Investigation of the snowmelt runoff in the Orumiyeh region, using modelling, GIS and RS techniques

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This research is dedicated to my kind parents

My Dear Father & My Dear Mother

And

My Wife

(January 2003)
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Abstract

Remote Sensing (RS) and Geographical Information System (GIS) are very important tools in snow monitoring. A small basin, Mirabad in the Orumiyeh Lake basin, has been selected for this study. Repetitive satellite images for the hydrological year 1996-1997 from NOAA-AVHRR were processed for snow cover recognition. Calibration of the Snowmelt Runoff Model (SRM) for the study area is the main objective of this research that simulates the daily snowmelt runoff.

We described a method for snow mapping using NOAA-AVHRR data and a procedure to estimate retrospectively the accumulated snow water equivalent volume with the SRM. Real-time snowmelt forecasts are generated with the SRM using area snow cover as an input variable. The Mirabad hydrometry station is located at the outlet with 1513m altitude and all rain and temperature stations are located outside of the catchment. The altitude ranges from 1513 in outlet to 3595 at the border of Iran and Turkish.

The main part of precipitation is as snow in winter that model calibrated it for the period of 1996-97 by using Mirabad station’s discharge data. The snow cover obtained by using NOAA images and by using super wised classification method in ILWIS and using Digital Elevation Model (DEM). The rainfall and temperature data extrapolated to different zones from Mirabad station.

Lack of temperature and precipitation data inside the study area gave inaccurate results but estimated results are acceptable. Graphical display of two measured and computed runoff shows that simulation is successful, and for more accurate hydrological analysis, installation of meteorological stations inside the study area is required. As snow is the main water source in the region, an accurate estimation of snow equivalent is necessary. For this, installation of meteorological stations inside the catchment is recommended.
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CHAPTER 1 Introduction

The Snowmelt - Runoff Model (SRM; also referred to in the literature as the “Martinec Model” or “Martinec-Rango model”) is designed to simulate and forecast daily stream flow in mountain basins where snowmelt is a major runoff factor. Most recently, it has also been applied to evaluate the effect of a changed climate on the seasonal snow cover and runoff. SRM was developed by (Martinec 1975) for small European basins. The snow cover area of a basin has a very important role to play in hydrological and climatological behaviour (Baral and Gupta 1997). In snow-fed streams, as in the case of Shahr-Chai River described in the following, it is important to describe the variability of snow cover.

Monitoring of snow-related processes can play a significant role in the hydrological analysis, water resources evaluation, control and management of mountainous reservoirs, flood controlling and hydropower production. Estimation of the rate and volume of water released from the snow is needed for the efficient management of water resources. The western mountains of Orumiyeh Basin are the main source of the Orumiyeh Lake’s water. The higher regions of the mountains are regularly covered with snow in the winter period.

The present research describes the snowmelt processes in a selected sub-catchment of the Orumiyeh Basin. The applied method includes the integration of remote sensing (RS), geographical information system (GIS) and numerical modelling techniques. Data measured in-situ, like show properties, precipitation, temperature, etc. were used for the parametrization of the SRM model to calculate the contribution of snowmelt and rainfall to runoff of the basin for the hydrological year of 1996-97.

The snow-covered area and its depletion with time were determined using satellite images and stream discharge data were used for calibration and validation the SRM model.

1.1 Problem definition

Lake Orumiyeh is located in the north-western part of Iran. It occupies the deepest part of its basin and receives water from the rivers draining into it. Its environment is unique in the world. It is a hipersaline lake without outlet: the water loss takes place only via evaporation. Many kinds of birds and animals live around the lake, but there is a limited number of living
organisms (Artemia and a blue-green algae) in the water. These are very important in feeding the birds and used for other purposes too.

The existence of the Lake and sustainability of the regional environment depends on the amount of water received from the catchment. By snowmelt runoff modelling the determination of the runoff is possible. This method can be used for the prediction of the Lake’s variability.

Snowmelt is a major source of water in the region, therefore discharge forecasting and estimation of snowmelt for this basin is essential. From the water harvesting point of view for irrigation and drinking the shortage of water is one of the most important problems in the dry seasons. As snowmelt runoff is one of the main factors in the water budget of the river, a special attention and recognition of the runoff processes is needed.

1.2 Objectives

Estimation of the snowmelt and simulating the daily runoff are the main objectives of this study. Further objectives are defined as follows:

- Determining and Recognition of the abilities of SRM model in snowmelt forecasting for the study area.
- Determining the contribution of snowmelt to the River.

1.3 Methodology

In order to predict hydrologic behaviour of a catchment it is necessary to analyse historical data and physical characteristics of the catchment. The main steps of the research are as follow:

- Analysis of hydrological and meteorological data (daily, monthly) from the stations located inside and outside the study area and calculating model parameters for SRM, such as rainfall and temperature gradients (laps rates).
- Using topographic maps for creating DEM (Digital Elevation Model) and the area-elevation curve of the basin. It is required for the physiographic studies. The physical characteristics of the basin are necessary for the determination of the model parameters, such as extrapolation of temperature data for different zones.
- Computation of degree-days from temperature data. This is used in the model for the calculation of the daily snowmelt depth.

- The precipitation data are recorded at stations inside and outside the study area. This is to be used for the calculation of the precipitation-altitude relationship.

- The SRM model requires the monitoring snow cover in the selected catchment during the snow season. A series of images from the NOAA-AVHRR sensor is to be used for monitoring the snow cover extent.

- Simulation of the runoff using SRM model. The following variables are needed: daily data of precipitation, temperature and discharge. The model parameters are: degree-day factor, runoff coefficient for snow, runoff coefficient for rain, temperature lapse rate, critical temperature, rainfall contributing area, recession coefficient and time lag.

- Assessment of the model accuracy: The SRM computer program includes a graphical display of the computed hydrograph and measured runoff. A visual inspection shows at the first glance whether the simulation is successful or not. (Martinec and Rango 1998).

The workflow is illustrated in Figure 1-1.
Figure 1-1 Workflow
1.4 A review of snowmelt runoff modelling

1.4.1 The SRM model

The Snowmelt Runoff Model (SRM) was designed to simulate and forecast daily stream flow in mountain basins where snowmelt is a major runoff factor. It requires remote sensing input relating to basin or zonal snow cover. The model has been applied in 60 basins in 19 different countries. The model structure and data required for running the model are described. Model variables are derived from actual observations of temperature, precipitation, and snow-covered area. Model parameters can either be derived from measurements or estimated by hydrological judgement taking into account the basin characteristics, physical laws, and theoretical or empirical relationships (Singh and Rango 1995).

Results of runoff computations by the Snowmelt Runoff Model (SRM) carried out at various institutes, universities and agencies on 24 basins ranging in size from 0.77 to 4000 km² and in elevation from 171 to 6000 m a.s.l. from 11 countries are reviewed. Based on this review, the physically and hydrologically understandable range of parameter values is assessed for the degree-day factor, runoff coefficient, temperature lapse rate, critical temperature (rain-snow), time lag, and recession coefficient. Consideration of SRM parameter values in these past applications may prove valuable for SRM applications on other basins and for initial selection of related parameter values in other snowmelt runoff models. (Martinec and Rango 1998)

Runoff regimes in most northern basins are controlled by the melting snow cover. A common method for evaluating runoff consists in correlating ambient air temperature and recorded hydrometric gauge values. The air temperature is the principal variable to estimate the importance of the melting of the snow cover when using a global conceptual model such as the snowmelt runoff model (SRM). The temperature, which is often only measured at one weather station, must be extrapolated to the whole basin according to some kind of lapse rate. This extrapolation often assumes that air temperature is representative for a wide region, which is often not the case. The estimation of temperature values is critical, especially for large basins where the surface processes are largely influenced by a forest cover. A statistical comparison between the different modelling attempts was performed. This allowed us to obtain a sensitivity analysis of the snow runoff modelling in relation to the extrapolation of the temperature values. Results showed that the weather station, used to perform the runoff modelling, should be located in the most representative land cover of the study area. Otherwise, the values of a synthetic regional weather station were more reliable for the modelling. Finally, before pursuing any snowmelt modelling with the SRM, the temperature
values must be evaluated based on the location of the weather station to see if they are representative of the total study area (Richard, Gratton et al. 2001).

