Global warming in the Alps: vulnerability and climatic dependency of alpine springs in Regione Valle d'Aosta (Italy) and Canton Valais (Switzerland)

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Mountain springs of mid- to high altitudes are particularly sensitive to climatic variations, as documented by spatio-temporal discharge measurements. Recent models predict significant modifications of the hydrological regime for the Alps within the next 100 years. Anticipating global warming effects, Action 3 of Project STRADA –"Strategies for adaptation to climate change for the management of natural hazards in the border region – Operational Program under the European Territorial Cooperation border, Italy/Switzerland 2007/2013" (www.progettostrada.net) *aims at better understanding short- and long-term mountain spring behaviour related to hydrogeological settings. Based on the interaction mechanisms between surface and groundwater, the physico-chemical parameters of springs are correlated with climatic events and used to determine general aquifer behavior. Particular attention is given to the role of snow melting in discharge basins. The resulting characterisation of monitored springs provides an objective solution to adequately surveying alpine hydrogeological systems. Furthermore, the approach supports the efforts of authorities in developing efficient strategies for sustainable groundwater resources management.*

Les sources de montagne en moyenne et haute altitudes sont particulièrement vulnérables aux changements climatiques, comme l'indiquent les mesures spatio-temporelles de débit. Des modèles récents prévoient, pour les Alpes, des modifications significatives du régime hydrologique, pour les cent prochaines années. En prévision des effets liés au changement climatique global, l'Activité N° 3 du Projet " STRADA" – "Stratégies d'adaptation au changement climatique pour la gestion des risques naturels dans la région frontalière – Programme opérationnel de la Coopération Européenne Territoriale frontalière, Italie/Suisse 2007/2013" (www.progettostrada.net) *-, a comme objectif une meilleure compréhension, à court et moyen termes, du comportement des sources de montagne au sein des contextes hydrogéologiques. Basés sur les mécanismes d'interaction entre les eaux de surface et souterraines, les paramètres physico-chimiques des sources sont corrélés avec les événements climatiques et utilisés pour déterminer le comportement général de l'aquifère. Le rôle de la fonte des neiges au niveau du bassin d'alimentation fait l'objet d'une attention particulière. Les résultats spécifiques propres au suivi des sources de montagne représentent une solution objective à l'étude appropriée des systèmes hydrogéologiques alpins. De plus, cette démarche soutient les efforts consentis par les autorités dans le cadre du développement de stratégies efficaces .pour la gestion durable des ressources en eau souterraine.*

Los manantiales de montaña de altitudes medias o altas son especialmente sensibles a las variaciones climáticas tal y como demuestran las medidas de descarga espacio-temporales. Modelos recientes predicen modificaciones significativas del régimen hidrológico en los próximos 100 años en los Alpes. Para anticiparse a los efectos del calentamientos global, la Acción 3 del proyecto STRADA "Estrategias para la adaptación al cambio climático de la gestión de los riesgos geológicos en las regiones de frontera. Programa operacional en la frontera de Cooperación Territorial de Europa entre Italia y Suiza 2007/2013" (www.progettostrada.net)*, tiene como objetivo, entender mejor el comportamiento a corto y largo plazo de los manantiales en sus entornos hidrogeológicos. En base a los mecanismos de interacción entre las aguas superficiales y subterráneas, se correlacionan los parámetros hidroquímicos con los eventos climáticos y se emplean para determinar el comportamiento general del acuífero. Se pone especial atención en el papel de la fusión de la nieve en las cuencas de descarga. La caracterización resultante de los manantiales monitorizados, proporciona una solución objetiva para el estudio adecuado de los sistemas hidrogeológicos alpinos. Además este enfoque apoya los esfuerzos de las autoridades en el desarrollo de estrategias eficaces para la gestión sostenible de los recursos de aguas subterráneas.*

The Alps are considered the "water castle of Europe" and influence surface and groundwater patterns in neighbouring countries. The complex tectonic evolution of the Alps and the resulting rock structural relationships control the storage and flow capabilities of groundwater resources. The understanding of hydrogeological systems, based on both geological interpretation and hydrogeological evidence, is therefore a prerequisite to optimising future exploitation strategies.

