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Simulation of Snow Covers Area by a Physical based Model

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Abstract**—**Snow cover is an important phenomenon in hydrology, hence modeling the snow accumulation and melting is an important issue in places where snowmelt significantly contributes to runoff and has significant effect on water balance. The physics-based models are invariably distributed, with the basin disaggregated into zones or grid cells. Satellites images provide valuable data to verify the accuracy of spatially distributed model outputs. In this study a spatially distributed physically based model (WetSpa) was applied to predict snow cover and melting in the Latyan dam watershed in Iran. Snowmelt is simulated based on an energy balance approach. The model is applied and calibrated with one year of observed daily precipitation, air temperature, windspeed, and daily potential evaporation. The predicted snow-covered area is compared with remotely sensed images (MODIS). The results show that simulated snow cover area SCA has a good agreement with satellite image snow cover area SCA from MODIS images. The model performance is also tested by statistical and graphical comparison of simulated and measured discharges entering the Latyan dam reservoir.

Keywords**—**Physical based model, Satellite image, Snow covers.

I. INTRODUCTION

FLOOD prediction and watershed modeling are main topics facing the hydrologist dealing with processes of transforming precipitation into a flood hydrograph and the translation of hydrographs throughout a watershed [1]. Snow cover is an important phenomenon in hydrology, hence modeling the snow accumulation and melting is an important issue in places where snowmelt significantly contributes to runoff and has significant effect on water balance [2]. The presence of snow modifies the energy and mass balances, and snowmelt is main resource of the runoff during the melting season [3].

Models range from simple degree-day methods to physics-based models containing equations for all the processes involved. The physics-based models are invariably distributed, with the basin disaggregated into zones or grid cells. Spatially distributed hydrologic modeling is becoming more and more commonplace. Such models have advantages in improving both the spatial resolution of the simulation and the conceptualization of physical processes by the model [4]. Grid-based distributed snowmelt modeling using a physically based mass and energy balance approach was successfully completed in several mountainous basins, where variations in energy transfer resulted from topographic effects [5].

Satellites now provide valuable data with higher spatial and temporal resolution. Nevertheless, field measurements are still required to validate the satellite data [6]. The moderate-resolution imaging spectrometer MODIS provides a good opportunity to study snow distribution on daily basis [7]. MODIS products are being produced to obtain daily snow cover data grids with a resolution of 500x500m and they are distributed by the NASA Distributed Active Archive Center (DAAC) located at the National Snow and Ice Data Center (NSIDC). The MODIS snow cover products compare favorably with operational products and represent improvement in terms of resolution, both spatial and spectral, and also in terms of automated snow mapping and cloud masking. There is no snow depth estimation in MODIS. Results from various studies show that the daily MODIS snow maps have an overall accuracy of about 93%, but lower accuracy is found in forested areas and complex terrain and when snow is thin and ephemeral. Very high accuracy, up to 99%, may be found in croplands and agricultural areas. Accuracies of the products depend on a number of factors such as time of day, season, land cover and topography [8].

The WetSpa model [9]–[11] includes a physically based and fully distributed description of hydrological processes for runoff prediction and energy balance approach for simulating snow accumulation and melt is applied. Modeled snow-covered area (SCA) is compared with remotely sensed SCA. The model performance is tested by simulation of snow accumulation and melt in the Latyan watershed, upstream of Roodak station, in the southern part of central Alborz mountain range in Iran.

II. WETSPA MODEL

The WetSpa model was developed by [9] and adapted for flood prediction by [10], [11]. The hydrological processes in the model are precipitation, interception, depression storage, surface runoff, infiltration, evapotranspiration, percolation, interflow, ground water flow, and water balance in each layer. The total water balance for each raster cell is composed of a separate water balance for the vegetated, bare-soil; open water and impervious part of each cell [12]. For each grid cell, the

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root zone water balance is modelled continuously by equating inputs and outputs [11]:

$$D\frac{d\theta}{dt} = P - I - S - E - R - F \tag{1}$$

where D [m] is the root depth, θ [m^3m^{-3}] is the soil water content in the root zone, t [d] is the time, P [md^{-1}] is the rainfall intensity, I [md^{-1}] is the initial loss due to interception and depression storage, S [md^{-1}] is the surface runoff resulting from snowmelt and rainfall, E [md^{-1}] is the evapotranspiration from the soil, R [md^{-1}] is the percolation from the root zone, and F [md^{-1}] is the amount of interflow. The surface runoff is calculated using a moisture-related modified rational method with a potential runoff coefficient depending on land cover, soil type, slope, the magnitude of rainfall, and antecedent soil moisture [11]:

$$S = C(P - I + M)(\theta/n)^{\alpha} \tag{2}$$

where M [md^{-1}] is snowmelt, n [m^3m^{-3}] is the soil porosity, and C [-] is the potential runoff coefficient. The values of C are taken from a lookup table, linking values to slope, soil type and landuse classes [11]. The exponent α [-] in the formula is a parameter reflecting the effect of rainfall intensity on the surface runoff.

