COMPUTER MODELING SNOW RELATIONSHIPS IN THE BIG EAU PLEINE WATERSHED, WISCONSIN

by

Mike Marano

A Thesis
submitted in partial fulfillment
of the requirements for the degree
MASTER OF SCIENCE

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ABSTRACT

To reduce problems in computer modeling the Big Eau Pleine Reservoir's winter oxygen conditions, it was considered desirable to have an index of solar radiation penetration through snow. To accomplish this, eleven measurements of solar radiation penetration through snow and ice were performed during the 1976 and 1977 winter using a Whitney submarine photometer and Thornthwaite net radiometer. A series of equations were obtained from literature and used to calculate both the reflectivity (albedo) and extinction coefficient of snow based on snow density. A comparison of these calculations with the field data showed a strong correlation for solar radiation penetration through snow (r = .961) and a slightly lower correlation for albedo (r = .928). Since a significant relation (alpha = .05) was obtained in applying these equations, it was decided to combine them with a snow model so as to obtain a predictive tool of light penetration through snow.

Two snow models, capable of calculating snow density, were obtained and calibrated for the winter periods of 1974 and 1975. Model calibration data was obtained from the Wisconsin Valley Improvement Company and consisted of snow data collected biweekly from a snow course within the Big Eau Pleine watershed. The two snow models selected were the LEAF (Leaf and Brink, 1973) modified according to Soloman (et al, 1976) and the NPS (Donigian and Crawford, 1976). To maintain objectivity a computer controlled optimization

technique (Monroe, 1971) was employed. For a stability test the models were run over an additional two year period (1976 and 1977). A comparison of results from the simulations and snow course data showed the NPS model was superior ($r = .945$, $s = .316$ in., $n = 36$) to the LEAF model in simulating conditions within the watershed.

Based on this superiority the NPS model was recalibrated with snow data collected on the reservoir during 1977. Comparing the calibration simulation with the field data showed good correlations for water equivalent ($r = .978$, $s = .109$ in., $n = 19$), snow depth ($r = .964$, $s = 1.112$ in., $n = 19$) and snow density data ($r = .957$, $s = 3.16\%$, $n = 19$).

Once calibrated the NPS model was used to simulate the previous three winters. Output from the simulations was then utilized in conjunction with the solar equations to calculate solar radiation penetration through snow. Although limited data was available and ignoring the minimal effects of an ice cover, initial research shows a reasonable correlation ($r = .881$, $n = 10$) between the solar radiation calculations and average surface chlorophyll a concentrations within the reservoir during the 1976 snow accumulation season.

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INTRODUCTION

Background

Water resources are considered a finite resource that requires protection by law to be available for future needs. Recognizing the scarcity of the resources, Congress has enacted measures to convert or maintain all waters in a fishable and swimable condition. This implies people are demanding improved natural resources that can provide a multiple function. In comparison to the previous decade, the economy of our overall nation requires fewer hours of employment to fulfill the needs of the average citizen, allowing an increased amount of time for recreation. The resulting recreational time is being spent enjoying the various forms of our water resources. With the increased used of the resources, there is also an increased recognition of the problems associated with our water resources. In particular, more people are becoming aware; hence, questioning the cause or source of problems such as prolific aquatic plants, nuisance algal blooms, unpalatable game fish or enigmatic fish kills that occur in some waters. Awareness by itself does not provide a solution to these persistent problems, but does provide the foundation for developing a remedy.

The Big Eau Pleine Reservoir (BEP)

The Big Eau Pleine Reservoir (BEP) is a water body that experiences two of the above problems. Constructed in 1939 and located in Marathon County, Wisconsin (Figure 1),

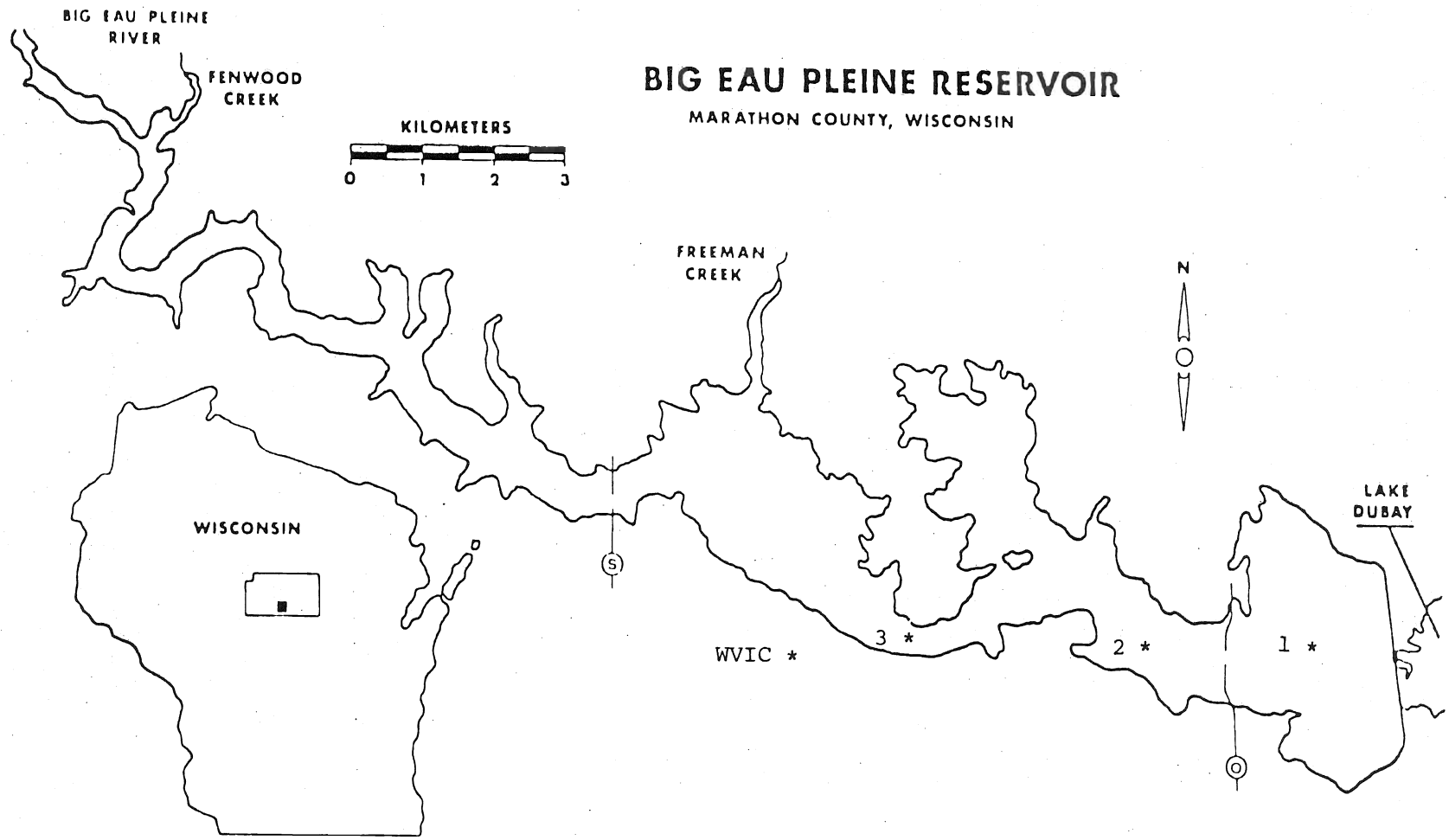


Figure 1. The Big Eau Pleine Reservoir indicating sample sites.

the BEP has experienced frequent winter fish kills (Shaw, 1976) and dense summer algal blooms (Sullivan, 1978). Constructed primarily for flow augmentation of the Wisconsin River, the BEP undergoes dynamic annual volume changes. The reservoir can obtain a maximum volume of 4457 MCF and a minimum volume of 60 MCF by late winter, resulting in approximately 98% of the reservoir's volume being diverted to flow augmentation of the Wisconsin River.

Both the drastic drawdown and corresponding rapid recharge influence the nutrient levels and dissolved oxygen within the reservoir. The process of drawdown causes scouring of bottom sediments resuspending particular material that can release nutrients and consume dissolved oxygen (Swalby, 1978). Spring refill, reversing the process of drawdown, provides similar physical effects.

The nature of the Eau Pleine watershed compounds the effects of spring runoff. A high concentration of dairy farms results in 75% of the 365 square mile watershed being used for agricultural requirements (Kaminski, 1977). Gentle rolling hills and fine textured soils along with the high agricultural use produce a rapid watershed response in the form of surface runoff, during periods of heavy rain and spring snowmelt. Nitrogen and phosphorus concentrations in the runoff are responsible for a large portion of the nutrient levels within the reservoir (Shaw, 1976).

In general, the high spring nutrient levels in the reservoir help promote dense summer algal blooms. To complete the cycle, the degradation and respiration of the

summer algal populations coupled with drawdown induce low winter dissolved oxygen levels producing periodic winter fish kills. The occurrence of a fish kill is a function of the rate and timing of winter drawdown and the amount of organic matter, viable and inviable, in the reservoir waters and uppermost sediments.