The air temperature is the principal variable to estimate the importance of the melting of the snow cover when using a global conceptual model such as the snowmelt runoff model (SRM). The temperature, which is often only measured at one weather station, must be extrapolated to the whole basin according to some kind of lapse rate. This extrapolation often assumes that air temperature is representative for a wide region, which is often not the case. The estimation of temperature values is critical, especially for large basins where the surface processes are largely influenced by a forest cover. This project has two objectives: (1) applying a mostly high mountain SRM to the Batiscan River Basin, in the Province of Quebec, an area occupied by a forest with a rolling hilltopography; (2) investigate the impact of the extrapolation strategy for estimating temperature values and its importance in the runoff modelling. A statistical comparison between the different modelling attempts was performed. This allowed us to obtain a sensitivity analysis of the snow runoff modelling in relation to the extrapolation of the temperature values. Our results showed that the weather station, used to perform the runoff modelling, should be located in the most representative land cover of the study area. Otherwise, the values of a synthetic regional weather station were more reliable for the modelling. Finally, before pursuing any snowmelt modelling with the SRM, the temperature values must be evaluated based on the location of the weather station to see if they are representative of the total study area (Richard, Gratton et al. 2001).

The snowmelt runoff model (SRM) is used to simulate and forecast the daily discharge of several basins of the Spanish Pyrenees. We describe a method for snow mapping using NOAA-AVHRR data and a procedure to estimate retrospectively the accumulated snow water equivalent volume with the SRM. A linear combination of NOAA channels 1 and 2 is used to obtain a snow cover image in which the product is the percentage of the snow-covered area in each pixel. Real-time snowmelt forecasts are generated with the SRM using area snow cover as an input variable. Even in basins with a total absence of historical discharge and meteorological data, the SRM provides an estimation of the daily snowmelt discharge. By integrating the forecasted streamflow over the recession streamflow, snowmelt volume is obtained as a function of time. This function converges asymptotically to the net stored volume of water equivalent of the snowpack. Plotting this integral as a function of time, it is possible to estimate for each basin both the melted snow water equivalent (SWE) and the SWE remaining in storage at any point in the snowmelt season Spanish hydropower companies are using results from the SRM to improve water resource management (Gomez-Landeses and Rango 2002).
1.4.2 Snow cover mapping with satellite data

A demonstration is presented of the capabilities of an integration of remote sensing (RS) image processing, GIS and database management systems (DBMS) technologies in combination with hydrological models. A basic request for such an integrated system is a completely digital transfer of data between the different software modules. The merit of an integrated approach is demonstrated with the Alpine Snow Cover Analysis System (ASCAS). In addition to the image processing system, the GIS and DBMS, a hydrological model the Snowmelt Runoff Model (SRM) is implemented in ASCAS. Snow cover variations in the Swiss Alps were studied using NOAA-AVHRR data during the hydrological years of 1983-84 and 1992/93. Snow cover ablation patterns, snow-line variations and snow cover depletion were compared for the two years under investigation. Furthermore, the use of these data in snowmelt runoff modelling with SRM is shown (Baumgartner, 1997 #27).

The required input to the Snowmelt Runoff Model (SRM) for different elevation zones is given by the snow-covered area (S), temperature (T) and precipitation (P) values. The seasonal changes in snow coverage can be monitored by earth observation satellites. The daily runoff can be simulated or forecasted. In addition, maps of regional water equivalent based on the seasonal snow cover accumulation during wintertime are derived (Martinec 1975).

Knowledge of the hydrological behaviour is a crucial step in water resources management of large-scale catchments. One of the important tools in acquiring spatial and temporal information of large-scale catchments is remote sensing imagery. In this study. (hammouda.h 1999).

This study has been done by integration of RS and GIS methodology to study the dependence of snow cover distribution on the topographic aspects and slope of a Himalayan basins (viz. Dokriani Bamak) in a hydrological year. A digital elevation model (DEM) and repetitive digital data from the IRS-1B LISS-II sensor have been used to yield data on snow cover. The satellite sensor data combined with terrain information in a DEM help overcome the local effects of shadows. The landform facet image has been taken by using slope and aspect combinations and for calculating snow covered pixels facet wise the landform facet image was superimposed over the snow cover area corrected image. Thus, the study reveals that local topographic slope and aspect have significant influence on the snow cover area and its depletion pattern (Baral and Gupta 1997)
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The global land 1-km AVHRR data set project represents an international effort to acquire, archive, process, and distribute 1-km AVHRR data of the entire global land surface in order to meet the needs of the international science community (Eidenshink and Faundeen).

1.4.3 Snowmelt runoff modelling in Iran and Central Asia

Hydrological analysis has been done by using SRM model and NOAA images has been used for snow cover area extraction in Namrud catchments. Cost efficiency and fine temporal resolution of images from the satellite-borne NOAA-AVHRR sensor indicate this source of information as a suitable candidate for monitoring snow cover extent for cloudy area the topographic data (digital elevation model) were used and by dividing the area to different zones (3 zones) the depletion curves of the snow coverage were plotted. The percentage of snow cover was used as input for the snowmelt runoff model (SRM). The result shows a good conformity between simulated and measured runoff... (Sanei 2000)

The realization of a snowmelt runoff-forecasting centre at the Hydro-Meteorological Survey of Uzbekistan in Tashkent is described. In the context of World Bank Project 2.1 for the "Saving of the Aral Sea", the estimation of the amount of snow stored in the Central Asian mountains represents an important economic factor with regard to hydro-electric power generation and irrigation. Based on satellite remote sensing, GIS and database technologies, real-time snowmelt runoff forecasts using SRM (Snowmelt Runoff Model) were performed for several basins in Uzbekistan and Kyrgyzstan (Weiss, Baumgartner et al. 2000).
CHAPTER 2  Description of the study area

2.1 Situation

The Mirabad catchment is located in northwest from Orumiyeh city in West Azerbaijan province, between 44° 35' & 44° 48' E and 37° 20' & 37° 33' N. This area is surrounded by Nazloo and Rozeh basins from the north, Barandooz basin from the south, Shahr-chai basin from east and by the Iran-Turkey border from west.

Topography maps (1:50000) have been used for extraction of the catchment’s boundary and physiographic parameters have been extracted from an elevation model based on 100 m contour interval. This catchment belongs to one of the main tributaries of the Shahr-chai River. The whole area of the catchment upstream from the Mirabad station is about 201 km².

2.2 Physiography

Physiography in fact is the study of physical characteristics and morphological conditions of a catchment those have important role and effect on the hydrological characteristics and the water regime. By knowing the physiographic characteristics of a catchment and its location, we can have a good quantitative and qualitative assessment of the hydrological system of the catchment. These factors have direct effects not only on the hydrologic regime, annual water production, flood volumes and soil erosion, but also it has an effect on the climate, ecological conditions and vegetation cover.

Mirabad catchment includes some small sub-catchments, which have not been taken into account separately because of their size. The study area is mountainous with high internal relief and the Max. Slope steepness is more than 50 % and the elevation has strong effects on the precipitation, temperature and other climatological parameters. The area is about 201 km² and its perimeter is about 61.3 km.

The hypsometric curve and the histogram of the Mirabad catchment are shown in Fig. 2-1 and Fig. 2-2, respectively. Because of the high elevation, most of the catchment has precipitation as snow in winter. The highest point is located in west with elevation of 3595 meter and the lowest part is in east with 1513-meter height.
The main water supply is the Mirabad catchment that is the main tributary of the shahr-chai river. The river originates from the Khalil and Kokaro mountains and with a west-east direction it drains into the Orumiyeh Lake.

Figure 2-1 Hypsometric curve of Mirabad Catchment
2.3 Climatology

West-Azerbaijan in Northwest of Iran has cold and moist winters and a mild temperature in the summers. This area is affected by the cold and moist Siberian anticyclones when the west winds from the Mediterranean Sea are dominant. The climatologic data including temperature and rainfall were obtained from stations, which are located in and around the study area.

To calculate the mean annual rainfall, the data of these stations were used. For the SRM model, daily rainfall, temperature and discharge data from the Mirabad station (which is located at the outlet of the catchment) have been extracted.

In the study area the temperature varies between a monthly mean maximum of 20.7 °C in July and a minimum of –3 °C in February with an average of 9.7 °C. Monthly temperature for 27 years at the Mirabad station is shown in Fig. (2-3).
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2.4 Hydrology

The Mirabad River originates from the Khalil and Zarineh mountains on the western part of the area. Mirabad River flows from west to east and joins the Koseh-lu River near Mirabad village. From this point, the river is named Shahr-chai, which finally flows into the Orumiyeh Lake.

Based on the Mirabad hydrometry station, the minimum discharge of the river is in October, and the maximum is in June. Water quality for agricultural purposes based on Wilcox classification is C2s1, (a good quality water), and salinity-related specific conductance is 483 micromhos/cm and alkalinity (according to SAR) is 0.86 (Oskouei 1997). Figure 2-4 shows the discharge and precipitation variations in Mirabad station for the period of 1996-97.

