IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 16 April 2024, accepted 13 May 2024, date of publication 27 May 2024, date of current version 4 June 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3405567

RESEARCH ARTICLE

H_2O-EduK, A Serious Game for Children to Educate on the Urban Water Cycle

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This work was supported in part by Ministerio de Ciencia, Innovación y Universidades (MCIN)/Agencia Estatal de Investigación (AEI)/10.13039/501100011033 under Grant PID2022-137647OB-I00, and in part by European Regional Development Fund (ERDF) a way of making Europe by European Union.

ABSTRACT Various educational resources have been incorporated into school curricula to support water education and related topics. In this paper, we present and test H_2O-EduK, a serious game designed to introduce the urban water cycle to school children. H_2O-EduK comprises seven mini-games designed to simulate the journey of pollutants generated from household activities and their impact on water quality. The game replicates this journey through pipes, wastewater treatment plants, and into rivers. To evaluate the game, we implemented two testing scenarios. In the first scenario, during last year's Science Week, H_2O-EduK was installed on two devices for children to play voluntarily. After playing, 18 participants aged 10 to 12 (that passed all the mini-games) answered three questions focused on game enjoyment, mechanics, and clarity of instructions using a smiley face rating system representing five levels of satisfaction. In the second scenario, 74 students aged 10 to 12 from two schools were divided into groups of 10 to 15 members. During one-hour sessions, they individually played the game and completed pre- and post-tests. A t-test was used to evaluate answers collectively and question-by-question independently. In the first test focused on game enjoyment, mechanics, and instructions, nearly 90% of participants expressed high satisfaction with the game, while approximately 70% indicated an understanding of their tasks. The results from the school tests indicate a significant improvement in students' understanding of water cycle principles after playing the game. Post-test scores averaged 1.054 points higher than pre-test scores. Additionally, the question-by-question evaluation highlights areas of particular efficacy within the game, underscoring its potential to address specific learning needs H_2O-EduK demonstrates its suitability for educational purposes, offering an engaging and effective platform for learning.

INDEX TERMS Gamification, serious games, urban water cycle.

I. INTRODUCTION

Water education is a main school curriculum topic, from early childhood through high school. It is an integral subject that explores, among others, the importance of water for life, the water cycle's complexity, the water's properties, related vocabulary, and challenges like water scarcity and sanitation. The depth of these topics increases as students progress through their education [1]. By learning about water, students develop responsible consumption habits and a sense of care and respect for the environment [2]. Different materials and activities have been designed for educators to convey these concepts effectively. Beyond traditional resources like text, audio, and video, a wealth of guides and examples exist to facilitate the preparation of experiments and more engaging student activities. Furthermore, in recent years gamification techniques and serious games have emerged as valuable strategies to incorporate in this context.

Gamification uses game design elements in non-game environments to make learning more motivating and

The associate editor coordinating the review of this manuscript and approving it for publication was Laxmisha Rai.

engaging [3]. It is applied across various fields, including commerce, tourism, health, industry, and education [4], [5], [6], [7]. One step further from gamification are serious games, i.e., games that entertain, teach, or transmit some knowledge [8]. These games can simulate real-life situations in a safe and controlled way providing a range of advantages that contribute to enhanced learning, skill development, and decision-making, among others. Serious games' popularity has grown considerably with demonstrably positive impacts in different areas including education, healthcare, and professional training.

In the water context, several serious games addressing water management and mainly targeted to adult audiences have been developed [9], [10]. Among them, there are serious games focused on urban water management that provide decision-makers scenarios to experiment with and learn from [11], [12], and [13]. Other examples are the Invitational Drought Tournament (IDT), proposed by Hill et al. [14], a goal-oriented game that educates and trains participants in decision-making skills around drought and water management, or the IDT extension, proposed by Muste et al. [15], that includes multiple hazards such as flood, drought, or water quality, and a model-based interactive decision-support system. Focused on water distribution, Morley et al. [16] proposed a game to optimize it, and recently, Khoury et al. [17] a serious game showcasing circular economy in the urban water cycle. For more examples please see [18]. Note that most of the described games have been designed as simulation environments and intended for users who are experts in the subject.