Past and Ongoing Studies

In the past years a number of research projects have been concerned with the Big Eau Pleine Reservoir and watershed. The projects include a 1972 study by the U. S. Environmental Protection Agency National Eutrophication Survey regarding the factors producing the reservoir's trophic state and studies by Kaster (1976) and Buchanan (1976) ascertaining the impact of drawdown on aquatic macroinvertebrate and zooplankton communities. More recently various aspects of the reservoir and watershed have been studied with greater intensity by graduate students at the University of Wisconsin, Stevens Point.

In regard to the watershed, research has involved hydrological modeling (Elbert, 1977) in conjunction with soil erosion modeling (Kaminski, 1977) and land use and cost analysis for implementing conservation practices (Hansen, 1979). Two studies still in progress are concerned with the amount of nutrient loss from land disposal of cheese factory wastewater (Pilger, 1979) and the efficiency of farm ponds in trapping nutrient and sediment runoff from agricultural land use (Linskens, 1979).

The various reservoir studies have had the overall objective of utilizing computer modeling techniques to provide both reservoir and watershed alternative management recommendations. Separate reservoir studies contributing to the overall objective include characterization of the phytoplankton and nutrient dynamics (Sullivan, 1978), delineating the biochemical oxygen demand with respect to time and source (Swalby, 1979) and evaluating sediment oxygen demand as a function of temperature and parent material (Hammermeister, 1979). Utilizing the base information provided by the above studies, further research includes the construction of computer data manipulation systems for the watershed and the reservoir, in addition to the development of a computer program to calculate the water budget for the reservoir (Vennie, 1978) and application of hydrological and limnological models to the reservoir (O'Flanagan, 1979).

Purpose of the Present Study

Computer modeling efforts for the Big Eau Pleine Reservoir consist of implementing the computer package LIMNOS. LIMNOS contains three programs, CLIMA, TERMA and AQUA (Baca, 1977). According to Baca, CLIMA organizes the basic meteorological and hydrological data, utilizing this data to calculate incident solar radiation and prepares output files to be used by TERMA. TERMA, using the output from CLIMA, calculates the reservoir's hydraulic and thermal regime to be used as input for AQUA. Finally, AQUA performs the limnological calculations for the simulation period.

An examination of these programs showed a potential problem could occur in simulating winter oxygen levels. TERMA calculates ice formation and uses the Lambert-Beer relationship to attenuate incident solar radiation when an ice cover is present. The reduced solar radiation is then used by AQUA in calculating photosynthesis. Unfortunately, TERMA does not contain algorithms to account for snow accumulation; hence, it ignores snow as an influencing factor in photosynthesis. Berg and Magnuson (1970) have shown that snow can have a considerable effect in reducing algal photosynthesis through light limitation. Since central Wisconsin has a snow cover present most of the winter months, simulations performed by these programs would overestimate dissolved oxygen levels within the reservoir during winter. In an attempt to eliminate the snow cover problem, this study was concerned with determining an index to solar radiation penetration through snow that could be used by TERMA on a daily basis.

METHODS

Theory

Solar Radiation

The process of solar radiation penetration through snow has been the interest of many studies. As early as 1945, Greenbank in his classical paper proposed that snow was a major factor in contributing to winter fish kills. Since that time numerous investigations have been conducted in an attempt to evaluate this process.

In these investigations of solar radiation penetration through snow, for simplicity, it is usually assumed that the Lambert-Beer law can be used to describe the behavior of snow (Gerdel, 1948; Mantis, 1951; Thomas, 1963; Mellor, 1966; Williams, 1969; O'Neill and Grey, 1973; Anderson, 1976).

$$Iz = Io \cdot \exp(-V \cdot z) \quad \text{(Lambert-Beer Law)} \tag{1}$$

Where:

Iz = net solar flux ($ly \cdot sec^{-1}$)

Io = net solar flux at the surface ($ly \cdot sec^{-1}$)

V = extinction coefficient (cm^{-1})

z = depth (cm)

This implies that snow has the properties of a homogeneous diffusing medium. Snow has these properties in the case of rapidly created deep snow covers (Gerdel, 1948; O'Neill and Grey, 1973). Although when a deep snow cover forms slowly,

developing layers with different optical properties observations deviate from the Lambert-Beer law (Giddings and LaChappelle, 1961; O'Neill and Gray, 1973). Shallow snowpacks, which tend to be more homogeneous, will deviate from this rule when present over soil (Anderson, 1971). In this situation, part of the solar energy, absorbed by the uppermost soil layer, is returned to the snow cover by conduction. But, with a shallow snowpack present over ice the validity of the Lambert-Beer law has been confined within experimental error (Maguire, 1975).

Assuming the validity of the Lambert-Beer law, Gerdel (1948), Thomas (1963), Bohren and Barkstrom (1974) showed that the extinction coefficient decreased as snow density increased. In addition, Bohren and Barkstrom developed a theoretical relationship for the extinction coefficient of snow based on snow density and grain size, and an expression for albedo under diffuse illumination as a function of snow grain size and the extinction coefficient for clear ice.

Anderson (1976) using these relationships developed an empirical equation for snow grain size based on snow density and then expressed the extinction coefficient in terms of both snow density and snow grain size. Combining equations, Anderson used the following relationships to calculate solar radiation penetration through snow in his point energy and mass balance model

of a snow cover.

$$ds = G_1 + G_2 \cdot Ps^2 + G_3\ Ps^4 \qquad (2)$$

$$As = 1.0 - 0.206 \cdot CV \cdot ds^{\frac{1}{2}} \qquad (3)$$

$$Io = Ii \cdot (1.0 - As) \qquad (4)$$

$$Iz = Io \cdot \exp\ ((-CV \cdot Ps \cdot ds^{\frac{1}{2}}) \cdot Z) \qquad (5)$$

Where:

ds = snow grain size (mm.)

Ps = snow density ($gm \cdot cm^{-3}$)

As = decimal fraction albedo of the snow cover

Ii = incident solar radiation flux at the surface ($ly \cdot sec^{-1}$)

Io = net solar radiation flux at the surface ($ly \cdot sec^{-1}$)

Iz = solar radiation flux at depth z ($ly \cdot sec^{-1}$)

Z = depth at which the solar radiation flux is to be calculated (cm)

CV, G_1, G_2 and G_3 are location dependent constants. By trial and error Anderson determined the values for the constants based on snow surface density and albedo measurements.

Maguire has shown that the overall extinction coefficient and thickness of a composite medium such as ice and snow is equal to the sum of the individual states. Furthermore, he states that reverse reflection at interfaces between different media is insignificant within experimental error. Since this study was concerned with snow over an ice cover, it was possible to use Maguire's work in determining the solar flux at the snow-ice interface by subtracting the affects of the ice media from the solar flux measured beneath the ice cover.

Knowing the solar flux at both the surface of the snow cover (Io), and at the ice-snow interface (Iz-snow), the albedo (As), depth (Z) and density (Ps), of the snow cover, it was possible to use the previous equations and calculate the values for the four constants based on both As and Iz-snow. The calculations were simplified by using an optimization technique (Monroe, 1971) programmed for a Burroughs 6700 computer. The criteria used for initial optimization was squared sum of both, the sum of the squares of the difference between observed and calculated As and Iz-snow, i.e.:

$$\left(\sum (Aso - Asc)^2 \right)^2 + \left(\sum (I_{zo} - I_{zc})^2 \right)^2$$

Where: As = Albedo of the snow cover

Iz = solar flux at the ice-snow interface

o = observed

c = calculated

To reduce the problem of snow density fluctuations with depth at point measurements and improve the determination of the coefficients, the snow cover was sampled vertically in 5cm intervals. Since the uppermost layer was used to calculate CV based on albedo, this procedure provided a stronger test for the soundness of the three equations. Since the results of the first layer calculations were used in calculating the lower layer's solar flux, any discrepancy in the first calculation would be magnified by the additional calculations and produce a larger variation between observed and calculated solar flux beneath the snow cover.

Application

In addition to solar radiation measurements, three snow courses were sampled periodically during the 1977 winter for snow depth and snow density. These measurements were used to calibrate a computer snow accumulation and melt model. Output from the snow model included daily simulation of snow depth and density. These results were used in the previous three equations to calculate the solar flux beneath a snow cover on a daily basis. The end product of these calculations were then used as input data for the reservoir models.

Solar Radiation

Introduction

Eleven complete experiments measuring solar radiation penetration through snow and ice were made during the 1977 winter. The experiments were made under various snow conditions. Due to meteorological and equipment limitations, only one experiment could be conducted per sampling date. The previous limitations, mainly equipment, reduced the success of the overall project. Where an experiment was not totally completed, approximately 40% of the cases, the results were disregarded.

Equipment

Solar radiation penetration through snow and ice was measured with one of three Whitney Submarine Photometers (Montedoro Corp. Model LMT-8A). Winter sampling rapidly

deteriorates electronic equipment of this nature. Therefore, it was necessary to take two units out in the field, one to be used as a replacement, while the third was generally in transit to be repaired.

The Whitney submarine sensor was fitted with a weighted styrofoam float (Reid, et al., 1975). When inserted under the ice cover, this resulted in the incident sensor floating in an upright position tightly against the ice cover.

A Thornthwaite net radiometer (Thornthwaite Assoc. Model MNR522) was used to measure the albedo of the snow or ice cover. The sensor for this meter was fitted with a bubble level to insure the uniformity of measurements. An opaque cap was constructed to cover the lower sensor when measuring incident solar radiation. This particular instrument proved to be very durable in the field and a replacement unit was not required.

