THRACE 2000

PROTECTION AND RESTORATION OF THE ENVIRONMENT V

Proceedings of an International Conference

Thassos

Greece

Volume I

- Groundwater resources management and contamination control - Geotechnology
- Surface water flow and quality: measuring, management and contamination control
- Physical and numerical modelling
- Coastal and open sea water quality and management
- Ecological engineering applications

THASSOS, July 2000

SNOW COVER DISTRIBUTION OVER ELEVATION BANDS IN A MOUNTAINOUS CATCHMENT

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ABSTRACT

The snow accumulation and ablation (SAA) model of the US National Weather Service (US NWS) was applied to implement the snow cover extent over elevation bands of a mountainous catchment (the Mesochora catchment in Central Greece), taking into account the indirectly included processes of sublimation, interception, and snow redistribution. The catchment hydrology is controlled by snowfall and snowmelt. The simulated discharge was computed from the soil moisture accounting (SMA) model of the US NWS and compared to the measured discharge. The elevationally distributed snow cover extent presented different patterns with different time of maximization, extinction and return during the year, producing different timing of discharge.

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ΠΕΡΙΛΗΨΗ

Το προσομοίωμα συσσώρευσης και τήξης χιονιού (SAA) της US National Weather Service (US NWS) εφαρμόσθηκε για να προσομοιώσει την έκταση του στρώματος του χιονιού σε υψομετρικές ζώνες ορεινής λεκάνης (λεκάνη της Μεσοχώρας, στην Κεντρική Ελλάδα). Η υδρολογία της λεκάνης ελέγχεται από χιονοπτώσεις και τήξη χιονιού και η προσομοιωμένη παροχή υπολογίσθηκε από το προσομοίωμα εκτίμησης εδαφικής υγρασίας (SMA) της US NWS και συγκρίθηκε με τη μετρημένη παροχή. Η υψομετρικά κατανεμημένη έκταση του στρώματος του χιονιού παρουσίασε διαφορετική ενδοετήσια κατατομή με διαφορετικό χρόνο μεγιστοποίησης, εξαφάνισης και επιστροφής με αποτέλεσμα το διαφορετικό χρονισμό της παροχής.

1. INTRODUCTION

A good understanding of the elevetional distribution of snow cover is necessary to predict the timing and volume of runoff. In a complex mountainous terrain the snow cover distribution within a watershed is highly variable in time and space and is dependent on elevation, slope, aspect, vegetation type, surface roughness, radiation load, and energy exchange at the snow-air interface [1, 2, 3]. Decreases in snowpack due to climate change could disrupt the downstream urban and agricultural water supplies [4, 5, 6, 7] while increases could lead to seasonal flooding [7, 8].

Solar and longwave radiation are dominant energy inputs driving the ablation process. Turbulent energy exchange at the snow cover surface is important during the snow season. The evaporation of blowing and drifting snow is strongly dependent upon wind speed. Much of the spatial heterogeneity of snow cover is the result of snow redistribution by wind. Elevation is important in determining temperature and precipitation gradients along hillslopes, while the temperature gradients determine where precipitation falls as rain and snow and contribute to variable melt rates within the hillslope.

Several attempts at process-based modelling of snow distribution have been successful in estimating snow-covered area through the ablation period but these required hourly to subdaily climate inputs and may be computationally demanding [3, 9, 10]. They modelled redistribution effects due to wind and gravity with an interpolating function based on slope and curvature. Their approach required a good initial estimation of spatially distributed snow cover parameters, thermal state, and hydrologic state. Simulations were performed for the ablation period only and excluded runoff processes.

The research reported in this paper is an application of the Snow Accumulation and Ablation (SAA) model which was developed by Eric Anderson (US National Weather Service Hydrologic Research Laboratory) [11] and has been tested in numerous mountainous watersheds in the United States and elsewhere. The SAA is a deterministic, continuous conceptual model consisting of a set of mathematical formulations, which describe explicitly the accumulation and ablation of the snowpack. The SAA itself can be coupled with almost any soil moisture accounting (rainfall-runoff) model. The output "rain plus melt" from the SAA model can be the input to the rainfall-runoff model. The model inputs are air temperature and precipitation at a six-hour time step. Other physical processes, such as water vapour transfer, interception and snow redistribution, are partially and indirectly included in the model. Vapour transfer is included in the form of condensation only during rain-on-snow periods, while the sublimation losses during the snow season are reflected in the value of the snow correction factor, SFC. Also the snow interception losses are implicitly reflected in the SFC. As regards the snow redistribution, the SAA model includes an areal depletion curve that drops off when ablation begins.

