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Spatial Simulation of Snow Processes

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A spatially distributed model for the simulation of snow accumulation and melt is presented. Watershed information on topography, vegetation and soils in digital terrain models (overlays) serve as the data base for watershed analysis, classification of snow in Landsat imagery and automatic generation of parameter decks for operating distributed simulation models of snowcover dynamics and streamflow generation. Snow processes are simulated within variable size grid-cell elements. The hydrograph resulting from spring snowmelt is simulated by a lateral flow model of streamflow generation driven by simulated snowmelt and rain inputs. Options are avilable for simulating the effects of forest management alternatives on selected areas. Snow course measurements and classified Landsat imagery are used for updating simulated parameters.

Introduction

Up-to-date resource information is of primary importance for water resource management. Information can be obtained from a number of sources. Most important are topographic maps, vegetation and soil surveys, measurements of snow depth and streamflow and other traditional sources. Remotely sensed information from spacecraft and other platforms above the ground are gaining importance in water resource mangement. Whereas traditional data sources provide the resource manager with historic data, remote sensing can provide real time information. Real time information is most important for dynamic or rapidly changing resources such as snow, reservoir levels, etc.

After collecting the necessary data, the watershed manager is faced with making resource management decisions. Computer simulation of watershed processes is a powerful tool available to the manager for evaluating land management alternatives and hydrologic forecasting. An important aspect of computer simulation is that hypothetical experiments can be performed on a watershed. For example, the effect of timber harvesting can be assessed without actually cutting any trees. Another advantage of watershed simulation is that near real time satellite imagery can be used for updating simulated parameters periodically for improved prediction of ongoing processes in the watershed, and consequently improved spring runoff forecasting.

The purpose of this paper is to present a system of simulation models designed to make efficient use of both traditional and remotely sensed data sources. Digitized map information, remotely sensed data and simulated hydrologic parameters are all in a common square grid format (overlays) facilitating automated data handling and display of parameters in a map-like form.

The Williams Fork Watershed in the Central Rocky Mountains of Colorado was selected as the sample area for model development and testing. The Williams Fork, a tributary to the Colorado River at Parshall, Colorado, has an area of 476 km^2 and an elevation range from 2,380 m to 4,137 m at the highest point on the continental divide.

Data Base for Simulation of Snowmelt

Overlays

For this study, a square grid technique was selected as the most efficient for registering and coding spatial data on topography, vegetation and soils. A 5.76 ha grid cell was selected as a compromise between digitization and computing time, and resolution of simulated parameters. A total of 11 parameter overlays were created. The elevation overlay for the Williams Fork study area can be seen in Fig. 1 in grey-mapped form.

Extraction of Watershed Parameters

A computer program (EXTRACT) was developed to automatically define hydrologic response units (HRU'S) and calculate their parameters from data in overlays. Hydrologic response units consist of grid cells with similar values of major parameters. The grouping scheme used in this study lumps cells with similar aspect, slope and vegetation type into the same HRU. For each HRU, elevation and other remaining parameters are calculated as the mean of individual grid cell values. The grouping scheme is flexible and can be modified. For application to other areas, it might be advantageous to use elevation or vegetation as grouping subscripts. More than three grouping subscripts might also be necessary. Ninety-

