A SIMULATION MODEL OF BOULDER'S ALPINE WATER SUPPLY

774-85

by

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INTRODUCTION

Two separate but related research efforts have led to the application of a simulation model to an alpine watershed owned and operated by the City of Boulder for water supply purposes. The primary research effort is the Long Term Ecological Research (LTER) project managed by the Institute for Arctic and Alpine Research (INSTAAR) at the University of Colorado. This ecosystem research endeavor seeks to identify the principal subsystems of the alpine that determine ecological response to short and long term disturbance. As the hydrologic cycle represents a key transport mechanism for sediments and nutrients, LTER sought a hydrologic modeling framework which performed well on a gross scale yet permitted detailed investigation of specific hydrologic processes.

The second research effort, funded by the State of Colorado, sought to explore methods for more precise water supply projection. While most water supplies in the state derive from snowmelt, present volumetric estimates of availability based on snow survey data do not provide the level of detail necessary to make short term reservoir operating decisions, especially important in drought situations. The model discussed below is the result of both these research programs although the emphasis herein is placed on its' water management capabilities.

Study Area

The Boulder Watershed is a 28 square kilometer catchment located along the continental Divide 24 kilometers west of Boulder, Colorado. The watershed ranges in elevation from 2900 to 4100 meters. The basin itself is predominantly alpine with steep rocky slopes, small glaciers, and tundra vegetation. The lower third of the basin is covered with subalpine fir and Englemann spruce. As shown in Figure 1, the basin consists of two valleys each of which contains lakes and reservoirs operated for water supply purposes. At the lowest end of the watershed a diversion structure channels reservoir releases and natural streamflow into an aqueduct which feeds the Betasso water treatment plant in the foothills west of the City. A resident watershed manager operates the reservoirs in response to demands in the City.

The climate in the watershed is characterized by a winter season lasting from October to May, during which eighty percent of the 102 cm of average annual precipitation occurs as snowfall, and by a shorter summer season characterized by intense but scattered afternoon thunderstorms. The winter precipitation results primarily from Pacific frontal systems in the early season and Gulf of Mexico (or upslope) frontal systems in the late season. These latter, very moist storm systems account for most of the annual precipitation. The temperature extremes in the watershed range from winter lows of -37°C to summer highs of +19°C (Losleben, 1983).

The watershed is very well instrumented for meteorological and hydrological research. Along the northern boundary of the basin is the Niwot Ridge Biosphere Preserve, an ecological research area supported by INSTAAR's Mountain Research Station (MRS). The MRS staff maintain meteorologic stations in 8 locations within and adjacent to the watershed and operate 2 streamflow recording sites in the northern arm of the watershed. The City of Boulder, in cooperation with the State Engineer and the Soil Conservation Service, operates additional precipitation and streamflow recorders as well as 2 snow courses in the valley. Additional streamflow recorders were installed as part of the research being discussed here. The locations of these instruments are also shown in Figure 1.

Most of the meteorological stations operated by the MRS provide continuous records of temperature, relative humidity, precipitation, and shortwave radiation. Discontinuous records of wind speed and direction and of evaporation are available at some sites. This monitoring network has been in operation for nearly 30 years and a statistical analysis of portions of these records is reported in an accompanying paper (Payton and Brendecke, 1985).

