal for use within the context of a short module on water governance and management in a hydrology or environmental science class. The game supports up to 50 players,

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divided into up to 5 distinct 'villages', each sharing an aquifer. Unlike the *River Basin Game* Hoekstra (2012), these villages are not hydrologically linked to each other. The game environment consists of three components (Figure 2):

- **Main Sheet:** This Google Sheet is intended for the instructor to use to pilot the game. All tabs and cells are locked except for three colored cells in the `MAIN` tab (`T2`, `T3`, and `T4`), which allow the instructor to initialize the game, move to the next game period, and make the water use decision of a randomly selected player public if required by the student-designed institutions. The spreadsheet also contains a series of tabs that include license information, the model (based on Hoekstra, 2012) linking players' choices to profits and groundwater stocks, and tabs for managing interfaces with other components.All these tabs are read-only, but their content is available for download.
- **Display Sheet:** This Google Sheet is read-only and accessible to players through a QR code or link provided on the `MAIN` tab of the main sheet. It contains all public information about the game, as well as dynamic links to the Google Forms that students use to interact with the game. Public information and relevant forms are progressively made available as the instructor advances the game by moving to the next period on the Main Sheet. The display sheet also includes a roster tab with student village and player ID assigments, which students should use to submit their water use decisions, and a profit calculator tab that students can use to compute their profits for each period.
- **Google Forms:** These forms are accessible to students via the dynamic links on the display sheet. The first form allows students to sign into the game and assigns them to a "village" and player number, which they use to submit their water use decisions in subsequent forms.

The instructor initializes the game by setting cell `T2` to 1 on the `MAIN` tab of the main sheet. If applicable, the instructor may also activate the `Sample Player Info` feature (cell `T5`) to display the water use decisions of randomly selected players from each village during each period, which students can use to design institutions that regulate water use. Students access the display sheet to register for the game via the provided Google Form link. Once registered, students appear in the `Roster` tab of the display sheet and are assigned a village letter and player number. The game proceeds through eight rounds of student submissions. Each round begins with students submitting their water consumption decisions through the Google Form linked on the display sheet. The instructor monitors submissions on the `MAIN` tab, but this information remains private. Once all decisions are submitted, the instructor advances the game by incrementing the 'previous period' cell (`T3`) by 1. This action updates the display sheet with the average water cost for the completed period, which students use to calculate their profits. It also shows the average profit for each village, the water consumption decision of a randomly selected player from each village (if enabled), and the cost of the first unit of water for the next period, helping students strategize their next decisions. Students then submit their decisions through the new Google Form link that appears on the display sheet, and the instructor increments the 'previous period' cell (`T3`) on the main sheet again, repeating the process for each round. After the eighth period, the game concludes, and the display sheet summarizes the total water use and profits for each player, providing an overview of both individual and collective performance.

