AN OPERATIONAL DISTRIBUTED SNOW DYNAMICS MODEL FOR THE SAVA RIVER, BOSNIA

Melloh[1], R., S. Daly[1], R. Davis[1], R. Jordan[1] and G. Koenig[1]

ABSTRACT

A method of estimating and forecasting snow pack dynamics for a large remote basin in Bosnia was developed and consists of a highly automated, spatially distributed model for operational simulation and forecasting of snow pack depth, snow water equivalent, soil freeze-thaw state, and flux of snow melt and rain infiltration to the base of the pack. The model, applied to hydrologic forecasts in Bosnia during the winter of 1996-1997, has potential use in domestic flood and water supply forecasting. SNTHERM, a complex one-dimensional energy balance model that takes into account most physical processes within the snow cover, was used for snow pack computations. The model was distributed across the landscape by 1-km pixels, using a categorical classification of the basin into 216 slope, aspect and meteorology types. The model system was highly automated. Runoff ratios (runoff/rainfall) for the winter of 1996-1997 compared well to long term average runoff coefficients, indicating precipitation data used to drive the model were reasonable. Supporting research issues are discussed.

INTRODUCTION

Operation Joint Endeavor, a NATO peace-keeping mission in Bosnia, provided the incentive for development of a highly automated model system for simulation and prediction of snow pack dynamics across a 89,000 km^2 portion of the Sava River drainage basin (Fig. 1). Model output parameters include the spatial distributions of snow pack depth, snow water equivalent, soil freeze-thaw state, and flux of snow melt and rain infiltration to the base of the pack at 1-hr or multi-hour time steps. The model system was used here to anticipate river stage fluctuations at the location of a temporary bridge at Zupanja, Bosnia. It has potential use in domestic flood and water supply forecasting. This paper describes the distributed model approach, and progress made toward an operational snow dynamics model for the Sava River Bosnia.

STUDY AREA

The Sava River at the bridging site in Zupanja (62,891 km^2 drainage area) experiences frequent rapid stage rises during the winter. An analysis of historical flow events indicates that out of bank, within levee flows, occur most winters (Fig. 2). Physiography, land use and weather patterns contribute to the dynamic water levels. The Sava River watershed is characterized by an extensive lowland with 37% of the elevation range (50 to 2650 m) lying below 250 m (Fig. 1). This large area of similar physiography adjacent to the main stem of the Sava River, is largely in agricultural land use. Snow can melt rapidly and simultaneously across the entire lowland due to both increased levels of solar radiation striking the open snow cover and uniform warm temperatures across the lowland during melt cycles. Improved drainage systems common in agricultural areas likely decrease the travel time of runoff. It is common for stages to rise rapidly and nearly simultaneously along the entire main stem of the river (Fig. 3) between Jasenovac and Zupanja.

The basin weather is influenced by the continental climate of the Panonian lowland to the north, and mountain climate of the Dinaridi highland to the south. The Dinaridi mountain ridge forms the southern Sava River basin boundary and rises to heights of 1000- to 1760-m elevation, influencing air flow between the Sava basin, and the maritime climate of the Adriatic Sea (Gajic-Capka 1991). Storms can deposit a substantial snow pack across the basin and are generally followed in a matter of weeks, by weather systems that melt the snow. Rain on snow events are common as are several cycles of snow pack build-up and melt during a single winter.

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[1] U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire

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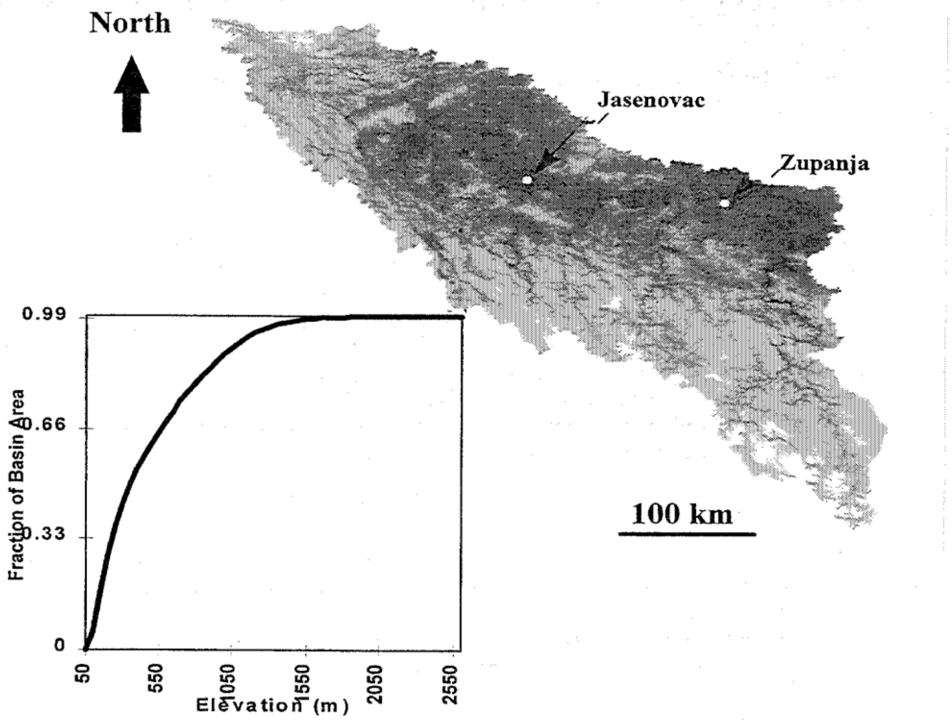

Fig. 1 - Elevation image and elevation-fractional area curve of the Sava River above Zupanja.

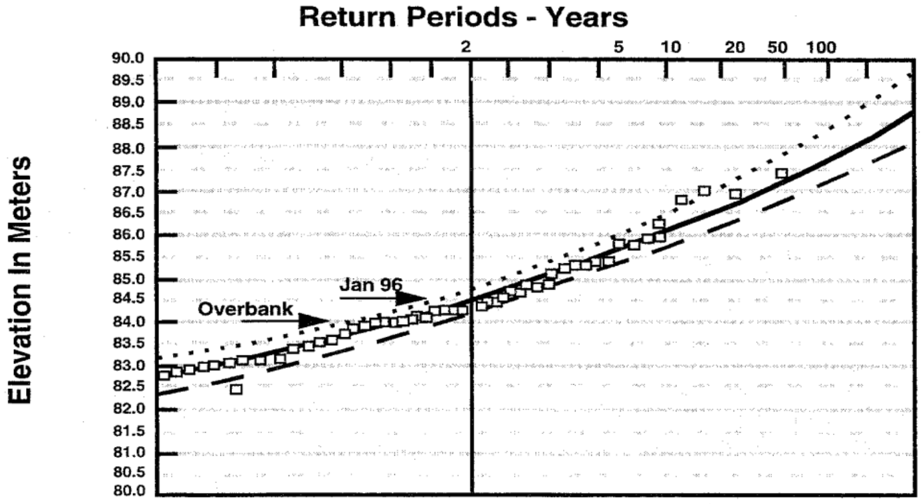

Fig. 2 - A frequency curve of peak events on the Sava River at Zupanja showing overbank floods occur in most winters.

Very little snow can be expected prior to November (Table 1). Historical snow depth records at Slavonski Brod (88m elevation), Bjelovar (130m elevation) and Puntijarka (988m elevation) indicate the magnitude of snow storms and total depth of snow on the ground that have occurred during the period of record at these three locations. Maximum snow depths ranged from 36 to 127 cm at low to high elevations. There were many days when there was no snow on the ground, particularly at lower elevations. A maximum average of 23 days of snow on the ground occured in January in Puntijarka.

Table 1 - HISTORICAL SNOW DEPTHS

Maximum Snowfall in one Day (cm)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Slavonski Brod	-	14	26	26	30	13	4	-
Bjelovar	-	24	14	29	18	14	5	-
Puntijarka	6	43	37	38	41	30	24	17

Average Total Monthly Snowfall (cm)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Slavonski Brod	0	5	9	15	14	4	1	0
Bjelovar	0	6	7	15	13	4	1	0
Puntijarka	0	33	46	38	46	33	17	2

Maximum Snow on Ground for Period of Record (cm)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Slavonski Brod	-	15	36	34	32	24	4	-
Bjelovar	-	79	74	37	40	42	9	-
Puntijarka	6	85	86	118	127	127	49	17