One major issue for the 21st century is the management of the water resources on both local and regional scales. This research focusses on the possibility to accurately determine the degree of vulnerability and resistance against climatic changes of mountain springs used for drinking water distribution.

In addition to the quantitative monitoring of springs' regime, the difficulty of protecting groundwater quality in the long term is highlighted. With increasing land use and development, human activities can represent a threat to rational and sound practice in sustainable water resource management that has to be properly evaluated.

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Figure 1: Map of the project area between Regione Valle d'Aosta, Italy, and Canton Valais, Switzerland. Five Swiss and eight Italian springs in various hydrogeological settings were investigated for the spatio-temporal analysis of spring behaviour in mountain areas. Monitored parameters are: discharge [l/s], temperature [°C], and electrical conductivity [µS/cm]. Detailed analysis in three catchment basins (one in Switzerland and two in Italy) has been conducted for studying the effect of snow cover on spring discharge.

Evidence of global warming

Models have been developed in recent years to predict global warming effects on water resources (see FOEN, 2012). Data are often incomplete and uncertainties affect most predictions. Nevertheless, direct observations permit us to confirm significant changes already. For example, glacial retreat is occurring nowadays in every major orogen, with the fastest rates observed in the Hindu Kush-Himalayan region (ICIMOD, 2011). In Switzerland, it is estimated that 60-80% of existing glaciers will be lost before the end of the 21st century (FOEN, 2012).

It is however uncertain how quickly such tendencies will impact on human activities in the near future. There is an evident need to address an analysis from an integrated point of view today and to base predictions on field observation data. In this context, monitoring of natural systems is particularly important in the development of adequate strategies and action plans. With robust indicators derived from direct evidence of water resources, the risk of making improper political decisions with respect to observed water use-conflicts is lowered.

Policy in Switzerland and Italy

In Switzerland, about 80% of all drinking water is supplied by groundwater. In Italy, this proportion is estimated to be 85%. Groundwater has accordingly to be considered a resource of public interest. In both countries, public authorities are by law responsible for ensuring adequate protection standards to maintain clean groundwater resources for future generations.

In Switzerland, the obligation to protect water from both a quantitative and qualitative perspective was introduced in the 1990s with federal policies for water protection (LEaux, 1991 & OEaux, 1998). To ensure resource protection, the compilation of water protection maps is a legal obligation to help regularise land-use practice according to different protection sectors, zones and areas. The cartographical delimitation of land organisation measures depends directly on the geological and morphological conditions. Although groundwater flow conditions are quite easily determined in relatively homogeneous settings (i.e. loose rock or low to medium fractured aquifers), it is more difficult to precisely determine groundwater behaviour in heterogeneous media such as highly fractured or karst aquifers. The increasing structural underground complexity is directly expressed by the size (e.g. land surface coverage) of protection sectors, zones and areas. Such considerations are particularly relevant for spring and catchment protection zones, as they result in severe land use regulation and private property restrictions.

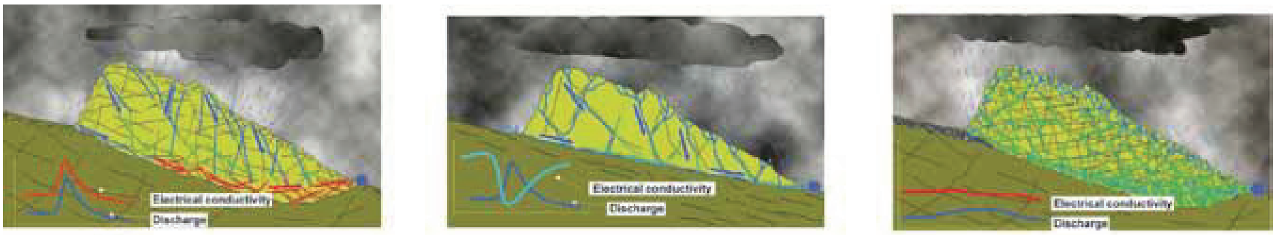
In Italy Regulation n° 152/2006 art. 94, integrated into Regulation n° 5/2012, describes the spring protection areas delimitation for groundwater intended for human consumption. The regulation distinguishes three different protection areas defined to preserve water quality. Spring protection areas are subdivided into three zones (Civita, 2008):