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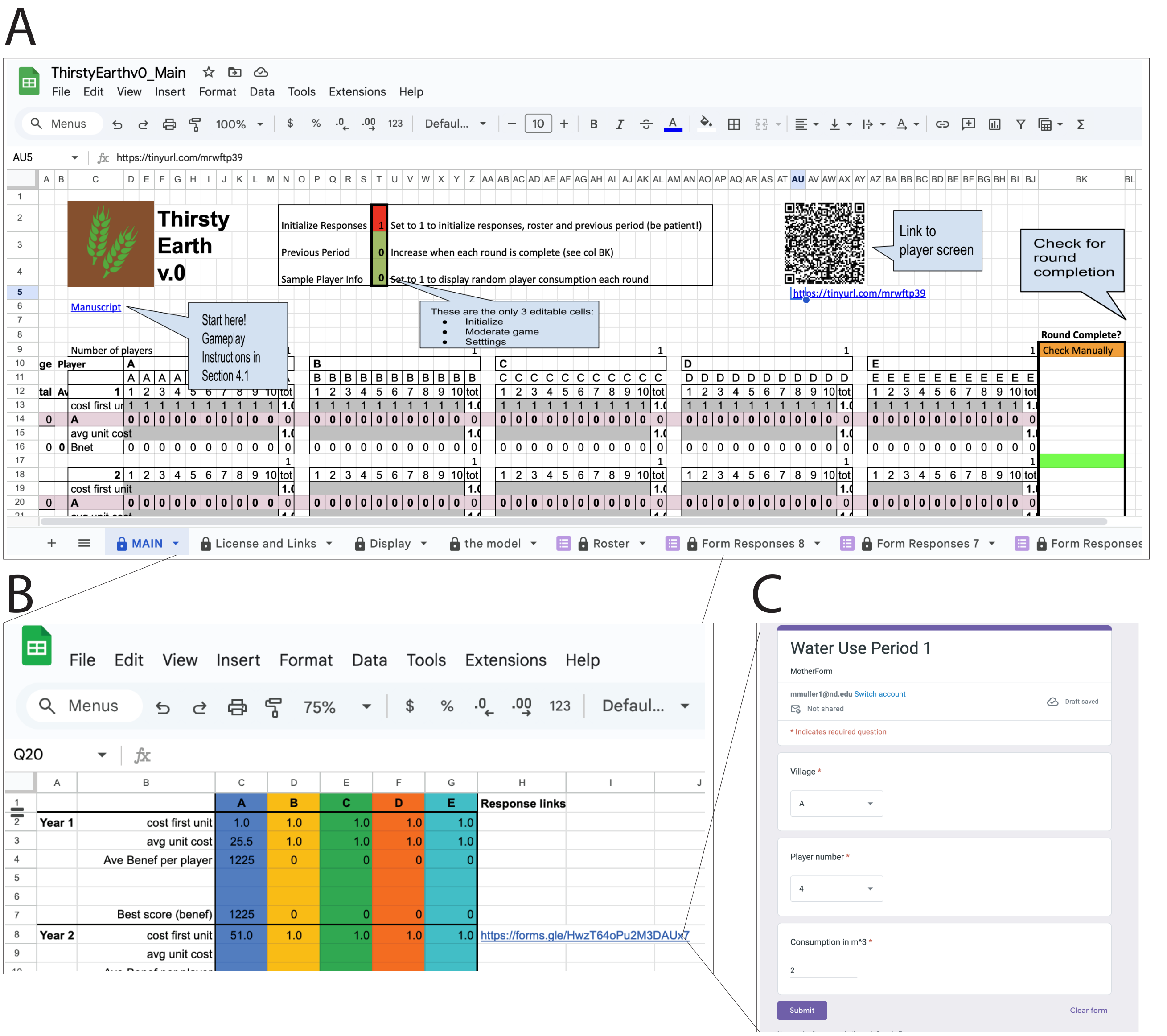

Figure 2. *Thirsty Earth*, Light (v0). (**A**) Main sheet that the instructor can use to initialize the game (cell T2), move to the next game period (cell T3) and display information for institution design (cell T4). (**B**) Display sheet to be visualized by the students with relevant game information and links to the (**C**) forms to submit water use decisions.

4.2 Full Version (v1)

The full version (v1) of *Thirsty Earth* builds upon the principles of the light version but is implemented as a web-based graphical user interface (GUI) to provide a more advanced, flexible, and interactive gameplay experience. The game supports up to

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99 players, grouped into equal sized, independent 'villages' of at least three students who share a common aquifer and surface water irrigation infrastructure. The full version introduces additional features, such as the ability to purchase multiple information bits to address social dilemmas, dynamic decision-making at the field level (three land uses × three irrigation options), and turn-based multi-player gameplay supported by a dedicated server and gaming environment. These features make the full version ideally suited to repeated gameplays, for example, within a semester-long class on water resources management. Such a format allows the game to be used successively to introduce students to distinct challenges in water resources management (environmental uncertainty, common-pool overdraft, and resource depletion), explore their compounding effects, and brainstorm institutional approaches to mitigate them. A semester-long structure suggested in Section 5 ensures that sufficient time is available for both students and instructors to familiarize themselves with the more complex gameplay and fully leverage the game's capabilities.

