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An experiment on risk-based decision-making in water management using monthly probabilistic forecasts

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1 **An experiment on risk-based decision-making in water**

2 **management using monthly probabilistic forecasts**

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17 **Capsule**

18 A role-playing approach to better understand the challenges of using monthly probabilistic
19 forecasts in sequential decision-making in water management.

20 **Abstract**

21 The use of probabilistic forecasts is necessary to take into account uncertainties and allow for
22 optimal risk-based decisions in streamflow forecasting at monthly to seasonal lead times.
23 Such probabilistic forecasts have long been used by practitioners in the operation of water
24 reservoirs, in water allocation and management, and more recently in drought preparedness
25 activities. Various studies assert the potential value of hydro-meteorological forecasting
26 efforts, but few investigate how these forecasts are used in the decision-making process.
27 Role-play games can help scientists, managers and decision-makers understand the extremely
28 complex process behind risk-based decision. In this paper, we present an experiment focusing
29 on the use of probabilistic forecasts to make decisions on reservoir outflows. The setup was a
30 risk-based decision-making game, during which participants acted as water managers.
31 Participants determined monthly reservoir releases based on a sequence of probabilistic
32 inflow forecasts, reservoir volume objectives and release constraints. After each decision,
33 consequences were evaluated based on the actual inflow. The analysis of 162 game sheets
34 collected after eight applications of the game illustrates the importance of leveraging not only
35 the probabilistic information in the forecasts but also predictions for a range of lead times.
36 Winning strategies tended to gradually empty the reservoir in the months before the peak
37 inflow period to accommodate its volume and avoid overtopping. Twenty percent of the
38 participants managed to do so and finished the management period without having exceeded
39 the maximum reservoir capacity or violating downstream release constraints. The role-
40 playing approach successfully created an open atmosphere to discuss the challenges of using
41 probabilistic forecasts in sequential decision-making.

42 **1. Introduction**

43 Seasonal climate forecasts are used in a large number of water resources applications ranging
44 from droughts (Anderson et al. 2000), urban water (Chiew et al. 2000), hydro-power
45 operations (Block 2011), water supply (Bracken et al. 2010), water allocation (Mushtaq et al.
46 2012), agriculture (Ghile and Schulze 2008) and ground water levels (Guo et al. 2009).
47 Without exception, seasonal forecasting systems are probabilistic. They incorporate
48 uncertainties about the future state of the climate (Brown and Ward 2013), which is
49 especially useful for risk assessment.

50 Coelho and Costa (2010) defined several challenges for integrating seasonal climate forecasts
51 in operational management, ranging from the production of the forecasts to the effective
52 implementation into user applications (e.g. Hartmann et al. 2002; Lemos et al. 2002). In
53 water resource applications, this often requires translating predictions of precipitation and
54 temperature into predictions of streamflow or inflows to reservoirs (Regonda et al. 2011).
55 Practitioners can then make management decisions that are informed by the hydrologic
56 forecasts.

57 Coelho and Costa (2010) particularly emphasise end-user decision-making as a key challenge
58 when implementing seasonal forecasts for water management, even given the common
59 existence of quantitative water decision support systems (e.g. Dutta et al. 2013; Regonda et
60 al. 2011). The decision-making process and the policies for water management are extremely
61 complex, for they have to satisfy a large range of possibly conflicting objectives, comprising
62 technical, socio-economic and environmental issues, and also cover a considerable range of
63 hydrologic conditions (Simonović and Marino 1982; Welsh et al. 2013). A number of studies
64 connect forecast performance to decision-making (e.g. Golembesky et al. 2009), but few
65 recognize that a skilful forecast does not necessarily lead to the forecast actually used by
66 decision makers (Chiew et al. 2003; Kiem and Verdon-Kidd 2011; Ritchie et al. 2004).

67 In addition, almost all studies are unable to incorporate all operating rules or key decisions
68 due to the complexity of the task. Technical complexities together with intricate governance
69 settings contribute to barriers which lower the uptake of seasonal climate forecasts in water
70 resource management (for a detailed review see Kirchhoff et al. 2013; Lemos 2008).
71 Amongst others, these barriers include the challenge in incorporating information in the
72 decision-making process, and the often insufficient human and institutional capacities.
73 Kirchhoff et al. (2013) highlight individual water manager behaviour and risk perception as
74 important areas which need to be addressed to realise the value of probabilistic seasonal
75 forecasts (Block and Goddard 2012).

76 These issues can be addressed through an improved decision-making process, using
77 structured decision-making models, and training. It is however extremely complex to
78 replicate a full reality, with all possible consequences. The use of role-play games can aid this
79 process, whilst allowing the investigation of key research questions, such as how decision
80 rules can be formulated or whether probabilistic forecasts lead to better decisions (Ramos et
81 al. 2013). The decision process includes a range of potential actions, a number of possible
82 events, various consequences for each combination of action and event, and a set of
83 probabilities for each combination (Faber and Stedinger 2001; Sankarasubramanian et al.
84 2009). These can be controlled in a game setting, whilst providing an experience which can
85 be close to reality (Cannon-Bowers and Bell 1997) and helpful to enhance understanding.

