Alp-Water-Scarce

Monitoring and Modelling of Mountain Water Resources

A short Guideline based on the Results of Alp-Water-Scarce

ALP-WATER-SCARCE OCT. 2008 – OCT. 2011

Alpine SPACE
EUROPEAN TERRITORIAL COOPERATION
THIS PROJECT IS CO-FUNDED BY THE EUROPEAN REGIONAL DEVELOPMENT FUND
investing in your future

AUTHORS

Saulnier G-M[1], Castaings W[1], Hohenwallner D[1], Brancelj A[2], Bertoncelj I[2], Brenčič M[3], Brun A[4], Cadoux-Rivollet M[5], Cainelli O[6], Calvi C[7], De Bona A[8], Doering M[9], Defrancesco C[10], Dutto E[11], Freundl G[12], Harum T[13], Jamsek A[14], Klemenčič-Kosi S[14], Kopeinig C[12], Klug H[15], Komma J[16], Lachenal P[4], Lascours S[17], Leskosek T[2], Mezek T[2], Mignone N[11], Mori N[2], Mourembles C[17], Neuwirth J[18], Paccard P[17], Pascariello A[11], Pergher P[10], Poltnig W[13], Pusenjak M[14], Rampazzo R[8], Reszler C[13], Rikanovic R[3], Robinson C[9], Rollando A[19], Schlamberger J[13], Scussel R[8], Siligardi M[10], Suette G[20], Valentar V[14], Vercelli C[8], Wagner K[18], Zadravec D[14], Zalavari P[15], Zessar H[12]

1) University of Savoie, EDYTEM (FR)
2) National Institute of Biology, Department for Freshwater and Terrestrial Ecosystems Research (SI)
3) Geological Survey of Slovenia (SI)
4) Society of Alpine Economics of Upper Savoy (FR)
5) Environmental Consultant, Brison (FR)
6) University of Trento, Department of Civil and Environmental Engineering (IT)
7) Province of Alessandria (IT)
8) Regional Agency for Prevention and Protection of the Environment of Veneto, Department for the Safety of Territory (IT)
9) Swiss Federal Institute of Aquatic Science and Technology (CH)
10) Provincial Agency for Environmental Protection, Trento (IT)
11) UNCEM Piemont Delegation (IT)
12) Regional Government of Carinthia, Dept. 8 (Competence Center Environment, Water and Nature Protection) (AT)
13) Joanneum Research (AT)
14) Slovene Chamber of Agriculture and Forestry, Institute of Agriculture and Forestry Maribor (SI)
15) Paris Lodron University Salzburg, Centre for Geoinformatics (AT)
16) University of Technology, Vienna Institute of Hydraulic Engineering and Water Resources Management (AT)
17) Local Government of Savoy (FR)
18) Federal Institute of Agricultural Economics (AT)
19) Development Agency Gal Genovese (IT)
20) Government of the Province of Styria (AT)

LEGAL NOTICE

PUBLISHER: University of Savoie, 27 rue Marcoz, 73000 Chambéry, France

RESPONSIBILITY FOR CONTENT: Alp-Water-Scarce Consortium

CONTACT: Georges-Marie Saulnier (georges-marie.saulnier@univ-savoie.fr); Daniela Hohenwallner (alpwaterscarce@gmail.com)

CITATION: Saulnier G-M, Castaings W, Hohenwallner D, Brancelj A, Bertoncelj I, Brenčič M, Brun A, Cadoux-Rivollet M, Cainelli O, Calvi C, De Bona A, Doering M, Defrancesco C, Dutto E, Freundl G, Harum T, Jamsek A, Klemenčič-Kosi S, Komma J, Kopeinig C, Klug H, Lachenal P, Lascours S, Leskosek T, Mezek T, Mignone N, Mori N, Mourembles C, Neuwirth J, Paccard P, Pascariello A, Pergher P, Poltnig W, Pusenjak M, Rampazzo R, Reszler C, Rikanovic R, Robinson C, Rollando A, Schlamberger J, Scussel R, Siligardi M, Suette G, Valentar V, Vercelli C, Wagner K, Zadravec D, Zalavari P, Zessar H, (2011), Monitoring and Modelling of Mountain Water Resources – A short guideline based on the results of Alp-Water-Scarce, Alp-Water-Scarce (Interreg IV B, Alpine Space Programme, project 5-1-3-F), 1-34.

LAYOUT: Ingrid Imser, Austria

PHOTOS: D. Zupanz, Karawanken/Hochobir; Fotolia.com © eyeami

PRINTING: Poncet, Chambéry, France

Lead Partner:

Université de Savoie, France

Project Partners:

1 Societé d'Economie Alpestre Haute-Savoie (F)	**9** Provincia Autonoma di Trento – Dipartimento Urbanistica e Ambiente (IT)
2 Conseil Général de la Savoie (F)	**10** Uncem Delegazione Piemontese (IT)
3 Amt der Kärntner Landesregierung, Abteilung 8 (AT)	**11** Agenzia Regionale per la Prevenzione e Protezione dell'Ambiente (IT) del Veneto – Dipartimento Regionale per la Sicurezza del Territorio (IT)
4 Amt der Steiermärkischen Landesregierung; Fachabteilung 19A, Wasserwirtschaftliche Planung und Siedlungswasserwirtschaft (AT)	**12** Geološki Zavod Slovenije (SI)
5 Paris Lodron Universität Salzburg (PLUS), Zentrum für Geoinformatik (Z_GIS) (AT)	**13** Nacionalni Inštitut za Biologijo; Oddelek za raziskovanje sladkovodnih in kopenskih ekosistemov (SI)
6 Bundesanstalt für Agrarwirtschaft (AT)	**14** Kmetijsko gozdarska zbornica Slovenije; Kmetijsko gozdarski zavod Maribor (SI)
7 Agenzia di Sviluppo Gal Genovese (IT)	**15** Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz (CH)
8 Provincia di Alessandria (IT)	**16** Bundesamt für Umwelt BAFU; Eidg. Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK (CH)

TABLE OF CONTENTS

1 Introduction 7

2 Monitoring Alp-Water-Scarce Pilot Sites 8

2.1 Monitoring complex environments 8

2.1.1 Meteorological monitoring 9

2.1.2 Hydro-ecological monitoring 13

2.1.3 Anthropogenic monitoring 16

2.2 Recommendations 19

3 Modelling Alp-Water-Scarce Pilot Sites 20

3.1 Natural water system and anthropogenic impacts 20

3.1.1 Natural water systems 20

3.1.2 Anthropogenic water system. 23

3.1.3 Guideline for model choice 24

3.2 Hydrological models in Alp-Water-Scarce 26

3.3 Recommendations 29

4 Balanced monitoring and modelling strategies 31

4.1 Which effort for which benefit? 32

4.1.1 Increasing data availability 33

4.1.2 Increasing model complexity 34

4.1.3 A virtuous path 35

4.2 Integrated view to improve knowledge of Alpine regions 36

4.2.1 Uncertainty analysis 36

4.2.2 Sensitivity analysis 37

4.2.3 Data assimilation 37

4.2.4 Adaptive management in an uncertain future 38

5 Conclusion 40

6 Contacts 41

7 References 45

7.1 Alp-Water-Scarce references 45

7.2 Cited references 45

LIST OF FIGURES

FIGURE 1:	Maintenance of a cumulative precipitation gauge, Savoie (FR).	8
FIGURE 2:	Altimetric distribution of around 1000 daily raingauges vs. Alps hypsometry	9
FIGURE 3:	A mountain hydrometeorological environment, Isére (FR).	21
FIGURE 4:	Hydro-meteorological components overlaid on a photograph of the catchment.	22
FIGURE 5:	Rotaliana agricultural plain (IT).	23
FIGURE 6:	The hydroelectric dam of Pian Palù (IT).	23
FIGURE 7:	Predictive performance vs. Data availability and Model complexity.	32
FIGURE 8:	Increasing data availability only leads to limited benefits.	33
FIGURE 9:	Increasing model complexity only leads to greater uncertainties.	34
FIGURE 10:	Balanced data availability and model complexity leads to higher usefulness.	35
FIGURE 11:	Temporal evolution of the modelled cumulative mass balance.	36

LIST OF TABLES

TABLE 1:	Minimum, medium, and optimal meteorological data sets.	11
TABLE 2:	Summary table of meteorological monitoring in Alp-Water-Scarce Pilot Sites.	12
TABLE 3:	Minimum, medium, and optimal hydrological data sets.	15
TABLE 4:	Summary table of hydro-ecological monitoring in Alp-Water-Scarce.	16
TABLE 5:	Minimum, medium, and optimal anthropogenic impacts data sets.	18
TABLE 6:	Synthetic Alp-Water-Scarce models.	26

1 Introduction

Water scarcity management in mountainous regions requires both monitoring and modelling. The two processes provide useful tools to support decision making in both short and long terms for water scarcity risk mitigation. Over the past few years, there has been increasing agreement among the scientific and user communities that these two issues should no longer be addressed independently but instead considered together. This booklet is therefore divided into three parts. The first part considers monitoring issues that arise in quantifying the meteorological, hydro-ecological and anthropogenic components of the water cycle. The second part deals with numerical hydrological modelling issues. Finally, the third part explains how monitoring and modelling efforts should be combined together.

The following pages are technically orientated and are dedicated to stakeholders. The aim is to list the main questions that should be addressed when undertaking both the monitoring and the modelling of the water resources of an Alpine region for the purposes of sustainable water scarcity management. These questions are not fully answered in this booklet: however complementary references are provided in the text.

Summary tables of the studies performed during Alp-Water-Scarce at each Pilot Site are also provided. Further details can be found in the final reports of the Alp-Water-Scarce project available on the project website[1] or on the Alpine Space projects website[2]. Additionally some contacts details are given[3] where supplementary informations may be obtained.

1 http://www.alpwaterscarce.eu
2 http://www.alpine-space.eu
3 See the Contacts section

2 Monitoring Alp-Water-Scarce Pilot Sites

2.1 Monitoring complex environments

Monitoring the natural and anthropogenic water cycle is crucial to obtain reliable information on which to base appropriate water management actions. However, this task has proven to be particularly difficult in the regions studied by the Alp-Water-Scarce project. The Alps are characterized by significant spatial heterogeneity in terms of topography (elevations and slopes), geology (small to large mountainous aquifers with varying dynamics/storage capacities and sensitivity to climatic conditions), socio-economical concerns (various economic models sensitive to water availability and types of urban development), flora and fauna gradients, etc. In addition, its position at the heart of Europe means that the mountain chain is affected by a variety of weather patterns and pollution-carying air currents at the continental scale that impact the quantity and quality of water resources.
As a consequence, monitoring in such mountainous environments remains a difficult but necessary task.