Figure 2-3 Monthly temperature in Mirabad Catchment (1983-2000)
2.5 Geology

Based on the geology map (at scale 1:250000), geological formations of the study area belong to different geological era from pre-Cambrian to Cambrian. The oldest lithological units, the Selvana complex, occur on the west elevations, near the borderline with Turkey and consists of rock such as: slate, phylite, dolomite and some limestone.

Other rocks of this era are metamorphosed quartz-porphyry, schist, gneiss (named as volcanic complex), schistosic acid tuff, and some undifferentiated metamorphic rocks (Oskouei 1997). Limestone, karstic and sandstone formations especially fractured rocks play important role on water recharging.

2.6 Soil

The depth of the soil in mountainous areas varies from very shallow to moderately deep (at a few places in the valleys and on the footslopes) with texture that ranges from sandy loam to clay with some gravel-rock outcrop. The main soils are Entisols on the steep slopes and
Inceptisols on the less steep areas like in some of the rather stable foot slopes. In the higher stable surfaces, Alfisols also were found. (Oskouei 1997)

## 2.7 Fieldwork

The following activities have been done in the field:

1. Controlling the snow packs in the field with regards to elevation.
2. Measuring the snow density
4. Infiltration and direct runoff surveying by using aerial photos and geological maps and classifying the infiltration condition.
CHAPTER 3 GIS and Remote Sensing

3.1 Map preparation

The maps for the analysis were compiled using the Integrated Land and Water Information System (ILWIS). The following subsections describe the compilation of the most important ones.

3.1.1 Topographic maps of the Orumiyeh Basin

The digital version of the topographic maps was provided by an antecedent project of the region. The basis of the digitisation was the printed map at a 1:100000 scale. By using these topographic maps of the region the boundary map and other necessary maps of the study area were prepared.

The origin of the digital contour map is the same. Unfortunately, the quality of the map was not very good, so intensive corrections were needed. The contours were drawn with 100 m intervals.

3.1.2 Digital Elevation Model

Digital elevation model (DEM) is one of the fundamental tools in GIS analysis and image processing. For creating DEM, the topographic maps of Orumiyeh basin were used as a base with a contour interval of 100 m. The DEM map of study area was prepared by interpolation in ILWIS. Digital elevation models were created for the whole Orumiyeh basin as well as for the Mirabad catchment separately.

3.1.3 Slope

The slope map (in percent) was prepared by using DEM, then by slicing method the slope map was classified into five classes. A slope aspect map was also created, which was used later in snow monitoring.

3.1.4 Zonation

For the modelling of snowmelt runoff, the catchment had to be subdivided into elevation zones. For creating the zone map for the study area the DEM of Mirabad sub-basin was used.
The area was divided into 3 main classes. The boundary altitudes between the zones were defined based on an elevation/area curve.

3.2 Image processing

3.2.1 Importance of snow cover mapping

Snow cover is an important variable for climate and hydrologic models due to its effects on energy and moisture budgets. A primary factor controlling the amount of solar radiation absorbed at the earth surface is the extent of snow cover due to its high albedo. Any decrease in snow cover resulting from a warming trend results in increased absorption of solar radiation and additional heat to melt additional snow.

This results in the classic positive temperature-albedo feedback mechanism, which is included in nearly all climate models. In addition to the albedo effect, snow cover represents a significant heat sink during the warming period of the seasonal cycle due to a relatively high latent heat of fusion. As a result, the seasonal snow cover provides a major source of thermal inertia within the total climate system as it takes in and releases large quantities of energy with little or no fluctuation in temperature.

Remote sensing offers a valuable tool for obtaining snow data for predicting snowmelt runoff. Historically, snow data have been obtained manually by means of snow courses, which are extremely labour intensive, expensive and potentially dangerous. From a remote sensing perspective, snow cover is one of the most readily identifiable measures of water resources from aerial photography or satellite imagery (Engman and Gurney 1992).

3.2.2 Snow monitoring by NOAA

Monitoring snow cover during the melting period is of a key interest for hydrological analysis and management. Classical methods make use of in situ measurements, such as snow gauges, which present a strong limitation mainly due the lack of their spatial covering. Since 1973, the NOAA and Landsat satellites have provided visible and infrared imagery of snow cover throughout the world. Procedures have been developed for analysing these data to determine snow cover area (Meier and Evans 1975).

The satellite remote sensing of the snow cover therefore is a useful tool in runoff forecasts and hydrological analysis. The NOAA AVHRR data were used and entered into a
Geographical Information System in order to evaluate the snow cover in the Orumiyeh Lake basin. The images were georeferenced with the help of the DEM and resampled to a common geometry. Some images of NOAA-AVHRR for snow cover mapping for the year (1996-97) has shown in Figure 3-1.

Figure 3-1 NOAA images used for snow mapping
Because of the changing position of the snow line during the snowmelt season, periodic snow cover mapping has been carried out with a sufficient frequency for the period of October 1996 – September 1997. A set of 15 NOAA satellite images were available.

The discrimination between snow and cloud using AVHRR imagery has proved a major barrier to the development of operational snow mapping procedures. The major difficulty with extensive cloud occurrence is that the underlying snow surface is often completely obscured from the view of the satellite sensor. With persistent cloud cover, observation of snow may be prevented for considerable periods of time during which significant changes in snow extent and condition (due to melting and/or accumulation) may take place.

Direct observation of snow from the AVHRR is therefore only possible in cloud-free conditions or where snow can be observed beneath the cloud layer (e.g., through thin stratus). Extraction of the snow area then becomes the main obstacle to snow mapping as the overlap in the response of snow and cloud in the spectral wavebands sensed prevents reliable separation of snow covered ground resolution elements. (Foody and Curran 1994)

In the visible and near infrared wavebands, snow cover and cloud have a similar spectral response and may be confused, although the contrast between snow covered and snow free surfaces is greatest in these channels, particularly in the visible bands. AVHRR channel 3 is sensitive to both reflected solar radiation and emitted terrestrial radiation (Raschke 1982).

Clouds exhibit at bright appearance in channel 3 where the particles of which they are composed are of a diameter less than the wavelength. Snow therefore contrasts dramatically with clouds composed of very small ice particles (e.g., cirrus) and small water droplets (e.g., altostratus) which have a greater response in channel 3 (Scorer 1987).

In AVHRR channels 4 and 5, higher elevation clouds have a dark appearance in calibrated imagery, due to low thermal emission, and contrast with the brighter snow surfaces while low altitude, warmer clouds exhibit some spectral overlap with snow surfaces. (Foody and Curran 1994).

For assessment of the snow cover in the hydrological year (1996-97) the snow-covered areas were derived from NOAA AVHRR images, and the daily precipitation and temperature data were used from ground stations.

Temperature and reflectivity (albedo) of the snow surface are the fundamental variables for snow detection. Snow cover mapping was carried out for three-elevation zones.
Table 3-1 Elevation zones of the Mirabad Catchment

<table>
<thead>
<tr>
<th>Zone</th>
<th>Elevation range (m a.s.l.)</th>
<th>Area (Km²)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1525-2200</td>
<td>59.57</td>
<td>29.67</td>
</tr>
<tr>
<td>B</td>
<td>2200-2900</td>
<td>115.96</td>
<td>57.75</td>
</tr>
<tr>
<td>C</td>
<td>2900-3595</td>
<td>25.27</td>
<td>12.58</td>
</tr>
<tr>
<td>Total</td>
<td>1525-3595</td>
<td>200.8</td>
<td>100</td>
</tr>
</tbody>
</table>

The choice of NOAA images is justified by the high acquisition frequency of them that can provide quasi-continuous information. The high acquisition frequency is useful especially in areas where clouds are frequently present, or where the snow cover changes rapidly.

For clear-sky conditions, the spectral classification of snow is straightforward because of the high reflectivity of the snow cover in visible band, which makes it quite different from any other kind of ground coverage (Choudhury 1979).

The spectral signature of snow shows higher reflectivity values in visible band than in near and medium infrared bands, while most of the other natural coverage types display higher reflectivity in the infrared band (Sanei 2000).

The snow cover was determined for the Lake basin as a whole and for zones with 100 m altitude steps in Mirabad sub basin. For this, different NOAA-AVHRR images were used. Analysis of remote sensing data showed different value ranges between clouds and snow surfaces in thermal bands, but ratio between visible and near infrared doesn’t give enough information to distinguish clouds from snow.

For using classification method, the temperature map was created and composed with 1 and 3 bands. Therefore, the images with much cloud coverage were eliminated, but images with less than 60 % cloud coverage were used.

