SOME ASPECTS ON THE DEVELOPMENT OF HYDROLOGICAL FORECASTING MODELS BASED ON MULTI-TEMPORAL SATELLITE REMOTE SENSING

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ABSTRACT:

Forecasting models for daily river discharge in the rivers of high mountainous catchments are important for management of water resources towards hydropower generation, irrigation, industrial and domestic water supply as well as flood control. The complex topography in high mountainous terrain create extremely difficult situation for observation and sampling of meteorological and hydrological parameters that are useful to model hydrological processes. Satellite remote sensing data in different wavelength regions of electromagnetic spectrum are most useful to extract near real time hydro-geophysical parameters to support development of hydrological forecasting models. In the present study digital image processing of multi-spectral, multi-temporal and multi-sensor satellite data has been carried out over two high mountainous river catchments of varied area extent viz., Cordevole (248 sq. km.) and La Vizza (7.5 sq. km.). The above catchments are located in the dolomites region of north-eastern Italian Alps.. The elevation of the region varies between 900 meters to 3150 meters above sea level. Nine sets of Landsat 4 and 5 Multi-spectral Scanner (MSS) and Thematic Mapper (TM) computer compatible tapes covering a hydrological year have been processed in the study using digital image processing techniques. Digital elevation model, slope, aspect and shaded relief maps coinciding with satellite passes were generated using locally developed Territorial Image Synthesis System (TISS) and utilized in the analyses. The areal extent of snow cover has been extracted by taking the catchment as a single unit as well as three elevation zones. Supervised parallelepiped, nearest-neighbourhood and maximum likelihood classification methodologies have been utilized to estimate the snow cover under different categories. A threshold based second and third order polynomial fit approach has been attempted to generate accurate daily snow cover distribution over the catchments as well as the elevation zones. A semi-distributed deterministic hydrological model has been developed based on the catchment characteristics to generate river discharges. Model performance evaluation indicates excellent correlation between measured and simulated discharges and the results are comparable with World Meteorological Organization (WMO) test basins.

1. INTRODUCTION

Precipitation is one of the most important inputs of hydrological and water management systems. In the climate of several parts of the world solid precipitation and snow-cover are of significance to the precipitation regime. About 30% of the earth's land surface is seasonally covered by snow. In high mountains the proportion of snow in precipitation exceeds 50% and the snowmelt becomes a dominant factor in the runoff regime. The alpine snow cover in the middle latitudes have a very large storage capability of water and consequently forms a water reservoir during melting season. Snowmelt accounts for 50 to 80% of the annual stream flow of many rivers originating from Sierra Nevada, Rocky, Alps, Andes and Himalayas (Ferris and Congalton 1989). In high mountain regions the distribution of snow controls the weather and climatic conditions and plays an important role in the hydrological processes of the region. Among the scientific community approaching the problems related to global changes, there is a general agreement that the temperature and precipitation are affected by the rising of green house gases in the atmosphere. Such changes may influence significantly the runoff regime of high alpine environment. The snowmelt runoff is being used for hydropower generation, domestic, irrigation and industrial water supply. Hence, hydrological forecasting of snowmelt runoff from catchments located in high mountainous terrain is very important for judicious management of water resources. Any modeling approach to the study of water balance in alpine areas should take in to account snow accumulation and melt processes which are to a great extent responsible for the flow pattern in winter and spring months.

