The production of artificial snow - ecological, social and economical aspects

Julia Snajdr

B.Sc. International Forest Ecosystem Management, HNEE Eberswalde

Master Student Mountain Forestry, University of Life Sciences and Natural Resources Vienna

Traineeship as a junior producer (motion picture), FECHNER Media in Baden Württemberg

Contact: Julia@snajdr.de, http://www.juliasnajdr.de/

Structure

1. Introduction

In the Alps, the temperature raises nearly three times faster compared to average global warming. Since 1985 the amount of drinking water drained from the Alps has declined by a quarter (DIE WOCHENZEITUNG (2011)).

Since the mid-1980s, snowfall has been decreasing considerably in the northern hemisphere, particularly in mountain regions. Some regions in the Alps have been losing four meters of average snow depth over the past 30 years. Frequently temporal and spatial snow cover on ski runs decreased to such an extent that continuous skiing during the winter season was no longer possible. Many ski resorts at low altitude in the European Alps are expected to have very little snow left within the next 1-2 decades (De Jong, C. (2009) (2)).
According to Prof. Dr. Wolfgang Seiler of the Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), the mean winter temperature is going to rise by 4 to 5°C, leading to an elevation of the zero degree line by 150 meters per +1°celsius (Doering, A. et al 1996).This line has risen by 300 meters due to an increasing temperature of 2°C during the last 50years (Canadarges (2010)).

In the next 25 to 50 years the orographic snow line of ski areas with guaranteed snow is going to rise to 1 200 – 1 500 meters above sea level (Rixen et al 2002). With a temperature increase of 1.3 to 6°C until the end of the century, the lower boundary for the production of artificial snow could rise by 250m to 1 000m a.s.l. (De Jong, C. 2010).

The first snow cannons were erected in the Austrian Alps already in the beginning of the 70ies, followed by Switzerland in 1976 and Germany in 1987 (Doering, A. et al 1996).The number of constructions producing artificial snow as well as the use of chemical substances has increased constantly, although the artificial snow production had severe ecological effects (Doering, A. et al 1996). The demand of the preparation of snow at any time is pushed by the commercialization of skiing and large scale events as the Ski World Cup. The time of producing artificial snow is often not adapted to climate- and weather conditions but rather to the demands of sport goods industry, tourism and television (Rixen, Ch. et al 2002).

2. *Impact on flora and soil*

The production of artificial snow impacts the vegetation period, regeneration, forest stands stability and contributes to species change and – freeze.

The vegetation period is altered by the insertion of artificial snow, remaining two to three weeks longer on the slopes as the natural snow cover. Accordingly, plant growth is delayed and species, typically found in regions of late deglaciation, augment at slopes of artificial snow (Schneetälchenarten). In general, species diversity and productivity is minimized compared to undisturbed areas (Rixen et al 2002). Pröbstl (2006) concludes that there is a modification in species and a permanent change in the plant communities. Thus above 1 200 meters the vegetation period is reduced to such an extent that regeneration is often not possible and soils and slopes degenerate from year to year. Commonly, the most important threshold is the forest boundary. Alpine meadows above this boundary mostly do not have the time and capacity to regenerate. They experience climatic and environmental conditions comparable to the Arctic. As for the Arctic, these mountain zones take hundreds of years to recover from landscape modification such as pipelines and reservoirs. High altitude forest will also take decades to regenerate (De Jong, C. (2009) (2)).

Soil temperature under the artificial and natural snow cover is differing. It ranges from 0°C under artificial snow cover and undisturbed snow cover and -10°C under the compressed natural snow cover. Species adapted to high alpine peaks with little snow cover ("Windheidearten") have increased significantly at slopes of natural snow (Rixen, Ch. et al 2002).

Under the dense artificial snow layer, particularly during ice formation, the oxygen content decreases followed by decomposition and an infestation by black snow mold (*Herpotrichia juniper*). In addition, plants get more prone to frost. As a consequence they freeze to death at temperatures which they are usually not harmed by (Doering, A. et al (1996)). Furthermore, vegetation is havocked by the freezing temperatures in the immediate vicinity of artificial snow canons (De Jong, C. (2009) (2)).Regeneration of trees at the forest edges is harmed by the salting used to defrost forest roads for the transportation of artificial snow. The harming effect is aggravated by the complete extraction of remaining snow and the passing over the slopes during the process of melting (Doering, A. et al 1996). Especially the stability of the bordering trees of the remaining stand is minimized by defects in the rooting zones by construction works. Forest aisles providing space for lifts make stands more susceptible to wind breaks and other atmospheric conditions.

