A Microcomputer-Based Alpine Snow-Cover Analysis System (ASCAS)

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Abstract
The paper describes the design of an Alpine Snow-Cover Analysis System (ASCAS) for monitoring snow-cover variations in mountainous regions. In addition to observation of snow-cover variations, the system permits derivation of interrelationships between snow cover and regional climate variables. ASCAS integrates several software modules, including image processing, geographic information systems (GIS), snow volume and runoff calculations, scientific visualization, and creation of a database. Problems involved with integrating the different modules into ASCAS and of transferring data from one module to another are discussed. Special attention is given to the necessary hardware because the integrated system is run on microcomputers. In a second part of the paper, a case study for the hydrological year 1990 shows first results of simulating snowmelt runoff using the Snowmelt Runoff Model (SRM) and of calculating snow-water equivalent for three basins in the Swiss Alps. In this study, the calculations show that the accumulated snow volume is less in the Inn/Martina basin than in the other two basins (Rhine/Felsberg and Ticino/Bellinzona) because it is drier as a result of it being a continentally influenced inner-alpine valley. Based on a temperature-increase scenario of +2°C in the Inn/Martina basin, the effects of climate change on ablation and runoff are estimated. Ablation occurs two to three weeks earlier than under present conditions, and runoff occurs about three weeks earlier, resulting in an earlier and higher snowmelt peak flow and a steeper recession flow in summer.

Introduction
Snow cover is one of the most easily recognized features in a visible-spectrum satellite image of the Earth's surface. Snow cover can be distinguished from other objects on the Earth's surface because of its relatively high albedo. As a result, the determination of the areal extent of the snow cover was one of the early accomplishments in satellite data interpretation (e.g., Rango *et al.*, 1977). Hydrologists quickly discovered the importance of satellite remote sensing data for improving the utilization of water resources (e.g., electricity production, irrigation planning, etc.).

In regions with a seasonally varying snow cover, the snowpack may store water for several months, thus causing a delay in the appearance of precipitation as runoff. In addition, in the European Alps (and other mountain snowpack regions of the world), the water from snowmelt runoff is stored in reservoirs for electricity production to be used during winter months (November through February) and during peak hours of electricity consumption (around noon). To meet the high electricity demand in Europe, many reservoirs were built in the Alps to store a significant part of the water originating from snowmelt (and glacial melt) for use later in the year.

For hydropower companies, the time and amount of the expected peak-snowmelt runoff in spring is of major interest for the operation of reservoirs. Runoff forecasting using satellite data is currently in a transitional phase but moving towards operational application (Martinec *et al.*, 1991; Kumar *et al.*, 1991). Until recently, computer power was a limiting factor in the transition to operational forecasting. Because the calculations had to be carried out on large computers, hydropower companies had little interest in adopting such procedures because of economic considerations. The development of powerful microcomputers in the last few years changed this situation in a dramatic way. It has been shown that satellite image processing and snowmelt runoff forecasting (e.g., with the Snowmelt Runoff Model (SRM) (Martinec *et al.*, 1983)) can be carried out on the same microcomputer (Baumgartner and Rango, 1991).

In addition to making forecasts of the current year's runoff, hydropower companies have also become interested in how climate change is likely to affect their operations in the future. One conclusion reached at the Second World Climate Conference in Geneva in 1990 was that climate change will affect the hydrologic cycle. Snow cover plays an important role in this context. It is likely that increasing temperatures over the next decades will influence snow-cover extent and accumulation in alpine regions. Because of different physical properties of snow cover compared to other natural features of the Earth's surface, the energy balance will change with a temperature increase (and a decrease of the snow coverage), resulting in feedback to the atmosphere. Figures 1 and 2 show differences in snow cover that were observed with satellite data in February 1982 and 1990. Figure 1 shows that in the Alps, several mountainous regions (Jura, Schwarzwald, Vosges), and even wide parts of the middle-European lowlands, are snow covered on 18 February 1982. The same region is shown in Figure 2 on 5 February 1990. By comparing the two figures, it becomes clear that most of the lower regions are snow free in 1990. This reduced snow-cover situation is representative not only for February 1990 but for most of the period 1987-1992. It is obvious that such changes

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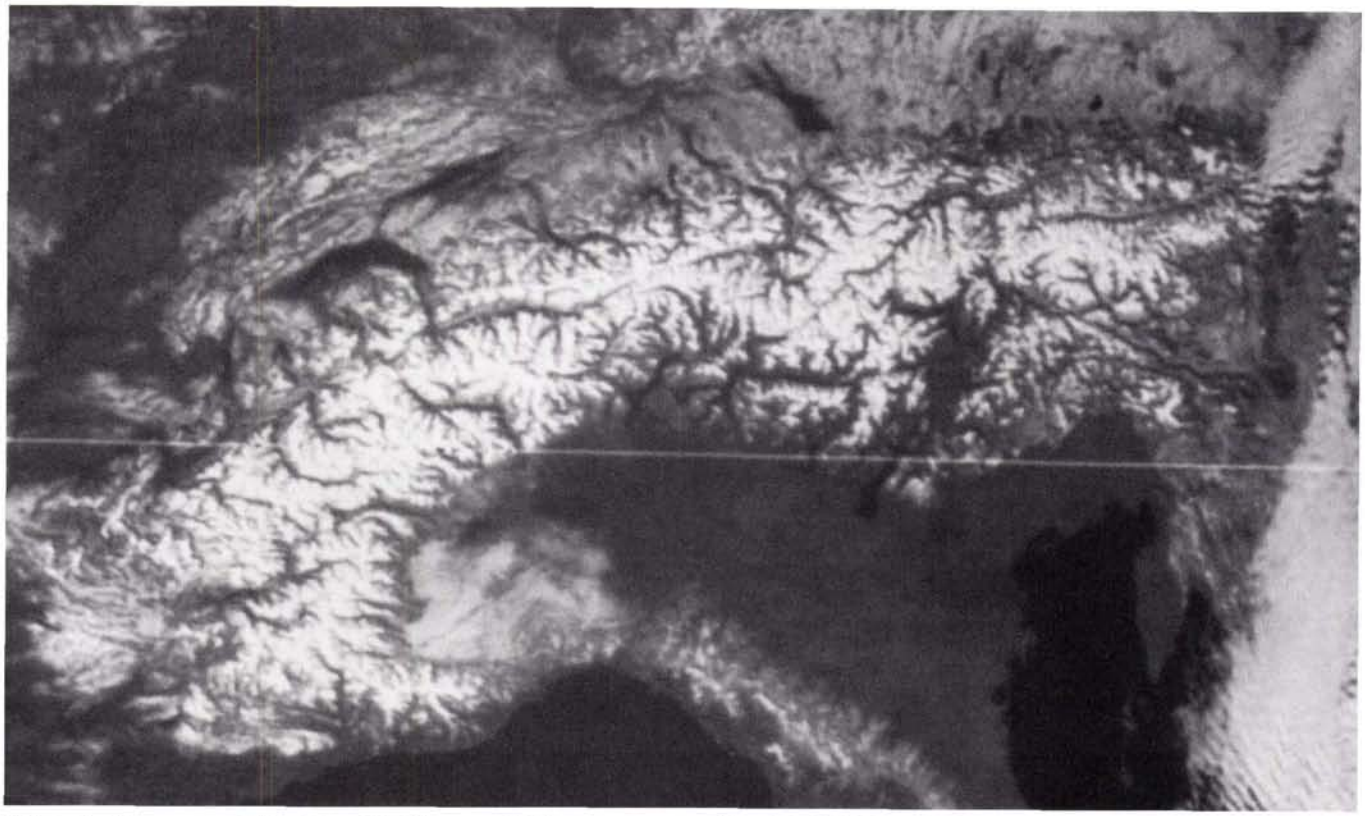


Figure 1. Snow cover in the Alps, 18 February 1982, NOAA-7/AVHRR, Band 2 (0.725 to 1.10 μm). (Source: Department of Geography, University of Berne, Switzerland).

Figure 2. Snow cover in the Alps, 5 February 1990, NOAA-11/AVHRR, combination of Bands 1 (0.58 to 0.68 μm) and 2 (0.725 to 1.10 μm). (Source: Department of Geography, University of Berne, Switzerland).