1. Immediate protection zone (ZTA) that includes the immediate area surrounding the spring or its drains. This zone must be adequately protected and must be used only for catchment works.
2. Inner protection zone (ZR) that includes a portion of the area surrounding the immediate protection zone. Activities forbidden in this area are described in the Italian law.
3. Outer protection zone (ZP) that overlaps the whole alimentation area of the spring.

In the Aosta Valley, Italian law is applied and regulated by rules L.r. 11/98 and Delibera del Consiglio Regionale n. 792/XI del 28/07/1999. The boundary of the protection areas is carried out following the Civita method, according to the final degree of vulnerability evaluated for the springs (Civita, 2005).

In both countries, policies for groundwater protection and management have the potential to introduce conflict between land use practice and water protection needs in the alimentation basins of springs. Typically observed conflicts in Canton Valais and Regione Valle d'Aosta concern mountain agriculture, remote inhabited zones, infrastructure of hydroelectric production plants, and the development of ski resorts.

The development of adaptative ground-



Reactive (piston effect) **Very reactive (replacement)** **Unreactive (homogenization)**

Figure 2: Generic models of aquifer behaviour, illustrating groundwater and spring reactivity to climatic events (adapted from Galleani et al. *2011).* ***A) Reactive:*** *spring discharge is a direct function of the climatic event, with a positive correlation between discharge and electrical conductivity (piston effect, e.g. medium risk of water pollution).* ***B) Very reactive:*** *Immediate spring reaction to the climatic event, producing an inverse relationship between discharge and electrical conductivity (replacement, e.g. high risk of water pollution).* ***C) Unreactive:*** *The spring discharge remains relatively insensitive to climatic events and the physico-chemical groundwater signature remains unaffected (homogenisation, e.g. low risk of water pollution).*

water protection strategies to climatic change and increasing land-use practices requires therefore an integrated understanding of hydrogeological systems and sustainable regulation possibilities on the administrative/political level.

Research and monitoring network

Project STRADA (*www.progettostrada.net*) is a research program consisting of six actions addressing the impact of climate change on territory planning and management. Action 3 focuses on mountain springs, based on EU-directive 2000/60/CE. It is conducted in partnership between the Regione Valle d'Aosta of Italy and Canton Valais in Switzerland, and it is subdivided into the two following sub-actions:

1. ACTION 3.1: Characterisation and temporal evolution of the snow cover in mountain areas in relation to its potential contribution to spring discharge (e.g. Snow Water Equivalent, Jonas et al. 2009).
2. ACTION 3.2: Characterisation of mountain springs in different hydrogeological settings based on physico-chemical observations and evidence from meteorological data stations.

Figure 1 shows the monitoring network that has been implemented in this regard since 2010 in the transborder territory between Italy (Regione Valle d'Aosta) and Switzerland (Canton Valais).

Direct and indirect acquisition methods for the meteorological, hydrogeological, geological and morphological observations