The WetSpa model has been applied in several studies. More information about model concept, development, and application, and parameter derivation can be found in [1], [10] -[17].

Energy balance equation in Snowmelt Module

Because part of the annual precipitation can be in the form of snow, a snow module based on energy balance is used to simulate snow accumulation and melt. Physical processes within the snowpack and involved in snowmelt are very complex. The energy balance of a snowpack is given by [18], [19], [6]:

$$\frac{dU}{dt} = S_n + L_a - L_t + H + E_l + G + Q_p - Q_m \tag{3}$$

where U is the internal energy of snowpack and the upper froze part of the soil (kJ m^{-2}), S_n is the net short wave solar radiation (kJ m^{-2} d^{-1}), L_a is the atmospheric long wave radiation (kJ m^{-2} d^{-1}), L_t is the terrestrial long wave radiation (kJ m^{-2} d^{-1}), H is the sensible heat exchange (kJ m^{-2} d^{-1}), E_l is the energy flux associated with the latent heat of vaporization and condensation at the snowpack surface (kJ m^{-2} d^{-1}), G is ground heat conduction to the snowpack (kJ m^{-2} d^{-1}), Q_p is heat advected by precipitation (kJ m^{-2} d^{-1}), and Q_m is the amount of heat removed by snowmelt (kJ m^{-2} d^{-1}).

The water balance of a snowpack is given by [18], [16]:

$$\frac{dW}{dt} = P_r + P_S - E_S - M \tag{4}$$

where W is the snowpack's water equivalence (m), P_r is the precipitation as rainfall (m d^{-1}), P_s is the precipitation as snowfall (m d^{-1}), and E_s is the sublimation from the snowpack (m d^{-1}). All terms on the right hand sides of equations 3 and 4 can be evaluated using energy balance approach as data input; the details can be found in [16]. The key point of this approach is that all calculations are physically based and all parameters are inherently known so that no calibration is necessary.

III. APPLICATION

A. *Study area*

The Jajrood River basin is located in the southern part of central Alborz mountain range in the northern part of Iran. The drainage area is 435.3 km^2 up to Roodak hydrometric station at the entrance of the Latyan dam reservoir. A digital elevation model (DEM) of the basin was obtained from the topography map (1:50000) and converted to a 50 m grid size DEM [17]. Fig. 1 shows a detailed map of the basin upstream of Roodak, with topography and location of precipitation stations indicated. The basin is mountainous with elevations ranging from 1700 to 4212 m. The mean elevation is 2830 m and the mean basin slope is about 45.6%. Land use map for this study with 50 m grid size is composed of 5 different types of land cover: 91% of the basin is covered by deciduous shrubs, 6.2% by deciduous broad trees, 1.8% by short grass, and about 1.0% by agriculture and impervious areas, mainly villages. The dominant soil texture is clay loam, which covers about 89.4% of the basin, and silt loam and sandy loam about 5.6% and 4.8% respectively. Hydrologic data set include, daily precipitation in 8 stations, temperature (maximum, minimum and mean) and evapotranspiration in 3 stations, windspeed and daily discharge data at one gauging station. All data are available for a one year period from September 2004 to September 2005. The mean annual precipitation of the watershed in this year is 802 mm and the mean observed temperature and potential evapotranspiration are 7.9 ˚C and 1095 mm respectively.

Since we couldn't find cloud free satellite images for this area and for this time period, so 3 satellite images; MODIS/Terra Snow Cover Daily L3 Global 500m SIN Grid with some clouds were chosen for the comparison.

B. *Model simulation*

After collecting and processing required data for the WetSpa model, identification of spatial model parameters is undertaken. All basic maps are in raster form with a resolution of 50m.