Some technical constraints can also be noted:

- difficult physical access conditions to field sites
  → *danger to field researchers/technicians*
- climatic conditions vs. sensor resistance tolerance
  → *expensive equipment/maintenance*
- limited energy access or autonomy
  → *complex to build and to ensure continuity*
- topographic masks
  → *limited access to remote transmission*
- floods, avalanche, lightning, etc.
  → *sensors vulnerable to hazardous events*

Despite these practical difficulties, monitoring activites should focus on meteorological, hydrological and anthropogenic aspects and consider the quantity and quality of the resource.

FIGURE 1:
Maintenance of a cumulative precipitation gauge, Savoie, 2200m,
photo University of Savoie, EDYTEM (FR)

2.1.1 Meteorological monitoring

Most meteorological sensors are installed at Alpine sites at low to medium elevations: far fewer are at high elevations. Figure 2[1] compares the altimetric distribution of nearly 1000 available daily raingauges (1948-2005) and the hypsometry of the Alps. It can be clearly observed that the precipitation above 2000 meters is poorly sampled. Whilst these poorly sampled areas may be small compared to the total area of the Alpine region they are extremely important because they receive the majority of the solid precipitation (snowfall) that will later be released during the melting period. They therefore have a significant influence on hydrological regimes and consequently on water resource dynamics.

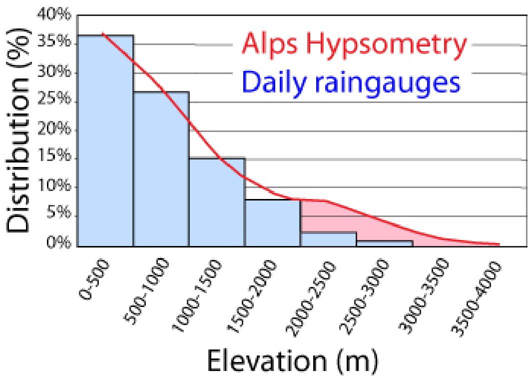

FIGURE 2: Altimetric distribution of around 1000 daily raingauges vs. Alps hypsometry

The Alpine regions are also characterized by a strong interaction between precipitation and temperature. Unlike other hydro-climatic circumstances that are primarily influenced by precipitation regimes, the water equivalent of snowpack is driven by a complex meteorological interaction between precipitation and temperature. This coupled process explains the temporal (inter-annual, inter-seasonal) and geographical (across several European countries during the same season) differences in the availability of solid and liquid water which contributes to the potentially large variations in levels of water resources available at the European scale.

Minimal meteorological data set:

However, temperature and precipitation are not easily correlated, particularly when considering climatic projections[2]. The two variables should be sampled and should be considered as the minimal meteorological data set (cf. table 1).

1 Adapted from Gottardi et al. (2008), see also Gottardi (2009) for full details.
2 See for example Alp-Water-Scarce “Climatic scenarios guideline“ technical report (Saulnier et al. 2011)

Meteorological sensors in mountainous regions:

Raingauges suitable for high-elevation regions are expensive. Self-heating raingauges are often required to avoid blockage of the container that could lead to loss of data or erroneous data. However, these sensors consume energy. If this system is not possible to use or is too expensive, at the least cumulative gauges can be installed (see Figure 1). As a minimal measure, these gauges provide information on the total amount of water (combining rainfall and snowfall) falling in the sampled region on a monthly or seasonal basis. A few new methods based on terrestrial photography are beginning to emerge (Farinotti et al. 2010) that maybe considered low-cost – but accurate – complementary approaches for measurement of both snow cover and snow depth.
Air temperature sensors should be properly sheltered from direct sunlight and wind. Otherwise, the bias in the recorded air temperature can amount to several degrees (see Jobard (2009)). However, recent field experiments (e.g. Lundquist and Lott (2008)) have made use of poorly sheltered inexpensive industrial temperature sensors. In these cases, it is hoped that the added information obtained by installing a large number of such sensors (significantly better spatial sampling) could compensate for a bias in temperature measurements at a few points.

Medium meteorological data set:

Monitoring solar radiation is also very valuable. Solar radiation data help to quantify snow melting/sublimation and evapotranspiration water volumes. However, analysis of these data requires more complex numerical tools. This variable could thus be considered as part of a medium meteorological data set (cf. Table 1).

Incoming solar energy:

The sun's trajectory is well-known and thus the maximum incoming energy can be accurately calculated. However, local meteorological conditions may dramatically decrease this theoretical incoming energy (clouds, fog, etc.). Regional solar radiation measurements provide reliable estimations of solar radiation at a given catchment point but local measurements may still be required if the local meteorological conditions are significantly different from the synoptic ones (frequently true in mountainous regions). If no solar radiation sensor can be installed within the catchment, a rough estimation of the local nebulosity can be obtained by the daily temperature indicator values (T_{max} – T_{min})(°C): clear sky conditions increase the value while high nebulosity conditions produce lower values.

Optimal meteorological data set:

Lastly, monitoring of wind (speed and direction) and relative air humidity could be considered as part of an optimal meteorological data set (cf. Table 1). These measurements allow the calculation of complex energy balances that permit more accurate calculation of the melting dynamic of the snowpack and the water demand of vegetation. Wind also impacts the spatial distribution and re-distribution of snowfall which may consequently affect the temporal and spatial dynamics of the water content of the snow cover. However, this may be considered of limited importance when studying water resources over large areas.

> *Snow cover measurement:*
>
> Accurate measurement of the spatial distribution of snow cover is a difficult task. A network of snow stakes can be installed or accurate satellite images can be used. An easier and cheaper method might be to install in-situ cameras capable of taking several pictures per day of the snow cover. Dedicated software can be used to establish the evolution of the snow cover at high spatial and temporal resolutions (see, for example, Farinotti et al. (2010)).

The following table summarizes the different variables that can be monitored to obtain a relevant sample of local meteorological forcing variables and precipitation inputs.

TABLE 1: Minimum, medium, and optimal meteorological data sets.

Minimum dataset	Medium dataset	Optimal dataset
- Precipitation	- Precipitation	- Precipitation
- Air temperature	- Air temperature	- Air temperature
	- Solar radiation	- Solar radiation
		- Wind speed and direction
		- Air relative humidity

Table 2 below lists the various meteorological monitoring undertaken by each partner as part of the Alp-Water-Scarce project. The minimum meteorological data set was available for each Alp-Water-Scarce Pilot Site. However, it is worth noting that the length of the available time-series differed significantly for each Pilot Site resulting in different degrees of statistical robustness.

Time-series lengths:

In mountainous regions, available time-series are generally shorter than what is usually scientifically required. Except for some regions with a particular data policy history (such as Alp-Water-Scarce partner Regional Government of Carinthia, Dpt. 8 (Competence Center Environment, Water and Nature Protection) (AT)in the region of Corinthia (AT), the difficulties and costs involved in monitoring mountainous areas generally result in short time-series for meteorological and hydrological data. Ten years of daily values may be seen as the minimum data set with which to investigate hydrometeorological inter-annual variability. Fifty years is usually considered to be the minimum time-series length for analysis of climate trends. Monitoring is definitely a crucial but long-term effort and is thus expensive, both in terms of financial outlay and human resources.

TABLE 2: Summary table of meteorological monitoring in Alp-Water-Scarce Pilot Sites.

(P=Precipitation, T=Temperature, R=Solar radiation, W=Wind (speed+direction), H=Air relative humidity) (NB: Adige (IT) and Fersina (IT) Pilot Sites were used only for experiments on thermo-peaking effects and are thus not listed in this table).

ID	Pilot Sites	Meteorological data		
		Minimal dataset	Medium dataset	Optimal dataset
1	Savoy (FR)	P, T	R	W, H
2	Arly River Basin (FR)	P, T	R	W, H
3	Koralpe (AT)	P, T	R	W, H
4	Karawanken/Karavanke (AT/SI)	P, T	R	W, H
5	Jauntal (AT)	P, T	R	W, H
6	Lower Gurktal (AT	P, T	R	W, H
7	Steirisches Becken (AT)	P, T	R	W, H
8	Steirisches Randgebirge – Wechsel (AT)	P, T	R	W, H
9	Entire Land Kärnten (AT)	P, T	R	W, H
10	Pohorje with Dravsko polje (SI)	P, T	R	W, H
11	Ptujsko polje (SI)	P, T	R	W, H
12	Scrivia River Basin (Alessandria IT)	P, T	R	W, H
13	Julian Alps (SI)	P, T	R	W, H
14	Piave River (IT)	P, T	R	W, H
16	Noce (IT)	P, T		
18	Entella River Basin (IT)	P, T	R	W, H
19	Scrivia River Basin (Genova IT)	P, T		
20	Sesia River Basin (IT)	P, T		H
21	Spöl River (CH)	P, T	R	
22	Sandey River (CH)	P, T	R	W, H

2.1.2 Hydro-ecological monitoring

Water scarcity is defined as a long-term imbalance between water availability and water demand. Water scarcity evaluation and mitigation must therefore quantify water input (meteorological forcing), water output (natural hydrological fluxes) and water demand (anthropogenic water withdrawals). Also required is the ability to quantify the amount of water unsuitable for human consumption or that would necessitate significant treatment costs (water quality).

One particular characteristic of mountainous regions should be highlighted: in addition to the measurement of classic natural or anthropogenic discharges, the various spring water sources and perched water tables must also be measured. The same technical difficulties previously listed for meteorological monitoring also apply here. Furthermore, there are a wide array of unconnected hydrological features that could provide valuable information if monitored, although these may be too local or isolated to justify costly investments in time and equipment.

Some simple recommendations are suggested below. They may provide a useful starting point in the design of a hydrological monitoring network. Further details can be found in the various published handbooks for hydrology, one of the most famous being Maidment 1993[3].

Minimal hydrological data set:

Gauged discharges, aquifer water levels, temperature and electrical conductivity of the main rivers and aquifers under water management could be considered the minimal hydrological data set for both quantitative and qualitative water monitoring (cf. Table 3). As a first step, only the discharges and aquifer water levels of the most sensitive water storage facilities within a water management system could be monitored to quantify water storage contents and dynamics. With regard to quality, water temperature provides information about the biological and biochemical activities of aquatic organisms, while electrical conductivity gives information about water mineralization.