86 This paper presents a game experiment that focuses on a realistic decision sequence for
87 managing a reservoir – one based on actual hydrology, seasonal forecasts, and typical
88 reservoir management objectives from a setting in the western United States (US). The game
89 was played with different groups of students, researchers, operational hydrologists,
90 forecasters, decision-makers and water managers during conferences and meetings. Players
91 were asked to manage a reservoir used for flood control and water supply, for a four-month

92 period (referred to as the management period). They were presented with a monthly series of
93 probabilistic inflow forecasts for runoff in the coming 1 to 4 months: such forecasts are
94 referred to as seasonal forecasts in practice due to their monthly to seasonal lead times.
95 Participants were required to plan outflows at each decision step while complying with
96 reservoir capacity and release constraints. The objectives of this paper are to present the
97 results obtained and to analyse the decision making process of the participants.

98 In the following sections, we present the game setup, the way it unfolded and how
99 participants managed their reservoirs. The last section is dedicated to discussion and
100 conclusions.

101 **2. Material**

102 **a. Game setup**

103 The setting of the game is a reservoir in a watershed with a pronounced annual runoff cycle
104 defined by a winter-spring snow accumulation and spring-summer melt period, followed by a
105 low runoff regime in the summer and fall. The reservoir management objectives are typical of
106 many managed systems: water supply, minimum environmental releases and flood control.
107 The game was adapted from training material for a course given at the 91st Annual Meeting
108 of the American Meteorological Society. It was modified to be played in an auditorium, in
109 20-25 minutes, and to be accessible for audiences ranging from students, researchers,
110 operational hydrologists, forecasters, decision-makers and water managers.

111 ***PLACE SIDEBARS HERE***

112 **b. Playing the game**

113 To collect the results of each participant, a worksheet was distributed at the beginning of the
114 game. It allowed participants to record their releases and update their reservoir volume. It
115 also provided information on the long-term flow climatology for each month (the median
116 inflow in Mm^3 over the past 30 years). Before starting the game, an example was given for

117 the month of March. Participants were guided on how to fill in the worksheet. Lastly, we
118 asked for a volunteer to play the game in front of the group, bringing a more lively
119 atmosphere to the experience. Since computations for the volunteer could not be executed in
120 real-time, the volunteer was presented with three pre-defined options of releases. They were
121 designed after several test-plays with small groups. For the volunteer, all possible
122 combinations of sequential decisions were pre-calculated, but only the chosen sequence was
123 displayed. Furthermore, the volunteer's choice and play did not interfere with the play of the
124 other participants, because participants had to define their releases before the choices
125 available for the volunteer were presented.

126 To illustrate the forecast-decision procedure, Figure 1 shows the slides presented for the first
127 month. First the inflow forecasts are displayed with the help of boxplots showing the 5%
128 (min), 25%, 50%, 75%, and the 95% (max) percentiles (Fig. 1a) and participants are given a
129 few minutes to decide on their reservoir releases. On the next slide (Fig. 1b), it is the
130 volunteer's turn to make a decision, choosing among options A, B and C. The next slide (Fig.
131 1c) displays the actual inflow of the month and participants update their reservoir levels
132 accordingly, balancing the inflow with the release they had decided on for that month. In the
133 last slide of the round (Fig. 1d), we assess the volunteer's decision, by showing the
134 calculation of reservoir volume at the end of the month for the release option chosen by the
135 volunteer. It also indicates whether the volunteer still has a job. This marks the end of a
136 forecast-decision-update sequence and the game moves on to the next decision (i.e., next
137 month).

138 The game is a repetition of this sequence of steps for forecasts issued once a month from
139 April 1st to July 1st until we reach August 1st. If participants are fired before the last round,
140 they are encouraged to keep playing and try to recover their jobs by lowering the reservoir
141 volume below its maximum capacity.

142 A major flow event was included to occur in June to test the participants' capacity to hedge
143 for the possibility of high inflows to the reservoir. In addition, the probabilistic forecasts were
144 designed such that their median values were below the actual inflow, to discriminate whether
145 participants became sensitive to the risk represented by the upper tail of the forecast
146 distribution. To help participants spot this pitfall, forecasts displayed both observed and
147 forecast inflows for the past month.

148 **3. Results**

149 **a. Worksheets collected**

150 We collected a total of 203 worksheets through eight distinct presentations of the game
151 (Table 1). Seventy-five percent presented release schedules filled in for each month (and not
152 only for the first month). Thirty-two percent showed a miscomprehension of the release
153 constraints and had releases greater than 60 Mm^3 or less than 15 Mm^3 . Miscalculations were
154 observed in 63 worksheets: most were small computational errors that did not impact the
155 reasoning process and few were miscalculations of the reservoir inflow-outflow balance. We
156 discarded the worksheets that did not respect the constraints in the releases for the first month
157 of the schedule and those that presented miscalculations that could have led to erroneous
158 decisions. In the end, the analysis considered 162 worksheets, 126 of which had complete
159 release schedules. The volunteer play was not considered.

160 **b. Decision-makers' behavior during the game: who won and who lost?**

161 In terms of the main decision-makers' constraint, i.e., keep the reservoir level below 500
162 Mm^3 , we observe (Fig. 2) that twenty percent of the participants (32) never exceeded the
163 reservoir capacity during the management period and kept their jobs until the end of the
164 game. Eighty percent of the participants (130) exceeded the reservoir capacity at some point
165 during the game. Among them, 103 exceeded the reservoir capacity once, in June, and lost
166 their jobs, but then managed to recover (i.e., released enough in July to achieve a reservoir

167 level back below 500 Mm³ on August 1st), and 27 exceeded the reservoir capacity in June, but
168 were unable to bring the volume below 500 Mm³ at the end.

