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SNOWMELT RUNOFF ANALYSIS IN THE MOUNTAINOUS BASIN OF IRAN WITH LACK OF SNOW OBSERVATIONS

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This study tests whether the lack of conventional ground-based snow observation for Snow Water Equivalent (SWE) can be overcome by using other Hydro-meteorological data. To this end, two different methods are described. The first one is introducing a methodology using a Distributed Hydrological Model (DHM) to estimate SWE, when the available data are just precipitation and river discharge. For the second one, a distributed version of a Temperature-index snow model is developed and applied, when the ground-based data is limited to precipitation and temperature. Two methods are applied in the upstream of Karaj basin (850 km^2), which is the most important water resources of Tehran, the capital of Iran. The estimated SWE is used for snow melt runoff forecast. It is found that forecast runoff correlates well with observed natural discharge. This high correlations suggest that a reliable SWE estimation and snowmelt runoff forecasting can be constructed using the methods in the absence of snow observation.

Key Words: *Mountainous basin, Snow Water Equivalent, Snowmelt Runoff, BTOPMC, PUB, Karaj basin*

1. INTRODUCTION

The climates in Iran vary from arid to semi arid, with an average annual rainfall about 250mm. In the mountainous basins of Iran, runoff from snowmelt often represents the dominant contribution to river flow. A vast amount of snow is deposited on the mountainous basins of Iran during the winter months forming biggest water resources which melt in dry seasons and feed the Iranian rivers, thus making some of them perennial. Hence, the estimation of snow accumulation during the preceding seasons provides a key basis for the seasonal runoff forecasting with leading a time around several months, which requires appropriate snow observations. But, it has been widely stated that one of the most limitations of snow melt runoff analysis in mountainous basins is the lack of the observed snow data with high quality and dense (spatial and temporal). Many causes lead to this shortage, among which, the sparse population distribution and limited economic resources are the main reasons. Additionally, another reason is that the climate is harsh and many of those mountainous basins are unreachable during winter.

In the recent years, the availability of the global satellite-based snow cover data makes it possible for improving prediction of snowmelt runoff[1),2)]. Moreover, for snow melt runoff modeling in ungauged or poor data basin, Temperature-index method is commonly used; while it is generally considered and are routinely justified under the auspices that process-based models require too many input data[3)].

A primary methodology of the “blind testing” for prediction in ungauged basins was introduced by Chavoshian *et al*[4)] with an application of BTOPMC model in the Mae Chaem Basin (Thailand). The proposed method was applied successfully in humid tropical basins in the Asian monsoon region. However, when the method was transferred to snow-covered regions; it shows limitation during the application. The modified method introduced in this paper can be used for snowmelt runoff prediction in the basin with lack of ground-based snow observations. The objectives of this study are to:

