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A review of water-related serious games to specify use in environmental Multi-Criteria Decision Analysis

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Highlights

Multi-Criteria Decision Analysis (MCDA) needs tools to enable citizen participation

43 reviewed water-related serious games reveal diverse approaches and uses

Serious games in MCDA entail communicating about and with models (behavioral OR)

No existing serious game allows MCDA-compatible preference elicitation

Abstract

Serious games and gamification are nowadays pervasive. They are used to communicate about science and sometimes to involve citizens in science (e.g. citizen science). Concurrently, environmental decision analysis is challenged by the high cognitive load of the decision-making process and the possible biases threatening the rationality assumptions. Difficult decision-making processes can result in incomplete preference construction, and are generally limited to few participants. We reviewed 43 serious games and gamified applications related to water. We covered the broad diversity of serious games, which could be explained by the still unsettled terminology in the research area of gamification and serious gaming. We discuss how existing games could benefit early steps of Multi-Criteria Decision Analysis (MCDA), including problem structuring, stakeholder analysis, defining objectives, and exploring alternatives. We argue that no existing game allows for preference elicitation; one of the most challenging steps of MCDA. We propose many research opportunities for behavioral operational research.

Keywords

Multi-Criteria Decision Analysis; sustainability; serious game; gamification; stakeholder participation; behavioral operational research

1. *Introduction*

This review paper aims at bringing together two fields of research, namely decision analysis and gaming, both being based on models. It focuses on environmental decision analysis related to water. Water is of undisputable importance for humans and the environment, but globally its use remains problematic. This is reflected in the many water-related Sustainable Development Goals set for 2030 (UN General Assembly, 2015). The paper starts with a brief introduction of prescriptive MCDA (Multi-Criteria Decision Analysis), specifically MAVT (Multi-attribute Value Theory; Keeney and Raiffa, 1976). Our aim is to identify improvement points, in particular regarding elicitation of preferences from the population. A concise overview of descriptive (behavioral) decision-making stresses that cognitive processes as well as emotions, attention, and motivation are important to achieve a mindful judgement (Weber and Johnson, 2009). We hypothesize that these emotional and motivational aspects can be addressed by gaming: using serious games or gamification. A manifesto opening the book *The Gameful World* claims that, after the century of image and information, we have entered the era of games and playfulness (Zimmerman, 2014). This results in gamification, namely using game design elements in non-game contexts (Deterding, 2012; Ramirez and Squire, 2014; Sicart, 2014). Serious games (Abt, 1970), i.e. games which are not meant to be played solely for entertainment (Mendler de Suarez et al., 2012), are equally widely spreading. Such games are starting to be used in the operational research community (Voinov et al., 2016). Voinov et al. (2016) argue that serious games are promising tools for participatory modelling due to (1) the stakeholders' engagement through intrinsic game motivational features, (2) the potential for interactive visualization, and (3) the ability to both create social learning and teach decision-making skills. This leads us to review existing serious games related to water issues.

The aim of this paper is to: (1) review water-related serious games to identify their characteristics, (2) highlight the possible match and mismatch between games and environmental MCDA, and (3) uncover associated research opportunities.

In Section 2, we briefly introduce MCDA. In section 3, we define the method used for reviewing the games. In Section 4, the review of 43 games leads us to define what a serious game is. We depict the high diversity according to two continua: low–high technology and low–high verisimilitude. In Section 5, we rely on this serious game definition to discuss the use of serious games and gamification for environmental MCDA. Section 6 consists of concluding words.

2. *Multi-Criteria Decision Analysis needs new tools*

2.1. Environmental decisions are messy and benefit from MCDA

Facing complex environmental management and policy problems, decision-makers may turn towards decision analysis methods. Environmental decisions are often controversial, i.e. stakeholder groups may disagree on the importance of the objectives they wish to pursue. They are also often characterized by (1) too few or too many decision alternatives (possible solutions), (2) many influencing factors, and (3) highly uncertain future outcomes (for reviews see e.g.: Gregory et al., 2012; Hajkowicz and Collins, 2006; Huang et al., 2011; Mendoza and Martins, 2006). Multi-Criteria Decision Analysis (MCDA) is an umbrella term for methods developed to tackle such messy decision situations (Belton and Stewart, 2002; Greco et al., 2016). Here, we focus on Multi-Attribute Value Theory (MAVT), based on axioms of rationality (Keeney and Raiffa, 1976). The philosophy of Value Focused Thinking (Keeney, 1996) is to first determine the values and preferences of stakeholders and then to evaluate the alternatives by calculating their overall performance regarding the achievement on a set of objectives.

2.2. Rational decision-making

MAVT is based on few, but solid axioms of rationality; essentially completeness and transitivity (Belton and Stewart, 2002; Eisenführ et al., 2010; Keeney and Raiffa, 1976). Completeness implies that a decision-maker can state her preferences (or indifference) concerning any pair of outcomes. Transitivity means that if one prefers alternative *a* over alternative *b* and *b* over *c*, then one should prefer *a* over *c*. Although sometimes violated by actual decision-making behavior, these axioms are hardly questioned as guiding principles. Furthermore, especially for larger environmental decisions that are financed by tax payers, it is desirable that decisions are transparent and justifiable to the public. Reichert et al. (2015) have presented in detail why MAVT is a good methodological choice for environmental decision-making, which satisfies important conceptual requirements. However, this is challenged in real applications as many factors, e.g. the response mode, context, or individual cognitive capacities, can affect people's choices (Payne et al., 1992).

2.3. MCDA/ MAVT step-by-step

In practice, MCDA starts with defining the decision context (Fig. 1). Problem structuring methods (Marttunen et al., 2017; Rosenhead and Mingers, 2001) such as cognitive mapping and stakeholder analysis (e.g. Lienert et al., 2013) are effective tools to frame the decision, decide what is important, and identify who makes the decision (decision-maker) or is affected by it (stakeholder). In the following, the term stakeholder will be used for anyone involved in the decision with responsibility, interest, and/ or decision power. Framing the decision includes generating a set of objectives, which are often organized in a hierarchy, and a set of decision alternatives (options). Usually the process starts with divergent thinking to capture the participant's different viewpoints. The decision analyst facilitates the participants to converge to a consolidated shared understanding of the problem (Franco and Montibeller, 2010; Kaner, 2014). Each objective is described with one or more measurable performance indicators, named attributes. Attributes quantify the objectives' achievement. For each alternative, the attribute of each objective is predicted using expert estimates, literature data, or simulation models (see textbooks, e.g.: Belton and Stewart, 2002; Eisenführ et al., 2010; Keeney and Raiffa, 1976). This is the "hard" science part of MCDA. In a next step, "softer" data are elicited: the subjective preferences of stakeholders (see section 2.4). This is commonly done in individual interviews or group workshops. Then, for each alternative, the predicted achievement of objectives and the stakeholders' preferences are integrated in a decision model to calculate an overall performance (value v(a) or utility u(a) of each alternative[1]). Practical applications mostly use a linear additive

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[1] Formally, the linear additive value model is: $v(a) = \sum_{i=1}^{m} w_i v_i(a_i)$

where:	*v(a)*	=	overall value of alternative *a (under risk, the value becomes utility)*
	a_i	=	attribute level of alternative *a* for attribute *i*
	$v_i(a_i)$	=	value for attribute *i* of alternative *a;* bounded to [0,1]
	w_i	=	weights (or scaling constants) of attribute *i*, and sum of w_i equals 1

The additive model is simple and intuitively understandable, but based on three strong axiomatic assumptions (Eisenführ et al., 2010):

- Simple preference independence (the preference of one objective does not depend on other objectives),
- Mutual preferential independence (generalization of the simple preference independence for any subset of the objective set)
- Difference independence, or compensation (the additional value attached to an improvement of objective does not depend on other objectives)

aggregation model. The assumptions of the additive model need to be tested with consistency checks during the elicitation of the stakeholders' preferences. Else, other models should be used (e.g. Langhans et al., 2014; Reichert et al., 2015). Finally, the results are discussed with the stakeholders and a consensus alternative is searched for. MCDA is often an iterative process.