In terms of architecture, the game platform is built using the `Boardgame.io` engine and `React` JavaScript, supported by a cluster of `Docker` containers, including an `R`-based model server and a `PostgreSQL` database. This architecture allows for real-time, turn-based interactions, and comprehensive tracking of game data. However, residual challenges remain related to platform stability, gameplay synchronization, and reliance on client-side data storage (see full technical description in Supplementary S3). The game environment consists of two distinct sequences of screens, for the instructor and the players respectively, which move throughout the different phases of gameplay as follows (Figure 3).

1. **Setup Phase:** Instructors create a game through the web application by setting parameters such as the number and size of villages (minimum 3 players per village), the number of game periods, the types of choices available to students, and other game-specific coefficients of the profit functions. Default parameter values are optimized to highlight the three core trade-offs students are intended to explore, as detailed in Supplementary S2. The setup interface also includes a link to teaching materials and game documentation. Once the game is created, the interface generates a unique game ID for students to log in on the game portal. The instructor assigns players to villages and, if relevant, assigns specific purchased information bits to each village. Any unfilled player slots can be filled with automatized 'BOT' players who follow the Nash Equilibrium strategy, optimizing their choices across all fields and periods under the assumption that all players adopt the same strategy and that all the land use and water options are available to all players. Once all players are assigned, the instructor starts the game.

2. **Playing Phase:** During each game period, students access the main gaming screen, which provides a graphical overview of their nine fields. They choose a combination of land use (fallow, low, or high-value crops) and irrigation option (rainfed, surface water, or groundwater) for each field using a simple mouse-click interface. Any incompatible combination of choice (e.g., fallow land use and groundwater irrigation) will generate a warning. The screen also includes information about the game parameters, profit functions, and links to supporting materials to help students make informed decisions, along with information on their own history of choices and profits. Additionally, students can communicate with their village or the entire class using a built-in chat function. The chat can also be used by the instructor to communicate with the students. Once students have finalized their choices, they submit them and move to the waiting phase.

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3. **Waiting Phase:** After submitting their choices, students are moved to a waiting screen while the instructor monitors submissions. The instructor can view which players have completed their decisions and terminate the period once all submissions are received. This phase ensures that all players in a village proceed simultaneously to the scoring phase.

4. **Scoring Phase:** When the instructor finalizes the game period, students are moved to a scoring screen that summarizes their current choices, profits for the elapsed period, historical data, and any purchased information bits. The scoring screen provides immediate feedback on the consequences of their decisions, helping students refine their strategies for subsequent periods. Meanwhile, the instructor monitors player outcomes and may rewind to the previous period if necessary.

5. **Concluding Phase:** Once all game periods are completed, students are directed to a game summary screen that compiles their overall performance, including cumulative profits and a history of their choices. The instructor can download a comprehensive game log in CSV format, containing all player choices, game parameters, and outcomes. This data can be used to establish a leaderboard, analyze class performance, or facilitate post-game discussions. Additionally, chat logs from the game are available for analysis, emphasizing the role of communication in addressing common-pool overuse incentives and institutional design. Students are informed beforehand that chat conversations are monitored, as specified in the terms and conditions they agree to upon login.

Figure 3. *Thirsty Earth*, Full (v1). Student and instructor screen components for each game phase.