In this paper, we present H_2O-EduK, a serious game designed to introduce the urban water cycle, i.e., the process by which water is used, treated, and returned to the environment. It is targeted at children aged 10-12, since these are the ages students often study the principles and main processes of the water cycle, including topics such as water purification plants. H_2O-EduK takes players on a journey following the urban water cycle. Through a series of engaging mini-games that start with wastewater from homes and end in a river, players learn the main steps of the urban water cycle (excluding drinking water production and distribution) and how water quality can be improved. The game also includes educational pop-ups featuring game characters explaining key water concepts, making in this way H_2O-EduK a valuable teaching tool. This paper aims to present the game and the tests that have been carried out to evaluate its enjoyment and its potential as a teaching resource. Through these tests, conducted at a Science Event in Girona and at two schools within the city, it will be demonstrated that players enjoyed the game and that a significant improvement in students' understanding of water cycle principles was achieved after playing.

Besides this Introduction, the paper has been structured as follows. The proposed game and the testing scenarios are described in Sections II and III, respectively. In Section IV, Results are given, and Conclusions and Future Work are presented in Section V.

II. THE H_2O-EDUK GAME

Designing serious games is challenging because, in addition to fun and entertainment, they must introduce serious content, i.e., specific concepts for players to learn while playing. To present the key decisions we made for H_2O-EduK design, we will first focus on the educational aspects and then on the gameplay elements. The development team benefited from the expertise of serious game design specialists and researchers from the Catalan Institute of Water Research (Institut Català de Recerca de l'Aigua, in catalan).

A. KEY DESIGN DECISIONS FOR EDUCATIONAL CONTENT

To ensure the educational effectiveness of H_2O-EduK, the development team, in collaboration with water resource experts, focused on the main key elements that need to be taken into account such as training content, assessment strategy, training environment, and instructional strategy. Experts evaluated each one of these elements and made the following decisions.

- To define the *Training Content*, i.e., the knowledge and skills that need to be transmitted, two primary goals were considered: (i) understanding how daily actions affect water quality and (ii) understanding how water treatment plants improve water quality. The ultimate goal is to establish the link between human activities, water quality changes, and the environment, with a specific interest in treatment plant processes. To reach these objectives, common household actions and their impact on the water were identified and prioritized. Particularly, actions such as showering, washing dishes, and medication use were considered, along with the pollutants they generate and their impact on water quality. The treatment plant phases and the different processes that are carried out were also taken into account. Key procedures of each phase were suggested as the gameplay basis. In addition, to enhance player engagement and knowledge retention, two in-game narrators, based on real-world water resource specialists, were integrated into the game. They will provide game instructions and information about the urban water cycle as embedded educational modules.
- To define the *Assessment Strategy* that evaluates player performance, a rewarding system (or game economy) was defined. The reward system aims to make players conscious of the impact of actions and processes performed in the game. Water quality, money spent, and game points were defined as the key parameters of the reward system. All player actions will influence one or more of these parameters, with water quality being the most crucial factor.

FIGURE 1. The main characters of the serious game, in addition to pollutants, oxigen, water, and bacteria are illustrated.

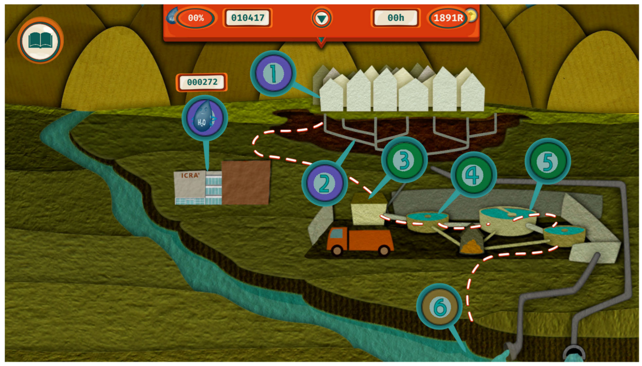

FIGURE 2. The main interface represents the urban water cycle with stopping points that indicate mini-games. The icon's color indicates if the mini-game has been completed or not and the water icon indicates the current state.