	PARAMETERS	ACQUISITION METHOD	DATA INTERPRETATION
HYDROGEOLOGICAL DATA (SPRINGS)	Discharge [l/s]	Automatic measurements (3 parameters-probes) with data transmission	Vulnerability methods (i.e. VESPA index, Galleani et al., 2011) & Cross correlation analysis (Fiorillo and Doglioni, 2010 ; Kresic and Stevanovic, 2010)
	Temperature [°C]		
	Electrical conductivity [µS/cm]		
	Bacteriology	Ponctual groundwater analysis (Laboratory)	
METEOROLOGICAL DATA	Snow	Automatic weather station with data transmission (STRADA)	SWE model (Jonas et al. 2009)
		Ground penetrating radar GPR in catchment basin	
		Ponctual manual measurements (avalanche probe)	
		Field measurements of snow and density	
	Relative humidity of air	Automatic weather station with data transmission (STRADA) + Swiss & Italian meteorological database	GEOtop model (ARPA, Valle d'Aosta)
	Solar radiation		
	Wind direction and speed		
	Rain		
	Air temperature		
GEOLOGICAL DATA	Lithology	Geological Atlas & Bibliography + Field observations + Geological investigations (geophysics)	Conceptual modelling
	Tectonics & Structures		
MORPHOLOGICAL DATA	Altitude	Swiss & Italian land-survey imagery	Geomorphometric analysis from DTM with GIS
	Slope		
	Drainage network		
	Concavity / convexity		
	Rugosity		
	Exposure		

Table 1: Direct and indirect acquisition methods used to conduct Actions 3.1 and 3.2 of Project STRADA. A compilation of hydrogeological, meteorological, geological and morphological data is performed to improve the understanding of mountain springs with regard to climatic changes.

SPRINGS		GEOLOGICAL SETTING	AQUIFER TYPE	REGIME	OBSERVATION PERIOD
CANTON VALAIS, SWITZERLAND	LA LÉ 1550 m.a.s.l.	Morenic + alluvial deposits	Porous / Heterogeneous	Snow melt	2008 - 2013
	LE BROCARD 620 m.a.s.l.	Bedrock : gneiss	Fissured	Snow melt	1981 - 2013
	LA VOUETTE 730 m.a.s.l.	Sandstone (Permo-Carbonifer)	Fissured	Snow melt	2010 - 2013
	LE PIERRIER DE VISSE 1605 m.a.s.l.	Limestone + Scree	Karst	Snow melt - Rainfall	2010 - 2013
	BRUNNENSTUBE 1 1460 m.a.s.l.	Bedrock : granite Quaternary deposit: morenic	Fissured / Porous	Snow melt - Rainfall	2011 - 2013
VALLE D'AOSTA, ITALY	ALPE PERROT 1280 m.a.s.l.	Bedrock: serpentinites – metabasalts Quaternary deposit: morenic - slope material	Porous	Snow melt - Rainfall	2010 – 2012
	CHESEROD BASSA 1100 m.a.s.l.	Bedrock: Calc-schist Quaternary deposit: morenic	Porous	Snow melt	2010 – 2012
	ENTREBIN 1000 m.a.s.l.	Bedrock: Calc-schist Quaternary deposit: morenic	Porous	Snow melt	2010 – 2012
	MASCOGNAZ1 1850 m.a.s.l.	Bedrock: metabasalts Quaternary deposit: morenic	Porous	Snow melt - Rainfall	2010 – 2012
	MASCOGNAZ2 1860 m.a.s.l.	Bedrock: metabasalts Quaternary deposit: morenic	Porous	Snow melt - Rainfall	2010 – 2012
	PIANET 1270 m.a.s.l.	Bedrock: Calc-schist – gneiss minuti	Porous	Snow melt - Rainfall	2010 – 2012
	PROMIOD 1650 m.a.s.l.	Bedrock: metabasalts Quaternary deposit: morenic	Porous	Snow melt - Rainfall	2010 – 2012
	VALMERIANA2 1700 m.a.s.l.	Bedrock: serpentinites – metabasalts Quaternary deposit: morenic - slope material	Porous	Snow melt - Rainfall	2010 – 2012

Table 2: Mountain springs studied within the framework of Action 3.2 of Project STRADA. See **Figure 1** *for geographical locations.*

have been implemented, as illustrated in ***Table 1***.

Based on the hydrogeological data, a physico-chemical characterisation of springs has been performed according to different approaches reflecting the Swiss and Italian experiences, strategies and policies. Spring vulnerability is accordingly estimated based on either a quantitative- or a qualitative-oriented perspective.