The importance of satellite remote sensing data as a potential source from complex high mountainous terrain has been widely recognized. The capabilities of optical and microwave satellite remote sensing technology enable us to map the snow cover on regular basis under adverse weather conditions also. When snowmelt starts, the snow conditions change and the high mountain basins are not accessible for regular snow surveys. However, daily observation by NOAA Advanced Very High Resolution Radiometer (AVHRR) make it possible to monitor snow cover changes from satellite over large high mountainous regions. However, to study the snow cover changes due to the impact of climate on small catchments moderate to high spatial resolution sensors like Landsat – MSS and TM, SPOT – HRV, IRS – LISS I, II, III, IV are quite useful. However, the repetitive cycles of the above satellite sensors are insufficient for frequent periodical snow cover mapping, since all the images cannot be used due to extensive cloud cover or acquisition after new snowfall. A successful forecast of the melt water runoff needs fairly accurate measurements of the area covered by snow and continuous monitoring of the changes about the gradually decreasing snow cover. Hence, various methodologies are to be adopted to interpolate/extrapolate the snow cover derived from few satellite scenes for longer periods at shorter time intervals, in order to input the same in to various hydrological forecasting models. The selection of appropriate sensor depends on a trade-off between spatial and temporal resolution (Rott, 1987).

This paper describes the results of a study undertaken over two high mountainous alpine catchments in north eastern part of Italy, the aim of which was to assess the suitability of remote sensing satellite data for hydrological forecasting. For this purpose, visible and infrared digital data from multi temporal Landsat MSS and TM sensors has been used for snow cover monitoring and snowmelt runoff forecast.

2. AREA OF INVESTIGATION

The study area is located in the Dolomiti Mountains of the north-eastern Italian Alps and is enclosed between latitudes 46° 23' N and 46° 33'N and longitudes 11° 47'E and 12° 10'E. There are two catchments known as Cordevole and La Vizza in this region. Both are drained by the main river Cordevole. The area of Cordevole river basin measures 248 km^2 with a mean altitude of 1900 m above sea level (Fig.1).

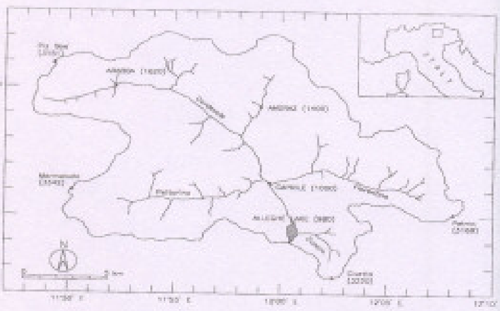

Figure 1 Physiographical map of Cordevole river basin

The La Vizza basin is a small catchment extending to 7.5 km^2. Its elevation ranges from 1800 meters above mean sea level to 3150 meters above mean sea level (Fig.2).

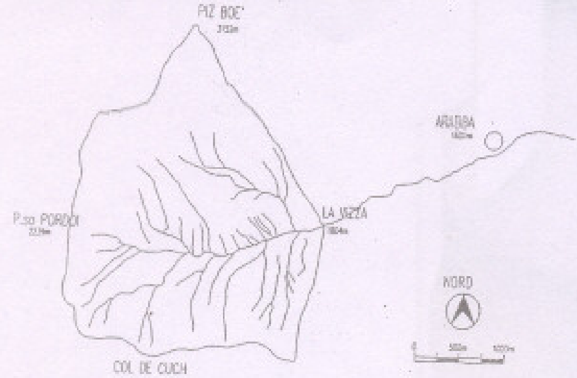

Figure 2 Physiographical map of La Vizza basin

Both the watersheds are characterized by the very low permeability geological formations of the area known as calcareous dolimitic rocks. The normal annual rainfall in this region is around 1070 mm. The hydrological regime shows a maximum water flow during the late spring and early summer and a minimum during the winter.