- To define the *Training Environment*, i.e., the space where the training will be conducted, a multiplatform and multilanguage solution was considered. The game will run on personal computers and mobile devices such as tablets and smartphones. In addition, different interaction modes will be supported to give the game flexibility enough to be used as a classroom supplement, complementing teacher-led sessions, or as a standalone learning tool. Note that the game's embedded educational modules reinforce the information presented by the in-game characters, making it suitable for independent use.
- The *Instructional Strategy* outlines the sequence and organization of learning content, guiding users toward achieving the game's objectives. H_2O-EduK will apply a ''learning-by-doing'' approach, a common strategy in serious game design where players reproduce in a virtual scenario the actions to learn [19].

B. ENTERTAINMENT PART

With the serious goal in mind, to design the entertainment part of the game, the four main elements involved in a game design process, i.e., the story, the aesthetics, the mechanics, and the technology, were considered [20].

- The *Story* defines the sequence of events that take place in the context of the game [20]. In H_2O-EduK, a simple story is proposed which consists of tracking the pollutants, generated in household actions, throughout the urban water cycle to finally observe how they impact the environment, particularly on the river's water. The game characters and the hub that allows players to access different mini-games are illustrated in Figures 1 and 2, respectively.
- *Aesthetics* refers to how the game looks and sounds and has the most direct relationship to a player's experience [20]. In our game, we selected a paper cutout style aesthetics (see Figure 2). Characters are depicted with small bodies and large heads, giving them a cute and childlike appearance (see Figure 1).
- The core *Mechanics*, defined by Schell [20], establishes the game's rules, goals, and player actions. To maintain player engagement, each of the seven mini-games that compose H_2O-EduK utilizes unique mechanics that challenge players. The game implements a tiered reward system based on points, money, and water quality. Money earned in the first mini-game covers the costs of actions related to water treatment or conservation efforts in subsequent mini-games. While water quality can decrease in the second mini-game, it can improve in others through correct choices, such as selecting water-efficient appliances or practicing proper disposal methods. A detailed description of each mini-game is given in Section II-C. In addition, in Table 1 for each mini-game the relationship between learning objectives and game challenges is presented.
- The *Technology* can be presented as the medium in which the aesthetics take place, the mechanics will occur, and through which the story will be told [20]. The game prioritizes accessibility by requiring only internet access and utilizing two-dimensional responsive graphics. This responsive design ensures adaptation across various devices, including smartphones, tablets, and computers. More technical details are given in Section III.

C. H_2O-EDUK MINI-GAMES

Each mini-game represents a stage in the water cycle, corresponding to the icons in Figure 2. Players must progress through the mini-games following the indicated path, as the outcome of one mini-game affects the starting conditions of the next. The mini-games utilize a unified reward system, where players earn points, spend money, and see the impact on water quality, with the final aim of achieving maximum water quality.

The name and main details of each mini-game are summarized below.

1) *Characters Presentation*. The first mini-game, set in a laboratory, introduces players to the game's main

TABLE 1. For each mini-game, the relationship between the learning objectives and the game challenge is presented.

MINI-GAME	LEARNING OBJECTIVE	GAME CHALLENGE
Characters Presentation	Identify pollutants. Relate basic actions with water pollution	Match pollutants with correct actions quickly and accurately before the flask breaks.
Household Actions and Pollutants	Identify sources of household pollutants.	Manage multiple household activities simultaneously and correctly assign them to corresponding rooms within a limited time.
Sewer System Maintenance	Identify and address sewer system problems	Identify problems promptly and select the appropriate tools for repair.
Sewer Plant Screening	Learn about screening wastewater at treatment plants. Differentiate pollutants from other materials. Importance of removing pollutants to maintain equipment	Balance energy consumption while controlling the screening process effectively to remove pollutants without causing equipment damage.
Oils, Greases, and Sand Removal	Methods to remove oils, greases, and sand. Importance of separation techniques in wastewater treatment plants. Consequences of ineffective removal on water quality.	Maintain optimal air levels and timing to ensure efficient removal of oils, greases, and sand.
Biological Treatment	Role of bacteria in biological wastewater treatment. How pollutants are broken down by bacteria in aerobic tanks. Importance of maintaining optimal conditions for bacterial activity.	Manage bacteria levels and pollutant reactions efficiently to meet the required number of reactions within a limited time.
Natural Pollutants Removal	Impact of untreated wastewater and solid waste on river ecosystems. Enhance natural pollutant removal with human intervention. Importance of effective waste management practices.	Collect solid waste and prevent pollutants from reaching fish while balancing various interventions to maintain a healthy river ecosystem.