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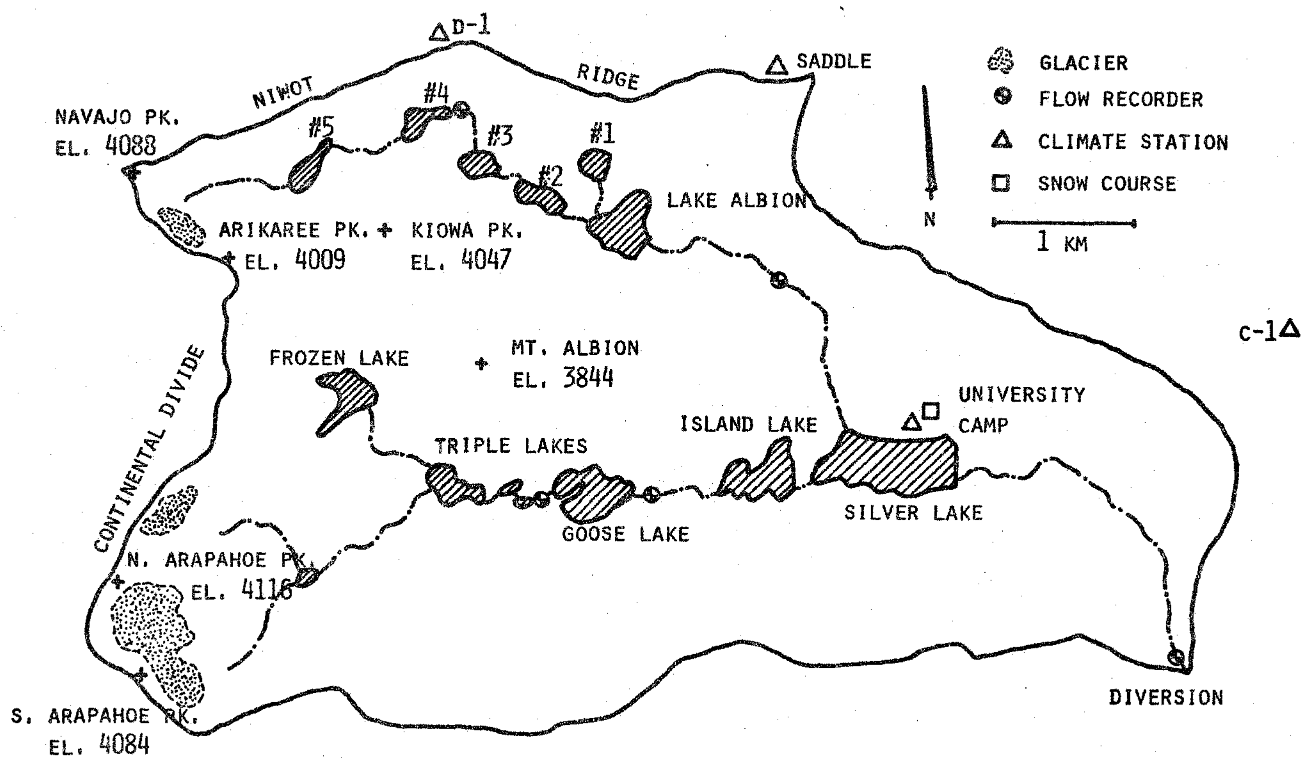

Figure 1. Boulder Municipal Watershed

The Niwot Ridge Biosphere Preserve and the northern arm of the watershed (commonly known as the Green Lakes Valley) are the site of the LTER project and are the best instrumented areas of watershed. The process of initial model selection focused on this area alone.

MODEL SELECTION AND DEVELOPMENT

Twenty-five candidate hydrologic modeling systems were reviewed for applicability to the alpine watershed. This field was screened to eight and ultimately to two based on a set of desired performance criteria. These criteria included: 1) maintenance of a continuous water balance, 2) distributed structure to allow modelling of individual watershed segments, 3) use of physically based process descriptions, and 4) the use of an energy budget approach for snowmelt computation.

The final two models compared were the Streamflow Synthesis and Reservoir Regulation (SSARR) model, obtained from the U.S. Army Corps of Engineers, and the Precipitation Runoff Modeling Systems (PRMS), obtained from the U.S. Geological Survey. These two models were compared by applying them to the Green Lakes Valley hydrologic system. Both models were found to simulate streamflow equally well, but considerations related to climatologic data requirements, ease of calibration, and simulation of reservoir operations lead to the conclusion that PRMS was to be preferred (Brendecke, et al, 1985).

PRMS Characteristics

The PRMS model is based on the concept that a watershed can be partitioned into hydrologically similar units, called hydrologic response units (HRU's) based on slope, aspect, vegetation, soil type and snow cover (Leavesley, et al, 1978). Underlying this partitioning are subsurface and groundwater reservoirs which may be common to several HRU's. The streamflow response of the basin is the sum of outputs from daily water balance computations on each HRU and the underlying reservoirs. Climatic inputs on each HRU may be computed from several climate stations in or near the basin.

Figure 2 illustrates the structure of PRMS as used in the present study. Computations up to and including generation of surface runoff are carried out daily for each HRU. Contributions to runoff from subsurface and groundwater reservoirs are then added to obtain daily streamflow.