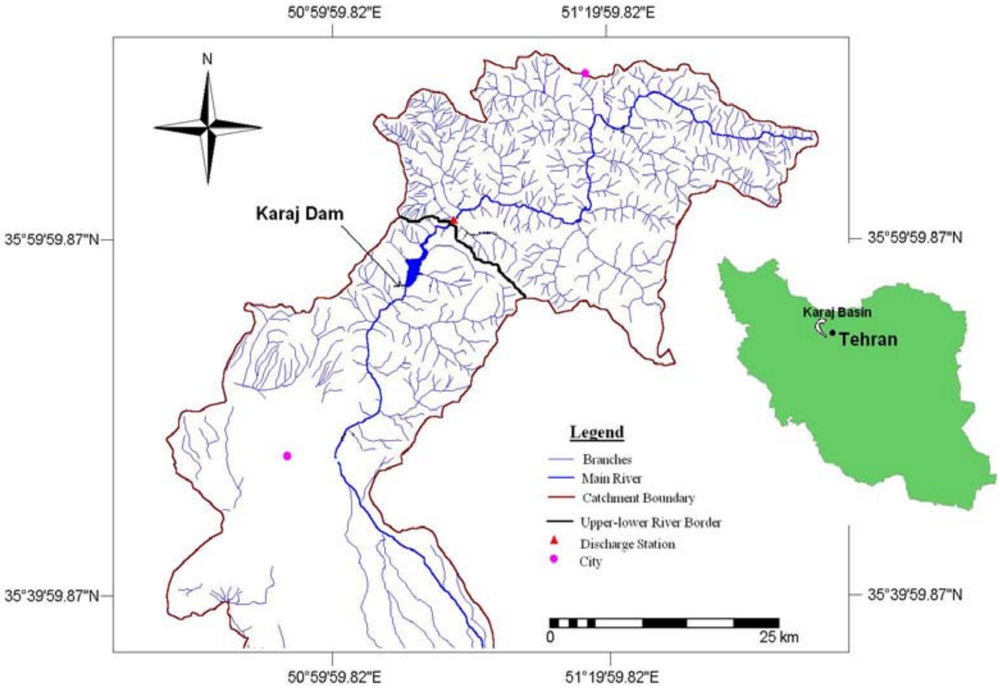


Fig.1 Location of Karaj basin and the upstream boundary

(a) Describe and application of a new Snow Water Equivalent (SWE) estimation methodology by using Distributed Hydrological Model (DHM)
(b) Identify the performance of the Temperature-index method coupled with satellite-based snow cover data for SWE estimation

2. STUDY AREA AND AVAILABLE DATA

The upstream of Karaj river basin (**Fig.1**), which is well-gauged basin, was selected to validate the methodology to estimate SWE and its correlation with snowmelt runoff. The Upstream of Karaj river basin is the most important water resources for the Tehran city, the capital of Iran. The upstream of Karaj basin has an area of 850km^2. It is located between 51˚02´& 51˚45´E and 35˚45´& 36˚15´N in the high elevation area near to the Tehran. The highest point of the basin is 4312m above mean sea level and the lowest point is 1585m.

The river is originated from the Alborz Mountain, where heavy snow is observed. Though snow melting in spring can be a cause of flood disaster, but snowmelt runoff is important for the water supply in the Tehran city. The Karaj-dam locates 63 km northwest of the Tehran at the outlet of basin. The Effective reservoir capacity of the dam is 195 millions m^3.

(1) Hydro-meteorological data

There are six installed rainfall gauges and three Pan Evaporation stations in the Upstream of Karaj basin. Daily precipitation and temperature data of those six stations are available from 1990 to 2001 as well as monthly evaporation data. Moreover, a time series of observed daily discharge data from 1968 to 2001 at one gauging station, near to outlet of basin, Karaj dam, is also available (35.51N, 51.11E).

The areal average annual rainfall of the study basin calculated using available data is 580mm and annual average flow volume to the Karaj dam station is observed 435 millions cubic meters. The Thiessen polygons method for areal extension of point data is used. Moreover, the daily rain gauge observations have been corrected for systematic measuring errors with special regard to under-catching of precipitation due to wind effect[7)].

(2) Observed Snow Water Equivalent (SWE)

Monthly-based SWE, snow depth, and density are observed from November to May (7 times a year) at five observation points in the upstream of Karaj basin. The data have been collected during monthly field surveying using manual snow sampling tubes method. The observed data is available from 1990 to 2001. These observed snow data are used only for validation of methodology in a Blind Test manner.

In the other hand, these observed values of SWE's are used only for verification and reliability check of proposed SWE estimation methods. To this end, the areal average of SWE in the upstream of Karaj basin was estimated for the period of 1990 to 2001.