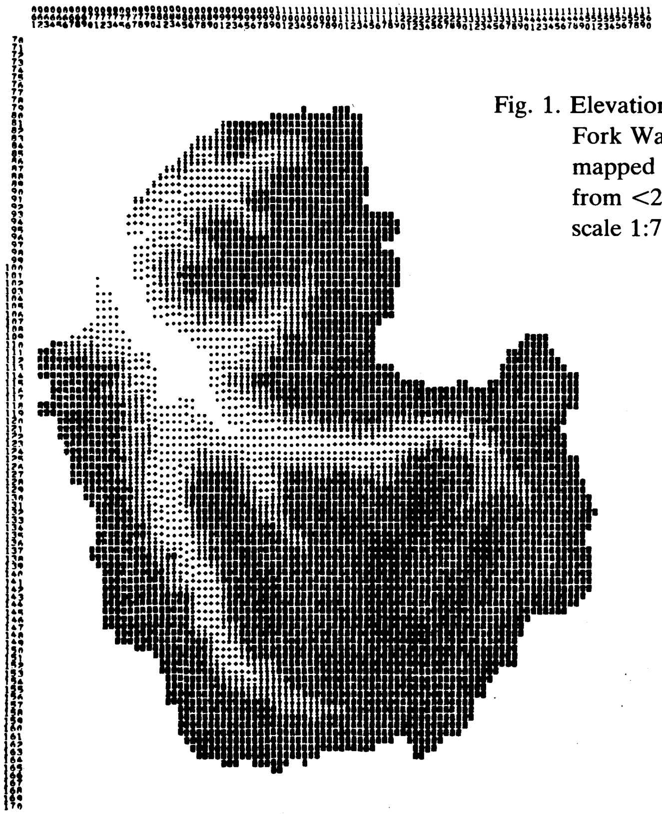

Fig. 1. Elevation overlay of the Williams Fork Watershed, Colorado, in grey-mapped form. Eight classes ranging from <2,743 to >3,658 m. Original scale 1:75,000.

three HRU's were defined within the entire Williams Fork study area (23.075 hectares). A total of 104 HRU's were present, but subunits with fractional areas less than 0.001 were excluded to reduce computing costs.

In the computer, watershed parameters are represented as three dimensional variables of the following form

ELEVAT (IASP, ISLP, IVEG)

where, ELEVAT = Elevation of HRU
IASP = Aspect of HRU
ISLP = Slope of HRU
IVEG = Vegetation Type of HRU

Generation of Parameter Decks

The computer program (EXTRACT) that extracts the parameter values also generates the parameter decks for operating a snow process model (WATBAL) developed by the U.S. Forest Service (Leaf and Brink 1973). A number of modifications were made to the model in order to facilitate spatial simulation of snow

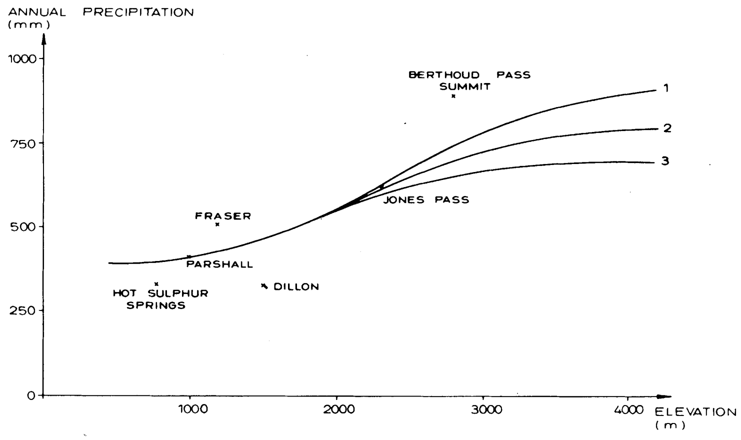

Fig. 2. Precipitation curves for the Williams Fork Watershed, Colorado, shown with annual precipitation for six stations near the study area.

processes. Most of the modifications were only concerned with the peripheral 'routines, and no significant changes, that would have required model revalidation, were made to core water balance routines.

Besides watershed overlays, EXTRACT uses data files with potential evapotranspiration data and slope/aspect correction factors for solar radiation for all combinations of HRU topographic parameters in generating parameter sets.

Calibration of Major Hydrologic Processes

In generating parameter decks for model operation program EXTRACT uses calculated watershed parameters to generate process parameters: e.g. vegetation transmissivity is a function of vegetation type and density, temperatures a function of elevation and aspect etc. In program EXTRACT these relationships are specified as families of curves constructed from information available in the literature or estimated from available watershed data. During model calibration, processes are calibrated one at a time by selecting the curve that gives the best fit between observed and simulated parameters. The curves used for calibrating precipitation as a function of elevation can be seen in Fig. 2. For all simulation runs included in this paper an initial calibration on 1970 data was maintained.