The topographic data are the best tools for recovering information about the snow cover under cloud. By using Digital Elevation Model and aspect maps the snow lines were defined for slopes with different aspects and the final snow maps were prepared by fusing the cloud-
Investigation of the snowmelt runoff in the Orumiyeh region, using modelling, GIS and RS techniques

Table 3-2 Snowline altitudes on slopes with different aspects (1996-97)

<table>
<thead>
<tr>
<th>No.</th>
<th>Image</th>
<th>South Alt. (m)</th>
<th>North Alt. (m)</th>
<th>West Alt. (m)</th>
<th>East Alt. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>961020</td>
<td>2850</td>
<td>2650</td>
<td>2670</td>
<td>2300</td>
</tr>
<tr>
<td>2</td>
<td>961120</td>
<td>2680</td>
<td>2340</td>
<td>2575</td>
<td>2030</td>
</tr>
<tr>
<td>3</td>
<td>961230</td>
<td>2000</td>
<td>1900</td>
<td>1850</td>
<td>1650</td>
</tr>
<tr>
<td>4</td>
<td>970125</td>
<td>1400</td>
<td>1300</td>
<td>1325</td>
<td>1320</td>
</tr>
<tr>
<td>5</td>
<td>970127</td>
<td>1450</td>
<td>1325</td>
<td>1350</td>
<td>1400</td>
</tr>
<tr>
<td>6</td>
<td>970202</td>
<td>1400</td>
<td>1285</td>
<td>1330</td>
<td>1300</td>
</tr>
<tr>
<td>7</td>
<td>970215</td>
<td>1585</td>
<td>1360</td>
<td>1520</td>
<td>1350</td>
</tr>
<tr>
<td>8</td>
<td>970302</td>
<td>1625</td>
<td>1430</td>
<td>1550</td>
<td>1400</td>
</tr>
<tr>
<td>9</td>
<td>970310</td>
<td>1400</td>
<td>1275</td>
<td>1330</td>
<td>1270</td>
</tr>
<tr>
<td>10</td>
<td>970315</td>
<td>1450</td>
<td>1400</td>
<td>1380</td>
<td>1320</td>
</tr>
<tr>
<td>11</td>
<td>970331</td>
<td>1775</td>
<td>1560</td>
<td>1550</td>
<td>1450</td>
</tr>
<tr>
<td>12</td>
<td>970429</td>
<td>2130</td>
<td>2100</td>
<td>2050</td>
<td>1920</td>
</tr>
<tr>
<td>13</td>
<td>970512</td>
<td>2600</td>
<td>2500</td>
<td>2450</td>
<td>2100</td>
</tr>
<tr>
<td>14</td>
<td>970525</td>
<td>2700</td>
<td>2550</td>
<td>2520</td>
<td>2300</td>
</tr>
<tr>
<td>15</td>
<td>970728</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
3.2.3 Estimation of zonal snow coverage (Depletion Curves)

It is a typical feature of mountain basins that the areal extent of the seasonal snow cover gradually decreases during the snowmelt season. Depletion curves of the snow coverage can be interpolated from periodical snow cover mapping so that daily values can be read off as an important input variable to SRM (Snowmelt Runoff Model). (Martinec and Rango 1998)

The image analysis taken from NOAA-AVHRR satellites for the study area indicates dependency of snow cover extent to topography and the relation between snow area and the elevation zones. Fig. (3-2) shows depletion curves of the snow coverage evaluated from periodical mapping in the elevation range of 1500-3500 m a.s.l.

![Depletion Curves](image)

**Figure 3-2 Depletion curves of the snow coverage for 3 elevation zones of the Mirabad Catchment (1996-97)**
It is understandable from the depletion curves, that whenever temperatures indicate no melting conditions the snow coverage is kept unchanged. At high altitudes the snowmelt occurs later than in the lower altitudes.

The analysis of snow cover extent in the Mirabad Catchment shows the real estimations of snow by remotely sensed data and it is useful source of information for management of water resources in different altitudes of mountainous areas.

After processing the images, about seven of them were selected with high reliability and 7 images with limited reliability for estimating snow cover of the study area. In the images with limited reliability, the snow line was defined with the help of the DEM, as described above. For each zone the area and percentage of snow cover area was extracted as input for the snowmelt runoff model (SRM).
CHAPTER 4  Hydrological Analysis

4.1 Precipitation

Precipitation is one of the most important climatological parameters, which includes – as the two most important types – rain, and snow. As the study area is located in semi arid region, where water shortage occurs frequently, it is necessary to have reliable information about precipitation.

The main part of the precipitation originates from western air masses in winter and spring. Because the study area is mountainous, a large part of the precipitation is in the form of snow that, by gradual increase in temperature in the spring, melts and causes runoff.

The rainfall data were collected from 15 rain gauge stations around the study area, related to the Water Company of Orumiyeh and a synoptic station, related to Meteorological Organization.

All stations are located outside the study area and in relatively low altitudes. Table 4-1 shows the information of the rain gauges and the synoptic station.

The monthly and yearly rainfall data for the period of 1973-1999 were used for the calculation of the rainfall-altitude relationship.

Rainfall-altitude relationship gives information about the orographic effect, i.e. the rainfall conditions related to altitudes. This relationship can be used for the estimate of rainfall for areas without any gauge in mountainous regions. For the study area, the relation has been calculated for the period of 1973-1999 for the whole Orumiyeh Basin and for 1996-97 only of the Mirabad Catchment, using annual rainfall data.

It is necessary to explain that all stations are located outside the study area and in lower altitudes that causes poor relation between rainfall and altitude in the higher altitudes. The correlation coefficient using the 27 years-long dataset is about 0.72 and using the one-year long rainfall is 0.62 (see below).
Table 4-1 Rain gauges and synoptic stations

<table>
<thead>
<tr>
<th>N.</th>
<th>Station</th>
<th>Type of station</th>
<th>Altitude</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Golmankhaneh</td>
<td>Rain gauge</td>
<td>1280</td>
<td>37, 36</td>
<td>45, 14</td>
<td>Outside</td>
</tr>
<tr>
<td>2</td>
<td>Camp Orumiyeh</td>
<td>Climatology</td>
<td>1381</td>
<td>37, 32</td>
<td>45, 02</td>
<td>Outside</td>
</tr>
<tr>
<td>3</td>
<td>Moshabad</td>
<td>Rain gauge</td>
<td>1290</td>
<td>37, 44</td>
<td>45, 12</td>
<td>Outside</td>
</tr>
<tr>
<td>4</td>
<td>Dizaj</td>
<td>Rain gauge</td>
<td>1320</td>
<td>37, 23</td>
<td>45, 04</td>
<td>Outside</td>
</tr>
<tr>
<td>5</td>
<td>Ghasemloo</td>
<td>Rain gauge</td>
<td>1330</td>
<td>37, 21</td>
<td>45, 09</td>
<td>Outside</td>
</tr>
<tr>
<td>6</td>
<td>Marz-E-Sero</td>
<td>Rain gauge</td>
<td>1640</td>
<td>37, 43</td>
<td>44, 38</td>
<td>Outside</td>
</tr>
<tr>
<td>7</td>
<td>Band</td>
<td>Rain gauge</td>
<td>1390</td>
<td>37, 30</td>
<td>45, 01</td>
<td>Outside</td>
</tr>
<tr>
<td>8</td>
<td>Tapik</td>
<td>Rain gauge</td>
<td>1450</td>
<td>37, 40</td>
<td>44, 54</td>
<td>Outside</td>
</tr>
<tr>
<td>9</td>
<td>Babarood</td>
<td>Rain gauge</td>
<td>1285</td>
<td>37, 24</td>
<td>45, 14</td>
<td>Outside</td>
</tr>
<tr>
<td>10</td>
<td>Orumiyeh</td>
<td>Synoptic</td>
<td>1313</td>
<td>37, 32</td>
<td>45, 05</td>
<td>Outside</td>
</tr>
<tr>
<td>11</td>
<td>Mirabad</td>
<td>Rain gauge</td>
<td>1513</td>
<td>37, 26</td>
<td>44, 53</td>
<td>Outside</td>
</tr>
<tr>
<td>12</td>
<td>Bibakran</td>
<td>Rain gauge</td>
<td>1485</td>
<td>37, 23</td>
<td>45, 04</td>
<td>Outside</td>
</tr>
<tr>
<td>13</td>
<td>Seger gan</td>
<td>Rain gauge</td>
<td>1495</td>
<td>37, 18</td>
<td>44, 58</td>
<td>Outside</td>
</tr>
<tr>
<td>14</td>
<td>Zharabad</td>
<td>Rain gauge</td>
<td>1590</td>
<td>37, 37</td>
<td>44, 58</td>
<td>Outside</td>
</tr>
<tr>
<td>15</td>
<td>Gharalar</td>
<td>Rain gauge</td>
<td>1350</td>
<td>37, 40</td>
<td>44, 51</td>
<td>Outside</td>
</tr>
</tbody>
</table>

The long-term relation is more reliable since the random effects are less affecting it, so this relation was used for the Mirabad Catchment in the calculation of the rainfall for ungauged regions.

\[ Y = 1032.5 \ln(x) - 7090.6 \quad R = 0.72 \quad (1973-2000) \]

\[ Y = 0.5436x - 416.47 \quad R = 0.62 \quad (1996-1997) \]

Figure 4-1 and Error! Reference source not found. show the rainfall-altitude relationship for period of (1996-97) and (1973-2000) respectively.
Investigation of the snowmelt runoff in the Orumiyeh region, using modelling, GIS and RS techniques

**Figure 4-1 Rainfall-Altitude Relationship (1996-97)**

\[ y = 0.5436x - 416.47 \]
\[ R = 0.622 \]

**Figure 4-2 Rainfall-Altitude Relationship (1973-2000)**

\[ y = 1032.5\ln(x) - 7090.6 \]
\[ R = 0.72 \]
4.2 Temperature

Temperature is one of the most important climatologic parameters in SRM model that forms the basis of some other necessary parameters too, such as the degree-days and the degree-day factor, which have important influence on the snowmelt.