Table 1 Location of snow observation in the upstream of Karaj basin

Station No.	1	2	3	4	5
Station Name	Chuiik	Ghasr	Dukhani	Heli chai	Yurdomghani
Latitude	36.11	35.98	36.07	36.11	36.05
Longitude	51.11	51.38	51.33	51.18	51.38
Elevation (m)	2100	2300	2425	2505	2987
Elevation zone (m)	1585-2200	2200-2363	2363-2465	2465-2746	2746-4312
Elevation zone area (km^2)	79	81	141	123	426
Ratio of area of each zone to the total area of basin (%) : R_i	9	10	17	14	50

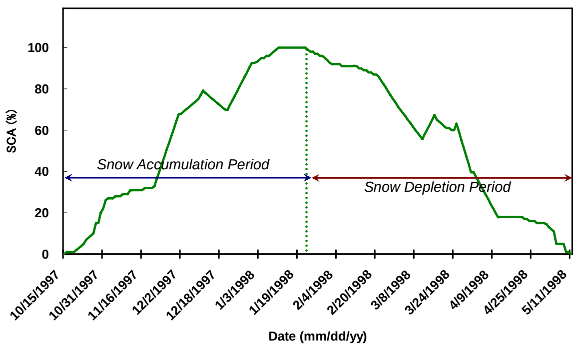


Fig.2 Snow Cover Area of 1997-98 using NOAA/AVHRR

The geographic locations and procedures of estimation basin-wide SWE by using point observation are shown in **Table 1**, which is described in the following. At the first step an elevation zone was allocated to each of the five snow observation points. By using the DEM of the basin, area of each elevation zone and its ratio to the total area of the basin was calculated. Finally this ratio was used to estimate basin-wide SWE based on point's SWE observations using Eq. (1).

$$SWE = \sum_{i=1}^{5} R_i \times SWE_i \qquad (1)$$

i= Station No.
R= Ratio of area of each zone to the total area of basin

(3) Snow Cover Area (SCA)

In the recent years, development of globally covered satellite-based snow cover data makes them suitable to be used for snowmelt runoff analysis in ungauged or poor data basins. For this study, Snow Cover Area (SCA) data were compiled from two satellites sensors NOAA AVHRR and MODIS/Terra. The Advanced Very High Resolution Radiometers (AVHRR) on the NOAA/TIROS was used to obtain SCA, 8km grid from 1990 to 1999. The SCA data was obtained from continues 10-day composite data set (to minimizing the cloud cover effect) of visible (channel 1) and also Near Infrared (channel 4) in 8km grid based on the method of Ishidaira *et al.*[5]. The Moderate Resolution Imaging Spectroradiometer (MODIS) is launched on December 1999. MODIS/Terra Snow Cover 8-day L3 global 500m grid was used to compile SCA between 2000 and 2001.

The SCA acquired from satellite images was used to identify the snow depletion curve and snow accumulation period. It is also used to identify start and end of the snowy period in the basin. As an example, **Fig.2** shows the SCA in the upstream of Karaj river basin during the water-year of 1997-98, which has the longest period of SCA acquired from satellite data, during the period of 1990 to 2001. The snow accumulation and snow depletion periods are also shown in the same figure.

(4) Other data

In this study, all other required data are obtained from publicly available global data sets.

a) Topographic data

GTOP30 developed by USGS was used for DEM of basin. Horizontal grid spacing of data is about 1 kilometer with 1m vertical resolution.

b) Land cover and soil types data

1km resolution IGBP (International Geosphere-Biosphere Program) version 2.0 developed by USGS was used for land cover classification. It shows that more than 75% of basin is covered by open shrub land. A 5km gridded soil type's data was used which produced by Food and Agriculture Organization (FAO). The average soil texture of the study basin is classified as 57% sand, 21% clay and 22% silt.