FIGURE 3. Screenshots of H_2O-EduK mini-games corresponding to: (a) Characters Presentation; (b) Household actions and pollutants; (c) Sewer system maintenance; (d) Screening; (e) Oil, grasses and sand removal; (f) Biological treatment and (g) Natural pollutants removal. The last images (h) and (i) show the two narrators that provide help to the player. The book icon integrated in all the mini-game gives access to help and teaching capsules. ***To play the game access at https://play.google.com/store/apps/details?id=com.gilab.H2Oeduk.*.**

characters, the pollutants. Players match basic actions and products, represented by pictures or symbols, with the pollutants that move into a laboratory flask (see Figure 3(a)). Correct matches earn money and points, while incorrect matches damage the flask. If the flask breaks completely, the game restarts.

2) *Household Actions and Pollutants*. This mini-game (see Figure 3(b)) focuses on how pollutants are generated in households. Players view house rooms connected to a sewer system and a billboard displaying icons depicting activities like washing dishes or flushing medications. Players drag these icons to the corresponding rooms, learning how everyday actions can create pollutants. The game emphasizes the impact of used oil and improper disposal of towels. Correct actions award points, while incorrect actions damage the billboard. If the billboard breaks, the game restarts. To illustrate the additional issue of improper waste disposal, the mini-game randomly simulates rain, showing how garbage can also enter the sewer system.
3) *Sewer System Maintenance*. This mini-game highlights the importance of sewer system maintenance, building upon the concepts from the *Household Actions and Pollutants* mini-game. Players take on the role of sewer maintenance workers, identifying problems like cracks or clogs (see Figure 3(c)). They then choose the appropriate tool icon, represented by an icon (trowel and cement for repairs, pressure washer hose for clogs), and apply it to the correct location on the sewer system. This reinforces the importance of proper maintenance for a functioning sewer system. Correct actions give points, while incorrect ones generate cracks in the pipes. Money is spent on tools or actions used during the mini-games.
4) *Sewer Plant Screening*. This mini-game simulates wastewater treatment plant screens. Players manage their energy consumption by monitoring gauges on either side of the screen while controlling two bladed wheels designed to collect waste (see Figure 3(d)). The goal is to sort out pollutants, rags, wood fragments, or plastics from the incoming wastewater to prevent them from clogging pipes or damaging equipment. Correct sorting awards points, while incorrect sorting returns the residue to the water stream.
5) *Oils, Greases, and Sand Removal*. This mini-game teaches about oil, grease, and sand removal during wastewater treatment (see Figure 3(e)). Players manage air levels by clicking the oxygen icon, allowing grease and oil to rise to the surface and sand to settle at the bottom. Visual indicators show when enough oil has accumulated, prompting players to trigger the collection system represented by icons depicting blades. Correct timing grants points, while mistakes shuffle oil, grease, and sand, hindering the removal.
6) *Biological Treatment*. This mini-game simulates the biological treatment stage at the wastewater treatment plant, where bacteria break down organic matter in sewage and convert ammonium into nitrogen gas. Players manage bacteria levels in aerobic tanks by feeding them with pollutants and oxygen whenever needed (see Figure 3(f)). The number of pollutant-bacteria reactions required is displayed on the top of the screen. Correct actions award points, while incorrect actions have no effect.
7) *Natural Pollutants Removal in rivers streams*. This final mini-game highlights potential effects of pollutants that escape from wastewater treatment on the river ecosystems. In addition, it illustrates several human interventions that can enhance the natural removal of these pollutants (see Figure 3(g)). It represents a river, with fishes, receiving treated water from a wastewater treatment plant and from combined sewer overflow structures that eventually discharge diluted untreated wastewater during a rain event. Human interventions that help restore river streams enhance the natural removal of pollutants. These interventions are related to the presence of stones, tree roots, and fallen trees which promote biochemical processes. The discharge of untreated wastewater, or water runoff, often carries human solid waste such as wet wipes, plastic bottles, and other debris, which ultimately find their way into river streams. It is imperative to remove this solid waste before it causes damage to ecosystems. In this mini-game, players must collect solid waste and deposit it into designated containers. If solid waste is not removed and reaches fishes, they will die. Similarly with pollutants, if human interventions are not effectively executed, pollutants will reach fishes and they will die. Correct actions give points while incorrect ones let the waste pass through to the fish impacting them.

