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HAL Authorization

# 1 Ecological quality of snowmaking reservoirs in the Alps and management 2 perspectives.

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## 13 Abstract

14 Alpine freshwater ecosystems are biodiversity hotspots providing key ecosystem services. They face threats from  
15 climate change and anthropogenic activities. Snowmaking reservoirs emerged in the world in response to snow  
16 rarefaction and increasing winter tourism. Despite efforts to assess their environmental impact, our understanding  
17 of their ecological quality after being built remains limited. Here, we evaluated the representation of snowmaking  
18 reservoirs in French Alpine counties and their potential to serve as aquatic ecosystems. A comprehensive approach  
19 was employed encompassing ski resort surveys and geographical analyses of 136 reservoirs, complemented by  
20 investigations into abiotic characteristics and biodiversity surveys in 28 sampled reservoirs. The findings indicated  
21 that the multiplication and proximity of these reservoirs to freshwater habitats make them components of the  
22 alpine aquatic landscape. Although sparse terrestrial vegetation was commonly present on their banks, they  
23 systematically lacked aquatic vegetation. Faunal diversity appeared limited, consisting of both indigenous and  
24 non-native species. Comparisons with mountain lakes revealed similarities in water quality, implying potentially  
25 similar oligotrophy and biotic communities. However, differences in conductivity, alkalimetry and pH were  
26 observed, possibly linked to distinct water sources or retention times. Snowmaking reservoirs displayed unique  
27 habitat features through their structure and functioning. Although reservoirs are attractive for biodiversity,  
28 concerns surround their capacity to support species due to observations of drowned mammals, stranded  
29 amphibians and dragonflies. Our observations revealed potential ecological traps in the design, exploitation and  
30 uses of snowmaking reservoirs. Recommendations are made to enhance existing structures and future designs by  
31 increasing ecological processes and better protecting biodiversity.

32 **Key words:** Ecological trap; Ecological continuity; Artificial ecosystem; Mountain lake; Ski resort; Water body

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36 Alpes). We also thank Hugues François for sharing and managing the spatial data. This study was funded by  
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## 38 Declarations

39 The authors have no competing interests to declare that are relevant to the content of this article.

## 40 I. Introduction

41 Mountain ecosystems provide essential resources such as timber, food and water for human populations (Harden  
42 and Fernández 2022). They are also recognised as biodiversity hotspots, with endemic species uniquely adapted  
43 to these challenging habitats (Noroozi et al. 2018). Characterised by extreme conditions such as high disturbance  
44 regime, strong winds, diurnal thermal contrasts, pronounced dry seasons, high solar radiation, and low oxygen  
45 concentrations (Körner 2007), mountain ecosystems are highly sensitive to both natural and anthropogenic  
46 perturbations, making them key indicators of environmental change (Schmeller et al. 2022).

47 The effects of climate change and human activities are particularly pronounced in mountain freshwater  
48 ecosystems. The consequences of global change on mountain aquatic habitats include disruptions to thermal  
49 regimes and hydrology, with knock-on effects on seasonal water availability and associated ecosystem services  
50 (Huss et al. 2017; Locatelli et al. 2017). Global warming projections indicate a rising rain-snow line (Lorrey et al.  
51 2022), impacting water storage, which is crucial for summer water supply in mountain regions. Socio-economic  
52 considerations play a pivotal role in water resource management in these regions (Reynard et al. 2014), with  
53 proposals for adaptation strategies involving artificial water storage infrastructures (Gonin et al. 2022). The  
54 increase in implementation of this type of infrastructure raises concerns related to environmental impact and  
55 biodiversity loss (Fait et al. 2020; Zamora-Marín et al. 2021). Snowmaking reservoirs have emerged in ski resorts  
56 around the world as a solution to the shortage of natural snow cover in winter (Scott et al. 2003; 2006) and are  
57 also considered as a future solution in high-latitude countries such as Norway (Dannevig et al., 2021).

58 Snowmaking reservoirs, typically found in ski resorts, serve as water reserves primarily for snowmaking activities,  
59 to facilitate rapid snow production under favourable conditions (Marnezy 2008). They are mostly filled during  
60 spring, leveraging high water availability from mountain sources and streams, or in autumn when rainfall is  
61 abundant (Marnezy 2008; Badré et al. 2009). However, some mountain reservoirs are filled several times during  
62 winter (Evette et al. 2011). Despite their utility for tourism and economic activities, concerns persist regarding  
63 their environmental impact. Although some of the water withdrawn is returned to the environment (Morin et al.  
64 2023), questions linger regarding how this return is temporally and spatially organised (Magnier 2016; Gerbaux  
65 et al. 2020). Snowmaking reservoirs are often located on flat areas (Marnezy 2008), potentially leading to the  
66 destruction or degradation of wetlands and other alpine ecosystems during their construction (Evette et al. 2011).  
67 This destruction raises issues regarding biodiversity interactions, particularly in comparison to lowland reservoirs  
68 (Clevenot et al. 2018; Cantonati et al. 2020).

69 Situated between 1,000 and 3,000 metres above sea level, snowmaking reservoirs are distinct from their lowland  
70 counterparts in several aspects. They are designed considering geological, geotechnical, and environmental  
71 factors, to ensure resistance against intense mountain conditions such as low temperatures, snow, avalanches,  
72 rockfalls, landslides and UV radiation (Mériaux and Peyras 2009). To mitigate risks and facilitate gravity-based  
73 water distribution for snowmaking, reservoirs are typically positioned on high plateaus (Marnezy 2008; Peyras et  
74 al. 2010). These reservoirs are very often made artificially watertight using Geomembrane Liner Systems (GLS)  
75 implemented over the entire surface to ensure water storage functionality (Peyras et al. 2010). However, GLS  
76 maintenance can be costly due to vulnerability to high mountain conditions, such as solar radiation, ice-cover and  
77 punctures. To limit these effects, it is now recommended that GLS be covered with granular materials (Poulain et  
78 al. 2011). Design considerations also extend to slope angles, with a recommended maximum of 18°, to balance  
79 geotechnical constraints with a minimised structure footprint and maximised volume-to-surface ratio (Mériaux  
80 and Peyras 2009).

81 Despite the presence of snowmaking reservoirs in numerous countries, few studies have begun to explore alpine  
82 biodiversity in snowmaking reservoirs, revealing their potential capacity to support wildlife, including species of  
83 conservation concern (Fait 2017; Fait et al. 2020). Although the habitat diversity of these reservoirs is relatively  
84 low, they can still provide opportunities for certain species and contribute to the stepping-stone dispersal of aquatic  
85 species in alpine freshwater ecosystems (Oertli et al. 2014; Oertli and Parris 2019; Fait et al. 2020). In the context  
86 of an ever-increasing number of anthropogenic habitats, existing snowmaking reservoirs could potentially move  
87 toward a "win-win" situation for both human use and native species, as defined by reconciliation ecology

88 (Rosenzweig 2003). This would entail managing these reservoirs for biodiversity, without any reduction in the  
 89 human utility of the system. However, artificial reservoirs may provide misleading environmental signals to  
 90 species, inaccurately representing the suitability of a habitat for reproduction and survival (Clevenot et al. 2018).  
 91 By selecting their habitats based on these environmental signals, which falsely indicate high-quality conditions,  
 92 alpine freshwater species could fall into an ecological trap (Dwernychuk and Boag 1972). Hence, a snowmaking  
 93 reservoir could be defined as an ecological trap if it leads to direct mortality of individuals or if, as a breeding site,  
 94 reproductive success is not high enough to support a stable or growing population without immigration (Battin  
 95 2004). Thus, ensuring ecological continuity and preventing potential ecological traps in these artificial structures  
 96 remain critical considerations.