Average Number of Days Snow on Ground (cm)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Slavonski Brod	0	3	7	11	8	2	0	0
Bjelovar								
Puntijarka	1	9	21	23	22	22	7	1

Period of Record 1970-1993 for Slavonski Brod and 1981-1993 for Puntijarka

METHODS

Progress was made toward a highly automated, spatially distributed model for operational simulation and forecasting of snow pack dynamics. The overall model concept consists of 1) an automated real-time meteorological data stream 2) automated distributed snow model runs, 3) periodic model update to observed snow depths 4) model update to satellite derived snow cover maps, 4) automated output to the World Wide Web (WWW), and 5) FTP (file transfer protocol) of basal outflow time series to the U.S. Army Corps of Engineers (USACE), Waterways Experiment Station (WES), in Vicksburg, Mississippi.

Automated Real-time Meteorological Data Stream

Software was designed to automatically interrogate meteorological data sources, prepare model input format, run the distributed snow model and produce output products. Hourly meteorological data was accessed from the

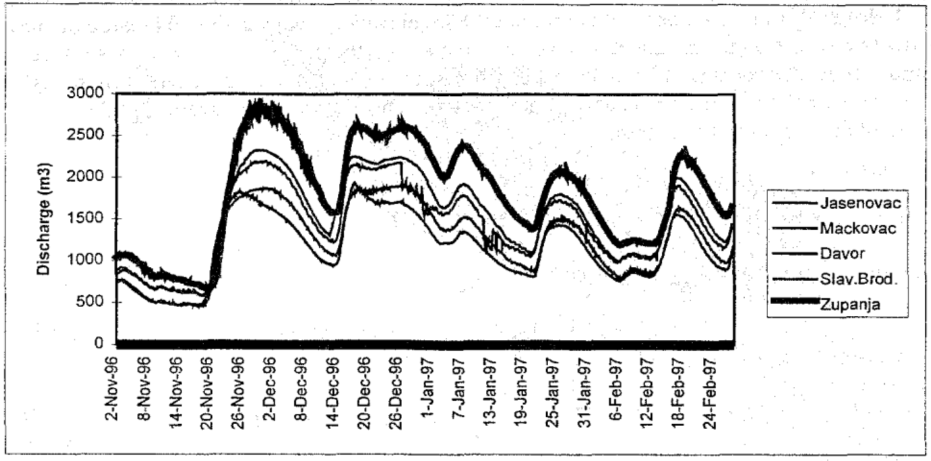

Fig. 3 - Dynamic stage rises along the mainstream of the Sava River during the winter of 1996-1997.

Air Force Global Weather Center (AFGWC), Air Force Weather Information Network (AFWIN) system on the WWW. Missing data interpolation schemes were devised and hourly air temperature, relative humidity, wind speed, precipitation, and cloud cover were reorganized into snow model input format. The FOXX35, a report available through AFGWC, provided daily tables of observed precipitation over the last 24 hours, current snow depth on the ground at 21 locations, and a 5-day forecast of precipitation and max./min. temperature. Forecast scenarios for model runs were based on the FOXX35.

A data base was established to provide a compact and efficient means of storing and preparing the continuous stream of meteorological data. All processes for entering data, editing data and preparing input required by the snow model were automated. The amount of data in the data stream would have quickly swamped any individual or group of individuals attempting to manage the large amount of data using non-automated procedures. The Hydrologic Engineering Center's - Data Storage System (HEC-DSS) (USACE 1995) data base was used for this application. This data base was developed specifically as a data storage system for water resources time series data, and uses a block of sequential data as the basic unit of storage. This approach is very efficient for time series data produced by stations at fixed locations. It avoids the processing and storage overhead required to assemble an equivalent record from a relational data base system.

Distributed Snow Process Model

SNTHERM, a complex one-dimensional (1-D) energy balance model that takes into account most physical processes within the snow cover, was used for snow pack computations. Originally written to predict snow surface temperatures (Jordan 1991), SNTHERM has been applied to a range of snow types and scientific inquiries, including prediction of the spectral signature of snow at an alpine site in California (Davis et al. 1993), snow profile evolution during summer snow melt on the Greenland ice sheet (Rowe et. al.1995), an energy balance study of a continental, and mid-latitude alpine snow pack at Niwot Ridge in the Colorado Front Range (Cline, 1997), and beneath canopy energy balance studies in the boreal forest in Saskatchewan, Canada (Hardy, et. al. in press; Davis et al. in press). SNTHERM was first spatially distributed at the plot scale to predict snow covered area and detailed snow property profiles for a mid-latitude, continental snow pack in Grayling, Michigan (Davis et. al. 1995). Excellent descriptions of SNTHERM, including the conservation equations, snow cover metamorphism and boundary condition methods used by the model, are given by Jordan (1991) and Rowe et. al. (1995).