3. METHODOLOGY

Two methods for Snow Water Equivalent (SWE) estimation in absence of any snow observations will be described in this section. The aim of describing methods in detail is to define a generally applicable framework for snowmelt runoff analysis in mountainous basins with the minimum requirement on ground-based Hydro-meteorological

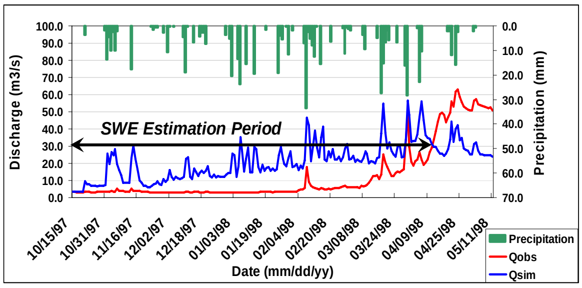


Fig.3 Hydrographs used for SWE estimation of 1997-98

data. The first method is to introduce a Distributed Hydrological Model (DHM) to estimate the SWE, when the ground-based observations are just precipitation and river discharge. For the second method of SWE estimation, a distributed version of temperature-index snowmelt model was developed and applied, when ground-based observations are limited to the precipitation and temperature.

(1) Application of Distributed Hydrological Model in SWE estimation

This method was used to estimate SWE in snow-covered basin, when the precipitation data and river discharge data are available. A parsimonious version of BTOPMC (Block-wise application of TOP model) in term of parameters need to be calibrated, is developed. The BTOPMC is a Distributed Hydrological Model, which is developed based on TOPMODEL concept to overcome the limitation of basin area, by dividing large basin to several blocks. The Muskingum- Cunge method is used for flow routing. The number of model parameters are five parameters as follows: the saturated soil transmissivity T_0 (m2 /h), the decay factor m (m) of T_0, the maximum storage capacity Srmax (m) of root zone due to vegetation, the initial value of averaged saturation deficit SDbar (m) and the Manning's roughness coefficient n_0[6] .

In this methodology at the first using the SCA compiled from satellite images, the annual non-snow and snowy periods will be identified. For the upstream of Karaj basin the annual snow period usually starts in the October and ends on the May of next year. In the second step, the BTOPMC is applied for runoff simulation of non-snow period. The simulated runoff is calibrated against available time series of observed river discharge to tune model parameters. Then, the same tuned parameter set of non-snow period, which was obtained from the pervious step, will be used for the runoff generation of snowy period. In this step, there is no need to any calibration or tuning of model's parameter set. As an example, simulated and observed hydrographs of the snowy period for 1997-98 is shown in **Fig.3**. In this example the Nash efficiency of non-snow period simulation is 81% with water balance efficiency of 99%.

Finally, while the value of simulated discharge is greater than observed one (see **Fig.3**), the difference between generated runoff hydrograph by model and observed discharge hydrograph is considered as the Snow Water Equivalent (SWE), which stored in the form of snow in the basin. Therefore using Eq. (2), it is possible to estimate SWE (**Fig.3**).

$$\text{For } Q_{sim} \ge Q_{obs} \rightarrow SWE = \sum Q_{sim} - Q_{obs} \quad (2)$$

(2) Distributed version of a Temperature-Index model (SNOW-17)

In this method the SWE will be estimated in a snow-covered basin, when the available hydro-meteorological data are limited to precipitation and temperature in the snowy period.

The most commonly used index for computing SWE in the mountainous basin with lack of snow observation is air temperature. There are two major reasons for using air temperature as an index for snow melting in poor data basin. First air temperature data are most likely available data in many mountainous basin from both climatologically and operational hydro-meteorological networks. Second it has been shown in many studies that air temperature is probably the best single index to areal snow cover energy exchange.

For this study, a distributed version of a well-known snowmelt model (SNOW-17) is developed and used for SWE estimation. The SNOW-17 is a conceptual model in which each of the significant physical processes affecting snow accumulation and snowmelt is mathematically represented. The model uses air temperature as the sole index to energy exchange across the snow-air interface and was developed to run in conjunction with a rainfall-runoff model[8,9].

