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Challenges of alpine catchment management under changing climatic and anthropogenic pressures

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Abstract: Water resources in mountain areas are particularly important with respect to new and increasing pressures in the headwater areas of catchments. Climate change has resulted in a decrease in precipitation and decrease in groundwater recharge in the western and southern Alps over the last few decades. This is coupled with changing anthropogenic pressures such as an increase in water abstraction for tourism and artificial snow in addition to the water demands of agriculture and hydroelectricity. Water consumption by tourism in winter is several times higher than that of the permanent population. To avoid the development of water shortages with relation to other users, a clear quantification of parameters within the water cycle is necessary. However, measurements of classical hydrological and biological components for model validation are often missing and terrestrial photogrammetry is not yet purposefully applied. An integrated hydrological model is applied to the ski resort of Les Arcs, Bourg-St-Maurice in Savoy, France, taking into account the impacts of artificial snow on torrent discharge under different climatological and anthropogenic scenarios with relation to interbasin water transfer. The classical arguments for the expansion of artificial snow are the necessity of winter tourism to maintain the local and regional economy but no empirical relation exists between snow production and ski frequentation. If the clear trend of increasing temperatures in the mountains continues, less and less reliable snowmaking days will be available and some regions may gradually turn into unprofitable zones depending on wind (e.g. foehn conditions), evaporation, aspect and altitude. New adaptation strategies for diversification of tourism in mountain areas, e.g. through a four seasons approach, have to be developed. Since mountain areas are highly fragile, powerful decision support systems are required to control hydrological modifications and prevent water conflicts. Scientists cooperating with stakeholders will be increasingly confronted with issues such as economical benefits versus environmental impacts. Even before the stage of developing decision support tools with the stakeholders concerned, important work is necessary to develop an interdisciplinary and intersectorial problem consciousness and acceptance. There is an urgent need for sub-scale catchment management plans that take into account local hydrological and economical requirements and conflicts that are linked to, but not overshadowed by large-scale catchment plans.

Keywords: Water management, artificial snow, tourism, hydrological modelling, economy.

1. INTRODUCTION

According to the most recent OECD report, approximately half the world's population will be living under water stress by 2030 if no appropriate measures will be undertaken [OECD, 2008]. Nevertheless, integrated watershed management plans based on modelling approaches do not exist for most regions of the Alps and specific mountain water laws still have to be developed. This is due to the assumption that unlimited water supply exists for all purposes, including household consumption, agriculture, hydroelectricity, industry, tourism and artificial snow production with enough remaining as minimal ecological discharge. However, often this is not the case, in particular at the sub-catchment scale, where water is naturally limited both due to seasonal runoff constraints and lack of well developed groundwater reservoirs as a function of altitude [de Jong 2007]. The rapidly changing cryosphere, with both glacier retreat and changes in seasonality of snow, has considerable effects on hydrology [Böhm et al 2007, de Jong et al in press, Koboltschnig et al 2007] and tourist attractiveness. According to the Alpine Space Operational Programme [2007] water availability has not been a problem in the past but the expected impacts of climate change may considerably change this favourable situation, especially in the southern Alps which may be effected by severe water scarcity in the future. Time series analyses over the past 100 years indicate increasing temperatures and decreasing precipitation in the southern Alps as well as up to 25% decrease of groundwater recharge in certain regions of Carinthia, Austria untouched by human development [Harum 2001]. However, in most catchments, representative climatological and hydrological measuring stations are missing and remote sensing techniques are not purposefully developed or applied [de Jong & Barth 2008]. In addition, there is a lack of modelling of the periodicity of flood and drought events in mountain catchments, primarily caused by a lack of data. Based on historical records, sedimentological and other evidence, their recurrence intervals can be estimated and should form the basis for modelling. This is essential to better predict the effects of future scenarios on the magnitude of such events.