The feasibility of using SNTHERM for monitoring snow dynamics was tested in 1-D at Loznica, a site representative of the dynamic lowland snow pack. The standard 1-D SNTHERM model underestimated both the accumulation and melt rates at Loznica (Fig. 4), and minor modifications of the code were required to match the

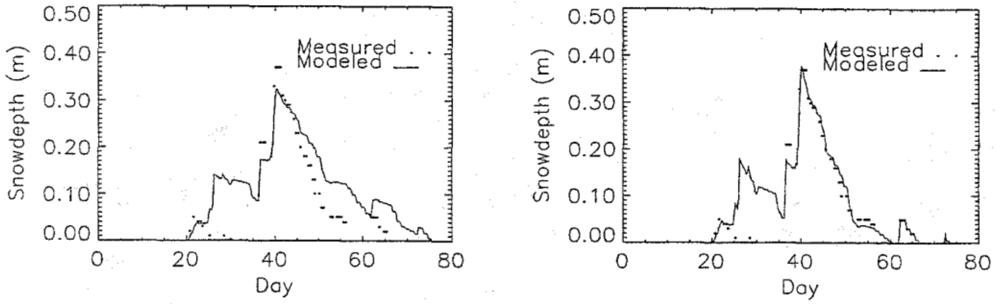

Fig. 4 - Losnica, Bosnia 1-D SNTHERM model runs with standard code (left) and with Bosnia version modifications (right).

observed data. SNTHERM accumulates a snow pack using measured precipitation data and new snow densityestimated from the Alta algorithm (LaChapelle 1961) and ranging from 50 to 169 kg m^{-3} for snow temperatures of -15 to +2°C. We matched the observed, accumulated snow depth by decreasing the new snow density by between 20 and 35 kg m^{-3}. The lower density is reasonable given the low wind speeds at Loznica during accumulation of this snow pack. We increased the precipitation rate by 15% to account for gauge catch deficiency. Adjustments to the SNTHERM longwave radiation module were required to match the observed snow ablation. The standard version of SNTHERM estimates longwave radiation from the formula of Idso (1981), with the addition of the Wachtmann correction (Hodges et al., 1983). A low cloud height, specified in the three layer solar insolation model of Shapiro (1982, 1987) is fixed in the standard version of SNTHERM. In the Bosnia version, we lowered the base of the low clouds and replaced the standard SNTHERM radiation modification by clouds with the procedure described in USACE (1956).

SNTHERM was distributed across the Sava River basin, using a categorical classification by 1-km pixels into 216 slope, aspect and meteorology classes (Fig. 5). Twelve meteorological regions were defined first, by subdividing the basin into equal fractional areas of low, mid and high-elevation, and secondly, four east-west sections. The Sava River basin drains from the west to east. The north basin boundary originates in the Panonian lowland and the south basin boundary along the ridge of the Dinaridi mountains. Low, medium and high elevations, thus, run from north to south, allowing for latitudinal weather system passage, while the east-west sections allow for longitudinal ones. Cloud cover, wind speed, air temperature, and relative humidity were averaged using stations lying within those twelve meteorological regions. Short and longwave radiation were estimated by SNTHERM and varied within the meteorological regions based on slope and aspect. Slope was assigned based on equal fractional area of the basin within three slope ranges. Aspects were fairly evenly distributed in all compass directions and were assigned to six classes using 60° increments with the first centered about North. The pixel counts in each of the 216 solution classes (product of 12 meteorological, 6 aspect, and 3 slope classes) varied (Fig. 6). Classes with only a few pixels occurred for combinations of low elevation and high slope, and for high elevation and low slope. We did not reassign or discard these small classes, but this could be done to save computation time. Each distributed snow model run consisted of 216, 1-D SNTHERM solutions mapped back out to the individual pixels by their assigned solution class.