However, the original version of SNOW-17 needs to the observed snow depletion curve as an input data. In the developed version of model, this depletion curve is acquired from satellite-based snow cover data, therefore no need to any ground-based snow observation. Moreover, its lumped structure of the model is developed to a distributed one. It makes the model more suitable to couple with Distributed Hydrological Models. More detail on SNOW-17 structure and basic equations of temperature-index method is described by Anderson[8,9]. The main emphasis here is to show usefulness of temperature-index method in term of SWE estimation in the mountainous basin of Iran with lack of snow observation.

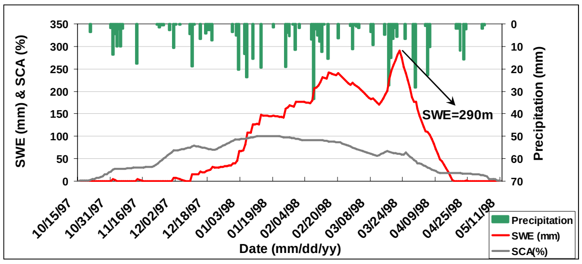
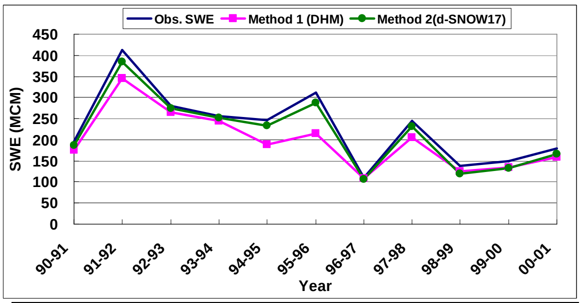


Fig.4 SWE estimated by SNOW-17 for 1997-98



Year	Obs. SWE (MCM)	Method 1 (MCM)	Method 2 (MCM)
1990-91	195.56	175.24	186.83
1991-92	412.21	345.29	384.54
1992-93	280.25	265.34	274.63
1993-94	256.33	245.23	251.94
1994-95	245.56	188.46	233.07
1995-96	312.48	214.21	286.62
1996-97	110.27	108.21	107.23
1997-98	245.25	205.13	231.21
1998-99	138.53	124.19	120.12
1999-00	150.29	135.22	133.36
2000-01	179.40	159.40	165.31

Fig.5 Observed SWE and estimated one using method 1 and 2 from 1990-91 to 2000-01

Using SNOW-17, observed precipitation, was portioned into rain and snow (both in terms of water equivalent depth) using a threshold air temperature above which all precipitation is rain and below which it is snow. The compiled SCA (%) was used in the model to identify snow accumulation and depletion period. **Fig.4** shows SWE and SCA of 1997-98. The maximum value of SWE in this graph is considered as the SWE of snowy period.

4. RESULT AND DISCUSSION

Two described methods have been conducted in the Upstream of Karaj basin for SWE estimation. The results are discussed as follows.

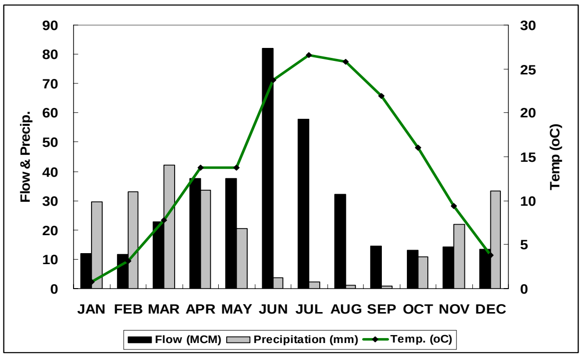


Fig.6 Long term monthly average of Precipitation, Temperature and River Flow in the upstream of Karaj basin

(1) SWE estimation result

The seasonal SWE's for snowy period of 1990-91 to 2000-01 are estimated. In the first method the only used data are precipitation and river discharge. BTOPMC as a Distributed Hydrological Model (DHM) was used for flow generation in snowy period of each year, using the parameter set of the non-snow period in the same year. The difference between two hydrographs was considered as SWE. For the second method, precipitation and temperature were used. Using SNOW-17, the areal average SWE's for upstream of Karaj basin in the snowy period of 1990-91 to 2000-01is estimated.