Spatial Simulation of Snow Processes

The snow process simulation model WATBAL requires daily extreme temperatures and precipitation as driving variables. If solar radiation data are available these can be used for driving the snowmelt routines. If radiation data are not available WATBAL will estimate daily solar radiation from temperature data using a regression model. Temperatures are also used for the separation of precipitation into rain, snow or mixed events. Calculated (or observed) radiation is mainly used in calculating the radiation balance (temperature) of the snowpack and actual evapotranspiration from potential. For each HRU temperatures and precipitation are adjusted according to topography. Temperatures are adjusted using estimated lapse rates for the Williams Fork Watershed. During initial model calibration it was found necessary to adjust summer and winter temperatures differently, since typical summer lapse rates are several times higher than winter values.

Linkage between WATBAL and other programs is established by a permanent file with daily observed and simulated parameters for each HRU. All simulated parameters (snow-water equivalent, snow temperature, and soil moisture deficit) can be displayed in grey-mapped form for any given date. Figs. 3 and 4 show the progression of snowmelt between June 1 and July 1, 1971. It is seen how spring snowmelt is controlled by terrain. Snow on »warm« slopes with aspects between south and west is melting faster than snow on »cold« slopes with aspects between north and east. Forest cover is also a major controlling factor reducing the amount of solar radiation available for snowmelt.

Simulation of Snowmelt Hydrograph

The snow process model, WATBAL, does not simulate stream hydrographs. No routing is performed and soil water in excess of field capacity is assumed to run off instantly.

In order to compare a simulated hydrograph with the observed hydrograph a lateral flow model, LATFLOW, was developed to route water from simulated snowmelt and input in the form of rain through soil and groundwater storages to the nearest stream channel. LATFLOW simulates overland flow and baseflow contributions to the snowmelt hydrograph as well as the dominant lateral flow component.

The model developed does not consider Hortonian-type infiltration excess-overland flow since infiltration rates within the Williams Fork Study area are generally much higher than any likely input (snowmelt and rain) event. Simulated overland flow can only take place when the entire soil horizon is saturated (saturation-overland flow).

The lateral flow model simulates lateral gravity flow and deep seepage within variable length slope segments (compartments). A Darcy-type equation and the continuity equation are used for the calculation of lateral flow. Deep seepage and baseflow, from groundwater storage are treated very empirically in this study.

Parameter decks for operating the lateral flow model on specified watersheds are generated automatically from information in watershed overlays. Input to model compartments are calculated on a daily basis from simulated snowmelt

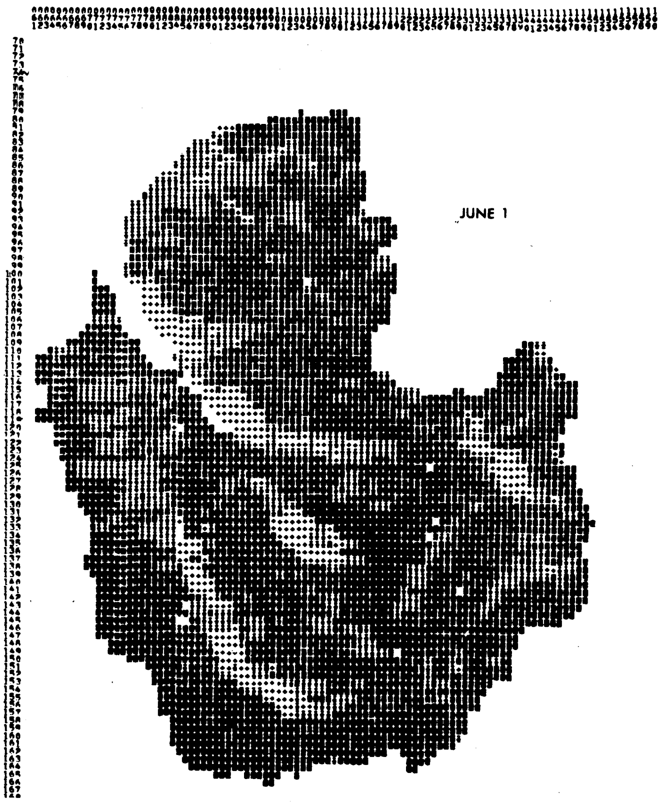

Fig. 3. Simulated snow water equivalent on June 1, 1971, for the Williams Fork Watershed, Colorado, in grey-mapped form. Eight classes ranging from 0 to >533 mm. Original scale 1:75,000.