3. GROUND DATA

There are three well-equipped hydro-meteorological observatories located at Arabba (1620 masl), Andraz (1400 masl) and Caprile (1000 masl) in the area. At all these observatories precipitation (both rain and snow) data and incoming solar radiation are collected every five minutes, while wind direction and wind speed are monitored at ten-minute intervals. The air temperature and relative humidity are also measured at hourly intervals, in addition to daily maximum and minimum air temperatures. These observatories are maintained by Centro Sperimentale Valanghe e Difesa Idrogeologica – Regione Veneto (CSVDI) which is a research center for avalanches and hydrological control located at Arabba. The Italian National Authority for Energy (Ente Nazionale per l'Energia Elettrica – ENEL), which maintains a hydropower station at Lake Alleghe, computes discharges of the Cordevole River from water level measurements of the lake (Fig.3). These discharges are corrected for water pumping carried out by the hydropower station. The computed discharges are in good agreement with the historical discharges of the river measured using conventional hydrological methods. For La Vizza catchment, the discharge measurements at the basin out let, La Vizza station which is at an altitude of 1804 meters above mean sea level are made by sharp crested weir with continuous digital recording equipment. The Arabba hydro-meteorological observatory is about 2 km from the outlet on the downstream side.

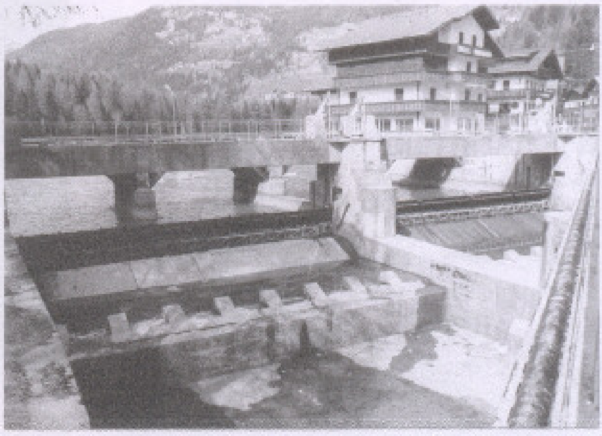

Figure 3 Discharge station at Caprile

Ground truth campaigns have been carried out twice coinciding with satellite passes over the area of investigation. The information was recorded on a number of black and white photographs. Some of the general observations on the first field campaign in April indicated that the catchment upstream of Arabba was uniformly covered with snow except on south-facing slopes where some pasture land had started to appear. On the downstream side of Arabba south-facing slopes were up to 70% snow free while those facing north were uniformly covered with snow. This was owing to the fact that in the middle latitudes of the northern hemisphere, hills that face would receive more sunshine and hence become warmer than the partly shielded north-facing hills. Consequently snow usually lingers on the ground for a longer time on north-facing slopes than on the warmer south facing slopes. The variation of snow depth and intensity of melt are observed to be dependent on altitude and discontinuous snow cover occurred at several melting regions in the basin. The break-up of snow cover was observed to be rapid at lower altitudes; the satellite sensor observes these areas as a mixture of snow-covered and snow-free terrain. Hence, at low altitudes mixed pixels prevail and at high altitudes pure pixels exist. The ratio of snow-covered to snow-free ground and the probability of a pixel coinciding with 100% snow-covered ground increased with altitude. There was no snow on coniferous tree branches while larchs (*Larix deciduas*) were without their needle-type leaves. But some snow was observed to occur on the land below the tree cover. About one-quarter of Lake Alleghe, towards the down stream side, was covered by a thin layer of melting ice.

4. TERRITORIAL IMAGE SYNTHESIS SYSTEM

The elevation, slope and aspect are the most obvious components of the landscape. In high mountain areas the snow distribution is not homogeneous owing to rapid variation of these parameters. In addition, the ruggedness of the terrain complicates interpretation of the satellite scene (Seidel et al 1983). The registration of remote sensing data on the digital elevation model enables correction for varying illumination angle and shadowing effect (Haefner, 1980; Dozier, 1984). Digital terrain data for the region has been produced by digitizing the contour lines for every 200 mewters and, for some specific areas, for every 100m from 1:50000 scale of the Istituto Geografico Militared'Italia (IGMI) using a graphic tablet and AUTOCAD software. The resulting vector data were manually edited to remove noise introduced in the digitization process. Digital elevation models have been generated from the vector contours using locally developed software known as Territorial Image Synthesis System (TISS) (Figure 4).