169 Figure 3 shows the monthly evolution of reservoir volumes (Fig. 3a) and the distribution of
170 releases at one-month lead (Fig. 3b), for participants who exceeded the maximum reservoir
171 capacity and for those who never did. All participants who won decreased their reservoir
172 volumes by 10 to 50 Mm³ in the first two months. These two months were crucial to make
173 the difference between winners and losers. April and May inflows summed to 73 Mm³,
174 which, given the minimum compulsory release (15 Mm³ for each month) and the initial
175 reservoir level (450 Mm³), forced participants to reach at most a reservoir volume of 493
176 Mm³ at the end of May. This level left little flexibility to keep the volume lower than the
177 maximum capacity in the subsequent months.

178 In the group of participants who won, releases are higher than 30 Mm³ in April, combined
179 with, in most cases, additional relatively high releases in May (higher than 50 Mm³). In
180 contrast, more than half of the participants who lost opted to release the minimum allowed in
181 April and consequently, saw their reservoir volumes increase by the end of the month since
182 the April inflow (18 Mm³) was greater than their releases. In May, 75% of these participants
183 had their reservoir volumes greater or equal to the initial volume of 450 Mm³, with the
184 highest value being the maximum possible, 493 Mm³.

185 In June, the month for which the high runoff event was forecast, 80% of all participants
186 released the maximum 60 Mm³. This represents 62% of the participants who won and 84% of
187 the participants who lost. At the end of the month, the reservoir volumes of participants who
188 lost were between 503 and 553 Mm³, while the volumes of participants who won were
189 between 473 and 498 Mm³.

190 All participants who won decreased their reservoir levels in the first two months, anticipating
191 the peak runoff month, which was reflected in both the forecasts and the climatology. In the

192 beginning of June, their reservoirs were then low enough to collect the water from the high
193 inflow without overtopping. Participants who lost had a general tendency of increasing their
194 reservoir volumes after the first decisions, reflecting emphasis on the goal of having the
195 reservoir level as close to 500 Mm³ as possible on August 1st, rather than on the risk of high
196 inflow in June. Therefore, in June, they suffered the consequence of overtopping the
197 reservoir. The maximum reservoir volume obtained by a participant reached 553 Mm³ at the
198 end of June, which corresponds to releasing the minimum 15 Mm³ in April and in May, and
199 the maximum 60 Mm³ in June. This is the profile of a decision-maker that ignored or failed to
200 comprehend the implications of the June inflow forecasts and climatology, and became
201 trapped by release constraints in June.

202 To recover their role as reservoir managers, participants who had exceeded the reservoir
203 capacity by the end of June had to release enough in July to decrease their reservoir volumes
204 by the end of the month. Almost 75% of this group released more than 40 Mm³ in July, while
205 75% of the participants who never exceeded the maximum capacity released, in the same
206 month, less than 40 Mm³. The return to a reservoir volume below 500 Mm³ was achieved by
207 79% of the participants who had lost their jobs with the high inflow in June. Despite their
208 efforts, 27 unfortunate players saw their reservoirs remain above the ‘spill’ volume.

209 The urgency to decrease the reservoir volume after June to avoid further overtopping, or
210 maybe just to secure their jobs, led participants who had lost to release large quantities of
211 water in July. Out of the 32 participants who had not exceeded 500 Mm³ after the event in
212 June and who had then more flexibility to adjust their reservoir volume so as to bring it as
213 close as possible to the goal on August 1st, 11 were able to increase their reservoir volumes in
214 July by managing their releases.

215 c. **And the winner is...: optimal one-month lead release schedule**

216 Figure 4 presents the reservoir volumes of each participant at the end of July as a function of
217 their one-month lead releases. We consider, progressively, their releases in April (Fig. 4a),
218 the summed releases for the months of April and May (Fig. 4b) and the summed releases for
219 all the months prior to the high inflow event, i.e., April, May and June (Fig. 4c). This figure
220 allows a retrospective analysis of which decisions led to overtopping the reservoir.

221 Figure 4a shows that participants who released 25 Mm^3 or less in April (61% of all 162
222 participants) lost their jobs on July 1st. The same is observed for participants who released an
223 accumulated volume of 80 Mm^3 or less by May (Fig. 4b). By this time, they already represent
224 72% of all participants. By the end of June, participants who had released an accumulated
225 volume of 140 Mm^3 or less (80% of all participants; Fig. 4c) had lost the game. On the
226 opposite end of the release spectrum, all participants who released 120 Mm^3 by May (i.e.,
227 that released the maximum allowed in April and May) did not overtop their reservoirs during
228 the game (Fig. 4b). At the end of the first three sequential decisions, all participants who had
229 released more than 145 Mm^3 had their reservoirs prepared for the high runoff event in June
230 (Fig. 4c).

231 In order not to overtop their reservoirs, participants had to lower the initial reservoir volume
232 of 450 Mm^3 by at least 10 Mm^3 in the first two decisions. In terms of releases, this means that
233 they had to release at least 83 Mm^3 over the first two decisions (given the 18 Mm^3 and 55
234 Mm^3 inflows of April and May, respectively). Given the constraint of maximum release (60
235 Mm^3), these two months were thus essential to adjust the reservoir volume prior to the high
236 inflow event. From the worksheets, it emerges that the high-score winner applied the
237 following sequence of releases – $35; 50; 60; 24 \text{ Mm}^3$ – to achieve the following volumes:
238 $433; 438; 498; 496 \text{ Mm}^3$. This winner was among the audience of the HEPEX 10th
239 Anniversary workshop, which was, most probably, the venue with the most specialized users
240 of probabilistic forecasts in the audience.