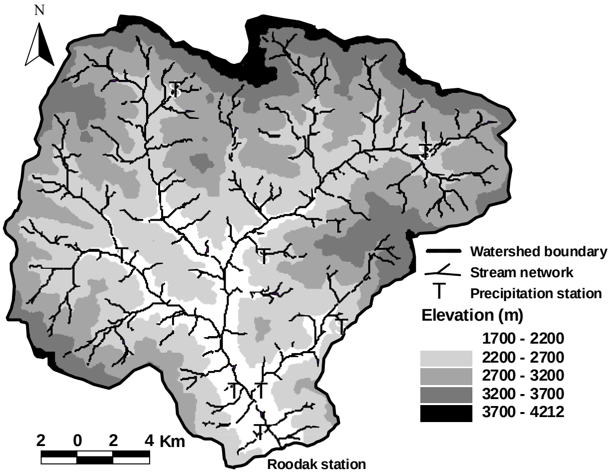

Fig. 1 A detailed map of the subbasin upstream of Roodak station showing stream network, topography and location of precipitation stations.

For the simulation of hydrographs at the basin outlet, the basin is divided into 193 subcatchments. The areas of the GIS derived subcatchments range from 0.005 to 11.47 km^2 with an average subcatchment area of 2.25 km^2. The grids for precipitation, temperature and PET are created based on the geographical coordinates of each measuring station and the catchment boundary using the Thiessen polygon extension of the ArcView Spatial Analyst.

IV. RESULTS AND DISCUSSION

One year (September 2004 – September 2005) measured daily discharge data at Roodak station are used for model calibration. The model calibration is performed manually for global WetSpa model parameters only, whereas the spatial model parameters are kept as they are. Initial global model parameters are specifically chosen according to the basin characteristics as discussed in the documentation and user manual of the model [11]. More information about model parameters calibration for Latyan dam watershed can be found in [17].

We select 3 satellite images; MODIS/Terra Snow Cover Daily L3 Global 500m SIN Grid, for this area and for this time period, one in the beginning of the snow accumulation period, one in the middle of the snow accumulation period and one after snowmelt. Fig. 2; a1 and b1 show processed MODIS SCA output for the Latyan dam watershed for November 24 and December 29, 2004, although there are some clouds in both images but most parts of free clouds zones are covered by snow. Fig. a2 and b2 show modeled SCA and snow water equivalent SWE (mm) distribution for the same days. Normally it is expected that low snow can not be shown in the images of surfaces with vegetation and high relief while model can calculate even less than 1mm of SWE. According to the model output all snow stored in the catchment is melted in the end of April 2005 (it hasn't shown in the Fig. 2), unfortunately there is no MODIS images available or free cloud image for those days, the only available and free cloud MODIS image is for May 11, 2005 (Fig. c) and as it shown there is no snow in the catchment in this image and it is a strong evidence to prove that the model simulation special for snowmelt is correct and regarding to images and modelled SCA maps presented in fig. 2, it can be said that there is a reasonable agreement between satellite images and model simulation SCA in this catchment. For example for the cloud free zones 86% of the modeled snow cover areas agrees with the satellite image of December 29, 2004.

Evaluation criteria for the model performance are given in Table 1. Four evaluation criteria used by [20] are selected. The model bias for water balance criterion evaluates the ability of the model to reproduce the water balance. The accuracy of the model to simulate the discharge is evaluated through the Nash-Sutcliffe criterion, and two adapted Nash-Sutcliffe efficiencies are used to assess the model's performance for low flows and high flows respectively. According to the results of the model evaluation criteria in Table 1, the model performance is satisfactory for this time period. This indicates that the WetSpa model is able to simulate hydrologic processes in a spatially realistic manner including snowmelt based only on topography, land use and soil type, resulting in a fairly high accuracy for both high and low flows.

Analysis of measured precipitation over a period from September 2004 – September 2005 shows that the main period of precipitation occurs during late autumn till late winter, while river flow rises gradually in early spring to reach peak values in May. From the foregoing it can be concluded that in the study area precipitation falls from October to March, while runoff occurs mainly from March till June depending upon the air temperature, indicating that most of the runoff is generated by snowmelt.

For discussion we select a period of time with large snow accumulation and melt. This is from mid November 2004 to early May 2005. All relevant information for this period is given in Fig. 3. The simulated snow accumulation and melt based on the energy balance approach together with basin average precipitation and mean air temperature is shown in in this figure. According to this figure, from mid November '04 till end February '05, the snowpack gradually builds up to reach about 260 mm of water equivalent at the end of February. From end February till 23 March about 150 mm of snow melts, while from 23 to 27 March 12 mm of snow is added to the snow cover. From then onwards the temperature becomes positive and at the end of April all snow is melted.