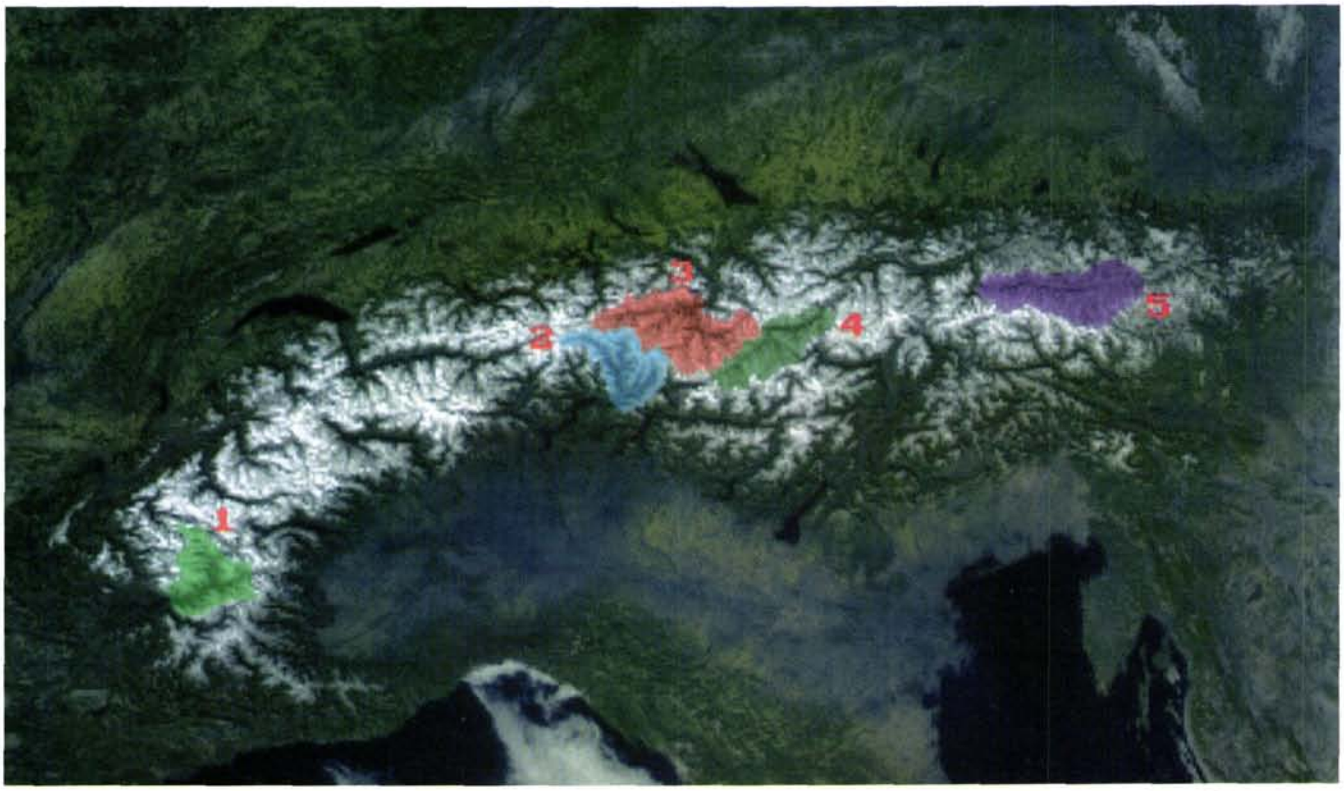


Plate 1. Test basins superimposed onto a NOAA-AVHRR scene. Durance, France (1), Ticino-Bellinzona, Switzerland (2), Rhine-Felsberg, Switzerland (3), Inn-Martina, Switzerland (4), and Salzach-St. Johann, Austria (5). (Source: Department of Geography, University of Berne, Switzerland).

have environmental and economic consequences (especially if they persist for extended periods of time): the electricity production from snowmelt will decrease if less snow is available for melting. Consequently, prices are expected to increase if other sources of energy cannot supplement these losses. Additionally, winter tourism, one of the most important business endeavors in the Alps, will suffer adversely from too little snow in existing ski areas.

The net effect of future climate change (temperature, precipitation, radiation, clouds) on snow-cover variations and on the economy is unknown and is an important topic for more intensive study. The study presented here monitors snow-cover variations in the Alps and surrounding lowlands over an extended time period through the development and testing of an integrated Alpine Snow-Cover Analysis System (ASCAS). ASCAS integrates several software modules, including image processing, geographic information system (GIS), hydrologic modeling, and database management. A useful tool for spatial analysis of the changing snow-cover situation is the combination of remote sensing and GIS technology to provide an established method for spatial data analyses. For storing and managing large amounts of data, a database is included, and for snowmelt and snow volume calculations, the SRM model is integrated into the system. This paper presents the initial results and problems of developing such an analysis system in a microcomputer environment, the integration of the different modules, and the interaction between the different modules.

Snow-Cover Study Areas in the Alps

In this study, snow-cover variations are monitored in two different ways: (1) monitoring of annual and seasonal snow-cover variations over most of the Alps (from Nice to Vienna, or about 1300 km in distance) and the pre-alpine lowlands (including regions in France, Italy, Switzerland, Austria, and Germany); and (2) monitoring of the areal extent of the snow cover for specific basins to allow more quantitative analyses of snowmelt runoff and water equivalent variations and to postulate future trends of climatic change. Therefore, selection of several study basins was necessary. Major emphasis in selecting these basins was based primarily on the availability of runoff and meteorological records and secondarily on prior experience in runoff simulation and forecasting in a particular basin. Additionally, the basins had to be distributed over different climatic regions of the Alps in order to investigate whether the consequences of climate change are regionally different or whether the Alps are influenced as a whole. The following five study basins were selected (Plate 1):

- *Durance (France).* This basin has an area of 2170 km^2 and an elevation of 786 to 4105 m (this and all subsequent elevations are in metres above mean sea level, unless otherwise noted) and represents the climate of the western Alps (influence of moist westerly winds with high precipitation rates and an early increase of temperatures in spring). Runoff simulations have been carried out for several years during a World Meteorological Organization test (WMO, 1986).

TABLE 1. PARAMETERS OF THE NOAA-AVHRR SYSTEMS

Altitude		833 - 870 km
Inclination		98.9 degree
Repetition rate for 1 orbit		102 minutes
Orbits per day		14.1
Field of view (FOV)		55.4 degrees
Instantaneous FOV (IFOV) at nadir		1.1 km (1.3 m rad)
Swath width		2600 - 3000 km
Radiometric resolution		10 bit
Spectral resolution,	Band 1	0.58 - 0.68μm
	Band 2	0.725 - 1.10μm
	Band 3	3.55 - 3.93μm
	Band 4	10.3 - 11.3μm
	Band 5*	11.5 - 12.5μm

*for odd numbered satellites in the series

- *Ticino-Bellinzona (Switzerland).* This basin (1515 km², 220 to 3402 m) is located in the central Alps, but it is more representative of a southern alpine climate (high precipitation rates, higher temperatures). Runoff simulations exist only for one year (Baumgartner *et al.*, 1991).
- *Rhine-Felsberg (Switzerland).* With an area of 3249 km² and an elevation range of 571 to 3614 m, this basin is also located in the central Alps with a climate similar to that of Ticino-Bellinzona but with a later increase of temperature in spring. Swiss investigators have simulated runoff for several years on this basin (Baumgartner *et al.*, 1986; Baumgartner, 1990; Baumann *et al.*, 1990).
- *Inn-Martina (Switzerland).* This basin has an area of 1943 km² and an elevation range of 1030 to 4049 m. It is located in the central Alps and represents an inner-alpine valley with continental character (dry, low temperatures in winter). Only runoff simulations exist for this basin (Baumgartner *et al.*, 1991).
- *Salzach-St. Johann (Austria).* This basin (2600 km², 570 to 3666 m) is representative of the eastern Alps. It is affected by both moist westerly winds and the continental east-European climate, resulting in wet (high precipitation rates) and dry periods with low temperatures. No prior snow-cover mapping or runoff simulation experience exists for this basin.