241 As noted earlier, the game was designed such that the seasonal forecasts were under-
242 predicting the coming high inflow event if judged on the 50% percentile. In fact, the observed
243 peak inflow of June was close to the 95% percentiles of the first three (April, May, June)
244 probabilistic forecasts for June. These forecasts foreshadowed that an upcoming major event
245 was possible, albeit with a low forecast probability of occurring. The flow climatology
246 information in the worksheets indicated that June was historically a month of high inflows
247 and also provided a warning for participants to be cautious and prepare for the coming event
248 with an appropriate release strategy.

249 **d. Evolution of release schedules**

250 The way participants were planning their releases months ahead, and how they changed their
251 planning or not as the June high inflow approached, was investigated with the help of the 126
252 worksheets (out of 162) that had release schedules fully filled. In both groups, i.e.,
253 participants who lost (102 worksheets) and participants who won (24 worksheets), we had
254 approximately the same proportion of players that fully filled in their release schedules (78%
255 and 75%, respectively).

256 We observe that participants who won had basically planned their releases for the month of
257 May and June already in the first decision on April 1st. When May 1st and later June 1st
258 arrived, the majority confirmed their previous decisions or just increased their releases of
259 approximately 5 to 10 Mm³ more to accommodate the high inflows in the reservoir without
260 overtopping.

261 On the other hand, participants who lost were, in general, planning very low releases on the
262 first months and already, since the first decision in April, planning to release the maximum in
263 June. What they had not anticipated was that this would not be enough to accommodate the
264 high inflow event and that a better strategy would have been to gradually empty the reservoir
265 already in April and May. On June 1st, players from this group may have been frustrated by

266 the fact that they had their reservoir volumes too high but could not release more than the
267 maximum allowed.

268 In general, the planned releases for July were progressively increased when moving from
269 April to June in both groups. On July 1st, however, when the only release they had to plan
270 was for the coming month and the highest inflow had already passed, the majority in the
271 group of participants who won was able to decrease the values they had planned to release
272 previously on June 1st and, therefore, better target the final goal of having the reservoir
273 volume as close as possible to 500 Mm³ on August 1st. On the other hand, in the group of
274 participants who lost, half of the players had to decide on releasing more than what they had
275 scheduled in the previous decisions to have a chance of getting their reservoir below 500
276 Mm³ and, consequently, their jobs back.

277 **e. How might participants have used the probabilistic forecasts and the flow**
278 **climatology when making decisions?**

279 It was left to participants to choose how they would take into account forecast and
280 climatology information in their decisions. We could not, unfortunately, follow this process
281 within each participant's mind. Nevertheless, using the worksheets only, we tried to identify
282 which forecast quantile participants based their releases on. To do so, we calculated the
283 August 1st reservoir volumes they would have obtained if the observed inflows had
284 consistently matched one of the forecast quantiles, or, alternatively, the flow climatology.
285 Volumes obtained with the observed inflows were also estimated. This was done for each
286 decision step (month), so that we could also evaluate the release planning strategy. Figure 5
287 shows the results.

288 The players who took proactive actions as early as April and May to balance the game
289 objective with the overtopping risk likely focused on upper quantiles of the forecasts (Q75
290 and Q95), with maybe also some support from the flow climatology. Indeed, most of these

291 participants would not have overtopped their reservoirs had the Q75 and even the Q95
292 forecast quantiles been verified as observed inflows throughout the game, as early as in the
293 first decision step. On the third and fourth decisions, they seemed to have set aside flow
294 climatology and rather used an 'adjusted' upper forecast quantile (Q95) to evaluate the
295 possible observed inflow and optimise their releases to the goals of the game. This might
296 have been the result of having previously noted that the forecasts were, in general, under-
297 predicting the observed inflows. The fact that part of the distribution for August volumes
298 given actual observed flows is above the reservoir maximum during the first two decisions
299 (April, May) means that participants tolerated or were not able to eliminate the overtopping
300 risk early in the management period, but took steps to eliminate it when the potentially high
301 inflow month was imminent.

302 In the group of participants who lost, most participants might have been guided by the
303 medium to lower quantiles (Q50 and Q25) in the first decisions. Figure 5 shows that if the
304 upper quantile forecasts or even the flow climatology values had verified as observed
305 inflows, these participants would have reached reservoir volumes much higher than the
306 allowed 500 Mm³ in August. In contrast, if lower quantiles had verified as observed inflows,
307 most would have been safe from overtopping their reservoirs. Later on, on the third and
308 fourth decisions, these participants might have acted based on the upper forecast quantiles
309 (Q75 and Q90) and, eventually, on the flow climatology to plan their releases.

310 **4. Discussion and conclusions**

311 This paper presented the results of a game experiment on risk-based decision-making in
312 water management using probabilistic forecasts of inflows to a reservoir. From the analysis of
313 the worksheets collected during the application of the game in eight different contexts, we
314 were able to illustrate key issues on the use of probabilistic forecasts in sequential decision
315 making.

316 In the game setup, seasonal forecasts had to be viewed as a whole and not as independent
317 monthly forecasts. Even though the forecast time evolution warned the participants about a
318 high inflow event, monthly 50% percentile forecast values were under-estimating flows.
319 Given the reservoir constraints, as expressed in the rules of the game, and the goals of the
320 management, it was necessary to look at forecasts months ahead before deciding on the
321 reservoir releases. A winning strategy would be the one that would gradually empty the
322 reservoir two months ahead of the expected high inflow to accommodate its potential volume
323 without overtopping. Although the worksheets were designed to invite participants to adopt
324 this long-term approach, notably by asking them to schedule their releases for the whole
325 management period, still about 25% of the participants only filled their releases for the
326 coming month.

