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Flipping Lakes: Explaining concepts of catchment-scale water management through a serious game

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Abstract

Ongoing anthropogenic and climatic pressures on inland waters have made water quality management a challenge of the 21st century. A holistic catchment-scale approach to water management which includes stakeholder participation will be a key in maintaining lake health. A first step toward community engagement is to bolster environmental literacy on lake management, ecology, and eutrophication concepts of stakeholders now and in future generations. However, communicating with nonwater professionals about effects of pollution on water quality and catchment-scale interactions across space and time can be difficult. Here, we present "Flipping Lakes," a games-based method for lake professionals to communicate and educate about catchment-level water quality management to diverse audiences. In Flipping Lakes, the players take on the role of water managers in a catchment and are tasked to prevent a lake from "flipping" from a clear to a turbid state. During the game, the catchment slowly becomes polluted by a range of sources of which the effects are exacerbated by societal or climatic scenarios. Players need to implement measures while taking into consideration the intrinsic properties of the catchment in order to keep lakes clean. The game was tested with a diverse range of user groups and was well-received. With its entertaining and accessible content, Flipping Lakes can lower communication barriers and increase understanding of difficult water quality concepts. The game is highly customizable, making it applicable to a variety of settings to support education and engagement of stakeholders and the broader community in order to address local water challenges around the globe.

Ongoing anthropogenic and climatic pressures on water systems have made water quality management a key challenge of the 21st century, reflected in legislation and policy such as the EU Water Framework Directive (2000), the US Clean Water Act (1972), and the Sustainable Development Goals (United Nations 2015). Water quality management is an interdisciplinary field, requiring knowledge of hydrology, ecology, governance, human behavior, and economics. The challenges affecting lake water quality and the need for management on a catchment-scale are often hard to communicate to a wider audience of nonwater professionals. As catchments can span large parts of regions, these hydrologically delineated areas are often too large for people to directly associate with their own living environment (Koroleva and Novak 2020). Processes that take place over decadal time scales as well as across large spatial scales may be difficult for people to grasp intuitively (e.g., climate change, critical state shifts in lakes due to eutrophication) or to visualize (e.g., loading from point and diffuse pollution sources) (*see* Seelen et al. 2019*a*).

Improving the environmental literacy of stakeholders regarding lake management, ecology and eutrophication concepts can aid in engaging them in management discussions. For instance, with heightened stakeholder understanding of how pressures are affecting local lake systems and the wider catchment, discussions about solutions can be facilitated. Well-informed and environmentally literate communities can aid management by integrating their local knowledge into management actions (i.e., co-design), thereby improving the effectiveness of management plans (Robertson and McGee

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2003). In some cases, informed stakeholders can also assist with mobilizing social support for enacting effective management actions that are costly or require community participation (Cooper et al. 2007; Franzen et al. 2015). The communication of catchment-level water quality management intricacies is a first, necessary step for creating a holistic management approach.

Applying game approaches to explain complex and discipline-specific concepts can improve knowledge accessibility by making the material more tangible, comprehensible, and simplified (Susi et al. 2007). Therefore, the use of games or game elements can be suitable to begin addressing the challenges of catchment-level water quality management (Albertarelli et al. 2018). Examples of effective game or game-element applications include classroom lessons (Boskic and Hu 2015), multistakeholder discussions (Medema et al. 2016), citizen-science projects (Eveleigh et al. 2013; Seelen et al. 2019*b*), and more. Serious games, which are defined as "games that are used for purposes other than mere entertainment" (Susi et al. 2007), have entered a wide range of scientific fields as a method for communicating complex concepts. The application of serious games into environmental sciences in particular has proven useful in education and engagement of nonexpert audiences (Madani et al. 2017). As the scales of environmental processes range from microscopic to global, it can be a challenge for individuals untrained in the research topic to visualize and therefore understand these processes. Presenting a concept within a set playing field with specific rules and a defined goal can engage audiences with their existing problem-solving skill set (Landers 2014).

Following the serious game approach, we have developed "Flipping Lakes." This game, with an underpinning in ecological knowledge and theory, is intended to facilitate outreach and education of catchment-scale water quality management. The game uses both simplified system processes and a customizable catchment structure to support its application as an effective water quality and ecology communication tool to a varied audience. We tested the efficacy of Flipping Lakes as a teaching tool with groups of students, lake scientists, and the broader public. Based on our findings, we developed best practices for gameplay and offer an outlook to future applications of the game.

Materials and procedures

Flipping Lakes is a serious game about eutrophication prevention and management at the catchment-scale. The game takes place within a customizable fictitious catchment that is constructed with the placement of the game's catchment cards on a table or similar playing surface. Nutrient pollution (i.e., excessive nutrients) is generated by catchment cards and transported from sources in the catchment toward a downstream focal lake. Players take on the role of water managers and are tasked with protecting the ecosystem services of this downstream focal lake (e.g., recreation, biodiversity). Introduction of pollution into any lake present in the game can cause its clear state to shift to a turbid state. During each turn, which represents 1 year in the game, players can carry out management actions throughout the catchment that are aimed at either stopping the impacts of pollution (adaptation measures) or reducing pollution sources (mitigation measures). These management actions have to be bought with "Aquabucks," which represent the allotment of public money for water management. A share of Aquabucks becomes available at each turn. Typical gameplay lasts for 15 turns, with pollution being transported through the catchment during each turn, and management actions implemented with the available Aquabucks. Failure to protect the focal lake situated at the downstream end of the catchment from the pollution will result in it flipping from a pristine (i.e., clear) to a deteriorated (i.e., turbid) state and the players losing the game. This game targets a wide audience, including a range of professional disciplines and ages (10+), as most people have some interest or investment in water quality (*see* Seelen et al. 2019*a*). The game is designed to educate citizens and students on catchment management and to facilitate intersectoral discussions among water professionals and other stakeholders.