These five basins should provide adequate information for determining whether the effects of climate change will vary in different parts of the Alps. If further information is required, additional basins can be selected in the future.

Data Sources

The basic source of data for observing and monitoring snow-cover variations in the Alps is the Advanced Very High Resolution Radiometer (AVHRR) of the NOAA weather-satellite series. The NOAA-AVHRR data possess major advantages compared to other systems: the spatial (1.1 km by 1.1 km near nadir) and temporal (12 hours; usually 6 hours with two satellites) resolutions are appropriate for the scale of this study. For a given basin, at least one to two images per week can be used for snow-cover evaluations even with the normally frequent cloud cover of the Alps. Table 1 gives an overview of the most important parameters of the NOAA-AVHRR series (Barnes and Smallwood, 1982; Kidwell, 1991). Other satellite systems (e.g., Landsat, SPOT) allow more detailed analyses, but, because of poor temporal resolution, these systems can only supplement the AVHRR data.

For the Alps, the access to NOAA-AVHRR data and especially to archives for the past years is guaranteed because a receiving station for NOAA-AVHRR-HRPT (High Resolution Picture Transmission) data is located at the University of Berne in Switzerland (Baumgartner and Fuhrer, 1991). The archives date back to 1981, allowing analyses and interpretations for the last ten years. For this study, however, we focus on a year with average snow conditions (1982) and one with a markedly reduced snow cover (1990).

At the same time in North America, satellite snow-cover data have become more and more available and are now distributed in near real time for over 4000 river basins in the United States and Canada (Carroll, 1993). Data from both the AVHRR on the NOAA polar orbiting satellites and data from the Geostationary Operational Environmental Satellite (GOES) are processed by the National Operational Hydrologic Remote Sensing Center (NOHRSC) of the U.S. National Weather Service in Minneapolis, Minnesota. The image processing is accomplished on minicomputers, and the data are distributed electronically to users in both alphanumeric and image format by basin and elevation zone. The satellite snow-cover maps are available to end-users in personal computer compatible format and in a raster format for use in geographic information systems or digital image processing systems (Carroll, 1993). The Alpine Snow Cover Analysis System (ASCAS) differs from the NOHRSC system in that ASCAS is microcomputer based, all functions are carried out on the same computer, and ASCAS has an integrated snowmelt runoff model that directly accepts the satellite snow-cover data.

Other sources of data have also become available over the last decade: (1) daily climate data such as air temperature (maximum/minimum), precipitation, and snow depth (at least one station within or near each basin); (2) daily runoff data from stream gauges in the different basins; (3) daily records of reservoir management by hydropower companies; (4) digital elevation model (DEM) data; and (5) topographic maps for extracting elevation zones, basin and subbasin boundaries, and ground control points for geometric corrections.

Climate data are widely available for Europe. Because several countries collect data separately, however, time consuming procedures are required to extract the information for the Alps. For the determination of the accuracy of runoff simulations, measured and calculated runoff are compared. Because the measured runoff is influenced by reservoir operations, the natural runoff must be reconstructed on a daily basis by taking into account reservoir operation records for each basin. Table 2 gives an overview of the selected reservoirs. The following example gives an impression of the magnitude of these influences and shows the importance of making a correction. On 27 June 1985, a discharge volume of $33{,}000 \cdot 10^6 m^3$ was measured at the Rhine/Felsberg stream

TABLE 2 RESERVOIRS WITHIN THE THREE SWISS TEST BASINS

Basin	Power Station	Lake	Volume
Rhine	Vorderrhine	Lai di Sta Maria	$67 \cdot 10^6 m^3$
		Lai da Nalps	$45 \cdot 10^6 m^3$
		Lai da Curnera	$42 \cdot 10^6 m^3$
	Zervreila	Zervreilasee	$100 \cdot 10^6 m^3$
	Hinter-Rhine	Lago di Lei	$197 \cdot 10^6 m^3$
		Sufnersee	$18 \cdot 10^6 m^3$
	City of Zurich	Marmorerasee	$60 \cdot 10^6 m^3$
Ticino	ATEL, Airolo	Lago di Lucendro	$25 \cdot 10^6 m^3$
		Lago di Sella	$9 \cdot 10^6 m^3$
	Swiss Railway	Lago di Ritom	$48 \cdot 10^6 m^3$
	Blenio	Lago Luzzone	$87 \cdot 10^6 m^3$
		Lago di Malvaglia	$4 \cdot 10^6 m^3$
	Misox	Lago del Isola	$6 \cdot 10^6 m^3$
Inn	Engadin	Lago di Livigno	$164 \cdot 10^6 m^3$

gauge. The corrected runoff amounts to 49,000·10⁶m³; that means that 33 percent less runoff was measured than would have been measured under natural conditions; i.e., a volume of 16,000·10⁶m³ was stored in reservoirs. On 4 April 1982 a discharge of 11,000·10⁶m³ was measured that was 83 percent more than would have occurred under natural conditions, i.e., a volume of 5000·10⁶m³ was released from the reservoirs for electricity production.

A digital elevation model (DEM) with a spatial resolution of 250 m × 250 m and an elevation resolution of 20 m is available from the Swiss Army covering a part of the Alps. Certain parts of the Salzach basin have to be supplemented. Topographic maps of the Alps and of the different basins are used for digitizing regions of interest such as basin boundaries, sub-basins, elevation zones, rivers, and lakes. The maps are also used for selecting ground control points for geometric corrections of image data onto a common map projection system. Such a common map projection system is essential because most of the European countries use different map projection systems.

System Configuration

Until recently, processing of satellite data and modeling of snowmelt runoff had to be carried out on mini or mainframe computers. During the past three to four years, however, microcomputer-based systems have become widely available. Processing speed and storage capacity are rapidly increasing while costs are decreasing. It has been shown that both satellite image processing and snowmelt runoff modeling using the SRM model can be run on the same microcomputer (Rango and Roberts, 1987; Baumgartner and Rango, 1988, 1991; Rango, 1989). The integration of all these processing procedures into an operational runoff forecasting system using microcomputers is envisaged to make the system economically attractive for hydropower companies and for other users of hydrological and environmental models.

ASCAS is being developed in a microcomputer environment with the aim of making quantitative estimates of variables and effects associated with climate change, e.g., increase of snow-line elevation, decrease of snow water equivalent, regional distributions of such changes, and scenarios for future changes. In developing ASCAS, we focused on the integration of existing software into one system. The microcomputer-based, integrated ASCAS system is being put together from five basic software modules (Figure 3): an image processing module, a GIS module, the SRM module, a database module, and a scientific visualization module.

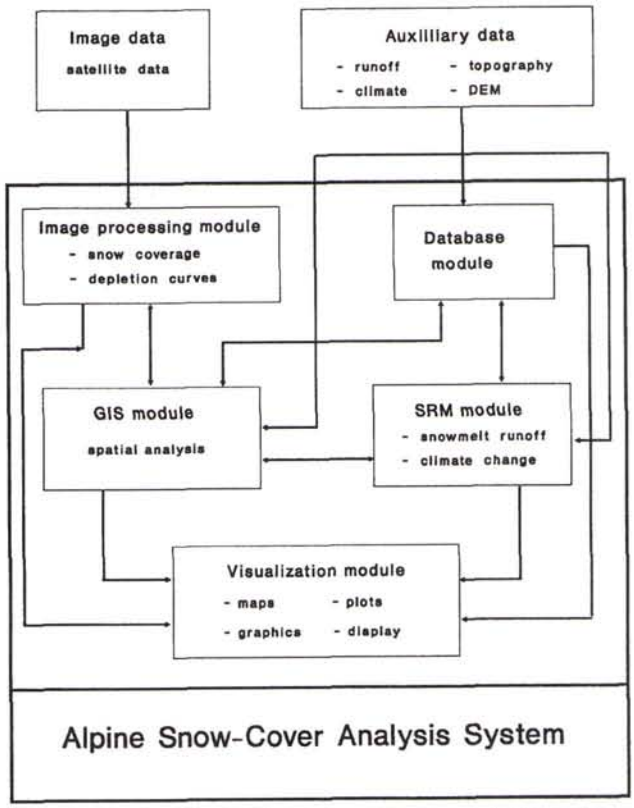


Figure 3. Software modules for a microcomputer-based, integrated system for snow-cover mapping, snowmelt runoff forecasting, and GIS analyses.