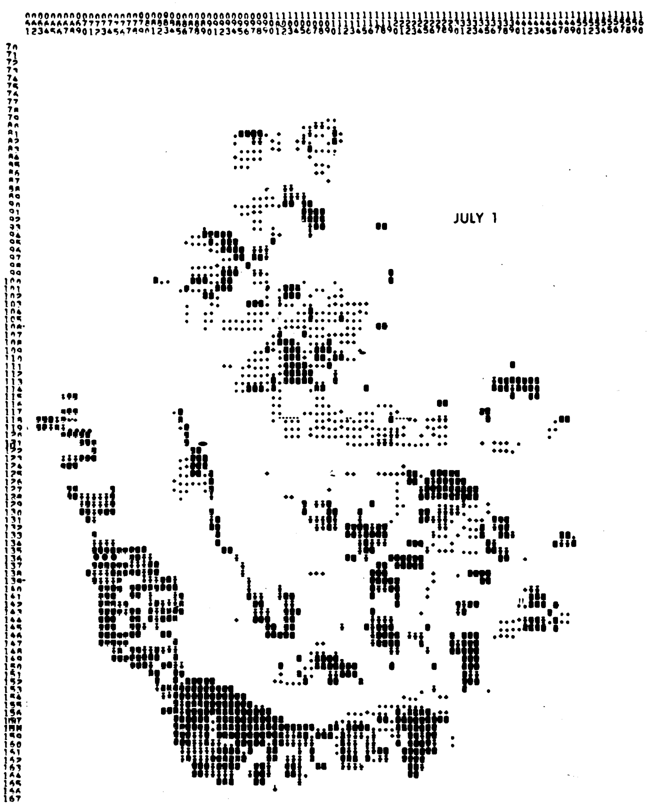

Fig. 4. Simulated snow vater equivalent on July 1, 1971, for the Williams Form Watershed, Colorado, in grey-mapped form. Eight classes ranging from 0 to >533 mm. Original scale 1:75.000.

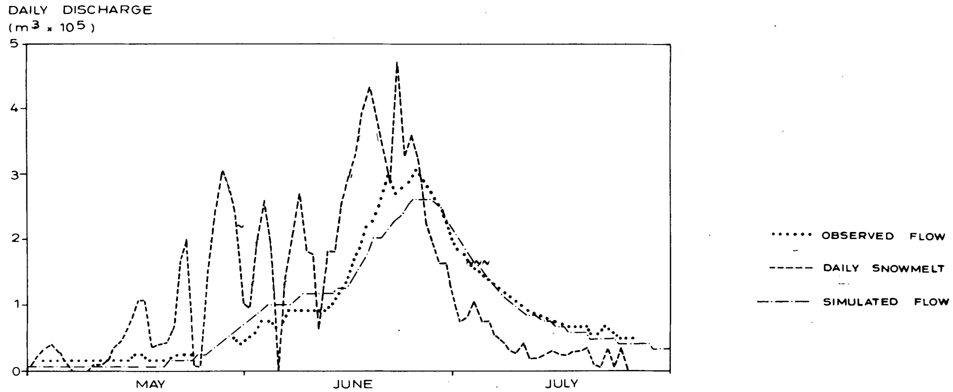

Fig. 5. Observed and simulated snowmelt hydrographs for the 1971 snowmelt season in the South Fork of the Williams Fork Watershed, Colorado. The daily simulated snowmelt is also shown.

data. Lateral flow compartments are defined by the distance in the direction of flow from the center of each grid cell to the nearest live stream channel. If the width of the lateral flow compartments is specified at 100 m, the compartment nearest to the stream is comprised of cells with distances to stream between 0 and 100 m. The next compartment contains cells with distances between 100 and 200 m and so on.