To reduce the effect that large fluctuation in air temperature has on electronic equipment, the instruments were stored at -10C when not in use. In particular, this facilitated the use of the Thornthwaite meter, since the sensors require a positive air pressure to maintain their spherical shape.

Procedure

Solar radiation measurements were conducted on cloudless or completely overcast days, between 10:00 a.m. and 2:00 p.m. This procedure was an attempt to standardize measurements and reduce the effects that fluctuating light conditions have on

duplication of measurements (Dirmhirn and Eaton, 1975). In addition, the time restriction reduced the variability in measurements produced by a changing snow cover (Frolov, 1963).

Both the submarine photometer and net radiometer were standardized in the field. The submarine sensor was attached to a three meter flexible probe and inserted beneath the ice cover. Measurements were made at two and three meters from the insertion hole. An opaque shield was used to identify the location of the sensor. Once these measurements were completed, snow depth was recorded and snow samples were obtained vertically at 5 cm intervals for snow density determinations. After the snow cover was sampled at both locations, a circle, radius 3 meters, enclosing both locations was cleared of snow. The ice was carefully brushed clear of remaining snow and the solar radiation measurements were repeated. Finally, a hole was drilled through the ice at both locations and ice thickness was determined. The averages of the measurements at the two locations represented the results of one experiment.

Albedo measurements were made before and after the submarine photometer measurements. Measurements were made 1 meter above the snow or ice cover.

Snow Data

Basin

Wisconsin Valley Improvement Corporation (WVIC) maintains several snow courses within the Wisconsin River basin. The snow courses are used in estimating spring

runoff events and anticipating storage requirements for the various impoundments within the basin. Data collected from the snow course adjacent to the Big Eau Pleine Reservoir (Figure 1) was used in this study to test the stability of two snow accumulation and melt models.

The snow course is located in an upland mixed hardwoods stand (6 to 10 in dbh) consisting primarily of oak (Quercus) species and maple (Acer) species with sparse understory. The course is laid out in a staggered circle enclosing approximately two acres. Twelve steel stakes, roughly 100 feet apart, are located on the perimeter of the circle and used to mark the sampling stations.

WVIC has sampled the snow course biweekly at the 12 stations, four measurements of snow depth and density per station. The measurements were made with a Friez tube and Friez Baltimore scale. Data collected by WVIC was obtained for the time period of December 1973 through April 1977. Values were averaged for each sample period and used to compare the two snow models.

Reservoir

Introduction

The measurement of snow cover water equivalent is difficult due to the relationship between snow accumulation and local wind conditions (Cox, 1975). Typical snow courses located in semi-wooded areas, are affected minimumly from wind fluctuations, and tend to have a uniform distribution of snow (Anderson, 1972). In contrast, a snow course located

in large, open areas is affected from scouring and drifting producing a variable snow cover during even moderate wind conditions (Kakela, 1971). Since snow cover water equivalent is a function of snow depth and snow density, factors increasing the variability of these parameters will increase the variability of water equivalent measurements.

In developing a snowpack sampling scheme designed on the basis of an acceptable level of error in determining average water equivalent, Dickenson, et al (1971) has shown that although snow depth is highly variable, requiring a large number of observations, snow density varies within a narrow range and hence requiring a relatively small number of observations. Similarly, McKay (1968) has recommended the use of fewer snow density observations and a greater number of snow depth measurements as a means of maximizing the amount of information collected while minimizing the financial expenditures.

To reduce the problem of a variable snow cover multiple measurements of snow depth were made along with duplicate measurements of snow density. Due to time, accessibility and equipment, it was not possible to completely random sample the whole reservoir. To circumvent this problem, subareas were chosen that in practicality would best represent the whole and these were then randomly sampled in detail.

Criteria for Subarea Selection

The Big Eau Pleine Reservoir is drawn down during the winter to augment the Wisconsin River flow. As this process

continues, an increasing percentage of the reservoir's storage capacity is located in the lower reaches while the upper reaches revert back to the original river channel. To maintain subareas representative of the majority of the winter reservoir area, sampling was concentrated in the reservoir's lower reaches.

Subarea selection was designed to account for the following problems:

1. Weather station snow gauges are affected by wind and tend to underestimate snowfall.

2. The reservoir's lower section is windswept; hence, less snow would tend to accumulate there.

3. The reservoir's middle section is predominately surrounded by trees which could reduce the effects of wind action.

4. As the reservoir's water level descends, ridges and contours appear which could influence a subarea by either sheltering it from the wind or producing a funneling effect.

Description of Subareas

Three subareas were chosen for extensive measurements of snow depth. To facilitate discussion, these subareas will be referred to as sites 1 through 3. Since the reservoir is usually partially drawn down prior to freeze-up, surface areas of the sites were compared to the 10 foot contour level of that particular section of the reservoir.

Site 1 was located essentially in the center of the first section of the reservoir (Figure 1). Ten rigid cylin-

drical snow posts were placed in a circle at this site. The diameter of the circle was 15 meters (m) and the posts were about 5m apart from each other. Three posts were located over the original river channel. Since the site was unprotected, snow loss due to wind should have occurred. When including the area of random sampling, the surface area of site 1 represents 2.3% of the effective area of the reservoir's lower section.

Site 2 was located on a 25 foot contour in the reservoir middle section (Figure 1). This site could be considered a control sample for site 3 as stage levels reach their minimum. By placement on the 25 foot contour, site 2 could be considered situated on a plateau at maximum drawdown. The plateau was large enough that other contours and ridges should not have influenced snow deposition. This would prevent the accumulation of additional wind blown snow during minimum stage levels. Eight rigid cylindrical snow posts marked the center of this site. The posts separated by 4m were arranged in a circle with a diameter of 10m. Considering the effects of random sampling, this site's surface area represents .5% of the reservoir's section 2 surface area.

The location of site 3 was partially over the original river channel (Figure 1). Drastic changes in water level could affect snow deposition due to the sheltering effect of contours and ridges. The site was chosen to monitor the effect of a deep snowpack on the ice cover. Seven rigid cylindrical snow posts were placed in a staggered line to obtain maximum coverage. The site's surface area including

the area covered by random sampling represents .5% of the reservoir's section 2 surface area.

Equipment

Typical snow sampling equipment (CRREL tube, ILTS box cutters, Friez tube, etc.) require obtaining a soil plug with a snow sample (Ferguson and Pollock, 1971). The soil plug holds the snow sample within the tube. When sampling snow over an ice cover, this procedure was not possible hence, a different type of snow sample had to be constructed. Differing only slighly from a CRREL tube, the aluminum sampler (2 in ID x 24 in) constructed had a slot formed at the base. The slot was fitted with a stainless steel plate shaped to fit the inside diameter of the tube. Normal operating procedures were to insert the sampler vertically in the snow cover, insert the plate into the sampler's base and remove the sampler. The plate prevented the loss of snow. Since the tube had a measureable volume of snow, to calculate snow density the sample was saved for weight determination. Snow density was recorded as: weight of snow divided by snow volume.

The snow courses were constructed of 30 in by 2 in ID white PVC pipe inserted vertically in the ice cover. The pipes had a linear scale constructed the full length corrected for ice thickness at the point of insertion.

Sampling Procedure

The three sites were sampled for snow depth extensively

between the months of December 1976 to March 1977. All sites were sampled the same day. Snow depth could not be measured directly from snow posts. Even though the snow posts were smooth and cylindrical, by the middle of winter snow had accumulated on the leeward side of the post. Snow was scoured on the snow posts windward side. To prevent bias in measurements, use of the snow post was discontinued.

Snow depth was measured along two transects whenever the sites were sampled. One transect ran north and south, the other east and west. Twenty-five snow depth measurements at equal intervals were made along each transect. The snow depth was measured with a meter stick and recorded to the nearest centimeter. Distance between measurements was determined prior to arrival at site. Starting point of transects was determined independent of surface topography and was not the same between any two consecutive sampling sessions. The purpose of these procedures was to insure that the effect of snow drifting would be included in the snow depth measurements.

Snow density and snow water equivalent were measured at each site. Using the snow tube, duplicate samples of snow were obtained from the area within the circle formed by the snow posts. In the case of site number 3, snow samples were taken adjacent to the mid-snow post. The snow sample of known volume was placed in a pre-weighed plastic bag, sealed and returned to the laboratory. It was then weighed on an analytical balance to the nearest .01 gram. After subtraction of bag weight, the snow density was recorded as grams per

cubic centimeter. Water equivalent was recorded as simply density times mean snow depth.

Statistical Procedures

Statistical procedures are useful in evaluating relationships between two or more conditions. This is especially true when evaluating the performances of computer models. Computer models simulating natural processes by mathematical procedures seldom duplicate the natural processes completely. Hence, a judgment has to be made regarding the accuracy of the simulation. In this study judgment of this type was based on correlation and regression analysis.

The two statistical tests were performed through the use of the "Minitab" computer statistical program (Ryan, et al. 1976). The results of the correlation and regression analysis are presented throughout this paper.

Computer Modeling

Introduction

Two snowmelt models were selected for use in this study based on their input data requirements and their output specifications. In addition, model selection was also based on the inclusion or the ability to include snow density calculations within the framework of the program. The two snowmelt models selected were LEAF (Leaf and Brink, 1975) and NPS (Donigian and Crawford, 1976). To maintain objectivity in calibration procedures, both models were restructured to include the Monroe optimization technique.