Ehlers *et al.* (1989) show in their paper that remote sensing and GIS should be seen as "one entity, concerned with handling and analyzing geographic data." Nevertheless, conventional approaches are far from a single data collection and analysis system. Due to the complexity and variety of the different data and the wide variety of user requirements, it is not feasible to use only one software package (Olivier *et al.*, 1990). Therefore, it is deemed essential to design ASCAS as a modular system fulfilling the following tasks (Ehlers *et al.*, 1989; Piwowar and LeDrew, 1990; Ahearn *et al.*, 1990):

- user-friendly, standardized menu-driven interfaces for all modules designed so that the interpreter does not have to deal with system specific problems.
- the system must permit the input of a variety of different data (image data, meteorological data, topographic data, etc.).
- the system must allow the exchange of data between the different modules.
- the image processing module must allow (a) input of image data; (b) input of auxiliary data (e.g., topographic information); (c) input of GIS and SRM data; (d) processing of image data (multitemporal, multispectral); and (e) transferral of image processing results to GIS and SRM.
- the GIS module has to guarantee (a) integration of data without major limitations in size and variety; (b) input of data from the image processing module and scanned data; (c) input of auxiliary data (digitized data as elevation lines, ASCII files, DEM data and their manipulation, etc.); (d) input of SRM results; (e) spatial analyses (scenarios); (f) internal and external database management (storing, retrieving, updating); and (g) transfer of data to the image processing and SRM module.
- the SRM module must make possible (a) input of auxiliary data (e.g., meteorological data); (b) input of results from the image processing module; (c) runoff simulation/forecasting; (d) climate change modeling; and (e) transfer of results to the GIS module.
- the database module has to provide external storage of meteorological and hydrological data (database management: storing, retrieving, updating).
- the visualization module must read and display (plot and print) data from all the other modules as well as original data. In addition, this module must be able to derive graphical representations of statistical analyses.

The hardware configuration of the system is based on an 80486/33 Mhz microcomputer with a frame buffer (1024 by 1024 by 32 bit) and a high-resolution RGB monitor (19-inch) for satellite image processing and display (Baumgartner and

Rango, 1991), and a VGA board and I/O-color monitor for GIS manipulation and display. A high-capacity hard disk of 1.2Gb is a basic need, especially due to the large amount of satellite data (raster data) and the size of the database. For storing this amount of data, an optical disk (600Mb) is required. Additionally, a digitizing tablet (36 by 48 inches), a color pen plotter, and a color printer are necessary for graphic and iconic output. Figure 4 gives an overview of the hardware configuration proposed for the ASCAS on a microcomputer-based integrated system.

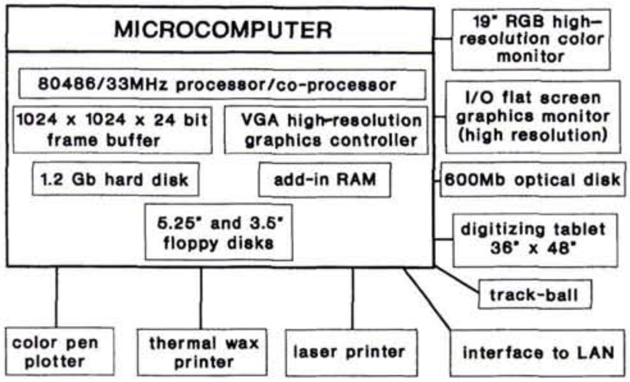


Figure 4. Hardware configuration for the microcomputer-based Alpine Snow-Cover Analysis System.

The Alpine Snow-Cover Analysis System (ASCAS)

The following section discusses some of the most important aspects which have to be considered in building the ASCAS. In practical work, many of the procedures described below are carried out in parallel and depend on each other. For a better understanding, the processes are described in the following order: analyses of satellite data, integrating data into the GIS, operating SRM, spatial and temporal analyses, and visualization of results.

Analyses of Satellite Data

Processing of satellite data can be based on many different methods. Supervised classification techniques are widely accepted. Unsupervised techniques are also frequently used; however, they are usually limited to relatively flat regions. Classification by the supervised learning approach (for theory, see Duda and Hart (1976)) was used in ASCAS because of the complexities involved with mountainous regions. It allows a precise separation between snow-covered and snow-free areas. A disadvantage is that this method is not fully automatic, i.e., the interpreter has to control the process and field training sites have to be used. The methods of extracting snow cover from satellite data are not described here but can be found in Keller (1987) or Baumgartner (1990).

For deriving snow-cover variations for a specific basin during a hydrological year (1 October to 30 September), it is necessary to have at least two to three images per snowmelt season and preferably more. As it has been shown, this can be achieved by using NOAA-AVHRR data. The entire range of the Alps are seldom cloud free at one time. Therefore, the snow-cover maps for the entire mountain range have to be mosaicked based on several satellite images from different days during the week. A basic condition for such a regional mosaic is that only images without new snowfall (e.g., snow having fallen with 48 hours prior to the satellite observation) be included. The result of processing a satellite image is a thematic map representing snow-covered and snow-free areas. For showing the seasonal variations of snow cover, i.e., accumulation and ablation, multitemporal evaluations are necessary. Plates 2a to 2e show a sequence of five snow-cover maps during the 1985 ablation period. These thematic maps are stored as bit-maps, transformed from raster into vector data, and then integrated into the GIS.

Integrating Data into the GIS

The most important part of integrating data into the GIS is to become familiar with the characteristics of the available GIS and to design a scheme for structuring the data. It is important to decide which data have to be integrated into the GIS. When using microcomputers, this question is especially crucial. Too much data make the system too slow and prevent efficient work. Therefore, it was decided to have an external database—in addition to the one in the GIS—where infrequently used large data sets, such as daily temperature, precipitation, runoff, and snow depth, are stored on an optical disk.

One of the basic questions in the utilization of a GIS is a geometric one: which scale and which map projection system are optimum? In our study, the scale is determined by the ground resolution of the AVHRR system (1.1 km by 1.1 km). Consequently, a map showing the entire Alps range with a scale of 1:750,000 was found to be acceptable for showing snow-cover variations. The data to be digitized are extracted from 1:200,000-scale topographic maps and, in special cases, from 1:50,000-scale maps.

Because most alpine countries have different map projection systems, all data from 1:200,000-scale maps (or larger) must be transformed to the 1:750,000-scale map which uses an Albers conical equal-area projection. The equal-area condition is essential for the areal computations. Table 3 summarizes the different map projection systems used.

The satellite data also needed to be transformed into this Albers map projection. The geometric transformation of AVHRR data is based on the ground control point approach and has to account for panoramic distortion due to the large field of view of the sensor (Frei, 1984). The transformation can also be carried out during the transfer procedure from the image processing to the GIS module.

A collection of all data layers—area, line, and point—that will finally be integrated into the GIS is listed in Table 4. The source of the information is given in parentheses. All data should be left in their original form and converted only when required (Piwowar *et al.*, 1990). All the data layers are supplemented by attributes that give specific information relative to each feature and that allow the retrieval and update of a specific piece of information through accessing the external database. A meteorological station could be characterized by an informal meta-attribute sheet as shown in Table 5. The data belonging to a specific station are stored in the external database and can be called up on request by utilizing an access code. Plate 3 gives an impression of several layers and of the associated attributes.