Hydrometric measurements:

Measurement of discharges remains a difficult task. In many cases, only river height is continuously measured. A long period of time may thus be required to empirically establish a rating curve linking discharge values (measured periodically, usually using the velocity-area method when discharges are not too hazardous for humans and sensors) and river heights (measured continuously). This is standard practice for medium to large rivers. New techniques such as the Acoustic Doppler Current Profiler (although the range of discharges that can be measured is limited) and camera-based sensors are now available and may be viewed as complementary approaches. For small rivers or springs, dilution gauging (constant or variable rate) using various chemical tracers may be more suitable. In any case, one should not forget that river morphologies can change significantly over time, which may invalidate these empirical rating curves. As a result, regular sampling must be planned to record relevant discharge values. Until new techniques can be developed, discharge measurement remains a costly but crucial exercise.).

3 See also Shaw et al. 2009

Basic water quality measurements:

Water temperature influences the dissolution of oxygen which is higher when the temperature is lower. Oxygen is the basis of respiration of organisms: water temperature thus provides useful information about aquatic health. Temperature also affects the growth and reproduction of aquatic organisms. Depending on the organisms, different temperature ranges are required for these processes. Temperature thus also provides information about aquatic activities.
The electrical conductivity of water gives an indication of the concentration of ions in the water: conductivity values increase with higher ion concentrations. Therefore, water conductivity must be monitored to ensure a balance between under-mineralized water (low conductivity) and excessive ionic concentrations. Conductivity between 50 to 750 μS/cm indicates good water quality.

Medium hydrological data set:

Soil moisture monitoring generates information on water availability for plants[4] and on water fluxes in the upper soil layers. It may also help in refining the description of the water cycle of a surveyed region by better quantifying the distribution of water resources between various hydrological components (surface, subsurface, deep hydrological compartments, etc.). However, these data have a large spatial variability. Dense sampling should therefore be considered to ensure reliable quantitative measurements of soil moisture. In addition, reasonably complex numerical tools are required to analyze such measurements. Soil moisture monitoring may be thus considered part of a medium hydrological data set (cf. Table 3).
In terms of water quality, more detailed analyses of the distribution of ions dissolved in water can help to refine the assessment of water quality and facilitate identification of possible sources of pollution (agriculture, industry, households, etc.).

Soil moisture measurements:

Two soil moisture threshold values are usually defined between the fully saturated and completely dry soil moisture states: the field capacity and the wilting point. After a significant irrigation or rainfall event, the soils dries slowly to reach the field capacity after a few days. Most of the largest pores in the soil are then empty. The wilting point corresponds to the soil moisture value at which plants can no longer extract water. The moisture level between the field capacity and the wilting point is known as the available water for plants. Soil moisture measurements may thus be very useful for irrigation management purposes.
Continuous monitoring is generally based on di-electric constant methods. The principle is to measure the soil's capacity to transmit high-frequency electro-magnetic pulses. This can then be linked, after calibration, to the soil's moisture content. The most popular sensors used for this technique are TDR (Time Domain Reflectrometry) and FDR (Frequency Domain Reflectrometry) sensors.

4 E.g. for agricultural concerns as for partner Slovene Chamber of Agriculture and Forestry, Institute of Agriculture and Forestry Maribor (SI)

Optimal hydrological data set:

Monitoring secondary springs, rivers and aquifers should also be considered, as these give an indication of the sensitivity of future water availability to climatic changes. These secondary sources may also offer an alternative interconnected water supply in the case of a severe water scarcity crisis. Given the costs (hardware and labour costs for maintenance) this may be considered as part of an optimal hydrological data set (cf. Table 3). This dataset could also include sampling of bacteriological parameters to help detect water contamination (for example overflowing sewers, viruses, etc.).

Chemical water properties:

Several water quality parameters are usually monitored. Phosphorus and phosphates are generally responsible for eutrophication. Although chloride and sulphates may have natural origins, sudden increases may raise an alert for pollution stemming from industrial emissions or agricultural or urban runoffs. The same can be said for nitrite, which generally should not be found in natural waters. Pesticides (agricultural pollution), bacteriological factors (sewer overflows) and turbidity are other common indicators to help monitor water quality.

TABLE 3: Minimum, medium, and optimal hydrological data sets.

Minimum dataset	Medium dataset	Optimal dataset
- Primary discharges / groundwater levels	- Primary discharges / groundwater levels	- Primary discharges / groundwater levels
- Water temperature	- Water temperature	- Water temperature
- Electrical conductivity	- Electrical conductivity	- Electrical conductivity
	- Soil moisture	- Soil moisture
	- Basic ions	- Basic ions
		- Secondary aquifers/ spring levels /discharges
		- Isotopes, organic components
		- pH, oxygen

Table 4 below lists the hydro-ecological monitoring activities conducted within the Alp-Water-Scarce project by each partner.

TABLE 4: Summary table of hydro-ecological monitoring in Alp-Water-Scarce.

(Q=Discharge, L=Groundwater level, T=Water temperature, B=Basic ions, I=Isotopes, O=Organic compounds, M=Trace Metals)
(NB: Adige (IT) and Fersina (IT) Pilot Sites were used only for experiments on thermo-peaking effects and thus are not listed in this table).

ID	Pilot Sites	Hydrological data		
		Minimal dataset	Medium dataset	Optimal dataset
1	Savoy (FR)	Q, T		
2	Arly River Basin (FR)	Q, L		I, O
3	Koralpe (AT)	Q, T	B	L, I, M
4	Karawanken/Karavanke (AT/SI)	Q, L	B	L, I, M
5	Jauntal (AT)	Q, L	B	L, I, M
6	Lower Gurktal (AT	Q, L, T	B	L, I, M
7	Steirisches Becken (AT)	Q, L, T		L, I, M
8	Steirisches Randgebirge – Wechsel (AT)	Q	B	L, I, M
9	Entire Land Kärnten (AT)			L, I, M
10	Pohorje with Dravsko polje (SI)	Q, L	B	O
11	Ptujsko polje (SI)	Q, L	B	O
12	Scrivia River Basin (Alessandria IT)	Q, T	B	
13	Julian Alps (SI)	Q	B	
14	Piave River (IT)	Q	B	
16	Noce (IT)	Q		
18	Entella River Basin (IT)	Q, T	B	
19	Scrivia River Basin (Genova IT)	Q, T	B	
20	Sesia River Basin (IT)	Q, T	B	
21	Spöl River (CH)	Q, T	B	
22	Sandey River (CH)	Q		

2.1.3 Anthropogenic monitoring

Drought conditions can increase the risk of water scarcity, but excessive water demand can lead to the same risk. Quantitative estimates of water consumption are therefore necessary, although this may not be an easy task. Depending on the area of the site, water withdrawal points can be numerous and difficult to monitor. For example, Alp-Water-Scarce partner Local Government of Savoy (FR)[5] reported considerable problems in obtaining data on withdrawals for drinking water from the 1400 water-extracting plants throughout the Pilot Site.

5 See for example, Alp-Water-Scarce "Water System Characterization" technical report (Suette et al. 2011)

In the case of industrial water use, volume estimates may also be difficult to obtain. One department might collect these data (for example, for invoicing purposes), while another department might be in charge of operational water management. Moreover, it should be noted that water and environmental database policies differ widely across Europe. As with measurement protocols and data collection and exchange procedures, local and national administrations may have varying practices regarding public access to data ranging from long-standing policies of free access to environmental databases[6] to more restrictive data management and access policies.
The various environmental and anthropogenic data collection and access policies at the regional and national levels across Europe can be seen as a limitation to collaborative transnational European water management in shared mountainous regions.

In fact such anthropogenic data – required for the estimation of water scarcity risk – are, as a rule:
– difficult to obtain,
– controlled by a variety of different stakeholders and consumers, and
– available to water managers only after a period of time has elapsed.

However, when faced with an impending water scarcity crisis, statistical estimates of water consumption could help to determine the best strategies to reduce vulnerability to the upcoming crisis (in the short term). Anthropogenic data is also needed to draw up future scenarios for water uses and to estimate the likely frequency of future water scarcity crises. If the relevant data were easily available, structural changes in the water system could be more accurately designed to reduce risk in the future (long-term planning).

Minimal anthropogenic data set:
As drinking water is the most important concern for every European region, knowledge of the average seasonal variations in inhabitants (permanent residents/tourists) and of their vital water needs and minimal comfort water uses may be considered to be the minimal dataset (cf.Table 5).

Medium anthropogenic data set:
Optimized water conciliation between drinking water and industrial uses should take into account the economic impact of water use restrictions in the case of a water scarcity crisis. Therefore, knowledge of the various industrial water uses and of their economic vulnerability can be considered a medium dataset (cf. Table 5).

6 See for example, the free environmental web database of the Provincial Agency for Environmental Protection, Trento (IT) and the free environmental web database concept promoted by partner Paris Lodron University Salzburg, Centre for Geoinformatics (AT)

Optimal anthropogenic data set:

The two data sets described above might help to establish the global behaviour of the anthropogenic system in the event of a water scarcity crisis and thus help to define long-term strategies. However, in a short-term water scarcity crisis, accurate knowledge of the actual water consumption of both inhabitants and industry could help to define optimized (more efficient and less costly) strategies for the ongoing crisis. Reducing the time delay for access to actual water use data may be thus considered a useful measure, although it remains part of an optimal dataset because it requires complex monitoring and the transfer of operational measurements of water use.

Data accessibility:

Data and anthropogenic data in particularly are not always easy to access. According to Flindt Jorgensen et al. (2007) five main constraints can be identified:

– economic: most data are usually available at a nominal cost but in some countries costs may be significant (usually for meteorological data)
– political: at times, a stakeholder might not want other organisations with conflicting interests to have access to certain data
– data formats: formats may vary widely and thus be difficult to exchange
– transboundary cooperation: it is still not always easy to obtain data from organisations in other countries
– fragmented databases: data may be available but might be spread across numerous databases which increases the complexity of collection

These points should be considered in detail by stakeholders.

TABLE 5: Minimum, medium, and optimal anthropogenic impacts data sets.

Minimum dataset	Medium dataset	Optimal dataset
- Seasonal variation of inhabitants	- Seasonal variation of inhabitants	- Seasonal variation of inhabitants
	- Economical vulnerability of industries to water restrictions	- Economical vulnerability of industries to water restrictions
		- Rapid actual water use measurements

2.2 Recommendations

The ability to maintain monitoring networks differs greatly from country to country and from region to region. For example, only a very few European regions have meteorological and hydrological time-series as long as those available for partner Regional Government of Carinthia, Dpt. 8 (Competence Center Environment, Water and Nature Protection) (AT). However, long-term historical time-series are extremely valuable and indeed irreplaceable to disaggregate the impact of global changes at the local level (among other uses). However, even when long-term monitoring is established, complex problems must be overcome, such as data storage, data publication and data homogenization (cf. scientific issues in the HistAlp project[7]). These difficulties may explain in part why monitoring programmes are often designed independently of one another, with little concern for optimising coherence with other monitoring networks, remaining instead exclusive to the project that funds them.

