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

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9 *Highlights*

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

11 43 reviewed water-related serious games reveal diverse approaches and uses

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

13 No existing serious game allows MCDA-compatible preference elicitation

14 *Abstract*

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

27 *Keywords*

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

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31   *1. Introduction*

32   This review paper aims at bringing together two fields of research, namely decision analysis and

33   gaming, both being based on models. It focuses on environmental decision analysis related to

34   water. Water is of undisputable importance for humans and the environment, but globally its use

35   remains problematic. This is reflected in the many water-related Sustainable Development Goals

36   set for 2030 (UN General Assembly, 2015). The paper starts with a brief introduction of

37   prescriptive MCDA (Multi-Criteria Decision Analysis), specifically MAVT (Multi-attribute Value

38   Theory; Keeney and Raiffa, 1976). Our aim is to identify improvement points, in particular

39   regarding elicitation of preferences from the population. A concise overview of descriptive

40   (behavioral) decision-making stresses that cognitive processes as well as emotions, attention,

41   and motivation are important to achieve a mindful judgement (Weber and Johnson, 2009). We

42   hypothesize that these emotional and motivational aspects can be addressed by gaming: using

43   serious games or gamification. A manifesto opening the book *The Gameful World* claims that,

44   after the century of image and information, we have entered the era of games and playfulness

45   (Zimmerman, 2014). This results in gamification, namely using game design elements in non-

46   game contexts (Deterding, 2012; Ramirez and Squire, 2014; Sicart, 2014). Serious games (Abt,

47   1970), i.e. games which are not meant to be played solely for entertainment (Mendler de Suarez

48   et al., 2012), are equally widely spreading. Such games are starting to be used in the operational

49   research community (Voinov et al., 2016). Voinov et al. (2016) argue that serious games are

50   promising tools for participatory modelling due to (1) the stakeholders' engagement through

51   intrinsic game motivational features, (2) the potential for interactive visualization, and (3) the

52   ability to both create social learning and teach decision-making skills. This leads us to review

53   existing serious games related to water issues.

54   The aim of this paper is to: (1) review water-related serious games to identify their

55   characteristics, (2) highlight the possible match and mismatch between games and

56   environmental MCDA, and (3) uncover associated research opportunities.

57   In Section 2, we briefly introduce MCDA. In section 3, we define the method used for reviewing

58   the games. In Section 4, the review of 43 games leads us to define what a serious game is. We

59   depict the high diversity according to two continua: low–high technology and low–high

60 verisimilitude. In Section 5, we rely on this serious game definition to discuss the use of serious

61 games and gamification for environmental MCDA. Section 6 consists of concluding words.

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

63 **2.1.   Environmental decisions are messy and benefit from MCDA**

64 Facing complex environmental management and policy problems, decision-makers may turn

65 towards decision analysis methods. Environmental decisions are often controversial, i.e.

66 stakeholder groups may disagree on the importance of the objectives they wish to pursue. They

67 are also often characterized by (1) too few or too many decision alternatives (possible solutions),

68 (2) many influencing factors, and (3) highly uncertain future outcomes (for reviews see e.g.:

69 Gregory et al., 2012; Hajkowicz and Collins, 2006; Huang et al., 2011; Mendoza and Martins,

70 2006). Multi-Criteria Decision Analysis (MCDA) is an umbrella term for methods developed to

71 tackle such messy decision situations (Belton and Stewart, 2002; Greco et al., 2016). Here, we

72 focus on Multi-Attribute Value Theory (MAVT), based on axioms of rationality (Keeney and

73 Raiffa, 1976). The philosophy of Value Focused Thinking (Keeney, 1996) is to first determine the

74 values and preferences of stakeholders and then to evaluate the alternatives by calculating their

75 overall performance regarding the achievement on a set of objectives.

76 **2.2.   Rational decision-making**

77 MAVT is based on few, but solid axioms of rationality; essentially completeness and transitivity

78 (Belton and Stewart, 2002; Eisenführ et al., 2010; Keeney and Raiffa, 1976). Completeness

79 implies that a decision-maker can state her preferences (or indifference) concerning any pair of

80 outcomes. Transitivity means that if one prefers alternative *a* over alternative *b* and *b* over *c*,

81 then one should prefer *a* over *c*. Although sometimes violated by actual decision-making

82 behavior, these axioms are hardly questioned as guiding principles. Furthermore, especially for

83 larger environmental decisions that are financed by tax payers, it is desirable that decisions are

84 transparent and justifiable to the public. Reichert et al. (2015) have presented in detail why

85 MAVT is a good methodological choice for environmental decision-making, which satisfies

86 important conceptual requirements. However, this is challenged in real applications as many

87 factors, e.g. the response mode, context, or individual cognitive capacities, can affect people's

88 choices (Payne et al., 1992).

89 ### 2.3. MCDA/ MAVT step-by-step

90 In practice, MCDA starts with defining the decision context (Fig. 1). Problem structuring methods

91 (Marttunen et al., 2017; Rosenhead and Mingers, 2001) such as cognitive mapping and

92 stakeholder analysis (e.g. Lienert et al., 2013) are effective tools to frame the decision, decide

93 what is important, and identify who makes the decision (decision-maker) or is affected by it

94 (stakeholder). In the following, the term stakeholder will be used for anyone involved in the

95 decision with responsibility, interest, and/ or decision power. Framing the decision includes

96 generating a set of objectives, which are often organized in a hierarchy, and a set of decision

97 alternatives (options). Usually the process starts with divergent thinking to capture the

98 participant's different viewpoints. The decision analyst facilitates the participants to converge to

99 a consolidated shared understanding of the problem (Franco and Montibeller, 2010; Kaner,

100 2014). Each objective is described with one or more measurable performance indicators, named

101 attributes. Attributes quantify the objectives' achievement. For each alternative, the attribute of

102 each objective is predicted using expert estimates, literature data, or simulation models (see

103 textbooks, e.g.: Belton and Stewart, 2002; Eisenführ et al., 2010; Keeney and Raiffa, 1976). This

104 is the "hard" science part of MCDA. In a next step, "softer" data are elicited: the subjective

105 preferences of stakeholders (see section 2.4). This is commonly done in individual interviews or

106 group workshops. Then, for each alternative, the predicted achievement of objectives and the

107 stakeholders' preferences are integrated in a decision model to calculate an overall performance

108 (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)

109   aggregation model. The assumptions of the additive model need to be tested with consistency

110   checks during the elicitation of the stakeholders' preferences. Else, other models should be used

111   (e.g. Langhans et al., 2014; Reichert et al., 2015). Finally, the results are discussed with the

112   stakeholders and a consensus alternative is searched for. MCDA is often an iterative process.
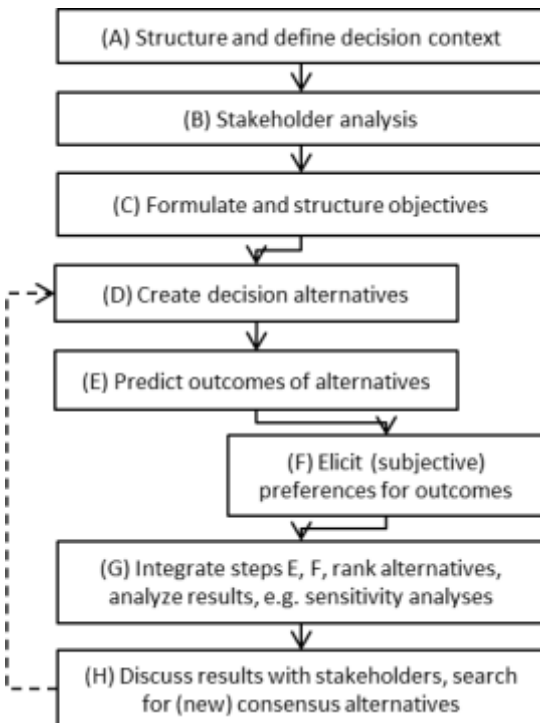

Figure 1: Multi-Criteria Decision Analysis process, step-by-step. (Adapted from Table 1 of Lienert et al., 2011)

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115   **2.4.   Stakeholders' preference, the strength of MCDA**

116   MCDA's strength is to combine hard sciences (the predictions) and softer data (the stakeholders'

117   preferences). MCDA methods make explicit the inherent subjectivity of decisions: the

118   expectations, objectives, and preferences of stakeholders regarding the achievement of and the

119   trade-offs between objectives (value functions and weights, respectively) (Gregory et al., 2012;

120   Scholten et al., 2017). In case of uncertainty, the value function is converted to a utility function

121   using the elicited stakeholder's risk attitude (Multi-Attribute Utility Theory; Keeney and Raiffa,

122   1976).