Operating SRM

Using SRM (Martinec *et al.*, 1983), snowmelt runoff simulation (and forecasting) is carried out for two reasons: (a) to derive estimates of daily runoff and the seasonal runoff hydrograph and (b) to determine areal snow-water equivalent. Both types of information will give quantitative input on the influence and interaction of temperature and precipitation with snow cover in the Alps. SRM proved to give good results in such studies (WMO, 1986). Because the results of many SRM application-oriented projects have been published (e.g., Baumann *et al*, 1990; Kumar *et al.*, 1991), SRM and its use are not outlined in detail here. Briefly, SRM is based on the degree-day approach using daily temperature (minimum, maximum), precipitation, and snow-cover charts (derived from satellite data) as input variables. With SRM, simulation and forecasting of the snowmelt runoff in alpine basins is possible as well as an estimation of the snow volume in a specific basin or elevation zone after the melt season has been completed. Because SRM is a simple model, melt from glaciers is handled much in the same way as melt from a snow field. The major differences are that higher runoff coefficients are used for glaciers and the melt season extends longer than for snowmelt. In a recently developed procedure (Rango and Martinec, 1994), the influence of temperature and precipitation changes on snow cover in the changed climate can be calculated.

From the multitemporal set of snow-cover layers in the GIS, snow-cover variations during a hydrological year can be derived. Because the ablation period is of special interest for runoff calculations, snow-cover depletion curves are extracted and input into SRM.

In a first step, interannual variations of the snowmelt runoff may be studied. Secondly, the snow reserves at the beginning of the melt period can be calculated. The areal snow-water equivalent is derived for each of the five basins as well as for several elevation zones (sub basins) within each basin. The comparison of similar elevation zones of the different basins gives an estimate of the climatic differences between the basins under investigation, i.e., western, central, and eastern Alps. These data are transferred to the GIS where similar elevation zones are compared related to regional and temporal variation of the water equivalent. For both snowmelt runoff and snow-water equivalent, scenarios of the influence of different temperature and precipitation patterns on snow cover are calculated, and the results are transferred to the GIS. In the next section, some of these results are discussed and graphically displayed.

Even for the SRM module, a user interface must exist, allowing SRM to have access to the external database and to the GIS for retrieving the necessary input variables: temperature in °C (TMAX, TMIN), precipitation in cm (PRECIP), and snow-covered area in fraction of zone (SNOW). Additionally, it must be possible to update the database and the GIS with results from SRM calculations. The results of snowmelt runoff simulations are transferred to the GIS only when needed for calculations, keeping the GIS flexible and not overloaded with too much data.

Table 3. Summary of Map Projection Systems and Parameters

France: Lambert conical conformal with three standard parallels (55°N, 52°N, 49°N), longitude of central meridian (2°20'14"E), based on Clark's ellipsoid
Switzerland: Oblique Mercator cylindrical conformal, latitude and longitude of projections origin (46°57'07.9" N and 7°26'22.3"E), false easting and northing (600,000 and 5,022,276.9), based on Bessel's ellipsoid (semi major and minor axis: 6,377,397.16 and 6,356,078.96)
Austria: Gauss-Krueger conical conformal with three central meridians (10°20'E, 13°20'E, 16°20'E), latitude of standard parallel (0°N), based on Bessel's ellipsoid (semi major and minor axes: 6,377,397.16 and 6,356,078.96)
Map of the Alps: Albers conical equal-area, latitude of first and second standard parallel (40°N and 62°N), longitude of central meridian (10°35'E), latitude of projections origin (51°N), based on Clark's ellipsoid

Table 4. List of Data Layers Used in the GIS

(a) area layer
- snow cover (from satellite data)
- snow volume (from satellite data and SRM)
- forest (from satellite data)
- lakes (from topographic maps)
- reservoirs (from topographic maps)
- basin boundaries (from topographic maps)
- elevation zones (from topographic maps)

(b) line layer
- rivers (from topographic maps)
- coast lines (from topographic maps)
- elevation contours (from topographic maps)

(c) point layer
- meteorological stations (geographic coordinates)
- stream gauges (geographic coordinates)

Table 5. Meta-Attribute Sheet Providing Information for a Point Data Meteorological Station

station name: SCUOL
second name: INN, SWITZERLAND
station code: 9849
longitude: 10°17'E
latitude: 46°48'N
elevation: 1298 m
variables: TMAX, TMIN, PRECIP., SNOW
period: 1931-1991
access code: \COUNTRY\BASIN\LOCATION\VARIABLE\YEAR

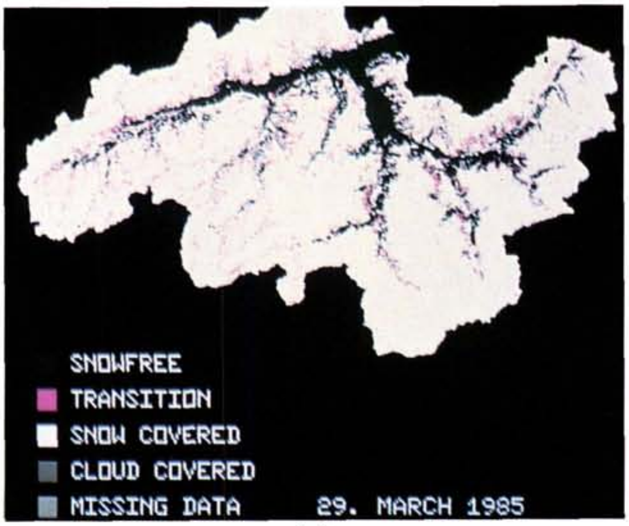
Spatial and Temporal Analyses

The aim here is to analyze and interpret the data integrated into the GIS, to simulate the changing temperature and precipitation, and to design scenarios for the impact of climate change on alpine snow cover and subsequent runoff.

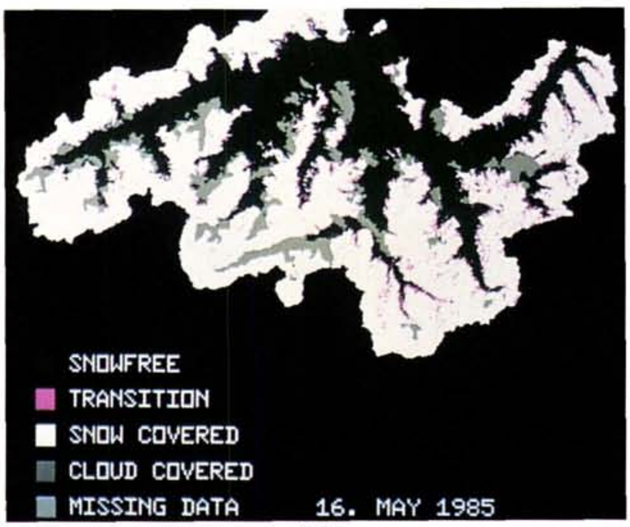
A first step is the derivation of snow-cover and snowline variation during the accumulation and ablation period for specific years (e.g., snow-rich/snow-poor years) and specific elevation zones. Therefore, the snow-cover layers are superimposed upon the region-of-interest masks as basin boundaries and elevation zones. The elevation zones can either be derived from a digital elevation model or digitized from topographic maps.

In Figure 5, snow-cover variations for the winter of 1989/1990 are presented for the three Swiss basins. Based on these data, snow-cover depletion curves for the ablation period are derived which serve as input into SRM for snowmelt runoff simulations and snow-volume estimations. In Figure 6, the depletion curves for the two upper elevation zones (A: 1100 to 2100 m; B: greater than 2100 m) in the Inn/Martina basin for 1990 are displayed.

