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Environmental risks and impacts of mountain reservoirs for artificial snow production in a context of climate change

André Evette, Laurent Peyras, Hugues François et Stéphanie Gaucherand

1 Mountain reservoirs are hydraulic structures built in mountain leisure resorts, used to store water mainly for the production of artificial snow. Their implantation in mountains with altitudes of between 1,200 and 3,000 metres means undoubtedly that they are highly specific reservoirs compared with reservoirs located in plains. This is because their position results in specific difficulties, given the complex geological and geotechnical contexts (slope, diversity of substrates, etc.), specific mountain hazards (avalanches, debris flows, etc.), and intense solicitations due to the snow and cold. From an ecological viewpoint, these reservoirs are built in environments that are very rich, but also very fragile. Given their dominant position above facilities with very high traffic and steep slopes of versants that are likely to create torrential flows in the event of a break, mountain reservoirs have relatively high risks in spite of the low volumes of water stored.

2 The number of mountain reservoirs in France has grown sharply since the beginning of the 2000s. In 2008, there were some 105 structures with a capacity of over 10,000 m³. In the next 10 to 20 years, a significant increase in the number of mountain reservoirs is expected and the observed trend is a marked increase in the size of structures, which has risen from an average capacity of 40,000 m³ to 100,000 m³ today on new projects (Peyras *et al.*, 2009).

3 Other countries of the Alpine chain such as Switzerland, Austria and Italy are facing similar problems concerning the risks and impacts of mountain reservoirs (Ancey C, 2009). However, it must be noted that very few studies have been conducted on the issues raised by mountain reservoirs and that there are practically no scientific or technical publications available on the subject in France or abroad.

4 Following various technical and ecological questions raised about mountain reservoirs by public authorities and professional mountain organisations in France, Cemagref has launched a research and development project aimed at building upon feedback from these structures in the various fields concerned and at laying down down technical recommendations on technical engineering and environmental protection. This research and development project called Baraltisur (safety of mountain dams) was conducted over two years between 2007 and 2008. It was financed by the Ministry of Ecology under the "Risque Décision Territoire" (hazards, decision-making, territory - RDT) research programme, by the Interministerial Delegation for Planning and Territorial Competitiveness and the Provence-Alpes Côtes d'Azur (PACA) region. It was conducted by a multidisciplinary project team made up of engineers and researchers from Cemagref, EDF and the engineering firm ISL. It was concluded with the publication of recommendation guidelines on the siting, design, construction and management of mountain reservoirs (Peyras *et al.*, 2009).

5 In 2007, in-depth, documentary and on-site surveys were conducted on mountain reservoirs in the Alps and the Pyrenees (Evette *et al.*, 2009). The structures studied were subjected to several investigations : analysis of structure project design studies (environmental impacts, risks for public safety, hydrology, mountain hazards, technical documents, etc.), in-depth inspections and occasional thorough assessments. A total of about 65 structures were thus examined, enabling the team to gather substantial information about the design, state, behaviour, incidents, operating and monitoring of mountain reservoirs. The survey also covered the factoring of environmental impacts in the data and impact studies established during the mountain reservoir design phase. These impacts were also observed on-site during field investigations.

6 This article aims at drawing up a detailed inventory of the risks and impacts on the environment related to mountain reservoirs in France, so as to establish a complete panorama in this area. It begins by putting mountain reservoirs into societal, social and environmental perspective : It establishes the historic and current framework of the economic development of mountain resorts and studies the influence of climate change on snow conditions. Next, the article develops the risks and impacts of mountain reservoirs. It provides a technical presentation of mountain reservoirs in France, analyses the various risks and specific hazards faced by these structures and describes the various environmental impacts linked to the construction and management of mountain reservoirs.

Snow cover : a central issue for the development of ski resorts

7 The rapid growth of ski resorts in France is part of the land-use planning rationale that promotes the spread of a resort model called the third-generation model according to the typology established by Cumin (1970). The representation of successive generations of ski resorts, is in itself, a testimony of the normative approach promoted by government services, mainly CIATM and SEATM[1]. What is generally called the "Snow Plan" has no real existence in the traditional sense of planning, but rather refers to an effort by public authorities to fit out new mountain sites based on a veritable doctrine of land-use planning (Knafou, 1978 ; François, 2007).