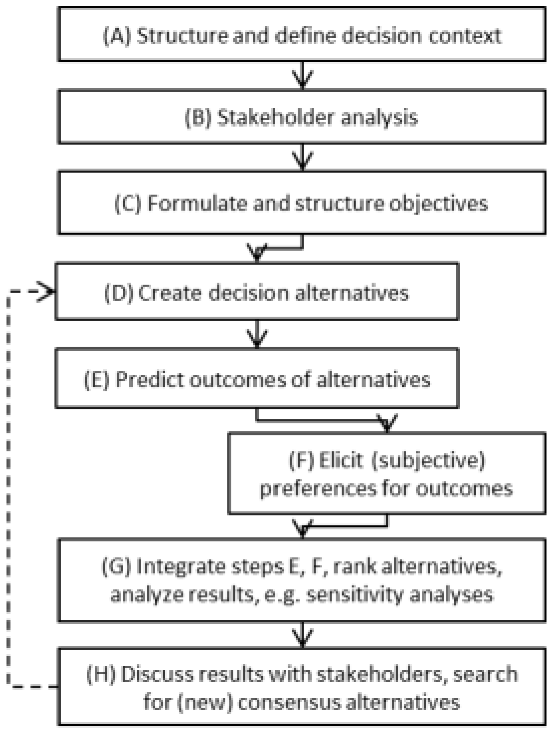

Figure 1: Multi-Criteria Decision Analysis process, step-by-step. (Adapted from Table 1 of Lienert et al., 2011)

2.4. Stakeholders' preference, the strength of MCDA

MCDA's strength is to combine hard sciences (the predictions) and softer data (the stakeholders' preferences). MCDA methods make explicit the inherent subjectivity of decisions: the expectations, objectives, and preferences of stakeholders regarding the achievement of and the trade-offs between objectives (value functions and weights, respectively) (Gregory et al., 2012; Scholten et al., 2017). In case of uncertainty, the value function is converted to a utility function using the elicited stakeholder's risk attitude (Multi-Attribute Utility Theory; Keeney and Raiffa, 1976).

Traditionally, economists assume that true preferences pre-exist, while decision psychologists (Slovic, 1995) postulate that tasks (response mode), context factors (experience, learning effort etc.), and individual abilities enable to construct preferences (Lichtenstein and Slovic, 2006; Payne et al., 1992). Thus, the decision analyst's role is to (1) verify that the axiomatic basis of MAVT is met, (2) ensure a transparent and fair procedure (understandable and meaningful to the participants, acknowledging all important views), and (3) facilitate preferences construction (by providing necessary neutral information, reducing the cognitive load, and limiting the occurrence of biases).

2.5. Focus on the importance of objectives: assigning weights

Weights reflect the preferences regarding trade-offs between objectives, i.e. the stakeholder's judgment on the relative importance of each objective. They quantify what matters in the decision. Asking directly for the weights (direct-ratio method) is the most straightforward method, however it is considered as highly problematic and other methods should be preferred (Eisenführ et al., 2010; Morton and Fasolo, 2009): e.g. the swing and trade-off methods. For a review on weight elicitation methods and their practical use see Riabacke et al. (2012), and for a review on methods validity see Van Ittersum et al. (2007).

2.6. The limits of current weight elicitation methods

High cognitive load. Assigning weights to objectives requires a significant mental effort for most stakeholders (Morton and Fasolo, 2009; Riabacke et al., 2012). This can be due to: (1) the lack of previous knowledge or information on the issue, and still unconstructed preferences, (2) the moral difficulty to make trade-offs when objectives are highly competing, and (3) technical reasons linked to the elicitation method (e.g. instructions are difficult to understand, cognitive tiredness created by repetitive tasks) (Chatterjee and Heath, 1996; Deparis et al., 2012; Payne et al., 1992; Riabacke et al., 2012). In other words, weight elicitation involves the three types of cognitive load distinguished in the cognitive load theory (van Gog and Paas, 2012): intrinsic (load related to the amount of information needed to be processed to perform the task, e.g. choice overload (Iyengar and Lepper, 2000)), extraneous (load imposed by the format in which the information is provided), and germane (how much effort an individual invests to understand the information). Moreover, it is influenced by the individual's prior knowledge (Brünken et al., 2003). Reaching cognitive load limits (overload) leads to situations where no further information can be mentally processed or considered, which can severely reduce the quality of elicited weights.

Biases. Weight elicitation is highly sensitive to biases (Hämäläinen, 2015; Hämäläinen and Alaja, 2008; Morton and Fasolo, 2009; Riabacke et al., 2012). Following biases occurring during weight elicitation were presented in the review of Montibeller and von Winterfeldt (2015): the affect influenced bias and desirability of option bias are motivational biases. Others are cognitive biases: the equalizing bias, gain-loss bias, proxy bias, range insensitivity bias, and the splitting bias. Describing all of them is outside the scope of this paper. If they occur, the weights may no longer represent the preferences of the stakeholder, which would distort the MCDA outcome. This problem is well-known in MCDA and an experienced facilitator will be attentive to avoid these biases, and use or develop methods limiting their occurrence, e.g. consistency check questions using another method.

Unconstructed preferences. Incompletely constructed preferences are unstable. They are especially critical for decisions with long term consequences (Gregory et al., 2012). Some consider that preference construction is a never-ending life-long learning process evolving with experiences and context (Amir and Levav, 2008; Warren et al., 2011), matching the transformative learning theory (see references in Merriam et al., 2007). Yet, factors such as the task or elicitation method (how the problem is presented, described, visualized, the task difficulty), knowledge/ expertise on the issue, and the experience of topic-connected events contribute to preference construction (Hoeffler and Ariely, 1999; Jorgensen et al., 2004; Liebe et al., 2012; Payne et al., 1992). The decision analyst can facilitate the construction and stability of preferences by influencing these factors. Defining the best practice is still an open research question (e.g. Anderson and Clemen, 2013).

Limited participation (time consuming, need of a facilitator). The limits mentioned above (i.e. high cognitive load, biases, and unconstructed preferences) justify that an experienced decision analyst elicits the weights. This is classically done in face-to-face interviews or in group workshops (Marttunen and Hämäläinen, 2008). However, both are time-consuming and strongly constrain the number of participants. This contradicts the increasing societal demand for participatory decision-making. Many studies within operations research (Gregory et al., 2016; Hämäläinen, 2015; Kellon and Arvai, 2011; Voinov et al., 2016), and e.g. in policy and governance (e.g. Dietz and Stern, 2008; Dupuis and Knoepfel, 2015; Étienne, 2011; Papadopoulos and Warin, 2007, and references therein; Renn, 2003), or transition management (e.g. Harris-Lovett et al., 2015), call for participatory decision-making. First approaches to increase citizen participation in environmental MCDA via online surveys yielded encouraging results (Bessette et al., 2016; Gregory et al., 2016; Lienert et al., 2016; Mustajoki et al., 2004). Certainly, online surveys have the advantage of reaching many participants and of speeding up the elicitation process. However, the validity of online preference elicitation has been questioned (Insua and French, 2010; Marttunen and Hämäläinen, 2008). These authors argue that direct interactions between respondents and decision analysts are the only way to prevent the occurrence of biases, to reduce the cognitive load, increase learning, and thus to enhance reliable preference construction. To involve the public and elicit reliable weights, MCDA needs an accessible tool, both literally (easy access for many) and figuratively (easily understandable and manageable).

2.7. Insights into people's judgements and descriptive decision analysis

While the above-introduced prescriptive decision analysis focuses on understanding and supporting rational decision-making processes, descriptive decision analysis focuses on how people actually make decisions (Fischhoff, 2010). Often, people's observed behaviors deviate from rationality principles. Both affect and cognition contribute to mindful decision-making (e.g. of descriptive decision reviews: Lerner et al., 2015; Oppenheimer and Kelso, 2015; Weber and Johnson, 2009), in particular the following four intertwined factors: (1) attention, (2) information processing, e.g. encoding, evaluation and memory processes, (3) emotions, and (4) learning. Each is briefly summarized hereafter.

Attention makes the participant notice the task and raise his/ her interest. It is selective and scarce. It can be exogenous, e.g. triggered by a changing environment that varies automatically, or endogenous, raising either deontological ("What is right?"), consequential ("What has the best outcomes?"), or affective ("What feels right?") considerations. The physical salience and endogenous attention influence thoughts of individuals (Kahneman, 2003), and thus choices and judgments. Judgements can be manipulated by increasing or reducing attention.

Information processing describes how the individual acquires information (encoding and evaluation) and retrieves it from memory. Information processing is most effective when it is context specific and in view of a clearly defined goal which make sense to the participant. Individuals seem to process information depending on how it is presented, how the task is formulated, how the available information is stored in memory, and depending on individual cognitive capacities. Some well-known biases can be explained by memory. The anchoring bias would result from short term memory: an individual is primed by a question preceding the decision task (Chapman and Johnson, 2000; Tversky and Kahneman, 1974). The endowment/ ownership or gain-loss biases would be caused by long term memory, and particularly how individuals retrieve long-term encoded information when making a decision. According to the query theory, the order of the information retrieval queries determine the decision (Johnson et al., 2007).