For quantitative aspects, the discharge reactivity of springs to climatic events in alimentation basins is considered. Generally, effects of particular climatic events are evaluated directly from hydrogrammes. For the Italian springs, a cross-correlation function has moreover been implemented to determine a time lag (in days) between rainfall (or snow melting) peaks and their effect on spring discharge (Fiorillo and Doglioni, 2010; Kresic and Stevanovic, 2010).

For qualitative aspects, the risk of spring water pollution is estimated either directly (field evidence and sample analysis) or indirectly, assuming three generic models of aquifer behaviors depicted in ***Figure 2***. An index for vulnerability (to pollution) can consequently be proposed following the VESPA method of Galleani *et al.* (2011).

Spring characterisation

Table 2 summarises the different Swiss and Italian mountain springs monitored during Action 3.2 of Project STRADA. For each spring, general indications about geology, aquifer structure and overall regime are given. Data acquisition is restricted to the duration of the project (2010-2013). When available, older chronicles have been taken into account and used for interpretation.

Springs in ***Table 2*** have been characterised in terms of their vulnerability, with a particular focus on the quantitative and qualitative perspectives described in the previous section. Results are presented in ***Table 3***.

Table 3 demonstrates that the quantitative and qualitative characterisation perspectives can be very consistent with each other. However, a lack of consistency is observed for several springs. This is particularly true for sensitive aquifers (heterogeneous or karst aquifers), probably due to the fact that the determination of the "quantitative vulnerability" is derived mostly from a relatively short observation period (≤ 3 years). Spring behaviour is accordingly either under- or over-estimated.

At this stage of the research, it has been shown that each characterisation method provides important information that is in some way complementary. From only monitoring of springs, however, the possibility to derive robust predictive models for the optimisation of spring protection and use is still incomplete and needs further development.

Comparison with climatic data

Between 2010 and 2013, a set of high-quality data was collected in the framework of Action 3.2 of the STRADA project and is currently used for:

1. developing monitoring techniques and strategies for mountain springs that are representative of various hydrogeological environments in order to achieve a better understanding of aquifers currently or potentially used for domestic needs.
2. adopting common and standardised criteria for the characterisation, survey and protection of groundwater resources in mountainous areas with regard to the structural and morphological complexity of mountain environments.
3. determining specific indices of vulnerability and resistance against climatic changes for springs that rely on an integrated cross-correlation analysis of parameters indicative of the spring hydrological regime and its mid- to long-term evolution.

Action 3.1 of Project STRADA allowed us to focus specifically on the mechanisms which regulate snow-water interaction. To derive short- and long-term management strategies for springs, it is now necessary to evaluate how the hydrogeological interpretation can be improved through a

	SPRING	AQUIFER BEHAVIOUR	VULNERABILITY OF SPRINGS: DISCHARGE REACTIVITY TO CLIMATIC EVENTS	VULNERABILITY OF SPRINGS: RISK OF SPRINGWATER CONTAMINATION	
			Estimated from field observations	Estimated from field observations and sample analysis	VESPA (vulnerability index V)
CANTON VALAIS (CH)	La Lé	Replacement and homogenisation	🟨	🟨	🟧 5.470
	Dilogne	Replacement	🟥	🟥	🟧 1.780
	Baltschieder	Replacement	🟨	🟨	🟧 5.140
	Brocard	Homogenisation	🟩	🟩	🟩 0.016
	Vouette	Homogenisation and replacement	🟩	🟩	🟩 0.002
			Cross correlation analysis Rainfall - Discharge (time lag in days)	Estimated from field observations	VESPA (vulnerability index V)
VALLE D'AOSTA (I)	Alpe Perrot	Homogenisation	🟥 0	🟨	🟩 0.032
	Cheserod bassa	Piston effect - homogenisation	🟩 >100	🟨	🟩 0.009
	Entrebin	Replacement	🟨 28	🟨	🟧 3.030
	Mascognaz1	Replacement	🟥 0	🟨	🟧 1.650
	Mascognaz2	Undefined	🟥 0	🟨	-
	Pianet	Replacement	🟥 1	🟨	🟥 12.060
	Promiod	Piston effect	🟧 5	🟨	🟧 1.390
	Valmeriana2	Replacement	🟥 0	🟨	🟨 0.260