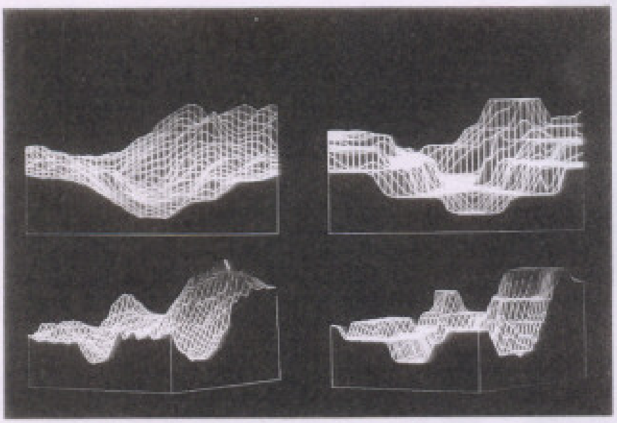

Figure 4 Digital elevation model of La Vizza catchment

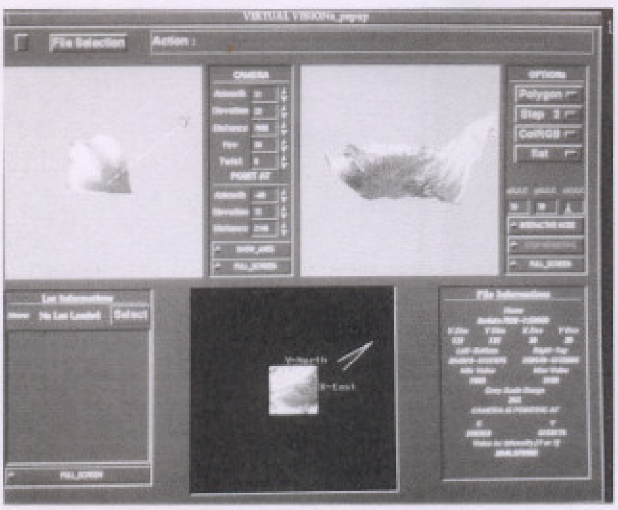

Figure 4 Black and White representation of false colour composite registered and superimposed over DEM using TISS

In addition, the slope, aspect and shaded relief maps were also developed. The integration of digital satellite data with the DEM has been carried out and three dimensional perspective views for different illumination angles have been generated to study the snow cover distribution in the catchment (Figure 5).

5. SATELLITE DATA

The nature of the snow cover must be characterized adequately if distributed models are to improve hydrological modeling through improved representation of the sate variables (Beven, 1989). Knowledge of the areal distribution of the snow cover within and between land limits is required in order to make reasonable estimates of the total water available in the snow cover of a watershed (Goodison et al 1987)

Altogether nine sets of digital Landsat Multispectral Scanner System (MSS) and Thematic Mapper (TM) Computer Compatible Tapes belongs to one hydrological year have been analyzed using digital image processing techniques (Table 1).

Table 1 Satellite scenes processed

Satellite	Sensor	Frame	Acquisition Date
Landsat-4	MSS	192-28	28 - OCT - 83
Landsat-4	MSS	192-28	15 - DEC - 83
Landsat-4	MSS	192-28	17 - FEB - 84
Landsat-5	TM	192-28	13 - APR - 84
Landsat-4	MSS	192-28	21 - APR - 84
Landsat-5	TM	192-28	16 - JUN - 84
Landsat-4	MSS	192-28	10 - JUL - 84
Landsat-5	MSS	192-28	18 - JUL - 84
Landsat-5	MSS	192-28	03 - AUG - 84

The sub-scenes of 350 x 512 pixels (MSS) and 800 x 1024 pixels (TM) containing the area of investigation haven been extracted from the full scenes of each image (Figure 6). All the sub-scenes were geometrically corrected by geo-coding on to the coordinate system of the topographic maps.