The estimated against observed SWEs are shown in **Fig.5** and its attached table in Million Cubic Meter (MCM). The observed SWE's using five snow measurement points are also shown at the same time. Result of each method can be evaluated for observed SWE's to identify efficiency of the each method. As it shown in **Fig.5** both methods were estimated SWE's during study period less than observed one. There are two main reasons for this. The first one is uncertainty due to areal extension of SWE from five point observation to the whole of basin and/or the second one is the uncertainty in SWE estimation period and ignoring some snowfall after SWE estimation period (see **Fig.3**).

However, the estimated SWE by method 2 using precipitation and temperature data are relatively higher than estimated one by method 1. It is obvious that temperature data, which is used in the second method, is a better index for SWE estimation.

(2) Correlation of estimated SWE with May to October (Spring-Summer) snowmelt runoff

A 30-year monthly average of observed precipitation, temperature and river flow in the upstream of Karaj river basin is shown in **Fig.6**. It is obvious that for the non-snow period (May to October), there is an increasing in river flow even with low rainfall, and this indicates the significant role of snowmelt runoff during this period.

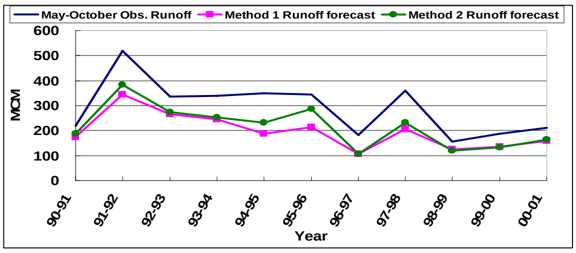


Fig.7 Obs. May-October Runoff and forecasted snowmelt Runoff

Forecasting snowmelt runoff from May to October is very important to utilize mountainous snow as water resources of Tehran. Using the SWE estimated by two methods and assuming that this SWE is the main source of runoff in the non-snow period from May to October, the Correlation factor of May-October observed runoff and estimated SWE was calculated. The correlation factor of May to October observed flow volume and estimated SWE by first method is 89%, while with second method is 96%. Total flow volume of May to October during period of 1990-91 to 2000-01 and estimated SWE's using two methods are shown in **Fig.7**. This high correlation between estimated SWE's and natural observed discharge in May-October can be used for seasonal snowmelt runoff forecast and optimizing operation of Karaj dam.

5. CONCLUSION

The amount as well as inter-annual variation of estimated SWE's compared with measured one show that the adopted methods were found reasonable. Both methods give a lower rate of SWE compared to observe one. It could be due to uncertainty in areal extension of SWE from five point observation to the whole of basin and/or uncertainty of proposed methods, which makes it necessary for an uncertainty analysis in future study.

However, it is observed that the uncertainty of first method is higher than second method, because the first method is kind of blind test application of DHM without any tuning of the parameters. Moreover, it is clear that temperature data, which is used in the second method, is better index for SWE estimation. It is also shown that the estimated SWE has a high correlation with flow volume of May to October. The overall performance and high correlation factor is considered encouraging. Using estimated SWE, it is possible to make a reliable forecasting of spring-summer flow in the mountainous basins of Iran without any snow observation. However, the neglecting effect of spring precipitation needs to be investigated for more reliable river flow forecast.

In addition of usefulness of satellite-based snow cover data and performance of Blind Test application of DHM to estimate SWE in mountainous basins in arid and semi-arid areas, application of described methods to several other basins in future studies and inter-comparison of result can be used for the better understanding of uncertainty of SWE estimation and its sources.

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