Scientific underpinning of the game

Flipping Lakes has its scientific basis in limnological theory. Regime shifts are a core concept in limnology, made famous in shallow lakes theory (Scheffer and van Nes 2007) where lakes go from clear, submerged macrophyte-dominated states to turbid, phytoplankton-dominated ones, or vice versa (van Nes et al. 2007; Janse et al. 2008). An important aspect of such regime shifts is the existence of hysteresis (van Nes et al. 2007), indicating the need for reducing nutrient loads far beyond the level at which the lake originally underwent a regime shift to a turbid state in order to return to a clear state. Similar ecological regime shifts driven by nutrient dynamics have also been described for deep lakes, revolving around phosphorus supply and hypolimnetic anoxia (Carpenter and Cottingham 1997). Lake ecological states and their resulting ecosystem services, especially in terms of nutrient retention, are also an important part of the inspiration for Flipping Lakes.

Lakes can serve as a net nutrient source (i.e., lower inflowing relative to outflowing nutrient load) or a net sink of nutrients (i.e., higher inflowing relative to outflowing nutrient load) in the catchment. There is evidence for increased retention of nutrients in submerged plant dominated systems compared to phytoplankton dominated ones (Hilt et al. 2017; Janssen et al. 2020). Furthermore, the water purification capacity (i.e., phytoremediation) of aquatic plants has long been acknowledged in scientific literature (Truu et al. 2015; Janssen et al. 2020). Phytoplankton, in contrast to macrophytes, are easily transported along with the water flow (Elliott 2010; Teurlincx et al. 2019), thereby transporting nutrients downstream. In addition, the nutrient legacy stored in many lake sediments due to decades of excessive nutrient loads (Søndergaard et al. 2003) can serve as a source of nutrient pollution from turbid lakes, a problem that is hampering the recovery of many lakes even when external loads are reduced (Zamparas and Zacharias 2014). Within the game context, the role of a lake as a net source or sink is intentionally oversimplified for ease of gameplay. The capacity of lakes to retain or release nutrients is reflected in the clear and turbid states which lake catchment cards can flip between.

Regime shifts can lead to cascading effects in connected lake systems (Hilt et al. 2011). For instance, there can be a cascading effect where a lake undergoing a regime shift into a turbid state can lead to an increase in nutrients which travel downstream, causing the receiving lake to undergo a regime shift due to the increased nutrient loading (Teurlincx et al. 2019). Managing systems for maximal nutrient retention has the potential to cause the inverse of this cascading effect, where the retention capacity in upstream systems helps to preserve water quality of downstream systems (Jarvie et al. 2013; van Wijk et al. 2021). These spatial cascading effects are represented in Flipping Lakes through the interactions among lakes within the catchment.

Specifics of gameplay

In this section, we first introduce the different game pieces that comprise the game and their purpose. Following this, we describe the overall progression of a game session in detail.

Nutrient pollution

Within the context of Flipping Lakes, players are challenged with managing the amount of nutrient pollution that is entering the catchment area and the impacts it has on lake water quality. Within the context of the game, the term "pollution" is specifically used to describe nutrient pollution (i.e., eutrophication), or the excess input of nutrients (both in dissolved and particulate form) that originate from sources throughout the catchment. Pollution is deemed to be a more accessible term than "nutrient pollution" or eutrophication, therefore making it easier to engage a wide audience and avoiding discussions regarding the need for some nutrients in water for a healthy ecosystem. Hence, from here on, the terms "pollution," "pollution removal," and "pollution load" will be used to refer to nutrient pollution, nutrient retention, and nutrient loading, respectively.

Catchment design

The game board consists of three types of cards: lakes, pollution sources, and waterways (connection cards). The game board always contains at least one focal lake, which is situated downstream, and an inflow point at the upstream end of the catchment. All other cards in between the inflow and the focal lake are entirely customizable. Therefore, the catchment can be designed to suit the needs of the user, such as by making it fit to an existing catchment or by emphasizing the presence of a specific pollution source in the game catchment.

Lakes

Lake cards are two-sided with one side representing a turbid system state and the other a clear system state (Fig. 1). The turbid state of the lake cards emulates internal loading processes (Søndergaard et al. 2003) by being a source of pollution within the game's catchment. Each card states the amount of pollution that the lake will add to the catchment each turn while the card is in the turbid state. In contrast, the clear state of the lake card acts as a sink of pollution within the catchment with its simulation of a lake's nutrient retention capacity (Jeppesen et al. 2011). Lakes in the clear state can assist with the management goal through the retention of nutrients in the lake sediment. In the game, this function of a clear lake will permanently remove a limited amount of pollution pieces from the card, and therefore from the catchment, every turn.

The lake cards within the catchment are dynamic over the course of gameplay as a lake may flip over into the alternate state depending on the amount of pollution pieces located on the card during a given turn. The number of pollution pieces that will result in a flip from one state to another are displayed on the card. Players can alter the lake state by implementing various management measures on the card itself or elsewhere in the fictitious catchment. Strategic decisions can be made that will either decrease pollution to a level that allows the turbid lake to change into its clear state, or to ensure that a lake stays in the clear state by remaining under the provided "flip" pollution threshold value (i.e., the lake critical nutrient limit, critical nutrient loading or lake resilience to a state shift; Scheffer and van Nes 2007; van Nes et al. 2007). As multiple lakes can be part of the game board, managing them effectively is a key aspect to achieving the goal of the game.

The main goal of the game is to keep the focal lake from flipping over into the card's turbid state. In general, this lake system is sensitive to pollution inputs as even small quantities can reduce the provisioning of lake ecosystem services that are desired by the fictitious community. The flipping over of the focal lake from clear to turbid denotes the end of the game.

Pollution sources

In addition to the nutrients released from the turbid state of the lake cards, there are other sources of pollution within the game's catchment. Cards representing upstream reaches, agricultural areas, urban areas and sewage overflows serve as structural sources of pollution to the water system. These cards are characterized by a pollution load value (1 to 10), which dictates how much pollution is added to the card, and ultimately into the catchment (Fig. 2). Pollution from the various sources is added every turn as a simulation of the continuous production and release of pollution through time (Greene et al. 2011). While the addition of a single unit of pollution to the catchment is unlikely to pose an immediate problem, there can be complications from the accumulation of pollution through time and by the movement of pollution along the catchment cards. The sewage overflow card is a special