Model Update

Methods of assimilating sparse snow depth observations and snow cover maps derived from AVHRR satellite data are in the process of being devised for periodic model correction. Only twenty-one daily snow depth observations are available from the FOXX35. Local wind or thermal environment may influence the data at these sites and at the meteorological sites, many of which are in cities. This and the sparse spatial representation of the point data make the use of satellite data in model update highly desirable. Advanced Very High Resolution Radiometer (AVHRR) satellite data were downloaded regularly for cloud free and partly cloudy days. Snow cover extent and subpixel snow covered area were analyzed in near real time using the AVHRR imagery and methods described by Rosenthal, (1996a; 1996b).

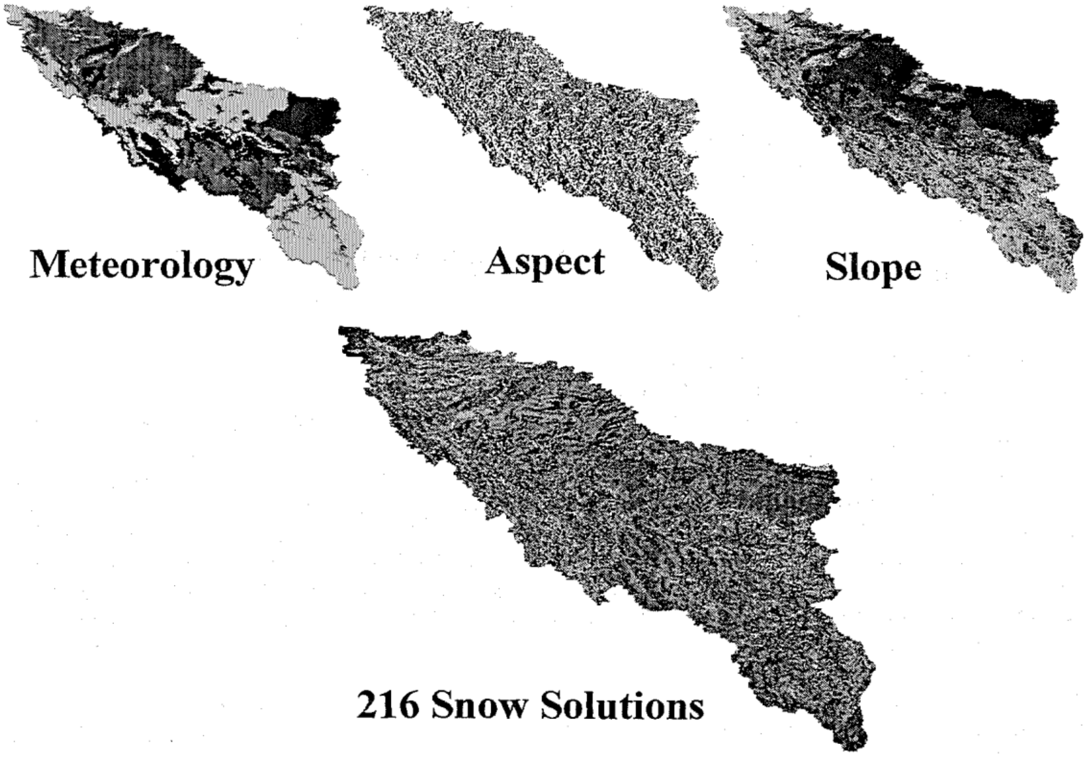

Fig. 5 - Categorical classification of the Sava River basin into 216 solution classes.

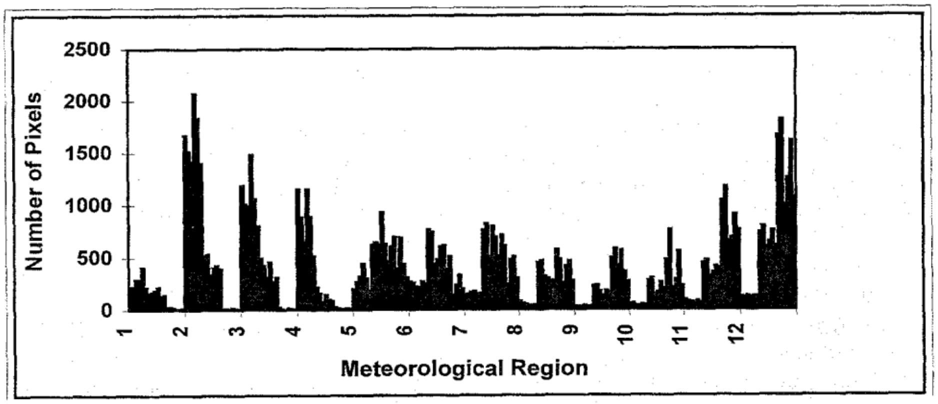

Fig. 6 - The histogram of solution class sizes arranged by meteorological region. Within each region the order of represented classes is low to high slope.