97 This study aimed to (a) describe the recent evolution of the number, size, location and design of snowmaking  
 98 reservoirs within the aquatic landscape of the French Northern Alpine regions; (b) determine if there is  
 99 spontaneous biodiversity associated with snowmaking reservoirs; (c) describe snowmaking reservoirs in terms of  
 100 potential habitat for alpine biodiversity through their water quality and embankment design; (d) assess whether  
 101 snowmaking reservoirs, due to their design and use, may act as ecological traps; and (e) suggest ways to make  
 102 these reservoirs more hospitable to biodiversity while reducing the risk of ecological traps and restoring ecological  
 103 processes.

## 104 II. Material and methods

### 105 1. Data collection on snowmaking reservoirs in the French Alps

106 The French Alps, located in the south-east of France, are divided into Northern and Southern Alps, based on their  
 107 climate (Joly et al. 2010). For this study, we focused on the four counties that are most concerned by the  
 108 development of ski resorts (Spandre et al. 2016): Hautes-Alpes in the Southern French Alps and Isère, Savoie and  
 109 Haute-Savoie in the Northern French Alps (Fig 1).

110 ***Table 1*** *Volume (m<sup>3</sup>), surface area (m<sup>2</sup>), elevation (m) and number of snowmaking reservoirs in the French*  
 111 *counties studied in 2021.*

| Variables                                      | Hautes-Alpes (05) | Isère (38) | Savoie (73) | Haute-Savoie (74) | mean    | sd        | total   |
|--|-------------------|------------|-------------|-------------------|---------|-----------|---------|
| Number of reservoirs                           | 23                | 21         | 42          | 50                |         |           | 136     |
| Number of visited reservoirs                   | 5                 | 6          | 15          | 2                 |         |           | 28      |
| Total volume (m <sup>3</sup> )                 | 1121821           | 897300     | 3210536     | 2051125           | 1820196 | 1052906.8 | 7280782 |
| Minimum volume per reservoir (m <sup>3</sup> ) | 3000              | 1000       | 5000        | 1000              | 2500    | 1914.9    |         |
| Average volume per reservoir (m <sup>3</sup> ) | 48775             | 44865      | 76441       | 41023             | 52776   | 16091.3   |         |
| Maximum volume per reservoir (m <sup>3</sup> ) | 125000            | 165000     | 403000      | 300000            | 248250  | 127471.2  | 993000  |
| Total area (m <sup>2</sup> )                   | 161402            | 23000      | 466925      | 361896            | 253306  | 199091.3  | 1013223 |
| Minimum area per reservoir (m <sup>2</sup> )   | 900               | 10000      | 1940        | 500               | 3335    | 4484.6    |         |
| Average area per reservoir (m <sup>2</sup> )   | 9494              | 11500      | 12288       | 8416              | 10424   | 1782.0    |         |
| Maximum area per reservoir (m <sup>2</sup> )   | 18600             | 13000      | 61800       | 29825             | 30806   | 21814.6   | 123225  |
| Minimum elevation (m)                          | 1454              | 1083       | 1262        | 1005              | 1201    | 199.9     |         |
| Average elevation (m)                          | 1987              | 1706       | 2034        | 1514              | 1810    | 244.9     |         |
| Maximum elevation (m)                          | 2393              | 994        | 2701        | 945               | 1758    | 919.7     |         |
| First year of construction                     | 1989              | 1993       | 1999        | 1990              | 1993    | 4.5       |         |
| Median year of construction                    | 2002              | 2006       | 2007        | 2005              | 2005    | 2.2       |         |

112  
 113 All the snowmaking reservoirs found in these counties were listed. For each reservoir, the location, altitude (m),  
 114 surface area (m<sup>2</sup>), volume (m<sup>3</sup>), year of construction and type of GLS coverage were collected (Table 1). These  
 115 data are mainly taken from Mériaux and Peyras (2009), from Gerbaux et al. (2020) for the Isère department, and  
 116 from the local state authorities that examine applications for authorisations to build reservoirs (i.e. Direction  
 117 Départementale des Territoires; abbreviated DDT) in Savoie, Haute-Savoie and Hautes-Alpes.

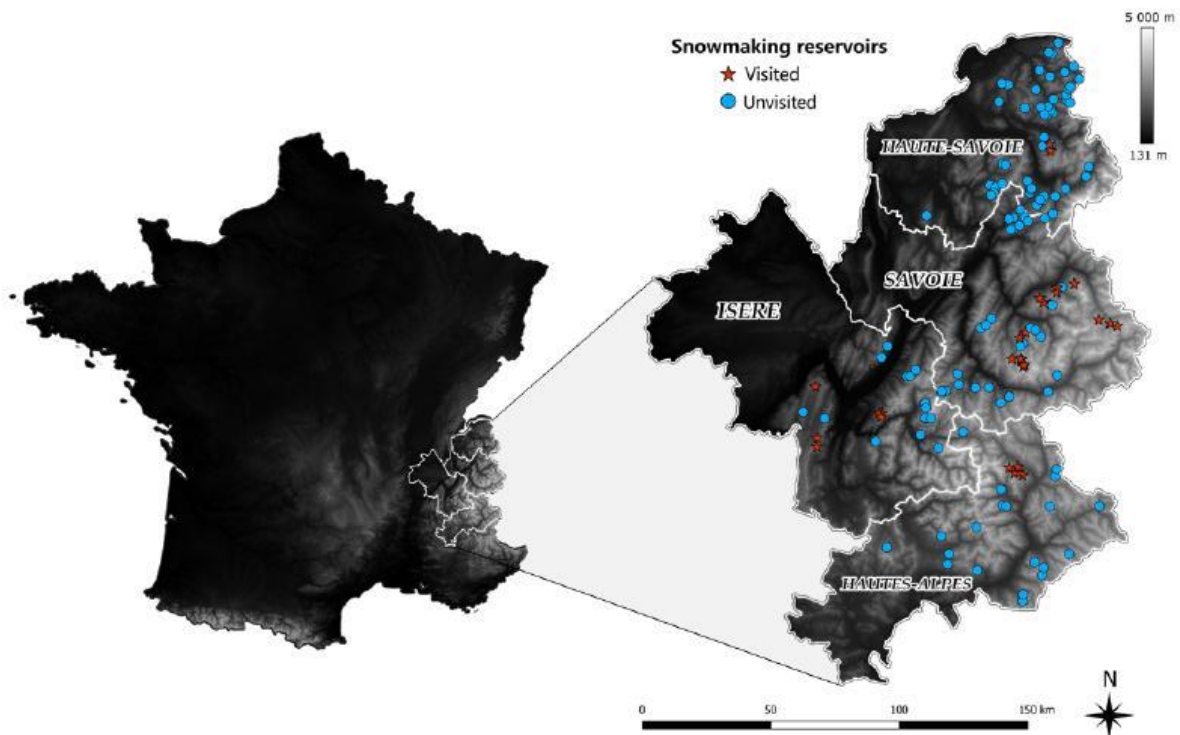
118 This dataset was completed by extracting the number, altitude and surface area of the natural water bodies located  
 119 between 1,000 and 2,700 m above sea level (according to the altitude range of snowmaking reservoirs, Table 1)