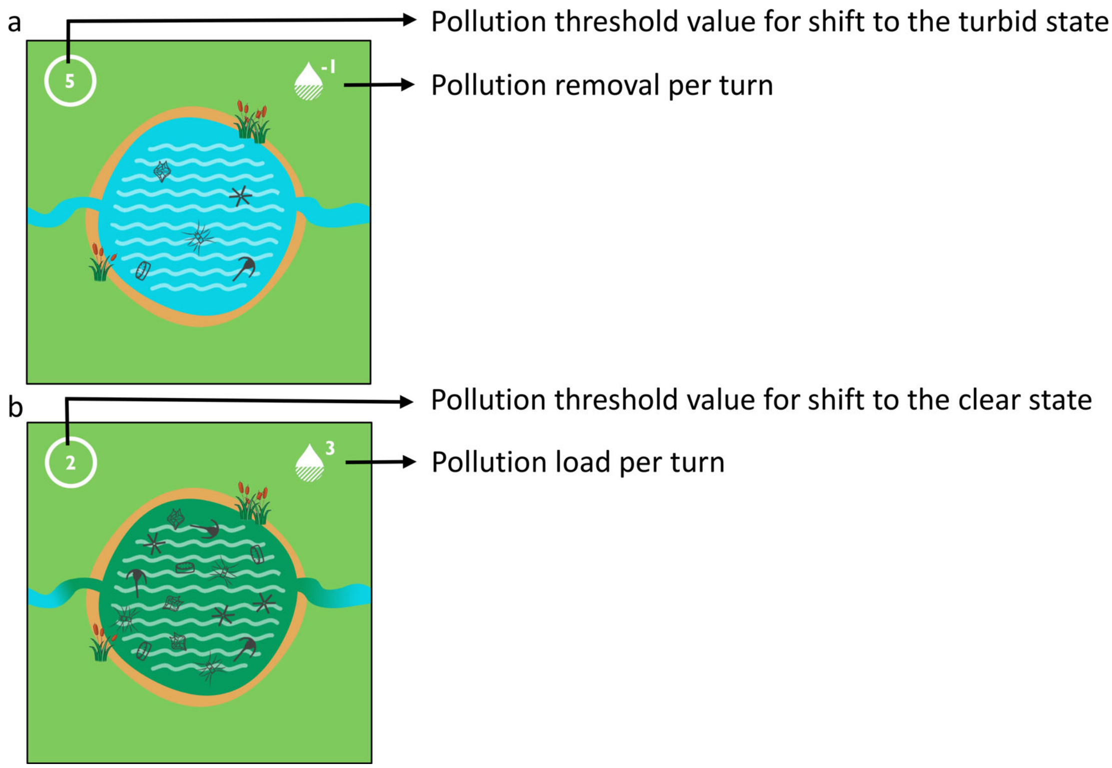

Fig. 1. Example lake catchment cards with the lake card's clear state (**a**) including the pollution threshold value and pollution removal value and the lake card's turbid state (**b**) including the pollution threshold value and pollution loading amount.

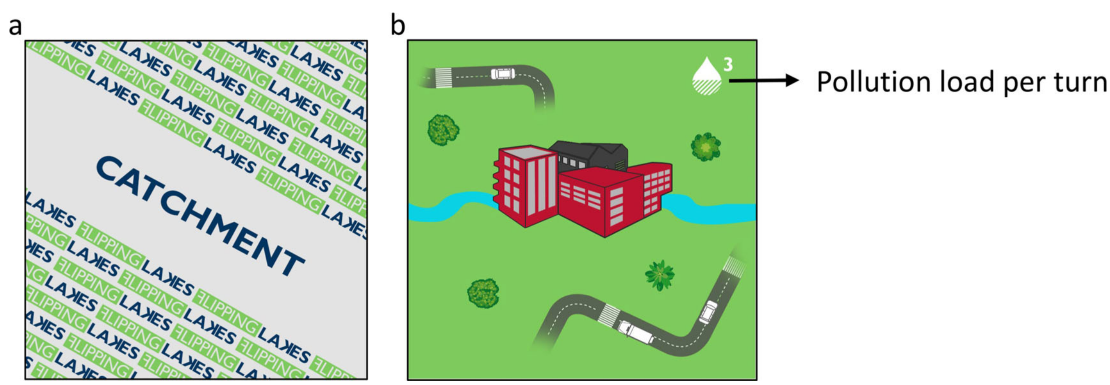

Fig. 2. Example pollution catchment card with the card back (**a**) and the gameboard side (**b**) containing the pollution load value and two river connections.

case as this card only delivers a point-source pollution load into the catchment during the *Extreme rainfall event* scenario (*see* Event scenarios). These pollution source cards can be deliberately chosen and placed within the game playing field to depict a specific catchment system. Conversely, these cards can be randomly selected and distributed within the playing field. Among the type of pollution cards chosen, the number of cards introduced to the playing field, the placement within the playing field, and the card's pollution load value, the resulting catchment can offer abundant variability in the scenario which players must manage.

Spatial connections

Cards representing waterways are used to connect pollution sources and lakes into a catchment network. The purpose of the waterways in the game is to transfer pollution through the catchment. In contrast to the lake cards with their dynamic system states, the spatial connection cards act as pollution