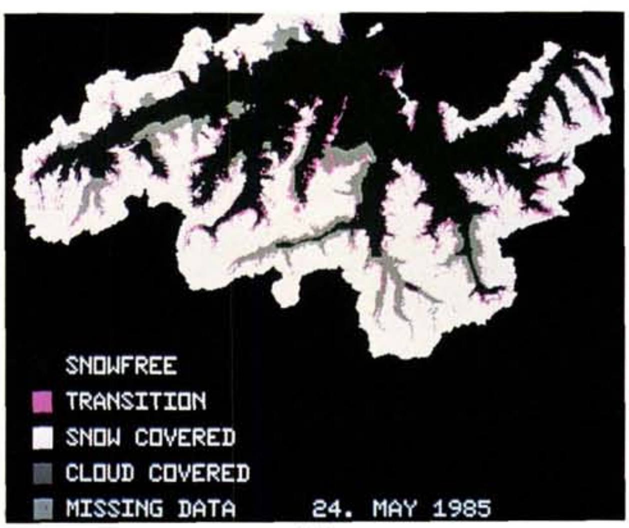
Furthermore, snow-cover maps and region-of-interest masks can be overlayed with the elevation model for determining the snowline variations depending on the elevation above sea level (Figure 7). It should be noted that, during the 1989/1990 hydrological year in all the Swiss basins, the snowline was never below 1600 m, which represents an unu-



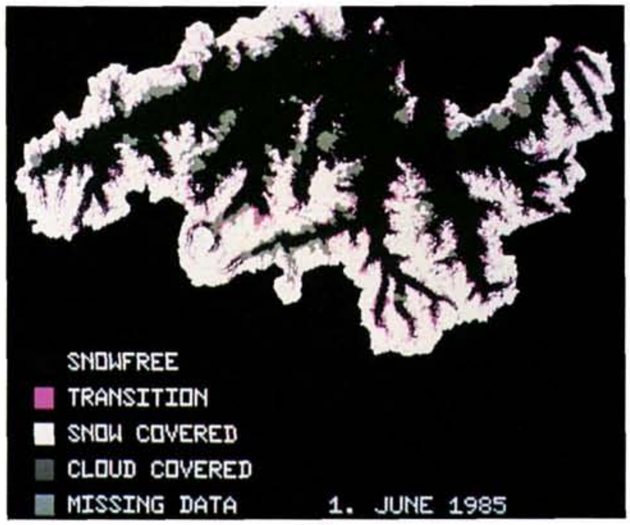
(a)



(b)



(c)



(d)

(e)

Plate 2. Satellite-derived snow-cover maps for the Rhine/Felsberg basin in 1985 (Baumgartner, 1990): (a) 29 March, (b) 16 May, (c) 24 May, (d) 1 June, and (e) 3 July.

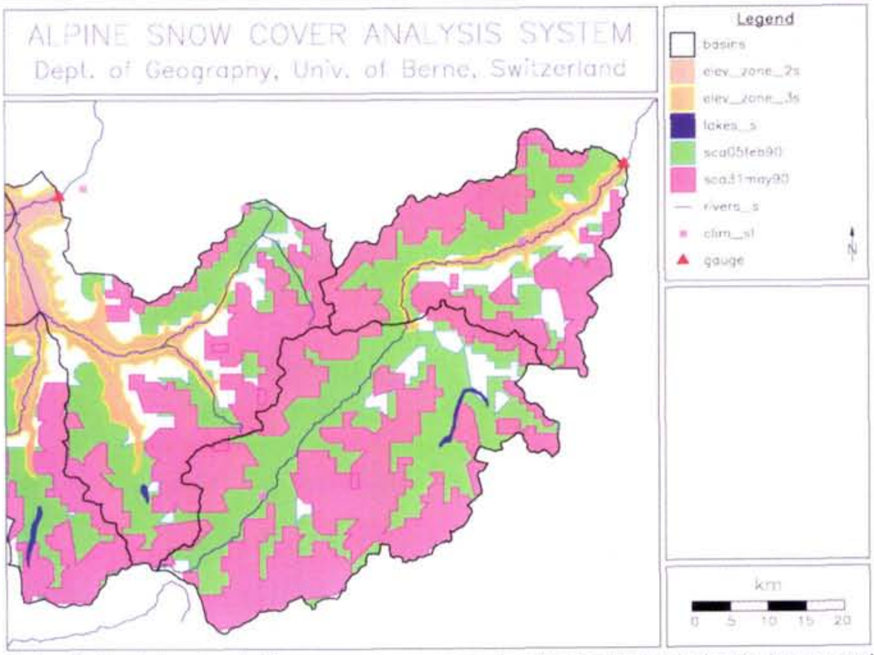


Plate 3. Vectorized satellite snow-cover maps for the Inn/Martina basin integrated into the GIS for 5 February 1990 and 31 May 1990.

sual situation (Schoenenberger, 1991). In a typical winter, persistent snow cover is expected even in the lowlands (200 to 800 m). Comparison of snowlines in elevation zones and basins over several years allows conclusions concerning actual variations and climatic differences between the basins.

As mentioned in the previous section, snow-cover depletion curves can be transferred to SRM for snowmelt runoff simulations or climate change calculations. The other data (TMIN, TMAX, PRECIP.) necessary for the comparison of the snow-water equivalent are extracted from the external database. Figure 8 shows an example for such a simulation in the Inn/Martina basin (1990). The calculated runoff is compared with the actual measured runoff after the actual runoff had been corrected for reservoir manipulations (see Data Sources section).

For a comparison of the climatic differences between the basins, modified depletion curves (MDC) are calculated (Martinec, 1985). Figure 9 compares the MDCs of the three Swiss basins—Rhine/Felsberg, Ticino/Bellinzona, and Inn/Martina (in the middle elevation zone (1100 to 2100 m) 1990). Integrating the area below the curve results in snow reserves (volume) at the beginning of the ablation period (1 April 1990). It can also be noted that the Rhine/Felsberg and Ticino/Bellinzona basins have in the middle elevation zone a significantly higher snow volume than does the Inn/Martina basin. This reflects expectations because the climate of the Inn/Martina basin is clearly continentally influenced (inner-alpine valley), i.e., it is much drier than the other basins.

The influence of temperature and precipitation changes on the snow coverage can be calculated following the procedure proposed by Rango and Martinec (1994). A scenario for a temperature increase of +2°C can be designed (van Katwijk and Rango, 1991). Using SRM and the submodule "climate change" allows the calculation of runoff and water equivalent for a specific zone or basin. The same is possible for any other changes in temperature or precipitation. Consequently, the hydrologic and climatic situation within and between basins can be compared before and after climate change, and the consequences for hydropower generation and tourism in the Alps can be estimated. Figures 10 and 11 give schematic representations of the consequences of a simulated increase of +2°C air temperature on snow cover and on runoff in the

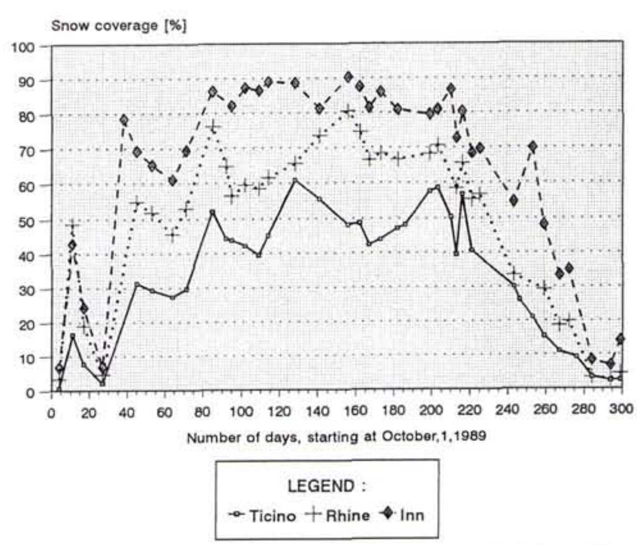


Figure 5. Snow-cover variations in the Rhine/Felsberg, Ticino/Bellinzona, and Inn/Martina basins, Switzerland during the winter 1989/1990.

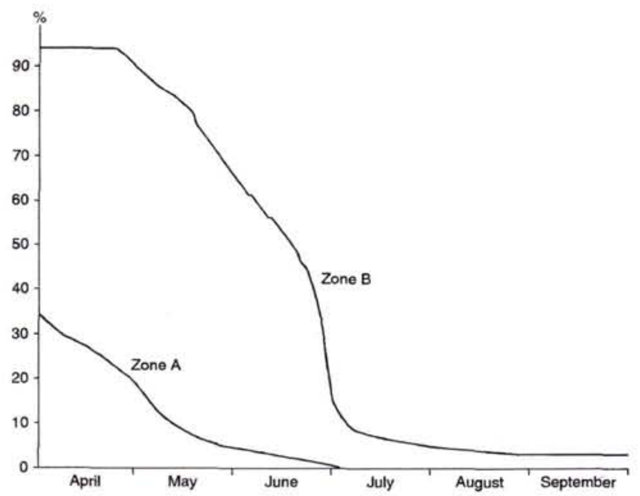


Figure 6. Snow-cover depletion curves in the Inn/Martina basin, Switzerland (1990) for zones A (1100-2100 m) and B (> 2100 m).