This should not be taken as a criticism of stakeholders. Quite the contrary, stakeholders are often the ones who suffer most from the lack of data and who need these data in their day-today efforts as they design and implement monitoring networks. Methods should be explored to support these valuable efforts undertaken at the management level and to promote them at the trans-national and the European level.

A significant monitoring effort was made in the Alp-Water-Scarce Pilot Sites by each partner. Not all were at the same stage of natural and anthropogenic monitoring but each partner initiated monitoring efforts that will be continued beyond the project's end. This is clearly an expensive long-term effort, but monitoring is one part of improved future water management that can not be replaced by numerical models.

As previously mentioned, Alpine regions are particularly hazardous for ordinary market sensors. Ongoing development of techniques (video recording, low-energy sensors, improved remote transmission in mountainous regions, etc.) should be encouraged and supported. This development is necessary to achieve better geographical sampling of mountainous regions and to obtain the long time-series required to more effectively estimate the impacts of global changes on our region.

Another point to consider is that quantitative estimates may benefit from improved interaction between monitoring efforts and the development of numerical models. A review of scientific publications and operational practices in meteorology and oceanography shows that model simulations constrained by relevant field observations may be seen as "virtual sensors", generating estimates where monitoring is impossible or too expensive to implement. This is discussed further in Section 4.2.3 on page 37.

Finally, all opportunities should be explored to increase national and transnational exchange of environmental data. The global changes faced by humanity are taking place on a very large scale but can lead to very local impacts. Easier access to and exchange of environmental data is crucial to facilitate the development and testing of optimal adaptation strategies for the benefit of all.

7 http://www.zamg.ac.at/histalp/, see also Auer et al. (2007)

3 Modelling Alp-Water-Scarce Pilot Sites

3.1 Natural water system and anthropogenic impacts

Hydrological modelling is an important complement to any significant monitoring network. Hydrological models are software programmes that represent the functioning of catchments, rivers, massifs, etc. These models can be of varying degrees of complexity. They make use of data acquired in the field, but they can also help to answer questions that cannot be resolved by field measurements alone. Models may be seen as programmes that incorporate all knowledge of catchment dynamics acquired by the technicians, engineers, and researchers who monitor, explore, observe, and manage the natural and anthropogenic systems.

For example, models may be useful in water management in order to:
– find solutions for sites where no data are available
  → *ungauged catchments*
– predict and forecast possible future scenarios
  → *knowledge-based anticipatory actions*
– study in detail water problems occurring elsewhere and/or in the past but which are not directly applicable
  → *knowledge transfer*
– obtain detailed information where only partial measurements are available
  → *use of models as "virtual" complementary sensors*

Models should focus on both the quantity and quality of natural water and used water. However, modelling water quality in an operational fashion remains a scientific and technical challenge. Water quality modelling over large areas with many feedback loops between the natural water cycle and anthropogenic uses is still a very difficult undertaking given the current state of knowledge and technical means available. This may partly explain why water quality is usually quantified using statistical criteria combining several indicators of water quality. The next paragraphs will therefore focus on quantitative models with limited abilities to predict water quality.

3.1.1 Natural water systems

When modelling the water cycle of mountainous regions, several hydrometeorological components must be considered (see Figure 3), among them meteorology, hydrology, geomorphology, geology, and hydraulics.
All these components have their own influences on the water cycle. In addition, they often involve feedback loops that in some cases have not yet been clearly quantified. Bearing in mind these most sensitive components, the following points (see also Figure 4) should be considered when undertaking monitoring and modelling activities:

FIGURE 3: A mountain hydrometeorological environment, Isiére (Vorz catchment, Belledonne, University of Savoie, EDYTEM (FR))

- **Meteorology:**
  The main forcing variables of the water cycle in Alpine regions are precipitation, temperature, solar radiation, clouds cover and wind. Influenced by the climate on a larger scale, these variables directly impact water availability and thus water scarcity issues. However, as previously mentioned, monitoring these variables remains a technical challenge that should be the focus of substantial efforts in the future.

- **Snowpack:**
  This dynamic clearly needs to be understood as it has an important impact on the hydrological regimes of the Alps. The ratio between solid and liquid precipitation must be quantified during the autumn and winter seasons to be able to calculate the snow water equivalent. This snow water equivalent is released during the melting period, feeding river discharge. Special attention should be paid to the snow pack dynamic, as this period is known to be shortening and beginning earlier due to climate warming. As a consequence, it is expected that the availability of water resources and thus water scarcity will change significantly over the coming years and decades.

- **Soil-vegetation-atmosphere exchanges:**
  The water cycle is closely related to energy balances. Solar radiation directly impacts snow melting and sublimation, weather conditions, bare soil evaporation, etc. It also indirectly impacts the water cycle via the vegetation growth and evapotranspiration. For example, the impact of climate change on the interaction between the vegetation cycle and the melting season is considered to be quite important.

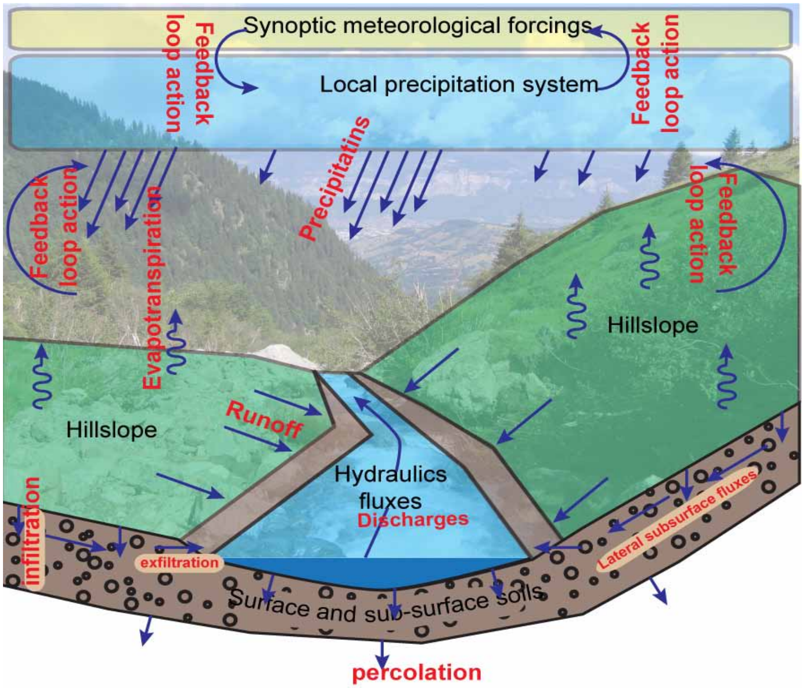

FIGURE 4: **Hydro-meteorological components overlaid on a photograph of the catchment** (Vorz catchment, Belledonne, University of Savoie, EDYTEM (FR))

– Surface/subsurface soil layers:

Incoming precipitation (rainfall and snowmelt) is redistributed in the upper soil layers (vertical water infiltration and lateral subsurface water fluxes). This component should be accurately quantified, as it impacts flood regimes, deep aquifer recharge, water availability for vegetation (vadose zone), etc.

– Groundwaters:

Underground aquifers (deep or near the surface) generally represent the main natural water storage used for many purposes (from anthropogenic to natural uses). Their role is crucial as, like the snowpack, they demonstrate greater inertia than river dynamics do. These hydrological features are thus very useful for addressing water management issues, in view of their sizeable water storage capacities.

3.1.2 Anthropogenic water system.

Anthropogenic water uses and impacts on the water cycle may be also complex to model. Several water uses and their inherent impacts on the water cycle can be identified.

Quantitative impacts

– Source-sink impacts: Some water demands (e.g., drinking water) require the transfer of water volumes from one point to another or even to different catchments using pumps, or by-channels. This type of anthropogenic impact is probably one of the easiest to conceptualize and to model.
– Areal impacts: Other water uses involve taking water from one point and re-distributing it over large areas (e.g. agricultural irrigation/sprinklers, see Figure 5). Quantifying such uses is more complex as they interact with meteorological factors (when to irrigate?[8]), vegetation (what level of water demand at each growing stage?) and hydrological processes (infiltration in the vadose zone).

FIGURE 5:
Rotaliana agricultural plain (IT)
photo partner University of Savoie, EDYTEM (FR)

Temporal concerns

– Artificial water storage facilities: Hydro-electric dams or man-made recreational lakes that impact the downstream hydrological regimes should be modeled. These uses may impact hydrological regimes and fluvial geomorphology at lower altitudes (as studied by partner Provincial Agency for Environmental Protection, Trento (IT)) and thus the downstream water scarcity risk.

FIGURE 6:
The hydroelectric dam of Pian Palù
photo Provincial Agency for Environmental Protection, Trento (IT)

8 See, for example, the Early Warning System for agriculture of partner Slovene Chamber of Agriculture and Forestry, Institute of Agriculture and Forestry Maribor (SI) (http://www.kmetijski-zavod.si)

– Artificial snow may also impact the hydrological regimes of upper head catchments. Even if the water withdrawals are not usually significant compared to precipitation volumes and/or other water uses, artificial snow impacts melting period regimes (delayed snow melting) and may raise some water scarcity risk when artificial storage facilities must be filled.

3.1.3 Guideline for model choice

The choice of a model should result from a knowledge-based decision. Stakeholders may have different degrees of human resources available to develop internal skills in model uses. Most stakeholders contract out modelling studies: for example, within the Alp-Water-Scarce project, some partners worked with subcontractors[9] while other partners developed or used their own models[10]. A large number of models are available, often with significantly different paradigms, but occasionally very similar. Posing certain relevant questions may help stakeholders to choose from the available models.

Three of these questions are discussed below:

– Which models for which objectives?

Not all models are capable of answering every question. This seems obvious but the alignment of the elements described in a model (surface water, spring water, aquifers, snowpack, etc.) and the primary concerns of the stakeholder (drinking water, hydropower, agriculture, tourism, etc.) is quite rarely discussed. A model should be able to answer the questions posed by the water manager but care should also be taken to ensure that the model is primarily designed to answer these questions, i.e. that the most complex part of the model is dedicated to these questions or to the hydrological components that are the most relevant to given objectives. For example, a SVAT model (Soil-Vegetation-Atmosphere-Transfers model) would not be the most suitable choice for flood mitigation studies, but such models are suitable for describing climate change impacts on agriculture. However, evaluating the adequacy of a model in terms of its complexity and sensitivity in light of the requirements of a given water management issue may itself be a complex question. This should form part of the discussion between the water manager and the modellers. This is also discussed in the section “Balanced monitoring and modelling strategies” on page 31.