These mini-games provide a comprehensive overview of the urban water cycle process. Beyond the core objectives of (i) highlighting the impact of everyday household actions on water quality and (ii) demonstrating how water treatment plants contribute to its improvement, H_2O-EduK also emphasizes the importance of (i) *sewer system maintenance* which reinforces the idea that proper wastewater management is crucial for environmental health and (ii) *in-stream pollutant removal* showcasing how elements like stones, tree roots, and fallen trees within rivers contribute to water-self purification (see Table1).

III. GAME IMPLEMENTATION

H_2O-EduK game leverages Unity3D, a widely-used cross-platform game engine, enabling efficient development of multi-platform games for desktops (Windows, Mac), mobile devices, and web browsers. C#, a high-level, object-oriented programming language well-suited for game development, was chosen for the game's core logic implementation.

The game utilizes a scene-based structure where: (i) The *Loading Scene* initializes game resources, such as the JSON-formatted translation files [21] required for user interface elements; (ii) The *Urban Water Cycle Map* scene acts as a hub, providing access to mini-games as players meet specific requirements and (iii) The mini-game Scenes where each mini-game has its dedicated scene, linked to

TABLE 2. Formulated questions to participants of the 2023 Science Week testing session and the results of their responses.

	1	2	3	4	5	mean	deviation
Do you think that by playing the game you have learned important things about the urban water cycle	0	0	0	0	18	5	0
	0%		0%	100%			
Did you have fun playing the game?	0	0	2	3	13	4,611	0,698
	0%		11%	89%			
Did you understand well what you had to do in each mini-games?	1	0	3	4	10	4,222	1,114
	5%		17%	78%			

a *LevelData script* that defines level parameters like time limits, scoring rules, and failure conditions. Additionally, each mini-game scene includes a tutorial and theoretical material to complement the serious purpose.

A key strength of this implementation is its scalability which allows new mini-games to be easily added to the project without modifying existing ones.

IV. TESTING SCENARIO

Two scenarios were considered for the H_2O-EduK testing, the first one in the context of 2023 Science Week held in Girona and the second one in two schools of Girona. The details of these testing scenarios are given below.

A. TESTING AT 2023 GIRONA'S SCIENCE WEEK

Science Week is a communication initiative that takes place every year in Girona (and in many other countries). It features a wide range of multidisciplinary activities for scientific and technological dissemination including seminars and round tables, open houses at research centers and museums, workshops, courses, and exhibitions. There are activities, prepared by universities and research centers, open to participants of all ages and backgrounds with special sessions for children. In the context of these activities, ICRA prepared one for children to present H_2O-EduK. With this aim, the game was installed on two devices, for children to play. After playing, if the player was aged 10 to 12 and completed all the mini-games, they answered three questions (see Table 2) The smiley face rating system (with five colored buttons representing different levels of satisfaction, ranging from a happy face to an unhappy face) was considered.

B. TESTING AT SCHOOLS

The game was also tested in two schools with students aged 10 to 12 (3rd cycle of primary education). A total of 74 students participated (25 from one school and 49 from the other). There was no selection process for the students other than being members of the class. For the testing sessions groups of 10 to 15 members were considered.