8 The dynamic of mountain tourist development was and mainly continues to be the subject of strong tensions and the issue of snow cover is going to play an increasingly dominant role in discussions on the issue. This is because the effectiveness of the granting of public loans in ski resorts on virgin sites was a key factor in justifying a policy that was controversial, as seen by the local conflicts arising from expropriations (including the one that pitched a section of the population of Hauteville-Gondon and Société des Montagnes de l'Arc, during the building of the Les Arcs ski resort) and in the development of national-scale environmental criticism (specifically the "La Vanoise affair" that broke out when the Val Thorens resort was created). As a corollary to the assertion of the superiority of third-generation ski resorts, the appearance of alternative mountain tourism development modes has aroused significant criticism. The "snowless" winters of the 1989/1990 and 1990/1991 skiing seasons played a central role and highlighted the general limitations of winter sports resorts as solutions for land-use planning.

9 In the context of climate change, the OECD report (2007) raised the alarm by differentiating between sites where future snow cover appears unlikely to significantly decrease and those that are directly threatened, depending on their altitude. Moreover, snow-deficient winters have contributed to raising the awareness of the general public, who represent potential tourists, to the issue of the opening of ski areas, which is a crucial factor for drawing tourists to ski resorts. There are therefore two different strategies : that of high-altitude resorts that focus mainly on downhill skiing and develop by providing technical solutions to snow-deficiency, and that of mid-altitude resorts that are mainly oriented towards the diversification of the tourist offering (successive policies where the resorts enter into contracts at regional level (with the Rhône-Alpes Region through the Diversified Development Contract in Isère or the Tourism Plan for the Savoie region). Although the implementation of the "Nivalliance" insurance system set up by the French national union of ski lift operators (SNTF) has developed a degree of solidarity between resorts, it has also acknowledged the gap between the modes of development of ski resorts.

10 There is indeed a huge difference between the different types of resorts, if only with respect to their ability to generate profit simply from ski lift operations that they can reinvest, in particular in equipment for producing artificial snow. Bolstered by the technical rationality that drove their design, mountain resorts have an attitude that some environmental groups describe as the "race for white gold". The increase in investments for the production of artificial snow has contributed to rekindling the debate about the environmental impact of ski resorts. Against a backdrop where the general public is highly aware of sustainable development (see the Ski resort Eco-guide, the Sustainable Development Charter of mountain resorts and the "war of words" – cultured snow *vs.* artificial snow, "snow-makers" *vs.* snow cannons, as well as the highlighting of the natural components of "production" snow, air and water, *vs.* the possibility of using additives such as Snomax – which pits operators against environmentalists), the supervision of practices to guarantee the opening of the ski area has become a crucial factor.

11 The practice of the use of water resources is particularly incriminated in line with the criticisms against urbanisation and the concentrated tourist flows. Drawing directly from water courses can thus give a negative image of the resort's activity. It also raises the question of availability during low-water periods and reinforces constraints related to the

legal obligation to protect reserved torrent flows. The margins for manoeuvre presented by the use of drinking water can also have a negative impact for the image of resorts given the rareness of the resource. In particular, this solution turns out to be rather paradoxical as it opens a ski area (with increased snow production), the operation of which depends on the tourist accommodation capacity (with an attendant increase in drinking water consumption). To justify these practices, operators argue the implementation of a controlled management that "stores water when it is abundant and restores it when it is scarce" (ANEM, 2007), stressing the "unsuspected talents of artificial snow"[2]. This rationale deals with only part of the reality of the impact of mountain reservoirs and their widespread use.

Increasingly unreliable snow cover due to climate change

12 Snow cover conditions in mountain resorts are increasingly unreliable because of climate change. For example, some authors predict that in a warmer climate, the snowline, as well as the line of natural snow reliability, will rise by 150 metres per 1°C warming (IPCC, 2007 ; OECD, 2007).