9 E.g., partners Society of Alpine Economics of Upper Savoy (FR), Local Government of Savoy (FR), Province of Alessandria (IT), Provincial Agency for Environmental Protection, Trento (IT), Slovene Chamber of Agriculture and Forestry, Institute of Agriculture and Forestry Maribor (SI)

10 E.g., partners Development Agency Gal Genovese (IT), Regional Government of Carinthia, Dpt. 8 (Competence Center Environment, Water and Nature Protection) (AT), Regional Agency for Prevention and Protection of the Environment of Veneto - Department for the Safety of Territory (IT), Geological Survey of Slovenia (SI)

– Technical aspects

Every model requires data inputs for calibration, simulations, and forecastings/predictions. The use of a model therefore implies a monitoring effort or other acquisition of data. These data could be historical data (e.g., for calibration) but might also be continuous operational data (to feed the model). in addition to IT costs (data server/calculation costs or subcontractor costs), data costs should be considered. This then raises questions about the amount and type of data needed for modelling:

- Is the model spatially distributed? This would imply the need to obtain geographical data and interpolated measurements. If the model is lumped, it will be less costly but in some cases may be less accurate.
- What are the spatial and temporal resolutions required by the models? Can the model use widely available raw data or does it need dense network measurements?
- What type of meteorological forcings are needed by the model?
- What type of geographical information is needed?

– Model-user environment.

It may be useful to share experiences with other users of a given model. This could help in implementing the model, analyzing its results, acquiring greater knowledge and obtaining information about results from other relevant studies. The number of other users of the model and/or access to technical support could be a concern for a future model user.

The user's future involvement in the technical development of the model should also be considered. An established and well-known model means that numerous subcontractors and users would be available to help to install and run the model. On the other hand a model that is still in development by a dedicated team might offer the opportunity for easier adaptation to the actual needs of a stakeholder. This usually also means that the learning process of the water manager would be easier compared to the "blind" use of a commercial model that is already so well-known that only a handful of experts are actively developing it.

3.2 Hydrological models in Alp-Water-Scarce

The following table lists the various models used within Alp-Water-Scarce.

TABLE 6: Synthetic Alp-Water-Scarce models.

(NB: Adige (IT) and Fersina (IT) Pilot Sites were used only for experiments on thermo-peaking effects and are thus not listed in this table. Sesia River Basin (IT) , Spöl River (CH) and Sandey River (CH) Pilot Sites conducted ecological studies and no models were planned to be implemented; consequently, they are not listed in this table).

ID	Pilot Sites	Hydrological models									
		1 MIKE-SHE	2 HBV	3 MIKE-SHE	4 NAM	5 TOPMODEL and GR4	6 IRRFIB	7 IHACRES	8 MRC	9 HYDRO	10 GEOTRANSF
1	Savoy (FR)								■		
2	Arly River Basin (FR)					■					
3	Koralpe (AT)	■									
4	Karawanken/Karavanke (AT/SI)	■									
5	Jauntal (AT)	■									
6	Lower Gurktal (AT	■									
7	Steirisches Becken (AT)	■									
8	Steirisches Randgebirge – Wechsel (AT)				■						
9	Entire Land Kärnten (AT)		■								
10	Pohorje with Dravsko polje (SI)						■				
11	Ptujsko polje (SI)						■				
12	Scrivia River Basin (Alessandria IT)							■			
13	Julian Alps (SI)	■									
14	Piave River (IT)			■							
16	Noce (IT)										■
18	Entella River Basin (IT)									■	
19	Scrivia River Basin (Genova IT)									■	

The main characteristics of these models are listed below. These are simple indicators[11] [12] of:

– their cost:
  → *do these models have a cost or can they be freely used, downloaded and adapted?*
– their outputs:
  → *what type of variables are the models able to calculate?*
– their needs in forcing data:
  → *do these models need a high, medium or low volume of data to run?*
– their dissemination:
  → *are these models in use by a small, medium or large number of users?*

In the following list, a large community of model-users is evaluated as better than a small one, since when a water management office has little previous experience in hydrological modeling, a larger user community can be helpful when developing model uses. If, however, significant skills are available, this criteria becomes of lower importance: in some cases, models tailored-made for specific purposes with a very limited user community might be preferable.
The complexity of the models should also be evaluated. Although this remains a difficult question to answer, the model codes presented in the Synthesis report of the Harmoni-CA[13] project are used below. This report assesses model complexity in three categories (from low complexity and easy application to high complexity and difficult application):

– Simple/Intermediate models: used for screening and planning applications.
– Comprehensive models: used for design purposes.
– Process studies models: used for research purposes.

1: MIKE-SHE	
Cost	With cost.
Main concern	Snow melt, runoff, infiltration, evapotranspiration, groundwater, water quality.
Type of model	Comprehensive/Process studies model.
Data cost	+++
User community size	+++

2: HBV	
Cost	Free or with cost (depending on version used).
Main concern	Snow melt, runoff, infiltration, evapotranspiration, water percolation.
Type of model	Comprehensive model.
Data cost	++
User community size	+++

11 The list on page 41 provides contact persons who can supply supplementary informations about each of the listed models
12 See also Alp-Water-Scarce „Monitoring and Modeling“ technical report (Brancelj et al. 2011)
13 Harmoni-CA (2007): Synthesis Report on Data Availability and Accessibility Harmonised Modelling Tools for Integrated River Basins Management

3: HYDRSTRA	
Cost	With cost.
Main concern	Snow melt, runoff, dam management.
Type of model	Simple/Intermediate model.
Data cost	+
User community size	+

4: NAM	
Cost	With cost.
Main concern	Snow melt, runoff, infiltration, evapotranspiration.
Type of model	Simple/Intermediate model.
Data cost	+
User community size	+

5a: TOPMODEL	
Cost	Free.
Main concern	Snow melt, runoff, infiltration, groundwater recharge, evapotranspiration.
Type of model	Comprehensive/Process studies model.
Data cost	+
User community size	+++

5b: GR4	
Cost	Free.
Main concern	Snow melt, runoff, evapotranspiration, groundwater recharge.
Type of model	Simple/Intermediate model.
Data cost	+
User community size	++

6: IRRFIB	
Cost	With cost.
Main concern	Crop water consumption.
Type of model	Comprehensive/Process studies model.
Data cost	++
User community size	+

7: IHACRES	
Cost	Free.
Main concern	Snow melt, runoff, evapotranspiration.
Type of model	Simple/Intermediate model.
Data cost	+
User community size	+

8: MRC (Master Recession Curve)	
Cost	Free.
Main concern	Groundwater discharges.
Type of model	Simple/Intermediate model.
Data cost	+
User community size	+++

9: HYDRO	
Cost	With cost.
Main concern	Snow melt, runoff, infiltration, groundwater recharge, evapotranspiration.
Type of model	Process studies model.
Data cost	+++
User community size	+

10: GEOTRANSF	
Cost	Free (GPL).
Main concern	Snow melt, runoff, infiltration, evapotranspiration.
Type of model	Process studies model.
Data cost	+
User community size	+

3.3 Recommendations

As explained in the Alp-Water-Scarce Climatic scenarios guideline report[14], Alpine regions are particularly sensitive to global warming. They are also expected to soon face very different meteorological conditions than in the past decades. This is likely to lead to changes in hydrological behaviour in the near future. As a consequence of such changing conditions, available historical data for particular water systems may soon no longer be representative. Models must therefore be able to extract from historical data the information that remains relevant in changing circumstances whilst also remaining relevant themselves under such changing conditions. Some models compensate for their shortcomings in representing the laws of physics by interpolating the dynamics of water systems using an intense calibration phase, e.g., statistical models. If the data used for such a calibration procedure are not relevant in the coming decades, the results provided by these models are unlikely to be relevant. Therefore, physically-based models seem to be more suitable for simulating water scarcity risk in the Alps in the decades to come than statistical or conceptual models.

14 Saulnier et al. 2011

Models should be also able to simulate changing anthropogenic impacts in the future. As explained in the section “Natural water systems and anthropogenic impacts” on page 20, both quantitative and temporal impacts must be taken into account. Some impacts can be more easily simulated using source-sink approaches with limited interaction with the natural hydrosystem. However, other impacts will interact more closely with natural processes such as infiltration, runoff, vegetation growth and energy balance (e.g. agriculture, water pollution, tourism). If scenarios of future water demand can be designed, one remaining challenge remains changes in land-use. First of all, the same point can be made as in thet previous paragraph: unless a significant correlation can be established between conceptual parameters and land-use, physics-based models should be preferred. However, this question should be explored further in close collaboration with Social Sciences experts. The adaptation of our society to climatic changes and in particular to the evolution of economic factors is beyond the scope of the monitoring and modelling activities of the Alp-Water-Scarce project. The future extension of urban zones and the spread of water-consuming industries into new territories increases the need for models of scenarios of future anthropogenic impacts on water scarcity risk.

Such questions are highly challenging and still require intense research and practical feedback. This is a long-term effort that demands cooperation between stakeholders, private consultants and universities. However, capitalizing on such shared efforts is not easy. Practical ways must be identified to share and develop these shared experiences at the transnational and European level in the long term. The need to exchange modelling best practices and to offer ongoing training to water management practitioners is crucial in order to define best practices at the European level.

4 Balanced monitoring and modelling strategies

As explained above, in order to be useful for water scarcity risk management models require a minimum level of complexity in terms of process description. Thus, modelling natural and anthropogenic water systems in an operational manner can be viewed as a very difficult task. While some tailored research models for smaller problems might be able to achieve this type of complexity, a greater challenge is presented for operational models that must manage constraints such as:

– operation over a wide range of surfaces
  → *from 100 km² to a few 1000 km²*
– reliance on varying amounts of available data
  → *varying time series length of a limited number of key variables*
– having different degrees of access to difficult-to-measure geometries
  → *underground soils/geographical layers*
– expectation to meet a variety of objectives
  → *risk mitigation, water management, droughts forecasting, etc.*
– management of sensitive anthropogenic data
  → *accurate water demand data, industrial water withdrawals, etc.*

Modelling of the natural and anthropogenic water cycle for a multi-objective water management activity should therefore be a compromise between:

– the objectives that may be achieved using such models
  → *what is the problem?*
– the available data to force, constrain and corroborate the models
  → *what data is available?*
– the appropriate level of complexity to obtain a reliable description of the main
  → *which models should be used?*

Reaching such a compromise should not be seen as simply doing as well as possible in defining problems, monitoring and modelling strategies. To achieve this compromise, a balanced path should be found to optimize the cost of any supplementary efforts dedicated to any of these three strategies. in other words, the key question is:

How should action priorities be ranked in order to
maximise the overall benefit in water management activity at the minimum cost?