The Experts from the Catalan Institute of Water Research conducted the testing sessions. Guided by teachers' testing sessions were organized as follows:

1) Introduction (5 minutes): A brief presentation introduced Catalan Institute of Water Research mission and the game's objectives. Participants also received instructions for the session;
2) Pre-test (15 minutes): Before playing students answered a pre-test consisting of 9 multiple-choice questions (see Table 6 in Appendix);
3) Gameplay (30 minutes): Students played individually the game for 30 minutes on the tablets provided; and
4) Post-test (15 minutes): After playing, students completed a 9 questions post-test covering the same topics as the previous one but using different questions(see Table 7 Appendix).

After each part, a short pause is taken to address any potential doubts, and then the next part begins. Regarding gameplay, all students completed all the mini-games.

The questions of pre- and post-playing tests were prepared considering the key stages of the urban water cycle. The relationship between each mini-game, the topics to evaluate, and the pre- and post-tests questions are summarized in Table 3.

V. RESULTS

Results will be presented considering the two testing scenarios.

A. 2023 GIRONA'S SCIENCE WEEK EVALUATION

The results from the first testing scenario, the 2023 Science Week activity, have been collected in Table 2. From this table, it can be seen that all participants who played the game considered that they learned something about the urban water cycle. Regarding game fun, 89% of participants enjoyed the game very much while 11% felt neutral. Regarding game mechanics and provided instructions, 78% of participants understood what they had to do, 17% felt neutral and 5% did not understand what to do.

Although the results are promising, they are not representative since only players who played all the games were asked to answer the questions (only 18 from almost 100 participants). The low participation in responses was attributed to having only two devices available for gameplay. Participants did not complete the survey at the end of the game. To address this issue, we have integrated a survey system into the game that

TABLE 3. Relationship between pre- and post- tests questions (represented as Pr and Po) with the serious content presented in the game (represented as Sc).

Correspondence between pre-, post-tests questions and the serious content of the game		
Q1	**Pr**	What happens if you flush wet wipes down the toilet?
	Po	Do you think it's correct to flush wet wipes down the toilet?
	Sc	*Waste management*
Q2	**Pr**	What should be done with expired medications?
	Po	Is it correct to flush expired medications down the toilet?
	Sc	*Waste management*
Q3	**Pr**	What should be done with used oil?
	Po	Do you think it's correct to pour used oil down the sink?
	Sc	*Waste management*
Q4	**Pr**	Do you think the water from the toilet and the sink go to different places once they leave the house?
	Po	Where do you think the dirty water from the house ends up?
	Sc	*City sewer system*
Q5	**Pr**	Do you think it's common for wastewater pipes to become clogged?
	Po	Do you think it's common for wastewater pipes to become clogged?
	Sc	*Proper maintenance of the city sewer system*
Q6	**Pr**	Do you know the function of a wastewater treatment plant?
	Po	What would happen if there were no wastewater treatment plants?
	Sc	*Wastewater treatment plants.* Function and importance in the urban water cycle
Q7	**Pr**	Do you know what happens to the water once it has been treated at the wastewater treatment plant?
	Po	What do you think is the correct order?
	Sc	*Key stages of the urban water cycle*
Q8	**Pr**	Do you think rocks and logs found in rivers contribute to removing dissolved contaminants from the water?
	Po	Is it beneficial to have a river with many rocks and logs?
	Sc	*Natural removal capacity of contaminants through the river*
Q9	**Pr**	Is the water completely clean when it reaches the river?
	Po	What organisms do you think live in a river?
	Sc	*Importance of our actions. How they affect river organisms*

requires participants to respond to receive their final score. In this way, it will be easier for us to gather information from all participants. We plan to test the game in other promotion sessions organized in our region.

B. SCHOOLS EVALUATION

To evaluate the outcomes of the second testing scenario, the responses of each player's pre- and post-tests were analyzed. Each answer was categorized as either incorrect (-1), unanswered (0), or correct (1). The t-student test, which is suitable for paired data analysis, will be employed to ascertain whether there exists a statistically significant difference in learning outcomes before and after playing H_2O-EduK game. Two separate analyses were conducted: one assessing all questions collectively (referred to as the *Global analysis*), and another examining each question independently (referred to as the *By questions analysis*)

1) GLOBAL ANALYSIS

For the global assessment, the cumulative scores from all pre- and post-test questions were totaled, enabling an observation of the extent of player learning following game participation. The results are presented in Table 4. Players demonstrated

TABLE 4. Global evaluation. Results of pre- and post-tests and comparison of pre- and post-game answers collectively.