13 A team of Swiss researchers has studied the probable impact of an average warming of 4° C on snow cover. This warming of 4°C is more in the upper range of the predictions for 2100 of the models presented by the GIEC (IPCC, 2007). This Swiss study concludes that this warming would decrease the volume of snow in the Alps by 90 % at 1,000 metres, by 50 % at 2,000 metres and by 35 % at 3,000 metres. Moreover, snow cover duration would be greatly reduced, ending 50 to 60 days earlier at high altitude (above 2,000/2,500 metres) and 100 to 130 days earlier at average altitudes close to 1,000 metres (Beniston *et al.*, 2003).

14 Lastly, with respect to skiing activity, an OECD study predicts that a 2°C increase in temperature would bring the number of naturally snow-reliable ski areas to around only 80 % of the current total ski areas in the Savoie, Hautes Alpes and Alpes de Haute Provence departments, where the highest ski resorts are located. However, if the temperature were to rise by 4°C, this percentage would drop to 71 % in Savoie, 33 % in the Hautes Alpes and 10 % in the Alpes de Haute Provence (OECD, 2007).

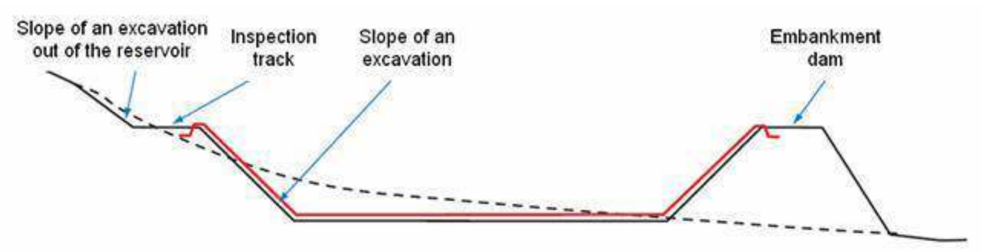
15 The probable reduction of periods of snow cover as a result of climate change, their heavy impact on skiing and on the increased production of artificial snow are issues that are also raised in other parts of the world such as the United States (Scott *et al.*, 2006) and Australia (Good, 1995).

The mountain reservoir population in France and their main technical characteristics

16 In 2008, there were some 105 mountain reservoir structures in France, of over 10,000 m3 in the Alps (85%) and Pyrenees (15%), knowing that the other French mountain ranges (Jura, Vosges and Massif Central) have about a dozen mountain reservoirs. This area is constantly growing, and in 2008, there were about 30 mountain reservoirs being built or being assessed by public authorities (Peyras *et al.*, 2009).

17 Nearly all mountain reservoirs are embankment dams, which have specific technical characteristics. The two main ones are presented below. First of all, given the topographical conditions of the mountain, they are located on shelf areas, and often do not contain a thalweg. They are therefore usually designed according to cut-and fill techniques, like a basin, partially surrounded with an embankment.

Figure 1 : Principle of the cut-and-fill design of a mountain reservoir with the entire basin sealed by a geomembrane



18 The geology of mountain sites creates natural sealing tightness issues: talus on slopes, moraines, fissured rock, cargneules, karsts, absence of clay at high altitude, etc. Hydro-geological analyses of foundations often show water inflows (70%). They are therefore often artificially sealed by laying geomembranes on the entire basin surface (85 %).

19 A large proportion of these dams (65%) have average embankment heights of between 5 to 10 metres above natural land, while 20% of mountain reservoirs are very small dams less than 5 metres high. It must be noted, however, that 15 % of these structures are embankments more than 10 metres high.

20 Embankments are built with the deposits of material available and excavated on the construction site. They mainly comprise moraines and schists (60 %). There are also, to a lesser extent, embankments made from silt and rock-fill mainly from quartzite, gneiss and limestone.

21 The average volume of water stored is approximately 40,000 m^3. However, today, there is a sharp increase in volume for structures under construction or for which applications are being processed, with an average volume of approximately 100,000 m^3.

22 With respect to their administrative situation (decree on hydraulic safety of 11 December 2007), mountain reservoirs are evenly divided between categories D and C, with a minority (10%) in category B. Future reservoirs that are being built should significantly change this breakdown.