120 from the “Inventaire National des Plans d’Eau” (abbreviated INPE; version 1.0, 2023) for each department using  
121 GIS software. The distances separating reservoirs from other natural freshwater habitats was calculated to estimate  
122 the proportion of reservoirs that are within 2 km of another favourable habitat. This is the distance reachable by  
123 most aerial-dispersing aquatic species (Peredo Arce et al. 2021).

## 124 2. Data collection for the 28-snowmaking-reservoir sample

### 125 Study sites

126 Among the 136 snowmaking reservoirs identified, 28 reservoirs located in 12 ski resorts were selected (Fig 1)  
127 according to two factors: (1) direct information was obtainable from the reservoir operators and (2) their  
128 representativity in terms of altitude, age and construction techniques. Each of these reservoirs was visited once  
129 between June and August 2021.



130

131 ***Fig. 1** Location of the 4 French counties studied and of the 136 snowmaking reservoirs identified in the study*  
132 *area. The reservoirs visited are represented by an orange star*

### 133 Biodiversity surveys in snowmaking reservoirs

134 Biodiversity protocols were adapted from those described by Fait (2017), Fait et al. (2020) and the CIMaE project  
135 (Lamouille-Hébert 2022), and were calibrated during a pre-field campaign involving six snowmaking reservoirs.

136 During each visit, the occurrence and abundance of terrestrial and aquatic vegetation (helophytes and hydrophytes)  
137 were assessed according to five abundance classes: “A” corresponds to an uncountable number of individuals,  
138 “B” to numerous but countable individuals, “C” to some individuals, “D” to few individuals and “E” to no  
139 individuals. For each reservoir, it was noted if there was more or less than five terrestrial plant species, as well as  
140 if the vegetation belt was continuous or non-continuous. Primary phytoplanktonic productivity was estimated  
141 based on the chlorophyll *a* concentration (Huot et al. 2007; Kasprzak et al. 2008).

142 The occurrence of spontaneous faunal species, based on visual observation from above the shoreline, was also  
143 systematically recorded according to the same five abundance classes as for vegetation. Amphibians were  
144 identified at the species level and at the different life cycle stages (egg, tadpole, adult). Odonates individuals were

145 divided into distinct categories based on their respective life stages (adult, larvae, exuviae). Other aquatic  
146 macroinvertebrates were distinguished by habitat (benthic, pelagic), and invertebrates living on the water's surface  
147 – mainly water striders (Gerridae) – were also monitored.

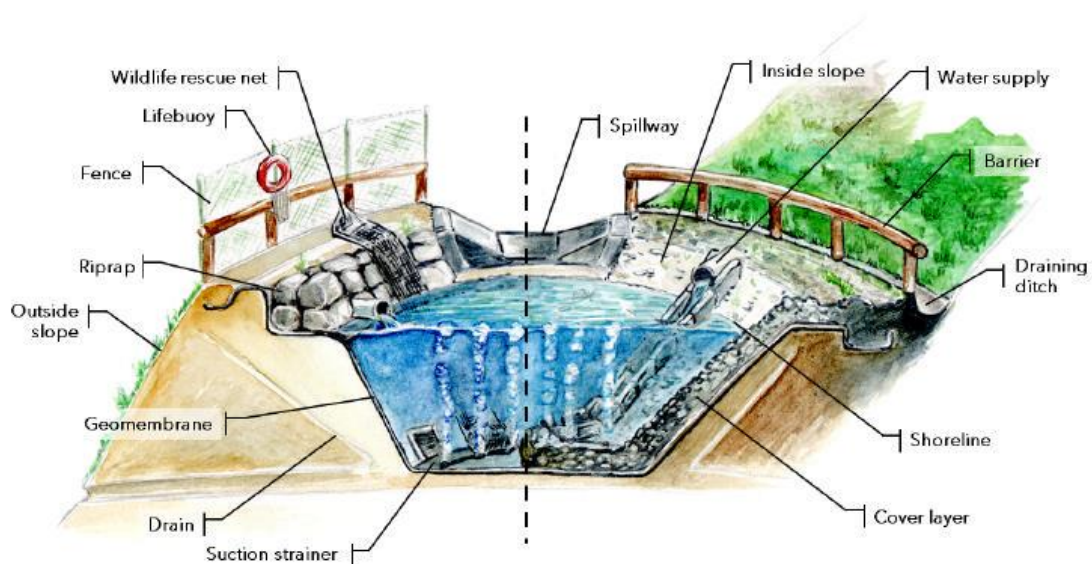
148 The presence or absence of introduced fish communities, represented by cyprinids and salmonids (Ventura et al.  
149 2017; Osorio et al. 2022), was determined *in situ*.

150 After each visit, all equipment in contact with the reservoir water was disinfected to limit the spread of amphibian  
151 pathogens (Dejean et al. 2010). The structure of biodiversity data is detailed in appendix 1.

## 152 Abiotic characteristics

153 Several physico-chemical parameters of the surface water were systematically measured at different points of each  
154 snowmaking reservoirs and pooled for analysis. Temperature (°C), conductivity (µS/cm), oxygen saturation (%)  
155 and pH were measured *in situ* using an HQ40d multimeter and two probes: a conductivity probe (CDC401) and a  
156 luminescence probe for dissolved oxygen (LDO101). The probes were placed at the bottom of the water, 1.5 m  
157 from the shoreline. The complete alkalimetric title (CAT) and the nitrate and chlorophyll *a* concentrations were  
158 measured *ex situ* by sampling 2 L of water at between 30 and 50 cm depth to avoid suspended matter. Samples  
159 were kept in coolers at 5 °C until their arrival at the laboratory for analysis within 24 hours (NF EN ISO 5667-3).  
160 The CAT was measured by potentiometry (NF EN ISO 9963-1), the nitrate concentration by automated  
161 spectrophotometry (NF ISO 15923-1), and the chlorophyll *a* concentration by spectrophotometry (LORENZEN  
162 method, NF T90-117). It should be noted that 11% and 50% of the reservoirs tested had chlorophyll *a* and nitrate  
163 concentrations below the limit of quantification (LQ = 0.5 µg/L and 0.5 mg/L, respectively). These low values  
164 were set to zero in our analyses. The physico-chemical parameters were compared with those of 91 mountain  
165 lakes taken as reference. The lakes were selected in the same geographical area and altitude range. The data on  
166 the surface water of mountain lakes were collected from the "Sentinel Lakes" network dataset (post-2018 data),  
167 extracted from SI-OLA (IS, AnaEE-France, INRAE of Thonon-les-Bains, Asters, GIS LACS SENTINELLES)  
168 and other unpublished data from the UMR CARRTEL laboratory.