During the production of the artificial snow wind-blown dispersal leads to its accumulation in adjacent stands, resulting in snow breakage and the enrichment of nutrients which are distributed in the forest during snow melt.

The production of artificial snow contributes to erosion effects and impacts grassland and wetlands. The melting water of artificial snow contains four times more minerals and nutrients than the melting water of natural snow. Consequently generalist species utilizing the provision with more nutrients increase beneath slopes with artificial snow (Rixen, Ch. et al 2002)). These less adapted and unstable species lead to an increase in erosion and consequently to a cutback of species diversity (Doering, A. et al (1996)).

Various consequences of artificial snow fabrication on soil conditions have been determined. The production of artificial snow comprises the hauling of electricity-, clime- and water tubes in ditches. The massive territorial impacts cause the disruption or loss of vegetation, humus layer and soil activity. The regeneration of soil and vegetation in susceptible mountain ecosystems could take decades or even centuries. Leveled slopes are more suitable for the provision with artificial snow than natural terrain. But the leveling of slopes is a severe intervention in the soil structure, vegetation and land form. Both, large scale construction sites and leveling are rarely implemented with site specific plant communities and the success of laborious restoration often undetermined.

Through the production of artificial snow the total amount of melting water rises up to 200 l/m^2. Due to its higher density, the amount of melt water of artificial snow is two times higher than of natural snow. Consequently erosion is increased locally at sites of inappropriate vegetation and soil condition. The minimum standard resulting from scientific investigations is 80% crown cover of site specific vegetation and sufficient root penetration. These demands are not met at most slopes (Doering, A. et al (1996).Models show that these circumstances lead to an increased flooding probability of 30% and an enhancement of erosion (De Jong, C. (2010)). The greater hardness and density of artificial snow compared to natural snow also causes the top soil to become compressed and impermeable (Rixen, Ch., Haeberli, W., and Stoeckli, V. (2004) in De Jong, C. and Barth, T. (2007).

The increase of melting water intensifies the problematic of already existing slope water at lower elevations. Together with the delayed melting of artificial snow especially at shadowy sites it is a concern for agriculture. Especially species-rich meadows, dry- and neglected grassland, and wetlands are harmed severely at all altitudes (KAMMER & HEOG 1989, HOLAUS u. PARTL 1994 in Wechsler, H.G. (1989)).

3. *Impact on fauna*

During winter time, *Lyrurus tetrix* and *Tetrao urogallus* are need to conserve energy and are vulnerable to disturbances. The noise of snow making facilities as well as night-time illumination is severely threatening the preservation of these species. Regarding *Cervus elaphus*, the extreme fragmentation of the habitat is a challenge. The possibility of feeding is cut off just in the times of food shortage from mid November until the beginning of March. In the Western Italian Alps lower bird species richness was detected in coniferous forests due to noise and disturbance from ski runs (Laiolo and Rolando 2005 in De Jong, C. (2009)).

Water organisms are endangered by the excessive water extraction and the dehydration of shore edges or the whole river bed.

4. *Impacts concerning water*

a. *Effect on water pollution and -quality*

The chemical composition of the water used for the production of artificial snow is a danger as spring- and drinking water contains much more minerals than rain and snow, thus causing fertilizing effects (Doering, A. et al (1996)).
The water quality is changed to a higher mineral content (De Jong, C. 2009 (2)). The concentration of magnesium is 40 times higher in artificial snow and for calcium it is 10 times higher (De Jong, C. 2010). The mineral and ion concentration in artificial snow melt water is four times higher than in neighboring streams causing a local fertilizing effect (Rixen and Steockli 2000). This directly effects vegetation growth and species diversity by promoting more woody plants, shrubs and weeds (De Jong, C. (2009) (2)).
Furthermore, the water output from streams and rivers can benefit the spreading of pathogens and contaminants, in the long run possibly not only affecting soils and vegetation but also spring- and subterranean water (Doering, A. et al (1996)). The quality of melt water from artificial snow is not comparable to the drinking water standards initially used for its

production. Sanitary risks due to bacteria may be a consequence of the long period of stagnation in reservoirs and pipelines (AFFSET (2008)).