LEAF Model

The LEAF model requiring a minimum amount of input data (Table 1), was modified for a shallow snowpack (Soloman, et al 1976). The thermal diffusion solution technique suggested by Soloman (and others) was not used due to insufficient documentation. Alternatively, the original thermal diffusion subroutine (Leaf and Brink) was modified to operate on an hourly basis instead of a 12-hour schedule. This was to insure mathematical stability for a shallow snowpack (less than 4.7 in. water equivalent). Additional modifications were to include a relationship for snow compaction (Hydrocomp, 1976) and a coefficient to compensate for catch deficiencies in rain gauges (Cox, 1975).

Table 1. Type of meteorologic input data required by the snow models (English units).

Type of Data	Leaf Model	NPS Model Original	NPS Model This Study
Solar Radiation	Daily	Daily	Daily
Precipitation	Daily	Hourly	Hourly
Temperature	Min-Max	Min-Max	Hourly
Wind Speed	*	Daily	Hourly
Dewpoint	*	*	Hourly

*Not Required

NPS Model

The snow algorithims present in the Nonpoint Source Pollutant Loading Model (NPS) (Donigian and Crawford, 1976) were separated from the main program and used in this study. Although the snow algorithims are actually only a submodel of the NPS main program, to clarify their source, they are referred to within this text as the NPS model.

Mathematically the snowmelt algorithims used in the NPS model are identical to those used in the HSP (Hydrocomp, 1976) and ARM (Donigian and Crawford, 1975) models. As such the NPS model represents a modified version of the STANFORD WATERSHED models (Anderson and Crawford, 1964; Crawford and Linsley, 1966). Additional versions of the STANFORD WATERSHED models have been published by James (1968), Claborn and Moore (1970), Ricci (1972), NWSRFS (1972) and Striffler (1973), but for the most part these were essentially FORTRAN translations of the hydrological model. In terms of snow, the major differences between the NPS model and the STANFORD WATERSHED Models (and the various translations) are the energy exchange calculations. The STANFORD WATERSHED Models used air temperature as the sole index to energy exchange (Anderson, 1976). The NPS model incorporated additional snow equations and input data, utilizing an energy balance method for the energy exchange processes (Donigian and Crawford). These equations and the basic snowmelt algorithims used in NPS were developed from the work of the Army Corps of Engineers (1956), Anderson and Crawford (1964),

Crawford and Linsley (1966) and Anderson (1968). Where quantitative equations were not available, empirical relationships were employed (Hydrocomp, 1976).

The input data that the NPS model originally required is shown in Table 1. Since precipitation was required hourly, to improve simulation results (Hydrocomp, 1976) the NPS model was modified to accept air temperature and wind speed on an hourly basis.

Dew point temperatures, calculated from minimum air temperature (Franc, 1974), were used to determine snow evaporation and whether precipitation was in the form of snow or rain. To improve the accuracy of these determinations (Hydrocomp, 1976), the NPS model was modified additionally to accept hourly dew point temperatures.

Documentation and Verification

The purpose of this study does not include the defense of one model in preference to another or one mode of calibration in favor of an alternative. Rather, this study was concerned with determining which of two models was more applicable in the present situation and utilizing that model as a predictive tool. Calibration procedures were chosen based on convenience, reliability and objectivity. Sources for additional information such as mathematics, logic, coefficient descriptions, and program applications are listed below.

Documentation for the LEAF model has been published by Leaf and Brink (1975) and Soloman, et al (1976). The

documentation includes a presentation of the major snow algorithims, program listing and a test data set. The two additional equations obtained from Hydrocomp (1976) and inserted in the program for this study were:

$$AMTSNOW = AMTSNOW \cdot SCF$$

Where:

AMTSNOW = water equivalent of the precipitation that occurred in the form of snow (in)

SCF = snow correction factor used to compensate for catch deficiency in rain gauges when precipitation occurs as snow

and for snow compaction:

$$DEPTH2 = DEPTH\ 1 \cdot (1.0 - .00002 \cdot (DEPTH1 \cdot (.55 - DENSITY))$$

Where:

DEPTH1 = initial snow depth

DEPTH2 = final snow depth after a specific amount of compaction

DENSITY = initial snow density

The snow algorithims for the NPS model has been documented by Donigian and Crawford (1976), Hydrocomp (1976), and Donigian and Crawford (1975). A users manual and magnetic tape containing the NPS program and test data are available from Hydrocomp. In addition, the Donigian and Crawford (1976) publication includes a users manual, explanation of the various snow algorithims, program listing, and a test data listing which was used for simulating the Monitou Way storm drain in Madison, Wisconsin.

The user manuals for both models include sections on the calibration coefficients along with the equations and/or

the processes they influence. Furthermore, the user manuals also include recommended values and ranges for the calibration coefficients.

As stated previously, both models were restructured to utilize the Monroe optimization technique. Monroe (1971) includes in his publication a users manual for the optimization procedure, program listing, test data listing and a practical application of the optimization technique in modeling a watershed. NWSRFS (1972) provides an additional example of an application of the Monroe optimization technique.

Meteorological Data

Meteorological data used in the two models, with the exception of solar radiation and hourly precipitation, was obtained from Wausau FAA Airport (Wisconsin). The Wausau FAA Airport is located 14 miles NNE from the Big Eau Pleine Reservoir Dam. Although precipitation and dry bulb temperature are measured by the reservoir's dam operator for the Wisconsin Valley Improvement Corporation, portions of the data were incomplete and therefore not used in this study.

Hourly precipitation was not available from Wausau FAA Airport. Alternatively, data was obtained from the Wausau 7SSW station. The Wausau 7SSW station is located eight miles NNE from the Big Eau Pleine Reservoir Dam.

Incident solar radiation, used in both models, was calculated by the reservoir model CLIMA (Baca, 1977) based on cloud cover and additional meterological data obtained from Wausau FAA. This method is the same as that used in

the overall Eau Pleine reservoir's modeling scheme. Hence, an incompatibility between data for the snow models versus data for the reservoir's models would not occur.

Optimization

Optimization procedures were the same for Anderson's equations and the two snow models. A range was determined for each coefficient based on published literature. Once determined the range was increased by 10 percent in both directions. Starting with an initial value equal to the mid-point of the range a coefficient was allowed to oscillate 45% of the range in either direction. The 45% was programmably reduced as optimization occurred. Once the change in criteria between consecutive pattern moves reached less than .1%, optimization had been achieved. After optimization, the range of the coefficient was doubled in the direction of optimization. The new initial value of the variable was then set to the end value of the obsolete range and the process of optimization continued. As a further check for isolated coincidental optimization, the process was repeated in the opposite direction of optimization. Ideally, without regard to direction of optimization, the coefficient should return to within 1% of the value obtained in the first optimization. Failure to achieve this in some instances required reducing the 45% oscillation to 40%. This effectively reduced the chance of coincidence optimization by altering the value of the coefficient prior to a pattern move.

It should be noted that calibration procedures of this type require a large if not excessive amount of computer processing time.

The sum of squares between simulated and observed data was used for the criteria during the initial optimization procedure. Once crude values for the various coefficients were determined, the criteria was altered to refine the optimization. The refined criteria was based on correlation and regression analysis.

$$\text{Criteria} = (1. - r^2) + (1. - b^2) + (o. - a^2)$$

Where:

r = correlation coefficient

b = regression slope

a = regression intercept

Utilizing the refined criteria was necessary since the sum of squares technique is not directional specific. In a simplified situation it is possible to have the same value for the sum of squares in the cases where a parameter is being continuously over-estimated and where a parameter is being continuously underestimated. In this example, the correlation coefficients may also be the same in the two predictions, but the regression line will be different. The difference in the regression line would produce a refined optimization and control the direction optimization would occur in.

An examination of WVIC data shows that based on their bi-weekly measurements, snow accumulation to be fairly similar for 1974 and 1975 winters, whereas 1976 had the greatest

amount of snow and 1977 the minimum for the four years of data. Based on these trends, the data was separated into a two-year calibration period and two-year test period. It was felt that the strongest test for a snow model would be to calibrate for the two similar years and attempt to simulate the two atypical years of 1976 and 1977. This procedure was followed in comparing the stability of the two models.

Since weather data was unavailable prior to January 1, 1974, both models were initiated with WVIC's December 31, 1973 snow measurements for the 1974 winter run.

RESULTS

Solar Radiation Reflection and Attenuation

Results of Field Measurements

Shortwave solar radiation is more rapidly attenuated by a snow cover than by an ice cover. Of greater significance is the high albedo (reflectivity) associated with a snow cover in comparison to an ice cover. While the percent reflection of an ice cover rarely exceeds 60%, the opposite is true of a snow cover (William, 1971). Results of the experiments with solar radiation (Table 2) show this trend. The ice cover had an average albedo of 48.7% in comparison to 72.1% for the snow cover. This amounts to a 23% reduction in solar radiation just due to the different spectral properties of snow and ice.

Snow albedo ranged from a maximum of 81.6% to a minimum of 52.7%, relating inversely with the fluctuations in snow surface density (.191 and .488 $g \cdot cm^{-3}$ respectively). Iz-snow (solar flux at the snow-ice interface) varied from a minimum of .22% to a maximum of 3.02% which corresponds to the maximum snow depth (16cm) and minimum snow depth (7cm) The relationship between Iz-snow and snow depth is not linear since snow density is an influencing factor.