For calculating the temperature-altitude relationship, 8 stations were considered. All these stations are located at lower altitudes and outside of the study area, as well as the distance from Lake Orumiyeh also has an effect on the air temperature in the region, the calculated relationship was not reliable neither for short-term average temperatures (daily, 15 days, monthly) nor for longer term averages, like yearly.

As an example, Figure 4-3 shows the calculated relationship using only one station’s data. The gradient is much larger, than the usually accepted. Therefore, in the SRM model parameter preparation, the extrapolation was done using 0.65 C/100 m, that is recommended for ungauged areas by the model developers.

Table 4-2 shows the information of the stations used for temperature-altitude relationship and for period of (1983-2000).

<table>
<thead>
<tr>
<th>N.</th>
<th>Station</th>
<th>T °C</th>
<th>Altitude</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Situated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Abajaloo</td>
<td>10.8</td>
<td>1290</td>
<td>37, 43</td>
<td>45, 08</td>
<td>Outside</td>
</tr>
<tr>
<td>2</td>
<td>Ghasemloo</td>
<td>10.7</td>
<td>1330</td>
<td>37, 21</td>
<td>45, 09</td>
<td>Outside</td>
</tr>
<tr>
<td>3</td>
<td>Golmankhaneh</td>
<td>12.6</td>
<td>1280</td>
<td>37, 36</td>
<td>45, 14</td>
<td>Outside</td>
</tr>
<tr>
<td>4</td>
<td>Bibakran</td>
<td>10</td>
<td>1485</td>
<td>37, 23</td>
<td>45, 04</td>
<td>Outside</td>
</tr>
<tr>
<td>5</td>
<td>Camp Orumiyeh</td>
<td>11.5</td>
<td>1381</td>
<td>37, 32</td>
<td>45, 02</td>
<td>Outside</td>
</tr>
<tr>
<td>6</td>
<td>Marz-E-Sero</td>
<td>7.7</td>
<td>1640</td>
<td>37, 43</td>
<td>44, 38</td>
<td>Outside</td>
</tr>
<tr>
<td>7</td>
<td>Mirabad</td>
<td>9.7</td>
<td>1513</td>
<td>37, 26</td>
<td>44, 53</td>
<td>Outside</td>
</tr>
<tr>
<td>8</td>
<td>MarcazPazhoheshi</td>
<td>11.2</td>
<td>1385</td>
<td>37, 31</td>
<td>45, 02</td>
<td>Outside</td>
</tr>
</tbody>
</table>
4.3 Runoff

Accurate prediction of runoff rates and runoff volumes is used for water supply forecasting, flood predictions and warnings, navigation, water quality management, hydropower production, and many other water resource applications. The objective most sought by hydrologists is the accurate and timely prediction of runoff at a given point in a drainage basin. The tools available to hydrologists encompass a wide range of equations and models as well as stream gauging stations where the stream flow or reservoir volume is measured directly in real time (Engman and Gurney 1992).

Rainfall and snowmelt partly infiltrates or evaporates, partly causes surface runoff. Based on water resources study in Mirabad Catchment and relying also on the Orumiyeh water balance report (Jihad Engineering Services Co. 2001), more than 25% of the water reaching the surface adds to groundwater (i.e. infiltrates) that comes out as springs at lower altitudes. This value was taken into account during the calibration of the runoff coefficient in the SRM model.
For determining the wet and dry years, discharge data were plotted for the period of (1973-2000) that shows the yearly discharge variations. Based on Figure 4-4, the years 1975, 87, and 92 are very wet and the years 1974 and 98 are very dry. A longer relatively dry period starts from 1978 up to 1984, and a relatively wet period is between 1985 up to 1994, and again a relatively dry period started from 1995 and it continues (see the smoothened, moving average line in the figure).

Analyzing the monthly mean discharge in Mirabad catchment shows that June with 12.22 m$^3$/s and October with 0.610 m$^3$/s have respectively high and low runoff.

Increasing in temperature and snowmelt in June, products much runoff in this month (Jihad Engineering Services Co. 2001).

Figure 4-5 shows the snowmelt that occurs in spring and coincidence of rainfall with sharp peaks in discharge.
The snowmelt runoff starts in April when temperature rises above zero degree at lower altitudes and culminates in May when all over the basin has temperature above zero.

The Mirabad Catchment has runoff all around the year, because of ground water discharge and springs (especially in karstic areas).

Hydrograph analysis is achieved by separating flow component of hydrograph on discharge of the stream. By plotting a hydrograph of stream discharge versus time and by drawing the line between rainfall flow snowmelt and base flow, the volume of them have been calculated for Mirabad catchment. Figure 4-5 shows flow component separation on the hydrograph of the daily runoff in 1996-97. This represents a first estimate of the different flow components, which was used in the judgment of the modeling results later.

The groundwater contributes to surface runoff by seepage and discharge from springs, therefore separation of snowmelt runoff and groundwater runoff is difficult. As Table 4-3 shows, snowmelt runoff includes about 50 % of the total runoff and base flow is about 29 % (most of it comes to snowmelt infiltration). The direct runoff from rainfall is about 21 %. This shows the importance of snow in runoff creation in the study area.

<table>
<thead>
<tr>
<th>Station</th>
<th>Q Total $(10^6 \text{ m}^3)$</th>
<th>Qs $(10^6 \text{ m}^3)$</th>
<th>Qr $(10^6 \text{ m}^3)$</th>
<th>Qb $(10^6 \text{ m}^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirabad</td>
<td>167.45</td>
<td>83.18</td>
<td>38.17</td>
<td>46.10</td>
</tr>
</tbody>
</table>

Table 4-3 Flow components of Mirabad catchment (1996-97)
Investigation of the snowmelt runoff in the Orumiyeh region, using modelling, GIS and RS techniques

Figure 4-5 Flow Separation of Daily Discharge of Mirabad catchment (1996-97) (Qb = base flow, Qs = snowmelt, Qr = rainfall discharge)
CHAPTER 5  Snowmelt Runoff Modeling

The Snowmelt Runoff Model (SRM; also referred to in the literature as the “Martinec-Rango Model”) is designed to simulate and forecast daily stream flow in mountainous basins where snowmelt is a major runoff factor. Most recently, it has also been applied to evaluate the effect of a changed climate on the seasonal snow cover and runoff. SRM was developed by Martinec (Martinec 1975) in small European basins.

Snowmelt runoff has been simulated with SRM in basins of different sizes. The smallest basins were of a few square kilometers. By progressing of satellite remote sensing of snow cover; SRM has been applied to larger and larger basins. The largest basin where SRM has been applied so far is about 120000 km². Runoff computations by SRM appear to be relatively easily understood. (Martinec and Rango 1998)

5.1 Model Structure

Each day, the water produced from snowmelt and from rainfall is computed, superimposed on the calculated recession flow and transformed into daily discharge from the basin according to Equation (1):

\[
Q_{n+1} = \left[ c_s \cdot a_n \left( T_n + \Delta T_n \right) + c_r P_n \right] \frac{A \cdot 10000}{86400} \left( 1 - k_{n+1} \right) + Q_n k_{n+1}
\]  

(1)

Where:

\( Q \) = average daily discharge \( (m^3/s) \)

\( C \) = runoff coefficient expressing the losses as a ratio (runoff/precipitation), with \( c_s \) referring to snowmelt and \( c_r \) to rain

\( a = \) degree-day factor \( (cm.\ C^{-1}.d^{-1}) \) indicating the snowmelt depth resulting from 1 degree-day

\( T = \) number of degree-days \( (C.d) \)
$\Delta T$ = the adjustment by temperature lapse rate when extrapolating the temperature station to the average hypsometric elevation of the basin or zone (C.d)

$S$ = ratio of the snow covered area to the total area

$P$ = precipitation contributing to runoff (cm). A preselected threshold temperature, $T_{CRIT}$ determines whether this contribution is rainfall and immediate. If precipitation is determined by $T_{CRIT}$ to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur.