This is discussed further in the following sections.

4.1 Which effort for which benefit?

Within a given budget, the choice between improving a monitoring network and improving the relevance of models is not an easy one. One way to address this problem is to recognize that the goal of any monitoring and modelling effort is to improve the predictive performance of the operational monitoring and modelling system to achieve better water management.

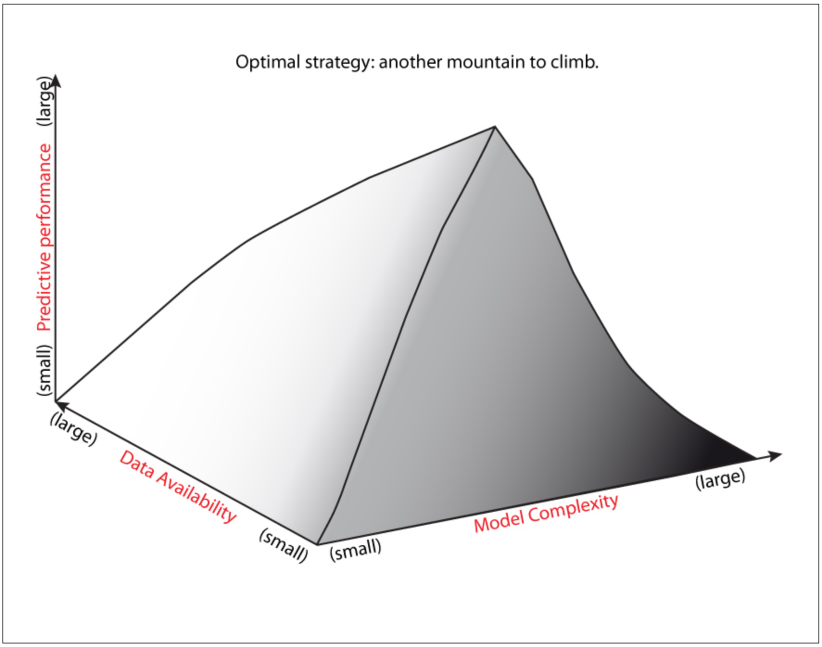

FIGURE 7: Predictive performance vs. Data availability and Model complexity.

This can be done by increasing data availability or by increasing model complexity, as shown in Figure 7[15]. If more data are acquired in the field, it is expected that the increase in field knowledge will contribute to more accurate and efficient water management actions. Similarly, if more complex numerical tools are available, it is expected that more complex water management strategies can be evaluated and better decisions taken.

Both strategies – increasing data availability and increasing model complexity – thus seem to be relevant courses ofaction to improve the predictive performance of an operational monitoring and modelling system. These two options are discussed in more detail below.

15 Adapted from Grayson and Blöschl (2001)

4.1.1 Increasing data availability

Field data facilitate an understanding of the behaviour of natural and anthropogenic systems. They also feed numerical tools (databases, statistical analyses) as well as numerical models. Every model needs information for calibration purposes, transforming input information (e.g., meteorological forcings) into useful outputs information (e.g., water availability). Once a model has enough data to be calibrated

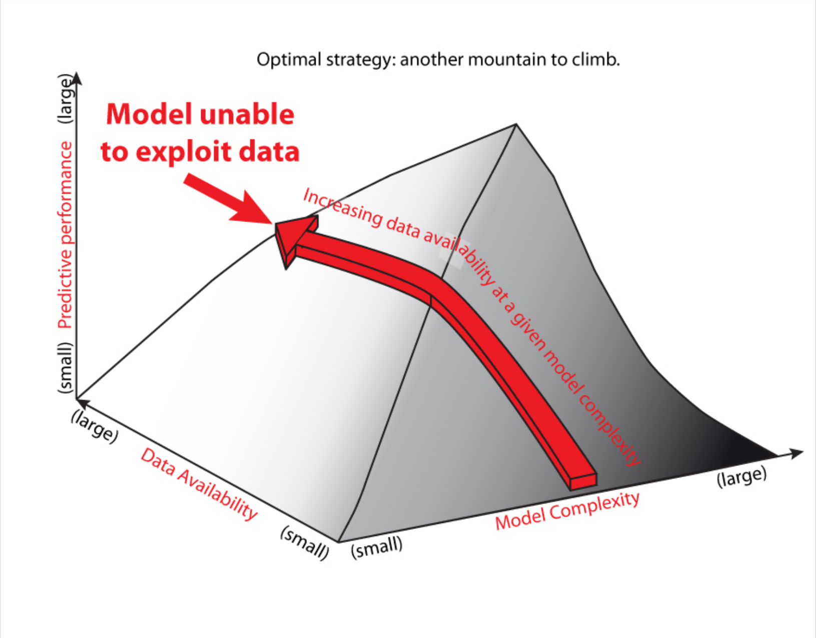

FIGURE 8: Increasing data availability only leads to limited benefits.

and used, however, any additional variable monitored may be seen as useless in terms of the predictive performance of the monitoring and modelling system. Indeed, the model may be seen as too simple in the light of the newly available data set if it cannot make significant use of this new information (Figure 8).

4.1.2 Increasing model complexity

Alternatively, increasing the model's complexity may be seen as a valid option. Increasing the number of modelled hydrological components, meteorological forcings and anthropogenic effects enables more complex and varied water management strategies to be quantified and thus helps to identify better optimized actions that could increase the overall socio-economical and ecological benefits of the water management activity.

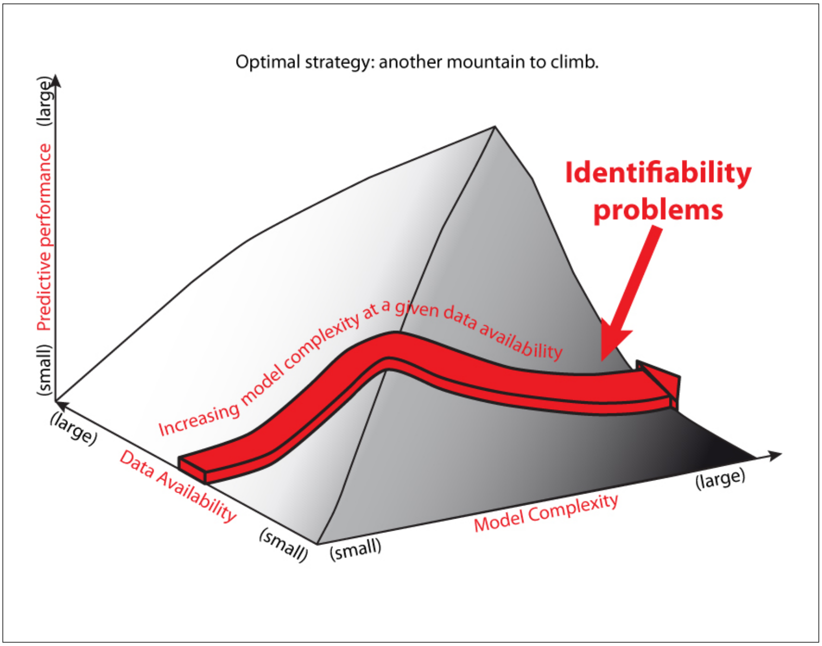

FIGURE 9: Increasing model complexity only leads to greater uncertainties.

However, if the data availability does not increase in line with the model complexity, some identifiability problems may arise as insufficient data are available to constrain the model. Calibration is thus not adequately addressed with (Figure 9), which is known to increase the range of uncertainties of the model outputs and therefore decrease their usefulness.

4.1.3 A virtuous path

Data availability and the representativeness of the models must to be increased in order to improve the predictive performance of integrated natural and anthropogenic water management systems, but the two actions should be considered together. Giving too much priority to one action or the other may result in money and effort being wasted and/or increased uncertainties[16].

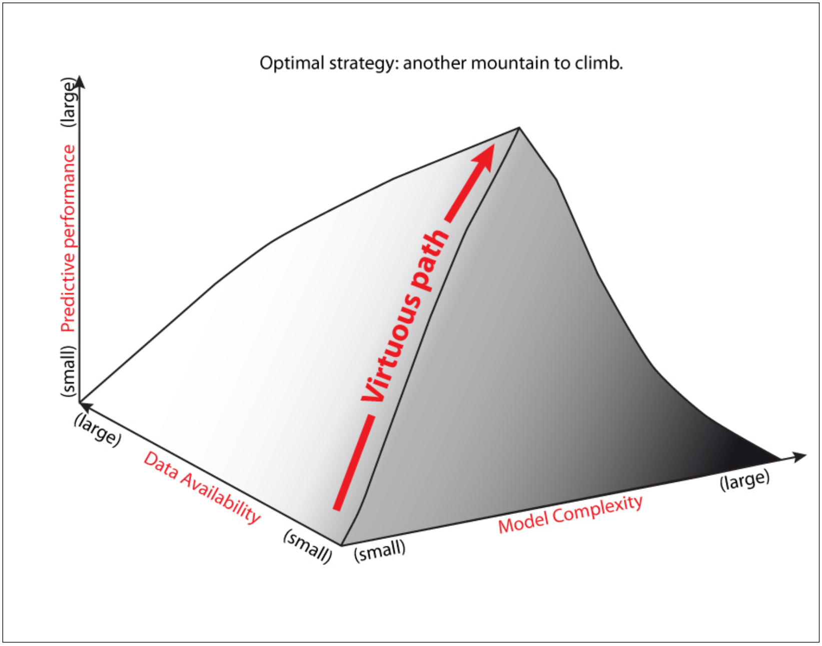

FIGURE 10: Balanced data availability and model complexity leads to higher usefulness.

Increasing model complexity should be encouraged when combined with relevant supplementary field monitoring. This "virtuous path" ensures an increase in the predictive performance of the integrated natural and anthropogenic water management system while optimizing the financial and human resources costs.
At the beginning of this virtuous path (low data availability – low model complexity) are simplified bucket models fed with lumped area data that involve low computational costs. At the other end of the path (high data availability – high model complexity), one may find models based on mechanistic descriptions of processes fed with geographical maps of parameters and involving medium-to-high computational costs.