5 Teaching applications

The two versions of *Thirsty Earth* were iteratively developed between 2017 and 2023 as educational materials to support two undergraduate engineering classes at the University of Notre Dame. Student feedback, gathered through forum writing assignments integrated into the curriculum, informed the game's refinement. The game has been integrated into both long and short teaching modules, depending on the class curriculum. For a long teaching module integrated within a class on water resources

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management, the full version (v1) of *Thirsty Earth* is better suited due to its versatility, advanced graphics, and enhanced gameplay, which allow exploration of various aspects of water governance. Conversely, the light version's (v0) simplicity and ease of play make it suited for shorter sessions, such as introducing basic water governance concepts in environmental science or hydrology classes. In both cases, the learning objective is for engineering students to experience the interdisciplinary nature of water resources management, bridging technical and governance aspects.

In the long-form teaching module, *Thirsty Earth* was used to support *Sustainable Development in a Changing World*, an introductory water policy course designed to introduce engineering students to the multifaceted challenges of water resources management and governance. The game served as the centerpiece of a water governance module that typically spanned 7–9 hour-long lectures, depending on whether the three governance challenges covered by the game (environmental uncertainty, common-pool overuse, and resource depletion) were introduced progressively. The module was structured as follows:

1. **Preparatory Readings and Introductory Lecture:** Students were assigned seminal readings on common-pool resource governance (e.g., chapters from Ostrom, 1990; Hardin, 1968; Olson Jr, 1971) and wrote reflections in an interactive online forum, with half the class responding to the other half's posts. This was followed by a lecture introducing the three governance challenges addressed in *Thirsty Earth* and the concepts outlined in Section 2.1.

2. **Game Introduction and Benchmarking:** Students were introduced to the game's principles and logistics. To guide initial gameplay, a simple solution concept (e.g., myopic first best in Supplementary S1 or S2) was derived in class, providing a benchmark for decisions. The assumptions and limitations of this concept were emphasized, making clear it was intended only as a reference point, not as prescriptive advice.

3. **Initial Gameplay and Reflection:** Students played the game one or multiple times (if the latter, over several lectures), depending on how gradually the governance challenges were introduced. After each session, they reflected on their experiences in an online forum, where they responded to prompts and interacted with peer posts. These reflections encouraged thoughtful engagement and enhanced participation in subsequent in-class discussions.

4. **In-Class Discussion and Formal Game Resolution:** Moderated by the instructor, this discussion is intended to highlight the coordination challenges experienced by students during the game and the difficulty of achieving optimal resource use. This was followed by a formal resolution of the game in class, using materials from Supplementary S1 and S2, with a focus on clarifying the distinctions between the different solution concepts and coordination challenges involved in achieving them.

5. **Institutional Design Lecture:** A subsequent lecture introduced students to long-enduring common-pool resources institutions and Ostrom's eight design principles (see Section 2.2).

6. **Institutional Design Workshop:** This session had students, grouped by game village, participate in an interactive workshop to create institutional rules. Students were given the possibility to collectively purchase bits of private information to be made accessible to all members of the village at each period. Students were tasked to collaboratively determine

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which information to purchase and how to enforce institutional rules to regulate water consumption to achieve optimal resources use. Tasks included using the ADICO grammar framework (Table 3) to formulate institutional statements involving the purchased information. A requirement was for these statements to explicitly incorporate one or more of Ostrom's principles (Table 2). Students were also tasked with agreeing on mechanisms for implementation, such as defining enforcement roles and processes for administering sanctions (e.g., naming judges and policepersons to adjudicate on rule violations and collect fines and redistribute their proceeds).

7. **Gameplay with Institutions and Final Reflections:** The game was replayed with the same village assignments, but this time with the designed institutional statements in place. Students reflected again in the online forum, focusing on the deliberative process of designing institutions, their impact on gameplay, and suggestions for improving the game. In addition to allowing students to formulate and interiorize lessons learned, these reflections provided valuable feedback for refining the game in subsequent class iterations.