$A$ = area of the basin or zone (km$^2$)

$k$ = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall:

$$k = \frac{Q_{m+1}}{Q_m}$$ (m, m+1 are the sequence of days during a true recession flow period).

$n$ = sequence of days during the discharge computation period. Equation (1) is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the $n^{th}$ day corresponds to the discharge on the $n+1^{th}$ day. Various lag times can be introduced by a subroutine.

$$\frac{1000}{86400} = \text{Conversion from cm.km}^2\cdot\text{d}^{-1} \text{ to m}^3\cdot\text{s}^{-1}$$

$T$, $S$ and $P$ are variables to be measured or determined each day. $C_R$, $C_S$, lapse rate to determine $\Delta T$, $T_{CRIT}$, $k$ and the lag time are parameters which are characteristic for a given basin or, more generally, for a given climate (Martinec and Rango 1998).

Because the elevation range of the Mirabad Catchment exceeds 500 m, it was subdivided into three elevation zones, therefore the model equation becomes:
Investigation of the snowmelt runoff in the Orumiyeh region, using modelling, GIS and RS techniques

\[
Q_{n+1} = \left[ \left( c_{S\text{An}} \cdot a_{An}(T_n + \Delta T_{An})S_{An} + c_{R\text{An}} \cdot P_{An} \right) A_n \cdot \frac{10000}{86400} + \right. \\
\left. \left( c_{S\text{Bn}} \cdot a_{Bn}(T_n + \Delta T_{Bn})S_{Bn} + c_{R\text{Bn}} \cdot P_{Bn} \right) A_B \cdot \frac{10000}{86400} + \right. \\
\left. \left( c_{S\text{Cn}} \cdot a_{Cn}(T_n + \Delta T_{Cn})S_{Cn} + c_{R\text{Cn}} \cdot P_{Cn} \right) A_C \cdot \frac{10000}{86400} \right] (1-k_{n+1}) + Q_n \cdot k_{n+1} \quad (2)
\]

The indices A, B and C refer to the respective elevation zones and a time lag of 18 hours is assumed (Martinec and Rango 1998).

5.2 Input data for running the model

The input data can be grouped as follows:

- Basin characteristics.
- Variables.
- Parameters.

5.2.1 Basin characteristics

5.2.1.1 Basin and zone areas

The basin boundary is defined by the location of the stream gauge (or some arbitrary point on the stream course) and the watershed divide is identified on a topographic map (Martinec and Rango 1998).

For the study area, digital topographic maps of 1:50000 scale were used with contour lines with 100 m intervals, as was described in Chapter 3.

Based on elevation range between Mirabad hydrometric station (1525m) and the highest point in the basin (3595m), three elevation zones have been delineated with intervals of about
700 m. In the first step, the catchment area was masked out from the DEM of the Orumiyeh basin. Using the histogram of the catchment DEM, the area-elevation curve was constructed in ILWIS. Figure 5-1 shows the elevation zones and Table 5-1 shows the areas and altitude variations of different zones in the Mirabad Catchment.

These zones form the basis of the calculations in SRM. For the calculation of snowmelt runoff, the various model variables and parameters had to be defined and applied to each zone.

Figure 5-1 Elevation zones of the Mirabad Catchment
Table 5-1 Areas and Altitude variations of different zones in Mirabad Catchment

<table>
<thead>
<tr>
<th>Zones</th>
<th>Area (km²)</th>
<th>Altitude range (m)</th>
<th>Mean Hypsometric Altitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>59.34</td>
<td>1525-2200</td>
<td>1917.22</td>
</tr>
<tr>
<td>B</td>
<td>116.35</td>
<td>2200-2900</td>
<td>2562.12</td>
</tr>
<tr>
<td>C</td>
<td>25.29</td>
<td>2900-3595</td>
<td>3058.57</td>
</tr>
</tbody>
</table>

5.2.1.2 Area-elevation curve

By using the zone boundaries plus other selected contour lines in the basin, the areas enclosed by various elevation contours determined in ILWIS environment. These data plotted (area vs elevation) and an area-elevation (hypsometric) curve derived for Mirabad catchment as shown in Figure 2-1.

The zonal mean hypsometric elevation, $\bar{h}$, was determined by using histogram data of zone map for each zone separately. The $\bar{h}$ value is used in SRM as the elevation to which the temperatures from the base station are extrapolated for the calculation of the zonal degree-days.

5.2.2 Variables

Variables basically describe the actual meteorological conditions for the simulated period. These data have to be obtained preferably from in situ measurements, but the snow cover, for example, can be also defined by remote sensing.

5.2.2.1 Temperature and degree-days, $T$

A degree-day is a day with an average temperature one degree above 32°F. A day with an average of 45° F. gives 13 degree-day. In order to compute the daily snowmelt depths, the number of degree-days must be determined from temperature measurements. The program
accepts either the daily mean temperature or two temperature values on each day: 
\( (T_{Max}, T_{Min}) \). The first method (daily mean) was used for the Mirabad Catchment.

The daily mean temperature data from Mirabad station was extrapolated to the hypsometric 
mean elevations of three zones using the temperature lapse rate \( (\gamma) \). Because the average 
temperatures refer to a 24-hour period starting always at 0600 hrs, they become degree-days 
\( T \left[ C \cdot d \right] \). The altitude adjustment \( \Delta T \) in Equation (1) is computed as follows:

\[
\Delta T = \gamma \cdot (h_{st} - h) \cdot \frac{1}{100}
\]

Where: \( \gamma \) = temperature lapse rate \( (C/100 \text{ m}) \)

\( h_{st} \) = altitude of the temperature station \( (\text{m}) \)

\( \bar{h} \) = hypsometric mean elevation of a zone \( (\text{m}) \)

Whenever the degree-day numbers \( (T + \Delta T \) in Equation (1)) become negative, they are 
automatically set to zero so that no negative snowmelt is computed. The program accepts 
either temperature data from a single station (option0, basin wide) or from several stations 
(option 1, by zone). With option 0, the altitude of the station is entered and temperature data 
are extrapolated to the hypsometric mean elevations of all zones using the lapse rate 
(Martinec and Rango 1998).

For extrapolating temperature data for different zones in the study area, Mirabad station that 
is located in outlet of the catchment was used (option 0), because other stations are located in 
low altitudes and also far from the Mirabad catchment. Figure 5-2 shows the relation between 
the temperature (increasing temperature results in snowmelt) and the discharge.
5.2.2.2 Precipitation

The evaluation of representative areal precipitation is particularly difficult in mountainous basins. Also, quantitative precipitation forecasts are seldom available for the forecast mode. Fortunately, snowmelt generally prevails over the rainfall component in the mountain basins. However, sharp runoff peaks from occasional heavy rainfalls must be given particular attention and the program includes a special treatment of such events (Martinec and Rango 1998). Figure 5-3 shows the daily rainfall and its relation with daily discharge in Mirabad Catchment (1996-97).
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The program accepts either a single, basin-wide precipitation input from one station or from a “synthetic station” combined from several stations (option 0) or different precipitation inputs zone by zone (option 1). For the study area option 1 was selected and daily precipitation data from Mirabad station extrapolated to different zones. For this the regression equation of rainfall-altitude relationship for the period of (1973-2000) was used as shown in chapter 4-1-1.

A critical temperature is used in the model to decide whether a precipitation event will be treated as rain \( (T \geq T_{CRIT}) \) or as new snow \( (T < T_{CRIT}) \). When the precipitation event is determined to be snow, its delayed effect on runoff is treated differently depending on whether it falls over the snow-covered or snow-free portion of the basin.

The new snow that falls over the previously snow-covered area is assumed to become part of the seasonal snowpack and its effect is included in the normal depletion curve of the snow coverage.

The new snow falling over the snow-free area is considered as precipitation to be added to snowmelt, with this effect delayed until the next day warm enough to produce melting. This
precipitation is stored by SRM and then melted as soon as a sufficient number of degree-days has occurred.

Sharp peaks of discharge are typical for rainfall runoff as opposed to the relatively regular daily fluctuations of the snowmelt runoff.

SRM has been adapted to better simulate these rainfall peaks whenever the average daily rainfall calculated over the whole basin equals or exceeds 6 cm. This is a threshold value that can be changed according to the characteristics of the basin (Martinec and Rango 1998). The above-mentioned value (6 cm) was used for the study area.