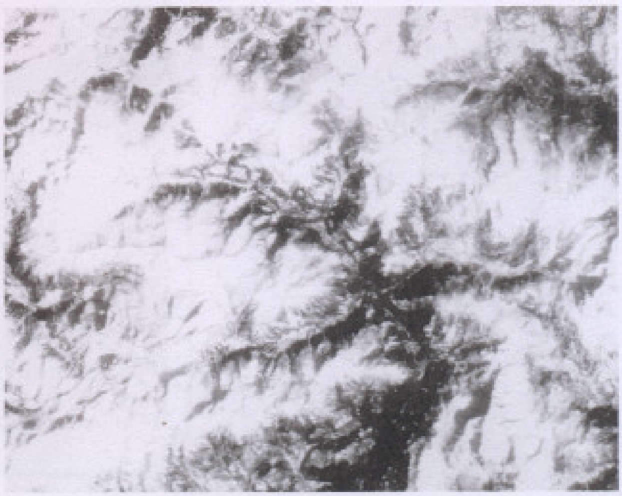

Figure 6 Black and white representation of Landsat-MSS subscene standard false colour composite on 21 April 1984, path/row 192/28

The areas of the two catchments from each satellite image have been extracted using overlay masks. The catchments are further subdivided into three elevation zones. The software for the above purpose has been developed locally. Figure 7 presents the extracted elevation zones of Cordevole river basin from standard false color composites acquired on different dates.

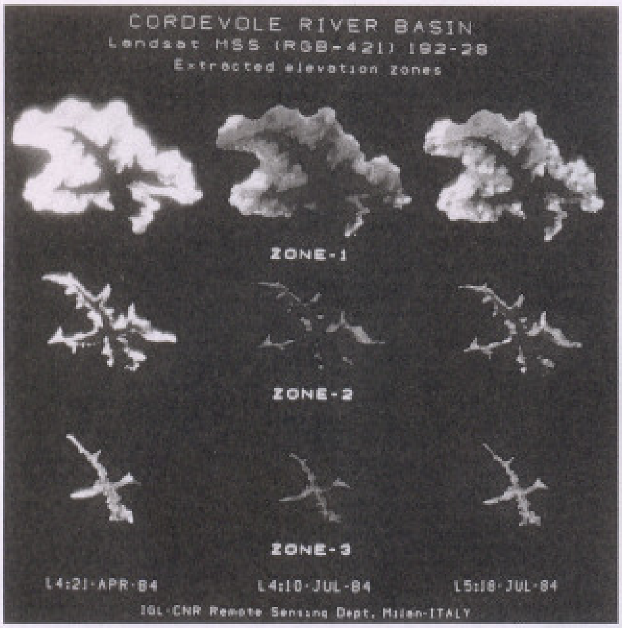

Figure 7 Black and white representation of extracted elevation zones from Standard False Color Composites of Cordevole river basin.

5.1 Classification of multi-spectral data

The classification problem has been subject of much research during past three decades. Classification is essentially the process of carrying out a mathematical transformation from one data space to another. In the remote sensing context this is from image digital count values to map classes relevant to the application of interest. While certain map classes may be clearly distinguished in the image data, there is often no clear relationship between the image digital count values and the map class on a pixel basis. The conventional classification process involves the division of the feature space defined by the raw or derived data features into disjoint regions each of which corresponds to a separate map class.