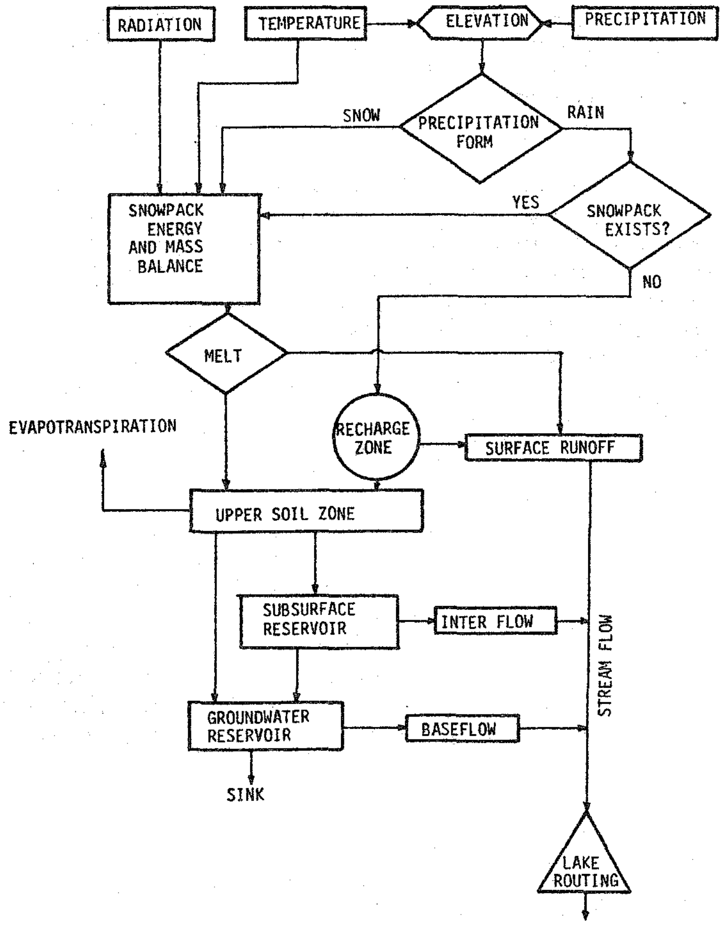

Figure 2. PRMS Flow Chart

Of particular interest in this application is the snowpack accounting procedure. In PRMS the snowpack on each HRU is represented as a two layer system. An upper surface layer exchanges heat with the environment and with the underlying pack. The transfer mechanisms considered are shortwave and longwave input, convection and conduction, longwave output (energy loss) and advection due to precipitation. An energy balance is computed twice daily and the heat content of the pack adjusted accordingly. When there is net heat added to the surface layer melt occurs which carries heat to the underlying snowpack. Once the underlying pack has been brought to isothermal conditions at freezing and the liquid water holding capacity is satisfied melt can reach the ground surface. Snowmelt becomes surface runoff only when the melt rate exceeds a user specified maximum infiltration value.

In PRMS the snowpack is assumed to be uniformly distributed over the entire HRU and melt proceeds at a uniform rate over the entire HRU. Thus, at the end of the melt season the snowcover on an HRU goes from 100% coverage to none in a single day producing a rather drastic cessation of contribution to runoff. Research is currently underway at the University of Colorado to develop a more realistic snow area depletion function which could simulate the late season existence of isolated snow patches formed by drifting.

Program Modifications

After selection of PRMS as the appropriate modeling system some program modifications were undertaken to permit a more realistic depiction of reservoir operations in the watershed (Charles, 1983). In the original form of PRMS, outflow from lake storage was computed by either linear routing or a modified-Puls algorithm based on a single storage-outflow curve. This procedure is satisfactory for uncontrolled lakes but not for reservoirs where releases might be modified on a daily basis.

Actual operation of the reservoirs in the watershed is accomplished by the watershed manager in response to water demands in Boulder and to maintain storage rights. Releases from the reservoirs are made through one or more gated outlet tubes. Releases from the older dams higher in the watershed are adjusted infrequently and are usually made to maintain storage rights or facilitate dam inspection. The age and condition of many of these outlet works discourages their operation on a regular basis. The main regulating reservoir, shown in Figure 1, is Silver Lake. The largest and newest of the reservoirs in the watershed, Silver Lake is equipped with a gas powered outlet valve and is regulated frequently to achieve the desired discharge at the diversion aqueduct two miles downstream.