RESULTS

Distributed Snow Model

The Sava River snow dynamics model is an initial adaptation of SNTHERM to a large basin and hydrologic use. Information on snow pack conditions and distribution throughout the Sava River basin were needed for basin flow forecasts. Snow depth observations were available at only 21 sites. These observations provided a daily record of snow depth change, but no information on snow water equivalent or timing of basal outflow. The distributed snow model provided a means to 1) estimate the snow water equivalent of the snow pack, 2) identify periods of snow compaction versus melt water production, 3) determine whether rainfall freezes in the pack, is stored in snow pores as liquid, or infiltrates through the snow pack, 4) simulate the timing and magnitude of basal outflow and 5) predict a basal outflow time series for a forecast scenario. Infiltration of water into the soil, runoff transformation into stream flow hydrographs, and channel routing are not addressed within the scope of this paper.

Runoff Ratio

Runoff ratios (measured runoff/precipitation) compared with historical ones, provided a qualitative check on whether the automated meteorological data stream adequately represented precipitation on the basin (Fig. 7). Runoff ratios for the Sava River at Zupanja compared with precipitation at Sarajevo and Ljubljana show long term average runoff ratios that are high in the winter and low in the summer. The seasonal trend is expected due to wetter antecedent moisture conditions in winter compared to drier conditions in summer when evapotranspiration dries the soil. Runoff during the 1996-1997 winter was higher than average (1971-1993), and runoff ratios would be expected to be higher than average. Using average precipitation across the basin between 12 November 1996 to 31 January, 1997, the runoff ratios for the twelve meteorological regions ranged from 0.7 for region five which includes Ljubljana to 1.1 for meteorological region 8 which includes Sarajevo. The average historical runoff ratios for 12 November through 31 January are 0.47 for Ljubljana and 0.75 for Sarajevo. Runoff ratios for the winter of 1996-1997 are within a reasonable range, and as should be expected, are higher than the long term average.

Product Summary

The output of our distributed snow model includes hourly images of 1) snow depth, 2) snow water equivalent, 3) basal outflow and 4) energy required to melt the remaining snow. The data from these hourly images can be averaged (lumped) over subbasins (Fig. 8). During melt or rain-on-snow events, combined simulation and forecast time series of basal outflow for 29 subbasins of the Sava River basin above Zupanja were electronically transferred to USACE, WES for use in their flow forecasting models.

Once daily, near-real time snow depth maps were posted to the WWW. Daily situation reports were provided to the Zupanja bridge site operation in a Joint USACE, WES/CRREL (Cold Regions Research and Engineering Laboratory) Situation Report. The reports included verbal descriptions of snow pack depth, distribution and ripeness across the Sava River Basin and the likelihood of a snow melt runoff event occurring in the next several days.

DISCUSSION

The priority research topics needed to support this operational distributed modeling effort include 1) the development and integration of mesoscale meteorology models with snow hydrology models, 2) integration of satellite data, especially AVHRR derived snow maps, 3) definition of basin classification schemes that assure the spatial and temporal fidelity of simulated basal outflow time series, 4) engineering tools for data assimilation, 5) improved computational efficiency without degradation of runoff predictions, and 6) validation of distributed snow dynamics models.