In the short-form curriculum, *Thirsty Earth* was typically integrated as a two-lecture module within an upper-level undergraduate hydrology class. The light version of the game (v0) was played twice. The first lecture usually included an introduction to the game, followed by an initial gameplay session and an in-class discussion. Students were then provided with a written solution to the game (Supplementary S1) and tasked to review it before the second lecture. The second lecture generally began with a brief introduction to Ostrom's design principles and institutional grammar, followed by a short deliberation session in which students, grouped by game village, designed institutional rules. To simplify the task, the private information available to students for public enforcement was limited to identifying the water consumption of a randomly drawn player—a feature now integrated into the light version of the game. After agreeing on institutional rules formulated using the ADICO framework, students played the game a second time. The session concluded with a discussion comparing the outcomes of the two gameplay sessions, emphasizing the critical role of well-designed institutions in ensuring infrastructure effectiveness and supporting sustainable resource management.

6 Conclusion

Educational games like *Thirsty Earth* represent a promising tool for integrating interdisciplinary literacy into STEM education, particularly for addressing complex challenges in water resource management. By simulating some of the key physical, economic, and institutional dimensions of common-pool resource dilemmas as they apply to water resources, *Thirsty Earth* provides an experiential platform that bridges technical problem-solving with key insights from the social sciences.

While no formal evaluation of teaching effectiveness has been conducted, patterns in student reflections and gameplay outcomes suggest that *Thirsty Earth* effectively achieves its learning objective of allowing students to experience and engage with the interdisciplinary nature of water resources management and governance. Comparisons of gameplay before and after the introduction of institutional rules consistently revealed substantial shifts in strategies and outcomes. In initial sessions without rules, resource overuse was common, leading to significant inequalities within villages with clear winners and losers. However,

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in subsequent sessions with institutional rules, outcomes became more egalitarian, with minimal rule-breaking. Over seven years of implementation, fines associated with trespassing institutional rules almost never needed to be collected, indicating that the mere presence of rules, rather than their enforcement, was sufficient to incentivize compliance. Students frequently attributed this outcome to peer pressure, reputational costs, and a shared understanding of optimal strategies. Interestingly, the low stakes of the game, where rewards were tangible, but symbolic (e.g., coffee or chocolate), were cited as a reason *not* to break the rules, suggesting that incentives to deviate might increase under higher stakes. This observation reflects a broader understanding among students of the role of misaligned incentives in water resource management, further supporting the achievement of the game's learning objectives. Students also highlighted the importance of systematic institutional frameworks for ensuring sustainable resource use, emphasizing that such frameworks are critical for addressing unsustainable behavior. Many noted that the game encouraged them to learn and adapt through experience rather than relying solely on theory, an aspect they found particularly engaging and impactful.

By fostering active learning, *Thirsty Earth* equips students to analyze, evaluate, and create solutions to real-world problems, emphasizing the critical role of well-designed institutions in sustainable water resource management. Beyond the classroom, the game's principles and insights have the potential to inspire innovative approaches to water governance, underscoring the vital interplay between technical expertise and social considerations in addressing contemporary environmental challenges.

Code availability. The light version (v0) of *Thirsty Earth* and its associated spreadsheet functions are available at https://tinyurl.com/37xnjjp5, with the spreadsheet content licensed under GPL v2. The full version (v1) of the game can be accessed at https://thirsty-earth.crc.nd.edu, with its source code available at [source code will be made available upon publication] under MIT license.

Author contributions. MFM designed the light version of the game. LEM and MFM designed the full version of the game, which was coded and implemented by CR and KP. LEM and MFM administered the game in undergraduate classes taught by MFM. MFM and LEM wrote the manuscript, which was edited by all authors.

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draft of each paragraph was entered into ChatGPT v4o with the prompt: 'Edit for clarity, flow and brevity'. The generated text was then manually edited to ensure that it fully, completely and accurately reflects all concepts, ideas, references and results of the original text. It was then incorporated into the manuscript text with the necessary manual edits to ensure a uniform flow and style. The complete manuscript was finally read, edited and approved by all authors.

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