The lateral flow model will simulate the hydrograph at the basin outlet or at arbitrary points along the major channel. The latter option is useful in stream quality modelling.

An example of output from the lateral flow model is given in Fig. 5. The observed and the simulated hydrographs are shown together with the daily input to LATFLOW. The volume difference between daily input and the simulated hydrograph is equal to the daily increase/decrease in soil and groundwater storage. During the simulated period there is a substantial increase in groundwater storage.

Simulation of Response to Changes in Forest Cover

The computer program, EXTRACT, also has options for simulating watershed response to thinning or clearcutting of all or selected timber stands.

To demonstrate this capability the effect of removing 75% of the crown cover in a uniform thinning of all timber stands in the study area was simulated. Predicted changes were small. Thinning reduced total evapotranspiration and reduced the soil moisture deficit at the end of the water year. Runoff was increased by only 15 mm, from 69% to 71% of total precipitation. However, the 75% thinning caused the hydrograph to start rising earlier (Fig. 6) due to increased early melt in the forest covered areas.

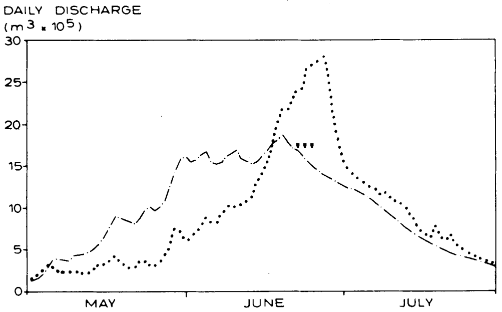

Fig. 6. Observed and simulated hydrographs for the 1971 snowmelt season in the Williams Fork Watershed, Colorado. The effect of removing 75% of the crown cover in a uniform thinning of all forest stands is simulated.

Simulation Update

Imagery from Landsat and lower resolution environmental satellites have been used in other models for updating snowcover simulation. Usually the snow-covered area within a watershed is first found from manual or machine-aided interpretation of satellite imagery. The areal snowcover is then directly input to the simulation model (Dillard and Owig 1979) or used in estimating the eater equivalent of snowpack (Shafer and Leaf 1979). The update procedures developed for this study differ in that simulated snowcover is directly updated on a pixel basis. Thus, more of the information content in the imagery is utilized.

Landsat imagery is only useful for simulation update when snowmelt is in progress and the watershed only partly snow covered.

During the study procedures for updating the accumulating snowcover with snow course measurements were also developed. Simulated relationships between elevation, aspect and snow-water content for a given date were used in relating snow course measurements to areal distribution of snow water content.

Simulation update can be performed in two modes. If only snowwater equivalent is updated during early spring, a complete simulation rerun will be made with the updated parameters as specified conditions. WATBAL will adjust precipitation to arrive at the specified snow depth on the date of update. If additional parameters (snow-pack temperature and soil moisture deficit) are updated, updated parameter values will serve as initial conditions, and simulation will restart from the date of update (hot start).

Classification of Landsat Imagery

A snow classifier, SNOWPCT, was developed for classifying the fractional snow covered area within Landsat pixels (ground resolution elements). The water equivalent of the snowcover is inferred from the classified Landsat image taking pixel elevation and aspect and the image acquisition date into consideration. The estimated snow-water equivalent is then used for simulation update on the date of satellite overpass.