The correlation between Iz-ice (solar flux at the ice-water interface) and ice thickness was not apparent in these experiments. The physical properties of the ice varied too greatly in the point measurements to show these relation-

Table 2. A summary of the data collected from the solar radiation experiments.

EXPERIMENT (NUMBER)	1	2	3	4	5	6	7	8	9	10	11
ICE COVER (CM.)	60.0	61.5	67.5	63.0	64.0	58.0	56.5	52.0	60.5	69.0	64.0
ICE ALBEDO (PERCENT)	56.0	60.0	48.9	42.5	45.0	38.0	42.3	44.0	54.0	50.0	55.0
IZ ICE (PERCENT)	34.6	29.4	14.1	12.0	12.6	10.9	15.7	22.1	12.9	10.2	34.8
EXT. COEF. ICE (%/CM.)	.004	.005	.019	.027	.023	.030	.023	.021	.021	.023	.004
SNOW COVER (CM.)	11.5	11.0	13.0	13.0	10.0	16.0	15.0	14.0	10.0	7.0	16.0
SNOW ALBEDO (PERCENT)	78.3	81.6	73.6	72.0	76.9	74.1	68.2	70.0	71.7	74.5	52.7
IZ SNOW AND ICE (PERCENT)	0.55	0.60	0.16	0.16	0.40	0.04	0.11	0.15	0.33	0.60	0.46
IZ SNOW (PERCENT)	0.72	0.82	0.59	0.90	1.78	0.22	0.42	0.45	1.20	3.02	0.60
* SNOW DEPTH (CM.)	1.5	1.0	3.0	5.0	5.0	2.0	5.0	4.0	5.0	2.0	6.0
SNOW DENSITY (G/CUBIC CM.)	.201	.191	.208	.305	.317	.327	.350	.347	.353	.332	.488
SNOW DEPTH (CM.)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
SNOW DENSITY (G/CUBIC CM.)	.371	.363	.270	.284	.245	.339	.262	.242	.284	.274	.484
SNOW DEPTH (CM.)	5.0	5.0	5.0	3.0		5.0	5.0	5.0			5.0
SNOW DENSITY (G/CUBIC CM.)	.251	.222	.215	.259		.207	.215	.209			.387
SNOW DEPTH (CM.)						4.0					
SNOW DENSITY (G/CUBIC CM.)						.194					

* SNOW SURFACE

ships. A reasonable portion of the variability in the ice cover could be explained by the amount of snow present and the rate of water movement in the local area. Both of these factors affect the rate of ice growth, and, altered the optical properties of the ice cover from point to point.

Calibration

Utilizing the results of these experiments the coefficients for Anderson's equations were determined. The values of the coefficients for both this study and Anderson's work are shown in Table 3.

Table 3. Values for the coefficients used in the solar radiation equations.

Coefficient	Anderson	This Study
CV	1.20	1.16
G1	0.16	0.63
G2	0.00	0.65
G3	110.00	61.31

Figure 2 (Table 4) shows the accuracy of the equations in representing the solar radiation reflection and attenuation processes in a multiple density snow cover. Data is plotted for both observed and calculated snow albedo and Iz-snow. A statistical comparison of calculated and observed albedo measurements results in an intercept of -0.45%, a slope of 0.99, and correlation coefficient of 0.928 and a standard error of estimate of 2.96%. A similar comparison of calculated and observed Iz-snow results in an intercept of -0.10%, a

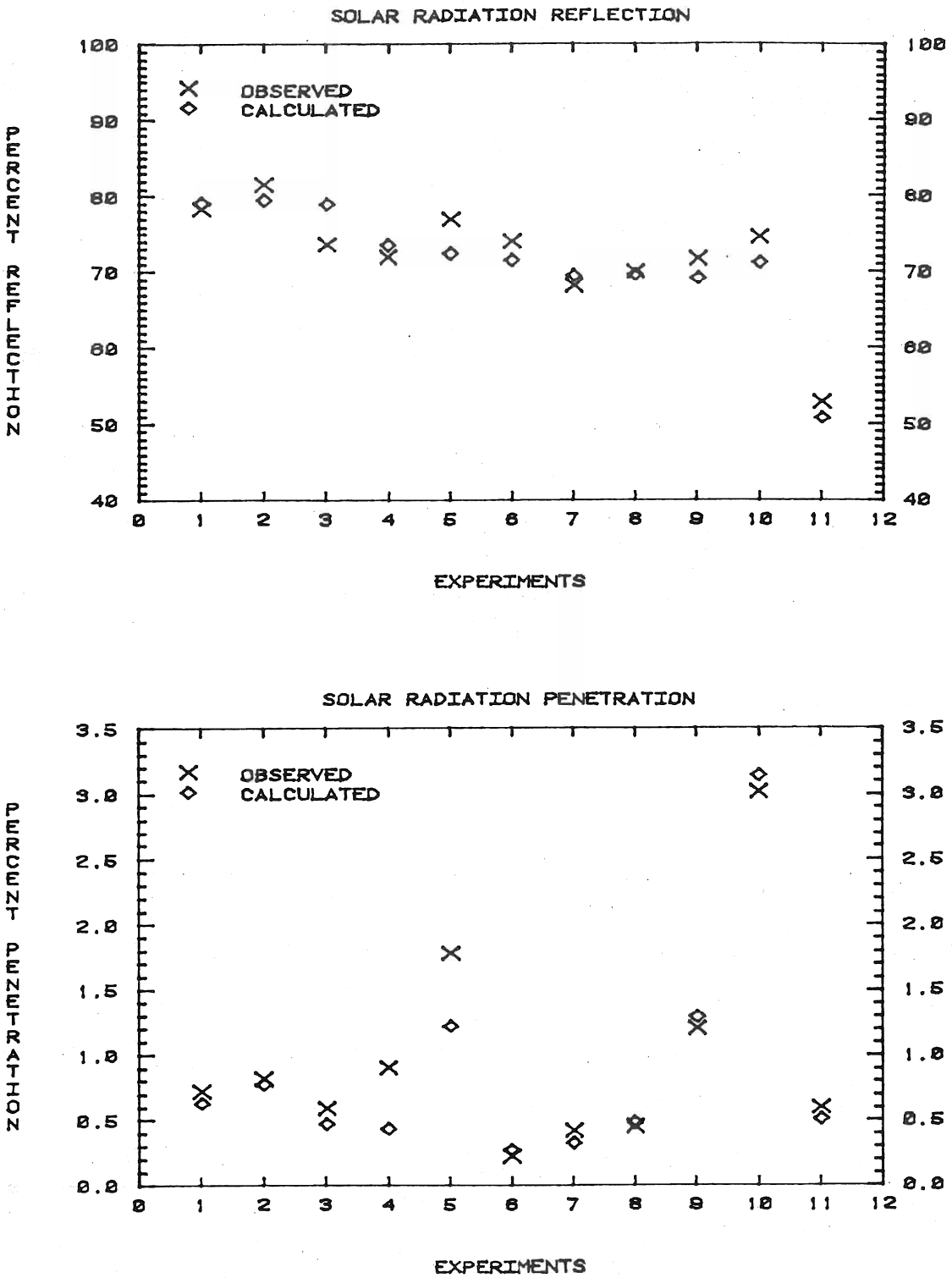


Figure 2. Comparison of observed and calculated albedo and solar flux at the snow-ice interface.

Table 4. Comparison of observed and calculated albedo and solar flux at the snow-ice interface (percent).

Experiment	Albedo		Iz-snow	
	Observed	Calculated	Observed	Calculated
1	78.31	79.17	0.72	0.63
2	81.58	79.46	0.82	0.78
3	73.63	78.94	0.59	0.47
4	72.00	73.54	0.89	0.43
5	76.92	72.49	1.78	1.22
6	74.06	71.61	0.22	0.26
7	68.18	69.42	0.41	0.32
8	70.00	69.69	0.45	0.47
9	71.68	69.08	1.20	1.29
10	74.54	71.22	3.02	3.14
11	52.73	50.60	0.60	0.51

slope of 0.99, a correlation coefficient of 0.961 and a standard error of estimate amounting to 0.23%.

A closer examination of Table 4 shows the capability Anderson's equations have for reducing solar flux in a snow cover. Experiment five with comparatively poor results had an observed Iz-snow of 1.78%, or 98.22% reduction in solar flux from 10cm of snow. The equations predicted a solar flux reduction amounting to 98.78%. The discrepancy of .56% would appear insignificant with respect to the overall magnitude of the attenuation in solar flux. This is obvious when the affect of an ice cover is accounted for. In this particular experiment the ice cover reduced the measured solar flux an additional 1.38% (Iz-ice = .40%).

Verification

Although very little of the literature contains examples of various extinction coefficients and albedo measurements as they relate to snow density, several examples are available from the work of Gerdel (1948) and Thomas (1963). Comparing Anderson's equations with these authors' work is possible by extrapolating their work to a theoretical snow cover 10cm deep, the size of the snow cover being relative to the work in this study.