An ***Emotion*** “revolution” started in descriptive decision analysis around 2004, with a growing number of publications focusing on affect-, mood-, and emotions-driven processes (Lerner et al., 2015). Affect in decision-making would have four functions (Peters et al., 2006). (1) Emotions can act as a spotlight that raises attention. (2) Emotions can act as immediate or longer-term information. (3) Emotions can act as common currency, i.e. respondents compare alternatives by the different emotional states they create. Finally, (4) emotions can act as motivator, and different emotions seem to trigger different action tendencies. As an example, anger might drive a person to focus on motives and responsibility, which in turn raises an eagerness to act and punish.

Learning from experience and feedback is an important process in judgement and decision-making (Elwin et al., 2007). This learning is based on expected feelings about options (decision utility) and actual feelings when experiencing the options (experience utility). Complete and holistic feedbacks are necessary to make an accurate decision (Hogarth, 1987). It is noteworthy that many prescriptive decision analysts consider MCDA as a learning process (Gregory et al., 2012; Hämäläinen et al., 2001; Karjalainen et al., 2013; Marttunen and Hämäläinen, 2008). Five categories of “what is learnt” are proposed (Belton and Elder, 1994): (1) understanding logical relationships, (2) formulating so far not carefully analyzed opinions, (3) clarifying the implication of the now carefully analyzed opinions, (4) changing opinions, and (5) creating new ideas.

3. *Method used for the game review*

First, we carried out a literature review on serious games and gamification from 02.02.-01.03.2016 [2]. Then, we identified serious games on water issues. Water is a global, but also region-specific challenge. An explorative search was carried out, starting from already existing lists provided by the Geneva Water Hub platform (Geneva Water Hub, 2015) and the world water day website (World Water Day, 2015). Additional serious games on water-related issues were identified using internet searches (google, google scholar, and web of science), and publications which reviewed several games, e.g. lists of five persuasive games for water management (Rizzoli et al., 2014), of four games about water infrastructures (Söbke and Londong, 2014), and of 12 educational water games (Hoekstra, 2012). We also found games by word of mouth. For each game we aimed at finding associated scientific publications, which do not, however, always exist.

We used a structured, generalized procedure to define each game, filling in a table of characteristics (Tab. SI1, Supporting Information), inspired from Djaouti et al. (2011). These comprised: general information (game title, name of credit owner and/ or developer, year released, country in which it was developed, link to the online game and/ or references to scientific publication). Additional characteristics were the game's purpose (exchange data/ broadcast message/ training), short notes on the gameplay (type of actions in relation to the narrative, if any), player information (targeted player, number of player(s), type of interaction(s) during the game: player-facilitator/ player-player and/ or player-IT interface), note on how engagement was created (identified game elements), support of the game (technology used), spatiotemporal frame (length, possibility to interrupt, location), and domain of application (water issue, if specified country). The main author experienced all the online games. In case of non-online games (e.g. board games, group games), the author relied on the available instructions and/ or the associated publications.

The game diversity was then represented in a two-dimensional graph where the axes represent the technology (classes from low to high), and the degree of verisimilitude (adapted from Lane

[2] Serious gaming and gamification being topical, the authors acknowledge that more recent projects are already available, e.g. 'The Tragedy of the Groundwater Commons Game' from the International Groundwater Resources Assessment Center, the gamified Digital Social Platform of the POWER (Political and sOcial awareness on Water EnviRonmental challenges) EU project.

(1995), classes from simplified reality (fully-fledge games) to modeled complexity (gamified non-entertainment applications)). Serious games and gamification features are then discussed, viewed through the lens of MCDA. The reason for this specific focus is that decision analysis researchers and practitioners have been challenged to find innovative approaches for public participation and preference elicitation, as discussed in section 2.6.

4. Results on water-related serious games review

4.1. What is a serious game?

Games can be defined as unsolicited activity (therefore self-engaging, motivating by itself), either mental or physical, with no aim other than leisure or fun, framed with rules, which offers a chance to win or lose, and requires a variable proportion of skill, dexterity, and hazard (Larousse, 2015). Regarding rules, games belong to a continuum from the *ludus* (rule-following) game-type, which has many rules to reach a clear objective, to the *paidia* (playfulness, fun) game-type, which has no pre-defined goal and is thus a more freeform game. Games offer an escape from ordinary life, i.e. are characterized by a degree of fiction, and are most often framed in time and space (Juul, 2005; Schmoll, 2011). This frame has been named the “magic circle” (Huizinga, 1949), because specific rules, different from the real world, prevail. In their seminal book *Rules of play*, Salen and Zimmerman (2003) consider games as systems in which players engage in artificial conflicts defined by rules, and which result in a quantifiable outcome. These artificial conflicts can be of various types (Mendler de Suarez et al., 2012), including the intrinsic tension of games mentioned above between fun *(paidia)* and rules *(ludus)*. Similarly, the theory of Csikszentmihalyi (2000) postulates that enjoyment and intrinsic motivation (being in the “flow”) is created by a constant trade-off between the challenges (action opportunities) offered to the player, and her skills (action capabilities). There is a flow path of intrinsic motivation, surrounded by worry (same action capabilities, but too high challenge) and boredom (same action opportunity, but too high skill requirements).

From the game definition, it appears that “serious game” is by essence a paradoxical notion, i.e. “serious” versus “no aim but leisure and fun”. Probably due to this contradiction, definitions of “serious game” are numerous and differ to some extent. A commonly accepted trait is that serious games are not only entertaining, but also have a specific aim. Mendler de Suarez et al. (2012) define serious games as "games with an explicit and carefully though-out educational purpose – not intended to be played primarily for amusement". In his book *Serious Games*, Abt (1970) considered any types of games, including card and board games, while more recently many tend to reduce serious games to those including video or simulation components. For this review, any serious game type (with and without information technology) is considered. Another definition less prone to debate is that any *a priori* non-entertaining application, including game concepts, technologies, and ideas, is a serious game, thus including all the "gamified" applications (Seaborn and Fels, 2015). Serious games and gamified applications can be classified based on the Game-Purpose-Scope framework from Djaouti et al. (2011). "Game" focuses on the degree of action/ interaction referring to *paidia* vs. *ludus*. "Purpose" is divided into three classes: broadcasting a message, training, and exchanging data. "Scope" focuses on the targeted gamers/ players.

Since the 18th century, serious games have been successfully used in military training. For a long time, computer-game simulations have also been used in behavioral decision research (Payne et al., 1992). In the last decade, serious games combining computer simulation and role playing games have been developing in education, including teaching water management (e.g. Carruthers and Smith, 1989; Ewen and Seibert, 2016; Hoekstra, 2012), water governance and policy (e.g. Adamowski, 2015; Douven et al., 2014; Geurts et al., 2007), and other common-resource management fields (e.g. Barreteau, 2003; Cleland et al., 2012; Ulrich, 1997); as well as more generally in operations research, e.g. with the Beer game created in the 1960s by MIT Sloan School of management professors, still used today (e.g. Lane, 1995; Thompson and Badizadegan, 2015).

4.2. The diversity of serious games

We illustrate the diversity of the reviewed games in a two-dimensional graph (Fig. 2). The axes derive from the debated aspects of the serious games definition (1) the technology used (x-axis), and (2) the degree of verisimilitude (y-axis). The technology axis is divided into five classes: group games using no or little paraphernalia (e.g. using dices and polls; low-tech end of the x-axis), regular board games, board games combined with IT interface, IT interface on its own, and virtual reality games (i.e. a fully immersive video; high-tech end of the x-axis). The degree of verisimilitude is divided into four classes: gamified applications (serious end of the y-axis, in the sense modeling the complex reality as close as possible from reality, “S”), serious games using scientific models and real-world data (“s”), games using simplified models and real-world data (“f”), and fully-fledged games with a serious or moral topic (opposed to previous classes, by not using any scientifically based models or real-world data in the game mechanics; end of the y-axis, further away from the complex reality, “F”).

Our review of 43 serious games on water-related issues spans the serious games/ gamification diversity. Further searches would not have revealed any new traits or game types, though we acknowledge that other water-related games exist. The only missing type of water-related serious game is a fully immersive virtual reality game. We did encounter immersive and interactive visualizations of water related projects based on geographical information systems (GIS) (for instance, about floods, Leskens et al., 2015; Zhang et al., 2013). However, we argue that they are outside the scope of this paper, as these decision support systems do not include game features.