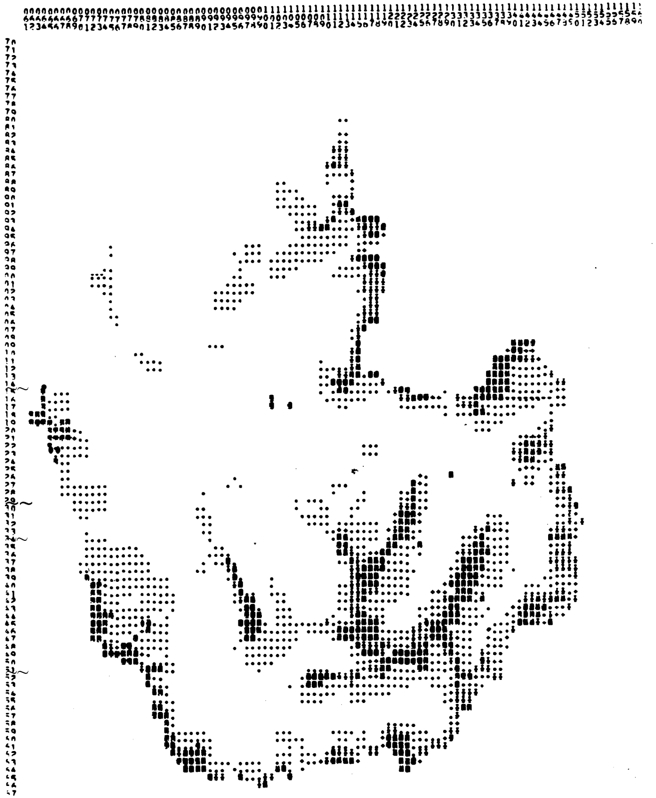

Fig. 7. Synthetic image of Landsat band 5 radiance on July 1, for the Williams Fork Watershed, Colorado, in grey-mapped form. Eight classes ranging from 0 to 320 radiometer counts. Original scale 1:75,000.

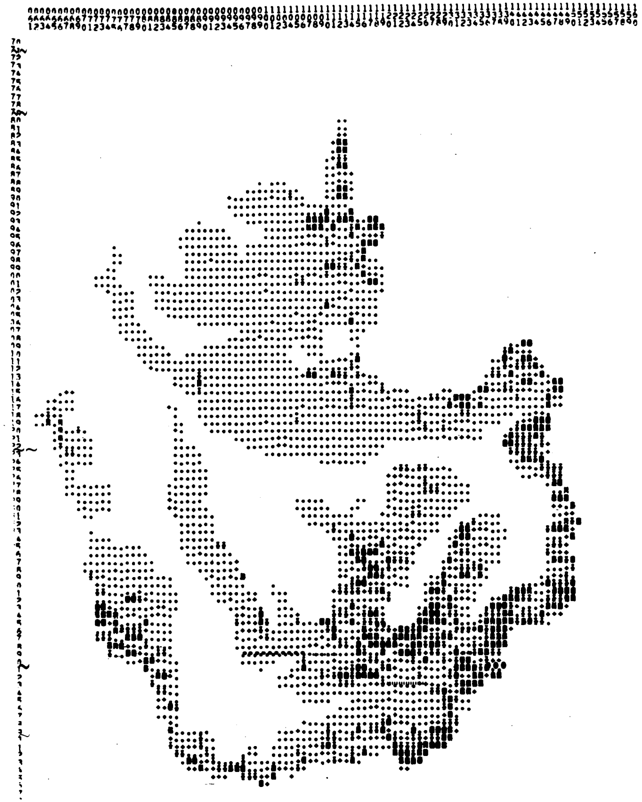

Fig. 8. Classified fractional snowcover in Landsat band 5 on July 3, 1976, for the Williams Fork Watershed, Colorado, in grey-mapped form. Six classes ranging from <20 to >79% snowcover within pixels. Original scale 1:75,000.

Before classification, the Landsat imagery is preprocessed in order to eliminate image distortion, convert data to square pixels (5.76 hectares) and overlay data on north-oriented overlays with watershed information. Accurate image registration is ensured by automatic registration of the Landsat scene with a synthetic image of Landsat Band 5 calculated from topographic and vegetation information in watershed overlays, spectral characteristics of the selected vegetation classes and solar position (Fig. 7).

The snow classifier, SNOWPCT, relies on change detection between a synthetic image calculated as being snow free and a real Landsat image in Band 5. Fractional snowcover is classified according to the radiance difference between Band 5 and calculated synthetic radiance (Fig. 8).