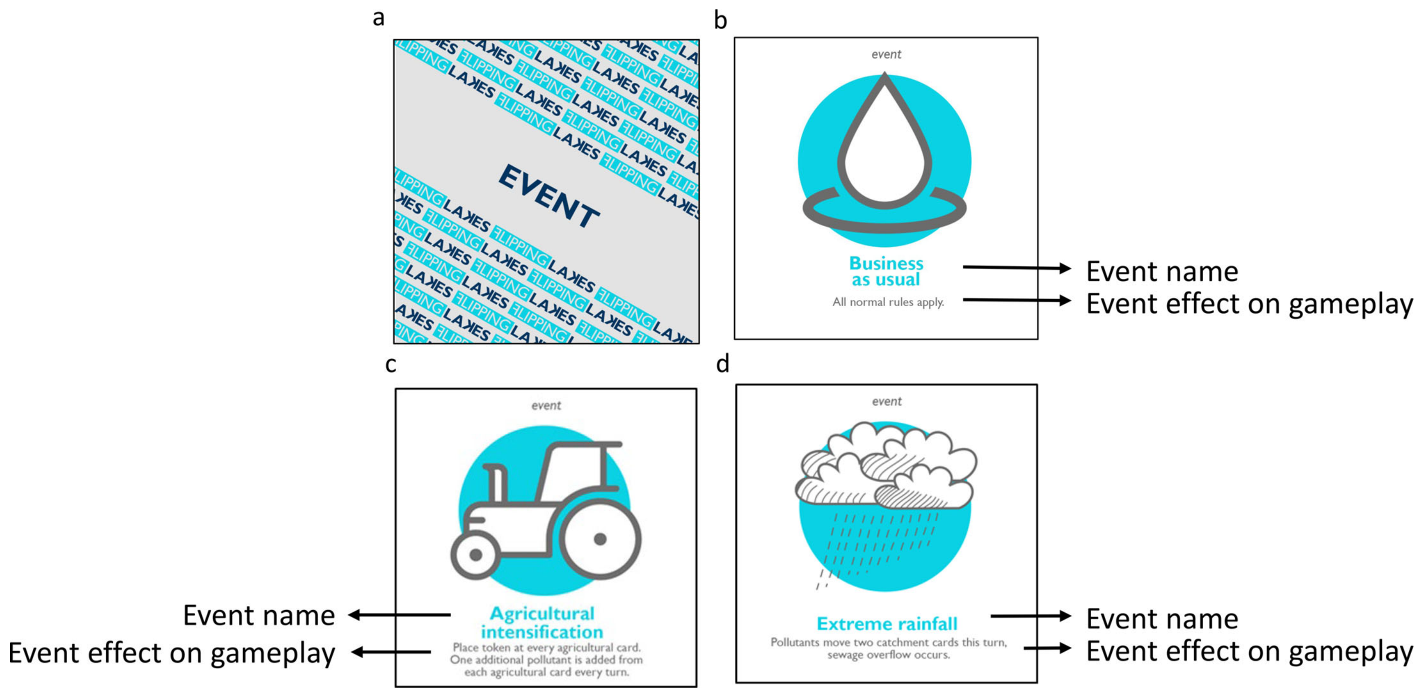

Fig. 3. Example event card with card back (**a**) and front (**b–d**) containing explanation of the scenario effect on gameplay for a *Business-as-usual*, *Agricultural intensification* (societal event) and *Extreme rainfall* (climatic event) scenario.

transferral pathways regardless of the amount of pollution on a card at any given time.

Event scenarios

Flipping Lakes was constructed to have various scenarios that players have to manage. An event card (Fig. 3) is revealed at the start of each turn and can influence the rules of the game for that turn of the game. There are seven types of event cards. The *Business-as-usual* scenario is typically the most common event and does not affect the rules of engagement for Flipping Lakes during that turn. The other six types are based on societal events and climatic events (Table 1). Compared to the complex impacts that these events can have on real-world catchments, the implications of these events in the context of the game are simplified in order to demonstrate how the compounding of pressures across turns can impede achievement of management goals. Presenting players with these events throughout the gameplay causes additional hurdles for management which can directly impact how players react during that turn. Additionally, the repercussions of these events could be long-lasting, requiring additional management measures over the course of a number of turns to address the impact of the event.

Societal events

Anthropogenic actions have the potential to shape and significantly alter the catchment landscape (Rashid et al. 2012). To represent the influence of such actions, this game has event cards related to the human actions and interventions of *Agricultural intensification*, *Feeding ducks*, and construction of a *Dog Park* (Table 1). All of these event cards directly influence the amount of pollution that enters into the catchment system each turn. In the absence of management measures, these events will be an additional and permanent source of pollution to the catchment.

Table 1. Overview of Flipping Lakes events.

Event type	Event card	Impact
Climatic	Heatwave	Multiply all pollution added this turn by 1.5
	Extreme rainfall	Pollution travels two catchment cards this turn, also over dams
	Extreme drought	Pollution does not travel this turn
Societal	Agricultural intensification	Agricultural catchment cards produce +1 pollution from now on
	Feeding ducks	One lake is flipped over to a turbid state
	Dog park construction	Adds a +1 pollution source to the catchment

Climatic events

Extreme climatic events, or weather events that lie on the extreme ends of the climate spectrum, are anticipated to become more intense and frequent with the continued trend of climate change (Seneviratne et al. 2012). The extreme event

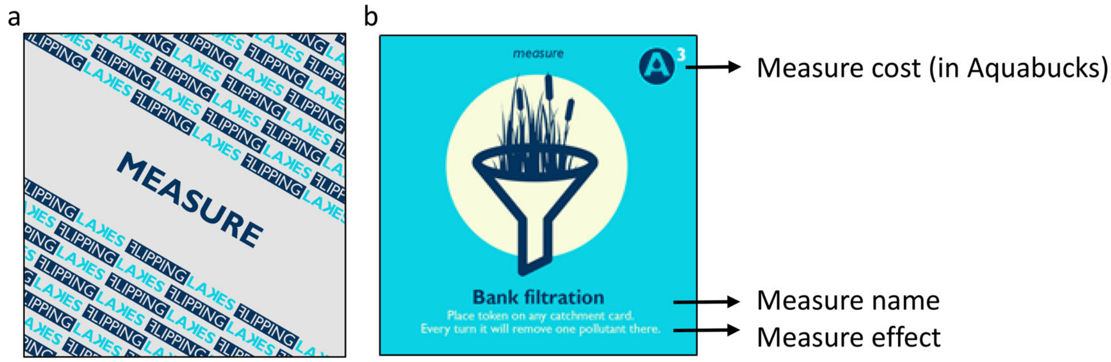

Fig. 4. Example management measure with card back (**a**) and front (**b**) containing explanation of the card effect on gameplay and cost of the measure.

cards of *Heatwave*, *Extreme rainfall*, and *Extreme drought* (Table 1) present simplified scenarios in which the climate can impact lakes and catchments. These events have implications on the game catchment in two ways. First, the *Extreme rainfall* and *Extreme drought* events alter water movement and thereby pollution transport through the system during that turn. Such changing flows of pollution can be both a hindrance and a help to the player. An example of this is the *Extreme rainfall* event which causes pollution to move two spaces over the course of one turn. This can hinder the player by speeding up the flow of pollution to their focal lake. However, it may also push the pollution that is flowing through a lake card into a subsequent waterway, thereby avoiding the lake card from flipping from a clear state to a turbid state (i.e., a flushing event). The underlying idea of these events is that they can temporarily change the rules of the game, much like climate change is doing for ecosystems in the real world. Second, the *Heatwave* event and the *Extreme rainfall* event can increase the amount of pollution added during that turn. The severity of all events is context dependent, with effects varying depending on the catchment configuration (amount of loading sources, presence of sewage overflows), the current state of pollution, and the previous management actions taken by the player.