A physically based, energy balance approach is preferred over an index model when it is important to represent meteorological variability, and when empirical calibrations are impossible or undesirable (Anderson 1976). The Sava River basin is meteorologically variable due to alternating weather systems, variable melt and rain-on-snow runoff events, extensive open lowlands subject to turbulent transfer and direct radiation, and the physiographic variability (slope, aspect, elevation, and forest cover) of the hill and mountain areas. Obtaining appropriate

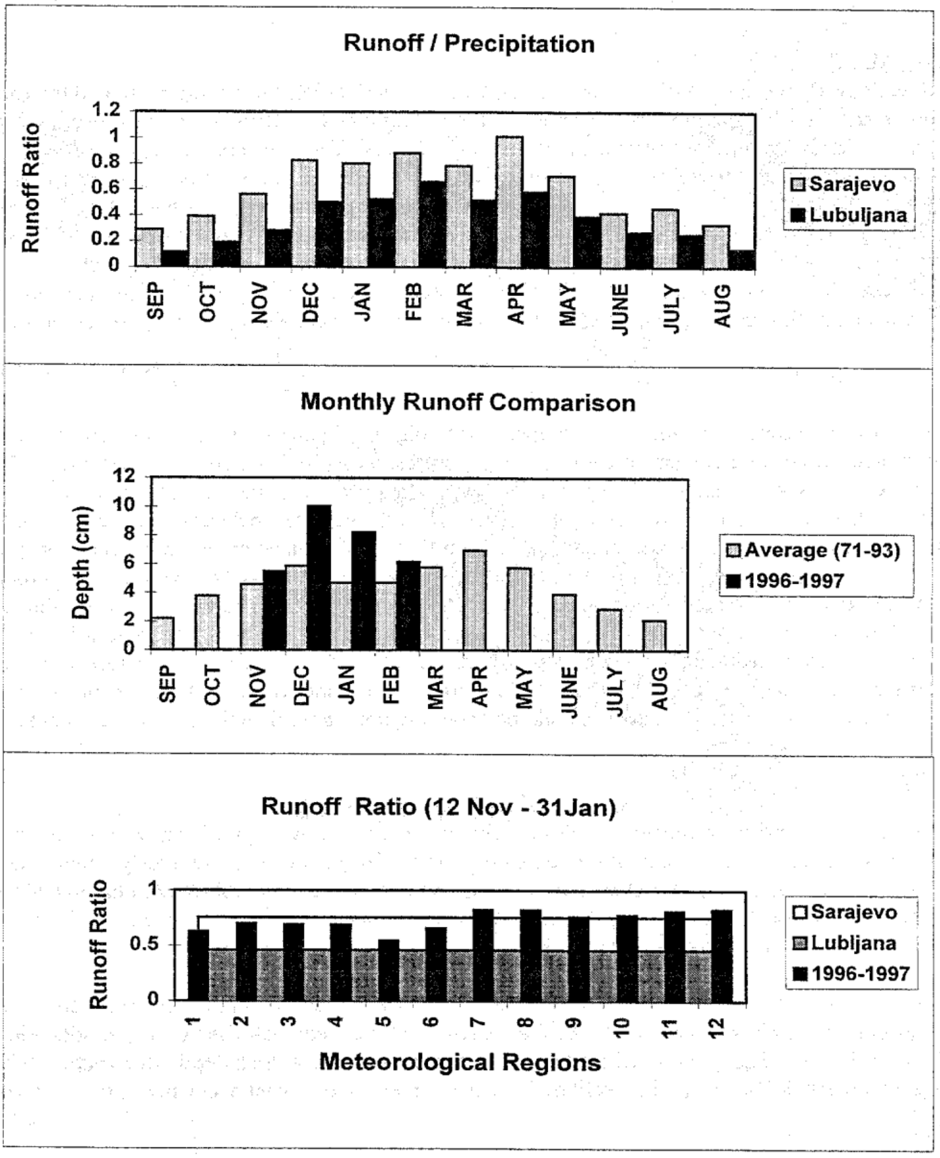

Fig. 7 - Long term average runoff ratios (runoff/precipitation) using discharge records at Zupanja (1971-1993) and precipitation records for Sarajevo and Ljubljana (top), comparison of long term average monthly runoff at Zupanja and runoff during 1996-1997 (middle), and the runoff ratio for the winter of 1996-1997 for the twelve meteorological regions, compared to the long term average (bottom).

meteorology to drive any model across this basin is a challenge. Available meteorological data is primarily representative of open, low slope, low elevation cities and may not be representative of the surrounding countryside. At higher elevations, meteorological data is extremely sparse. Development and integration of mesoscale meteorology models should bring improvements in meteorological interpolation. Integration of satellite data, such as AVHRR derived snow cover extent and subpixel snow covered area maps, should aid in correcting and extrapolating model results across the landscape. In the future, automated, satellite derived cloud cover information could improve radiation distribution across the basin.