Additional substances are admixed to the water to maintain artificial snow at temperatures above 0C°. Skin diseases and pneumonia are consequences for staff member responsible for the snow cannons (DIE WOCHENZEITUNG (2011)).
In some regions of the Alps the US bacteria Pseudomonas syringae is introduced into the water to be able to produce artificial snow at higher temperatures. The bacteria are inactivated through radioactive radiation and then utilized as crystallization germs to safe energy (ROCHLITZ 1989 in Doering, A. et al (1996)). The use of these bacteria is still prohibited in Germany but they are generally hard to detect. The outer membrane of *Pseudomonas syringae* contains lipopolysaccharides, which correspond to endotoxins. The high concentration of endotoxins (>90 unit of endotoxins per m^3) near snow canons can provoke hemodynamic and inflammatory diseases as well as fever, shortness of breath, coughing fits and dysfunctions of respiration organs (De Jong, C. (2010)).

Another factor lowering water quality is regarded concerning stream discharge. A discharge that is lower than the minimum defined discharge can menace the survival of flora and fauna as well as lowering the water quality (De Jong, C. (2009) (2)).
AFSSET (Agence Francaise de Securite Sanitaire de l`Environnement et du Travail) recommends to use water of good microbiological quality for the production of artificial snow to preserve the water quality, especially the water intended for human consumption (SePT/ACPT (2009)).

b. Reasons for a lack of data concerning water extraction

Analytical models and methods applied to evaluate development effects are often unsuitable for montane settings as they lack algorithms to treat snow pack accumulation and ablation. A range of hydrologic processes obscured through empirical approaches to rainfall and runoff relationships and are, due to a lack of a high-elevation monitoring network, largely unvalidated against observed conditions (Wemple, B. et al (2007)).

In the environments of high altitudes, liquid water is not omnipresent as it is mostly frozen or prevalent below the subsurface. Further difficulties are the representativeness of sites in remote locations and the effects of extreme weather events (De Jong, C. and Barth, T. (2007)). The measurement of classical hydrological components such as precipitation, discharge and evapotranspiration is rare and terrestrial photogrammetry or remote sensing are not purposefully applied (De Jong, C. & Barth, T. (2007)).

In the following, terrestrial and aerial photography, remote sensing, satellite images, and radar methods are examined.
The ablation of the prolonged snow cover from ski runs with artificial snow can be measured by terrestrial photography. The reservoirs are increasingly built at high altitudes where surface and runoff water is naturally limited (De Jong, C. and Barth, T. (2007)). Terrestrial photography together with accurate Digital Elevation Models (DEMs) can be applied to monitor daily snow cover and evaluate snow water equivalent from ski runs at low installation costs.

Unless too outdated, aerial photography and Google Earth or IGN images provide a precise method for field orientation and establishment of status quo of ski resort development but are inadequate for continual monitoring or establishing a pre-development stage. Remote sensing has been applied to discover changes in glacier extents and snow cover and serves as a tool to overcome the remoteness of most sites but also to represent the vast variability of small-scale topography. However, as water phenomena occur on a sub-basin scale, suitable remote sensing techniques have to be adapted or developed. Additionally, airborne remote sensing from either small aircrafts or ultralight trikes should be applied regularly to collect relevant meteorological data. Air humidity can be used as an indicator of evaporation from artificial snow and detailed images could be obtained during the process.

Artificial snow is highly variable over time and altitude. This makes derivations form satellite images almost impossible if grid size resolutions around 15 m at high temporal resolution are not available. Yet the changeable weather conditions on montane areas pose a great challenge to the application of remote sensing.
A common difficulty is that inventories of humid zones were not conducted before water retention reservoirs for snow production were build and that the resolution of remote sensing images is not high enough which makes it difficult to reconstruct the situation nowadays (DIE WOCHENZEITUNG (2011)).

For example, one problem associated with snow water reservoirs for artificial snow production is the lack of high resolution images showing the extent of wetlands or lakes that existed prior to their construction. These reservoirs are increasing rapidly in number. Radar inferometry should provide useful information for monitoring the filling levels of these reservoirs for hydrological monitoring and to establish the thickness of snow cover on the ski runs.

Radar methods should provide data about the filling levels of new reservoirs build to store water for the production of artificial snow (De Jong, C. and Barth, T. (2007)).

The intensification of snow monitoring through snow pillows or snow lysimeters is essential (De Jong C., Masure P., Barth T. (2008)).

A special semi-distributive module for the simulation of snowmelt was developed by Barth based on the degree-day method and classified according to 100 m iso-altitudinal bands. Its input parameters consist of temperature, precipitation, daily snow melt and contribution of artificial snow. The surfaces covered by artificial snow are subdivided into different altitudinal bands together with the amount of water necessary to produce the snow. The altitudinal bands with artificial snow are adapted to those with natural snow, so that the excess in water produced by snowmelt from artificial snow is added to the natural torrent regime (De Jong, C. and Barth, T. (2007)).

c. The period of water extraction and return to the water cycle

The water for artificial snow production is taken during the season where water resources are naturally at their lowest in the Alps. The water withdrawal coincides with a period when tens of thousands of tourists accumulate in few big skiing areas, consuming water for cooking, showering and bathing (DIE WOCHENZEITUNG (2011)).