327 Approximately 20% of the participants to the game were able to finish the management
328 period without exceeding the maximum reservoir capacity at any time during the sequenced
329 decisions, and approximately 17% of the participants not only caused the reservoir to
330 overtop, but also were unable to bring its volume back below the threshold. Winners were
331 those who had programmed the releases in a way that they succeeded to adequately decrease
332 their reservoir volumes in the first two months, anticipating the potential high inflows. Losers
333 of the game were those who did not recognize early enough the significance of the high
334 inflow risk, or did not comprehend its potential impact on the reservoir volume.

335 In this paper, answers that showed signs of miscomprehension of the balance equation were
336 not used in the interpretation. Therefore, it has been implicitly assumed in the analysis of the
337 remaining results that the participants were able to take full advantage of the proposed
338 information, once given the necessary tools to read the probabilistic graphs and understand
339 the climatological values at the beginning of the game. The results based on the remaining
340 answers may however still be influenced by the comprehension of the proposed tools and the

341 way they were presented. It is possible that given the timed nature of the game (participants
342 had to decide within a limited amount of time), some participants could understand the way
343 forecasts were displayed, but were not fast enough in applying their understanding.
344 Communicating forecasts and, more generally, probabilities is still a major challenge in
345 hydrometeorology, and can be a barrier to the widespread use of ensemble forecasts in
346 operational contexts.

347 The information collected from the worksheets shows *which* decisions were taken, but not
348 *why* they were taken. Therefore, care has to be taken in the interpretation of the results of this
349 game experiment. We can only speculate on what could have been the reasons for many
350 participants to take a certain sequence of release decisions, and on what strategy winners had
351 with respect to the forecast inflows. Therefore, even if the results indicate that the participants
352 who won the game might have considered the upper quantiles of the forecasts, at least in their
353 first decisions, information on *why* they followed this procedure is not available through the
354 game setup. A possible solution to this limitation could be to expand the game by asking
355 these relevant questions orally or directly in the worksheets. Recording whether participants
356 had prior water resource management or forecasting experience could also help indicate the
357 value of training toward improving the application of probabilistic information. Collecting
358 specific information on the main occupation and background of each participant could also be
359 helpful to evaluate how strategies may vary between different groups (e.g., students,
360 managers or forecasters).

361 Finally, this game is a simplified representation of reality and does not intend to reproduce
362 the full context of operational environments in reservoir management. Indeed, a participant
363 who had real-life experience managing reservoirs noted during one game session that the
364 winning strategy (described in Section 3.2) could have raised alarms in practice for having
365 allowed too much flooding risk en route to achieving a near-perfect target level. Despite the

366 simplifications, however, we received positive feedback after the different applications, even
367 though howls of indignation were often heard in the rooms when the observed June inflow
368 was revealed. The role-playing approach, and the penalty experienced by participants of
369 being fired from their jobs, added a light touch to the experience and created a pleasant
370 atmosphere to discuss the challenges of using probabilistic seasonal forecasts in sequential
371 decision-making, where choices have delayed consequences. Notably, the game has been
372 successfully used as material to teaching and training activities.

373

374 **Resources and acknowledgements**

375 This game is part of the Hydrologic Ensemble Prediction EXperiment and is available at
376 <http://www.hepex.org/> to be freely used for teaching or training. Special thanks to Kevin
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379 playing the volunteer. L. Crochemore was partly funded by the EU Interreg IVB NWE
380 project DROP.

381

382 Sidebar1: Game setting

383 Each participant plays the role of a water manager for ‘Lake Dual’, which is a reservoir with
384 a capacity of 500 Mm³ that serves two primary functions: water supply for ‘Swof Town’ and
385 flood control for ‘Safe Town’. The residents of ‘Swof Town’ would like to see the reservoir
386 full (500 Mm³) on August 1st to ensure drinking water supply until the end of summer, while
387 the residents of ‘Safe Town’ are interested in keeping monthly releases below 60 Mm³ to
388 prevent flood damage to their homes. Probabilistic forecasts of monthly inflows are available
389 and updated on the first day of each month during the management period running from April
390 to August. At the beginning of each month, participants have to decide on the monthly
391 reservoir releases for the remaining months in this period.

392

393 Sidebar2: Management objectives

394 The goal of each participant is to have the reservoir volume as close as possible to 500 Mm³
395 on August 1st without ever exceeding this maximum capacity. Participants also have to
396 maintain a minimum release of 15 Mm³ for environmental flow and their maximum release
397 cannot exceed 60 Mm³. As a penalty, participants are fired from their management role in the
398 game if they fail to meet the constraint of maximum capacity. At the end of the game, the
399 ‘winner’ is the manager that has the highest reservoir volume on August 1st without having
400 exceeded its maximum capacity during the management period.

401

402

403

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488 **Table**

489 **Table 1:** Characteristics of the applications of the game.