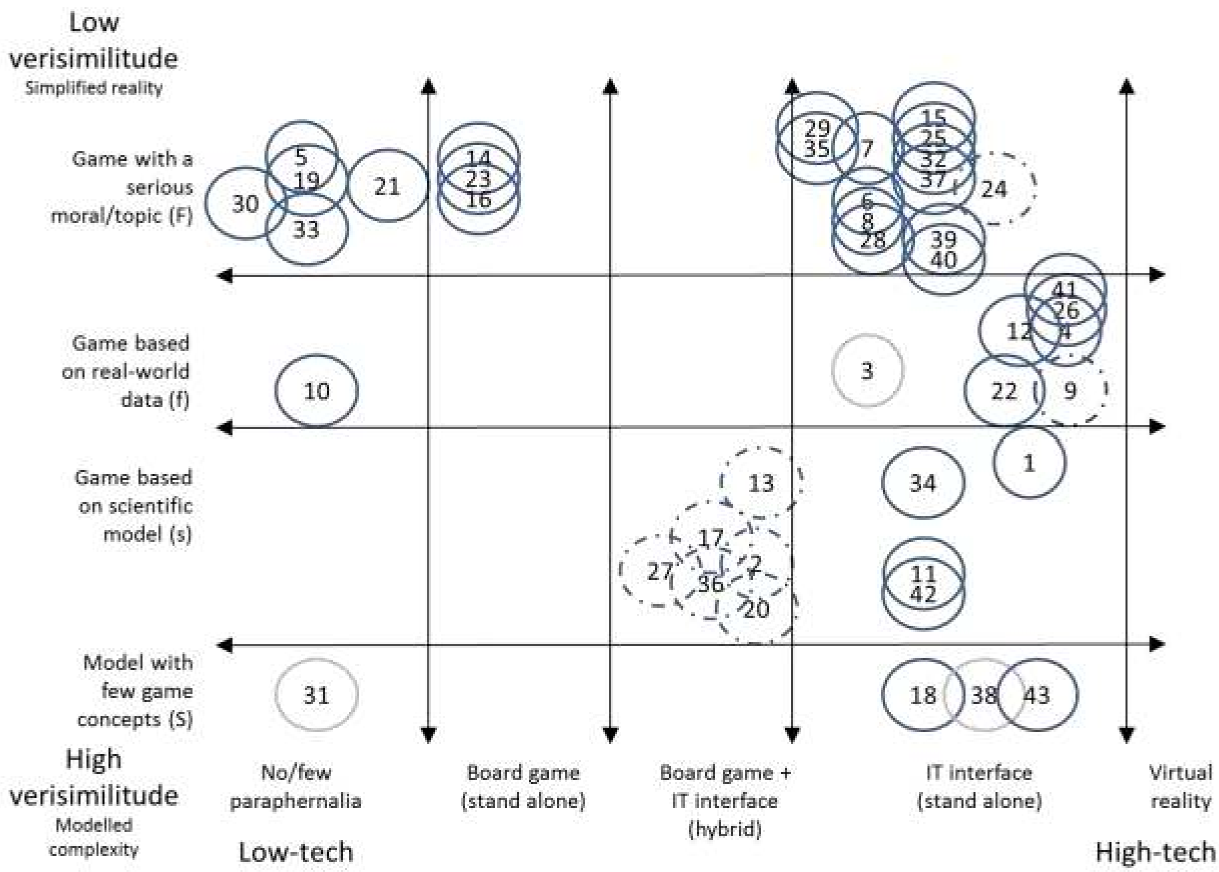

Figure 2. Various serious game definitions lead to a wide diversity of games in the water sector. We propose to classify them according to the technology (x-axis) and verisimilitude (y-axis) degree: potentially 20 types exist. Numbers refer to Tabs. 1, SI (games ordered alphabetically). The games' purpose is highlighted: broadcasting a message (plain dark circles), exchanging information (dashed-dotted circles) and training games (plain gray circles). The letters in brackets at the end of the verisimilitude class titles are used in Tab. SI1. Finer clustering of games is variable, based on other characteristics, e.g. developed by the same institution, same game mechanics (e.g. tiled-based) (see in the text).

4.2.1. Water-related serious games span all purposes

4.2.1.1. ***"Broadcasting a message"*** games include those games developed to raise awareness on water related issues such as household water consumption (e.g. #15, 29, 32, 37; Tabs. 1 and SI), integrated water resources management (e.g. #1, 4, 12, 28), or flood risk (e.g. #9, 19, 26, 30, 38), to mention a few. They also include games used as teaching materials at universities, and many other simulation games (e.g. Ewen and Seibert, 2016; Hoekstra, 2012; Magombeyi et al., 2008; Rajabu, 2007; Rusca et al., 2012).

Table 1. Summary of the reviewed serious games related to water issues. Games are numbered in alphabetical order. IWRM: integrated water resources management. NA: not available. Additional information and direct link to the games are available in Tabs. SI (Supporting Information) and in Fig. 2.

#	Game title	Author/ owner institutions	Water issue	Reference if available
1	Aqua Republica	UNEP-DHI centre for water and environment	IWRM	NA
2	AtollGame	Australian national university and Cirad (agricultural research for development)	IWRM	Dray et al. (2007) Dray et al. (2006)
3	AWQA Water	Wilson, M.	Water quality	NA
4	Catchment Detox (the basin challenge)	ABC science	IWRM	NA
5	Cauldron	Climate center red cross/ red crescent	Risk (water scarcity for farming)	Suarez et al. (2015)
6	Contaminator	iMoMo Hydrosolutions	Water quality	NA
7	Darfur is dying	mtvU	Risk (water scarcity, hygiene & sanitation)	NA
8	Fish Game	The cloud institute for sustainability education	Sustainable fishing	NA
9	Floodsim	Playgen	Risk (flood)	Rebolledo-Mendez et al. (2009) Wortley (2014)
10	Flood-WISE	Play-Time and Hastijns	Risk (flood)	NA
11	Irrigania	University of Zurich	IWRM, Risk (water scarcity for farming)	Ewen and Seibert (2016) Seibert and Vis (2012)
12	L' eau c' est plus qu' un jeu	Swiss federal office for the environment	IWRM	NA
13	Lords of the valley (Floodplain Management Game)	Center for systems solutions	IWRM	Stefanska et al. (2011)

14	Meru	iMoMo Hydrosolutions	Risk (water scarcity for farming)	NA
15	Mission H2O	Swinburne University	Risk (water scarcity for household)	NA
16	Ni trop, ni trop peu, nitrogène	Inra (French agricultural research institute)	Water quality	NA
17	Njoobari	Irstea, Cirad, and Inra	Risk (water scarcity for farming)	Barreteau et al. (2001)
18	NoMix tool	FiBL and Eawag	IWRM (urban water management)	Pahl-Wostl et al.(2003)
19	Paying for predictions	Climate center red cross/ red crescent	Risk (water scarcity, flood)	NA
20	Reef game	Australian national university, CSIRO marine and atmospheric research and conservation international	Sustainable fishing	Cleland et al. (2012)
21	ReNUWIt Water/City Design Challenge	ReNUWIt / Lawrence Hall of Science	IWRM (urban water management)	NA
22	Run the river	Murray-Darling basin authority	IWRM	NA
23	Shumbara	iMoMo Hydrosolutions	Risk (water scarcity for farming)	NA
24	SmartH20	Idsia and other research partners	IWRM (urban water management)	Rizzoli et al. (2014)
25	SOS mission eau	SEDIF	Urban water management	NA
26	Stop disasters!	UN/ International Strategy for disaster Reduction	Risk (flood)	Pereira et al. (2014)
27	Sustainable delta	Deltares	IWRM	van der Wal et al. (2016) van Pelt et al. (2015) Valkering et al. (2013)
28	System_blue	RésEAU Share-Web	IWRM	NA
29	Tip Tank, water use it wisely	Park&Co	Risk (water scarcity for household)	NA

30	The gender and climate game (2nd ed: Gender walk)	Climate center red cross/ red crescent	Risk (water scarcity, flood)	Koelle (2014)
31	The river Wadu role play (or the irrigation management game)	University of London	IWRM, Risk (water scarcity for farming)	Carruthers and Smith (1989)
32	Thirsty for knowledge	US EPA, water sense	Risk (water scarcity for household)	NA
33	Traveling with N on the hillslope	University of Giessen	Water quality	NA
34	TWIST++/ Visimple	Takomat	IWRM (urban water management)	Kropp et al. (2014)
35	WASH game	Eawag	Risk (hygiene & sanitation)	NA
36	Wat-a-game	Irstea	IWRM	Ferrand et al. (2009)
37	Water busters	Home water conservation USA	Risk (water scarcity for household)	NA
38	Water coach	Deltares	Risk (flood)	De Kleermaeker and Arentz (2012)
39	Water life: sea turtles and the quest to nest (2nd ed)	NOAA	Sustainable fishing	NA
40	Water life: where rivers meet the sea (2nd ed)	NOAA	Water quality	NA
41	Water wars	University of Washington Seattle	IWRM, Risk (water scarcity for farming)	Hirsch (2010)
42	Wastewater RPG	University of Girona	IWRM (urban water management)	Prat et al. (2009)
43	World Water Game	Deltares/ Softonic	IWRM, Risk (water scarcity for farming)	NA