For the SAA analysed model, daily precipitation was interpolated to six-hour increments and six-hour temperature was estimated from daily temperature maxima and minima using equations given by Anderson [11]. The calibration of SAA can be performed concurrently with any rainfall-runoff model since the SAA provides the input to the rainfall-runoff model, which in the examined case is the US NWS Soil Moisture Accounting model-SMA [12]. Due to the lack of digital orthophotographs of a remotely sensed snow-cover area the model evaluation was against measured stream discharges, since the SAA model accounts for the areal depletion curve. For better representation of discharge resulting from snow-covered areas the mountain watershed was partitioned into elevation bands in order to compute eleventionally based temperature and

TABLE 1. Elevation bands of the catchment

Band	Elevation range [m]	Median elevation [m]	Area [%]
Upper	1580-2200	1830	30.54
Middle	1280-1580	1400	29.51
Lower	780-1280	1080	39.95

precipitation gradients and simulate the differential timing and rate of snow accumulation and melt along each band.

The primary goal of this research was to determine how adequately eleventional snow distribution could be modelled with algorithms that require only commonly available climate drivers at a daily time step. This research showed the need to hillslope partition into bands in order to capture the timing, amplitude, and duration of discharge in a mountainous catchment.

2. THE STUDY CATCHMENT

Mesochora's catchment, which is drained by the upper Acheloos river, was used for analysis of elevationally distributed snow cover. Mesochora is of great significance for Greece because the river will be partially diverted at the outfall of te catchment through the Pindus mountains in order to irrigate the arid Thessaly Plain. It is the largest project in Greece. It includes five dams (one is Mesochora's dam), 24 miles of large tunnels and about 5000 miles of buried irrigation pipes.

Mesochora's catchment lies in the central mountain region of Greece and extends from north (30° 42') to south (39° 25') with an area of about 633 km^2 The mean elevation is 1390 m and its climate is elevation-dependent, with hot summers and mild winters at low elevations and mild summers and cold winters at high elevations. The catchment hydrology is controlled by snowfall and snowmelt at high elevations. In the catchment three elevation bands can be distinguished (Table 1).

The network of meteorological stations (precipitation, temperature, sunshine, humidity and wind) installed in and around the catchment is relatively dense. However, some daily values, particularly of precipitation and min-and-max temperature time series for the 21-year study period (1972-1992), have not been recorded. The mean annual precipitation (rain plus melt) weighted over elevation bands is 1900 mm, while the catchment's runoff is 1140 mm. A more detailed description of the catchment has been presented by Panagoulia [6].

The measured data and the methods used to average the data over the area and the elevation are presented in the calibration of SAA model.

3. SAA MODEL DESCRIPTION

The structure of the SAA model can be summarized as follows. When air temperature [T_a] is less than the delineation temperature (0°C or other), accumulation of snowpack occurs. In the opposite case (T_a> delineation temperature), the SAA assumes that the precipitation is rain. The ablation of snowpack is controlled by the heat exchange at the air-snow interface. For the heat exchange computations there are two basic conditions: (a) when T_a>0°C, melt takes place at the snow surface, and (b) when T_a<0°C for melt to occur. Yet, the melt is computed for rain or non-rain periods. For melt during rain periods the following assumptions are made: (1) there is no solar radiation, (2) incoming longwave radiation is equivalent to blackbody longwave radiation at T_a, (3) snow surface temperature is 0°C, (4) the dew point is T_a, and (5) the rain temperature is T_a. Under these assumptions, the amount of melting snowpack expressed as heat losses (ΔQ) is the sum of long wave radiation (Q_n), latent heat transfer due to condensation (Q_e), sensible heat transfer (Q_h) and heat transfer by rain water (Q_{px}): $\Delta Q = Q_n + Q_e + Q_h + Q_{px}$.