Context of the application (oral presentations)	Place	Number of worksheets collected	Participants
European Geophysical Union General Assembly 2013 (Session ‘Ensemble hydro- meteorological forecasting for improved risk management: across scales and applications’)	Vienna, Austria	85	Students, researchers, operational hydrologists, forecasters, decision-makers, water managers
Users workshop of the European Flood Awareness System (EFAS)	Reading, UK	23	Operational forecasters from EU flood forecasting national services
Trans-national ‘Drought team’ meeting of the Interreg NEW IVB DROP project	Brittany, France	8	Operational hydrologists and water-supply reservoir operators from France and Germany
Seminar at Université du Québec à Chicoutimi (UQAC)	Chicoutimi, Canada	11	Undergraduate and post- graduate students, professors
Seminar at Centre d’Expertise Hydrique du Québec (CEHQ)	Québec city, Canada	10	Operational hydrologists and flood forecasters
Seminar at Hydro-Québec’s research institute (IREQ)	Varenes, Canada	11	Researchers, operational forecasters, and decision- makers
Training course on Predictability, Diagnostics and Forecasting at ECMWF	Reading, UK	20	Undergraduate and post- graduate students
HEPEX 10 th Anniversary international workshop	Maryland USA	35	Scientists, operational forecasters in meteorology and hydrology, decision- makers
TOTAL		203	

490

491 **Figure captions**

492 **Fig. 1.** Example of a sequence of forecast-decision in the game: forecast issued on April 1st
493 and results for a volunteer that chose option C as release schedule.

494 **Fig. 2.** Results of participants in terms of the main reservoir constraint: not exceed the
495 maximum reservoir capacity of 500 Mm³.

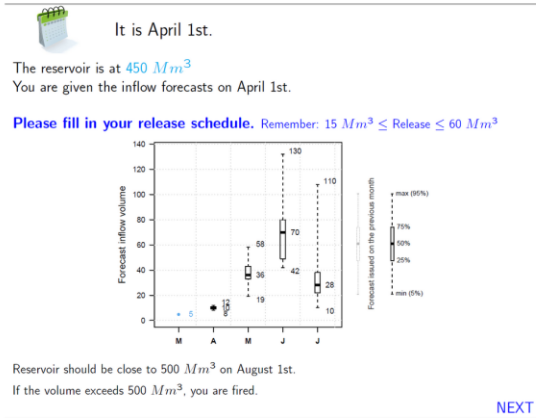
496 **Fig. 3.** (a) Evolution of reservoir volumes at the end of each month and (b) distribution of
497 releases for the coming month (one-month lead) for participants who exceeded the reservoir
498 capacity (participants who lost, 130 worksheets, in yellow) and participants who did not
499 (participants who won, 32 worksheets, in blue). In (a), the grey and red horizontal lines mark
500 the reservoir volume at the beginning of the game (450 Mm³) and the constraint of reservoir
501 capacity (500 Mm³), respectively. In (b), the grey horizontal lines mark the minimum (15
502 Mm³) and the maximum (60 Mm³) allowed for releases. Box plots display minimum value,
503 percentiles 25%, 50%, 75% and maximum value over 162 participants.

504 **Fig. 4.** Reservoir volumes of 162 participants at the end of July as a function of the one-
505 month lead releases for April (a), April plus May (b) and the sum of April, May and June (c).
506 Participants who won (never exceeded the maximum reservoir capacity) are indicated in blue,
507 and participants who lost, in yellow. The darker the dot, the more participants adopted the
508 volume/release scenario. Shaded areas highlight the strict separation between winners and
509 losers by indicating the domain occupied exclusively by participants who won, and by
510 participants who lost, in the blue and yellow colors respectively. A percentage indicates the
511 proportions of dots in these areas.

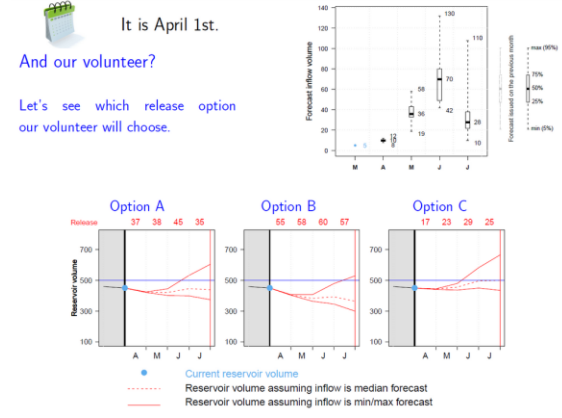
512 **Fig. 5.** Volumes that participants would have in their reservoirs on August 1st by applying
513 their release programs at each decision month (April-July) to the cases where inflows are
514 equal to: the forecast quantiles Q5% to Q95% (shades of green), the flow climatology

515 (orange) and the observed inflows (red). Boxplots represent statistics over 24 participants
516 who won (top) and 102 participants who lost (bottom).
517

(a)



(b)



April has gone by.

April inflow was: 18 Mm^3



You can update your reservoir volume:

The volume on May 1st is:

April 1 volume + 18 Mm^3 - April release = ?

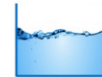
Did you overtop your reservoir?

- NO, I still have my job.
- YES, I got fired...

What about our volunteer?

April has gone by.

April inflow was: 18 Mm^3



Our volunteer's April release was: 17 Mm^3

The volume on May 1st is therefore:

$450 \text{ Mm}^3 + 18 \text{ Mm}^3 - 17 \text{ Mm}^3 = 451 \text{ Mm}^3$

No overtop!

The volunteer still has a job!

Let's go to the next forecast!