16 See also Flindt Jorgensen et al. (2007)

4.2 Integrated view to improve knowledge of Alpine regions

In addition to finding the relevant balance between monitoring and modelling efforts, some supplementary tools are also required to climb the virtuous path described above in order to achieve good predictive performance by the water management system.
Databanks and numerical models can provide the necessary information for taking knowledge-based decisions, but this information is not sufficient. Tools suitable for analysing field measurements and model outputs are now available and are widely used in other operational fields – for example, in meteorological surveys. These tools are described below.

4.2.1 Uncertainty analysis

Uncertainty analysis seeks to evaluate the sources of uncertainty: what is the uncertainty of rainfall data/forecast, water demand statistics, future climate change scenarios, etc.
Uncertainty analysis quantifies how these input uncertainties spread within the integrated natural and anthropogenic water management system. For example, Figure 11[17] illustrates the uncertainty of mass balance forecast calculations

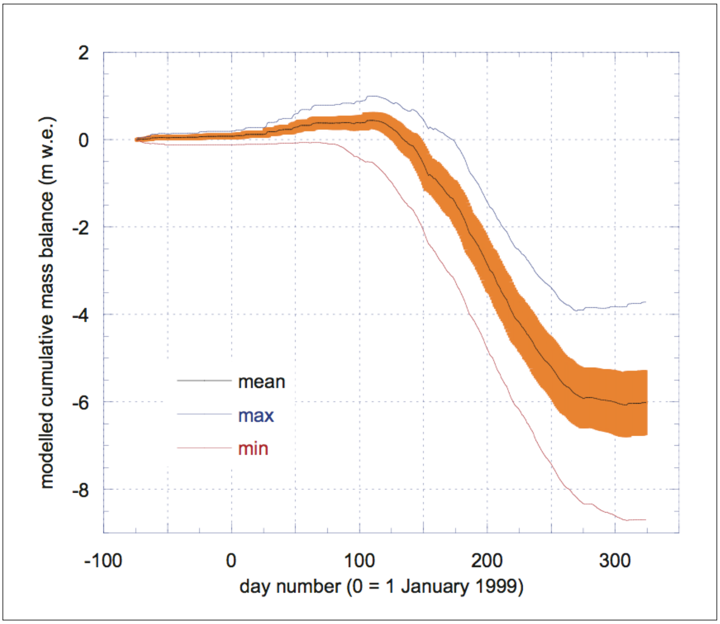

FIGURE 11: Temporal evolution of the modelled cumulative mass balance (18 Oct 1998 – 20 Nov 1999) on Morteratsch Glacier, Switzerland. Calculated uncertainty (+/- 1 standard deviation) is depicted with orange shading.

17 From Machguth et al. (2008)

according to input uncertainties (air temperature, precipitation, ice albedo, global radiation, etc.). The uncertainties at the end of the melting period are considerable. A minima in the same range of uncertainties could be thus expected in the impacts of decision making on water management at the seasonal level.

Uncertainty analysis can contribute to answering the following question:
Given the uncertainties in the input data and in knowledge of the water system what are the uncertainties of the variables/descriptors of the management system?

This can be an important question, as it helps to determine if the system is in a discernible management state.

4.2.2 Sensitivity analysis

Sensitivity analysis can be seen as the inverse of uncertainty analysis. Given an output (such as the risk value for a scarcity event, the cost/benefit ratio of a given management action, etc.), a sensitivity analysis attempts to determine which inputs impact this information. It then ranks these input variables in terms of their relative impact on the output information in question.
This type of sensitivity analysis is currently rarely used. One reason is the relative complexity of the methods and concepts. However it is considered a very useful tool as it permits an answer to the following question: Within a given budget, what supplementary effort should be made to maximize the cost/benefit ratio? The answer depends on the main objectives of the integrated natural and anthropogenic water management system, i.e., the main concerns of a given region (drinking water, hydropower, agriculture, tourism, etc.).
This question gives rise to other questions, such as what supplementary sensors should be installed and where, and which model component should be improved as a priority in order to maximize the expected improvement in water management. In other words, sensitivity analysis is the key element to identifying the virtuous path between monitoring and modelling efforts described in Section 4.1.3 on page 35 and can help to define improved and more efficient practices.

4.2.3 Data assimilation

Once the models of the integrated natural and anthropogenic water management system are calibrated and are operational, the next objective might be to reduce their estimated uncertainty. This can be achieved by observing the differences between the model outputs and the available data from operational monitoring: if the

model outputs are seen to deviate from the observed data, could this information be used to adjust the model's calculations and suggest corrective action? This is usually done using so-called data assimilation techniques.
These methods seek not only to "fit" model simulations to observations and to build statistical error models, but they also ensure that the dynamics of the corrected model simulations respect the model's assumptions (which are based on a priori knowledge) and also make full use of knowledge of the model's errors (which represent the remaining gaps in this a priori knowledge).
In other words, data assimilation techniques make use of available observational data to constrain a model's simulation errors. They thus help to better constrain uncertain inputs and parameter estimations.
If models make use of a priori knowledge within an integrated natural and anthropogenic water management system and take advantage of available observational data to intelligently modify their simulations, some credibility might be given to the model's estimations of unsurveyed geographical points and/or non-monitored variables. To some extent, reliable models using data assimilation techniques may be seen as virtual sensors and may thus help to estimate variables that are too difficult or expensive to measure.

4.2.4 Adaptive management in an uncertain future

The methods cited thus far, whilst innovative for some regions or organizations, focus on data and models. The particular context of climatic/global changes that are advancing at significant speeds in the Alpine region should also raise the question of an adaptive integrated natural and anthropogenic water management system.

As suggested in the definition of Early Warning Systems provided in the Alp-Water-Scarce project, water management to avoid scarcity crises should focus on two time scales:

– crisis time scale
  → *Who is allowed to take water? Where and when? How much?*
– long-term time scale
  → *How should the structural system and water policies be modified to ensure a sustainable water resources in the future?*

This implies the ability to propose and evaluate risk mitigation measures, and to optimize water allocation among competing uses across space and over time (in order to avoid a scarcity event). On a longer time scale, it implies the use or development of climatic and socio-economic scenarios in order to evaluate adaptation strategies to climate change (to decrease the risk of water scarcity in the future).

In addition to the methods and concepts cited above, certain new concepts[18] should also be implemented to ensure efficient integrated natural and anthropogenic water management systems appropriate to an uncertain and changing world:

- Definition of performance indicators that measure the multi-objective aspect of decision support.
  → *legal constraints (e.g. drinking water demand, optimal ecological flow)*
  → *socio-economic constraints given the vulnerability of the elements at risk*

- Definition of criteria for evaluating the possible performance of natural and anthropogenic integrated water management systems:
  → *how likely is a system to fail? (reliability)*
  → *how quickly can it recover from failure? (resiliency)*
  → *how severe might the consequences of failure be? (vulnerability)*

- Optimization and reliability analysis: In identifying the best compromise solution for a general multi-objective optimization problem, reliability analysis seeks to estimate the probability of failing to achieve a certain target

- Tools from decision-making theory (decision trees, influence diagrams, belief networks) can be used to structure the management and implementation of actions.

18 E.g. see Bruen (2008) or Mahmoud et al. (2009)

5 Conclusion

Water management for better water scarcity mitigation requires monitoring, modelling and system analysis skills. These are clearly long-term efforts that require significant investments in both human resources and hardware/software. As explained in the "Balanced monitoring and modelling strategies" section on page 31, year-on-year collected data and model simulations may help to continuously optimise these investments to better satisfy defined water management goals. Thus, although long-term efforts are required, a continuous benefit can be expected.

Within the Alp-Water-Scarce project, various levels of investment in monitoring and modelling were observed among the project partners. This diversity was actually valuable in sharing and promoting the idea that these efforts should be encouraged and maintained[19]. However, the benefit of sharing experiences and best practices between stakeholders, consultants and researchers should also be considered. Bringing together knowledge and technical ideas would increase our capacity to develop adaptation strategies to deal with global changes at the European level.

This is clearly beyond the scope and goals of this project; rather, it is an issue that should be addressed by decision-makers at a political level. However, it is hoped that some of the practices applied in Alp-Water-Scarce may contribute to the definition of a network of trans-national skill platforms.

19 E.g. partner Local Government of Savoy (FR) had no model at the beginning of the project and is now considering contributing to PhD studies to develop an integrated water management strategy.

6 Contacts

University of Savoie, EDYTEM (FR)	
Contact:	**Dr Georges-Marie SAULNIER**
Physical address:	EDYTEM (UMR 5204, CNRS, Université de Savoie) Pôle Montagne Campus Scientifique FR - 73376 Le Bourget du Lac Cedex
E-mail:	georges-marie.saulnier@univ-savoie.fr

Society of Alpine Economics of Upper Savoy (FR)	
Contact 1:	**Mr Philippe Rousset**
Physical address:	Régie Départementale d'Assistance 1 rue du 30eme RI BP 2444 FR - 74041 Annecy Cedex
E-mail:	georges-marie.saulnier@univ-savoie.fr
Contact 2:	**Dr Georges-Marie SAULNIER**
Physical address:	EDYTEM (UMR 5204, CNRS, Université de Savoie) Pôle Montagne Campus Scientifique FR - 73376 Le Bourget du Lac Cedex
E-mail:	georges-marie.saulnier@univ-savoie.fr

Local Government of Savoy (FR)	
Contact:	**Mr Stéphane LASCOURS**
Physical address:	Conseil Général de la Savoie Direction de l'environnement et du paysage Hôtel du Département BP 1802 FR - 73018 Chambéry Cedex
E-mail:	Stephane.Lascours@cg73.fr

Regional Government of Carinthia, Dept. 8 (Competence Center Environment, Water and Nature Protection) (AT)	
Contact:	**DI Jürgen Komma**
Physical address:	Technical University of Vienna Research Center of Hydrology and Water Resources Management Karlsplatz 13/222 A - 1040 Wien
E-mail:	sekr223@hydro.tuwien.ac.at

Government of the Province of Styria (AT)	
Contact 1:	**Dr Gunther Suette**
Physical address:	Amt der Steiermärkischen Landesregierung Wasserwirtschaftliche Planung und Siedlungswasserwirtschaft Stempfergasse 7 A - 8010 Graz
E-mail:	gunther.suette@stmk.gv.at
Contact 2:	**Joanneum Research (AT)**
Physical address:	Leonhardstraße 59 A - 8010 Graz
E-mail:	pr@joanneum.at

Development Agency Gal Genovese (IT)	
Contact:	**Dr Maria Traverso**
Physical address:	Pianificazione Generale e di Bacino L.go Francesco Cattanei, 3 (GE) IT - 16121 Genova
E-mail:	traverso@provincia.genova.it