5.2.2.3 Snow Covered Area, S

It is a typical feature of mountain basins that the areal extent of the seasonal snow cover gradually decreases during the snowmelt season. Depletion curves of the snow coverage can be interpolated from periodical snow cover mapping so that the daily values can be read off as an important input variable to SRM.

The snow cover can be mapped by terrestrial observations (in very small basins), by aircraft photography (especially in a flood emergency) and, most efficiently by satellites. The minimum area, which can be mapped with an adequate accuracy, depends on the spatial resolution of the remote sensor. (Martinec and Rango 1998)

For snow cover extraction in the Mirabad Catchment, 15 NOAA-AVHRR satellite images were used. The images were available for the period from October 1996 to July 1997. The first image with snow cover relates to 20 of October and the last image (28 /July/1997) becomes snow free at July 1997. For more information about snow extraction refer to Section 3.2.3. The snowmelt starts from end of March and its peak is in May.

Figure 5-4 shows the snow cover changes in the Mirabad catchment mapped from NOAA-AVHRR data (1996-97).
Figure 5-4 Snow cover changes in the Mirabad Catchment (Yellow = snow, White = snow free)
5.2.3 Parameters

The SRM parameters are to be calibrated or optimized by historical data. They can be either derived from measurement or estimated by hydrological judgment taking into account the basin characteristics, physical laws and theoretical relations or empirical regression relations. Occasional subsequent adjustments should never exceed range of physically acceptable values (Martinec and Rango 1998).

5.2.3.1 Runoff coefficient, C

This coefficient takes care of the losses, that is to say of the difference between the available water volume (snowmelt + rainfall) and the outflow from the basin. On a long-term basis, it should correspond to the ratio of the measured precipitation to the measured runoff. In fact, comparisons of historical precipitation and runoff ratios provide a starting point for the runoff coefficient values. At the start of the snowmelt season, losses are usually very small because they are limited to evaporation from the snow surface, especially at high elevations. In the next stage, when some soil becomes exposed and vegetation grows, more losses must be expected due to evapotranspiration and interception. Towards the end of the snowmelt season, direct channel flow from the remaining snowfields and glaciers may prevail in some basins that leads to a decrease of losses and to an increase of the runoff coefficient. In addition, C is usually different for snowmelt and for rainfall. The computer program accepts separate values for snow, C_s, and rain, C_r, and allows for half-monthly (and, if required, daily) changes of values in each elevation zone. (Martinec and Rango 1998)

Monthly and yearly estimated runoff coefficients showed unreal and unexpected results for the Mirabad catchment, but by using the SCS method it was estimated about 0.87 that by taking into consideration the basin characteristics, after calibration, 0.75 was used in the model.

5.2.3.2 Degree-day factor, (a)

The degree-day factor \( \alpha \left[ cm.C^*.d \right] \) converts the number of degree-days \( T \left[ C^*.d \right] \) into the daily snowmelt depth M (m):
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\[ M = a \cdot T \]

Degree-day ratios can be evaluated by comparing degree-day values with the daily decrease of the snow water equivalent which is measured by radioactive snow gauge, snow pillow or a snow lysimeter. Such measurements (Martinec 1960) have shown a considerable variability of degree-day ratios from day to day. This is understandable because the degree-day method does not take specifically into account other components of the energy balance, notably the solar radiation, wind speed and latent heat of condensation. The effect of daily fluctuations of the degree day values on the runoff from a basin as computed by SRM is greatly reduced because the daily meltwater input is superimposed on the more constant recession flow. (Martinec and Rango 1998)

The range of degree-day values changes between 0.1 to 1.37 based on the hydrological condition of the basins. For maximum runoff content is 1.37 and the minimum runoff content is 0.1, and the mean condition for the basin without forest and with vegetation cover, is between 0.27 to 0.4 (Mirab 1997).

In the absence of detailed data, the degree-day factor can be obtained from an empirical relation (Martinec 1960).

\[ \alpha = 1.1 \cdot \frac{\rho_s}{\rho_w} \]

Where \( \alpha \) = the degree-day factor (cm \( \circ \) C\(^{-1}\) d\(^{-1}\))

\( \rho_s \) = density of snow

\( \rho_w \) = density of water

When the snow density increases, the albedo decreases and the liquid water content in snow increases. Thus the snow density is an index of the changing properties, which favor the snowmelt. In glacierized basins, the degree-day factor usually exceeds 0.6 cm \( \circ \) C\(^{-1}\) d\(^{-1}\)
towards the end of the summer when ice becomes exposed (Kotlyakov and Krenke 1982). The computer program accepts different degree-day factors for up to 8 elevation zones, which are usually changed twice a month (although daily changes are possible). Sometimes the occurrence of a large, late season snowfall will produce depressed a-values for several days due to the new low-density snow. The a-values in the model can be manually modified and inserted to reflect these unusual snowmelt conditions. As is evident from Equation (1), the degree-day method could be readily replaced by a more refined computation of snowmelt without changing the structure of SRM. Such refinement appeared to be imperative in a study of outflow from a snow lysimeter but is not considered to be expedient for hydrological basins until the necessary additional variables and their forecasts become available (Martinec and Rango 1998).

Lack of snow data in the study area caused to use Mahabad catchments snow data (snow density) for calculation of degree-day factor by using Equation (6) for different months. Also some snow density samples taken during fieldwork were taken into account.

5.2.3.3 Temperature lapse rate, $\gamma$

If temperature stations at different altitudes are available, the lapse rate can be predetermined from historical data. All temperature stations are located out of the study area and in low altitudes. This caused the inaccurate results in lapse rate. Based on SRM Model manual, a lapse rate of 0.65 °C per 100 m was used. By this lapse rate, temperature data of Mirabad Station were extrapolated to different mean hypsometric elevations.

5.2.3.4 Critical temperature, $T_{\text{crit}}$

The critical temperature determines whether the measured or forecasted precipitation is rain or snow.

SRM needs the critical temperature only in the snowmelt season (unless a year round computer run is made) in order to decide whether precipitation immediately contributes to runoff (rain), or, if $T < T_{\text{crit}}$, whether snowfall took place. In this case, SRM automatically keeps the newly fallen snow in storage until it is melted on subsequent warm days.
At certain times, SRM may not take notice of a sharp rainfall runoff peak because the corresponding precipitation is determined to be snow, the extrapolated temperature being just slightly below the critical temperature. In such cases the assignment of critical temperature and the temperature lapse rate values should be reviewed and logical adjustments made in order to change snow to rain. It is of course difficult to distinguish accurately between rain and snow because the temperature used is the daily mean while precipitation may occur at any time, day or night, i.e., in the warmer or colder portion of the daily temperature cycle. (Martinec and Rango 1998)

The Critical temperature used for the study area is about 2° for March and April, and 1.5° for May (Mirab 1997). Also it is 1.5°C for all year and for Azerbaijan condition (Sheikhvand 2002). These values are extrapolated for the condition of Iran and Mirabad Catchment.

5.2.3.5 Rainfall contributing area, (RCA)

When precipitation is determined to be rain, it can be treated in two ways. In the initial situation, it is assumed that rain falling on the snowpack early in the snowmelt season is retained by the snow which is usually dry and deep. Rainfall runoff is added to snowmelt runoff only from the snow-free area, that is to say the ratio snow-free area/zone area reduces the rainfall depth. At some later stage, the snow cover becomes ripe. Now, if rain falls on this snow cover, it is assumed that the same amount of water is released from the snowpack so that rain from the entire zone area is added to snowmelt. The melting effect of rain is neglected because the additional heat supplied by the liquid precipitation is considered to be small (Wilson 1941).

5.2.3.6 Recession coefficient

As is evident from Equation (1), the recession coefficient is an important feature of SRM since (1-k) is the proportion of the daily melt water production which immediately appears the runoff. Analysis of historical discharge data is usually a good way to determine k.