Since water resources are not only influenced by climate change but more importantly by changing anthropogenic use, integrated water management is very important to avoid the development of conflicts that are already emerging locally in several regions of the Alps. Apart from assuming that water is ubiquitous, decision makers often compare water availability, demand and use in small sub-catchments to that of the whole basin, indicating that proportions are nearly insignificant and therefore negligible. By strongly understating the local significance of water resources, this classical argument is used as a pretext to continue unlimited water resources exploitation. However, territorial conflicts and water stress are increasingly developed at the local scale, where space and water is limited and are related to altitude. At high altitudes, water storage is poor (restricted to fractures) and the quantity of rain- or snowfall is limited by the limited surface areas of the basin. Therefore, in the context of integrated catchment management, it is important to change the common assumptions and mentalities of water consumers and managers in mountain catchments, in particular those that are highly frequented by tourists. A fundamental shift in focus is essential away from "whole" catchment concept with its diluting effects to the sub-catchment scale with its intensive local use. Misleadingly, the role of mountains as "water towers" both for mountains catchments and those further downstream is constantly emphasised. As a result, decision makers and managers, especially those involved in the snow making industry, assume that water can be exploited continually even when there is a lack of precipitation and surface water retention. Consequently, groundwater reservoirs are increasingly sapped with possible long term effects such as drying up of springs in areas with vulnerable geology. It is therefore crucial to build up consciousness on the long term spatial and temporal consequences of intensive water use in these highly dynamical and fragile zones. In addition, rapid flow of climate change information from scientists to water managers is critical for planning as is training in non-stationarity and uncertainty of hydroclimatological data [Milly et al 2008].

In this paper the hydrological and ecological effects of dam reservoirs will not be discussed.

2. ANTHROPOGENIC AND CLIMATIC PRESSURES

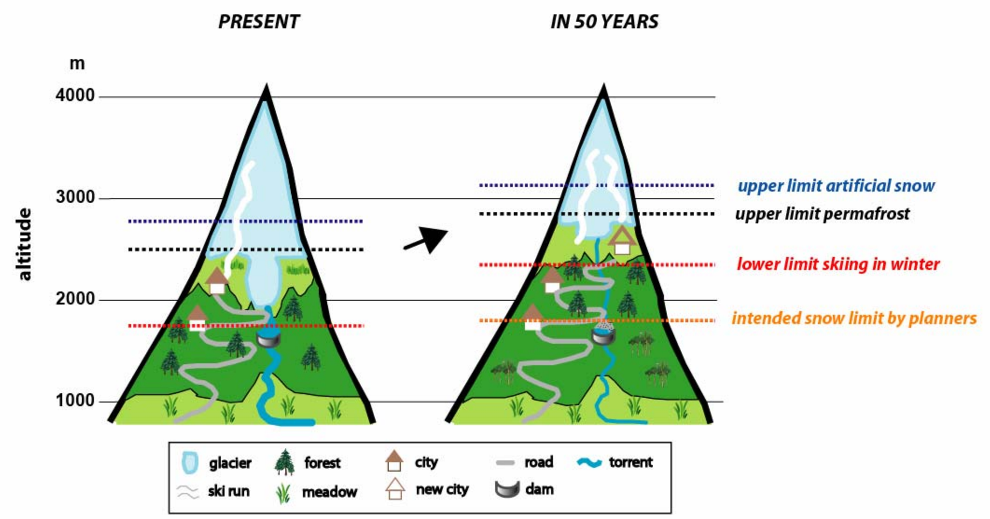

Figure 1 Model of increasing pressures on different mountain zones at present and in 50 years according to global change scenarios adapted to mountain regions. The image represents face of a typical alpine mountain during the winter season. With the recession of glaciers and snowfields, the average limit of the highest city, infrastructure and vegetation will increase; however, these will be constrained by altitude.

Figure 1 illustrates the increasing pressures exerted on different mountain zones at present and those projected in 50 years. It reflects the core assumption by planers associated with the economic development of tourism regions: that the present type of tourism offer, in particular skiing, is maintained. Since climate change and the associated reduction and increased uncertainty of snowfalls have become a reality, skiing is becoming more and more dependant on artificial snow production (Figure 2 & 3). As well as permanently increasing the upper limit of artificial snow production, planners also want to ensure the preservation of the present lower limit to avoid any disruptions. However, the maintenance of this lower limit will not be possible for two reasons. Firstly, under the current and future predicted effects of global warming, conditions will be too warm to manufacture or maintain artificial snow down to the lower limit.