Modification of reservoir release essentially implies modification of the storage-outflow curve and the reservoir routing algorithm in PRMS was rewritten to permit this. In the current version of the model each reservoir may be assigned up to three storage-outflow curves, one representing the uncontrolled spillway and the other two representing outlet discharges under a full open condition. Reductions in the full open discharge value for each outlet are then made to reflect the actual percentage opening of the outlet valve. This reduction is a non-linear function of the number of turns made to the outlet valve wheel (Sweeten, 1984). Total reservoir release is then the sum of adjusted outlet discharges plus spill, if any. When the change in storage in a day lowers the reservoir pool level below the spillway crest a further correction is made to reflect the fact that spill did not occur for an entire day. This modification of the routing algorithm thus permits realistic simulation of actual outlet operation.

A second modification was made to the reservoir algorithm to permit a demand driven release determination. Under this option, which applies only to the lowest reservoir, Silver Lake, a target diversion hydrograph is provided by the user. The predicted discharge at the diversion, which consists of uncontrolled spill and runoff originating below Silver Lake, is compared to the target value for the day and any deficit is made up by release. The model then prints out a table of release requirements to meet the target hydrograph. In this way the model can be used to actually develop operating strategies. Validation of the reservoir algorithm modifications is evident from the results of calibration and verification runs.

MODEL APPLICATION

Two basic types of data are required to apply PRMS to the Boulder Watershed, namely, data describing the watershed itself and data containing the daily climatologic inputs to the hydrologic system. The latter data set also includes observed hydrographs for calibration purposes.

Data describing the watershed itself includes watershed segmentation, hydrologic characteristics of individual HRU's, delineation of subsurface and groundwater reservoirs and their respective parameters, assignment of climate station data to individual HRU's, and description of reservoir operating scenarios. A total of 35 HRU's were defined, a somewhat larger number than would be optimally be used. The primary reason for this finer segmentation is to better allocate runoff to the various lakes and reservoirs. Areas which would normally be modeled as a single segment were divided into subareas contributing to different reservoirs. Additional segments were also used to describe glaciers and permanent snowfields.

The 35 HRU's were overlain on six subsurface reservoirs and five groundwater reservoirs based primarily on topography and geology. Initial estimates of the routing parameters for these reservoirs were made from recession characteristics of observed hydrographs made in the Green Lakes Valley.

Three climate stations were used to provide the climatologic input data. Station D-1, at the top of Niwot Ridge, provided a precipitation record for those HRU's lying above 3400 m elevation. The Silver Lake precipitation gage provided that data for the remaining HRU's. Radiation and temperature data were based on records from the D-1 climate station. Temperatures on each HRU are computed using monthly maximum and minimum temperature lapse rates determined from the 30 year temperature records at C-1 and D-1.

Model Calibration and Verification

The streamflow recorders shown in Figure 1 provide locations in the watershed where predicted and observed hydrographs can be compared for model calibration and verification. Recorders in the Green Lakes Valley have been in operation since 1981 allowing calibration to extend over two water years, 1982 and 1983. The recorders in the southern arm of the watershed were installed in 1983 allowing use of only a portion of water year 1983 for calibration there. Water year 1984 was used for verification at all recording sites.

The hydrographs for the upper basin of the Green Lakes Valley are shown in Figure 3. The upper basin encompasses an area of 227 hectares and was represented by four HRU's. Agreement between observed and predicted flows improves after the end of snowmelt in all years. This is partly explained by the hydraulic characteristics at the flow recorder. Caving in of snowbanks downstream of the recorder produces backwater effects at the gaging section sometimes flooding it completely. This results in rather dramatic fluctuations in the observed discharge. Similar problems may exist at the lower basin flow recorder.