For determining the k values for the study area, the discharge data of Mirabad station were used for the period of (1996-97). Then values of $Q_n$ and $Q_{n+1}$ are plotted against each other and the lower envelope line is considered to indicate the k values. Figure 5-5 shows the recession plot $Q_n$ vs $Q_{n+1}$ for the Mirabad Catchment.
It is necessary to mention that $k$ is not constant, but increases with the decreasing $Q$ according to the equation. (Martinec and Rango 1998)

$$k_{n+1} = x \cdot Q_n^{-y}$$

The parameters describing the recession coefficient as a function of the discharge were determined as follow:

$$k_1 = x \cdot Q_1^{-y}$$

$$k_2 = x \cdot Q_2^{-y}$$

$$\log k_1 = \log x - y \log Q_1$$

$$\log k_2 = \log x - y \log Q_2$$

The $Q_n$ and the corresponding $Q_{n+1}$ values were taken out from the recession flow plot (Figure 5-5) for both the low ($Q_1$) and the high ($Q_2$) discharges:

$$k_1 = 0.80$$

$$k_2 = 0.85$$

$$x = 0.8482$$

$$y = 0.015$$
5.2.3.7 Time Lag, $L$

The characteristic daily fluctuations of snowmelt runoff enable the time lag to be determined directly from the hydrographs of the past years. If, for example, the discharge starts rising each day around noon, it lags behind the rise of temperature by about 6 hours. Consequently, temperatures measured on the $n$th day correspond to discharge between 1200 hrs on the $n$th day and 1200 hrs on the $n+1$ day. Discharge data, however, are normally published for midnight-to-midnight intervals and need adjustments in order to be compared with the simulated values. Conversely, the simulated values can (Martinec 1975)

Time lag is the main criterion for temporal relation between different hydrological parameters in modeling and simulation of the catchments. Time lag for the Mirabad catchment is about 1.8 hours, which calculated by SCS method. For calculating the time lag, mean slope and length of mainstream are the main parameters that use in calculation.

5.3 Simulation

Runoff simulation has been carried out for the Mirabad catchment as illustrated in Figure 5-6. The simulation was done using snowmelt runoff modeling (SRM) for the period of (1996-97). The rainfall and temperature data input the model from Mirabad station. Reliability and situation of this station was important in using its data for simulation.

As Figure 5-6 shows, the simulation is acceptable and it confirms on snowmelt runoff as main water resource in the region.

Figure 5-5 Recession flow plot $Q_{n+1}$ vs $Q_n$ for the Mirabad catchment and the envelop line
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The catchment is free of snow in summer and it has caused the computed runoff to settle lower than measured runoff in this period, also in period of winter especially in February and March there isn’t any snowmelt that is because of low temperature and degree-days.

![Simulated vs Measured Runoff](image)

**Figure 5-6** Runoff simulation in the basin of the Mirabad at Orumiyeh Lake basin, Mirabad Station (1996-97)

5.4 Assessment of the result accuracy

The SRM computer program includes a graphical display of the computed hydrograph and of the measured runoff. A visual inspection shows at the first glance whether the simulation is successful or not. SRM additionally uses two well-established accuracy criteria, namely, the coefficient of determination, $R^2$, and the volume difference, $D_v$. (Martinec and Rango 1998)
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The coefficient of determination is computed as follows:

\[ R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - \overline{Q})^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \]

Where:  
- \( Q_i \) is the measured daily discharge  
- \( \overline{Q} \) is the computed daily discharge  
- \( \overline{O} \) is the average measured discharge of the given year or snowmelt season  
- \( n \) is the number of daily discharge values

The deviation of the runoff volumes, \( D_v \), is computed as follows: (Martinec and Rango 1998)

\[ D_v (\%) = \frac{V_R - \overline{V_R}}{V_R} \times 100 \]

Where:  
- \( V_R \) is the measured yearly or seasonal runoff volume  
- \( \overline{V_R} \) is the computed yearly or seasonal runoff volume

For the simulation of the Mirabad Catchment, the coefficient of determination \( R^2 \) is 0.81 and the volume difference \( D_v \) is 2.75%. Table 5-2 shows the simulation results in detail.

The analysis of Figure 5-6 proves that the model simulates the runoff peaks with correct delay related to the causing event. Unfortunately, the simulated peaks are smaller than the measured ones in the beginning of the snowmelt period, and the model overestimates the peak runoff in the second half of the snowmelt period. This is most probably attributed to the change of runoff coefficient (e.g. to the melting-up of the frozen soils) in time, which could not be accounted for without proper field data.

There is no data about water storage in the snow pack (especially liquid water in the snow during melting), which fact also might contribute to the discrepancies between the simulated and the measured runoff.
The base flow in the dry and snow accumulation period is difficult to model with SRM. It can be assumed that the groundwater-fed base flow has completely different depletion characteristics compared to the direct runoff and quick through-flow, and SRM is not fine tuned for the modeling of this process.

The model was accepted to be calibrated. Further fine-tuning of the model could be done with extra fieldwork and data collection.

The validation of the model was planned by extending the simulated period with meteorological and snow data for the hydrological year of 1997-98. Unfortunately, due to practical reasons, it was not possible to complete this exercise.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Run results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Runoff Volume (10^6 m^3)</td>
<td>167.45</td>
</tr>
<tr>
<td>Average Measured Runoff (m^3/s)</td>
<td>5.31</td>
</tr>
<tr>
<td>Computed Runoff Volume (10^6 m^3)</td>
<td>162.84</td>
</tr>
<tr>
<td>Average Computed Runoff (m^3/s)</td>
<td>5.16</td>
</tr>
<tr>
<td>Volume Difference (%)</td>
<td>2.75</td>
</tr>
<tr>
<td>Coefficient of Determination (R^2)</td>
<td>0.81</td>
</tr>
</tbody>
</table>
Chapter 6

6-1 Conclusion

The Mirabad catchment is one of the important sub basins of Orumiyeh Lake basin that is located in west of the Lake. The main part of the precipitation appears as snow in winter and feeds the Orumiyeh plain, together with other small catchments.

Estimation of snow cover based on field observations is difficult in mountainous areas, but the use of satellite images overcomes this difficulty. Using the satellite NOAA-AVHRR images in Orumiyeh Lake basin and in Mirabad catchment helped snow-covered area estimation using bands 1, 3 and 4. A time series of 15 images was used for the snow mapping. Surface temperature images were calculated for distinguishing the snow from cloud and water bodies. For this, the formulae presented in the NOAA Polar Orbiter Data User’s Guide were applied using Band 4 of NOAA. Unfortunately, in many cases, the cloud cover did not allow the direct observation of the snow, so the DEM was used to extrapolate the snow line visible on the cloud-free parts of the image.

Hydrological analyses were carried out to highlight the relation between snow, rain and the discharge at the outlet of the catchment.

The snowmelt runoff for the hydrological year of (1996-97) was simulated using SRM model. Graphical display of the computed runoff and the measured runoff shows that the simulation is successful, because the coefficient of determination ($R^2$) is 0.81, and the volume difference ($D_V$) is 2.75%. By considering the obtained results, the SRM model is best tool for computing the snowmelt runoff in the region and it is recommended for other parts of the Orumiyeh Lake basin.

Results have revealed that:

- The SRM model is a suitable tool to calculate runoff from snow using meteorological data and remote sensing derived snow cover maps.

- In mountainous area the satellite images have great potential to determine and map the snow cover.
• Monitoring of snow covered area with satellite images (NOAA-AVHRR), as quantitative data, improves the standard methods and hydrological tools by using spatial analysis. Satellite data accompanied with GIS method can be used to define the snow line and snow depletion curve for different elevation zones.

• Graphical display of simulation results proved the reliability of the SRM model in snowmelt runoff determination.

• Temperature is the most important variable in snowmelt that some of the model parameters (degree-day, T_{crit}) are related to it. Difference between measured and computed runoff proved that using only one station outside the catchment is not sufficient for modeling the small details of the hydrograph. Based on the simulation, because temperature is negative there isn’t any snowmelt in the period of February and March.

• During the period of April (the last decade), May and Jun (the first half) the measured runoff is less than computed that is effected by small irrigation activities in the valleys and evapotranspiration loss.

• In the period of July-September the computed runoff is less than measured one. Based on the snow data, the catchment is clear of snow in this period. Most probably, geological formations, especially karst, sandstone and some fractured and undifferentiated metamorphic rocks play important role in base flow. Because in melting period a considerable amount of water recharge these formations and cause the base flow in duration of year.

• It was proved to be difficult to define the change of the runoff coefficient in time, and to use SRM for the modeling of the base flow in dry periods.

6-2 Recommendations

By considering that the SRM model is very sensitive to input data especially temperature laps rate and precipitation, and since the meteorological stations are located in low altitude range, it is recommended that some key catchments of the Orumiyeh Basin should be equipped with temperature stations and rain gauges at as high altitudes as possible.
Since snow density and snow pack thickness are important in snowmelt, it is recommended to equip these stations.

Since critical temperature and degree-day factor are two main parameters in snowmelt runoff forecasting and snow studies, it is recommended to determine them for different places and times by research centers and meteorological organization.

For water resources studies in the Orumiyeh Basin, the snowmelt model of the Mirabad catchment has to be validated in the next step for a longer period. This validation process may help the further calibration of it. The calibrated and validated model then can be an important tool in the evaluation of the snowmelt runoff of ungauged catchments too. Creating scenarios of wet and dry years for all the important catchments of the basin will give a more detailed and accurate insight into the potentials and limitations of the water resources in the Orumiyeh Lake basin.
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