519

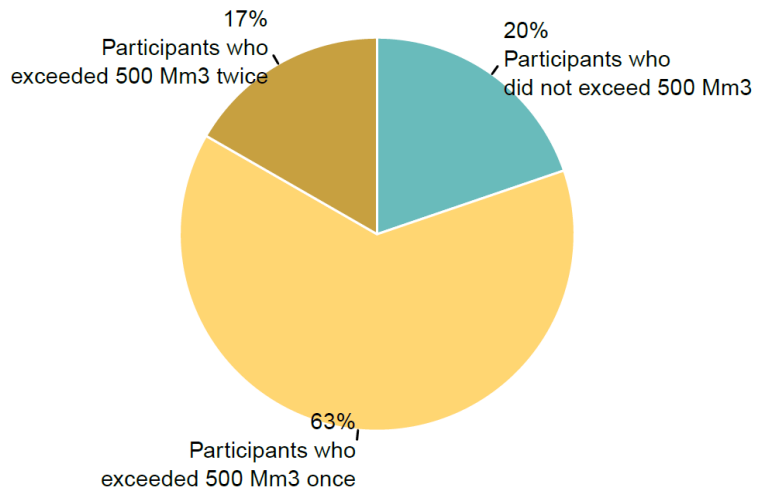
(c)

(d)

520 **Fig. 1.** Example of a sequence of forecast-decision in the game: forecast issued on April 1st

521 and results for a volunteer that chose option C as release schedule.

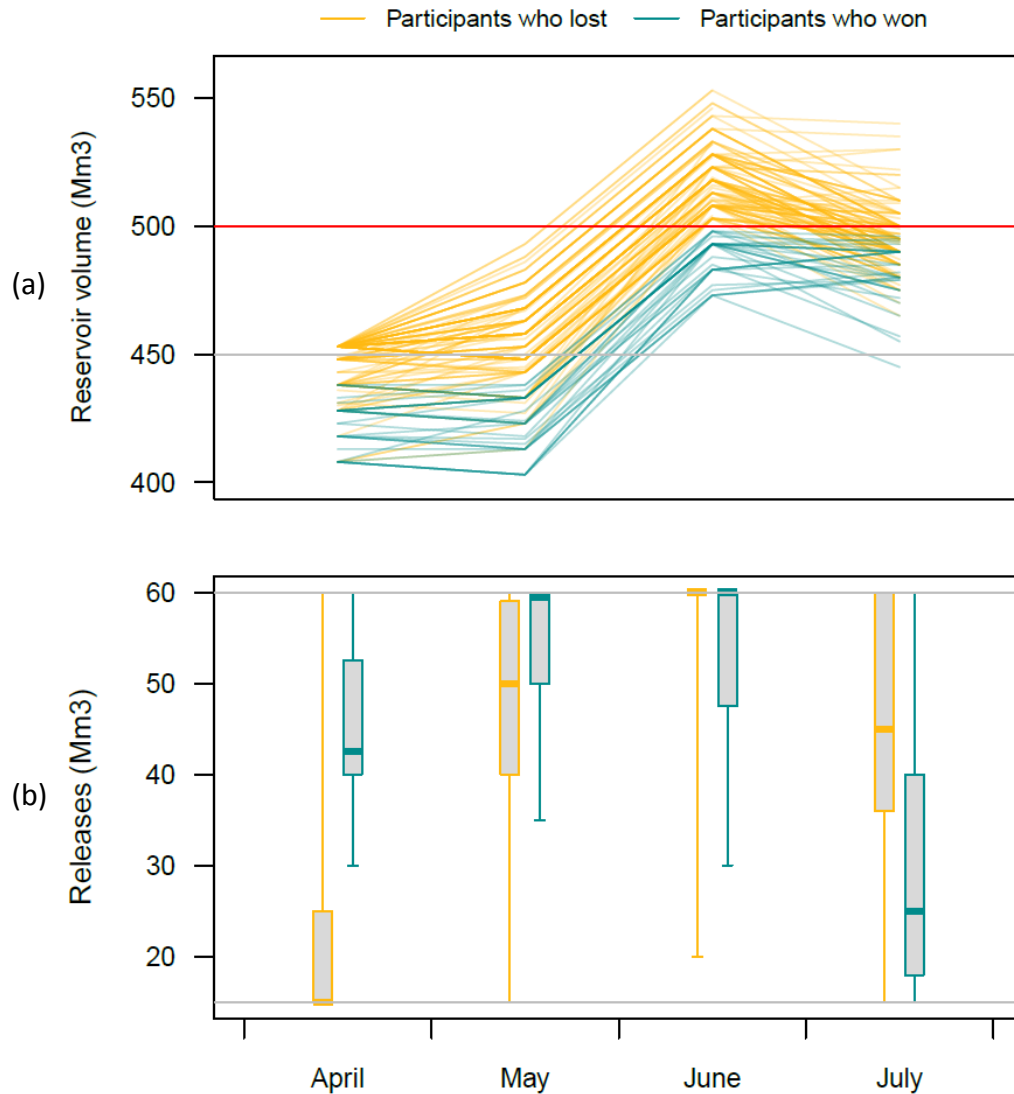
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523

524 **Fig. 2.** Results of participants in terms of the main reservoir constraint: not exceed the
525 maximum reservoir capacity of 500 Mm³.