169 For each snowmaking reservoir, the main uses were identified by interviewing the ski resort managers. During  
170 each visit, the type of GLS coverage (partially covered, fully covered, no coverage) was noted, and the slope  
171 (Vertical/Horizontal) was measured at various points along the upstream embankment (Fig. 2).



172

173 Fig. 2 Classic structure and equipment of snowmaking reservoirs. Left, a snowmaking reservoir with partial GLS  
174 coverage (geomembrane visible under the shoreline and riprap visible above). Right, a snowmaking reservoir  
175 with full GLS coverage. Drawing by B. Testi

### 176 3. Data analyses

177 R software (version 4.2.3; R Core Team 2023) was used for data and statistical analyses. Geographic data was  
178 explored and mapped using QGIS (version 3.6.0-Nooza).

179 Before each statistical test, the sample size, data independence, as well as the normal distribution and  
180 homoscedasticity of the related variables were checked. This led to the use of non-parametric tests in most cases.  
181 Spearman's correlation was used to test evolutions in snowmaking reservoir size over time. Changes to the  
182 elevation of snowmaking reservoir over time were analysed by applying a parametric Pearson's correlation. A  
183 Kruskal-Wallis test was used to test the changes in the use of each type of GLS coverage in relation to key dates,  
184 and the link between the abundance classes of terrestrial vegetation and the age of the reservoirs. The water quality  
185 was compared for each physico-chemical parameter between snowmaking reservoirs and mountain lakes by  
186 applying a Wilcoxon test.

187 **III.** The distance separating each snowmaking reservoir from the closest stream was calculated thanks to the  
188 NNjoin plugin. The geographical data for the water streams was collected from the BD TOPAGE ®  
189 (2022). The distance separating each snowmaking reservoir from the closest water body was determined  
190 by extracting their geometrical centroids and calculating the distance matrix thanks to the vector analyse  
191 tools.**Results**

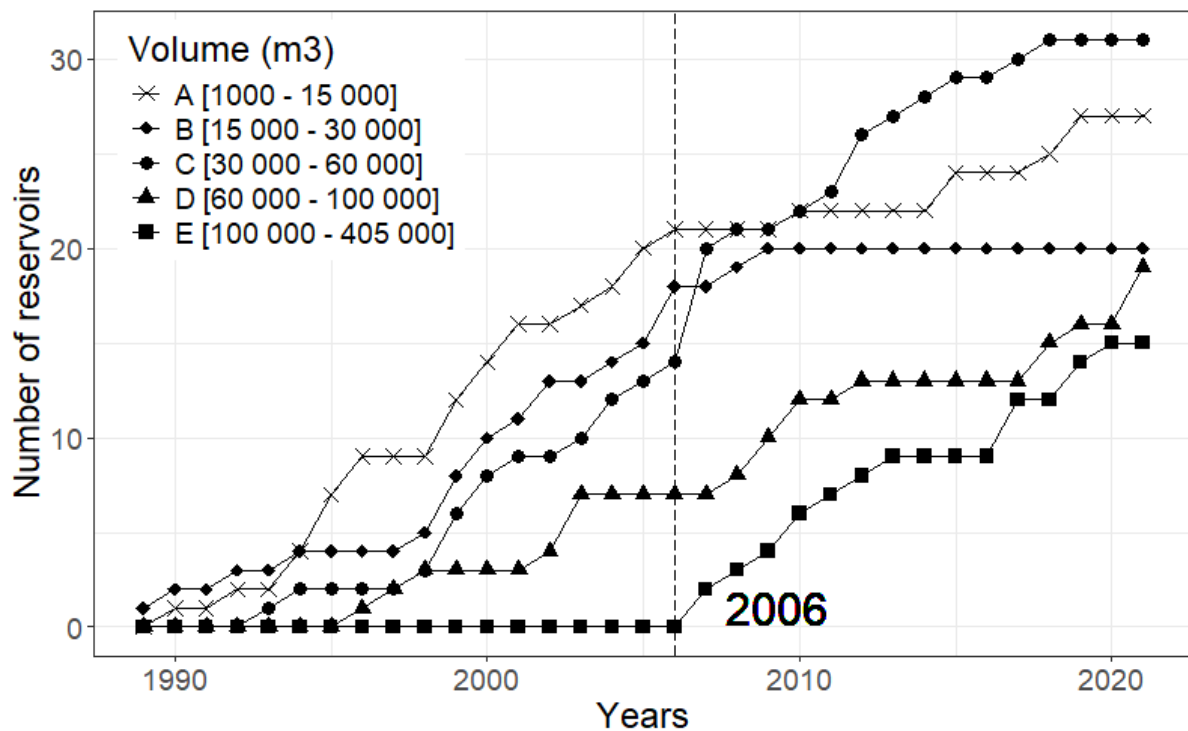
#### 192 1. Overview of snowmaking reservoirs on the scale of the French Alps: where, when and how?

##### 193 a. Number, size and location of snowmaking reservoirs in 2021

194 In 2021, a total of 136 snowmaking reservoirs located at altitudes ranging from 1,000 to 2,700 m above sea level  
195 were documented in the studied area. Their surface areas ranged from 500 to 61,800 m<sup>2</sup>, and their capacities from  
196 1,000 to 403,000 m<sup>3</sup> (Table 1). These artificial reservoirs coexist alongside 2,593 natural water bodies in the same  
197 altitude range, with surfaces areas measuring between 9 m<sup>2</sup> and 375,000 m<sup>2</sup> and which median surface area is 331  
198 m<sup>2</sup> according to the INPE (2023). Thus, the total number of water bodies was 2,729. In this water framework,  
199 snowmaking reservoirs accounted for 8.4% of the water surface area and 5.0% of the total number of water bodies  
200 (Table 1). The vast majority (99%) of snowmaking reservoirs identified were located within 2 km of a stream and  
201 73% were situated within 2 km of another water body. Their median distance was  $412 \pm 504$  m from a stream and  
202  $1,149 \pm 1,502$  m from a natural water body.

##### 203 b. Evolution of snowmaking reservoirs construction and design between 1989 and 2021

204 The year of construction was available for 112 of the 136 reservoirs, which were analysed. These reservoirs were  
205 constructed between 1989 and 2021, with half of them built before 2006 (Fig 3; Table 1). Over this 32-year span,  
206 an average of almost 4 reservoirs were constructed per year. From 1999 to 2012, the number of constructions  
207 increased, peaking at 9 reservoirs in 1999. In the last 5 years analysed (2016-2021), the construction rate dropped  
208 to between 1 and 5 reservoirs per year.