For melt during non-rain periods, the model checks whether the snowpack is isothermal at 0°C. If the snowpack is not isothermal, no melt occurs. If the snowpack is isothermal and T_a>0°C, melt occurs at a proportional rate to a seasonally varying melt factor and the difference between T_a and 0°C.

During non-melt periods, an antecedent temperature index (*ATI*) is used as an index to the temperature of the surface layer of snowpack. The heat exchange is assumed proportional to the temperature gradient, which varies seasonally as does the melt factor of non-rain periods. The SAA model accounts also for the areal extent of snow cover. During the periods of snow accumulation, this is assumed to be 100%. During periods of depletion, the model uses an areal depletion curve of snow. The SAA involves six major and six minor parameters that are described in the section of model calibration.

3.1 Accumulation of the snowpack

The SAA model uses the ambient six-hourly air temperature ($T_{a,6h}$) to estimate the form of precipitation. A model parameter (*PXTEMP*, °C) indicates the temperature, which distinguishes rain from snow. When $T_{a,6h}>PXTEMP$, the precipitation is rain and when $T_{a,6h}\leq PXTEMP$ the precipitation is snow. Because the measurements of precipitation gauges are biased during snowfall periods the model uses a mean snowfall correction factor (*SCF*). Thus, precipitation, which is classified as snow, is adjusted with the *SCF* (model parameter) and added to the existing snowpack. Rain which falls on bare ground immediately enters to the SMA model. Rain falling on the snowpack is added to the computed surface melt water.

3.2 Areal extent of snow cover

The SAA model accounts for the areal extent of snow cover. During the periods of snow accumulation, this is assumed to be 100%. During periods of depletion, the model uses an areal depletion curve snow, that is a function of the areal extent of snow cover versus the ratio of mean areal water equivalent to an index value, which is the smaller of the maximum water equivalent (since snow began to accumulate), or a preset maximum.

3.3 Snowmelt

The SAA model uses the air temperature as an index to energy exchange across the snow-air interface. The freezing of melt water due to a heat deficit and the retention and transmission of liquid-water, are parameterized in the SAA model which cause snowpack outflow to differ from snowmelt. A complete description of the SAA model algorithms is given by Anderson [11].

4. SAA MODEL IMPLEMENTATION

4.1 Input data

Daily data from eleven precipitation stations, installed within and around the Mesochora catchment, were used in the SAA-SMA models. The precipitation stations are consistent and representative of the catchment but a small amount of daily precipitation values were missing over the 21-year study period (1972-92). In order to preserve the real nature of precipitation series and to avoid

TABLE 2. SAA parameter description and calibrated parameter values.

Parameter	Description	Calibrated values
SCF	A multiplying factor to correct for gauge catchment deficiency in the case of snowfall	1.10
MFMAX	Maximum melt factor during non-rain periods which occurs in June 21	0.90 mm/°C/6hr
MFMIN	Minimum melt factor during non-rain periods which occurs in December 21	0.40 mm/°C/6hr
UADJ	Average wind function during rain on snow periods	0.10 mm/mb/6hr
SI	Mean areal water-equivalent above which there is always 100% areal snow cover	100 mm
NMF	Maximum negative melt factor	0.12 mm_e/°C/6hr
TIMP	Antecedent temperature index parameter	0.30
PXTEMP	Temperature which delineates rain from snow	1 - 0°C
MBASE	Base temperature for snow melt computation during non-rain periods	0°C
PLWHC	Percent liquid-water holding capacity of ripe snow	0.05
PAYGM	Average daily ground at the snow-soil interface	0.020 mm
EFC	Percent area over which evapotranspiration occurs for 100% snow cover	0.61

Areal mean water-equivalent/A_i	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Snow cover extent	.05	.11	.18	.20	.22	.25	.33	.42	.53	.71	1.0

computational errors introduced by the data filling methods, the missing data were not interpolated. Thus, the technique used to estimate the mean areal daily precipitation was a combination of the Thiessen method and availability of the station data, including elevation correction [6, 9]. The great importance given to the accurate integration of precipitation over area and elevation (same as temperature integration described below) is necessary for the SAA model operation as well as to SMA model operation which is based on an numerical difference scheme input driven.