123 Traditionally, economists assume that true preferences pre-exist, while decision psychologists

124 (Slovic, 1995) postulate that tasks (response mode), context factors (experience, learning effort

125 etc.), and individual abilities enable to construct preferences (Lichtenstein and Slovic, 2006;

126 Payne et al., 1992). Thus, the decision analyst's role is to (1) verify that the axiomatic basis of

127 MAVT is met, (2) ensure a transparent and fair procedure (understandable and meaningful to

128 the participants, acknowledging all important views), and (3) facilitate preferences construction

129 (by providing necessary neutral information, reducing the cognitive load, and limiting the

130 occurrence of biases).

131   **2.5.   Focus on the importance of objectives: assigning weights**

132 Weights reflect the preferences regarding trade-offs between objectives, i.e. the stakeholder's

133 judgment on the relative importance of each objective. They quantify what matters in the

134 decision. Asking directly for the weights (direct-ratio method) is the most straightforward method,

135 however it is considered as highly problematic and other methods should be preferred

136 (Eisenführ et al., 2010; Morton and Fasolo, 2009): e.g. the swing and trade-off methods. For a

137 review on weight elicitation methods and their practical use see Riabacke et al. (2012), and for a

138 review on methods validity see Van Ittersum et al. (2007).

139   **2.6.   The limits of current weight elicitation methods**

140 *High cognitive load.* Assigning weights to objectives requires a significant mental effort for

141 most stakeholders (Morton and Fasolo, 2009; Riabacke et al., 2012). This can be due to: (1) the

142 lack of previous knowledge or information on the issue, and still unconstructed preferences,

143 (2) the moral difficulty to make trade-offs when objectives are highly competing, and (3) technical

144 reasons linked to the elicitation method (e.g. instructions are difficult to understand, cognitive

145 tiredness created by repetitive tasks) (Chatterjee and Heath, 1996; Deparis et al., 2012; Payne

146 et al., 1992; Riabacke et al., 2012). In other words, weight elicitation involves the three types of

147 cognitive load distinguished in the cognitive load theory (van Gog and Paas, 2012): intrinsic

148 (load related to the amount of information needed to be processed to perform the task, e.g.

149 choice overload (Iyengar and Lepper, 2000)), extraneous (load imposed by the format in which

150 the information is provided), and germane (how much effort an individual invests to understand

151 the information). Moreover, it is influenced by the individual's prior knowledge (Brünken et al.,

152 2003). Reaching cognitive load limits (overload) leads to situations where no further information

153 can be mentally processed or considered, which can severely reduce the quality of elicited

154 weights.

155 *Biases*. Weight elicitation is highly sensitive to biases (Hämäläinen, 2015; Hämäläinen and

156 Alaja, 2008; Morton and Fasolo, 2009; Riabacke et al., 2012). Following biases occurring during

157 weight elicitation were presented in the review of Montibeller and von Winterfeldt (2015): the

158 affect influenced bias and desirability of option bias are motivational biases. Others are cognitive

159 biases: the equalizing bias, gain-loss bias, proxy bias, range insensitivity bias, and the splitting

160 bias. Describing all of them is outside the scope of this paper. If they occur, the weights may no

161 longer represent the preferences of the stakeholder, which would distort the MCDA outcome.

162 This problem is well-known in MCDA and an experienced facilitator will be attentive to avoid

163 these biases, and use or develop methods limiting their occurrence, e.g. consistency check

164 questions using another method.

165 *Unconstructed preferences*. Incompletely constructed preferences are unstable. They are

166 especially critical for decisions with long term consequences (Gregory et al., 2012). Some

167 consider that preference construction is a never-ending life-long learning process evolving with

168 experiences and context (Amir and Levav, 2008; Warren et al., 2011), matching the

169 transformative learning theory (see references in Merriam et al., 2007). Yet, factors such as the

170 task or elicitation method (how the problem is presented, described, visualized, the task

171 difficulty), knowledge/ expertise on the issue, and the experience of topic-connected events

172 contribute to preference construction (Hoeffler and Ariely, 1999; Jorgensen et al., 2004; Liebe et

173 al., 2012; Payne et al., 1992). The decision analyst can facilitate the construction and stability of

174 preferences by influencing these factors. Defining the best practice is still an open research

175 question (e.g. Anderson and Clemen, 2013).

176 *Limited participation (time consuming, need of a facilitator).* The limits mentioned above

177 (i.e. high cognitive load, biases, and unconstructed preferences) justify that an experienced

178 decision analyst elicits the weights. This is classically done in face-to-face interviews or in group

179 workshops (Marttunen and Hämäläinen, 2008). However, both are time-consuming and strongly

180 constrain the number of participants. This contradicts the increasing societal demand for

181 participatory decision-making. Many studies within operations research (Gregory et al., 2016;

182 Hämäläinen, 2015; Kellon and Arvai, 2011; Voinov et al., 2016), and e.g. in policy and

183   governance (e.g. Dietz and Stern, 2008; Dupuis and Knoepfel, 2015; Étienne, 2011;

184   Papadopoulos and Warin, 2007, and references therein; Renn, 2003), or transition management

185   (e.g. Harris-Lovett et al., 2015), call for participatory decision-making. First approaches to

186   increase citizen participation in environmental MCDA via online surveys yielded encouraging

187   results (Bessette et al., 2016; Gregory et al., 2016; Lienert et al., 2016; Mustajoki et al., 2004).

188   Certainly, online surveys have the advantage of reaching many participants and of speeding up

189   the elicitation process. However, the validity of online preference elicitation has been questioned

190   (Insua and French, 2010; Marttunen and Hämäläinen, 2008). These authors argue that direct

191   interactions between respondents and decision analysts are the only way to prevent the

192   occurrence of biases, to reduce the cognitive load, increase learning, and thus to enhance

193   reliable preference construction. To involve the public and elicit reliable weights, MCDA needs

194   an accessible tool, both literally (easy access for many) and figuratively (easily understandable

195   and manageable).

196   **2.7.   Insights into people's judgements and descriptive decision analysis**

197   While the above-introduced prescriptive decision analysis focuses on understanding and

198   supporting rational decision-making processes, descriptive decision analysis focuses on how

199   people actually make decisions (Fischhoff, 2010). Often, people's observed behaviors deviate

200   from rationality principles. Both affect and cognition contribute to mindful decision-making (e.g.

201   of descriptive decision reviews: Lerner et al., 2015; Oppenheimer and Kelso, 2015; Weber and

202   Johnson, 2009), in particular the following four intertwined factors: (1) attention, (2) information

203   processing, e.g. encoding, evaluation and memory processes, (3) emotions, and (4) learning.

204   Each is briefly summarized hereafter.

205   *Attention* makes the participant notice the task and raise his/ her interest. It is selective and

206   scarce. It can be exogenous, e.g. triggered by a changing environment that varies automatically,

207   or endogenous, raising either deontological ("What is right?"), consequential ("What has the best

208   outcomes?"), or affective ("What feels right?") considerations. The physical salience and

209   endogenous attention influence thoughts of individuals (Kahneman, 2003), and thus choices and

210   judgments. Judgements can be manipulated by increasing or reducing attention.