Management measures

The primary method to influence the outcome of the game is applying management measures (Fig. 4). During each turn, players receive a specified amount of the fictitious currency Aquabucks to spend on different measures, either during that turn or in subsequent turns. The costs of the measures were purposely expressed in a fictive currency as to avoid direct association to real world monetary costs. Rather, prices of measures were scaled only to have some reflection of expensive vs. inexpensive approaches. There are nine options for managing the pollution sources and stressors within the catchment (Table 2). These measures can be used to mitigate pollution loads or to adapt the catchment when dealing with pollution.

Mitigation measures

Several measures are aimed at directly addressing the pollution source(s) within the catchment setting. These types of mitigation measures reduce or prevent the entrance of pollution into the water system, thereby taking action to solve the problem underlying the ecosystem's health. Within Flipping Lakes, there are three ways in which mitigation measures can influence gameplay. First, anthropogenic practices can be made more sustainable. In the game, this can be done by applying the management actions of *Agricultural legislation* or *Increase public awareness*. Second, nutrient loading from the sediment of a turbid lake into the water column can be halted with *Sediment capping*. Last, prevention of sewage overflow pollution entering the catchment can occur when the measure *Increase water storage capacity* is applied to the sewage overflow catchment card.

Adaptation measures

Adaptation measure options are built into Flipping Lakes as a method for dealing with the impacts of pollution once it is already in the catchment. Site-specific pollution treatment can be implemented by construction of a *Water treatment plant* and with the establishment of *Bank filtration*, as both options permanently remove a limited amount of pollution from the catchment. Pollution located on a catchment card can also be removed directly through *Dredging* of the sediment, causing the removal of all pollution present on the card during the turn in which it is used. *Dredging* is a one-time measure, in contrast to the pollution treatment measures (*Bank filtration*, *Water treatment plant*) which last throughout the game. Water flow can be manipulated by constructing *Dams* within the catchment impeding the movement of pollution in the catchment under most circumstances of gameplay. Using the *Increase water storage capacity* anywhere on the catchment except for sewage overflows (see above) allows it to be used as an adaptation measure to temporarily keep pollution in place.

Foreknowledge

Players can benefit from foreknowledge gained through playing the *Predictive model* card. This measure allows players

Table 2. Overview of Flipping Lakes management measures.

Management type	Measure card	Impact
Mitigation	Agricultural legislation	Agricultural card produces 1 pollution every turn from now on
	Increase public awareness	Pollution is reduced by 1 from now on
	Sediment capping	Turbid pollution production is prevented on the lake card
	Increase water storage capacity	Pollution is retained for an extra turn
Adaptation	Water treatment plant	Up to 8 pollution is removed from the card each turn
	Bank filtration	Up to 1 pollution is removed from the card each turn
	Dredging	All pollution is removed from the lake card
	Dams	Pollution movement is prevented
	Increase water storage capacity	Sewage overflow from the extreme precipitation event is prevented
Foreknowledge	Predictive model	Preview the event scenario for next turn

to see the event card for the next turn, providing an opportunity to adapt their strategy to the impending pollution sources and movement thereof.

Playing the game

A game moderator can direct the players in the aspects of gameplay by first creating the board lay-out and choosing the types and order of events that are appropriate for the session at the start of the game. The players may be given an overview of the measures that can be implemented during the game play and the impacts that the various events could have. Flipping Lakes games are typically run for 15 turns. The scenario card is revealed at the start of each turn. This event scenario will dictate whether special rules are applied to the gameplay during that turn (*see* Table 1). The player or group of players will receive an allotment of Aquabucks as a representation of public money available for management actions. The players then have an opportunity to consider, pay for and enact one or more of the management actions (*see* Table 2). Purchased measures are implemented immediately within the catchment. Next, pollution is added into the catchment according to the sources present on the board and as indicated by the event scenario. There are opportunities to remove pollution from the catchment cards if there is a purifying effect, such as with clear lake cards, helophyte filters (i.e., *Bank filtration*) and mechanical water treatment (i.e., *Water treatment plants*). Pollution then moves downstream along the catchment cards toward the focal lake (at a pace of one catchment card per turn under *Business-as-usual* scenario). At the end of each turn, players review the current status of pollution in their catchment area and flip lake cards to the turbid state if the amount of pollution exceeds the pollution threshold value or to the clear state if pollution is below the given threshold value. If the focal lake has not exceeded the pollution threshold and therefore remains in the clear state, players have successfully managed the catchment for that turn and may proceed with the next turn. Players have won the game when they keep the focal lake in pristine condition until the end of the 15th turn (a detailed game manual is supplied in Appendix 1).

Availability

Flipping Lakes is an open communication tool under a Creative Commons license (CC-BY-NC-SA). The game will be made available upon publication at www.nioo.knaw.nl/flippinglakes and www.nioo.knaw.nl/en/flippinglakes. Game instructions and all materials are provided on the website. An explanatory video and other supporting materials will also be available for learning about and applying this communication tool.

Assessment

Methodology for assessing the impact of Flipping Lakes

Flipping Lakes has been introduced to a diverse range of players through trial runs in Europe, Asia and North America (as shown in Table 3). On these different occasions, players were asked for their opinion on whether they learned something by playing the game or not. Below, we describe the qualitative impressions from various groups as expressed by the game moderators (authors of this article). An opportunity to ask for anonymous feedback on the usefulness of the Flipping Lakes game for broader application by water professionals presented itself at the Global Lake Ecological Observatory Network All Hands' Meeting in Huntsville, Canada (GLEON 21; Fig. 5). During this meeting, professional and student members of lake science and associated disciplines along with local lake managers could play Flipping Lakes as a team. Meanwhile, observers and participants were given the option to provide anonymous feedback on the game and its usefulness for communication, education, and public outreach purposes through a survey form on a standard laptop of one of the game moderators.

We also tested the application of Flipping Lakes in an academic setting with bachelor students from Utrecht University participating in an Aquatic Ecology course. During this course,

Table 3. Flipping Lakes trial runs.