Figure 2 Image of Les Menuires on 25th October 2007 several weeks before the onset of winter. Note the newly produced fields of artificial snow in preparation for the oncoming winter above the new tourist housing area. Intensive slope failure (grey areas) on bare ski runs is visible at the left of the photo.

Secondly, water resources will not suffice to satisfy both the needs of the increasing spatial and temporal extend of snow covered surfaces as well as the growing water demand by tourists. Snow production is being pushed to higher and higher limits, including over glaciers. Available water resources become more and more limited at these altitudes, restrained by the reduced catchment area and shorter discharge season. To compensate the lack of water, water is increasingly pumped over longer distances, either from the valley floors up the slopes to where it is re-distributed, or via inter-basin transfer. This has serious consequences on the hydrological cycle, in particular on flood discharge and the seasonal distribution of discharge (Section 4).

3. WATER CONSUMPTION AND TOURISM

Figure 3 a) Vine irrigation in the Upper Rhône, Valais, Switzerland (Photo: C. Dupont) and **b)** artificial snow production on ski runs in Savoy, France (Photo A. Marnezy), whose water consumption is approx. 3 x higher than irrigated maize or 4 x higher than vine.

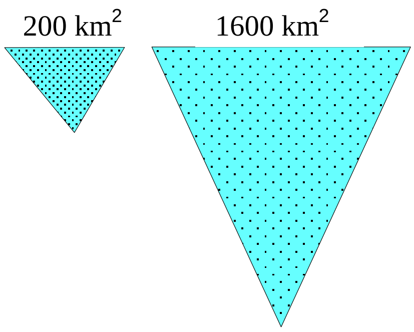

Figure 4 Catchment of 1600 km², Upper Rhône, with a relative winter discharge of 10 L/s/km² and tourist density of 190 beds/km². Its subcatchment of 200 km² has the same relative discharge but 300 tourist beds/km² Dot density indicates tourist density.

It is now estimated that there are more than 340 million tourist overnight stays in the Alps, of which approximately half are in summer [Keller & Förster 2007]. Some higher altitude ski tourist resorts count more than 50 000 overnight stays in winter. Therefore it is important to compare the hydrological pressure exerted by tourists at different scales. At the subcatchment scale, the actual amount of water consumed may not be high compared to that of the total catchment (Figure 4) however, the relative amount of water consumed by the number of tourists compared to the available resources is nearly double as high. This explains why water conflicts have started to arise at the local, subcatchment level.

Differences in water consumption are presented (Fig. 5) for Albertville, a holiday gateway town with a population of 18000, a typical non ski village, Les Chapelles with a population of 400 and two typical tourist resorts, Bourg St. Maurice and St. Martin de Belleville, with a permanent population of 6750 and 2532 respectively. Table 1 gives an indication of the maximum drinking water consumed per person during the month of December, with the highest tourist frequentation of the year. With a tourist population 5 times higher than its permanent population over a period of 2 weeks, the ski resort of Bourg St. Maurice consumes triple the amount of water for December. Note that the relative consumption of water of a ski tourist resort compared to a non-ski resort is

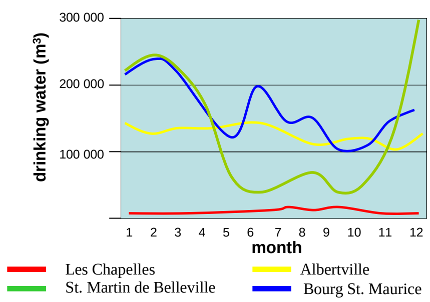

Figure 5 Seasonal water consumption for the city of Albertville compared to a non-ski resort (Les Chapelles) and two larger ski resorts (St. Martin de Belleville and Bourg St. Maurice) (modified after APTV 2007).