211   *Information processing* describes how the individual acquires information (encoding and

212   evaluation) and retrieves it from memory. Information processing is most effective when it is

213   context specific and in view of a clearly defined goal which make sense to the participant.

214   Individuals seem to process information depending on how it is presented, how the task is

215   formulated, how the available information is stored in memory, and depending on individual

216   cognitive capacities. Some well-known biases can be explained by memory. The anchoring bias

217   would result from short term memory: an individual is primed by a question preceding the

218   decision task (Chapman and Johnson, 2000; Tversky and Kahneman, 1974). The endowment/

219   ownership or gain-loss biases would be caused by long term memory, and particularly how

220   individuals retrieve long-term encoded information when making a decision. According to the

221   query theory, the order of the information retrieval queries determine the decision (Johnson et

222   al., 2007).

223   An *Emotion* "revolution" started in descriptive decision analysis around 2004, with a growing

224   number of publications focusing on affect-, mood-, and emotions-driven processes (Lerner et al.,

225   2015). Affect in decision-making would have four functions (Peters et al., 2006). (1) Emotions

226   can act as a spotlight that raises attention. (2) Emotions can act as immediate or longer-term

227   information. (3) Emotions can act as common currency, i.e. respondents compare alternatives

228   by the different emotional states they create. Finally, (4) emotions can act as motivator, and

229   different emotions seem to trigger different action tendencies. As an example, anger might drive

230   a person to focus on motives and responsibility, which in turn raises an eagerness to act and

231   punish.

232   *Learning* from experience and feedback is an important process in judgement and decision-

233   making (Elwin et al., 2007). This learning is based on expected feelings about options (decision

234   utility) and actual feelings when experiencing the options (experience utility). Complete and

235   holistic feedbacks are necessary to make an accurate decision (Hogarth, 1987). It is noteworthy

236   that many prescriptive decision analysts consider MCDA as a learning process (Gregory et al.,

237   2012; Hämäläinen et al., 2001; Karjalainen et al., 2013; Marttunen and Hämäläinen, 2008). Five

238   categories of "what is learnt" are proposed (Belton and Elder, 1994): (1) understanding logical

239   relationships, (2) formulating so far not carefully analyzed opinions, (3) clarifying the implication

240   of the now carefully analyzed opinions, (4) changing opinions, and (5) creating new ideas.

241

3. Method used for the game review

242

243 First, we carried out a literature review on serious games and gamification from 02.02.-

244 01.03.2016 [2]. Then, we identified serious games on water issues. Water is a global, but also

245 region-specific challenge. An explorative search was carried out, starting from already existing

246 lists provided by the Geneva Water Hub platform (Geneva Water Hub, 2015) and the world

247 water day website (World Water Day, 2015). Additional serious games on water-related issues

248 were identified using internet searches (google, google scholar, and web of science), and

249 publications which reviewed several games, e.g. lists of five persuasive games for water

250 management (Rizzoli et al., 2014), of four games about water infrastructures (Söbke and

251 Londong, 2014), and of 12 educational water games (Hoekstra, 2012). We also found games by

252 word of mouth. For each game we aimed at finding associated scientific publications, which do

253 not, however, always exist.

254 We used a structured, generalized procedure to define each game, filling in a table of

255 characteristics (Tab. SI1, Supporting Information), inspired from Djaouti et al. (2011). These

256 comprised: general information (game title, name of credit owner and/ or developer, year

257 released, country in which it was developed, link to the online game and/ or references to

258 scientific publication). Additional characteristics were the game's purpose (exchange data/

259 broadcast message/ training), short notes on the gameplay (type of actions in relation to the

260 narrative, if any), player information (targeted player, number of player(s), type of interaction(s)

261 during the game: player-facilitator/ player-player and/ or player-IT interface), note on how

262 engagement was created (identified game elements), support of the game (technology used),

263 spatiotemporal frame (length, possibility to interrupt, location), and domain of application (water

264 issue, if specified country). The main author experienced all the online games. In case of non-

265 online games (e.g. board games, group games), the author relied on the available instructions

266 and/ or the associated publications.

267 The game diversity was then represented in a two-dimensional graph where the axes represent

268 the technology (classes from low to high), and the degree of verisimilitude (adapted from Lane

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[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.

269   (1995), classes from simplified reality (fully-fledge games) to modeled complexity (gamified non-

270   entertainment applications)). Serious games and gamification features are then discussed,

271   viewed through the lens of MCDA. The reason for this specific focus is that decision analysis

272   researchers and practitioners have been challenged to find innovative approaches for public

273   participation and preference elicitation, as discussed in section 2.6.

274

275   *4. Results on water-related serious games review*

276   **4.1.   What is a serious game?**

277   Games can be defined as unsolicited activity (therefore self-engaging, motivating by itself),

278   either mental or physical, with no aim other than leisure or fun, framed with rules, which offers a

279   chance to win or lose, and requires a variable proportion of skill, dexterity, and hazard

280   (Larousse, 2015). Regarding rules, games belong to a continuum from the *ludus* (rule-following)

281   game-type, which has many rules to reach a clear objective, to the *paidia* (playfulness, fun)

282   game-type, which has no pre-defined goal and is thus a more freeform game. Games offer an

283   escape from ordinary life, i.e. are characterized by a degree of fiction, and are most often framed

284   in time and space (Juul, 2005; Schmoll, 2011). This frame has been named the "magic circle"

285   (Huizinga, 1949), because specific rules, different from the real world, prevail. In their seminal

286   book *Rules of play*, Salen and Zimmerman (2003) consider games as systems in which players

287   engage in artificial conflicts defined by rules, and which result in a quantifiable outcome. These

288   artificial conflicts can be of various types (Mendler de Suarez et al., 2012), including the intrinsic

289   tension of games mentioned above between fun *(paidia)* and rules *(ludus)*. Similarly, the theory

290   of Csikszentmihalyi (2000) postulates that enjoyment and intrinsic motivation (being in the "flow")

291   is created by a constant trade-off between the challenges (action opportunities) offered to the

292   player, and her skills (action capabilities). There is a flow path of intrinsic motivation, surrounded

293   by worry (same action capabilities, but too high challenge) and boredom (same action

294   opportunity, but too high skill requirements).

295   From the game definition, it appears that "serious game" is by essence a paradoxical notion, i.e.

296   "serious" versus "no aim but leisure and fun". Probably due to this contradiction, definitions of

297   "serious game" are numerous and differ to some extent. A commonly accepted trait is that

298 serious games are not only entertaining, but also have a specific aim. Mendler de Suarez et al.

299 (2012) define serious games as "games with an explicit and carefully though-out educational

300 purpose – not intended to be played primarily for amusement". In his book *Serious Games*, Abt

301 (1970) considered any types of games, including card and board games, while more recently

302 many tend to reduce serious games to those including video or simulation components. For this

303 review, any serious game type (with and without information technology) is considered. Another

304 definition less prone to debate is that any *a priori* non-entertaining application, including game

305 concepts, technologies, and ideas, is a serious game, thus including all the "gamified"

306 applications (Seaborn and Fels, 2015). Serious games and gamified applications can be

307 classified based on the Game-Purpose-Scope framework from Djaouti et al. (2011). "Game"

308 focuses on the degree of action/ interaction referring to *paidia* vs. *ludus.* "Purpose" is divided into

309 three classes: broadcasting a message, training, and exchanging data. "Scope" focuses on the

310 targeted gamers/ players.

311 Since the 18th century, serious games have been successfully used in military training. For a

312 long time, computer-game simulations have also been used in behavioral decision research

313 (Payne et al., 1992). In the last decade, serious games combining computer simulation and role

314 playing games have been developing in education, including teaching water management (e.g.