Purpose	Audience	Occasion	Location	Country
Communication	Water managers	Innovation fair	Hoogheemraadschap van Schieland en de Krimpenerwaard	The Netherlands
Community interest, scientific communication	Water professionals	GLEON 21 All-Hands' Meeting	Huntsville	Canada
Education	Faculty & administration staff	"Blue Monday" event	Erasmus University Rotterdam	The Netherlands
Education	Master & PhD students	Masters course	Yangzhou University	People's Republic of China
Education	Bachelor students	Bachelor's course	Utrecht University	The Netherlands
Public outreach	General audience	NIOO Open Day	Netherlands Institute of Ecology	The Netherlands

Fig. 5. Photograph showing a game of the Flipping Lakes game being played at the GLEON 21.5 All Hands' Meeting in Huntsville, Canada.

we measured perceived comprehension of select lake science concepts (*see* Appendix 2) by having students self-score their familiarity of the concepts on a scale from 0 (not familiar) to 10 (expert) prior to playing the game. Each student re-scored their familiarity of the same concepts after playing the game two to three times in groups of four students under the supervision of a game moderator. The scoring was carried out anonymously on a standardized scoring sheet which was printed on both sides, guaranteeing that participant results remained paired. Students provided their explicit permission for using the data for scientific publication through completion of an online survey form (Appendix 3). The results of the students' scores were analyzed using a paired Two-sample Fisher-Pitman permutation test (R package coin; Hothorn et al. 2019). We analyzed the results both by grouping all the lake concepts together, and by looking at each of the concepts separately.

General reception of Flipping Lakes by diverse user groups

Reception by professional water managers

Flipping Lakes was introduced to professional water managers at the Dutch water management agency Hoogheemraadschap van Schieland en de Krimpenerwaard (HHSK). During this introduction, the catchment was modeled after part of the urban water system of the city of Rotterdam, the Netherlands. The game received positive responses with immediate outlooks to using it as a tool for simple scenario demonstrations for local water system restoration projects. The water management professionals also indicated their desire to own a set of the game for outreach events.

Reception by the general public

Flipping Lakes was used as an educational tool to facilitate public outreach through moderated sessions. We used the game at an open day at the Netherlands Institute of Ecology (attended by over 1600 people of diverse demographics). At this event, we used the game in a demonstration format to discuss water quality concepts and challenges with approximately 150 people, of whom 29 decided to play a full game with a game moderator.

Reception by university students and administration staff

The game was also used for outreach with the academic and administrative staff of the School of Business at Erasmus University Rotterdam during the "Blue Monday" event. Players showed an understanding of the underlying societal and ecological logic of Flipping Lakes with improved comprehension of cause-effect chains of measures and pollution reduction over the course of the gameplay. Additionally, we observed that the game's interactive nature helped ease player participation in discussing the fate of pollution within the catchment system, implications of degrading lake ecosystems, and strategies for reducing pollution. This allowed the game moderators to discuss and explain some of the more difficult concepts in catchment management and lake ecology (e.g., point vs. diffuse pollution, hysteresis of lake ecosystems, adaptive vs. mitigative measures).

The game was also used within an introductory course on aquatic ecology for Master and Ph.D. students in civil engineering and microbial ecology disciplines at the Yangzhou University in China. Here, the lecturer gave students a hands-on review experience of the course lecture materials by using Flipping Lakes as a visual and interactive tool. Upon finishing the game, the players informally reported that the game helped them to better understand the consequences of connectivity in water systems for the accumulation of pollution over time and space.

Quantifying the usefulness to water professionals

Ten water professionals at the Global Lake Ecological Observatory Network All Hands' Meeting (GLEON 21) provided feedback on their experience with the game. On average, they rated the usefulness of the game for communication and education purposes at 9.1 out of 10 (min: 8, max: 10). Further, respondents thought that this game was suitable for use with students (90%), communicating to local general public (90%), and communicating with local stakeholders (60%). A main conclusion of the event was that there was a high potential application of the serious game in an educational context.

Perceived learning of water quality concepts through Flipping Lakes

Perceived learning outcomes of the bachelor course students ($n = 12$) for different concepts encompassed by Flipping Lakes showed an overall positive result (Fig. 6). Nineteen out of 20 concepts showed a significant improvement in perceived knowledge post-gameplay (Appendix 4). The overall results show that, with the exception of the concept of pollution impacts ($p < 0.1$), there was a significant increase in perceived knowledge of the concepts after playing the game (Fig. 6, Appendix 4). The paired data points of individual students are based on their self-reflection of concept familiarity, opening up the possibility of opinion and personal beliefs to influence the scores. For instance, the knowledge and professional experiences that students had prior to participating in the serious game session can influence the value of the numeric scores reported in the pregame survey. It is therefore likely that a diverse class can have a range of values on the scale of 0–10 for the pregame scores. The scores reported following gameplay will similarly be subject to each individual's perception of their previous knowledge, of their experience with the serious game and of how they quantify that difference. It is the overall trend of improvement throughout the student data that supports the notion that important concepts behind catchment-scale management are elucidated by playing the Flipping Lakes serious game (*see* Appendix 4 for results per concept).

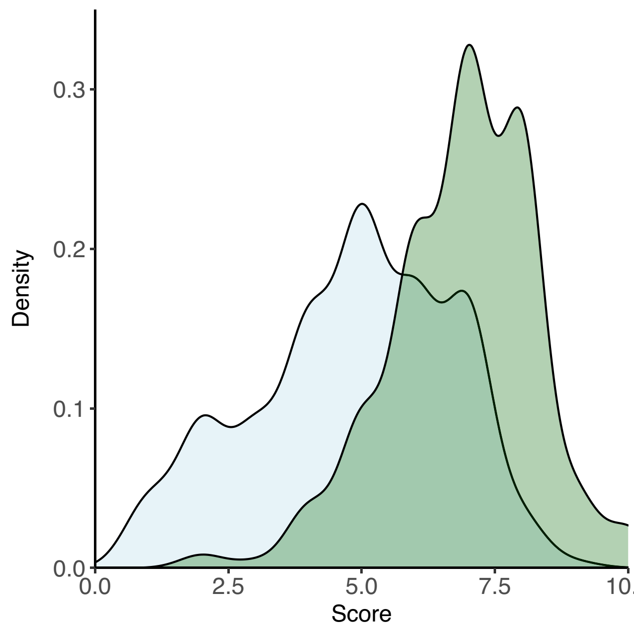

Fig. 6. Overall level of perceived concept knowledge ($n = 12$) before playing Flipping Lakes (light blue) and after (dark green). The scores (*x*-axis) range between 0 (not familiar with the concept) to 10 (expert on the concept) and the *y* axis gives the cumulative probability density (fraction of participants) based on the kernel density estimation method of Sheather and Jones (1991).