4.2.1.2. ***"Exchanging information"*** games present either a direct or indirect exchange of information, which can be data, knowledge, worldviews, etc.. (1) *Direct exchange* games are mostly simulation games, typically played during workshops, aiming at problem structuring or scenario development (e.g. #2, 17, 20, 27, 36; Tabs. 1, SI). Here, a two-sided information exchange occurs. First, the game facilitator, often a scientist, learns about the resource sharing context and the point of view of each player. Hence, the players' attitudes are collected as input data for a scientific model. Second, the players, often referred to as "participants", learn about the other players' understanding of the issue (worldview) and about the co-constructed model, i.e. social learning occurs (Barreteau, 2003; van der Wal et al., 2016). (2) *Indirect exchange* games allow for learning or awareness raising and at the same time data collection (e.g. #9, 24). FloodSim (#9) raises awareness on flood prevention issues in the United Kingdom and collects data about the players' chosen flood protection alternatives (implicitly considered as most preferred). SmartH2O (#24) raises awareness on household water consumption, while it concurrently encourages players to provide water consumption data.

4.2.1.3. ***"Training"*** games reproduce a real-world situation with accurate reality (e.g. AWQA Water (#3), The river Wadu role play (#31), and Water Coach (#38)). They do not involve an exchange between scientists/ experts and users, because the player is usually an expert, who already knows much about the topic, but needs to practice in a safe environment, i.e. in a fictional situation.

4.2.2. A diversity of water issues is reflected in the serious games

Most games deal with sustainable water use, in a broad sense, and at various scales: at the level of households, watersheds, transboundary watersheds, and globally. Two sub-themes are predominant: user conflicts regarding resource use (e.g. #17, 27, 36), and water-related risks such as droughts, floods, and pollution (e.g. #6, 9, 38). Four games highlight innovative urban water management: the NoMix tool (#18) (Pahl-Wostl et al., 2003), SmartH20 (#24), TWIST++ (#34), and wastewater RPG (#42) (Prat et al., 2009).

4.2.3. Water-related serious games target many different players

We found serious games for all ages. However, on the verisimilitude axis, we observe a differentiation based on the player's expertise. Most complex games with few game concepts and/ or that are based on scientific models target students and/ or professionals from water management and the natural sciences (e.g. #31, 42; Tab. 1). In contrast, games that use many game concepts and a simplified representation of the real-world, target non-experts such as adult and/ or child laypeople (e.g. #21). On the technology axis, there is no apparent differentiation, and any game technology is used for any targeted player group, independently from expertise or age. The only discernible trend would be that hybrid games, those associating physical games and computer elements for simulations, seem to target adults, i.e. advanced students, professionals from water management and the natural sciences, and sometimes local stakeholders (e.g. #2, 27, 36).

4.2.4. The variety of technology

4.2.4.1. ***Low technology games*** are games with no/ few paraphernalia or stand-alone board games: group games with no paraphernalia (e.g. #30; Tabs. 1, SI), role playing games with few paraphernalia (e.g. #31), card games (e.g. #10, 33), construction games with blocks of different materials and tape (e.g. #21), and board games with several paraphernalia such as a board, dices, polls, or cards (e.g. #14, 16, 23). Low technology games are mostly used in real meetings and workshops organized by humanitarian or development organizations (e.g. #5, 19, 30). Low technology serious games are also used in private consultancy (e.g. #10), in science museums (e.g. #21), in outreach fairs (e.g. #16), in schools (e.g. #33), and in universities (e.g. #31).

4.2.4.2. ***Hybrid games*** are board games or role playing games, backed by computer simulations. They are so-called simulation games, or policy games. They enable the gamers to foresee the impact of their decisions or actions over time and to build an understanding of the complex interactions of social, environmental, and economic factors. The players virtually experience the consequences of alternatives. These games stimulate discussion and learning among stakeholders, thus enhancing social learning. Furthermore, they enable to explore a range of plausible futures, using different scenarios, e.g. the International Panel for Climate Change scenarios in Mendler de Suarez et al. (2012). Such games are a media to communicate about complexity (Duke and Geurts, 2004). They would thus allow exploring and better understanding wicked problems, i.e. problems that cannot be definitively formulated and that present no right-or-wrong answer nor definitive solution (e.g. policy planning) (Hansson and Hirsch Hadorn, 2016; Rittel and Webber, 1973). They are often used in conflict situations about a shared resource (e.g. #17) (Barreteau, 2003). The participants can hardly ever lose: in the worst case, they witness a non-consensual end of the play that is in contradiction with their interest and/ or belief. These games require a facilitator or game leader to introduce the game context and rules, to deal with the modelling, to encourage collaboration, as well as to facilitate the debriefing phase, often leading to decision-making in the real world. The participant embodies the role of a stakeholder (sometimes his own real role) and is asked to answer a challenge according to fixed rules. Some games include a scoring system (e.g. #36).

4.2.4.3. *Simplified games with a standalone IT interface*

Simplified games with IT interface are also well represented. Most of these games were developed in transdisciplinary teams, particularly when they are based on real-world data.

Some of these simple computer games are highly successful and wide-spread. The most famous may be Darfur is dying (#7; Tabs. 1, SI), alerting the general public to the South Sudan water crisis in refugee camps. Another game which quickly spread after its launch, particularly among the targeted United Kingdom population is the FloodSim game (#9), partly based on real-world data.

Many standalone IT interface games use tile-based space management, which might be a reminiscence of the commercial game SimCity. The latter is originally a fully-fledge commercial game which can hardly be classified as a serious game. However, in its fourth version, it also includes an improved and more realistic urban hydrology model (D'Artista and Hellweger, 2007). The tiled-based space management games promote the understanding of water cycles, or more precisely of water use at the catchment scale (e.g. Aqua Republica (#1), Catchment Detox (#4), later renamed the basin challenge, L'eau c'est plus qu'un jeu (#12), Stop disasters! (#26), and Water wars (#41)).

Other games use simple online IT interfaces. Some are inspired from the memory game (Tip Tank (#29)), or the television show "Who wants to be millionaire" (WASH game (#35)). They target the general public and aim to broadcast a message on e.g. household water consumption, with the background intention of enhancing water saving practices (e.g. Mission H2O (#15), Thirsty for knowledge (#32), Water busters! (#37)).

To conclude, our review illustrates a high diversity of serious games on water. This partly results from the very broad definition of what a serious game is. We would like to emphasize that serious gaming continues to develop and that the diversity will likely increase strongly, if no strict consensual definition emerges. This definition issue is being discussed in the gaming community, which even suggest the new term "applied games" (Schmidt et al., 2015). The sub-community of gamification is also defining itself (Seaborn and Fels, 2015). New types keep appearing such as documentary games, e.g. Fort McMoney by Arte TV (Dufresne, 2013), which associate reporting based on real-world video images with gaming, or opinion games, which aim at presenting the pros and cons of viewpoints concerning a referendum, e.g. GOT by Opinion Games (Lemcke et al., 2016). To our knowledge, these new types of serious games have not focused on water issues yet.

4.3. The common features of serious games

4.3.1. Gameplay loop: the cornerstone of gamification

A game is a sequence of gameplay loops, also referred to as micro cycles by Duke (1980) (Fig. 3). Its most basic form is to face a challenge. This means that a player has to take an action or decide between several options on how to play (in accordance with the rules), whereby only one option is "correct". Then, the game reacts. If the action taken was correct, the player can play the next loop, but if the action taken was wrong, she has to repeat the loop. The game reaction, or output, can also be more complex. For instance, the player can be rewarded or punished according to an accounting or scoring system. Sometimes, the gameplay also depends on the choices of other players, on external forces (if random events are planned to occur in the game), or on the context (e.g. how the player played in previous loops).