315 Carruthers and Smith, 1989; Ewen and Seibert, 2016; Hoekstra, 2012), water governance and

316 policy (e.g. Adamowski, 2015; Douven et al., 2014; Geurts et al., 2007), and other common-

317 resource management fields (e.g. Barreteau, 2003; Cleland et al., 2012; Ulrich, 1997); as well as

318 more generally in operations research, e.g. with the Beer game created in the 1960s by MIT

319 Sloan School of management professors, still used today (e.g. Lane, 1995; Thompson and

320 Badizadegan, 2015).

4.2. The diversity of serious games

322 We illustrate the diversity of the reviewed games in a two-dimensional graph (Fig. 2). The axes

323 derive from the debated aspects of the serious games definition (1) the technology used (x-axis),

324 and (2) the degree of verisimilitude (y-axis). The technology axis is divided into five classes:

325 group games using no or little paraphernalia (e.g. using dices and polls; low-tech end of the x-

326 axis), regular board games, board games combined with IT interface, IT interface on its own,

327 and virtual reality games (i.e. a fully immersive video; high-tech end of the x-axis). The degree of

328 verisimilitude is divided into four classes: gamified applications (serious end of the y-axis, in the

329 sense modeling the complex reality as close as possible from reality, "S"), serious games using

330 scientific models and real-world data ("s"), games using simplified models and real-world data

331 ("f"), and fully-fledged games with a serious or moral topic (opposed to previous classes, by not

332 using any scientifically based models or real-world data in the game mechanics; end of the y-

333 axis, further away from the complex reality, "F").

334 Our review of 43 serious games on water-related issues spans the serious games/ gamification

335 diversity. Further searches would not have revealed any new traits or game types, though we

336 acknowledge that other water-related games exist. The only missing type of water-related

337 serious game is a fully immersive virtual reality game. We did encounter immersive and

338 interactive visualizations of water related projects based on geographical information systems

339 (GIS) (for instance, about floods, Leskens et al., 2015; Zhang et al., 2013). However, we argue

340 that they are outside the scope of this paper, as these decision support systems do not include
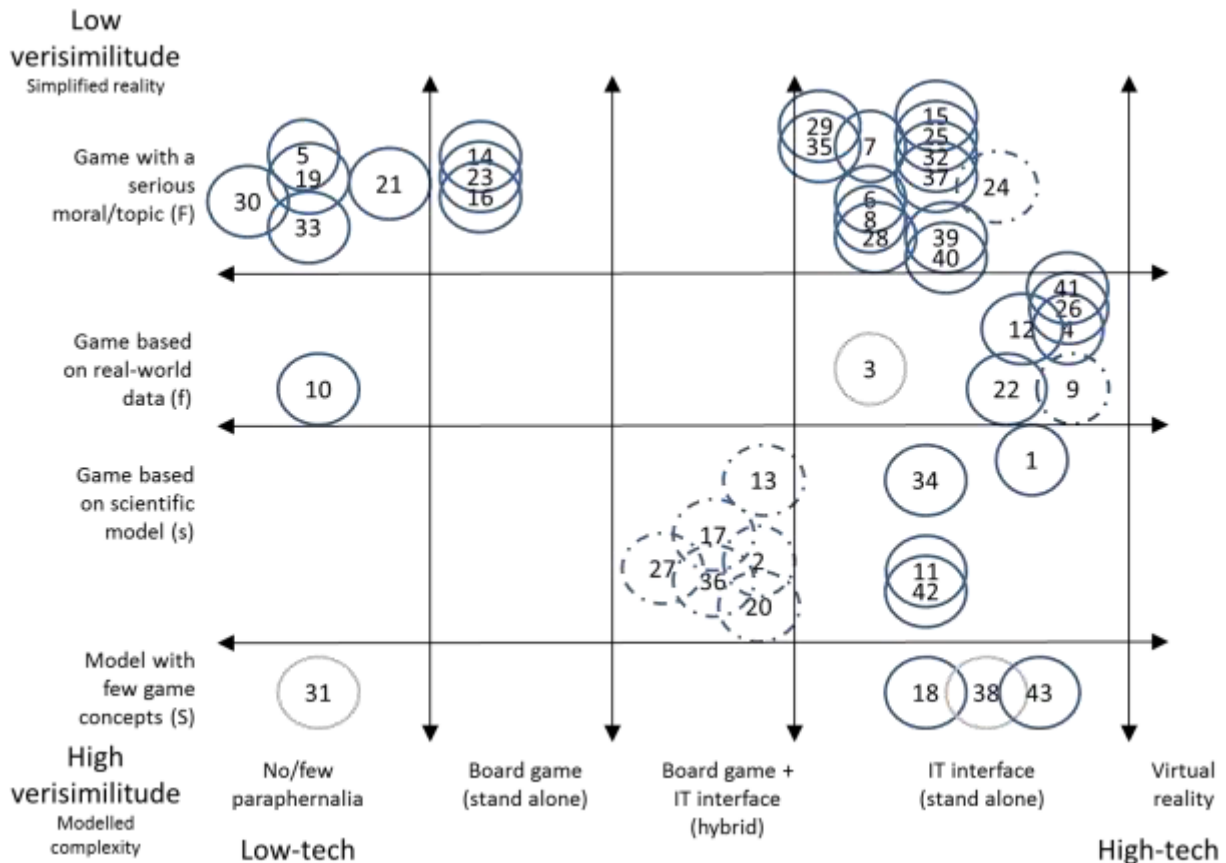
341 game features.

342

343 Figure 2. Various serious game definitions lead to a wide diversity of games in the water sector. We propose to

344 classify them according to the technology (x-axis) and verisimilitude (y-axis) degree: potentially 20 types exist.

345 Numbers refer to Tabs. 1, SI (games ordered alphabetically). The games' purpose is highlighted: broadcasting a

346 message (plain dark circles), exchanging information (dashed-dotted circles) and training games (plain gray circles).

347 The letters in brackets at the end of the verisimilitude class titles are used in Tab. SI1. Finer clustering of games is

348 variable, based on other characteristics, e.g. developed by the same institution, same game mechanics (e.g. tiled-

349 based) (see in the text).

350   4.2.1. Water-related serious games span all purposes

351   4.2.1.1. **"Broadcasting a message"** games include those games developed to raise

352   awareness on water related issues such as household water consumption (e.g.

353   #15, 29, 32, 37; Tabs. 1 and SI), integrated water resources management (e.g.

354   #1, 4, 12, 28), or flood risk (e.g. #9, 19, 26, 30, 38), to mention a few. They also

355   include games used as teaching materials at universities, and many other
356   simulation games (e.g. Ewen and Seibert, 2016; Hoekstra, 2012; Magombeyi et
357   al., 2008; Rajabu, 2007; Rusca et al., 2012).

358   Table 1. Summary of the reviewed serious games related to water issues. Games are numbered in alphabetical
359   order. IWRM: integrated water resources management. NA: not available. Additional information and direct link to the
360   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)

Aubert, Bauer, Lienert

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

361

362 4.2.1.2. *"Exchanging information"* games present either a direct or indirect exchange of
363 information, which can be data, knowledge, worldviews, etc.. (1) *Direct exchange*
364 games are mostly simulation games, typically played during workshops, aiming at
365 problem structuring or scenario development (e.g. #2, 17, 20, 27, 36; Tabs. 1, SI).
366 Here, a two-sided information exchange occurs. First, the game facilitator, often a

17

367   scientist, learns about the resource sharing context and the point of view of each

368   player. Hence, the players' attitudes are collected as input data for a scientific

369   model. Second, the players, often referred to as "participants", learn about the

370   other players' understanding of the issue (worldview) and about the co-

371   constructed model, i.e. social learning occurs (Barreteau, 2003; van der Wal et

372   al., 2016). (2) *Indirect exchange* games allow for learning or awareness raising

373   and at the same time data collection (e.g. #9, 24). FloodSim (#9) raises

374   awareness on flood prevention issues in the United Kingdom and collects data

375   about the players' chosen flood protection alternatives (implicitly considered as

376   most preferred). SmartH2O (#24) raises awareness on household water

377   consumption, while it concurrently encourages players to provide water

378   consumption data.