Multi-spectral classification of remote sensing images bas been dominated by hard algorithms that produce one class per pixel. An example is the level slice algorithm that uses parallelepiped regions in feature (multi-spectral) space. A pixel is labeled with the class name corresponding to the parallelepiped that contains the pixels feature vectors (Schowengerdt, 1996). Another non-parametric method of classification is the Euclidean minimum distance classifier. Approaches based on statistical analyses of the data and derivation of parameters of distribution characterizing each map class in the data set are also available and known as parametric methods. A good example of this approach is the maximum likelihood classifier. It bases its hard decision on a comparison of a posteriori probabilities among the candidate classes. All the non-parametric and parametric classifiers give different classified information. Hence in the present study the classification of the digital satellite data has been made using the non-parametric and parametric classifiers viz., parallelepiped, minimum distance and maximum likelihood classifiers to categorize snow covered area into i) two classes as snow and snow free area as well as ii) three classes as snow, transition snow and aper. The suitability of these methods for snow melt runoff forecast has been studied. Figure 8 shows examples of the supervised classification of elevation zones extracted from various satellite scenes for La Vizza catchment using Euclidean minimum distance classifier. The area covered by each class in each elevation zone has been determined by counting the number of pixels classified under each category and multiplying them with their respective pixel dimension. The mixed snow cover representing the transition zone was given a weighting of 50% and added to the pure snow to obtain total snow-covered area for each elevation zone.

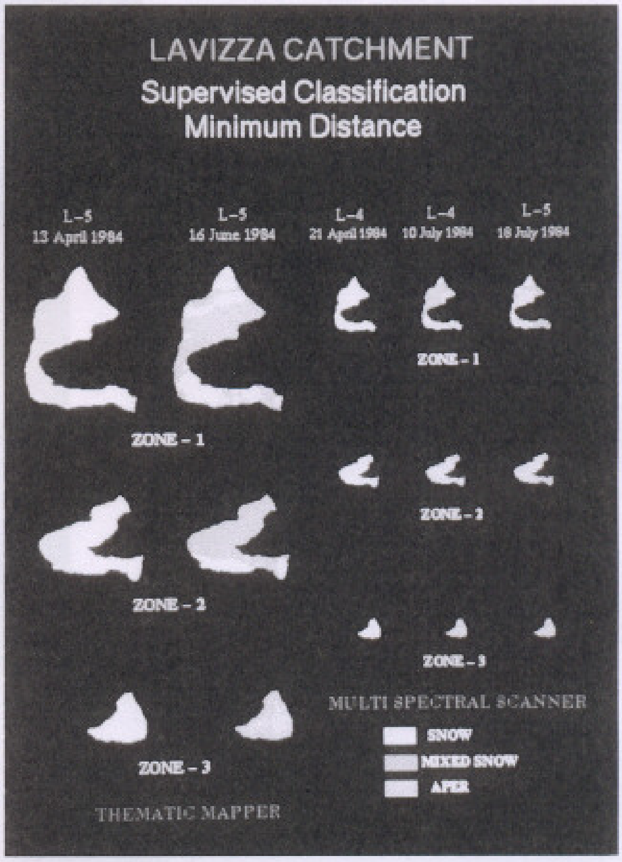

Figure 8 Black and white representation of multi-spectral classification of various elevation zones of La Vizza basin using supervised minimum distance classifier

6. DEPLETION CURVES

The rate of snowmelt during summer months varies from one catchment to another in different high mountainous regions of the world, depending on the prevailing meteorological conditions. Consequently the snowmelt depletion curves reflect the seasonal decrease of the snow cover as it is influenced by the dominant meteorological factors like temperature and precipitation. The spatial distribution of the snow cover is described by snow cover depletion curves, which summarize the percentage areal coverage of the snowpack. Snow cover depletion curves have been developed for, and applied in, hydrological models on a watershed or elevation zone basis. Watershed-wide snow depletion curve relationships are used in lumped hydrological models such as the National Weather Service River Forecast System (Anderson, 1973) to describe the snow cover distribution as the snow melts, while elevation zone basis relations were used in distributed hydrological models such as the snowmelt runoff model (Martinec et al., 1994). The snow depletion curves are watershed specific, in that they represent the characteristic response of the watershed to snowmelt, which is a function of the land cover and elevation characteristics within the basin. Hall and Martinec (1985) proposed an approximation to compute snow cover depletion curves and estimate daily snow cover variation from Landsat MSS scenes. This procedure seems to fit well for some alpine catchments when the depletion curves are computed by taking the entire basin as a single unit. When the snowmelt depletion curves are derived on an elevation zone basis, the above approximation may not be suitable for some catchments. This is evident in particular for the lower elevation zones of the catchment, where the snow cover disappears rapidly.