DISCHARGE REACTIVITY TO CLIMATIC EVENTS		RISK OF SPRINGWATER CONTAMINATION			
		Field observations		VESPA (vulnerability index V)	
🟥 Very high	T < 1	🟥 Very high	Karst	🟥 Very high	V > 10
🟧 High	1 < T ≤ 10	🟧 High	Very heterogeneous fissure aquifers	🟧 High	1 < V ≤ 10
🟨 Medium	10 < T ≤ 50	🟨 Medium	Low thickness of unsatured zone with medium permeability	🟨 Medium	0.1 < V ≤ 1
🟩 Low	T > 50	🟩 Low	Important thickness of unsatured zone with low permeability	🟩 Low	V ≤ 0.1

Table 3: Mountain spring characterisation results obtained during Action 3.2 of Project STRADA. Aquifer behaviour correspond to the models of **Figure 2**. *To optimise in practice effective spring protection measures, vulnerability is evaluated according to a quantitative (reaction to climatic events) or qualitative (contamination by meteoric water) perspective. The vulnerability (to pollution) index V is calculated following the VESPA method of Galleani* et al. *(2011).*

process-oriented integration of meteorological and geological/morphological data, as performed for the snow modelling. In this sense, the following approaches are considered:

1. Analysis of seasonal water inputs, such as the onset of the snow melting process in spring alimentation basins. For example, springs showing a maximum annual discharge rate directly related to the available volume of snowmelt can accordingly be characterised as "unresistant/very sensitive to climatic change".
2. Improved determination of springs' alimentation basin geometry based on combined hydrogeological and morphological constraints ("3D conceptual models"). Accordingly, relevant alimentation basins with a high contribution of meteoric water in both territories must be identified.
3. Integration of long-term observations on springs and climate evolution whenever available. As a matter of fact, those data allow us to draw inferences on the dimensions of mountain aquifer systems, which in turn provide better assessment of their future evolution.
4. Further research on the development of specific indexes for the sustainable use of groundwater resources (e.g. a spring drought resistance index).

Perspectives

Investigating the effects of global warming on spring behavior in mountainous areas requires the possibility to access hydrogeological, meteorological and geo(morpho)logical data. To do so, coordination between public services and research centers is a prerequisite, allowing the introduction of particular standards for the constitution of databases.

It is therefore of prime importance for authorities to support efforts in the development of modern information systems able to provide quick access to relevant and integrated information. In the framework of Action 3 of Project STRADA, a global management system for spring monitoring and vulnerability determination has already been proposed. It demonstrates that groundwater protection would clearly benefit from a risk reduction and a probabilistic approach, based on the temporal evolution of spring discharge measurements. To develop sustainable protection and management strategies for springs, the possibility to confront the hydrogeological evidence with different climatic scenarios and a predictive model of land use practice has to be considered.

Guidelines for good practice should accordingly implement not only scientific but also societal and political considerations. In particular it is recommended to focus on:

- modernization of existing policies to cover new requirements in terms of land-use practices, resource use, and ground property restrictions,
- education of third parties and development of controlling organs,
- coordination of authorities responsible for different water sectors for rational budgeting of water resource monitoring.

In terms of sustainable development, the three following axes should be addressed for groundwater resource management in mountain areas:

- *Water monitoring strategies*: observation must integrate springs, water tables, precipitation (rain/snow) and glaciers. To ensure spring protection in mountainous areas, a primary requirement is to secure catchment works.
- *Water use strategies*: before considering water shortage in function of climate change, optimisation of water distribution networks has to be considered (drinking water, irrigation, and hydro-electrical purposes). Technical improvements offer an interesting rationalisation of current practices to avoid water waste.
- *Strategies for protection against water*: ensuring access to an integrated hydrogeological database, as expected from Action 3 of Project STRADA, the adoption of measures for the mitigation of natural hazards in mountain areas can be greatly facilitated.

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