Fig. 3 also shows a graphical comparison between observed and simulated daily flows at Roodak station. From mid November '04 till early March '05 there is no direct runoff and river discharge is only maintained by groundwater drainage which is well simulated by the model. At the end of February and beginning of March, the temperature increases and together with snowmelt there is considerable rainfall, which leads to a huge flood in the basin with an observed peak of 120 m^3 s^{-1} on 12 March.

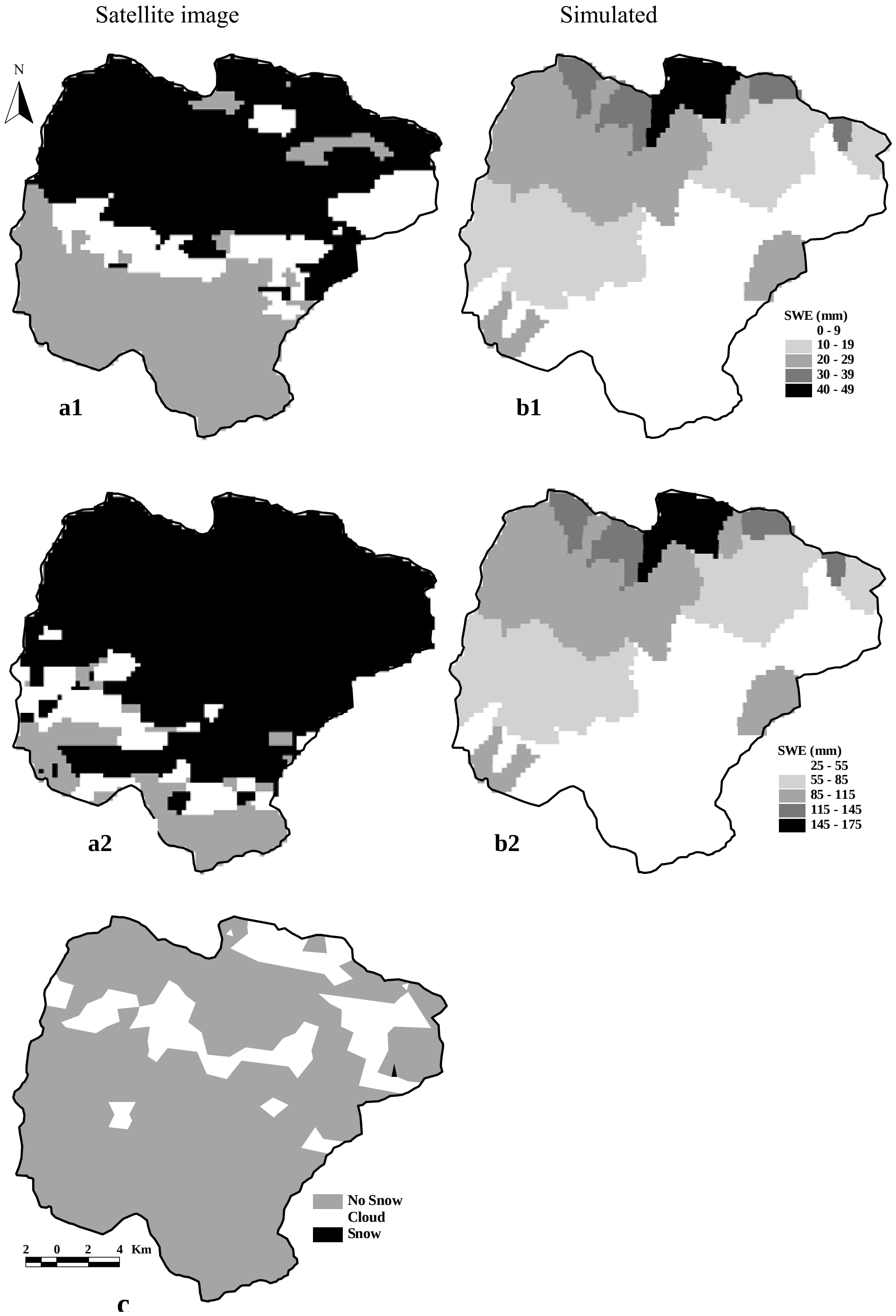

Fig. 2 MODIS SCA output (left) and the correspondent modelled SCA and snow water equivalent SWE simulation (right); MODIS SCA output for the Latyan dam watershed for November 24, 2004 (a1), December 29, 2004 (b1), and May 11, 2005 (c) and modelled SCA and SWE simulation for the Latyan dam watershed for November 24, 2004 (a2) and December 29, 2004 (b2)