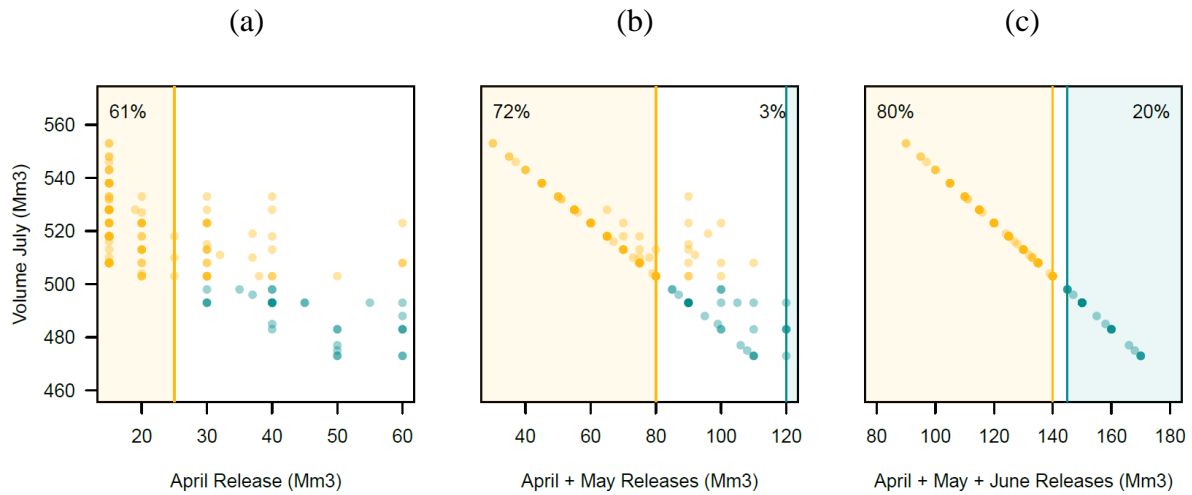
526



527

528 **Fig. 3.** (a) Evolution of reservoir volumes at the end of each month and (b) distribution of
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 535 percentiles 25%, 50%, 75% and maximum value over 162 participants.

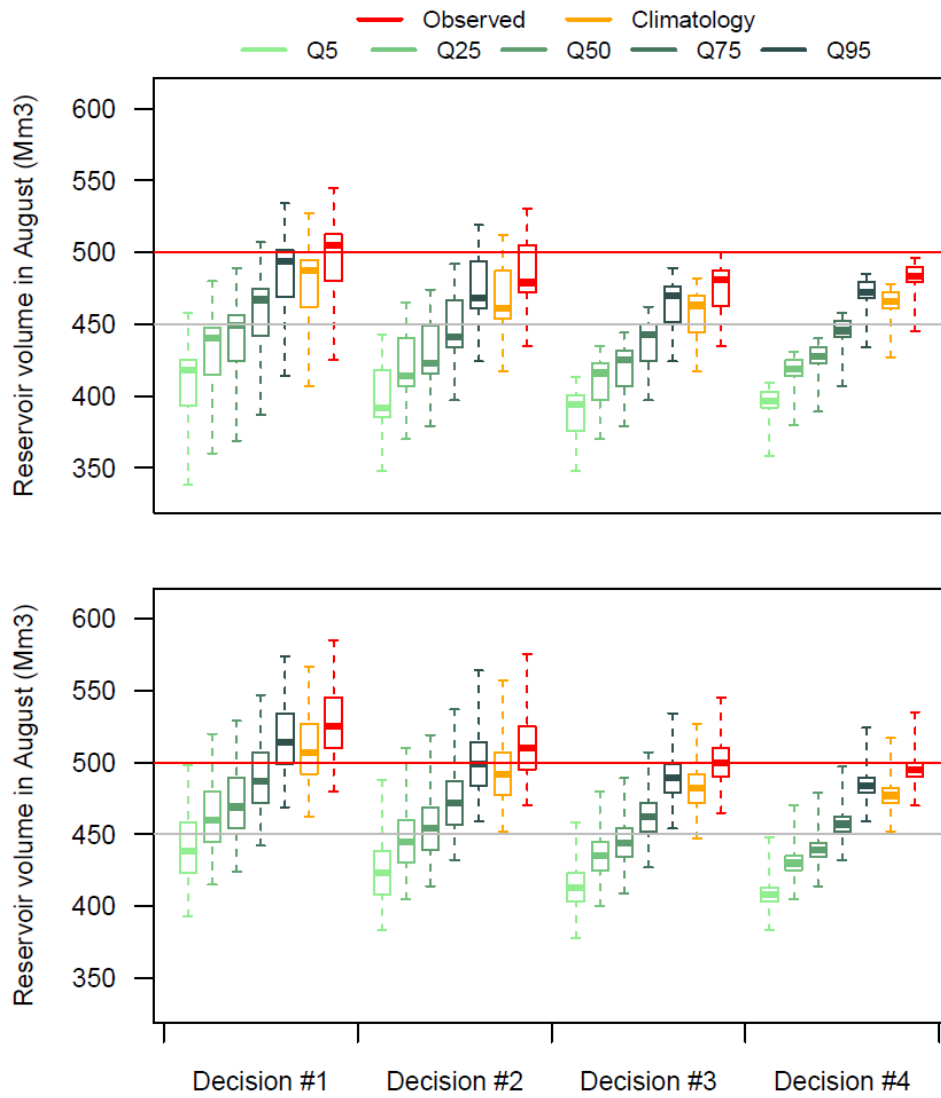
536



537

538 **Fig. 4.** Reservoir volumes of 162 participants at the end of July as a function of the one-
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 545 proportions of dots in these areas.

546



547

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