209

210 *Fig. 3 Cumulative number of reservoirs built between 1989 and 2021 (n = 112) by volume class (in m<sup>3</sup>). 2006 is*  
 211 *marked with a vertical dashed-line as a reference*

212 In contrast to the recent slowdown in their construction, the storage capacity of snowmaking reservoirs has tended  
 213 to grow ( $S = 119.6$ ;  $\rho = 0.49$ ;  $p\text{-value} < 0.001$ ) and they have moved to higher altitudes over the years ( $t = 3.05$ ;  $r$   
 214  $= 0.28$ ;  $p\text{-value} = 0.001$ ). From 2006, some reservoirs were constructed with volumes exceeding 100,000 m<sup>3</sup> (Fig  
 215 3). Since then, construction of smaller reservoirs, with volumes of less than 30,000 m<sup>3</sup> (Fig 3), have declined in  
 216 favour of larger reservoirs. As a result, the mean capacity of the reservoirs constructed post-2006 (n = 60) rose by  
 217 269% compared to the pre-2006 period (n = 57). In 2021, we estimated the potential storage capacity of reservoirs  
 218 in the study area to be close to 7.3 million m<sup>3</sup> (Table 1).

219 The reservoirs' design and structure has evolved over time. The first snowmaking reservoirs had no coverage to  
 220 protect the geomembrane (Fig 2). Partially covered reservoirs (Fig 2) appeared in 1992, and the first reservoir  
 221 with a fully covered GLS (Fig 2) was built in 1999. Our research revealed that the year of construction significantly  
 222 influenced the type of coverage used. From 2015 onwards, full GLS coverage were used more than partial  
 223 coverage when new reservoirs were built ( $H = 36.6$ ;  $p\text{-value} < 0.001$ ). In 2021 almost half of the snowmaking  
 224 reservoirs (n = 59) in the studied area still lacked coverage to protect the geomembrane.

## 225 2. Biodiversity, water quality, embankment design and uses of 28 snowmaking reservoirs

### 226 a. Biodiversity presence and mortality in snowmaking reservoirs

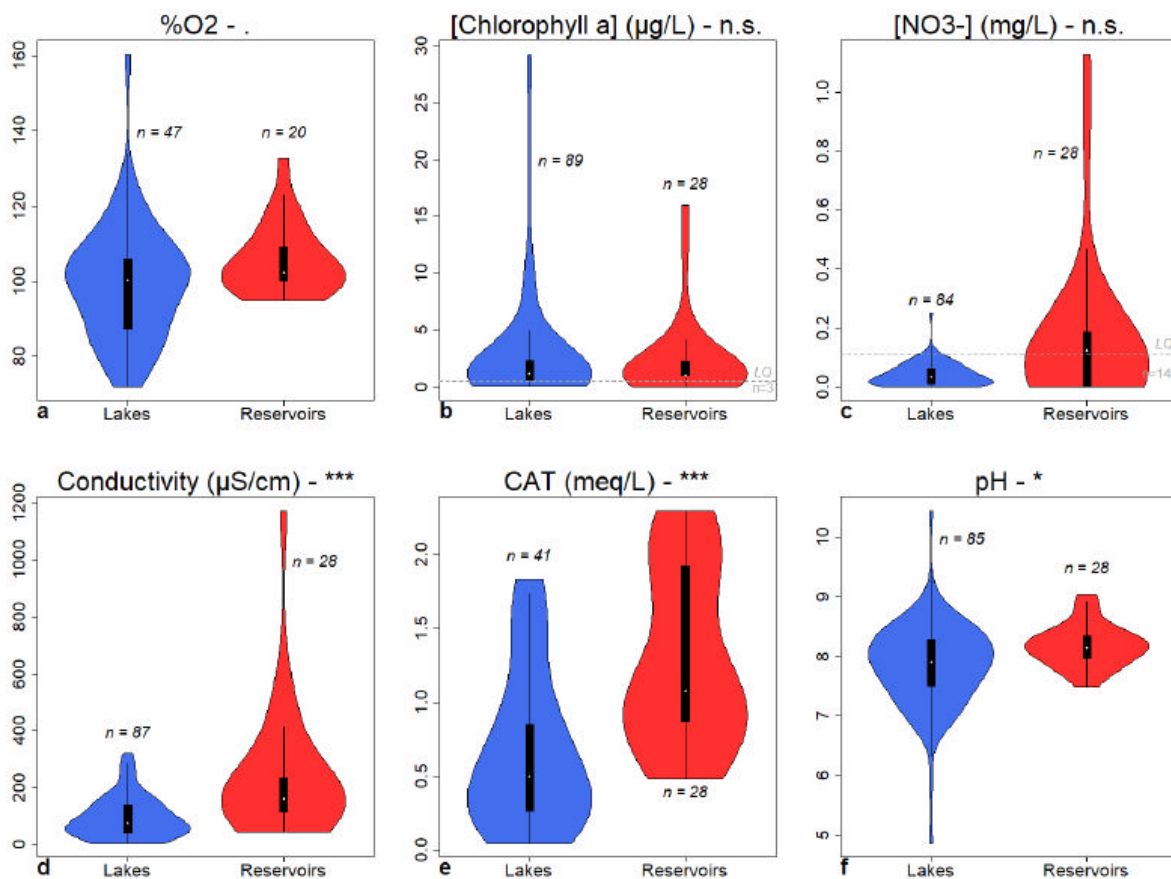
227 No aquatic vegetation was found in the reservoirs visited. In contrast, 82% of the reservoirs visited had terrestrial  
 228 vegetation on their banks; in only 29% of cases the vegetation belt was continuous. It should be noted that among  
 229 the reservoirs with terrestrial vegetation, 57% hosted more than 5 plant species. The presence of this vegetation  
 230 was independent of altitude, but its abundance and regularity tended to increase with the age of the reservoirs ( $H$   
 231  $= 4.1$ ;  $p\text{-value} = 0.4$ ). In general, terrestrial vegetation was found on the banks of reservoirs that had been built for  
 232 10 years earlier on average.

233 Spontaneous faunal species were observed in 89.3% of the reservoirs visited, not including introduced fish. This  
 234 percentage includes amphibians in 68% of the reservoirs, macroinvertebrates excluding odonates (61%), and

235 odonates (7%). Introduced fishes were observed in 28.6% of the reservoirs. In the reservoirs studied, the red-legged  
 236 frog (*Rana temporaria*) was the amphibian species most frequently observed (50.0%) followed by the alpine newt  
 237 (*Ichthyosaura alpestris*, 39.3%) and the common toad (*Bufo bufo*, 35.7%). Eggs or tadpoles of *Rana temporaria*  
 238 and *Bufo bufo* were found in 39.3% and 32.1% of the visited reservoirs, respectively. Odonates were observed at  
 239 different stages of their life cycle including adults and larvae, although no exuvia were found. Benthic and pelagic  
 240 macroinvertebrates were both observed in 50.0% of the reservoirs visited, and 21.4% were home to water strider  
 241 species. In the 8 reservoirs containing fish, the species identified were minnow (*Phoxinus phoxinus*) or Salmonids.  
 242 The presence of all amphibian species decreased with altitude (W = 144; p-value < 0.01).