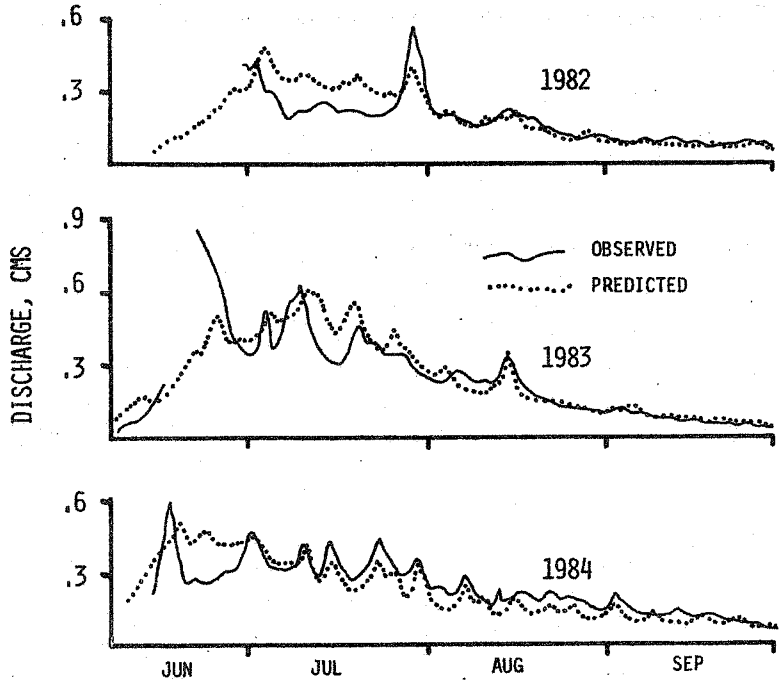

Figure 3. Upper Basin Hydrographs

Figure 4 shows the hydrographs for the lower basin of the Green Lakes Valley. The area tributary to this gage is about 481 hectares and was represented by 13 HRU's (including the four defining the upper basin). Again, agreement improves near the end of snowmelt. The operation of Green Lake No. 2 is evident in the 1983 hydrograph. The opening of the outlet value in July produced a sharp peak in the hydrograph and the closure of the outlet in August produced a sharp drop. The model appears to mimic this reservoir operation well.

The flow recorder at the diversion aqueduct provides a comparison for the entire watershed. Only water year 1983 was used for calibration there. As can be seen in Figure 5 the onset of spill from Silver Lake is predicted to occur somewhat earlier than was the true case in both years. In 1983 the error was three days and in 1984 the error was eight days. Part of the problem in 1984 may be related to the early season over prediction shown in the 1984 lower basin hydrograph. After the onset of spill the predicted and observed hydrographs agree quite well. While not shown in Figure 5, the predicted releases over the winter period (when there is not record of observed flow) hover around the 0.5 m^3/s capacity of the diversion aqueduct. Table 1 presents a statististical summary of correlations and runoff volume agreement for all three recorder sites.

Another measure of model validity is possible for the upper basin of the Green Lakes Valley. Actual observations of soil moisture budgets along Niwot Ridge were made in 1982 and 1983 as part of the LTER project. These observations can be compared to the predicted soil moisture storage for the upper basin of the Green Lakes Valley, an area with similar soil development. Although the field capacity estimates used in the model are about 20% lower than those estimated for the Ridge, a dimensionless plot of the predicted and observed soil moisture storages, shown in Figure 6, demonstrates good agreement between the two. This validation of the soil moisture component of the model is especially important to the LTER project.