379   4.2.1.3.   *"Training"* games reproduce a real-world situation with accurate reality (e.g.

380   AWQA Water (#3), The river Wadu role play (#31), and Water Coach (#38)). They

381   do not involve an exchange between scientists/ experts and users, because the

382   player is usually an expert, who already knows much about the topic, but needs

383   to practice in a safe environment, i.e. in a fictional situation.

384

385   4.2.2. A diversity of water issues is reflected in the serious games

386   Most games deal with sustainable water use, in a broad sense, and at various scales: at the

387   level of households, watersheds, transboundary watersheds, and globally. Two sub-themes are

388   predominant: user conflicts regarding resource use (e.g. #17, 27, 36), and water-related risks

389   such as droughts, floods, and pollution (e.g. #6, 9, 38). Four games highlight innovative urban

390   water management: the NoMix tool (#18) (Pahl-Wostl et al., 2003), SmartH2O (#24), TWIST++

391   (#34), and wastewater RPG (#42) (Prat et al., 2009).

392   4.2.3. Water-related serious games target many different players

393   We found serious games for all ages. However, on the verisimilitude axis, we observe a

394   differentiation based on the player's expertise. Most complex games with few game concepts

395　and/ or that are based on scientific models target students and/ or professionals from water

396　management and the natural sciences (e.g. #31, 42; Tab. 1). In contrast, games that use many

397　game concepts and a simplified representation of the real-world, target non-experts such as

398　adult and/ or child laypeople (e.g. #21). On the technology axis, there is no apparent

399　differentiation, and any game technology is used for any targeted player group, independently

400　from expertise or age. The only discernible trend would be that hybrid games, those associating

401　physical games and computer elements for simulations, seem to target adults, i.e. advanced

402　students, professionals from water management and the natural sciences, and sometimes local

403　stakeholders (e.g. #2, 27, 36).

404　　　4.2.4.　The variety of technology

405　　　4.2.4.1.　***Low technology games*** are games with no/ few paraphernalia or stand-alone

406　　　　　　　board games: group games with no paraphernalia (e.g. #30; Tabs. 1, SI), role

407　　　　　　　playing games with few paraphernalia (e.g. #31), card games (e.g. #10, 33),

408　　　　　　　construction games with blocks of different materials and tape (e.g. #21), and

409　　　　　　　board games with several paraphernalia such as a board, dices, polls, or cards

410　　　　　　　(e.g. #14, 16, 23). Low technology games are mostly used in real meetings and

411　　　　　　　workshops organized by humanitarian or development organizations (e.g. #5, 19,

412　　　　　　　30). Low technology serious games are also used in private consultancy (e.g.

413　　　　　　　#10), in science museums (e.g. #21), in outreach fairs (e.g. #16), in schools (e.g.

414　　　　　　　#33), and in universities (e.g. #31).

415　　　4.2.4.2.　***Hybrid games*** are board games or role playing games, backed by computer

416　　　　　　　simulations. They are so-called simulation games, or policy games. They enable

417　　　　　　　the gamers to foresee the impact of their decisions or actions over time and to

418　　　　　　　build an understanding of the complex interactions of social, environmental, and

419　　　　　　　economic factors. The players virtually experience the consequences of

420　　　　　　　alternatives. These games stimulate discussion and learning among

421　　　　　　　stakeholders, thus enhancing social learning. Furthermore, they enable to explore

422　　　　　　　a range of plausible futures, using different scenarios, e.g. the International Panel

423　　　　　　　for Climate Change scenarios in Mendler de Suarez et al. (2012). Such games

424　　　　　　　are a media to communicate about complexity (Duke and Geurts, 2004). They

425	would thus allow exploring and better understanding wicked problems, i.e.
426	problems that cannot be definitively formulated and that present no right-or-wrong
427	answer nor definitive solution (e.g. policy planning) (Hansson and Hirsch Hadorn,
428	2016; Rittel and Webber, 1973). They are often used in conflict situations about a
429	shared resource (e.g. #17) (Barreteau, 2003). The participants can hardly ever
430	lose: in the worst case, they witness a non-consensual end of the play that is in
431	contradiction with their interest and/ or belief. These games require a facilitator or
432	game leader to introduce the game context and rules, to deal with the modelling,
433	to encourage collaboration, as well as to facilitate the debriefing phase, often
434	leading to decision-making in the real world. The participant embodies the role of
435	a stakeholder (sometimes his own real role) and is asked to answer a challenge
436	according to fixed rules. Some games include a scoring system (e.g. #36).

437   4.2.4.3.   ***Simplified games with a standalone IT interface***

438	Simplified games with IT interface are also well represented. Most of these games
439	were developed in transdisciplinary teams, particularly when they are based on
440	real-world data.
441	Some of these simple computer games are highly successful and wide-spread.
442	The most famous may be Darfur is dying (#7; Tabs. 1, SI), alerting the general
443	public to the South Sudan water crisis in refugee camps. Another game which
444	quickly spread after its launch, particularly among the targeted United Kingdom
445	population is the FloodSim game (#9), partly based on real-world data.
446	Many standalone IT interface games use tile-based space management, which
447	might be a reminiscence of the commercial game SimCity. The latter is originally
448	a fully-fledge commercial game which can hardly be classified as a serious game.
449	However, in its fourth version, it also includes an improved and more realistic
450	urban hydrology model (D'Artista and Hellweger, 2007). The tiled-based space
451	management games promote the understanding of water cycles, or more
452	precisely of water use at the catchment scale (e.g. Aqua Republica (#1),
453	Catchment Detox (#4), later renamed the basin challenge, L'eau c'est plus qu'un
454	jeu (#12), Stop disasters! (#26), and Water wars (#41)).

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

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

472

473   **4.3.   The common features of serious games**
474   4.3.1.   Gameplay loop: the cornerstone of gamification

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

484   In serious games, a win/ loss state is constructed to make the player analyze her choice

485   (Mendler de Suarez et al., 2012; UNEP-DHI centre for Water and Environment, 2012). A loss

486   state may create cognitive dissonance (or conflict) within an individual, and can hereby enhance

487   learning if the person aims at reducing this inner conflict (identifying the reasons, and adapting)

488   (Adcock, 2012). Reflecting based on an experience is a learning process known in many

489   learning theories, e.g. Kolb's experiential learning cycle (Merriam et al., 2007), or Argyris' single-

490   and double-loop learning (Argyris, 1978). In game-based learning, when taking an action, the

491   player has some expectations concerning how the model will work. Her action induces a change

492   in the game environment which leads to a reward or penalization. Then, the player can evaluate

493   her prior expectation by confirming it and continuing to play, or by formulating a different

494   expectation to be tested in the trial of this loop. The game offers a safe environment to learn

495   from trial and error.