The water is mainly extracted in seasons with extreme low water level with climatologic frost periods. The water abstraction is highest when artificial snow production reaches its maximum at degrees of -11°C (Wechsler, H.G. (1989) in Doering, A. et al (1996)). Besides

streams, rivers and springs even the drinking water supply is affected (Doering, A. et al 1996).
In general, the return of the water extracted for snowmaking to the water cycle is delayed by 8-10 months (De Jong C., Masure P., Barth T. 2008).

d. Quantity of water abstraction, water release and water loss to the athmosphere

In average, the snow cover of artificial snow is 70cm higher compared to the snow cover of natural snow and it contains double as much water (Rixen, Ch. et al (2002)).The more water the artificial snow contains the denser it is. It can be four times heavier than new snow or primed snow (Doering, A. et al (1996)).

- Water extraction -

The water consumption amounts to 200-600 l per square meter and season for “basic artificial snow cover” (Grundbeschneiung) and “additional snow making” (Nachbeschneiung) (Doering, A. et al (1996)).

In the test area of Bourg-Saint-Maurice in Savoy, France, approximately 200 000 m^3 water are consumed annually to cover 58ha of ski runs (De Jong, C. and Barth, T. (2007)).

One m^3 of water is sufficient to produce 2.2m^3 of artificial snow (OPINION (2012)). In the Austrian and Swiss Alps, between 20-40% of the total annual water consumption is taken for snow production, which correlates with more than 50% of the total drinking water consumption (Teich et al 2007; Vanham et al 2008 in De Jong, C., Masure P., Barth T. (2008)).
In some regions of the French Alps more than 50% of the available drinking water is directly used for snow production at a daily scale. The minimum low flow discharge can be reduced by up to 75% during the winter as a consequence of the abstraction of artificial snow (Strasser 2008; Campion 2002 in De Jong, C., Masure P., Barth T. (2008)).

Modern snow producing machines produce 96 m^3 artificial snow per hour with a water consumption of 638 l per minute (De Jong, C. (2010)).
Per year and hectare of artificial snow, 3 300 m^3 water are consumed (De Jong, C. (2010)).

For the production of two m³ of artificial snow, one m³ of water is needed (ODIT France, 2008a in SePT/ACPT (2009)).
In average, 3500m³ water per ha and year are necessary for the production of artificial snow for a skiing area (ODIT France, 2008b in SePT/ACPT (2009)).

Water is increasingly stored in new, high alpine artificial snow water reservoirs with dimensions resembling medium-size dam reservoirs (De Jong C., Masure P., Barth T. (2008)).

In the French Alps, more than one third of the resorts experience shortages in water supply for domestic uses because in 25% of resorts, snow production competes with human uses consumption (Bravard 2008 in De Jong, C. (2009).

The artificial production of snow is a problem for the local drinking water supply, qualitatively and quantitatively. In the whole Alps, the area covered by artificial snow increased from 24 000 ha in 2007 to 50 000 ha in 2011. The amount of water used for the manufacture more than doubled within three years. Half of the resources originate from water storing reservoirs, further from local streams, lakes, ground water and drinking water sources (DIE WOCHENZEITUNG (2011)).

Snow making requires quantities which are locally not available. Technological investment are often necessary to supply and establish large artificial water reservoirs with sizes up to 400 000 m³ (De Jong, C. (2009) (2)).

The quantity of water removal is determined, but can´t be controlled during winter time.

Only 5-10% of the water stored in reservoirs for the production of artificial snow comes directly from precipitation, the rest is provided by pumping up over hundreds of meters height difference and dozens of kilometers (OPINION (2012)).

- Water release -

Through the production of artificial snow the total amount of melting water rises to about 200 l per $m^{2.}$

Six torrents were compared regarding their natural and artificial snow melt-induced discharge**.** The difference was negligible for the month September to February; largest distinctions were modeled for July and August with the increase of nearly one third. Seasonal impacts of artificial snow extent far into the summer season and are of particular concern after May. For all scenarios, there is a 20-30% increase in discharge between the months of May to August and between 3-5 % decreases in discharge for the months of February to April due to the delay of the melting of artificial snow.