Table 1 Maximum drinking water consumption for the month of December

Town	permanent/ average tourist population	Max. drinking water in winter (m^3)	Ratio water (m^3)/ person
Albertville	18 000	140 000	7.8
Les Chapelles	400	2 000	5
Bourg St. Maurice	6750 20 000	160 000	23.7/ 8

1.5 times higher. In the region of Flaine, Haute Savoy, France, the increase in the number of overnight stays and the associated increase in water consumption does not allow sufficient residual flow in the Vernant torrent for artificial snow production [CIPRA, 2007]. Since stream discharge is to be reserved solely for potable water, groundwater reservoirs are being sampled for potential exploitation for snow production. Their potential may be limited due to their kartic nature. Apart from tourism, agriculture can also be water intensive, for example irrigation of vines on slopes (Figure 3) and maize in the valleys. In Savoy, French Alps, the reduction in precipitation over the last 6 years has seriously menaced the livelihood of cattle farmers both due to the direct shortage of drinking water for cattle as a result of drying up of springs and due to the reduction in good quality pasture as a basis for cheese production [Blandon per comm.].

4. HYDROLOGICAL AND ECONOMICAL MODELLING OF SNOWMAKING

4.1 Modelling the hydrological effects of snowmaking in Les Arcs

To manage the exponential expansion of artificial snow production on ski runs in the Alps and its effects on discharge of mountain torrents, a combination of hydro-ecological monitoring and modelling under different scenarios is a prerequisite. Water is increasingly stored in new, high alpine artificial snow-water reservoirs with dimensions resembling medium-sized dam reservoirs. This affects both local hydrology, biodiversity and pasture areas since wetlands and cattle grazing areas are very limited at these altitudes. Water and important nutrients are stored as artificial snow over many months, inevitably subject to high evaporation losses and delayed snowmelt. Such modifications not only affect the regional hydrology but also have direct impacts on drinking water availability. Thus it is essential that integrated catchment management is considered within a wider territorial context in the future.

The “Societé le Montagnes de l’Arc” (SMA or Association of the Mountains of the Arcs) was the first in the region of Savoy to initiate a scientific hydrological study at the University of Savoy on the possible impacts of the interbasin water transfer for artificial snow production in Les Arcs. The impacts of water transfer from the Arc 2000 basin to the Arcs 1800 basin was modelled for six torrents using a global, conceptual, rainfall runoff model, the GR (Genie Rural) developed by the CAMAGREF and adapted by Barth in 2007. This low parameter model is run at daily time steps and considers the catchment as a black-box consisting of a number of reservoirs, with one known input, precipitation and one known output, discharge. Module optimisation is difficult, since no discharge measurements are available for the different torrents. Therefore, parameters are optimised mathematically and return periods with similar discharge are classified according to return periods with similar precipitation. Daily and maximum discharge are then calculated for the different torrents. A special semi-distributive module for the simulation of melt from manmade snow was developed [Barth 2007] based on the degree-day method and classified according to 100 m iso-altitudinal bands. Its parameters include temperature, precipitation, daily snow melt and the contribution of artificial snow. Surfaces covered by artificial snow are subdivided into different altitudinal bands with relation to the amount of water necessary for snow production. Altitudinal bands with artificial snow are adjusted to those with natural snow, so that excess water produced by snowmelt from artificial snow is added to the natural torrent regime. The hydrological model is then calibrated with measured discharge data from the adjacent torrent Pissevieille (Arcs 2000), on the basis of the specially developed snow module and additional meteorological data.

The results show that the difference in natural and artificial snowmelt induced discharge are negligible for the autumn and winter months (Figure 6) but significant for the summer months, especially July and August [de Jong & Barth 2008]. The possible evolution of monthly discharge under different climatic and snow-making scenarios show that during the peak snowmelt months between April to June, discharge increases by 10-20% due to melt contribution from artificial snow. During mild winters the impact of artificial snow is strongest. In all scenarios, a 20-30% increase in discharge due to the anthropogenic influence of snowmaking is apparent between the months of May and August. In general, water abstracted for snowmaking in autumn may be delayed by 8-10 months before returning to the water cycle. Model accuracy should be increased through an improved knowledge of evaporation. In terms of validation and development of existing hydrological models, it is suggested that detailed, low altitude flight experiments are necessary for routine measurements of evaporation loss during artificial snow production. The first experiment of this kind has been carried out in the Austrian Alps [Arabas et al 2008]. In future, the ablation of prolonged snow cover from artificial snow runs should be monitored continually and regionally through radar technology and oblique photography, since remote sensing techniques lack a high enough spatial resolution [de Jong & Barth 2008]. Thus, modelling should be used to synthesise observations but can never replace them [Milly et al 2008].