23 50% of these water reservoirs are built at an altitude between 1,500 and 2,000 metres, 30% under 1,500 metres and 20% above 2,000 metres. Future projects show a sharp decrease in mid-altitude reservoirs at below 1,500 metres.

Structures subject to potentially high mountain-specific hazards and public safety risks

24 In addition to the usual hazards encountered in lowland areas (floods, earthquakes), mountain reservoirs may be exposed to hazards that are specific to mountain areas: avalanches, rapid flows and geological hazards – slope slip-offs, cavings, falling blocks. The intensity of most of these mountain hazards is very difficult to quantify during rare

to exceptional return periods, which makes it even more difficult to design mountain reservoir protection structures when they become necessary.

25 The breakdown of the exposure to avalanches, torrential and geological hazards is as follows:

- about 20 % of mountain reservoirs are built on proven avalanche-prone sites. Half of them are subject to very high hazards. For some of these reservoirs, structures to protect against these hazards (deflecting and retarding structures, etc.) have been provided and they generally take routine events to events with moderately significant impacts into account.

Figure 2 – Mountain reservoir impacted by an avalanche

Image2

(credit: Cemagref)

- one out of two mountain reservoirs is subject to debris flow and about one out of three is exposed to a major hazard.

Figure 3 – Mountain reservoir exposed to a proven debris flow hazard

(credit: Cemagref)

- one quarter of mountain reservoirs are exposed to moderate to major geological hazards, broken down by order of frequency into risks of falling blocks, underground instability, mass cavings and landslides.

26 Should the mountain reservoir be impacted by one of these phenomena, the volume of water stored in the reservoir may be expelled very quickly and cause a flood wave that may spread downstream. On the whole, the survey showed that one out two mountain reservoirs « affect public safety" in the sense that a break of the embankment part of the structure or any sudden expulsion of stored water would have significant adverse effects on downstream population and properties. There are several reasons for this (Peyras *et al.*

, 2009) : (i) their towering position above highly touristic facilities or ski resort residential areas ; (ii) steep slopes and hillside geological conditions that would lead to rapid flows (bed-load or debris flow) in the event of a release of substantial flows that could significantly increase the destructiveness of the accident ; (iii) short distance between the reservoir and downstream challenges, and extremely reduced time interval for the arrival of a break wave.

Figure 4 – Mountain reservoir overlooking challenges

(credit: F. Dinger, Cemagref)

Impacts of mountain reservoirs on the environment

27 The siting and management of mountain reservoirs have an impact on Alpine and sub-Alpine land and aquatic environments. These environments have a very high biodiversity. For example, in a 100 km long square, the Alps harbour between 2,000 and 3,000 vascular plant species (ferns, conifers and flowering plants) (Aeschimann *et al.*, 2004). These environments are particularly fragile because of their extremely slow growth dynamics. Therefore any damage to them will require longer recovery times than at lower altitudes and the natural reconstruction dynamics may last for several decades. Furthermore, mountain species already undergo pressure related to climate change. For example, a study conducted on 171 forest species showed that there was an upward shift in plant species by about 30 metres each decade (Lenoir *et al.*, 2008).

Impacts on surface runoffs

28 Artificial snow requires 3,000-4,000 cubic metres of water per hectare of slope, and snow-covered surfaces are on the rise (Marnezy, 2008). In 2008, 23 % of ski slopes were using artificial snow, drawing an estimated annual volume of 15 million cubic metres of water from the environment (Paccard 2010). The figure was 70 % in Italy, 59 % in Austria and 23 % in Switzerland (Paccard 2010). In winter there is already great pressure on water resources due to the demand in drinking water (De Jong *et al.*, 2008). The traditional operation of mountain reservoirs usually consists in creating a water reserve in summer and autumn, during a period where the adverse impact of the water used on aquatic environments is lowest. However, some mountain reservoirs are filled continually in winter or are filled several times during the season. In these situations, the quantitative impacts on torrents and surface runoffs may be substantial. This is because the greatest impacts correspond to the water collected during the winter period of minimum flow, during which significant collection may freeze small outlets and reduce the survival abilities of fish fauna (pollution dilution, compensation water). In a study presented in 2002 by the Rhone-Mediterranean and Corsica water agency, it was estimated that 61 % of water collected for artificial snow accounted for less than 10 % of minimum annual flow while 31 % collected between 10 and 50 % of minimum annual flow (Dugleux, 2002).