Thomas' work shows that the theoretical snow cover having a density of .285 g cm^{-3} would reduce incident solar radiation by 98.79% whereas the equations predict a 98.96% reduction. Similarly the snow cover with a density of .316

g cm^{-3} would reduce incident solar radiation by 97.8% in comparison to the predicted 98.9% reduction. Applying the same principal to Gerdel's work shows that a 10cm deep snow pack with a density of .261 g cm^{-3} would produce a reduction in solar radiation amounting to 98.29% while the equations predict a 98.74% reduction.

If the solar flux at the euphotic compensation depth is assumed to be 1% of the surface flux (Maeda and Ichimura, 1973) the results of this study compares well with the work of Maguire (1975). Utilizing quantum sensors and expressing results in terms of PAR (photosynthetically active radiation), Maguire found that as little as 10cm of powder snow on clear ice would effectively inhibit net photosynthesis. Similarly, in this study (experiment five) 10cm of snow present over ice reduced the solar flux to less than 1%.

It should be pointed out that 10cm of snow is not the absolute upper limit for photosynthetic inhibition. Besides being algal related, this level is also a function of snow density. Although Maguire did not express his results in terms of snow density, historically powder snow is considered snow of low density. As snow density increases, the amount of reduction in solar flux decreases, allowing for a greater snow depth prior to photosynthetic inhibition. Experiments 3 and 4 show this density relationship. Snow depth (Table 2) is similar in both experiments (13cm) but experiment 4 had an overall higher density snow cover, hence a higher Iz-snow.

Limitation

A comparison between Thomas' measurements and the equation predictions show an approximate 3% difference for snow density greater than .400 g cm^{-3}. Similarly, Gerdel's measurements which show a difference of 7% are inconsistent with Thomas' data at these higher snow densities. Yen (1964) has theorized that the radiation properties of snow are strongly dependent on both the surface characteristics and the internal structure of the snow cover. Therefore, as a snowpack ripens, increasing in density and undergoes the corresponding dynamic structural changes, inconsistence in spectral measurements is very probable. Furthermore, Yen suggests that the data compiled by the University of Minnesota (SIPRE 1951) which covers a period of several decades including the work of Gerdel, substantiates the inconsistencies that occur in measuring the spectral properties of snow.

Weller (1969) while showing that the extinction coefficient of snow is inversely proportional to the snow grain size, states that additional factors such as free water content, hoar layers and the degree of contamination will also affect the extinction coefficient. Since the equations used in this study form an empirical relationship solely between snow grain size and snow density, they would be somewhat inconsistent with measured data for a snow cover of high density. In particular, the equations would overestimate the reduction in solar flux from a high density snowpack that contains very little free water. Since such

conditions are typically created metamorphically in a deep snow cover, the problem would not be that significant in this study.

Computer Modeling the Watershed Snow Cover

Calibration

A comparison of the output from the snow models with WVIC measured data is shown graphically in Figure 3 and tabulated in Table 6. Both models produced good seasonal trends, demonstrating the variability that occurs in a shallow intermittent snow cover. Although both models showed a discrepancy in simulating the March 2, 1974 WVIC measurement, for the most part there is a strong fit between measured and simulated data during both winters. This is especially true when considering the large standard deviation associated with WVIC data (Table 6).

Statistically the NPS model performed better than the LEAF model (Table 5).

Table 5. A statistical comparison between output from the two snow models and WVIC water equivalent data (inches)

	Sample Size	Intercept	Slope	Correlation Coefficient	Standard Error of Estimate
NPS MODEL					
2 Yr. Calibration	18	.453	.773	.937	.306
2 Yr. Simulation	18	.183	.892	.945	.316
4 Yr. Period	36	.288	.845	.944	.313
LEAF MODEL					
2 Yr. Calibration	18	.193	.724	.881	.410
2 Yr. Simulation	18	.453	.876	.638	1.040
4 Yr. Period	36	.380	.743	.695	.806

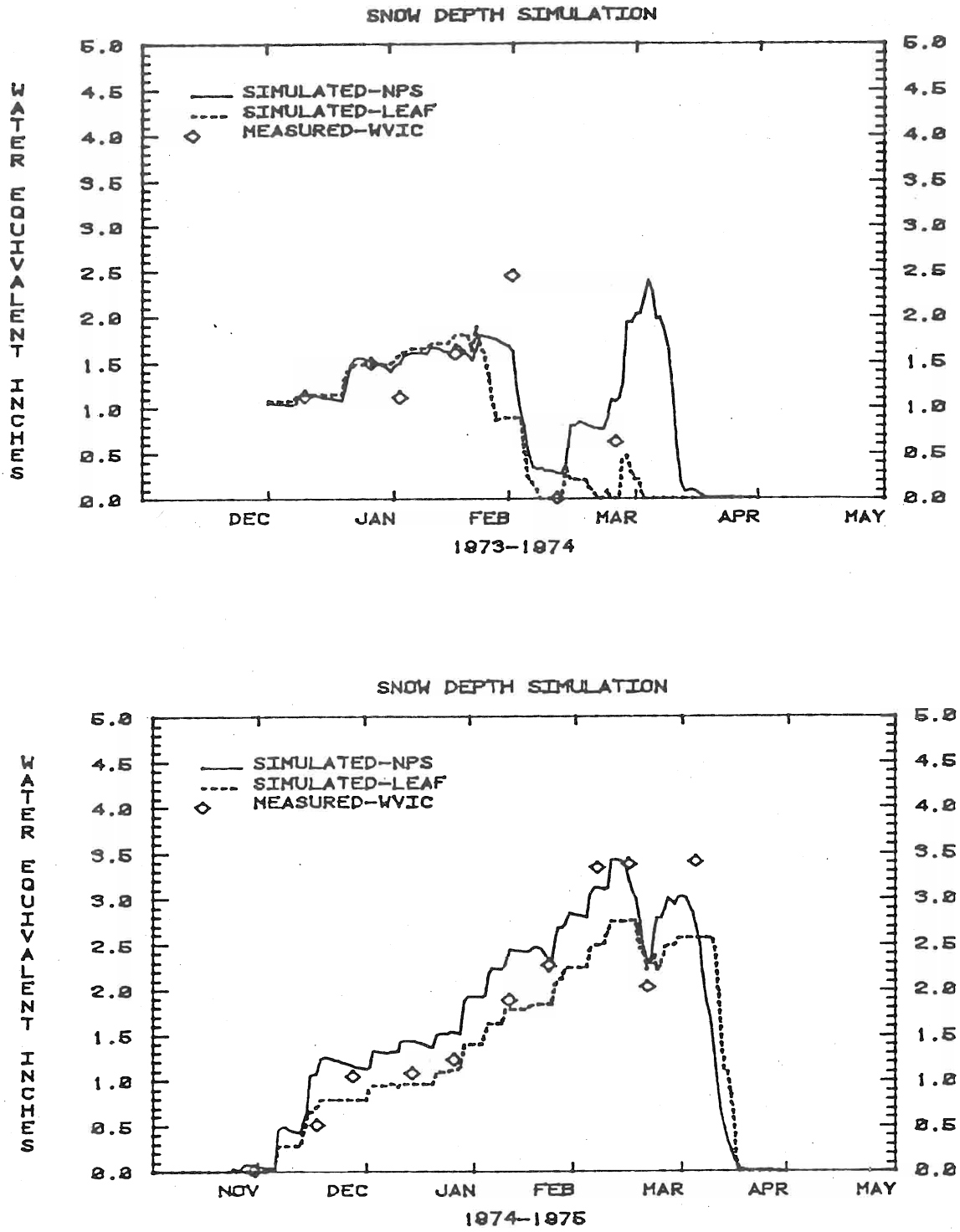


Figure 3. Calibration comparison between output from the two snow models and WVIC water equivalent data.

Table 6. A summary of the WVIC data and comparison with the snow models simulation.