Discussion

The need for catchment-level management is widely accepted (Falkenmark 2004; Hughes and Quinn 2014). Establishing a holistic approach to system management requires the active engagement of lake stakeholders and users in the conversation around lake pressures and management thereof. To support these groups, insight about the types of challenges that are occurring, the pressures that are impacting the catchment system and the different management options must be communicated. As the role of serious games as a tool to aid stakeholder engagement with the game's topic is increasingly recognized (Rumeser and Emsley 2019), Flipping Lakes can assist in increasing players' comprehension of catchment-level ecological and management concepts within a game setting. Moreover, engaging players with complex topics through boundary objects such as serious games can help lower communication barriers and cross intersectoral boundaries. Through enhancing the environmental literacy of stakeholders and lake users, the first step toward holistic and inclusive decision-making can be achieved (Larson et al. 2015; Jean et al. 2018). Here, we have shown that a diverse group of players from the limnological community sees potential for the Flipping Lakes game as a communication tool, and that it can facilitate education of scientific and management concepts (Fig. 6).

A plethora of other serious games already exist that tackle some of the subject matter present within Flipping Lakes (*see*, e.g., Shapiro and Squire 2011 for some examples "Citizen Science" and "Trails Forward"). We argue that the diversity of serious games focusing on water management should be valued, much as we value biodiversity for filling niches in a physical environment (*see* Janssen et al. 2015 for a similar argument with respect to aquatic ecosystem model diversity). Each game has its own unique merits that can fulfill a role in expressing environmental concepts with their different focuses on certain limnological concepts and with their own gameplay mechanics. Flipping Lakes with its unique set of design principles serves to expand the diversity of serious games available to the limnological community as a whole. With the addition of another tool to the toolbox of scientists and water professionals to engage and educate other stakeholders, the capacity to co-design watershed management plans across knowledge boundaries (*see* Jean et al. 2018) is closer to becoming a reality.

Flipping Lakes distinguishes itself from existing serious games on catchment-scale water management through its core design principles as well as its scientific basis. This game's first core design principle is the medium through which the game is played. A number of recent serious games within the discipline of limnology are web-based virtual games (*see*, e.g., Gaydos and Squire 2012). In contrast, Flipping Lakes is played with a physical board, cards and game pieces. With a table-top approach, this game promotes real-time and collaborative interactions between players and moderators (Castronova and Knowles 2015). While video games can support this same experience to an extent when the game is based on real-time team play (*see*, e.g., Wendel et al. 2013), aspects of the discussion can be lost through a virtual interface. The face-to-face promotive interactions of board games (such as Flipping Lakes) are known to support collaborative learning (Kristiansen et al. 2019) as they allow players to directly help, assist, support, encourage and praise the success of other participants (Johnson and Johnson 1999).

The second core design principle of the game is its fully customizable nature. This game's design is intended to allow for the widespread application across cultural and social boundaries (Jean et al. 2018). The flexibility of the game allows participants to have a continually shifting and enriching experience enacting management decision-making in different catchments with various combinations of pressures. Paired with the freedom to choose which events will occur throughout the duration of gameplay, there are multitudes of scenario combinations that individual players and teams can experience. Flipping Lakes can be structured to facilitate scenarios ranging from purely fictitious situations up to simulating a real catchment area with semi-realistic climatic or societal-based scenarios.

The third core design principle of the game was to remove barriers for potential users to access and apply the tool. Accessibility of serious games is an important aspect in determining their uptake by students (Tsekleves et al. 2014). We ensure wide access by making the game materials openly and freely accessible through the Flipping Lakes webpage (www.nioo.knaw.nl/flippinglakes). All of the cards, pieces and instructions required for gameplay are provided in an easily printable format, allowing potential users to print the game themselves. We thereby remove paywalls (e.g., shipping costs) and minimize the technological structure necessary for acquiring a physical copy of the game. The added advantage is that unique game sets can be made that are collated for individual game play needs. This can be done by printing out different quantities of the game pieces associated with the catchment, events and measures. Also, we actively encourage the community to expand the game cards to suit their own purposes and share such work through the Flipping Lakes webpage.

While serious games are frequently referenced as relevant for education, communication and facilitating discussions (Jean et al. 2018), reports on their application in real world settings is limited. Especially reports of quantitative assessments on the efficacy of these tools are seldom presented in literature. For Flipping Lakes, we have carried out both qualitative explorations of its reception as well as a small quantitative assessment with 12 students. This quantitative assessment clearly illustrated the usefulness of the game as a communication and education tool, despite its low sample size. Nonetheless, future applications will need to show its applicability with other stakeholder groups and for other purposes such as facilitating co-design of management plans. We see a role here for the community of users and facilitate them to supply both qualitative and quantitative feedback to us and each other through the Flipping Lakes webpage (www.nioo.knaw.nl/flippinglakes).

The scientific basis underlying Flipping Lakes has a strong focus on lake ecological processes and functioning. Other serious games exist that have included ecology as a concept of their gameplay in some shape or form (*see*, e.g., Mathevet et al. 2007; van Hardeveld et al. 2020), though often it serves as an end result of actions taken by the player. Flipping Lakes is one of a small number of serious games where the ecological functioning of the lake systems directly impacts the game's outcome, making ecological recovery of lake systems a means to reach the goal of the game rather than the goal itself. Ergo, Flipping Lakes makes a much needed contribution to the existing set of serious games by incorporating lake ecology as a guiding theme (*see* chart in Madani et al. 2017).

Through the unique combination of the above described design principles encompassed by Flipping Lakes, we aim to contribute to the improvement of scientific literacy of a wide audience regarding limnology, ecology and water management.