The snow covered area on each day during the snowmelt period was estimated for each elevation zone, using either second order or third order polynomial fit employing a threshold to the snow cover data of each elevation zone, estimated from remote sensing satellite data. Interestingly the equations developed gave a high coefficient of determination. The daily snow cover was computed using the above equations for each elevation zone and expressed as a percentage of the total area in order to be input into the model. Figure 9 presents an example of the modified depletion curves for three elevation zones of Cordevole river basin indicating the distribution of daily snow cover areal extent on each day of melt period. However, these snow depletion values do not reflect short-term changes resulting from snowfalls during the snowmelt period. Weekly satellite images with high spatial resolution may be more useful for precise estimation of daily snow cover and the resulting depletion curves.

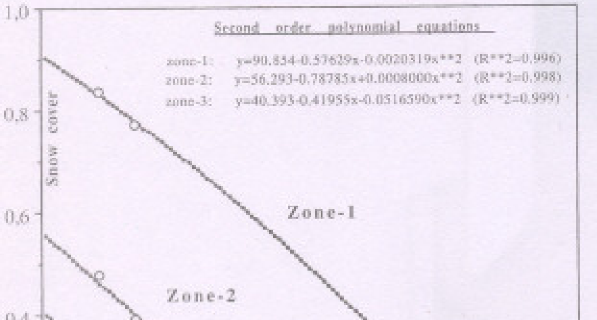

Figure 9 Modified depletion curves for three elevation zones of Cordevole river basin

7. HYDROLOGICAL MODEL

The main aim of hydrological modeling is to provide a forecast of the future performance of a hydrological system. The snowmelt runoff model should be able to simulate the contribution owing to the snow depletion in the basin to the total river discharge, day by day, during the melting season. Snowmelt runoff simulation models generally consist of a snowmelt model and a transformation model. A snow model is defined as a mathematical description of melt related processes which gives the flux of melt water at the bottom of the snowpack as output. The snowmelt and transformation model can be lumped or distributed in nature. Lumped models use one set of parameter values to define the physical and hydrological characteristics of a watershed. Distributed models attempt to account for the spatial variability by dividing the basin into sub-areas and computing snowmelt runoff for each sub-area independently, with a set of parameters corresponding to each of the sub-areas. The distributed representation used in most snowmelt runoff simulation models is the separation of the watershed into distinct elevation zone. These elevation zones are appropriate for alpine regions, where snowmelt and temperature are strongly related to elevation.

During the inter-comparison of various snowmelt runoff models conducted by the World Meteorological Organization (1986), of the models tested, the snowmelt runoff model (Martinec et al., 1983) exploited the increasing availability of snow cover mapping from satellites. This model is a deterministic distributed temperature index model that takes into consideration the precipitation and air temperature, along with all other predetermined catchment parameters. An advantage of this model is that it is easy to use operationally because of a limited amount of data is required for the forecast, usually precipitation and temperature

The Snow Runoff Model (SRM) considered for three elevation zones in the present study reads as:

$$\begin{aligned} Q_{n+1} = \Big\{ & [\alpha_{an}(T_{an} + \Delta T_a) C_{asn} S_{an} + C_{arn} P_{an}] \frac{A_a \cdot 10^{-2}}{86\,400} \\ & + [\alpha_{bn}(T_{bn} + \Delta T_b) C_{bsn} S_{bn} + C_{brn} P_{bn}] \frac{A_b \cdot 10^{-2}}{86\,400} \\ & + [\alpha_{cn}(T_{cn} + \Delta T_c) C_{csn} S_{cn} + C_{crn} P_{cn}] \frac{A_c \cdot 10^{-2}}{86\,400} \Big\} \\ & \times (1 - k_{n+1}) + Q_n \cdot k_{n+1} \end{aligned}$$