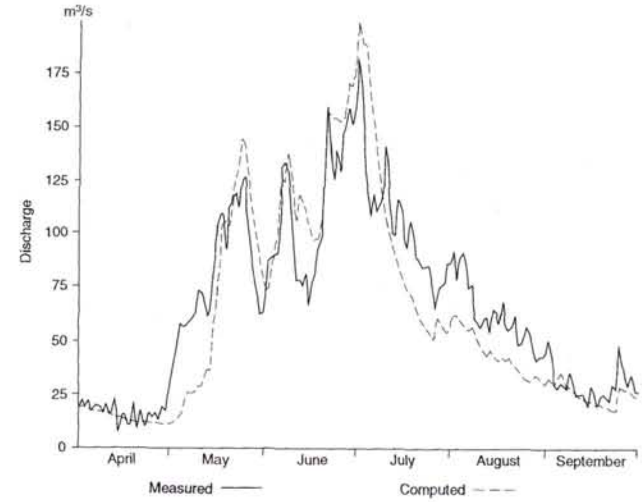


Figure 8. Snowmelt runoff simulation in the Inn/Martina basin, Switzerland (1990).

Inn/Martina basin. It must be noted that no changes in precipitation patterns and no changes in model parameters were assumed. Ablation occurs two to three weeks earlier than under present conditions (Figure 10). Consequently, runoff also increases about three weeks earlier, resulting in an earlier and higher snowmelt peak flow and a steeper recession flow in summer (Figure 11). Similar results were reported from basins in the U.S. (van Katwijk and Rango, 1991). Such a scenario means a change in the production of electricity for water power stations and adaption to the new snow distribution for winter tourism.

Visualization of Results

For the visualization of data and results, there are several possibilities. The most convenient way of checking the accuracy is displaying results on a color monitor (RGB or I/O). High resolution color monitors are, therefore, a basic need. For graphical representations of data (e.g., air-temperature vs. time) or statistical output (e.g., tables), conventional laser printers can be used. For best results, two different options have to be available: (a) a high resolution color pen plotter is

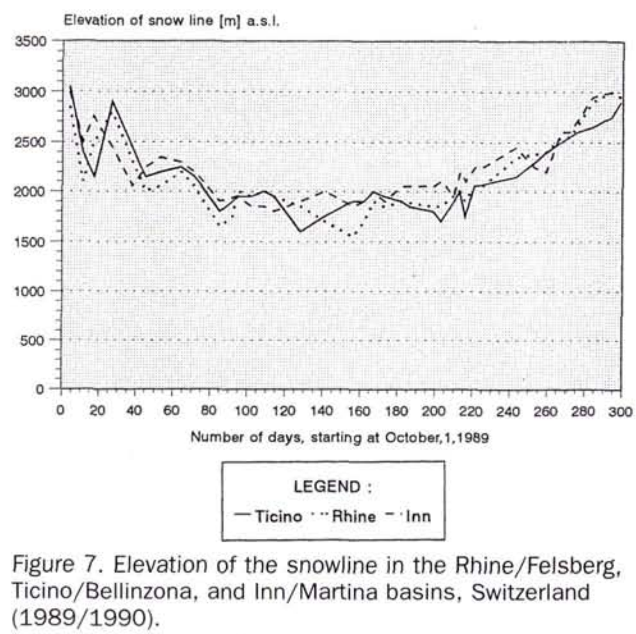


Figure 7. Elevation of the snowline in the Rhine/Felsberg, Ticino/Bellinzona, and Inn/Martina basins, Switzerland (1989/1990).

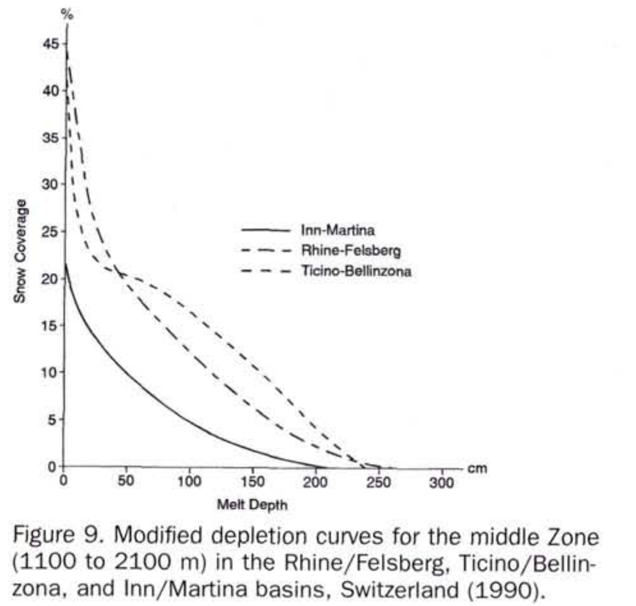


Figure 9. Modified depletion curves for the middle Zone (1100 to 2100 m) in the Rhine/Felsberg, Ticino/Bellinzona, and Inn/Martina basins, Switzerland (1990).

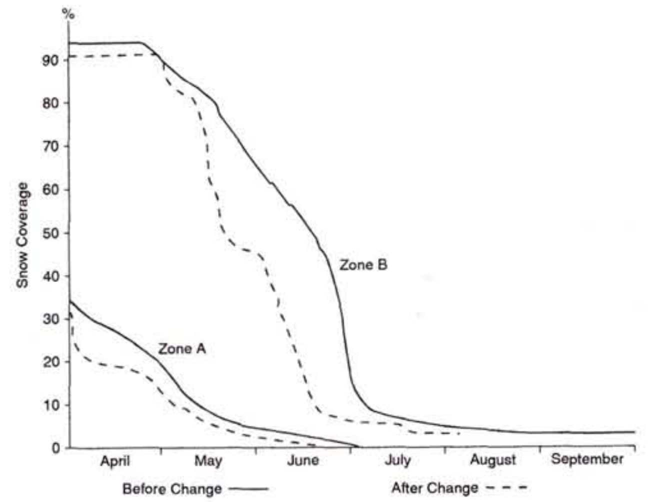


Figure 10. Comparison of depletion curves before and after a +2°C climate change in the Inn/Martina basin, Switzerland (1990).

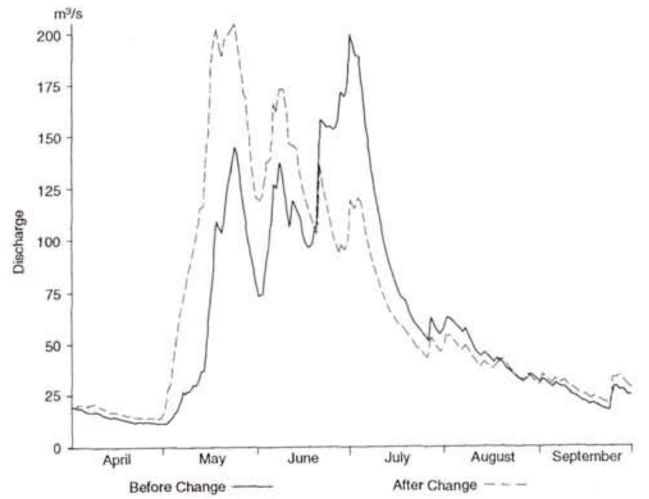


Figure 11. Comparison of snowmelt runoff before and after a +2°C climate change in the Inn/Martina basin, Switzerland (1990).

used for GIS output and (b) a high resolution color printer is useful if raster (image data) and vector data are superimposed for output.

In using this module, the interfaces between the different modules and between the user are essential. The user must be able to print out the following data:

- satellite data,
- data and results from the database,
- results from the SRM module,
- data and results from the GIS,
- combinations of satellite and GIS data and results, and
- statistical output.

In addition, the module must enable the user to retrieve graphical representations of statistical analyses.