Impacts on humid zones and peat bogs

29 Mountain reservoirs are sometimes built directly on humid zones. According to a survey conducted by Cemagref, an estimated one-third of these structures are established on humid zones. Furthermore, during the construction phase, the circulation of machines and the storage of materials also have potential impacts on these environments. Over and above the direct impacts on these environments that are part of the national heritage, mountain reservoirs can also act indirectly. Peat bogs and humid zones are under the natural control of the quality as well as the quantity of water supply. The drop in groundwater basins is thus likely to result in drying, while earthworks upstream of these zones create fines and clog up humid zones. There is also a possible risk from fertilisers and composts used when banks or slopes are replanted upstream. These may alter the physical and chemical qualities of the waters that cross humid mountain zones that are usually oligotrophic.

Figure 5 – Mountain reservoir partly built on a humid zone

(credit: Cemagref)

Impacts on groundwater

30 Mountain water reserves are low and usually restricted to fractured rocks (De Jong *et al.*, 2008). Furthermore, the extreme general permeability of mountain soils and the gradual nature of snow-melt runoff make aquifers and therefore drinking water catchment relatively vulnerable. The water that supplies the mountain reservoirs is derived from surface waters and therefore more mineralised than meteoric waters. These waters may sometimes be contaminated by pollutants from human activities (water treatment, breeding, etc.) (Dinger *et al.*, 1995 ; Wipf *et al.*, 2005). The French agency for environmental and occupational health safety (AFSSET) concluded in a study (AFSSET, 2008) that pollution of drinking water storage sources by artificial snow made with water of bad microbiological quality was a risk that could not be ignored.

Impacts on land environments

31 Aside from the direct impacts of mountain reservoirs during their construction or during related works, these structures also have an indirect impact on land environments with respect to the spreading of artificial snow. This is because, as mentioned above, the water used for artificial snow is generally richer than meteoric water and therefore provides the environment with nutrients, which may be present in sufficient quantities to alter the composition of vegetation in the areas concerned in the medium term. To illustrate this assertion, a study by a team of Swiss scientists has shown changes to the number and types of plant species of plant communities, an increase nitrophilous species and snow-

bed species and a reduction in true grasses (Wipf *et al.*, 2005). This same study showed that plant diversity was lower on groomed slopes than in neighbouring meadows. It has also been sometimes observed that there is a pollution by hydrocarbon from the snow cannons themselves, mainly from “high pressure” ones (Dinger *et al.*, 1995). “If we consider that the quantity of snow produced corresponds to 300 litres of water per square metre and per season, corresponding to nearly one metre of snow, then 0.1 g of hydrocarbon is deposited per square metre of slope at the same time as the snow”. This hydrocarbon pollution, when present, is in addition to the pollution by grading machines.

Impacts to the landscape

32 Landscape impact can be significant because of earthworks and structures that may mar the appearance of mountain slopes. However, these impacts may be reduced, in particular when mountain reservoirs are positioned on flat sites, (as long as they are not occupied by humid areas), when they are given the same shape as that of natural lakes and when the slopes are replanted (Peyras *et al.*, 2009).

Impacts on human activities

33 There may also be impacts on pastoral and leisure activities, in particular during the construction phase because of restricted access or the dust generated.

Conclusion

34 This article presents the environmental risks and impacts linked to the building of mountain reservoirs as well as the management issues raised by these structures. It highlights the original and current social context of the development of mountain leisure activities. It also provides several avenues to explore on the possible consequences of mountain climate warming (probable decrease in snow cover periods with a significant impact on skiing activity and an increase in artificial snow production).