Province of Alessandria (IT)	
Contact:	**Ms Nuria Mignone**
Physical address:	Provincia di Alessandria Piazza Libertà 17 IT - 15100 Alessandria
E-mail:	europa@provincia.alessandria.it

Provincial Agency for Environmental Protection, Trento (IT)

Contact:	**Ing. Paola Pergher**
Physical address:	Provincia Autonoma Di Trento Ufficio Grandi Derivazioni Idroelettriche Servizio Utilizzazione delle Acque Pubbliche Palazzo ITAS Piazza Silvio Pellico, 8 IT - 38122 Trento
E-mail:	Paola.Pergher@provincia.tn.it

UNCEM Piemont Delegation (IT)

Contact:	**Ms Nuria Mignone**
Physical address:	UNCEM Delegazione Piemontese Via Gaudenzio Ferrari n.1 IT - 10124 Torino
E-mail:	uncem@provincia.torino.it

Regional Agency for Prevention and Protection of the Environment of Veneto - Department for the Safety of Territory (IT)

Contact:	**Dr Renzo Scussel**
Physical address:	Agenzia Regionale per la Prevenzione e Protezione dell’Ambiente del Veneto Dipartimento Regionale per la Sicurezza del Territorio Via Matteotti, 27 IT - 35137 Padova
E-mail:	gscussel@arpa.veneto.it

Geological Survey of Slovenia (SI)

Contact:	**Dr Mihael Brenčič**
Physical address:	Geološki Zavod Slovenije Dimičeva ulica 10 SI - 1000 Ljubljana
E-mail:	mbrencic@geo-zs.si

National Institute of Biology; Department for Freshwater and Terrestrial Ecosystems Research (SI)	
Contact:	**Dr Anton Brancelj**
Physical address:	Nacionalni Inštitut za Biologijo Oddelek za raziskovanje sladkovodnih in kopenskih ekosistemov Večna pot 111 SI - 1000 Ljubljana
E-mail:	anton.brancelj@nib.si

Slovene Chamber of Agriculture and Forestry, Institute of Agriculture and Forestry Maribor (SI)	
Contact:	**Dr Stanislava Klemenčič-Kosi**
Physical address:	Kmetijsko gozdarska zbornica Slovenije Kmetijsko gozdarski zavod Maribor Vinarska ulica 14 SI - 2000 Maribor
E-mail:	stanka.klemencic@kmetijski-zavod.si

Swiss Federal Institute of Aquatic Science and Technology (CH)	
Contact:	**Dr Christopher Robinson**
Physical address:	Eidgenössische Anstalt für Wasserversorgung Abwasserreinigung und Gewässerschutz Ueberlandstrasse 133 CH - 8600 Duebendorf
E-mail:	robinson@eawag.ch

7 References

7.1 Alp-Water-Scarce references

The following reports are cited in this booklet. The PDF files may be downloaded from the Alp-Water-Scarce web site (http://www.alpwaterscarce.eu) or from the Alpine Space website (http://www.alpine-space.eu).

A. Brancelj et al. (2011). Monitoring and Modeling (WP6 final report). Tech. rep. Alp-Water-Scarce project (5-1-3-F, Interreg IV B, Alpine Space Programme). URL: http://www.alpwaterscarce.eu, http://www.alpine-space.eu

G. Suette et al. (2011). Water System Characterization (WP5 final report). Tech. rep. Alp-Water-Scarce project (5-1-3-F, Interreg IV B, Alpine Space Programme). URL: http://www.alpwaterscarce.eu, http://www.alpine-space.eu

G.-M. Saulnier et al. (2011). Climatic scenarios guideline. Tech. rep. Alp-Water-Scarce project (5-1-3-F, Interreg IV B, Alpine Space Programme). URL: http://www.alpwaterscarce.eu, http://www.alpine-space.eu

7.2 Cited references

Auer, I. et al. (2007). “HISTALP-historical instrumental climatological surface time series of the Greater Alpine Region”. In: International Journal of Climatology 27.1, pp. 17-46.

Brancelj, A. et al. (2011). Monitoring and Modeling (WP6 final report). Tech. rep. Alp-Water-Scarce project (5-1-3-F, Interreg IV B, Alpine Space Programme). URL: http://www.alpwaterscarce.eu, http://www.alpine-space.eu

Bruen, M. (2008). “Systems Analysis? a new paradigm and decision support tools for the water framework directive”. In: Hydrology and Earth System Sciences 12.3, pp. 739-749.

Farinotti, D. et al. (Mar. 2010). “Snow accumulation distribution inferred from time-lapse photography and simple modelling.” In: Hydrological Processes 24, pp. 2087-2097.

Flindt Jorgensen, L. et al. (2007). ``The inadequacy of monitoring without modelling support”. In: Journal of Environmental Monitoring 9, pp. 931-942. DOI: 10.1039/B706617C

Gottardi, F. (2009). ``Estimation statistique et réanalyse des précipitations en montagne. Utilisation d’ébauches par types de temps et assimilation de données d’enneigement. Application aux grands massifs montagneux français.” PhD thesis. Docteur “Terre Univers Environnement”, Institut Polytechnique de Grenoble, 284pp. URL: http://tel.archivesouvertes.fr/tel-00419170_v1/

Gottardi, F. et al. (2008). “Regionalization of precipitations on the French mountains using local regressions and weather types - Régionalisation des précipitations sur les massifs montagneux français à l’aide de régressions locales et par types de temps.” In: Climatologie 5, pp. 7-25.

Grayson, R. and G. Blöschl (2001). “Spatial modelling of catchment dynamics”. In: Spatial Patterns in Catchment Hydrology: Observations and Modelling, pp. 51-81.

Harmoni-CA (2007). Harmonised Modelling Tools for Integrated Basin Management. Tech. rep. (Key action “Sustainable Management, Quality of Water” within “Energy, Environment, and Sustainaible Development”, EVK1-2001-00192- European Fith Framework Programme,) URL: http://www.harmoni-ca.info

Jobard, S. (2009). “Retour d’experience sur l’instrumentation d’un glacier du Baounet : quels apports de la traçabilite des mesures environnementales ?” In: Neige et glace de montagne : Reconstitution, dynamique, pratiques. Vol. 8. Collection EDYTEM - Cahiers de Geographie, pp. 157-162. URL: http://hal-sde.archives-ouvertes.fr/halsde-00404045/en/

Lundquist, J.D. and F. Lott (2008). `Using inexpensive temperature sensors to monitor the duration and heterogeneity of snow-covered areas”. In: Water Resources Research 44, W00D16. DOI: 10.1029/2008WR007035

Machguth, H. et al. (2008). `Exploring uncertainty in glacier mass balance modelling with Monte Carlo simulation”. In: The Cryosphere 2.2, pp. 191-204.

Mahmoud, M. et al. (2009). `A formal framework for scenario development in support of environmental decision-making”. In: Environmental Modelling & Software 24.7, pp. 798-808.

Maidment, D.R. (1993). Handbook of hydrology. McGraw-Hill (ISBN: 9780070397323), 1424p.

Saulnier, G.-M. et al. (2011). Climatic scenarios guideline. Tech. rep. Alp-Water-Scarce project (5-1-3-F, Interreg IV B, Alpine Space Programme). URL: http://www.alpwaterscarce.eu, http://www.alpine-space.eu

Shaw, E.-M. et al. (2009). Hydrology in practice. 4th. Taylor & Francis (ISBN: 978-0-415-37042-4), 546p.

Suette, G. et al. (2011). Water System Characterization (WP5 final report). Tech. rep. Alp-Water-Scarce project (5-1-3-F, Interreg IV B, Alpine Space Programme). URL: http://www.alpwaterscarce.eu, http://www.alpine-space.eu

Partners and Pilot Sites index

LP : IM - University of Savoie, EDYTEM, 2, 8, 12, 16, 20-24, 26, 41

PP01: SEA - Society of Alpine Economics of Upper Savoy, 2, 12, 16, 24, 26, 41

PP02: CG73 - Local Government of Savoy, 2, 12, 16, 17, 26, 40, 41

PP03: KTN - Carinthian Regional Government, 2, 12, 16, 19, 24, 26, 42

PP04: SMTK - Government of the Province of Styria, 2, 12, 16, 26, 42

PP05: Z_GIS - Paris Lodron University Salzburg, Centre for Geoinformatics, 2, 16

PP06: AWI - Bundesanstalt für Agrarwirtschaft

PP07: GAL - Development Agency Gal Genovese, 2, 12, 16, 24, 26, 42

PP08: ProvAles - Province of Alessandria, 2, 12, 16, 17, 26, 42

PP09: ProvTn - Provincial Agency for Environmental Protection, Trento, 2, 12, 16, 17, 26, 43

PP10: UNCEM - UNCEM Piemont Delegation, 2, 12, 16, 26, 43

PP11: ARPAV-DST - Regional Agency for Prevention and Protection of the Environment of Veneto - Department for the Safety of Territory, 2, 12, 16, 24, 26, 43

PP12: GeoZs - Geological Survey of Slovenia, 2, 12, 16, 24, 26, 43

PP13: NIB - National Institute of Biology; Department for Freshwater and Terrestrial Ecosystems Research, 2, 12, 16, 26, 44

PP14: Zavod MB - Slovene Chamber of Agriculture and Forestry, Institute of Agriculture and Forestry Maribor, 2, 12, 10, 16, 24, 26, 44

PP15: EWAG - Swiss Federal Institute of Aquatic Science and Technology, 2, 12, 16, 26, 44

PS01: Savoy, 12, 16, 26

PS02: Upper Arly River Basin, 12, 16, 26

PS03: Koralpe, 12, 16, 26

PS04: Karawanken, 12, 16, 26

PS05: Jauntal, 12, 16, 26

PS06: Lower Gurktal, 12, 16, 26

PS07: Styrian Basin, 12, 16, 26

PS08: Steirisches Randgebirge - Wechsel, 12, 16, 26

PS09: Entire Land Kärnten, 12, 16, 26

PS10: Pohorje with Dravsko, 12, 16, 26

PS11: Ptujsko polje, 12, 16, 26

PS12: Scrivia River Basin (Alessandria), 12, 16, 26

PS13: Julian Alps, 12, 16, 26

PS14: Piave River, 12, 16, 26

PS15: Fersina, 12, 16, 26

PS16: Noce, 12, 16, 26

PS17: Adige, 12, 16, 26

PS18: Entella River Basin, 12, 16, 26

PS19: Scrivia River Basin (Genova), 12, 16, 26

PS20: Sesia River Basin, 12, 16, 26

PS22: Spöl River, 12, 16, 26

PS23: Sandey River, 12, 16, 26

Alp-Water-Scarce