In serious games, a win/ loss state is constructed to make the player analyze her choice (Mendler de Suarez et al., 2012; UNEP-DHI centre for Water and Environment, 2012). A loss state may create cognitive dissonance (or conflict) within an individual, and can hereby enhance learning if the person aims at reducing this inner conflict (identifying the reasons, and adapting) (Adcock, 2012). Reflecting based on an experience is a learning process known in many learning theories, e.g. Kolb's experiential learning cycle (Merriam et al., 2007), or Argyris' single- and double-loop learning (Argyris, 1978). In game-based learning, when taking an action, the player has some expectations concerning how the model will work. Her action induces a change in the game environment which leads to a reward or penalization. Then, the player can evaluate her prior expectation by confirming it and continuing to play, or by formulating a different expectation to be tested in the trial of this loop. The game offers a safe environment to learn from trial and error.

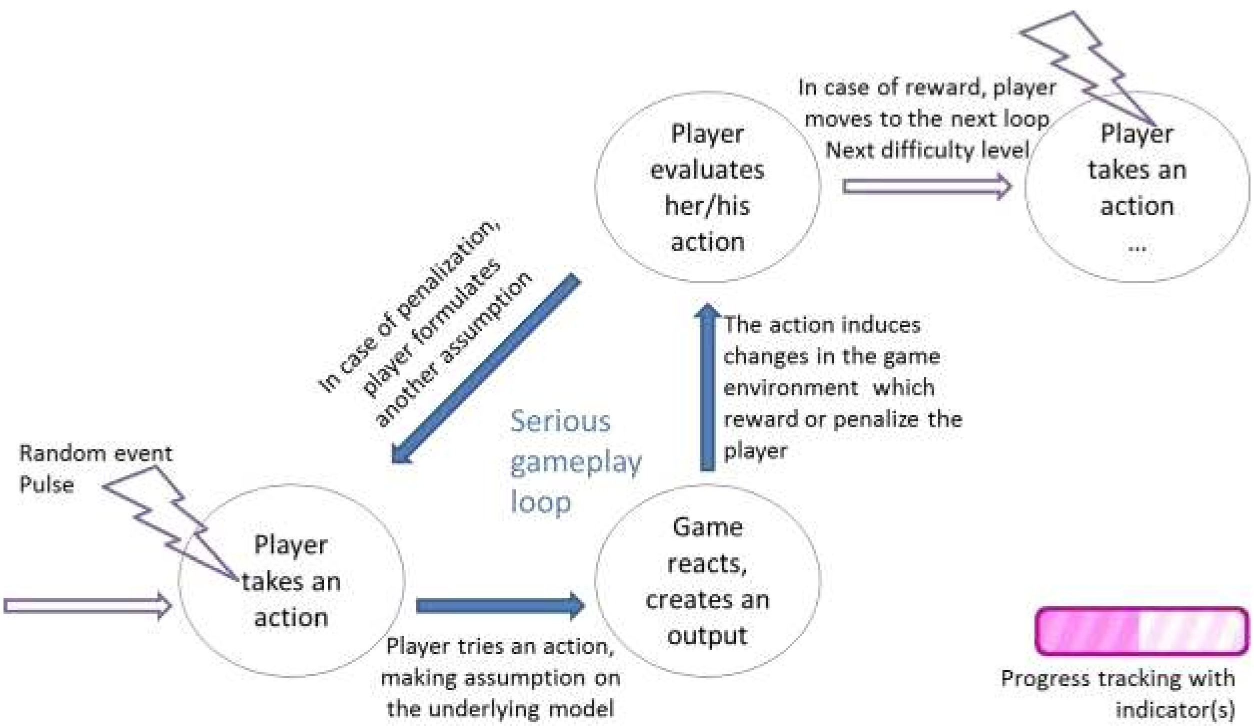

Figure 3. A model of a serious gameplay loop or micro cycle (adapted from Mendler de Suarez et al., 2012; Plass et al., 2015; UNEP-DHI centre for Water and Environment, 2012). It is very similar to many learning theories, based on loops/ cycles.

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4.3.2. Other common game elements to engage and motivate

Other game elements are used to balance the seriousness of serious games (Tab. 2). They aim to enhance intrinsic motivation. Serious games thus not only offer a safe trial and error environment, but they are also engaging, motivating and attractive.

The sequence of gameplay loops is part of a macro sequence (Duke, 1980). This overall frame interconnects all gameplay loops defining the evaluation process. It also provides preconditions, an introduction, and the end.

According to Christen et al. (2012), the narrative, the gameplay, and an attractive virtual environment (i.e. design and graphics) are the key elements to make a serious game successful. While judging the attractive power of the virtual environment is quite a subjective task, neglecting this component is instantly noticeable, and commented by users. Among the games reviewed, some presented significantly developed narratives. These narratives assign a mission to the player as an immersive motivation element; e.g. Water life: sea turtles and the quest to nest (#39), Water life: where the rivers meet the sea (#40), TWIST++ (#34), and SOS mission eau (#25).

The motivation created from games has long-been a “black box” (Rigby, 2014). First attempts of theorization exist (for a review, see Seaborn and Fels, 2015). One of them is based on the Self-Determination Theory, and suggests that a game, or a gamification can enhance the internalization of extrinsic motivation by providing a feeling of competency, autonomy and relatedness to others, and, when relevant, by stressing the intrinsic goals of the player (Rigby, 2014; Ryan et al., 2006).

Table 2. Elements of serious games (highlighted in bold). Common: elements are found in all serious games; optional: only in some.

Level	Elements
Macro sequence (common)	A **scenario**, or **narrative**, assigns the player…
	…with a **mission**. The player accepts the **challenge**,…
	…whereby she **can win or fail**. Winning (or losing) can have different forms…
	…either the player receives an **award** at the end of the game (or not),…
	…or her **score** according to the accounting system is higher (respectively lower).
Gameplay loop or micro cycle (common)	A **pulse** triggers the start of the gameplay loop,…
	…often in the form of a **random event** (external force).
	Within each loop, the player has a **chance to win or fail**. Thus,…
	…justifying a **rewarding or penalizing feedback**. The reward often enables the player…
	…to **proceed** in the game to the next loop, or to the **next difficulty level**.
	The player should be able to **track her progress**, with **indicators**.
Macro sequence (optional)	**Virtual reality** (but no water-related example was found).
	Collaborate or compete with other players (directly or via a game community).
	Play a role (role playing games).
	Take part in the **debriefing** (for most simulation games).

4.3.3. Additional features of serious games

Other game elements can be seen as motivational affordances (Tab. 2). Many of the reviewed simulation games trigger collaboration through role play, and end with a debriefing on what happened, and what was learnt. An emerging way to engage players is to broadcast the message intuitively through gestures. For instance, the player see the intensification of a phenomenon through the graphical representation (water use, or water pollution), but she will also experience it physically as she will have to intensify the frequency of her actions. In Run the river (#22; Tabs. 1, SI), the player allocates water between the needs of various users and the number of clicks needed depend on the water consumption. In System_blue (#28), the gameplay is similar but focuses on pumping river water for a village. The player experiences that some users need a bigger allocation of water than others. In Fish game (#8), about the shared fish resource, and in Contaminator (#6), about river water quality, the player is faced with exponential worsening once the problem appears. In the Fish game (#8), if the player thinks only about her interests, all other fishers behave egoistically too, leading to fast complete depletion of the fish resource. In Contaminator (#6), river pollution starts mainly by upstream input; as soon as this happens, it becomes harder and harder – even impossible – to maintain a good water quality status.

Additional features must be characterized when developing games, including serious games (Duke, 1980): (1) rules that indicate how to play (particularly important in *ludus,* rule-based gaming); (2) models that enable to track the logical process; (3) decision sequence and linkage that represent the typical player sequence of decisions for each role (if any) and each step of the gameplay. This sequence answers the question "*who* is doing *what*, *when* and *how*?". If it is properly developed it ensures adequate feedbacks. Points (1) to (3) define the game mechanics (Sicart, 2008). In addition, the paraphernalia need to be defined, i.e. lists of all objects and materials required to play.

5. Discussion

5.1. Rationales to use serious games or to gamify MCDA

Overall, serious games and gamification are designed to offer an engaging, and challenging frame. They can present current states of real-world issues, and sometimes simulate possible future states. Serious games can facilitate the players' involvement in and comprehensive learning about real-world issues, sometimes supporting deliberation and decision-making. Different strategies could be possible to cover the real-world complexity of an issue: e.g. one can develop a serious game or gamified application with high-verisimilitude, or one can gradually increase the verisimilitude bringing in the complexity step-by-step (e.g. with different levels), or one can cut down the complexity into a sequence of low-verisimilitude games (e.g. dealing with single aspects independently). The chosen gamification depends on the targeted audience:

experts will be attentive longer when facing complexity than laypeople. Gamification triggers motivational factors which in turn encourage pursuing a task (Ramirez and Squire, 2014; Rigby, 2014). Plass et al. (2015) offer a general framework and suggest that game-based learning fosters many facets of engagement, i.e. cognitive, behavioral, affective, and sociocultural engagement. Yet, for serious games and gamification research, better structuring and more rigorous evaluation of the benefits and/ or possible drawbacks are needed. Ideas for future research work are listed hereafter. For instance, while game elements are reported as effective motivational factors (Hamari et al., 2014), the behavioral consequences are unclear. Using theoretical frameworks from psychology, e.g. self-determination theory and other theories from intrinsic and extrinsic motivation (Seaborn and Fels, 2015) could help, as well as carrying out comparative studies (e.g. Haug et al., 2011).