Daily temperature data were obtained from three stations. One is installed inside the catchment, while the other two are installed outside. There are also missing data of daily max-and-min values over the 21-year study period (1972-1992). The consistency of the data was checked by the double-mass curve on a monthly basis [11] and the inconsistent data were corrected by applying an appropriate corrective factor. For the same reasons, the missing daily max-and-min values were not interpolated and the mean areal max-and-min daily temperature was estimated through a technique combining the Thiessen method and the availability of the station daily data, including elevation correction [4, 6].

The daily discharge data of the Mesochora station were used for the period 1972-1992. Most of the discharge records were complete, but some daily data were missing. In order to estimate the missing data a downward station was used as a backup station. The Mesochora missing data were estimated by multiplying the complete daily data of the downward station by the ratio of the monthly average discharge. Details of the stations and their data quality, as well as the data filling methods used have been presented by Panagoulia [4, 6].

4.2 SAA model calibration

For the simulation of the elevationally distributed snow cover, the Mesochora catchment was divided into three elevation bands. The daily rain plus melt (pseudo-precipitation) was averaged over the elevation band areas. The SAA and SMA models were manually calibrated over the 15-year period (1972-1986) through a trial and error approach, which was carried out concurrently for both models. The initial estimates of the number and the areas of elevation bands, and model parameters were based on the hydrograph characteristics, climate and observed catchment features. The final scheme for making initial parameter estimates was that suggested by Anderson [11] for the SAA model and that suggested by Peck [13] for the SMA model. The description of the number and the areas of elevation bands, and the SAA model parameters and their calibrated values are shown in Tables 1 and 2, respectively. Following calibration, verification was performed using the 6 years of record following the calibration period.

The statistics (standard error, average bias, mean, etc.) of the error analysis of daily flow and its components (surface, upper level, lower level), as well as the statistics of three day volume error analysis, including peaks, showed that the SAA and SMA models are capable to accurately reproducing the observed discharge (the SAA indirectly and the SMA directly) [6]. However, some discrepancies were pointed out which were related to antecedent dry conditions and extreme rainfalls. The typical monthly simulation errors, expressed in percent of observed flows, were of the order of 10-15%, higher in low runoff months (August and September) and lower in high runoff months [6].

5. SNOW COVER RESPONSES OVER ELEVATION BANDS

This paper restricts the analysis of the SAA model simulations to the snow cover distribution over the three elevation bands into which the Mesochora catchment was divided. The average daily snow cover over the three elevation bands for the total period (1972-1992) is presented in Figure 1. The snow cover of the upper band was more extensive and longest into the mean year compared to that of the other two bands (medium and lower). In the upper band the extent of snow cover reached 95% from mid-December to mid-March. The snow cover was extinct in June and returned in the first days of October and in turn it was extending until December.

In the medium band the snow cover was less uniform during the four months (from December to March) against the upper band snow cover. The maximum value of the snow cover extent was 85% in the mid-February, while the snow disappeared in the last days of April and appeared again in November. The shortest extent of snow was presented in the lower band and it was lasting four months (from December to March). The maximum value of snow areal extent was 55% in mid-January. The different patterns of elevationally distributed snow cover play a major role to the shifting of the runoff hydrograph peak from the winter months to the spring months. The peak of the snow water equivalent weighted over the three bands occurred in March shifting the discharge hydrograph peak in April [7].

6. CONCLUSIONS

For the Mesochora catchment, the SAA model produced good estimates of discharge when the catchment was partitioned into elevation bands. Elevation bands improved the timing of simulated discharge, and the monthly discharge and snow distribution were sensitive to elevation bandwidth. The modelled snow distribution showed reasonable agreement with the observed snow-covered area particularly during the early melt season in last days of March and April (from local information).