35 Mountain reservoirs are small-sized dams (65 % of mountain reservoirs have a height of between 5 to 10 metres) that store limited volumes of water (average volume of 40,000 m^3). Despite their small size, the feedback from the survey conducted on mountain reservoirs in France has shown that one out of two mountain reservoirs »affects public safety” in the sense that a break of the structure or the sudden expulsion of stored water would have serious consequences for downstream population and properties. This is because of their dominant position above facilities and the steep slopes of versants that would lead to rapid flows. Mountain reservoirs are also liable to be impacted by mountain-specific hazards such as avalanches, geological hazards and rapid flow hazards. Feedback shows that nearly one out of two mountain reservoirs is exposed to at least one mountain hazard. In the event of an impact by one of the above phenomena there could be a very rapid expulsion of the volume of water stored in the mountain reservoir.

36 Mountain ecological environments are rich, but also fragile because of their very slow recovery dynamics. Mountain reservoirs have significant impacts on these environments, not only during their construction, but also when they are operated. For example, feedback showed that during the construction phase, one third of these structures had

been built on humid zones or in other environments of high ecological importance with impacts on protected species (animal or plant). In addition to these direct impacts, indirect impacts linked to the suspension of sediments or hydrological alterations have also been observed. During the operating phase, potential impacts mainly concern water courses when water is collected during minimum annual flows or during the emptying of unusable water into the environment.

37 There are solutions for keeping environmental impacts and risks to a minimum. These are described in the book *Mountain Reservoirs* (Peyras *et al.*, 2009). This reference guide has established best practices concerning the technological risks. In particular, to limit natural risks, it is important to choose sites with very low hazard levels. To keep environmental impacts to a minimum, the preliminary choice of the mountain reservoir site is also essential : siting principles are described in *Mountain Reservoirs*. It must be based on an in-depth comparative analysis of the different potential sites, taking all potential impacts into account, whether on land or aquatic environments, landscape or occupied by humans. Lastly, it is important that potential project owners consult and involve the various stakeholders, mountain professionals, qualified design firms and public authorities, right from the preliminary study phase and in the choice of site.

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NOTES

1. Following the experiment in Courchevel to which it significantly contributed, the findings of the Chambery unit of the Public Works administration were supervised, from 1964, by the Interministerial Commission for Mountain Tourism Development (CIATM) and became its technical department.This unit was then institutionnalised by the creation, in 1971 of the Mountain Tourism Design and Development department (SEATM, tody the DEATM, which is a division under the Atout France economic interest grouping)

2. See the SNTF campaign:http://www.lamontagneenmouvement.com/

RÉSUMÉS

Les retenues d'altitude sont des ouvrages hydrauliques implantés dans les stations de loisirs de montagne et destinés à créer une réserve d'eau, dédiée principalement à la production de neige de culture. Leur implantation en altitude en fait indubitablement des retenues spécifiques, subissant et induisant des risques et des impacts sur leur environnement anthropique et écologique. Le Cemagref a engagé un projet de recherche sur la sûreté des retenues d'altitude. Le présent article est issu de ces travaux et vise à établir un état des lieux des risques liés aux retenues d'altitude et de leurs impacts sur l'environnement. Il replace le développement des retenues d'altitude dans leurs contextes sociétal, social et environnemental. Il développe ensuite les risques et impacts des retenues d'altitude, en focalisant son analyse sur les différents risques et aléas spécifiques auxquels sont exposés les ouvrages, et sur les différents impacts environnementaux liés à la réalisation et la gestion des retenues.

Mountain reservoirs are hydraulic structures established in recreational mountain resorts designed to provide a water reserve mainly used for the production of artificial snow. Their siting in high-altitude zones makes them highly specific reservoirs subjected to and inducing risks and impacts on their human and ecological environment. Based on in-depth bibliographic and field research, Cemagref has launched a study on mountain reservoirs. The present article aims to establish the current state of the risks related to mountain reservoirs and their impacts on the environment, placing the development of mountain reservoirs in their societal, social, and environmental contexts. It will then develop mountain reservoir risks and impacts, focusing on the specific risks and uncertainties to which these structures are exposed, and the different environmental impacts related to the construction and management of these reservoirs.

INDEX

Keywords : artificial snow, environmental risks and impacts, ski resorts
Mots-clés : impacts environnementaux, neige de culture, retenues d'altitude, risques, stations de sport d'hiver

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