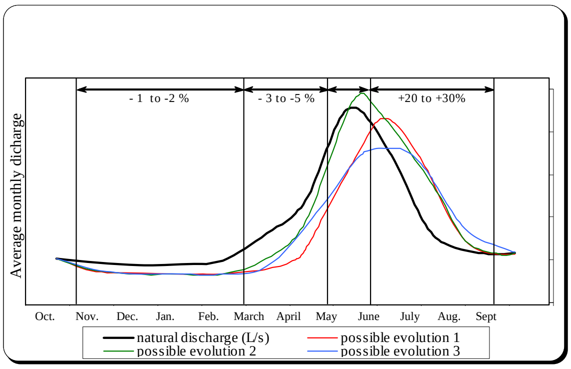

Figure 6 Possible monthly discharge evolution under the impact of artificial snow melt for torrents in Arcs 1600-1800.

4.2 Modelling the economical effects of snowmaking in Grisons

Studies in Grisons, Swiss Alps show that there is no empirical relation between the production of artificial snow and the daily number of skiers over the past 6 years [Teich et al 2007]. This result is important when related to the investment and running costs of snow infrastructure and the amount of water used to produce snow. The attractiveness of winter tourism e.g. in Davos seems more dependant on the general snow situation than on the presence or absence of artificial snow. Therefore in future, instead of seeking for relationships between tourist numbers and artificial snow, it would be important to investigate the relation between tourist numbers and the general snow situation, including natural and artificial snow. According to Teich [2007], snow production can prevent a reduction in winter tourists in poor winters but a classical cost-benefit analysis cannot be carried out since influencing parameters are difficult to parameterise, economical benefits are unequally distributed and it has not been considered whether this money could be better invested elsewhere. Prognoses from scenarios with an average global warming of 1°C for 2030 and 1.8 °C for 2050 for the valley stations in the regions of Davos and Scuol, Switzerland show a reduction in the number of potential snow making days by between 15 to 50 % for the months of November and December [Teich et al 2007]. Thus the reliability of snow making under the predicted future climatic conditions will no longer be feasible for mid-altitude stations (1500m) by the year 2050. Another economical risk is that it takes 15-20 years on average to amortize the costly artificial snow infrastructure, taking into account 100 snowmaking days, i.e. days with subzero temperatures, per season. In future, it may be important to regard climate change as a chance [Masure 2008] rather than a pessimistic scenario that makes strong demands on the maintenance of the cryosphere.

4.3 Relations between drinking water, snow making and minimal flow

The proportion of water used for artificial snow production is increasing at the annual, seasonal and daily scale. Thus, in the Austrian and Swiss Alps, between 20-40% of the total water annual water consumption goes into snow production, which is the equivalent of more than 50% of the total drinking water consumption [Teich et al 2007, Vanham et al 2008]. Furthermore, 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. Since the remaining water is used for drinking water it does not essentially cover minimal ecological discharge of local torrents. This underlines once more the small-scale hydrological and ecological facet of the problem. Up to 75% of the minimum low flow discharge can be reduced during the winter due to water abstraction for artificial snow [Strasser 2008, Campion 2002] which has extreme consequences for ecology and downstream water use. If these figures are relativised, the total amount of water consumed for snow production would only amount to 0.5% of the total national drinking water. The situation is particularly problematic when water retention reservoirs for snow production do not contain enough water towards the end of the winter season. Often they are directly refilled from streams or springs which results in their naturally low winter discharge being reduced below the ecological threshold. [Teich et al 2007]. From a hydrological point of view, water is abstracted from the streams when flows are lowest during the winter and released again when flows are naturally high, e.g. during the spring snowmelt. The perturbations to the water cycle can persist practically over the whole year. Water diverted during the autumn and immobilised as snow on the ski runs may not be released back into the water cycle and drink water intakes again until the following summer season [APTV 2007, de Jong & Barth 2008]. Although laws on minimal flow exist for nearly all alpine countries, it is not clear whether they are respected and how they are monitored and controlled. In addition, water agencies and water tax offices assume that between 30-50% of water can be lost by evaporation related to snow production including from retention reservoirs, during actual snow production and by sublimation and evaporation from the snow surface [de Jong 2007]. The seasonal reduction in discharge and evaporation losses can cause real water scarcity problems in certain alpine regions, e.g. downstream of certain ski resorts where nearly all natural discharge and humid zones have disappeared. A common difficulty is that inventories of humid zones often did not exist before water retention reservoirs were built for snow production and that the resolution of remote sensing images is not high enough, so that it is difficult nowadays to reconstruct or access the situation.