Pre-test		Post-test	
Mean	Deviation	Mean	Deviation
4,797	1,872	5,851	3,064

Pre- and post comparison			
Mean	Deviation	Statistic	p-value
1.054	3.281	2.764	**0.003**

TABLE 5. By question evaluation. Comparison of pre- and post-tests answers considering questions independently.

Question	Mean	Deviation	Statistic	p-value
1	0	0.597	0	0.5
2	0.094	0.528	1.542	0.062
3	0.243	0.658	3.179	**0.001**
4	0.054	0.7	0.664	0.253
5	0.243	0.616	3.402	**0.001**
6	0.216	0.556	3.347	**0.001**
7	0.149	0.676	1.891	**0.029**
8	0.041	0.607	0.575	0.283
9	0.203	0.641	2.722	**0.003**

an acquisition of previously unfamiliar concepts, with an average increase of 1.054 correct answers post-game. Moreover, a p-value of $0.003 < 0.05$ was obtained, indicating rejection of the null hypothesis and signifying a significant difference in results pre- and post-game, independent of each other.

2) BY QUESTIONS ANALYSIS

For the question-by-question analysis, it is important to remember that each question relates to a particular theme and corresponds to one of the mini-games (see Table 3). Using the same methodology as in the previous case, pre and post-test answers were assessed question by question using t-test. The obtained results are presented in Table 5. Note that questions 3, 5, 6, 7, and 9 exhibit p-values below 0.05, indicating areas where students experienced a significant learning enhancement after playing the game. On the other hand, questions 1, 2, 4, and 8 indicate the necessity for additional refinement in the game design to enhance knowledge retention. Different actions can be carried out to overcome detected limitations.

VI. CONCLUSION AND FUTURE WORK

The goal of this research was to enhance education on water and related topics by introducing new teaching resources, specifically through the use of serious games. The study presents the design, implementation, and evaluation of H_2O-EduK, a serious game created to teach children about the urban water cycle. Aimed at students aged 10 to 12, the game reproduces the journey of pollutants through water and the processes involved in improving water quality. The game was tested with 74 students in this age group to assess its impact on their comprehension and retention of water cycle concepts. The results showed a significant improvement in students' understanding of water cycle principles after playing the game. Additionally, despite a small sample size of only 18 participants for the enjoyment evaluation, the results were highly satisfactory.

The findings of this study align with existing literature that highlights the effectiveness of serious games as educational tools. The significant enhancement in students' understanding supports theories that interactive and engaging learning methods can improve comprehension and retention of complex scientific concepts. These results suggest that incorporating serious games into educational curricula can bridge the gap between theoretical knowledge and practical understanding, providing a dynamic and effective learning experience.

The results of this study are highly relevant to educational practitioners and curriculum developers. By demonstrating that serious games like H_2O-EduK can effectively teach complex concepts such as the urban water cycle, this research supports the integration of gamified learning tools into educational programs. Schools and educational institutions can adopt similar serious games to foster student engagement and improve learning outcomes in various subjects. Additionally, policymakers and educational managers can leverage these findings to advocate for increased investment in educational technology and innovative teaching methods.

While the study provides valuable insights, it has several limitations. The sample size for the enjoyment evaluation was relatively small (only 18 participants), which may affect the generalization of the results. Additionally, the study focused on a specific age group (10 to 12 years), limiting the applicability of the findings to other age groups. The testing was conducted in a controlled environment, which may not fully replicate real-world educational settings.

Future research should address the limitations identified in this study. Expanding the sample size and including a more diverse age range would provide a more comprehensive understanding of the game's effectiveness. Further studies should also explore the long-term impact of serious games on knowledge retention and application. Additionally, refining and expanding the mini-games within H_2O-EduK to cover more aspects of the urban water cycle could enhance learning outcomes. Researchers should also investigate the potential of integrating serious games into different educational contexts and subjects to further validate their efficacy as educational tools.