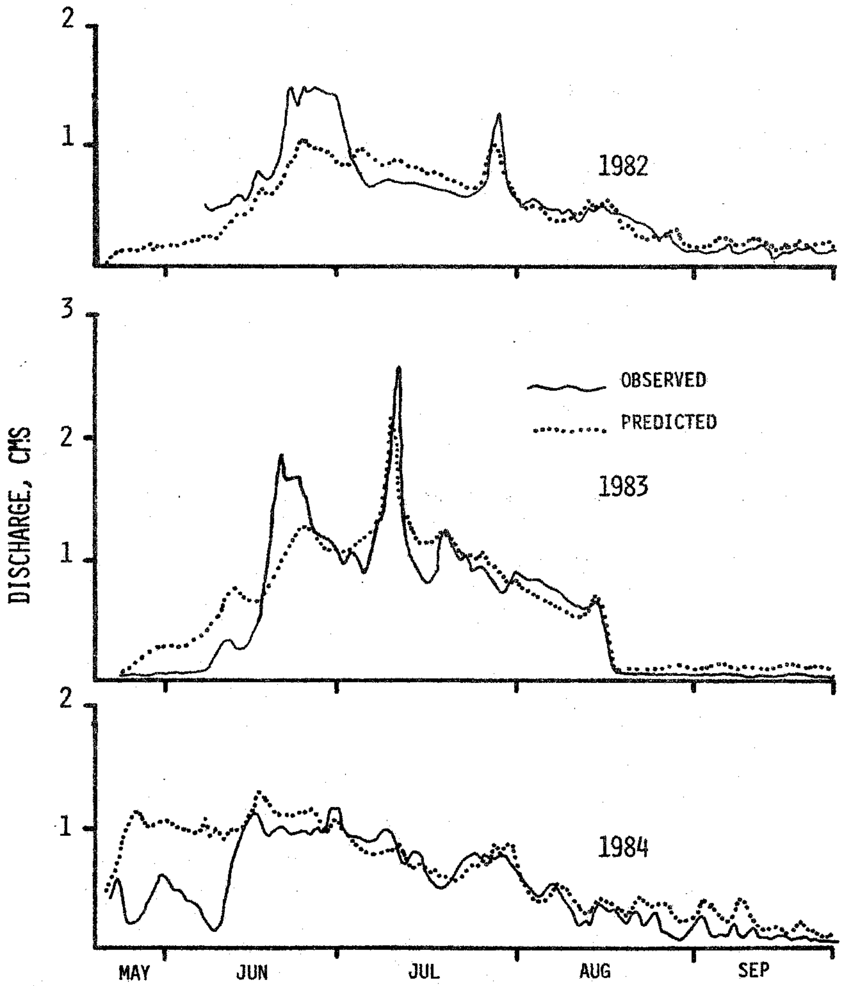

Figure 4. Lower Basin Hydrographs

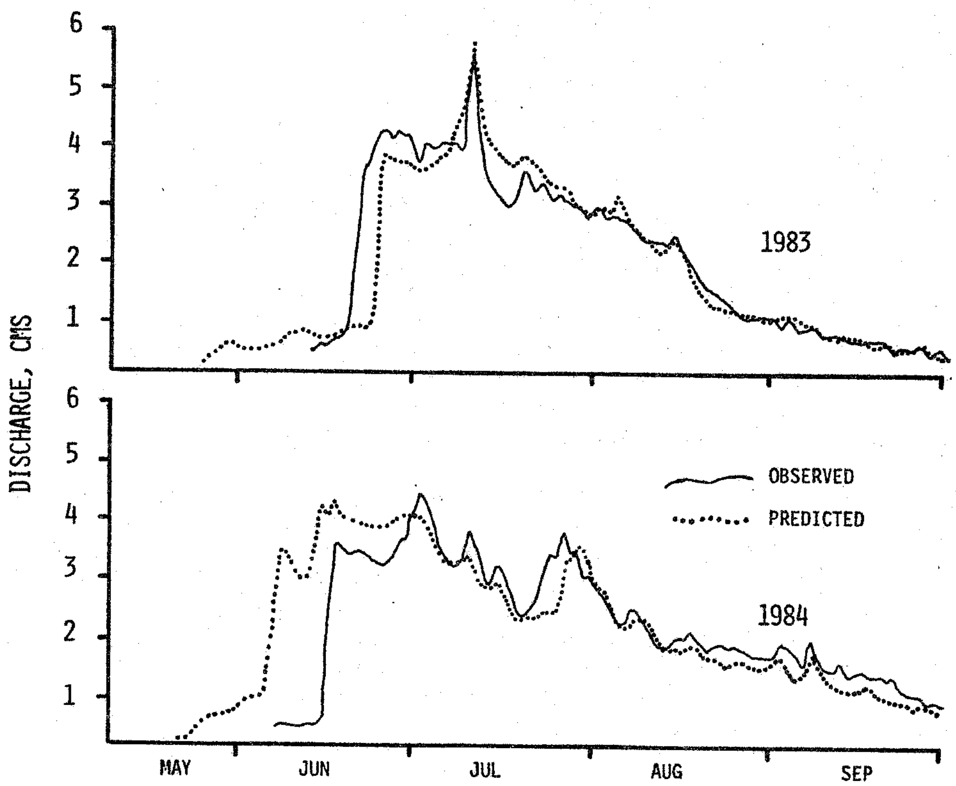

Figure 5. Diversion Flume Hydrographs

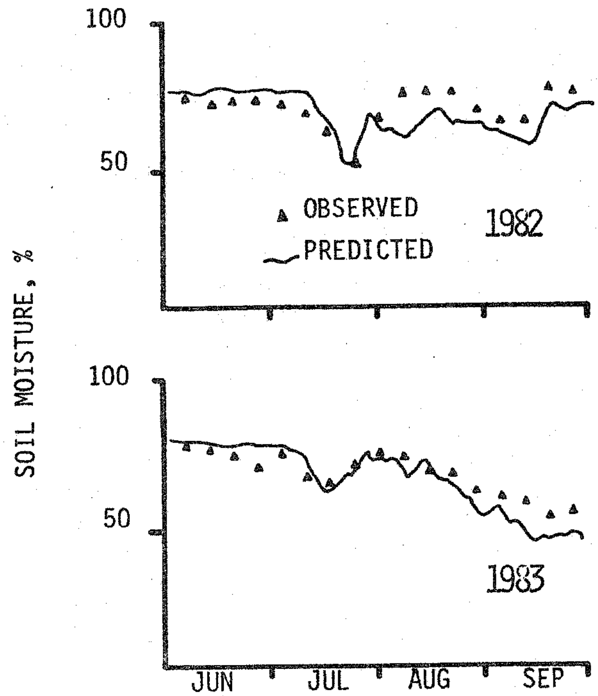

Figure 6. Soil Moisture Storage

Table 1

Statistical Summary
Daily Streamflow Correlation[1] and Runoff Volume Agreement[2]

Year		Upper Basin	Lower Basin	Aqueduct
1982	correlation	.75	.79	
	volume	111%	93%	
1983	correlation	.81	.89	.92
	volume	105%	113%	98%
1984	correlation	.72	.69	.62
	volume	93%	134%	107%
all	correlation	.77	.80	.80
years	volume	102%	113%	103%

[1]Correlation between predicted and observed daily flows where observed record exists. All are significant to $p < .01$.

[2]Predicted volume/observed volume as %.

USES OF THE WATERSHED MODEL

As stated at the beginning of this paper, two research goals have driven the development of the Boulder Watershed Model and, as a result, two general areas of application exist, namely, water supply management and ecological research.

Potential water supply management applications of the model include analysis of reservoir operating strategies, evaluation of proposed additions to reservoir storage, and assessment of watershed manipulation such as snowpack augmentation. With respect to reservoir operating strategies, the model can answer two types of questions, i.e., what are the effects of a given set of operating scenarios, and what operating strategy is needed to provide a predetermined discharge hydrograph at the diversion. These questions are likely to arise in the context of drought contingency planning and hydropower generation. Reservoir operations under drought conditions can be analyzed using the model by initializing basin conditions, e.g. reservoir storage and snow water equivalent, and predicting snowmelt and streamflow based on short and medium-range weather forecasts. In this way projected runoff and reservoir operating strategies to maximize water availability can be updated on a weekly basis.

The City of Boulder is currently installing hydroelectric turbines in several of its raw and treated water pipelines to utilize the large amounts of potential energy available due to the elevation difference between source areas and the city itself. Presently much of this energy is dissipated through pressure reduction valves. Once these turbines are in place the operation of the City's entire water supply network must be analyzed on a system basis. A system wide optimization study is likely to indicate general release patterns from the watershed and the Watershed Model can then be used to determine specific reservoir operating scenarios to provide those optimal system inputs.