496
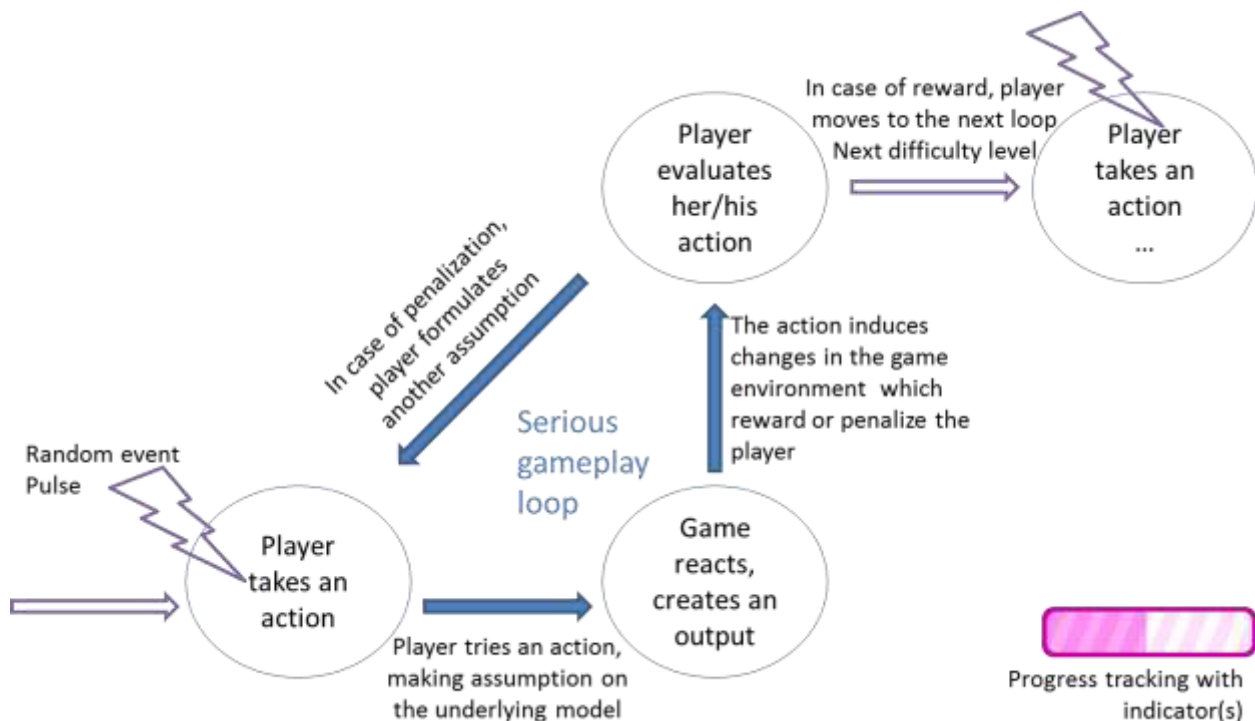
497   Figure 3. A model of a serious gameplay loop or micro cycle (adapted from Mendler de Suarez et al., 2012; Plass et

498   al., 2015; UNEP-DHI centre for Water and Environment, 2012). It is very similar to many learning theories, based on

499   loops/ cycles.

500

4.3.2. Other common game elements to engage and motivate

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

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

508 According to Christen et al. (2012), the narrative, the gameplay, and an attractive virtual
509 environment (i.e. design and graphics) are the key elements to make a serious game successful.
510 While judging the attractive power of the virtual environment is quite a subjective task, neglecting
511 this component is instantly noticeable, and commented by users. Among the games reviewed,
512 some presented significantly developed narratives. These narratives assign a mission to the
513 player as an immersive motivation element; e.g. Water life: sea turtles and the quest to nest
514 (#39), Water life: where the rivers meet the sea (#40), TWIST++ (#34), and SOS mission eau
515 (#25).
516 The motivation created from games has long-been a "black box" (Rigby, 2014). First attempts of
517 theorization exist (for a review, see Seaborn and Fels, 2015). One of them is based on the Self-
518 Determination Theory, and suggests that a game, or a gamification can enhance the
519 internalization of extrinsic motivation by providing a feeling of competency, autonomy and
520 relatedness to others, and, when relevant, by stressing the intrinsic goals of the player (Rigby,
521 2014; Ryan et al., 2006).

522

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

524 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).

525

526 ### 4.3.3. Additional features of serious games

527 Other game elements can be seen as motivational affordances (Tab. 2). Many of the reviewed

528 simulation games trigger collaboration through role play, and end with a debriefing on what

529 happened, and what was learnt. An emerging way to engage players is to broadcast the

530 message intuitively through gestures. For instance, the player see the intensification of a

531 phenomenon through the graphical representation (water use, or water pollution), but she will

532 also experience it physically as she will have to intensify the frequency of her actions. In Run the

533 river (#22; Tabs. 1, SI), the player allocates water between the needs of various users and the

534 number of clicks needed depend on the water consumption. In System_blue (#28), the

535 gameplay is similar but focuses on pumping river water for a village. The player experiences that

536 some users need a bigger allocation of water than others. In Fish game (#8), about the shared

537 fish resource, and in Contaminator (#6), about river water quality, the player is faced with

538 exponential worsening once the problem appears. In the Fish game (#8), if the player thinks only

539 about her interests, all other fishers behave egoistically too, leading to fast complete depletion of

540 the fish resource. In Contaminator (#6), river pollution starts mainly by upstream input; as soon

541 as this happens, it becomes harder and harder – even impossible – to maintain a good water

542 quality status.

543 Additional features must be characterized when developing games, including serious games

544 (Duke, 1980): (1) rules that indicate how to play (particularly important in *ludus,* rule-based

545 gaming); (2) models that enable to track the logical process; (3) decision sequence and linkage

546 that represent the typical player sequence of decisions for each role (if any) and each step of the

547 gameplay. This sequence answers the question "*who* is doing *what*, *when* and *how*?". If it is

548 properly developed it ensures adequate feedbacks. Points (1) to (3) define the game mechanics

549 (Sicart, 2008). In addition, the paraphernalia need to be defined, i.e. lists of all objects and

550 materials required to play.

551

552 *5. Discussion*

553 **5.1. Rationales to use serious games or to gamify MCDA**

554 Overall, serious games and gamification are designed to offer an engaging, and challenging

555 frame. They can present current states of real-world issues, and sometimes simulate possible

556 future states. Serious games can facilitate the players' involvement in and comprehensive

557 learning about real-world issues, sometimes supporting deliberation and decision-making.

558 Different strategies could be possible to cover the real-world complexity of an issue: e.g. one can

559 develop a serious game or gamified application with high-verisimilitude, or one can gradually

560 increase the verisimilitude bringing in the complexity step-by-step (e.g. with different levels), or

561 one can cut down the complexity into a sequence of low-verisimilitude games (e.g. dealing with

562 single aspects independently). The chosen gamification depends on the targeted audience:

563 experts will be attentive longer when facing complexity than laypeople. Gamification triggers

564 motivational factors which in turn encourage pursuing a task (Ramirez and Squire, 2014; Rigby,

565 2014). Plass et al. (2015) offer a general framework and suggest that game-based learning

566 fosters many facets of engagement, i.e. cognitive, behavioral, affective, and sociocultural

567 engagement. Yet, for serious games and gamification research, better structuring and more

568 rigorous evaluation of the benefits and/ or possible drawbacks are needed. Ideas for future

569 research work are listed hereafter. For instance, while game elements are reported as effective

570 motivational factors (Hamari et al., 2014), the behavioral consequences are unclear. Using

571 theoretical frameworks from psychology, e.g. self-determination theory and other theories from

572 intrinsic and extrinsic motivation (Seaborn and Fels, 2015) could help, as well as carrying out

573 comparative studies (e.g. Haug et al., 2011).

574 After reviewing the literature, we observe a potentially promising match between the aims of

575 serious games and gamification and the challenges that MCDA is facing. MCDA needs to be

576 more participatory, i.e. to allow citizen involvement. Thus, MCDA requires methods that allow

577 laypeople, who are newly confronted with a decision topic, to construct reliable preferences.

578 These methods should limit the cognitive load, avoid biases, and allow for experimentation and

579 learning. Descriptive decision analysis tells us that various factors are important for mindful

580 judgments and preference construction. These include e.g. learning, in particular from

581 feedbacks, processing and retrieving memorized information, and motivation. Serious games

582 and gamification exactly address these factors, in addition to being easily understandable and

583 accessible by many. Hereafter, we discuss in more detail the high potential of using serious

584 games and gamification in MCDA, while pointing out the possible drawbacks. Future research is

585 needed to properly evaluate the use of serious games and gamification in MCDA.

586 **5.2.   Most MCDA steps can be addressed with an already existing serious game**

587 5.2.1. Gamified MCDA workshops (steps A, C, D, and H)

588 According to our review, the simulation games used in the companion modelling approach (e.g.

589 #2, 17, 20) (Étienne, 2011 and references therein), and other role playing policy games (e.g.