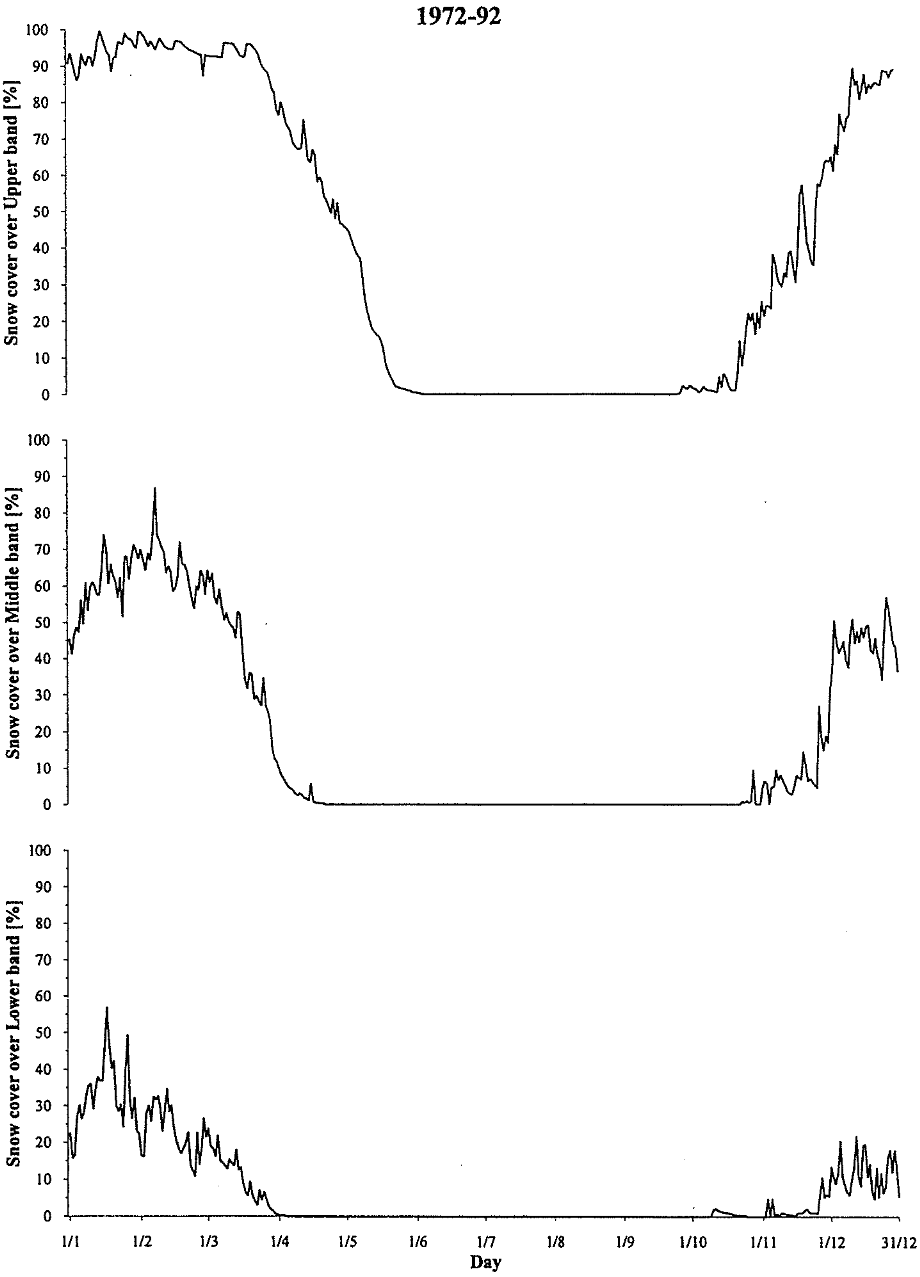

Figure 1. Average daily snow cover over elevation bands.

Model performance could be improved with enhancements of the snow sublimation, interception and redistribution processes which in the specific model could be done by using different sets of the relative parameters over the three elevation bands. Under these improvements a more correct daily discharge estimate and elevational heterogeneity of snow water equivalent is expected. In addition to estimating the timing and magnitude of discharge, modelling snow distribution would be important to modelling biogeochemical processes that depend on the elevational distribution of soil moisture.

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