The current methods of operating many of the reservoirs in the watershed do not take advantage of the storage available in the watershed. Reservoirs which are not operated each runoff season essentially represent unused storage. The watershed model can be used to determine the increased yield that would result from more frequent operations of these reservoirs and could indicate the prioritization of outlet works rehabilitation projects. The model can also be used in a similar manner to determine yields from additions to storage.

Suggestions have been made that watershed yield might also be enhanced by land use manipulation. Examples of this are snowpack augmentation via artificial enhancement of drift formation and runoff generation by selective clear cutting. As discussed in an accompanying poster paper (James and Brendecke, 1985), the dry winds common along the Front Range result in significant redistribution of snow and may produce substantial water loss to sublimination. The construction of snow fences to encourage drift formation and the initiation of avalanches to compact and concentrate snow accumulation might result in the retention of more moisture higher in the watershed producing a longer lasting reserve of snowmelt runoff. The increased yields from these and other watershed manipulations can also be simulated by the model.

Ecological research applications of the model revolve around the prediction of moisture storage and flux. The hydrologic cycle represents a major transport mechanism for nutrients in the alpine and thus provides a fundamental basis for plant and animal community development. Preliminary LTER research suggests that there may be significant relationships between phenology and population dynamics and the throughput of moisture in the alpine tundra system.

Continuing research to improve the model's applicability to the watershed is focusing now mainly on snow accumulation and ablation, with particular reference to wind effects, and on soil moisture movement, where storage, snowmelt infiltration, and freeze-thaw characteristics may be important. These improvements will enhance the applicability of the Boulder Watershed Model for both water supply management and ecological research.

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