- Water loss –

Water agencies and water tax offices assume that between 30-50% of water can be lost by evaporation related to snow production including the retention in reservoirs, the process of actual snow production and the sublimation and evaporation from the snow surface (De Jong, C. 2007 in De Jong, C., Masure P., Barth T. (2008)).

High water losses through evaporation (on average 30%) are to be expected from snow-making. The main sources of water losses by evaporation are the artificial reservoirs storing water at high altitudes in liquid form throughout the year. This does not correspond to the natural hydrological situation, where, under highly permeable conditions, water is transported and stored mainly at the sub-surface and is frozen in winter, protecting it from evaporation. Another cause of evaporation is the snowmaking process itself (Arabas, S. et al 2008 in De Jong, C. (2009) (2)).

In order to form snow from water, it has to be cooled and condensed. This cooling requires evaporation. When conditions are windy and dry and manufactured snow is transported particularly high into the atmosphere, considerable amounts of water are lost through evaporation. A final source of water loss is by sublimation and direct evaporation from the snow surface during long periods of prolonged snow cover. As the snow melts, it is prevented from infiltrating into the highly compact snow column and stagnates at the surface. This makes it vulnerable to evaporation. The water lost by evaporation can easily leave the catchment and no longer be available for discharge and local use. Dirmeyer et al (2008) found that nations with mountainous terrain, a humid climate or at high altitudes are those that have the highest import and export ratio of atmospheric water vapour. Thus ski areas are particularly prone to atmospheric water exchange (De Jong, C. (2009) (2)).

In China, evaporation under the low relative humidity is high, thus the sublimation of snow (direct loss of snow by evaporation into the atmosphere) on the ski runs is high. Losses from artificial snow in the order of 50% can be expected under these arid conditions (De Jong, C. (2009) (2)).
Water and important nutrients are stored as artificial snow over many months and at the same time subjected to high evaporation losses and delayed snow melt (De Jong C., Masure P., Barth T. 2008)).

5. *Ski accidents related to artificial snow density*

With a density of 300-500 kg/m³, artificial snow is four times harder than natural snow (De Jong, C. 2010). In the papers on hand no information about ski accidents has been found.

6. *Financial aspects concerning artificial snow production*

The construction of a snow making systems with subterranean development cost one million Swiss Francs per kilometer (DIE WOCHENZEITUNG (2011)).

In France, 20% of the skiing pistes are covered by artificial snow and represent 5-10% of the flat rate (Montagnes Magazine (2009)).

The economic costs and benefits of snow making have to be evaluated. Investments may require between 15-20 years amortize, taking into account at least 100 days per year of snow-making with temperatures below -3°C.
The production of one m³ artificial snow costs 2.50Euros, including digging and leveling work, electricity for compressors and canons and compaction (Canardages (2010)).
In the season 2007/2008 the average costs of one m³ of artificial snow amounted to 0.83Euros, while the prize of the water is the least expensive factor regarding the whole production: 0.05Euros for water, 0.16Euros for servicing, maintenance and insurance cover, 0.11Euros for setting up and displacement of snow canons, 0.14Euros for personnel expenditures and 0.37Euroscovering electricity costs (SePT/ACPT (2009)).

The total production costs, comprising the amortization of the installations, would be in the order of 2-2.50 Euros per m³ of snow (Badré, Prime *et al.*, 2009 in SePT/ACPT (2009)).

The high costs of snow making constructions are used for the argumentation of producing artificial snow for whole ski areas. This contradicts the necessity of saving water and energy (quelle?). Snow-making initially aimed on the compensation for missing snow cover, but has evolved to a routine procedure of covering entire ski runs before the start of natural snow fall to ensure snow certainty during the entire season (December to April) (Bürki et al 2008 in De Jong, C. (2009)).

7. Outlook

The Alps are prone to receiving less snowfall and more rainfall as temperature increase due to global warming (De Jong, C. (2009) (2)).
Those valleys having balanced winter and summer tourism or four-season tourism from the beginning are today's winner of climate change (De Jong, C. (2009)).

The future of European ski resorts is strongly limited by global warming. Even with sophisticated technological advancements in snow-making, artificial snow will be principally limited by increasing temperatures within the next 10-30 years. Technical adaptation will also be limited by natural (water availability), economic (costs of energy and investments), social (decreasing demand and acceptance) and legal (regulatory) aspects, with negative feed backs concerning the environment. Intensification of this process is not sustainable. Thus artificial snow-making can only be considered as a medium-term solution (De Jong, C. (2009) (2)).

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