After reviewing the literature, we observe a potentially promising match between the aims of serious games and gamification and the challenges that MCDA is facing. MCDA needs to be more participatory, i.e. to allow citizen involvement. Thus, MCDA requires methods that allow laypeople, who are newly confronted with a decision topic, to construct reliable preferences. These methods should limit the cognitive load, avoid biases, and allow for experimentation and learning. Descriptive decision analysis tells us that various factors are important for mindful judgments and preference construction. These include e.g. learning, in particular from feedbacks, processing and retrieving memorized information, and motivation. Serious games and gamification exactly address these factors, in addition to being easily understandable and accessible by many. Hereafter, we discuss in more detail the high potential of using serious games and gamification in MCDA, while pointing out the possible drawbacks. Future research is needed to properly evaluate the use of serious games and gamification in MCDA.

5.2. Most MCDA steps can be addressed with an already existing serious game

5.2.1. Gamified MCDA workshops (steps A, C, D, and H)

According to our review, the simulation games used in the companion modelling approach (e.g. #2, 17, 20) (Étienne, 2011 and references therein), and other role playing policy games (e.g. Douven et al., 2014; Duke and Geurts, 2004; Geurts et al., 2007; Haug et al., 2011) are existing examples of gaming that could be transferred to certain phases of MCDA. These include the initial steps of structuring and defining the decision context, formulating the objectives, and creating the decision alternatives (steps A, C, and D), and the final step of discussing results with the participants and searching for consensus alternatives (step H) (Fig 1). Typically, about five to 20 targeted players/ workshop participants are selected as representative stakeholders, they either have decision-making power, or are affected by the decision. The workshop is organized around the role play game, often involving simulation. Thus, it requires a real meeting and an experienced facilitator, sometimes backed by an assistant for computer modelling. The game fosters interaction between the role playing participants, who are acting in the protected environment, and with the facilitator. The game can last from half a day to two days, but can be interrupted. Interruptions are opportunities to discuss and reflect on whether learning occurred, and the outcomes are fair. In other words, these existing games can be seen as gamified decision analysis workshops. The game and its set of rules are usually a co-construction, emerging from the players' input and the facilitating team. The designed rules translate the complex issue of competing objectives among stakeholders. This co-construction of a tailored game warranties that every worldview represented in the meeting is taken into account, and that the complexity of the real world is represented in the game. This is required to (1) depict the complexity of the issue, (2) initiate social learning and (3) create ownership of the outcome. The game is meant to model real-world relations between the participants and the resource, as well as among participants. A rich literature on this type of games is available and discusses pros and cons based on case studies (e.g. Dray et al., 2007; Étienne, 2011). We are not aware of hypotheses testing in an experimental deductive approach, apart from the attempt of Haug et al. (2011). Possible future developments for the MCDA community could be to integrate an MCDA preference elicitation and aggregation model in such gamified workshops or policy games (step F; Fig. 1), and test whether the complexity of the issue is better understood and social learning is enhanced. Hereby, behavioral aspects need to be thoroughly considered, in particular how individual preferences are expressed through this group exercise.

5.2.2. Serious games for stakeholders analysis (step B)

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In the review, the game The gender walk (#30, in its prior version) aimed at identifying the role or importance of the stakeholders. The game does not target any specific group; as illustrated by the wide intended audience, which includes community members, donors, disaster managers, volunteers, branch officers, etc. The number of players can range from ten to 40, and the game lasts one to two hours. The game requires a real meeting, an experienced facilitator, and assistants if there are many players. The game fosters understanding of inequality between genders, or among the stakeholders regarding climate variability and change. All players start on the same line. The facilitator asks questions; to answer yes, the player steps forwards, to answer no, the player steps backwards. After a series of questions, the players are clustered. A debriefing session follows to discuss the clusters composition, and ways to homogenize. We see this game as a stakeholder analysis, whereby we can identify how important each stakeholder is, whether she is affected by the decision or influencing it as decision-maker (see e.g. Lienert et al., 2013). It could also promote social learning if players share their perception of the problem. However, practically, selecting players that are invited to participate can be critical. Therefore, this exercise would be especially interesting in an early phase of decision-making, on occasions where many people are gathered, for instance in an information meeting, open to the public. In addition, one could develop an online version of such a game, which would allow broader participation. Many design questions arise; we give some examples: Should the game be played simultaneously by all players or would a gaming community be sufficient? How strongly are people influenced by social norms when they play the game? Does the influence of social norms differ between a real and virtual meeting?

5.2.3. Serious games to learn about the decision context to define objectives (step C)

Learning about what objectives to consider is a major part of problem structuring; this choice can strongly impact the outcome of the decision (Rosenhead and Mingers, 2001). In this review, most games broadcasting a message are games to aid problem understanding. They would stimulate learning about the problem at three levels: cognitive, relational/ social, and normative learning (Haug et al., 2011; Plass et al., 2015). However, most of these games broadcasting a message could be qualified as “biased” as they often depict a single worldview. Yet, in some cases, the games assess the player's choices using several indicators, which if developed carefully could represent the main trade-offs. These indicators are often simplified, and can be considered as general objectives. Another possibility would be to develop topic-related training games, mimicking policy games, but using fictional representative situations. They could be based on a master list of objectives. In either case, following the broadcasting a message or training game session, those general objectives could stimulate generating a comprehensive set of objectives (following the recommendations of Bond et al., 2010), which can then be challenged, reduced, and structured into an objectives hierarchy. Whether serious games for the generation of objectives should be played by a single or by multiple players needs to be tested. A multi-player serious game should gather the entire range of stakeholders (see 5.2.2), or assign roles representing this diversity, to cover all existing worldviews and knowledge (Duke and Geurts, 2004). It would ideally require the presence of an experienced facilitator to prevent the groupthink bias (Janis, 1982), i.e. to prevent too early convergence of thoughts and agreement on objectives, and to facilitate the debriefing session. The debriefing session would aim at moving from the fictional game situation to the real-world decision situation. Since a group setting with a facilitator limits the number of repetitions, one option could be to first carry out a qualitative analysis. Based on these results, a more-rigorous experiment comparing the single- and multiple player setting should then be carried out. Whatever set-up is chosen, game use for the purpose of objectives generation needs to be thoroughly evaluated.

5.2.4. Games to learn about alternatives and explore the consequences (step E)

Moreover, some of the games broadcasting a message offer to play with various alternatives. Training games also invite to test a subset of typical alternatives, in a fictional – but highly plausible – situation. The choice of alternatives is evaluated with rules, based on a predefined set of indicators/ objectives. Some researchers on serious gaming claim that simulation games players are better informed about the alternatives and their outcomes (D'Artista and Hellweger, 2007; Devisch, 2008; Tanes and Cemalcilar, 2010). Through the simulations, the player experiences the alternatives in a safe trial environment, i.e. before having to handle possibly undesirable outcomes in the real world. These games might particularly help to communicate about complex never-definitively-defined “wicked problems”. The game model could take into account the choices for alternatives of the player, and react showing how the problem/ situation has evolved: with the new situation, the problem needs to be redefined, and new sets of actions should be taken. To be used in a decision-making process, the decision analyst should guarantee that the serious game is based on the best actual (if possible local) available knowledge, e.g. using the predictions made for the MCDA. This would require using games or gamified applications which are developed in such a way that they are easily adaptable to the specific conditions of any given case. The serious game should not support a specific alternative, which requires careful rule design in particular to develop a neutral feedback loop. Moreover, in the case of a single player serious game, the player might solely verify her own pre-understanding of the topic, as described in the biased search process (Hoeffler et al., 2006). This would enhance the confirmation bias, i.e. when one is unconsciously looking for information or evidences confirming one’s beliefs (Hogarth, 1987; Klayman, 1995; Montibeller and von Winterfeldt, 2015; Nickerson, 1998). Addressing this question is a further prerequisite to develop the use of games in MCDA.