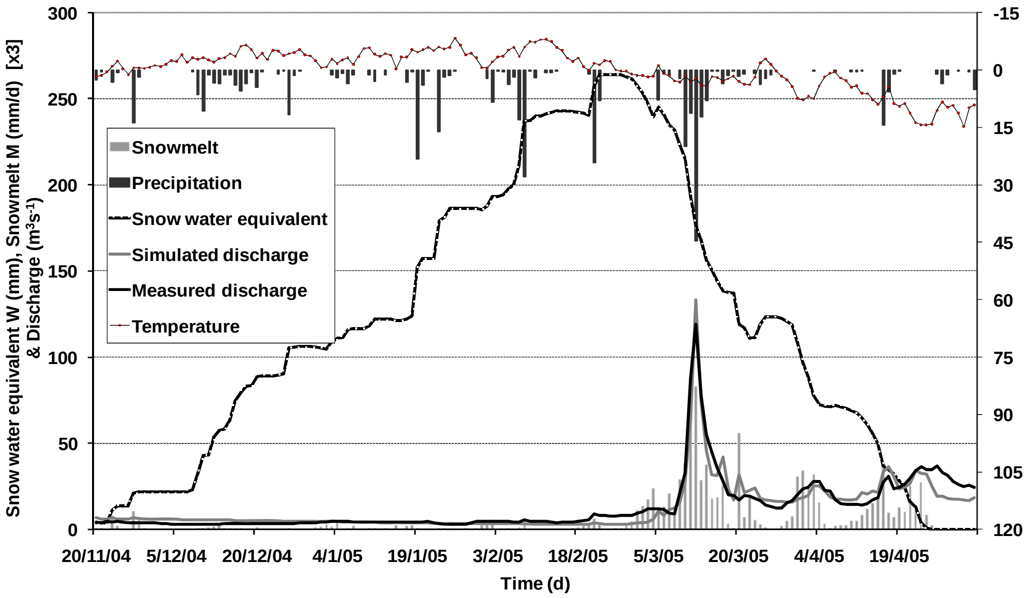

Fig. 3 Daily average precipitation, temperature, snow layer water equivalent, snowmelt, and graphical comparison between observed and simulated flow at Roodak station in Latyan dam watershed between 20/11/2004 and 3/5/2005 (b).

TABLE I EVALUATION CRITERIA FOR THE ASSESSMENT OF MODEL PERFORMANCE

Criteria	Model performance
Model bias for water balance	0.8%
Nash-Sutcliffe efficiency	87.9%
Model efficiency for low flows	79.6%
Model efficiency for high flows	91.8%

V. CONCLUSIONS

A physically based distributed hydrological model, WetSpa, was applied to predict snow accumulation and melt. Simulated snow cover area was compared with satellite image snow cover area. The generation of runoff depends upon rain intensity, soil moisture status, and snowmelt. Snow accumulation and melt is simulated by an energy balance approach. The model performance was tested by simulating snow accumulation and melt in the 435 km^2 Latyan dam watershed, upstream of Roodak station, in the southern part of central Alborz mountain range in the northern part of Iran. The model is applied and calibrated with one year (September 2004 – September 2005) of observed daily precipitation, air temperature, windspeed, and daily potential evaporation. Daily discharge data at the gauging station of Roodak station were used for model calibration. The model calibration is performed manually for global parameters of the WetSpa model only, whereas spatial model parameters related to topography and soil and land-use types remain prefixed in a data base. The model efficiency turns out to be rather good for this period. The resulting hydrographs compare favorably with measurements with model efficiencies of more than 87%. In order to show the performance of the model a period with snow accumulation and melt are discussed in detail. It is shown that modeled snow cover area SCA has a good agreement with satellite image snow cover area SCA from MODIS images. This study shows that the model has great potentiality to determine the impact of snow accumulation and melt on the hydrological behavior of the river basin. Hence, it can be concluded that accurate snowmelt prediction is possible with a physically based energy and mass budget approach. It is evident that energy and temperature variations in a snowpack can be more complex than assumed in the present model. However, a more comprehensive approach would need very accurate temporal and spatial observations of snow depth, water content, temperature, and energy fluxes, which in practice are usually not available. Possibly such data can be obtained by remote sensing techniques. Hence, the methods presented in this study show to be useful tools for simulating snowpack processes and snowmelt, but should be verified in the field and improved provided more comprehensive datasets become available.

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