243 Finally, we noted mortality of *Ichthyosaura alpestris* in 10.7% of the reservoirs, of *Bufo bufo* in 7.1%, of *Rana*  
 244 *temporaria* in 3.6%, and of odonate imago in 3.6%. These cases were systematically observed when bank slopes  
 245 exceeded 16.5°. Some stranded tadpoles and eggs were also observed after a low and partial emptying of the  
 246 reservoirs. Additionally, observations of drowned mammals, stranded amphibians and dragonflies, and other  
 247 animals stuck into pipes during the emptying process, despite the presence of a suction strainer, were regularly  
 248 reported by the managers. An unexplained clutch mortality of red-legged frogs was also reported in one reservoir.

249 **b. Water quality comparison between snowmaking reservoirs and mountain lakes**



250

251 **Fig. 4** Comparison of the physico-chemical characteristics of snowmaking reservoirs (red) and mountain lakes  
 252 (blue). The characteristics compared were: (a) oxygen percentage, (b) chlorophyll a concentration, (c) nitrate  
 253 concentration, (d) conductivity, (e) complete alkalimetric titre, and (f) pH. The limit of quantification (LQ) for  
 254 each assay is indicated by a grey dashed line. The statistical significance of differences, as determined using a  
 255 Wilcoxon test, is indicated as follows: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 'n.s' |

256 Conductivity, total alkalimetric titre and pH were significantly higher in surface water of snowmaking reservoirs  
 257 than in the surface water of mountain lakes (respectively W = 529; p-value < 0.001; Fig 4d; W = 221.5; p-value

258 < 0.001; Fig 4e; W = 812; p-value = 0.01; Fig 4f). The pH range was 3.6 times wider in lakes than in reservoirs.  
259 However, we found no significant differences in water quality in terms of surface oxygen saturation, nitrate  
260 concentration or chlorophyll *a* concentration between snowmaking reservoirs and natural mountain lakes  
261 (respectively W = 348; p-value = 0.09; Fig 4a; W = 348; p-value = 0.09; Fig 4a; W = 1,209, p-value > 0.05; Fig  
262 4b).

### 263 **c. Embankment design of snowmaking reservoirs**

264 Among the 28 altitude reservoirs we visited, thirteen reservoirs had full GLS coverage on their banks, whereas  
265 eight had only partial coverage, and seven had no coverage at all. The slopes of their upstream embankments  
266 ranged from 1/4.7 (V/H) to 1/1.6 (V/H), and were steeper than 1/3.1 (V/H) in 23 reservoirs. The average upstream  
267 embankment slope was steeper for reservoirs without a cover layer ( $1/2.15 \text{ V/H} \pm 7^\circ$ ) than for those with a cover  
268 layer ( $1/2.75 \text{ V/H} \pm 7^\circ$ ) as a gentler slope is required to ensure the stability of the GLS on the upstream  
269 embankment.

### 270 **d. Uses of snowmaking reservoirs**

271 Almost half of the snowmaking reservoirs were used solely for snow production (n = 15). The remainder were  
272 also allocated to various uses, predominantly fishing (n = 8), recreational activities (n = 8), drinking-water storage  
273 (n = 4), or sometimes for pastoralism or irrigation support (n = 4). The use of snowmaking reservoirs for drinking-  
274 water supply was only observed for reservoirs built after 2008. Similarly, only reservoirs built from 2017 onwards  
275 were used for water sports activities.

## 276 **IV. Discussion**

277 The environmental impact of snowmaking reservoirs has been outlined and assessed (Evette et al. 2011; Magnier  
278 2016), yet their potential as aquatic ecosystems remains incompletely understood (Fait et al. 2020). The survey  
279 performed for the present study revealed their recent multiplication in number and their proximity to other water  
280 bodies, with a trend towards the construction of larger reservoirs at higher altitudes over time. Snowmaking  
281 reservoirs represented distinct habitats through their homogenous morphometry and GLS coverage. Whereas  
282 sparse terrestrial vegetation was commonly present along their banks, aquatic vegetation – crucial for a  
283 functioning aquatic ecosystem – was notably absent. The fauna observed in the reservoirs surveyed consisted of  
284 spontaneous native and introduced non-native species, including protected species but with relatively limited  
285 overall biodiversity. Comparisons with mountain lakes revealed similarities in terms of surface area, volume, and  
286 water quality. However, distinctions emerged in conductivity, complete alkalimetric title, and pH. Observations  
287 and accounts of drowned mammals and stranded amphibians and dragonflies underscore the role of snowmaking  
288 reservoirs in alpine biodiversity loss, potentially acting as ecological traps (Dwernychuk and Boag 1972).

### 289 ***General evolution of snowmaking reservoirs in the aquatic landscape of the French Alps***

290 The proliferation of snowmaking reservoirs in the French Alps accelerated from the late 1980s to the early 2010s,  
291 responding to burgeoning demands related to tourism as well as escalating environmental considerations on water  
292 retention during low-water periods (François et al. 2023). However, our analysis revealed a shifting trend towards  
293 the construction of fewer but larger and higher-altitude reservoirs since 2006, possibly influenced by regulatory  
294 changes enacted at that time (Mériaux and Peyras 2009). Moreover, considerations regarding the long-term impact  
295 of climate change on snow requirements could have motivated efforts to increase water storage capacities  
296 (Gerbaux et al. 2020; Vorkauf et al. 2022). Promising technological advancements and potential rebound effects  
297 further suggest that both the number and capacity of snowmaking reservoirs will increase in the coming years  
298 (Cognard and Berard-Chenu 2023).

299 Our survey of the study area revealed that more than one-twentieth of all water bodies larger than 9 m<sup>2</sup> are now  
300 snowmaking reservoirs, they thus have a significant presence in this area and possibly throughout the French Alps  
301 and more widely in all mountain regions of the world with ski resorts. Our observations also underscored the

302 spatial proximity between snowmaking reservoirs and other freshwater habitats, indicating that snowmaking  
303 reservoirs may constitute potential habitats for the dispersal of freshwater organisms (Oertli et al. 2014). These  
304 organisms may thus spread beyond the confines of traditional aquatic networks (Bilton et al. 2001; Kovar et al.  
305 2009; Smith et al. 2009). According to our hypothesis, snowmaking reservoirs are a new component in the aquatic  
306 landscape of the French Alps. Their role in species dispersal must be considered as part of maintaining ecological  
307 connectivity, particularly for alpine species, such as amphibians, that are vulnerable to wetland destruction and  
308 habitat fragmentation due in particular to the development of ski resorts (Boncourt 2019; Boncourt et al. 2023).