Update with Landsat Imagery

Suitable Landsat imagery with no to moderate cloud cover was available for 1976 only. The results from using both snow course measurements and Landsat imagery for simulation update are summarized in Table 1. The curve numbers in Table 1 refer to the relationships shown in Fig. 9. The relationship between snowcover and water content is likely to vary with location (topography) time of year and

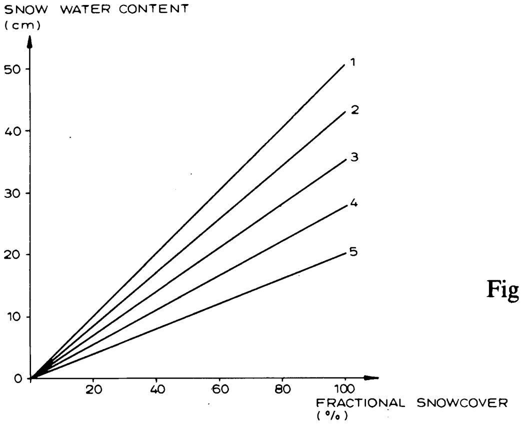

Fig. 9. Assumed relationship between fractional snowcover within Landsat pixels and the water content of the snow.

Table 1 – Summarized results from using snow course measurements and Landsat imagery for simultation update on May 1st, 1976. Williams Fork Watershed, Colorado.

Update option	Simulated runoff (mm)
1. No update or recalibration	354
2. Update with index of snow course measurements	347
3. Update with Landsat imagery using curve 2 in Figure 9	334
4. Update with Landsat imagery using curve 3 in Figure 9	325

Recorded runoff for wateryear 1976: 333 mm

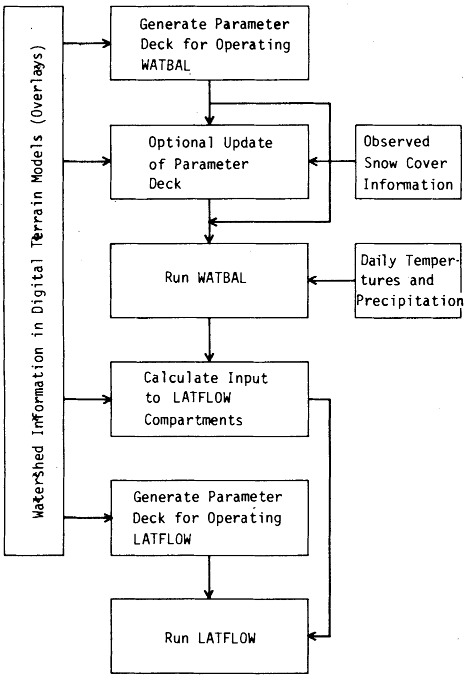

Fig. 10. Flow chart for complete simulation run including the update option.

past history of snowpack. For the update runs included here, a particular snowcover/snow depth curve from the family of curves shown in Fig. 9 was selected by comparing grey-maps of the classified Landsat image and the simulated water content. The selection can be further improved by considering the accumulated precipitation up to the date of update, storms during the late snowmelt season etc.

A flow chart of a complete simulation run including the update option can be seen in Fig. 10.

Summary and Conclusions

The computer programs and simulation models discussed in this paper can operate individually or be used together depending on the complexity of the simulation to be performed. This is attained by a modular design of the entire system and standardized input and output formats.

Calibration of WATBAL and other models (if necessary) is performed by selecting built-in calibration options. Default options will assign probable initial values to less critical watershed parameters, if these are not specified.

Although the system is developed for the simulation of high mountain watersheds in the Central Colorado Rockies, it should perform equally well in other areas with either continuous or intermittent snowcover. Update capabilities using Landsat (or lower resolution imagery) would be especially valuable in the simulation of alpine or prairie environments, where snow relocation by wind action is an important factor.

In conclusion, the spatial approach to watershed simulation is very promising. Parameter decks are generated automatically from objectively calculated parameters, and snow in Landsat imagery is »machine« classified before being used in simulation update on a pixel basis. This approach should have many applications in watershed research and mangement problems.

Acknowledgement

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