where Q is the average daily discharge (m^3 s^{-1}), C_n is the runoff coefficient, with C_{sn} referring to snowmelt and C_{rn} to rain, α_n is the degree day factor (cm $^{o}C^{-1}$ day^{-1}), T_n is the number of degree days above the base of 0^o C, ΔT_n is the adjustment by temperature lapse rate for different altitudes of meteorological stations, S_n is the ratio of snow-covered area to the total area, P_n is the precipitation contributing to the runoff, K_n is the recession coefficient derived from historical discharges, n is the index referring to the sequence of days, A is the area of the basin (m^2), a, b, c refer to elevation zones 1, 2, 3 respectively, and $10^{-2}/86400$ coverts cm m^{-2} day^{-1} to m^3 s^{-1}.

Using the above model daily discharges have been computed for the two basins for the snowmelt period of April to July. The pre-determined morphological parameters and hydrological parameters and daily snow cover area estimated from three elevation zones from satellite remote sensing data has been utilized in computing the discharges. Figure 10 presents the distribution of measured and simulated discharges for La Vizza basin for the period of 122 days starting from 1 April 1984. Visual comparison of the discharges indicates there is a good correlation between measured and simulated discharges.

7.1 Model performance

To analyze the performance of the model, linear regression analyses has been made and correlation between measured and simulated discharges has been determined. The correlation coefficient ® of 0.94 for Cordevole river basin and 0.96 for La Vizza basin indicates the existence of a high degree of correlation between measured and computed discharges.

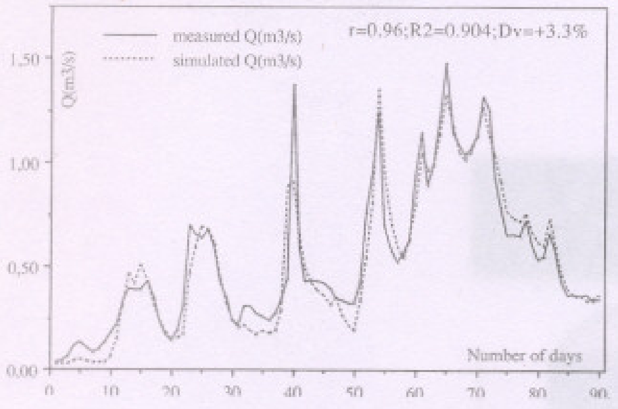

Figure 10 Comparison of measured and simulated discharges for La Vizza river basin.

The model performance is further evaluated using the Nash-Sutcliffe Coefficient (Nash and Sutcliffe 1970). The R^2 value of 0.89 for Cordevole river basin and 0.904 for La Vizza catchment are found to be highly comparable with values obtained for various test basins by World Meteorological Organization, as given by Hall and Martinec (1985). The model accuracy is also studied by deriving the percentage volume deviation (Seidel et al., 1989). During the study period the volume deviation between measured and simulated discharges for the Cordevole river basin is +4.6% and for La Vizza basin +3.3%. These values are in good agreement with the values of catchments in the Swiss Alps.

8. CONCLUSIONS

The use of satellite optical remote sensing data for developing hydrological forecasting models over Italian Alps has been analyzed and the possible application of satellite remote sensing data in conjunction with ground and meteorological and hydrological data has been investigated over two catchments in the eastern Italian Alps. This study is important for the management of water resources in the region. The snow cover estimated by using supervised maximum likelihood classification algorithm fits well into the present hydrological model study. The results of the study demonstrate that optical satellite remote sensing data can be used for snowmelt runoff forecast in the high mountainous Italian Alps.. However, multi-sensor data from various high spatial resolution optical remote sensing sensors must be taken jointly into consideration to solve the temporal coverage problem.

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