309 The shift to the preferred use of a full GLS coverage layer when constructing new reservoirs has been driven by  
310 the desire to protect the waterproofing geomembrane system from physical and chemical degradation (Mériaux  
311 and Peyras 2009). Such measure may have reduced mortality risks for biodiversity, creating the means to escape  
312 from the reservoirs. This also led to the emergence of reservoirs with more suitable habitats with riprap and gentler  
313 bank slopes, increasing colonisation opportunities for both aquatic and terrestrial vegetation, which require bank  
314 slopes and substrate compatible with retention of organic matter and sediments for their roots to anchor (Håkanson  
315 1977; Schutten et al. 2005).

### 316 *Snowmaking reservoirs host spontaneous biodiversity*

317 During our inventories, we observed terrestrial vegetation on the banks of 82% of snowmaking reservoirs.  
318 Terrestrial vegetation remained scarce, requiring an average of 10 years to establish, and rarely formed a consistent  
319 vegetation belt. Plant growth is slower in ecosystems at altitude, creating slower ecological and biological  
320 processes (Körner 2003). This is particularly true on riprap, as reported by Tisserant et al. (2020, 2021) from their  
321 observation of the quasi absence of successional pattern observed in riprap. In contrast, aquatic and semi-aquatic  
322 vegetation is abundant in mountain lakes (personal communication) but completely absent from snowmaking  
323 reservoirs. The absence of aquatic plant may highlight an inadequate substratum or slopes on reservoir banks for  
324 vegetation roots anchorage (Håkanson 1977; Schutten et al. 2005). The unnatural fluctuations of water levels in  
325 snowmaking reservoirs, including complete emptying in some cases, could also explain the absence of helophytes  
326 and hydrophytes (Coops et al. 1991). The water analyses revealed comparable chlorophyll *a* concentrations  
327 between snowmaking reservoirs and mountain lakes, indicating possibly similar phytoplankton abundances (Huot  
328 et al. 2007; Kasprzak et al. 2008). Nevertheless, the data do not permit the conclusion that the phytoplankton  
329 communities are similar in terms of specific composition.

330 The results presented here corroborate the findings of Fait et al. (2020) regarding the potential of snowmaking  
331 reservoirs to host spontaneous biodiversity, regardless of their design or use and despite the absence of aquatic  
332 vegetation. Fait et al. (2020) investigated in detail the presence of beetles and dragonflies in eight Swiss  
333 snowmaking reservoirs where biodiversity was occasionally encouraged to colonise by the addition of aquatic  
334 plants or associated habitats. Spontaneous fauna has also been documented in other types of artificial reservoirs,  
335 such as urban and stormwater ponds (Clevenot et al. 2018; Oertli and Parris 2019; Jumeau et al. 2020). In our  
336 case, spontaneous fauna was encountered in 89% of the surveyed reservoirs, including individuals from several  
337 fauna compartments (i.e. macroinvertebrates, dragonfly imagos, water striders, amphibians, fishes) normally  
338 found in the trophic webs of mountain lakes (Sánchez-Hernández et al. 2015) and including protected amphibian  
339 species in decline particularly in mountain areas (Kyek et al. 2017).

340 We recorded all life stages of red-legged frogs and common toads, but were unable to detect all life stages or any  
341 reproduction of the alpine newt. The newt female usually lays single eggs on submerged leaves (Miaud 1993),  
342 which were absent from all the snowmaking reservoirs visited. We might have missed potentially less visible and  
343 accessible clutches due to parental behaviours such as the female wrapping eggs into vegetation (Schulte et al.  
344 2020). We were also unable to find all odonate life stages, indicating that these species may not complete their  
345 entire life cycle in snowmaking reservoirs as they require emerging support, typically provided by aquatic  
346 vegetation (Huikkonen et al. 2020).

347 Although animal species are evidently drawn to snowmaking reservoirs, the observed biodiversity remains  
348 limited, relying on single and isolated visual observations for each reservoir.

349 ***Snowmaking reservoirs share some abiotic characteristics with natural mountain lakes***

350 Given their shared altitude range, snowmaking reservoirs should experience analogous thermal regimes to  
351 mountain lakes in summer, with temperatures influenced by local climatic and meteorological factors, as well as  
352 watershed attributes such as orientation and topography (Novikmec et al. 2013). This can result in estival  
353 dynamics similar to those observed in mountain lakes (Hampton et al. 2017), characterised by short photosynthetic  
354 periods constraining vegetation growth (Chacornac 1986; Körner 2003).

355 The water composition of snowmaking reservoirs is similar to that of mountain lakes for most parameters,  
356 suggesting oligotrophic habitat conditions. Surface oxygen saturation values greater than or close to 100%  
357 indicated oxygen saturation or oversaturation in surface waters during summer for 76% of mountain lakes and  
358 82% of snowmaking reservoirs. These oxygen levels are caused by photosynthetic activity, probably generated  
359 by the phytoplankton communities, surpassing respiration (Dordoni et al. 2022). Despite relatively low nitrate and  
360 chlorophyll *a* concentrations compared to lowland water ecosystems for both lakes and reservoirs (Sáros et al.  
361 2005), chlorophyll *a* concentrations exceeding 5 µg/L were still measured in some snowmaking reservoirs,  
362 possibly explaining the occasional occurrence of algal blooms.

363 Snowmaking reservoirs show however higher conductivity and CAT than mountain lakes. This could be explained  
364 by the water supply, primarily coming from downstream water pumping (Vanham et al. 2009). In contrast,  
365 mountain lakes mostly receive water from snowmelt and precipitation, which may result in lower ion  
366 concentrations (Zhao et al. 2018). If differences in these parameters are not known to impact macroinvertebrate  
367 communities (Canton et al. 2011), they may structure plankton communities, as Zhu et al. (2024) shown that  
368 conductivity can be positively or negatively correlated with phytoplanktonic diversity in alpine lakes depending  
369 on the species, with a range of optimal values for diversity. Moreover, conductivity can be positively correlated  
370 with amphibian richness and abundance, but increased conductivity can alter their behaviour, growth and  
371 development, increase malformation and decrease larvae survival, depending on the species tolerance (Calderon  
372 et al. 2019), even if it does not represent a risk of direct mortality (Chambers 2011).

373 Snowmaking reservoirs are fully man-made water bodies, the exploitation of which induce specific hydrological  
374 characteristics compared to mountain lakes and influence their abiotic parameters and may limit the ability of  
375 species to develop. The exploitation of snowmaking reservoirs leads to rapid and extensive water-level  
376 fluctuations compared to natural water bodies, where levels usually decrease progressively during summer due to  
377 thermal evaporation, but remain relatively stable throughout the winter months (White et al. 2008). The filling  
378 and emptying cycle for snowmaking reservoirs (Marnezy 2008), in contrast, means that these bodies of water are  
379 empty at the end of winter and completely filled during summer. However, we don't know yet the impact of such  
380 water level fluctuations over biodiversity and water quality in snowmaking reservoirs.

381

382 It should be noted that these abiotic data are based on a pool of several samples collected once in each snowmaking  
383 reservoir. Therefore, the interpretation of the results should be made with caution. Despite this, although such  
384 specific thermal and trophic conditions should filter the species capable of colonising and surviving in both  
385 snowmaking reservoirs and mountain lakes (Poff 1997), the results suggest that the quality of the water in  
386 snowmaking reservoirs could be suitable for the establishment of certain species similar to those found in natural  
387 mountain lakes, if they are able to withstand the impact of unnatural water level fluctuations and higher ion  
388 concentrations.