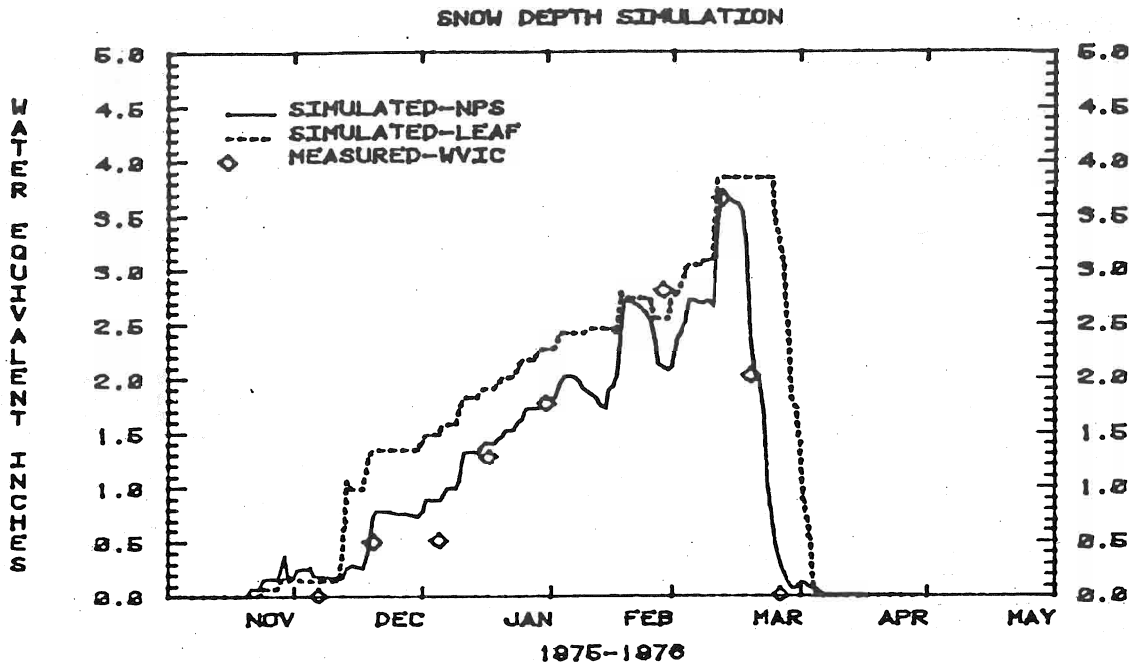
Date Mn Dy Yr	W V I C Water In.	W V I C S. D. Water	NPS Water In	LEAF Water In.
		Calibration		
12/31/73	1.07	0.174		
1/10/74	1.13	0.219	1.14	1.15
1/26/74	1.49	0.253	1.50	1.48
2/ 2/74	1.11	0.282	1.48	1.58
2/16/74	1.59	0.435	1.69	1.79
3/ 2/74	2.44	0.421	1.62	0.89
3/13/74	0.00	0.000	0.27	0.00
3/27/74	0.63	0.288	1.06	0.00
11/30/74	0.00	0.000	0.06	0.00
12/18/74	0.50	0.113	1.07	0.71
12/28/74	1.04	0.227	1.16	0.79
1/14/75	1.08	0.357	1.44	0.97
1/26/75	1.22	0.380	1.53	1.12
2/11/75	1.88	0.391	2.45	1.78
2/22/75	2.26	0.565	2.33	1.84
3/ 8/75	3.33	0.698	3.11	2.49
3/17/75	3.38	0.708	3.21	2.74
3/22/75	2.02	0.664	2.34	2.22
4/ 5/75	3.40	0.867	2.71	2.56
		Simulation		
12/ 7/75	0.00	0.000	0.18	0.14
12/20/75	0.49	0.123	0.74	1.35
1/ 5/76	0.51	0.207	0.87	1.49
1/17/76	1.27	0.395	1.40	1.90
1/31/76	1.76	0.371	1.82	2.26
2/28/76	2.81	0.501	2.09	2.55
3/13/76	3.65	0.729	3.74	3.85
3/20/76	2.03	0.753	2.32	3.85
3/27/76	0.00	0.000	0.28	3.23
12/31/76	0.16	0.125	0.46	0.18
1/14/77	0.65	0.124	0.84	0.24
1/28/77	1.00	0.361	0.82	0.00
2/12/77	1.15	0.329	0.66	0.00
2/25/77	1.12	0.521	1.77	1.51
3/ 9/77	1.74	0.515	1.74	1.94
3/18/77	0.74	0.209	0.28	0.01
3/26/77	0.00	0.000	0.30	0.00
4/ 2/77	0.00	0.000	0.01	0.40

For the two-year calibration period the NPS model had a higher correlation coefficient (.937) and a lower standard error of estimate (.306 inches) than the LEAF model (r = .881, s = .410 inches).

Simulation

Once calibrated, both models were tested over the 1976 and 1977 simulation period. The NPS model simulated the 1976 winter exceptionally well but under-simulated the month of February during the 1977 winter (Figure 4). The LEAF model over-simulated the 1976 winter and under-simulated January and February, 1977. In addition, the LEAF model showed a full week delay in simulating the final 1976 spring melt while the NPS model was in excellent agreement with the measured data.

Although both models showed some difficulty in simulating the 1977 winter, the NPS model was superior to the LEAF model during the two-year simulation. Statistically the NPS model had a correlation coefficient of .945 and a standard error of estimate of only .316 inches. In comparison, the LEAF model had a correlation coefficient of .638 and a standard error of estimate of 1.040 inches. Furthermore, as Table 5 shows, the overall performance of the NPS model was noticeably superior to that of the LEAF model. In contrast to the LEAF model (r = .695, s = .806 inches) the NPS model had a higher correlation coefficient (.944) and a much lower standard error of estimate (.313 inches) for the full four-



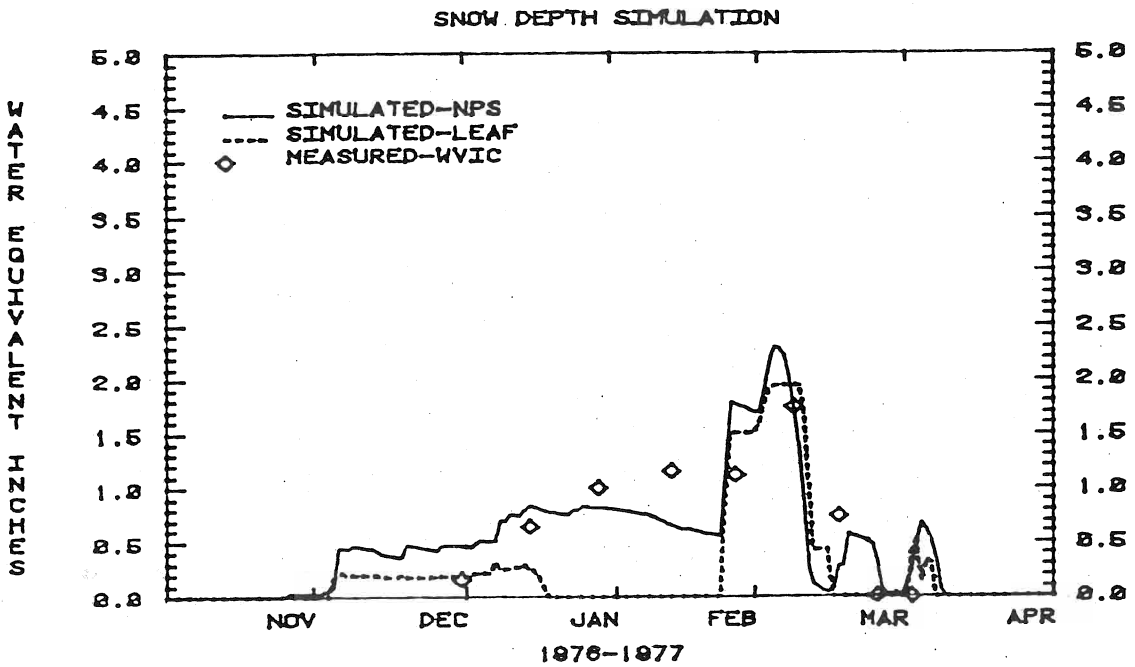


Figure 4. Simulation comparison between output from the two snow models and WVIC water equivalent data.

year period. Additional support for the NPS model is provided by the observation that the four-year standard error of estimate or the "average error" (Nic, 1975) that the NPS model had in predicting the measured WVIC values is lower than the average standard deviation (.337 inches) for that data.

Yearly Evaluation and Comparison to River Flow

Introduction

Snowmelt in the Eau Pleine Basin is a rapid process. Often the reservoir is refilled from spring runoff within three to five days (Wiley, 1977). Since this process is so dynamic, the NPS snow depth simulations should correlate inversely with the spring inflow hydrographs for the reservoir.

1974

The Big Eau Pleine River provides a major source of water for the reservoir. River flow, monitored by USGS at Stratford is the resultant drainage from 224 square miles or 61 percent of the catchment basin. Therefore, the hydrograph recorded by USGS would be an accurate, although smaller, representation of the hydrograph defining total inflow to the reservoir and as such would be directly comparable to snowmelt. Figure 5 shows the relationship between river flow at Stratford, snow water equivalent and precipitation for 1974. An examination of this figure shows a good agreement between spring snowmelt and river flow, although it appears that based on river flow the second melt occurred several days prior to what the