590 Douven et al., 2014; Duke and Geurts, 2004; Geurts et al., 2007; Haug et al., 2011) are existing

591 examples of gaming that could be transferred to certain phases of MCDA. These include the

592 initial steps of structuring and defining the decision context, formulating the objectives, and

593 creating the decision alternatives (steps A, C, and D), and the final step of discussing results

594 with the participants and searching for consensus alternatives (step H) (Fig 1). Typically, about

595 five to 20 targeted players/ workshop participants are selected as representative stakeholders,

596 they either have decision-making power, or are affected by the decision. The workshop is

597 organized around the role play game, often involving simulation. Thus, it requires a real meeting

598 and an experienced facilitator, sometimes backed by an assistant for computer modelling. The

599 game fosters interaction between the role playing participants, who are acting in the protected

600 environment, and with the facilitator. The game can last from half a day to two days, but can be

601 interrupted. Interruptions are opportunities to discuss and reflect on whether learning occurred,

602 and the outcomes are fair. In other words, these existing games can be seen as gamified

603 decision analysis workshops. The game and its set of rules are usually a co-construction,

604 emerging from the players' input and the facilitating team. The designed rules translate the

605 complex issue of competing objectives among stakeholders. This co-construction of a tailored

606 game warranties that every worldview represented in the meeting is taken into account, and that

607 the complexity of the real world is represented in the game. This is required to (1) depict the

608 complexity of the issue, (2) initiate social learning and (3) create ownership of the outcome. The

609 game is meant to model real-world relations between the participants and the resource, as well

610 as among participants. A rich literature on this type of games is available and discusses pros

611 and cons based on case studies (e.g. Dray et al., 2007; Étienne, 2011). We are not aware of

612 hypotheses testing in an experimental deductive approach, apart from the attempt of Haug et al.

613 (2011). Possible future developments for the MCDA community could be to integrate an MCDA

614 preference elicitation and aggregation model in such gamified workshops or policy games (step

615 F; Fig. 1), and test whether the complexity of the issue is better understood and social learning is

616 enhanced. Hereby, behavioral aspects need to be thoroughly considered, in particular how

617 individual preferences are expressed through this group exercise.

618

619   5.2.2.   Serious games for stakeholders analysis (step B)

620 In the review, the game The gender walk (#30, in its prior version) aimed at identifying the role or

621 importance of the stakeholders. The game does not target any specific group; as illustrated by

622 the wide intended audience, which includes community members, donors, disaster managers,

623 volunteers, branch officers, etc. The number of players can range from ten to 40, and the game

624 lasts one to two hours. The game requires a real meeting, an experienced facilitator, and

625 assistants if there are many players. The game fosters understanding of inequality between

626 genders, or among the stakeholders regarding climate variability and change. All players start on

627 the same line. The facilitator asks questions; to answer yes, the player steps forwards, to answer

628 no, the player steps backwards. After a series of questions, the players are clustered. A

629 debriefing session follows to discuss the clusters composition, and ways to homogenize. We see

630 this game as a stakeholder analysis, whereby we can identify how important each stakeholder

631 is, whether she is affected by the decision or influencing it as decision-maker (see e.g. Lienert et

632 al., 2013). It could also promote social learning if players share their perception of the problem.

633 However, practically, selecting players that are invited to participate can be critical. Therefore,

634 this exercise would be especially interesting in an early phase of decision-making, on occasions

635 where many people are gathered, for instance in an information meeting, open to the public. In

636 addition, one could develop an online version of such a game, which would allow broader

637 participation. Many design questions arise; we give some examples: Should the game be played

638 simultaneously by all players or would a gaming community be sufficient? How strongly are

639 people influenced by social norms when they play the game? Does the influence of social norms

640 differ between a real and virtual meeting?

641

642   5.2.3.   Serious games to learn about the decision context to define objectives (step C)

643 Learning about what objectives to consider is a major part of problem structuring; this choice can

644 strongly impact the outcome of the decision (Rosenhead and Mingers, 2001). In this review,

645 most games broadcasting a message are games to aid problem understanding. They would

646 stimulate learning about the problem at three levels: cognitive, relational/ social, and normative

647 learning (Haug et al., 2011; Plass et al., 2015). However, most of these games broadcasting a

648 message could be qualified as "biased" as they often depict a single worldview. Yet, in some

649 cases, the games assess the player's choices using several indicators, which if developed

650 carefully could represent the main trade-offs. These indicators are often simplified, and can be

651 considered as general objectives. Another possibility would be to develop topic-related training

652 games, mimicking policy games, but using fictional representative situations. They could be

653 based on a master list of objectives. In either case, following the broadcasting a message or

654 training game session, those general objectives could stimulate generating a comprehensive set

655 of objectives (following the recommendations of Bond et al., 2010), which can then be

656 challenged, reduced, and structured into an objectives hierarchy. Whether serious games for the

657 generation of objectives should be played by a single or by multiple players needs to be tested.

658 A multi-player serious game should gather the entire range of stakeholders (see 5.2.2), or assign

659 roles representing this diversity, to cover all existing worldviews and knowledge (Duke and

660 Geurts, 2004). It would ideally require the presence of an experienced facilitator to prevent the

661 groupthink bias (Janis, 1982), i.e. to prevent too early convergence of thoughts and agreement

662 on objectives, and to facilitate the debriefing session. The debriefing session would aim at

663 moving from the fictional game situation to the real-world decision situation. Since a group

664 setting with a facilitator limits the number of repetitions, one option could be to first carry out a

665 qualitative analysis. Based on these results, a more-rigorous experiment comparing the single-

666 and multiple player setting should then be carried out. Whatever set-up is chosen, game use for

667 the purpose of objectives generation needs to be thoroughly evaluated.

668

669   5.2.4.   Games to learn about alternatives and explore the consequences (step E)

670 Moreover, some of the games broadcasting a message offer to play with various alternatives.

671 Training games also invite to test a subset of typical alternatives, in a fictional – but highly

672 plausible – situation. The choice of alternatives is evaluated with rules, based on a predefined

673 set of indicators/ objectives. Some researchers on serious gaming claim that simulation games

674 players are better informed about the alternatives and their outcomes (D'Artista and Hellweger,

675 2007; Devisch, 2008; Tanes and Cemalcilar, 2010). Through the simulations, the player

676 experiences the alternatives in a safe trial environment, i.e. before having to handle possibly

677 undesirable outcomes in the real world. These games might particularly help to communicate

678 about complex never-definitively-defined "wicked problems". The game model could take into

679 account the choices for alternatives of the player, and react showing how the problem/ situation

680 has evolved: with the new situation, the problem needs to be redefined, and new sets of actions

681 should be taken. To be used in a decision-making process, the decision analyst should

682 guarantee that the serious game is based on the best actual (if possible local) available

683 knowledge, e.g. using the predictions made for the MCDA. This would require using games or

684 gamified applications which are developed in such a way that they are easily adaptable to the

685 specific conditions of any given case. The serious game should not support a specific

686 alternative, which requires careful rule design in particular to develop a neutral feedback loop.

687 Moreover, in the case of a single player serious game, the player might solely verify her own

688 pre-understanding of the topic, as described in the biased search process (Hoeffler et al., 2006).

689 This would enhance the confirmation bias, i.e. when one is unconsciously looking for information

690 or evidences confirming one's beliefs (Hogarth, 1987; Klayman, 1995; Montibeller and von

691 Winterfeldt, 2015; Nickerson, 1998). Addressing this question is a further prerequisite to develop

692 the use of games in MCDA.