5.3. No serious game for preference elicitation (step F)

According to our review, no existing serious game allows to elicit the preferences in a suitable way for MCDA, and specifically for MAVT (step F. in Fig. 1). A preference elicitation game, or gamified procedure, would fall into the “exchange information” category (Tab. 1). It would allow preference elicitation from experts, as well as from novice citizens, if enough factual background information is provided in a neutral way. The gamified preference elicitation requires real world data, and thus ought to offer an adaptable design, that allows easily producing different versions that include context-specific information. Players would receive information on the decision issue, while the decision analyst would collect reliable preferences. It could either be a single player game to collect individual preferences, or a multi-player game to address preference formation in groups. To increase the number of participants, the game should be made as easily accessible as possible, for instance by using an online IT interface. If this is done, the gamified online procedure should be as short as possible, and/or successful in engaging, to avoid tiring and drop out of the participants (Dillman et al., 2009).

As for the other steps for a use in MCDA, the main challenge to gamify preference elicitation lies in creating rules, including a win-fail situation for learning with feedbacks, that does not manipulate or judge the player's preferences. The usual system that assumes that correct actions lead to a higher score and wrong actions to a lower score does not hold as there is no right or wrong answer concerning personal preferences. We suggest a possible solution for weight elicitation in another paper (Aubert and Lienert, in prep.).

As such an application of gaming to MCDA seems to be completely new, debiasing the procedure needs to be considered in its development (for a recent overview of debiasing in MCDA see Montibeller and von Winterfeldt, 2015). Moreover, scientifically sound evaluation is required in an experimental set-up that allows comparing the preference elicitation game with a similar non-gamified MCDA application, as well as with the classic face-to-face preference elicitation procedure.

6. *Conclusion*

This review paper started with a brief introduction of MCDA and MAVT revealing improvement points, in particular regarding preference elicitation. Methodological progress is needed to (1) limit the cognitive load for the participant, (2) limit the occurrence of various motivational and cognitive biases, (3) enhance the construction of preferences, e.g. by enhancing learning, and (4) increase participation by involving citizens. A short overview of the relevant descriptive decision-making literature was provided. It stressed the importance not only of cognitive processes, but also attention, and motivation to achieve a mindful judgement. Thereafter, more than 43 serious games related to water issues were reviewed, in order to (1) define serious games and gamification, (2) capture their diversity, and (3) identify their common underlying gameplay elements. Reviewing the decision literature and the game literature highlighted potentially promising matches between MCDA needs and the affordances of serious games and gamification. Therefore, we discussed in the last part how serious games and gamification could be used in each step of the MCDA process (Fig. 1); highlighting the pitfalls that should be avoided, and suggesting many new research opportunities. The main challenge for the use of serious games and gamification in MCDA is the neutrality requirement of a prescriptive decision-making process. Consequently, we think that gamified application might be more appropriate than fully-fledged games. However, this statement needs to be proven. More specifically, we propose following research ideas at different steps of a Multi-Criteria Decision-Making process:

- Experimentally test hypotheses using gamified workshops for parts of the MCDA process; namely the initial steps of problem structuring (steps A, C, and D) and the final step H of discussing results.
- Integrate an MCDA preference elicitation and aggregation model (step F) into gamified workshops, and test whether the complexity of the issue is better understood and social learning is enhanced.
- Use games for stakeholder analysis (step B), i.e. to assess the stakeholders' importance and interests. The advantages and disadvantages of a real workshop, as part of a public information meeting for instance, or of an online game need to be carefully assessed.
- Develop games to define the decision objectives required for MCDA (step C). One proposition is to use games developed for broadcasting a message, but enhance these with multiple worldviews and/or using several indicators/ objectives. Test (first qualitatively, then experimentally), whether games to generate objectives should be played by single or multiple players. The latter requires avoidance of the groupthink bias (Janis, 1982).
- Use simulation games to explore multiple decision alternatives (step E). Ensure that simulations are based on best-available scientific knowledge, and avoid biased preference of some alternatives. This requires the development of a neutral feedback loop, which should again be experientially tested, and of game mechanics inviting the player to explore all alternatives.
- Finally, according to our review, no existing serious game allows to elicit the preferences in a suitable way for MCDA (step F). This requires a completely new application to gaming. Needless to say, this needs to be thoroughly evaluated in a controlled

experiment, where the gamified version is compared to a similar non-gamified "classical" preference elicitation procedure.

A note on the costs of such an integration of MCDA decision processes with serious games: whether higher costs of game development are justified depends on the decision context. In large policy decisions, which are by nature expensive, the additional costs of gamifying an MCDA process may be negligible or justified by the importance of the problem (see Langhans and Lienert, 2016 for a more in-depth argumentation concerning the costs of decision support for river rehabilitation). A major aim might specifically be public participation including a large number of laypeople, which might be best achieved exactly by gamification. Moreover, in the case of repeated decisions of a similar type, it might be possible to develop a game that is either able to address this issue on a more-general level, allowing to transfer the insights to the specific decision situation, or it might be possible to construct the game in such a way that it can be easily adapted to the specific local decision context. In other cases, including simple elements of gamification might be cheaper and sufficient.

Gamification in itself induces trade-offs: there are within- and between-worlds dilemmas, culminating in a trilemma between play, meaning and reality (Harteveld, 2011). Gamifying the MCDA process implies involving game developers and the players, e.g. the general public (Fig. 4), additionally to the MCDA analysts and the environmental experts or decision-makers, traditionally included in environmental decision-making. Active participation of the latter is probably the only way to guarantee a neutral and unbiased game. The four parties may have various conflicting interests: trade-offs between the requirements of MCDA tools, the requirements of games and gamification, and those of "traditional" environmental decision-making will occur. As for any decision-making process, clarifying and prioritizing the objectives is a pre-requisite. Studying the entire overarching game design process could be an interesting research topic in itself, which may also benefit from MCDA to decide on the best gamification options (e.g. Sangkyun, 2014).

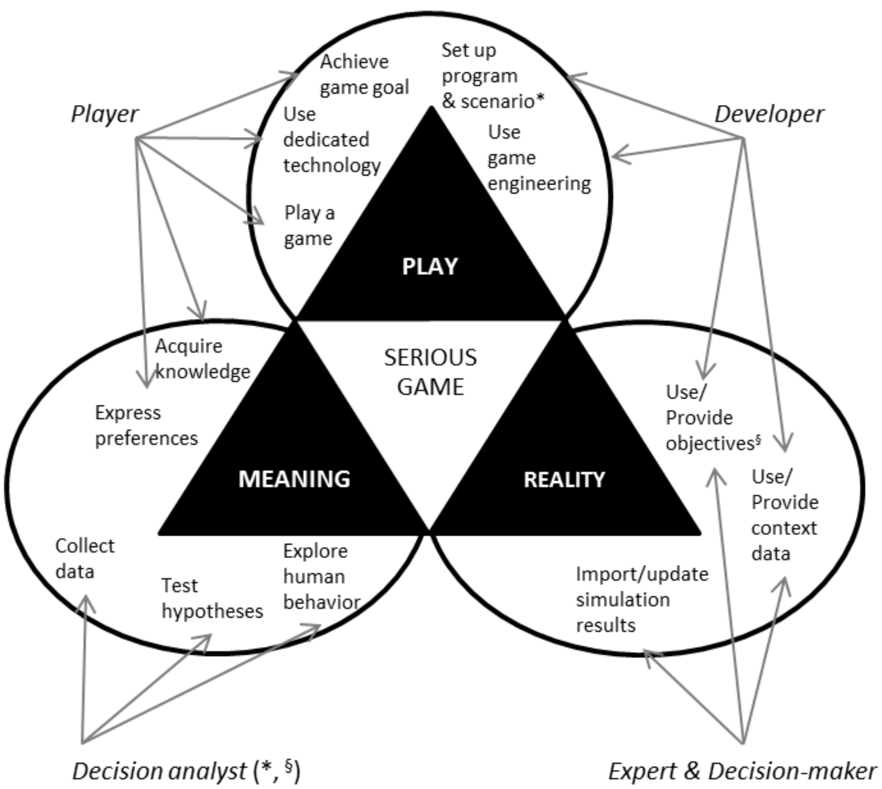

Figure 4. Triadic game design for an MCDA serious game and gamification (adapted from Harteveld, 2011). The triadic design illustrates the various dilemmas occurring when designing a serious game. To design an MCDA serious game or gamified application, more actors – including decision analysts – stand at the meaning-reality dilemma. There are two additional links/ arrows from the decision analyst to the * and § symbols (to "play", "reality"), which were omitted for esthetic reasons.

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8. Supplementary Information

Supplementary information associated with this article is available online at xxx. It includes the gamography, with direct links to the games.

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