Comments and recommendations

Based on the experience of moderating and playing Flipping Lakes ourselves, we have formulated a number of recommendations for gameplay and for future development.

Recommendations for first time players

When introducing Flipping Lakes to first time players, it is recommended to create a set-up that promotes learning of the game rules and that safeguards players from losing the game during this learning period. Therefore, the first step of supporting comprehension of the game without overwhelming players is constructing a board in a configuration with minimal pollution sources. In practice this could be including one agricultural card and one urban card in the catchment. Similarly, having one or more of the nonfocal lakes embedded in the catchment start in their clear state will offer both a buffer against the pollution while players figure out the management actions options and simultaneously offer a discussion point regarding the stable alternative states of the lakes. Ensuring that three consecutive connection cards are located between the focal lake and the closest source of pollution will also assist with the simplified set-up. We recommend that the first three turns of the game will be *Business-as-usual* events, paired with a simple catchment system. This effectively permits players to become familiar with the basic rules of engagement that occur each turn and with how the various aspects of the game interact to create the management challenge.

Recommendations for advanced players

Conversely, when players are familiar with the Flipping Lakes game, additional rules can be added in order to increase the difficulty of the game or to more realistically reflect existing management challenges. Modifications of the game can occur with the board configuration, the events, the management measures options and the Aquabucks allotment. The board can be configured in a number of ways in order to increase the challenge. Three of these methods include (1) increasing or randomly selecting the number or type of pollution cards within the catchment (e.g., agricultural and urban cards), (2) starting the nonfocal lakes in a turbid state, and (3) having two or more recreational lakes in the system. By randomizing the catchment cards in play, the chances of having a catchment setup that is (near) impossible to manage successfully increase. While this may disappoint players, it can serve as a great example of how past landscape geographical design choices can lead to nearly unmanageable catchment systems. Furthermore, event cards can be customized to reflect different future scenarios. To introduce players to the difficulties of management in a changing world, we recommend that players go through two play-throughs of the game on the same catchment. The first play-through has a mixture of event cards with half of the set being *Business-as-usual*. In the second play-through, the event cards could be ordered to have more societal events or climatic events to demonstrate scenarios with more human intervention and climate change pressures, respectively. Communicating the importance of climate variability for managing lakes (Havens et al. 2016) can be attained through smart stacking of the event card deck with climatic events combined with random shuffling of the deck between two games. While Flipping Lakes is unlikely to reflect real world climatic variability, randomizing the climatic events has the potential to illustrate the difficulties of managing a catchment in a stochastic world. Furthermore, the availability of management measures options could be adjusted either before the game begins or in the middle of gameplay. Removing some of these options will force players to adjust previous approaches to address the pollution situation or to develop entirely new strategies. If this is done in combination with stacking specific event card types, the management scenario can reflect real-world situations and restrictions due to policy changes (e.g., Downing et al. 2014). Finally, the amount of Aquabucks that the player or team receives each turn could be adjusted at the start of the game or in the middle of gameplay. Such a scenario can reflect changes in governance with relation to the funding for water management. The limitation of funds can force players to reconsider which management actions should be implemented, when they should be done and where in the catchment they would have the most impact. An extreme case of funding insecurity could be introduced by letting players roll a six-sided dice to determine the amount of Aquabucks that they receive each turn.

Recommendations for game moderators

When applying the game as a learning tool, having a game moderator that can build, run and explain the game will help enrich player understanding of the underlying game concepts. For instance, moderators can provide varying degrees of explanations regarding the water quality management concepts that are tailored to the player background knowledge, educational level (e.g., elementary school player vs. university student player) and interest levels. When moderating games, it was found that player teams consisting of two to five people were optimal. Larger groups are also possible, though the trade-off can be the reduced capacity of the moderator to facilitate discussions and answer questions. Additionally, a longer time frame is usually needed for larger groups to provide sufficient time for the deliberation of management actions and strategies each turn. In the event that a game moderator is leading a group of six or more players, a more stringent approach to the game may be implemented. Examples of this include a time limit for planning management actions each turn and designating responsibilities for the gameplay among the group, such as one player handling the Aquabucks while another moves the pollution pieces each turn.

Flipping Lakes as a sandbox model

Future applications of Flipping Lakes have the potential to explore new avenues of the game as a scientific sandbox/toy box. Flipping Lakes is specifically suitable as a model for scientific experimentation as there is a full knowledge of pollution sources, lake pollution threshold values and management effectiveness within the game-world. Such a situation is seldom encountered in real-world cases on a catchment-scale (*see*, e.g., van Gils et al. 2019). Therefore, the game may serve as a fictitious arena to experiment with scientific questions revolving around water quality management and decision-making (e.g., a form of a social ecological model, [Mooij et al. 2019]), such as single player vs. group decision-making or human vs. artificial intelligence in finding optimal solutions to winning the game. Along with these applications, we encourage and support the community (through the open availability of the game) to create new and previously unforeseen uses of Flipping Lakes in communication, education and science.

Concluding remarks

Translating water quality issues to a broad audience is necessary to maintain social support for managing the often invisible pollution of our catchments (Dean et al. 2016). Learning and working together to create fictitious solutions, such as with utilizing Flipping Lakes, can stimulate discussions around real-world issues. Importantly, the simplified and structured nature of the game makes participants relay their perspectives and insights in terms of the same tangible system and challenges being presented to everyone (Eisenack 2013). This creates a playing field disconnected (in part) from their real-world stakes (Flood et al. 2018). Being on the same page, or the same board in this case, can translate sectoral terminology into a joint understanding of the water quality issues faced by our lakes.

Author contribution statement

M.A. and S.T. were responsible for the core conceptualization of Flipping Lakes and a first card and game design with assistance from L.S., D.v.W. and W.M. Improvements to the game design and setup were made with help from L.K. and D.v.W. Trial runs of the game were executed by M.A., L.K., D.v.W., A.G., and S.T. L.K. and S.T. analyzed the result of the perceived learning experiment. M.A., L.K., A.G., and S.T. made the first outline of the manuscript which was greatly improved with help from L.S. and D.v.W. M.A., L.K., and S.T. wrote a first draft of the manuscript with all authors supplying valuable comments and suggestions that led to the final manuscript. All authors contributed to the improvements to the manuscript in response to comments from the reviewers and editors.

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Conflict of interest

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