5. INTEGRATING QUALITATIVE DATA IN BASIN MANAGEMENT

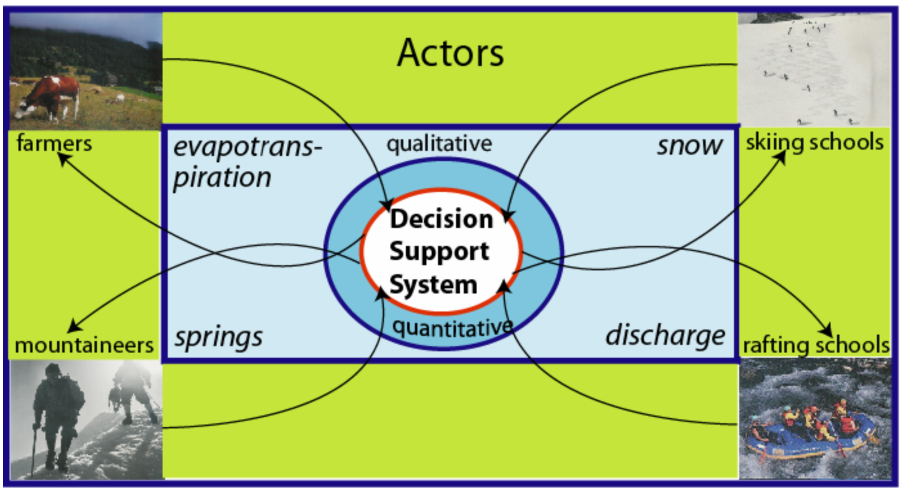

Figure 7 The potential of integration of qualitative data from stakeholders as well as traditional quantitative data for decision support systems.

If research is to be applied in decision support systems, it has to integrate stakeholder knowledge as well as both qualitative and quantitative knowledge (Figure 7). Stakeholder knowledge can be secured through participatory meetings with the local, long-term inhabitants of local mountain villages or towns as well as those organisations that are directly involved in seasonal water related issues, e.g. hydroelectric companies. Examples could include skiing schools (for snow conditions and the duration of snow), rafting schools (for river stage, discharge and flooding characteristics), farmers (related to evapotranspiration e,g for the drying of their hay) as well as information from long-term tourists, hikers and farmers on e.g. the drying up or emergence of new springs. Both "hard" (quantitative) and "soft" (qualitative) data gained from such observations should then be integrated into flexible integrative hydrological modelling frameworks. Such an approach would facilitate the development of decision support systems according to the "soft" needs of the stakeholders involved and not remain rigid with the software-focus of scientists alone.

6. CONCLUSIONS AND PERSPECTIVES

The way forward for integrated watershed management in alpine catchments is to intensify long-term observational networks in combination with short-term in situ measurements and integrate hydrological "soft" (or qualitative) stakeholder knowledge. Care should be taken to expand traditional hydrometeorological stations by adding automated evaporation pans and lysimeters to measure evapotranspiration and by carrying out more direct measurements on plant and forest physiology and their mechanisms of water exchange. With the expected climate change and resulting modification of the quantity and seasonality of snow, the intensification of snow monitoring through snow pillows or snow lysimeters is essential. In addition, the significant spatial and temporal re-distribution of water through anthropogenically induced activities such as snow production or temporary water consumption for tourism should be integrated in future hydrological management and research. Adaptation and mitigation strategies to these new environmental concerns need to be developed. Economical factors related to snow production and tourism have to be analysed and innovative alternatives considered such as diversification of tourism, e.g. through a four seasons approach. In mountain regions, there is an urgent need for sub-scale catchment management plans that take into account local hydrological and economical requirements and conflicts that are linked to, but not overshadowed by large-scale catchment plans. The challenge is to develop an interdisciplinary and intersectorial problem consciousness and acceptance.

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