Conclusions

The ASCAS is designed and assembled using satellite snow-cover data, meteorological data, runoff data, and topographical information. All processing procedures necessary—such as image processing, GIS scenarios, database evaluations, and runoff modeling—are integrated into a microcomputer-based system.

In general, it is feasible to run such an integrated system on state-of-the-art microcomputers. Major limitations are related to the man-machine interface and the interfaces between the different software modules. The following recommendations for facilitating the interpreter's work are stated:

- the transfer of data to and from the image processing and GIS modules, though possible, must be simplified;
- the transfer from the image processing to the SRM module is not operational; therefore, an interface will be designed;
- for the input of auxiliary data, interfaces have to be designed individually because the format of these data vary widely; and
- visualization is possible in most cases but should be coordinated between all the software modules.

Initial results of the influence of climate change on alpine snow-cover and runoff patterns are presented. For three basins in the Swiss Alps, snow-cover classifications during a case study (1990) were carried out and transferred to the GIS module. Snow volume calculations with SRM show the climatic snow accumulation differences between the three basins. Assuming a climate change scenario with a temperature increase of +2°C, the influence on snow-cover and runoff patterns is shown. In such a case, snowmelt would start about three weeks earlier than under average conditions, requiring a change in the management strategy for hydropower reservoirs. For winter tourism, a shorter season (i.e., economic losses) would be expected.

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References

Ahearn, S.C., J.L.D. Smith, and W. Catherine, 1990. Framework for a Geographically Referenced Conservation Database: Case Study Nepal, *Photogrammetric Engineering & Remote Sensing*, 56(11): 1477–1481.

Barnes, J.C., and M.D. Smallwood, 1982. *TIROS-N Series Readout Services Users Guide*, U.S. Dept. of Commerce, NOAA-NESS, 118 p.

Baumann, R., U. Burkart, and K. Seidel, 1990. Runoff Forecast in an Alpine Catchment by Satellite Snow Cover Monitoring, *Proceedings of the International Symposium on Remote Sensing and Water Resources*, International Association of Hydrogeologists, Enschede, The Netherlands, pp. 181-190.

Baumgartner, M.F., 1990. *Snowmelt Runoff Simulations Based on Snow Cover Mapping Using Digital Landsat-MSS and NOAA-AVHRR Data*, U.S. Department of Agriculture/ARS/Hydrology Laboratory, Technical Report, HL-16, 53 p.

Baumgartner, M.F., and M. Fuhrer, 1991. A Swiss AVHRR and Meteosat Receiving Station, *Proceedings of the 5th European AVHRR Users Meeting*, Tromso, Norway, pp. 23–33.

Baumgartner, M.F., and A. Rango, 1988. Microcomputers for Snow Cover Analyses Using Multisensor Satellite Data, *Proceedings of the IEEE/IGARSS'88 Symposium*, Edinburgh, Scotland, ESA Ref. SP-284, pp. 459–460.

———, 1991. Snow Cover Mapping Using Microcomputer Image Processing Systems, *Nordic Hydrology*, (22):193–210.

Baumgartner, M.F., A. Schoenenberger, and U. Stalder, 1991. Snow Cover Variations in the Alps Using NOAA-AVHRR Data, *Snow, Hydrology, and Forests in High Alpine Areas* (H. Bergmann, H. Lang, W. Frey, D. Issler, and B. Salm, editors), XXth General Assembly of IUGG, IAHS Publ. No. 205, pp. 41–50.

Baumgartner, M.F., K. Seidel, and J. Martinec, 1986. Large Area Deterministic Simulation of Natural Runoff from Snowmelt Based on Landsat-MSS Data, *IEEE Transactions on Geoscience and Remote Sensing*, GE-24(6):1013–1017.

Carroll, T.R., 1993. Airborne and satellite snow cover mapping for the coterminious U.S., Alaska, and Canada, *Proceedings of the 10th Annual Pacific Climate Workshop*, Asilomar, California.

Duda, R.O., and P.E. Hart, 1976. *Pattern Classification and Scene Analysis*, Wiley Interscience, New York, 482 p.

Ehlers, M., G. Edwards, and Y. Bedard, 1989. Integration of Remote Sensing with Geographic Information Systems: A Necessary Evolution, *Photogrammetric Engineering & Remote Sensing*, 55(11): 1619–1627.

Frei, U., 1984. *Geometrische Korrekturen von NOAA-AVHRR Daten (geometric corrections of NOAA-AVHRR data)*, Remote Sensing Series, Vol. 8, Department of Geography, University of Zurich, Switzerland, 87 p.

Keller, M., 1987. *Ausaperungskartierung mit Landsat - MSS Daten zur Erfassung oekologischer Einflussgroessen im Gebirge (Snow Cover Mapping Using Landsat-MSS Data for Deriving Ecologically Relevant Information in Alpine Regions)*, Remote Sensing Series, Vol. 10, Department of Geography, University of Zurich, Switzerland, 111 p.

Kidwell, K.B. (editor), 1991. *NOAA Polar Orbiter Data Users Guide*, U.S. Department of Commerce (NOAA/NESDIS), 294 p.

Kumar, V.S., H. Haefner, and K. Seidel, 1991. Satellite Snow Cover Mapping and Snowmelt Runoff Modelling in Beas Basin, In: *Snow, Hydrology, and Forests in High Alpine Areas* (H. Bergmann, H. Lang, W. Frey, D. Issler, and B. Salm, editors), XXth General Assembly of IUGG, IAHS Publ. No. 205, pp. 101–110.

Martinec, J., 1985. Snowmelt Runoff Models for Operational Forecast, *Nordic Hydrology*, 16:129–136.

Martinec, J., A. Rango, and E. Major, 1983. *The Snowmelt Runoff Model (SRM) User's Manual*, NASA Reference Publication 1100, Washington, D.C., 118 p.

Martinec, J., K. Seidel, U. Burkart, and R. Baumann, 1991. Areal Modeling of Snow Water Equivalent Based on Remote Sensing Techniques, *Snow, Hydrology, and Forests in High Alpine Areas* (H. Bergmann, H. Lang, W. Frey, D. Issler, and B. Salm, editors), XXth General Assembly of IUGG, IAHS Publ. No. 205, pp. 121–130.

Olivier, J.J., P.H. Greenwood, A.K. Cooper, D.R. McPherson, and R. Engelbrecht, 1990. Selecting a GIS for a National Water Management Authority, *Photogrammetric Engineering & Remote Sensing*, 56(11):1471–1475.

Piwowar, J.M., and E.F. LeDrew, E.F., 1990. Integrating Spatial Data: A User's Perspective, *Photogrammetric Engineering & Remote Sensing*, 56(11):1497–1502.

Rango, A., 1989. Evolution of a Research-Oriented Snowmelt Runoff Simulation Model into an Operational Forecasting Tool, *Proceedings of the 57th Annual Western Snow Conference*, Fort Collins, Colorado, pp. 45–51.

Rango, A., and J. Martinec, 1994. Areal Extent of Snow Cover in a Changed Climate, *Nordic Hydrology*, 25(4):233–246.

Rango, A., and R. Roberts, 1987. Snowmelt Runoff Modeling in the Microcomputer Environment, *Proceedings of the 55th Annual Western Snow Conference*, Vancouver, B.C., pp. 1–9.

Rango, A., V.V. Salomonson, and J.L. Foster, 1977. Seasonal Streamflow Estimation in the Himalayan Region Employing Meteorological Satellite Snow Cover Observations, *Water Resources Research*, 13(1):109–112.

Schoenenberger, A. 1991. *Saisonale Schneeflaechenveraenderungen im Alpenraum aus NOAA-AVHRR Satellitendaten (Seasonal Snow Cover Variations in the Alps Using NOAA-AVHRR Data)*, Diploma, Department of Geography, University of Berne, Switzerland 91 p.

van Katwijk, V., and A. Rango, 1991. The Effect of Climate Change on Snowmelt Runoff in Two Different Climatic Regions of the Western United States, *Proceedings of the American Meteorological Society Special Session*, Salt Lake City, pp. 210–213.

WMO, 1986. *Intercomparison of Models of Snowmelt Runoff*, Operational Report No. 23, World Meteorological Organization, Geneva, 36 p.

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