693

694 **5.3.   No serious game for preference elicitation (step F)**

695 According to our review, no existing serious game allows to elicit the preferences in a suitable

696 way for MCDA, and specifically for MAVT (step F. in Fig. 1). A preference elicitation game, or

697 gamified procedure, would fall into the "exchange information" category (Tab. 1). It would allow

698 preference elicitation from experts, as well as from novice citizens, if enough factual background

699 information is provided in a neutral way. The gamified preference elicitation requires real world

700 data, and thus ought to offer an adaptable design, that allows easily producing different versions

701 that include context-specific information. Players would receive information on the decision

702 issue, while the decision analyst would collect reliable preferences. It could either be a single

703 player game to collect individual preferences, or a multi-player game to address preference

704 formation in groups. To increase the number of participants, the game should be made as easily

705 accessible as possible, for instance by using an online IT interface. If this is done, the gamified

706 online procedure should be as short as possible, and/or successful in engaging, to avoid tiring
707 and drop out of the participants (Dillman et al., 2009).

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

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

720

721   *6. Conclusion*

722 This review paper started with a brief introduction of MCDA and MAVT revealing improvement
723 points, in particular regarding preference elicitation. Methodological progress is needed to
724 (1) limit the cognitive load for the participant, (2) limit the occurrence of various motivational and
725 cognitive biases, (3) enhance the construction of preferences, e.g. by enhancing learning, and
726 (4) increase participation by involving citizens. A short overview of the relevant descriptive
727 decision-making literature was provided. It stressed the importance not only of cognitive
728 processes, but also attention, and motivation to achieve a mindful judgement. Thereafter, more
729 than 43 serious games related to water issues were reviewed, in order to (1) define serious
730 games and gamification, (2) capture their diversity, and (3) identify their common underlying
731 gameplay elements. Reviewing the decision literature and the game literature highlighted
732 potentially promising matches between MCDA needs and the affordances of serious games and
733 gamification. Therefore, we discussed in the last part how serious games and gamification could

734   be used in each step of the MCDA process (Fig. 1); highlighting the pitfalls that should be

735   avoided, and suggesting many new research opportunities. The main challenge for the use of

736   serious games and gamification in MCDA is the neutrality requirement of a prescriptive decision-

737   making process. Consequently, we think that gamified application might be more appropriate

738   than fully-fledged games. However, this statement needs to be proven. More specifically, we

739   propose following research ideas at different steps of a Multi-Criteria Decision-Making process:

740   • Experimentally test hypotheses using gamified workshops for parts of the MCDA
741   process; namely the initial steps of problem structuring (steps A, C, and D) and the final
742   step H of discussing results.

743   • Integrate an MCDA preference elicitation and aggregation model (step F) into gamified
744   workshops, and test whether the complexity of the issue is better understood and social
745   learning is enhanced.

746   • Use games for stakeholder analysis (step B), i.e. to assess the stakeholders' importance
747   and interests. The advantages and disadvantages of a real workshop, as part of a public
748   information meeting for instance, or of an online game need to be carefully assessed.

749   • Develop games to define the decision objectives required for MCDA (step C). One
750   proposition is to use games developed for broadcasting a message, but enhance these
751   with multiple worldviews and/or using several indicators/ objectives. Test (first
752   qualitatively, then experimentally), whether games to generate objectives should be
753   played by single or multiple players. The latter requires avoidance of the groupthink bias
754   (Janis, 1982).

755   • Use simulation games to explore multiple decision alternatives (step E). Ensure that
756   simulations are based on best-available scientific knowledge, and avoid biased
757   preference of some alternatives. This requires the development of a neutral feedback
758   loop, which should again be experientially tested, and of game mechanics inviting the
759   player to explore all alternatives.

760   • Finally, according to our review, no existing serious game allows to elicit the preferences
761   in a suitable way for MCDA (step F). This requires a completely new application to
762   gaming. Needless to say, this needs to be thoroughly evaluated in a controlled

763   experiment, where the gamified version is compared to a similar non-gamified "classical"

764   preference elicitation procedure.

765 A note on the costs of such an integration of MCDA decision processes with serious games:

766 whether higher costs of game development are justified depends on the decision context. In

767 large policy decisions, which are by nature expensive, the additional costs of gamifying an

768 MCDA process may be negligible or justified by the importance of the problem (see Langhans

769 and Lienert, 2016 for a more in-depth argumentation concerning the costs of decision support for

770 river rehabilitation). A major aim might specifically be public participation including a large

771 number of laypeople, which might be best achieved exactly by gamification. Moreover, in the

772 case of repeated decisions of a similar type, it might be possible to develop a game that is either

773 able to address this issue on a more-general level, allowing to transfer the insights to the specific

774 decision situation, or it might be possible to construct the game in such a way that it can be

775 easily adapted to the specific local decision context. In other cases, including simple elements of

776 gamification might be cheaper and sufficient.

777 Gamification in itself induces trade-offs: there are within- and between-worlds dilemmas,

778 culminating in a trilemma between play, meaning and reality (Harteveld, 2011). Gamifying the

779 MCDA process implies involving game developers and the players, e.g. the general public

780 (Fig. 4), additionally to the MCDA analysts and the environmental experts or decision-makers,

781 traditionally included in environmental decision-making. Active participation of the latter is

782 probably the only way to guarantee a neutral and unbiased game. The four parties may have

783 various conflicting interests: trade-offs between the requirements of MCDA tools, the

784 requirements of games and gamification, and those of "traditional" environmental decision-

785 making will occur. As for any decision-making process, clarifying and prioritizing the objectives is

786 a pre-requisite. Studying the entire overarching game design process could be an interesting

787 research topic in itself, which may also benefit from MCDA to decide on the best gamification

788 options (e.g. Sangkyun, 2014).

789
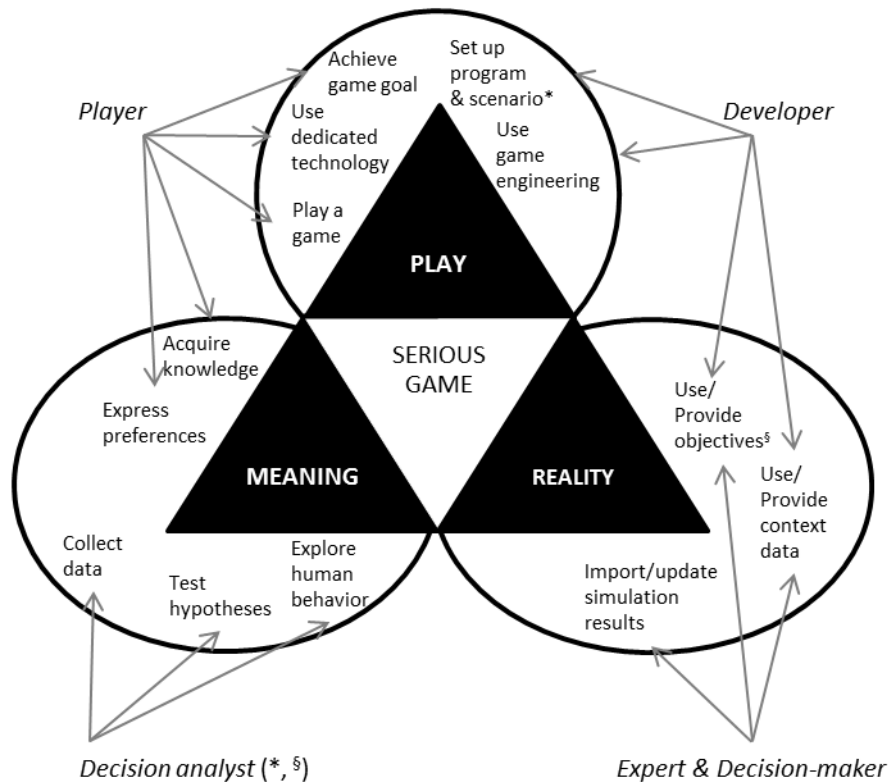
Figure 4. Triadic game design for an MCDA serious game and gamification (adapted from Harteveld, 2011). The triadic design illustrates the various dilemmas occurring when designing a serious game. To design an MCDA serious game or gamified application, more actors – including decision analysts – stand 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.

795

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8. Supplementary Information

800

801 Supplementary information associated with this article is available online at <mark>xxx</mark>. It includes the

802 gamography, with direct links to the games.

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804

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