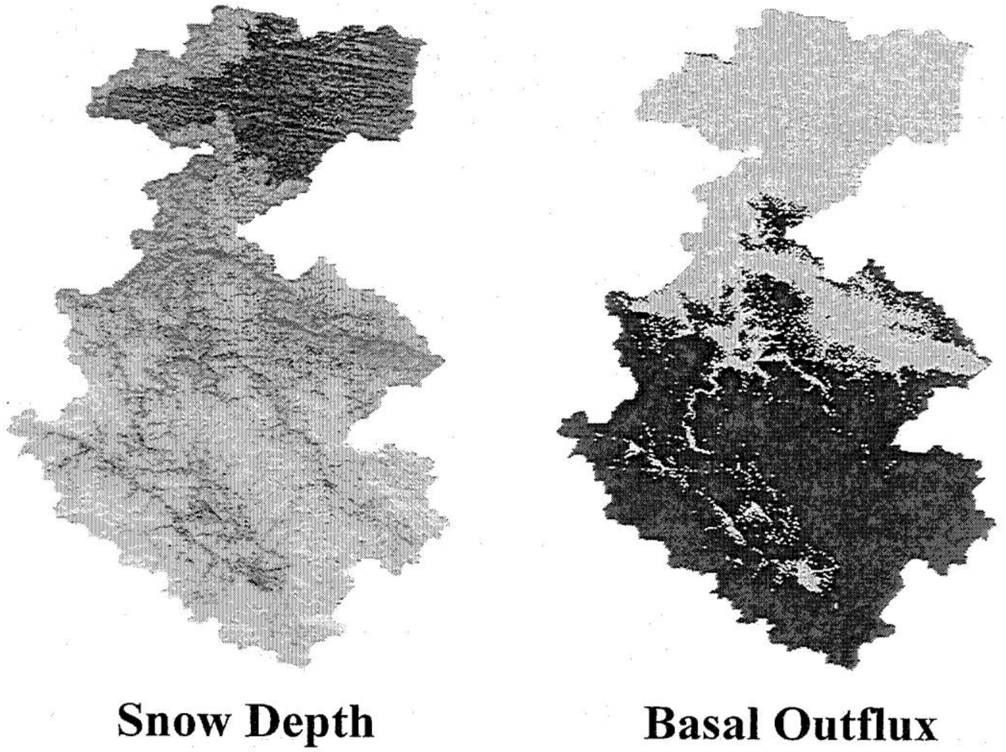

Fig. 8 - Graphical output products of snow depth (left), and basal outflow (right) for the Bosna Subbasin and other contributing drainage areas between Zupanja and Slavonski Brod.

The applicability of SNTHERM to flow forecasting in Bosnia and other large basins requires segmentation of the basin into representative snow solution classes that result in optimal spatial and temporal fidelity of the simulated basal outflow time series. Methods of obtaining this optimal classification within operational computational time frames need to be further explored. Snow solution classes must represent the meteorological variability of the basin. An approach that integrates a time series of gridded output from mesoscale meteorology models with local slope, aspect, and forest cover information could be rapidly applied to any basin. In highly developed basins, it may be necessary to integrate landuse if this influences the rate of snow accumulation and melt.

Periodic updating of snow model results and computational efficiency are necessary aspects of an operational tool. Data assimilation refers to the process of using observed data to constrain and/or correct model results to establish accurate initial conditions prior to forecasts. Updating is especially important for remote theaters of operation where the meteorological observations that form the basis of SNTHERM's input data are sparse and possibly inaccurate. Updating techniques for snow models range from empirical to optimal estimation procedures such as the Kalman filter technique (Day 1990, Huang and Cressie 1996). Increasing SNTHERM computational efficiency without serious degradation of basal outflow predictions is being addressed by reducing the number of computation nodes lower in the snow pack.

Our Bosnia application is river flow forecasting; however, runoff is a highly integrated measure, and improved methods of transforming distributed basal outflow from the snow pack to stream flow are needed. Snow cover depletion patterns are shown to be superior to runoff data for validating model parameter selection for distributed hydrologic models (Kirnbauer 1994). Runoff ratios (model precipitation/actual runoff) provide a qualitative evaluation of whether the method of extrapolating precipitation across the basin appears reasonable.

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