DECLARATIONS

a: CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

b: OPEN ACCESS

TABLE 6. **The questions with possible answers responded before playing the video game.**

PRE-TEST QUESTIONS WITH POSSIBLE ANSWERS
Q1. What happens if you flush wet wipes down the toilet?
a) It could cause a blockage in the city's pipes b) Nothing, wet wipes dissolve upon contact with water c) It serves as food for the fish, so it is beneficial
Q2. What should you do with expired medications?
a) Flush them down the toilet b) Store them and throw them in the waste bin c) Store them and take them to the special containers found in pharmacies
Q3. What should you do with used cooking oil?
a) Store it and take it to the nearest recycling point b) Store it and throw it in the waste bin c) Pour it down the kitchen sink
Q4. Do you think toilet water and sink water go to different places once they leave the house?
a) Yes, one goes directly to the river and the other needs to be treated at the wastewater treatment plant b) No, both go directly to the river c) No, both are routed to a wastewater treatment plant
Q5. Do you think it is common for the pipes that transport wastewater to become blocked?
a) No, the pipes are large enough b) Yes, they can become blocked when we flush wet wipes or oil down the toilet c) Yes, but they only get clogged when it rains heavily
Q6. Do you know what the function of a wastewater treatment plant is?
a) Purify water so that we can drink it b) Treat dirty water that comes from our homes to remove contaminants c) Clean the water that comes from cities, purify it, and return it to the river
Q7. Do you know what happens to water once it has been treated at the wastewater treatment plant?
a) It is bottled and sold as drinking water b) It is conveyed to the river or the sea c) It is redirected to cities to be reused
Q8. Do you think rocks and logs found in rivers help remove contaminants dissolved in the water?
a) They do not affect the river b) No, on the contrary, they further pollute the water c) Yes, they harbor bacteria capable of removing remaining contaminants from the water
Q9. Is the water completely clean when it reaches the river?
a) Yes, because all contaminants have been removed at the wastewater treatment plant b) No, the wastewater treatment plant cannot remove all contaminants c) Water is never completely clean, as the fish living in it are constantly polluting it

DATA AVAILABILITY

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

TABLE 7. The questions with possible answers responded after playing the video game.

POST-TEST QUESTIONS WITH POSSIBLE ANSWERS
Q1. Do you think it's correct to flush wet wipes down the toilet?
a)Yes, they dissolve in contact with water, just like toilet paper. b)No, when mixed with water and other waste, they cause major blockages in the pipes. c)No, because they are not pollutants and serve as food for fish.
Q2. Post. Is it correct to flush expired medications down the toilet?
a)No, they are pollutants and should be disposed of in special containers. b)Yes, if the medications have been expired for over 10 years. c)Yes, if they are tiny pills.
Q3. Do you think it's correct to pour used oil down the sink?
a)Yes, but since it's poured in small amounts, it dissolves in water and is harmless. b)No, it's fish food. c)No, it can contribute to the clogging of wastewater pipes.
Q4. Where do you think the dirty water from the house ends up?
a)At Aqualandia. b)At a wastewater treatment plant. c)At a water treatment plant.
Q5. Do you think it's common for wastewater pipes to become clogged?
Yes. No.
Q6. What would happen if there were no wastewater treatment plants?
a)There would be more fish since they would have more food to survive. b)River organisms would disappear because the water would be contaminated. c)Nothing would happen because contaminants degrade quickly in rivers naturally.
Q7. Which sequence do you think is correct?
a)House; 2. Pipes; 3. Wastewater treatment plant; 4. River b)River; 2. Pipes; 3. Wastewater treatment plant; 4. House c)Wastewater treatment plant; 2. River; 3. Pipes; 4. House
Q8. Is it beneficial to have a river with many rocks and logs?
a)Yes, they help grow algae and bacteria that allow for the removal of water contaminants. b)No, they block the flow of water and can cause stagnation and bad odors. c)Yes, they serve as a net to trap large contaminating waste.
Q9. What organisms do you think live in a river?
a)Fish b)Fish and algae c)Fish, algae, bacteria, and other microorganisms

APPENDIX

See Tables 6 and 7.

ACKNOWLEDGMENT

The authors would like to thank Xabier Goenaga for his work on the game's implementation.

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