389 ***The embankment design, exploitation and uses of snowmaking reservoirs can lead to biodiversity loss***

390 The construction of snowmaking reservoirs has prioritised storage volume safety without taking biodiversity into  
391 account (Mériaux and Peyras 2009), possibly making them ecological traps. The slopes of the visited snowmaking  
392 reservoir banks were generally homogeneous and steeper than the ~18° threshold recommended by the regulations  
393 (Mériaux and Peyras 2009) or than the slopes of the banks of mountain lakes (Martinot 1979). Sliding

394 geomembranes associated with steep bank slopes can lead to animal mortality (Scher 2005; Parris 2006). Over  
395 the course of this study, several drowned mammals and stranded amphibians or dragonflies were observed or  
396 reported in the reservoirs. This mortality was found to systematically occur in reservoirs with bank slopes steeper  
397 than 16.5°, and 73% of the mortality observed occurred in reservoirs without or with a partial GLS coverage.

398 The exploitation of snowmaking reservoirs can also be a cause of death for many species. Stranded tadpoles and  
399 eggs after a low and partial emptying of the reservoirs were observed. Snowmaking reservoirs typically have an  
400 optimal water level for the start of amphibian reproduction in spring. The filling and emptying processes at key  
401 points in their life cycle could result in clutch drowning or young stages becoming stranded (Clevenot et al. 2018).  
402 Additionally, there have been reports of mortality for amphibians and other animals stuck into pipes during the  
403 emptying process, despite the presence of a suction strainer.

404 More than half of snowmaking reservoirs were used for purposes other than snowmaking. These other activities  
405 may be incompatible with the presence of some alpine species. We discovered introduced fish in 28.6% of the  
406 reservoirs we visited. Similar introductions in mountain lakes are known to impact the habitat and indigenous  
407 species such as amphibians (Ventura et al. 2017; Osorio et al. 2022). In addition, nautical sports have become  
408 popular in more recent reservoirs, potentially affecting biodiversity through excessive human presence, wave  
409 action on the shoreline, noise, trampling and vibration (Coops et al. 1991; Fleissner et al. 2022).

410 An unexplained clutch mortality of red-legged frogs was observed in one reservoir. One possibility could be that  
411 snowmaking reservoirs are good vectors for pathogens such as *Batrachochytrium dendrobatidis* (Dejean et al.  
412 2010). As water is often pumped from downstream, its transfer could also lead to pathogen introduction (Brookes  
413 et al. 2004). In addition, the location of snowmaking reservoirs within ski resorts puts them at the forefront of  
414 overuse and recreational activities that may involve contaminated equipment. Finally, pastoralism and fishing  
415 activities can introduce pathogens into reservoirs from cow excrement and imported fish, both of which are  
416 pathogen carriers (Pastorino et al. 2019).

#### 417 ***Encouraging ecological processes in snowmaking reservoir to promote biodiversity establishment***

418 The results of the present study suggest that we could go further in encouraging ecological processes and thus in  
419 integrating biodiversity into snowmaking reservoirs. Existing snowmaking reservoirs could support the survival  
420 of biodiversity. Covering their banks with at least a partial layer of riprap appears essential to reduce wildlife  
421 mortality. Reserving part of the reservoir banks for biodiversity could limit the perturbation due to summer tourist  
422 traffic, incompatible human activities and fish predation. The survival of amphibian populations could especially  
423 be improved in existing reservoirs, by providing potential breeding or migratory sites if the water elevation is  
424 adjusted during the breeding season to allow tadpoles enough time to emerge (Clevenot et al. 2018). This could  
425 be complemented by limiting the emptying of the reservoir to ensure a permanent aquatic environment (Jumeau  
426 et al. 2020) and by stopping practices to control herbaceous vegetation on the banks.

427 To reduce biodiversity loss, future snowmaking reservoirs could include aquatic micro-habitats with slopes under  
428 16.5°, connected to the main reservoir but protected from incompatible human activities and fish predation. Given  
429 that the majority of mountain lakes are currently stocked with fish, it is even more imperative to ensure the  
430 continued existence of predator-free habitats for alpine biodiversity (Ventura et al. 2017). This can also be  
431 achieved by prohibiting the introduction of fish species in future snowmaking reservoir constructions. Raising the  
432 level of the suction strainer in future designs could also reduce mortality for fauna during emptying.

433 Existing snowmaking reservoirs could also improve the dispersal of biodiversity, giving spontaneous species the  
434 opportunity to complete their life cycle, and potentially leading to the colonisation of new species. The ability of  
435 amphibians to disperse effectively on bare surfaces, such as the banks of snowmaking reservoirs covered with a  
436 geomembrane or riprap, is limited. The addition of GLS coverage on the banks of snowmaking reservoirs created  
437 the conditions to allow the slow development of sparse vegetation. Whereas ligneous plants are prohibited on the  
438 dykes of snowmaking reservoirs (Mériaux and Peyras 2009), it is considered acceptable to promote the growth of  
439 harmless herbaceous terrestrial plants (Evette et al. 2014; Vennetier et al. 2015). Active revegetation of the riprap-

440 covered banks using techniques available for terrestrial species (Venetier et al. 2015; Tisserant et al. 2020) could  
441 improve ecological connectivity between the surrounding natural ecosystems and the artificial aquatic  
442 environment (Amoros and Wade 1996; Martin et al. 2021; Boncourt et al. 2024), and increase the number of  
443 species present in the reservoirs (Janssen et al. 2019).

444 Finally, promoting aquatic vegetation in both existing and future snowmaking reservoirs seems essential to ensure  
445 the establishment, survival, reproduction and colonisation of biodiversity by creating microhabitats, egg-laying  
446 supports, hiding places from fish predation and improve water quality (de Melo et al. 2017; Gleason et al. 2018;  
447 Gutierrez et al. 2021). The addition of such vegetation appears to be a crucial issue in all larger-scale artificial  
448 reservoirs (Briggs et al. 2019; Rodrigo 2021; Lozano et al. 2022). However, no study has yet investigated active  
449 revegetation with aquatic or semi-aquatic plants in such specific habitats as snowmaking reservoirs.

## 450 **Conclusion**

451 The existing snowmaking reservoirs in the aquatic landscape of alpine regions have significant ecological  
452 potential due to their number, proximity to other natural habitats and their water quality, which is in part similar  
453 to that of mountain lakes. These reservoirs are already home to spontaneous and limited biodiversity, and their  
454 specific design, management and use can affect water quality and the survival of this biodiversity, potentially  
455 acting as ecological trap. Biodiversity can be better taken into account in existing snowmaking reservoirs and in  
456 the design of the potential future structures to achieve a “win-win” situation for both alpine species and human  
457 activities. This reflection must be carried out at the scale of the aquatic landscape in the light of the ecological  
458 processes of biodiversity in mountain ecosystems.

459

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