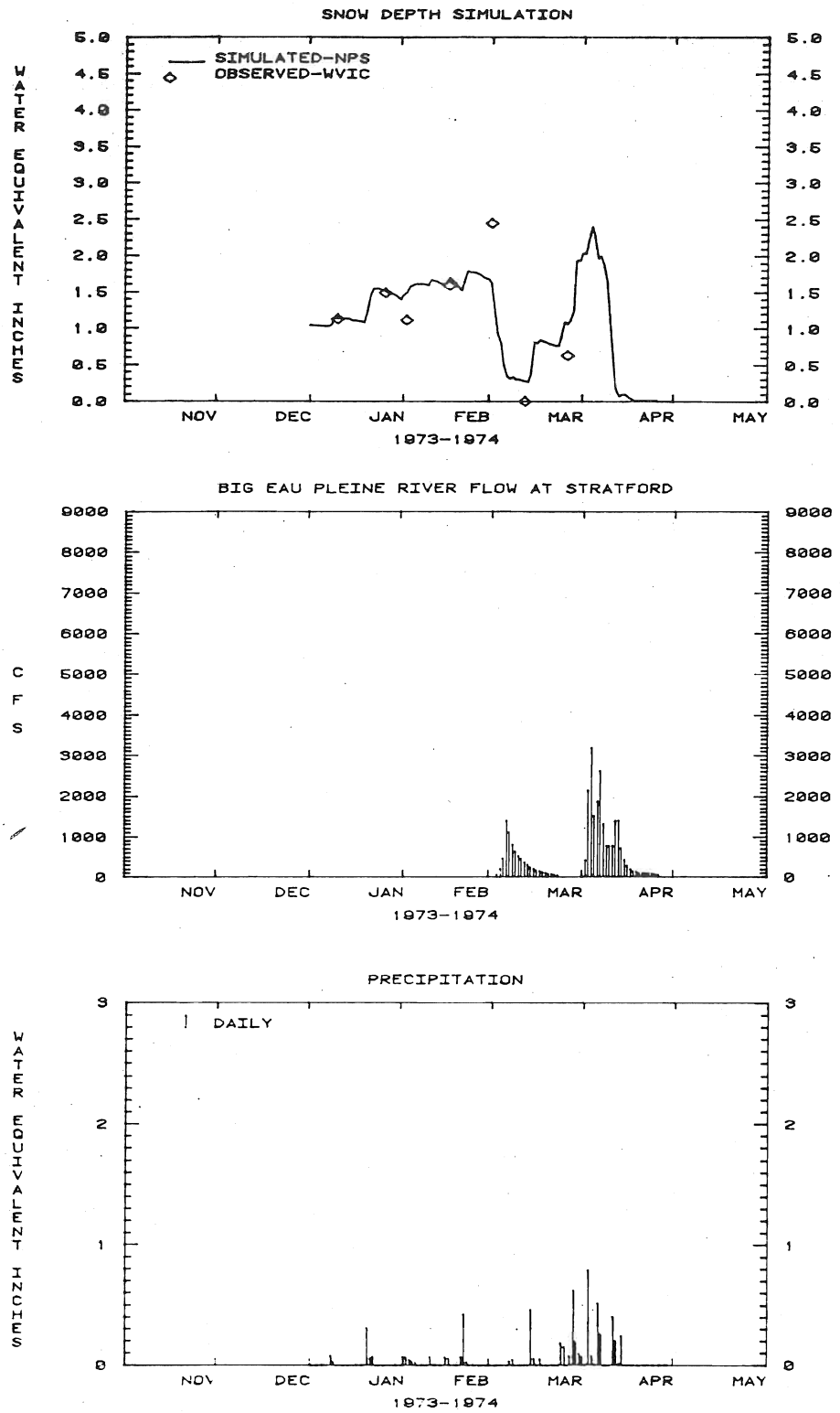


Figure 5. Basin snow depth simulation, river flow and precipitation for 1974.

NPS model predicted. Precipitation data indicates that between WVIC's last measurement (March 27) and the predicted disappearance of the snow cover (April 18) 3.5 inches of precipitation occurred, yet, the water equivalent of the snowpack increased only 1.4 inches prior to melting. Since the precipitation occurred rather uniformly throughout the period a large portion of the precipitation must have resulted in mixed rain-snow events thereby contributing to the river flow. For an example, from April 2 to April 5, .85 inches of precipitation occurred yet the snowpack increased only .25 inches water equivalent (from 2.03 to 2.28 inches). Hence, there was a net release of .6 inches water equivalent from the snowpack to the underlying soil. Similarly, .75 inches of precipitation occurred from April 5 to April 7, but the snowpack had a net decrease of .28 inches water equivalent (from 2.28 to 2.00 inches). Since there was a net decrease in the snowpack, this permitted 1.03 inches of water to contribute to river flow.

Large fluctuations in air temperature and high solar radiation levels during this period (Figure 6) reveal that mixed rain-snow events were very probable. Air temperatures averaged a minimum of 28 degrees F. and a maximum of 42 degrees while incident solar radiation averaged .3 $kcal/cm^2 \cdot day$.

Mixed rain-snow events were partly responsible for the discrepancy between WVIC's March 2 snow measurements of 2.44 inches water equivalent and the NPS model's predicted 1.62 inches. There was .5 inches precipitation in the period from

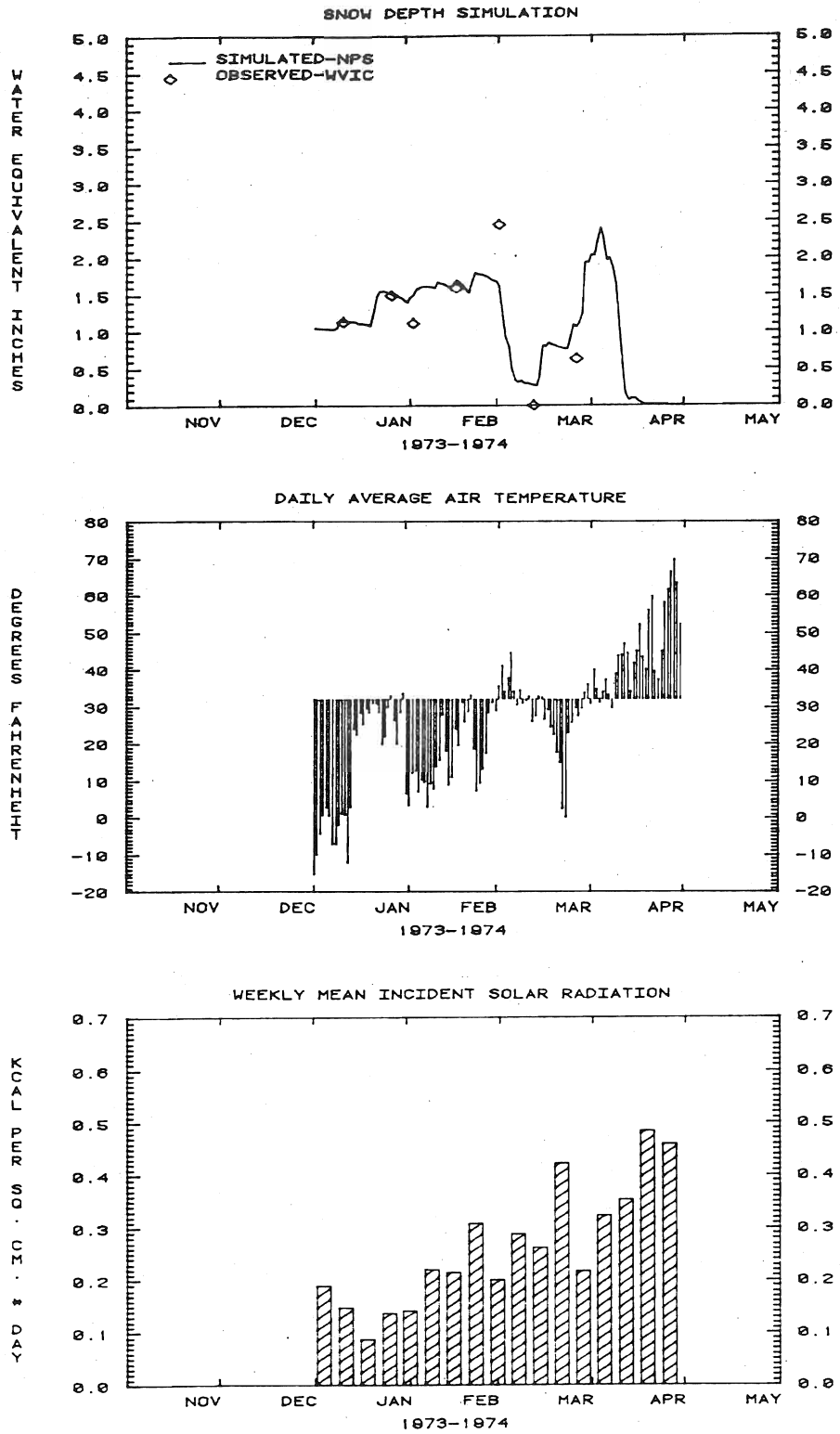


Figure 6. Basin snow depth simulation, average air temperature and mean incident solar radiation for 1974.

WVIC's February 16 to the March 2 measurement, all of which occurred February 21. Daily average air temperature for February 21 was 33 degrees F. Hence, the NPS model predicted the precipitation as a mixed rain-snow event which amounted to 20 percent rain. This was similar to observations recorded by the Wausau FAA airport weather station.

When rain falls on a snowpack, four sources of heat are available to melt the snowpack. Since rain usually occurs when air temperatures are above freezing, convection from the warmer air masses is possible. Additional heat is released during the process of lowering the rain temperature in the snowpack to that of the freezing point of water. Thirdly, the rainwater that is frozen within the snowpack releases its latent heat of fusion (203.2 langleys per inch of rain) to the surrounding snow. Finally, rain often occurs at relatively high atmospheric humidity when condensation of the saturated vapor pressure can proceed. Considering that condensation of water vapor in the amount of .1 inch water equivalent will produce .75 inches of melt, this could be a significant heat source.

The NPS model calculated these heat sources and predicted that .3 inches water equivalent was released from the snowpack, consequently the snowpack had a net increase of only .2 inches from the mixed rain-snow event. Although the WVIC measurements show that the snowpack increased .85 inches during this time period (from 1.59 to 2.44 inches), the NPS model predicted that the snowstorm accounted for only .2

inches of the increase in water equivalent. However, even if the precipitation was completely snow, the snowpack would increase only .5 inches, therefore, some other factor such as snow drifting must be providing additional influence to the WVIC measurement.

1975

The 1975 winter also shows a good relationship between spring melt and river flow (Figure 7). The first melt, extending from March 16 to March 23, produced a decrease in the snowpack of 1.06 inches water equivalent (from 3.34 to 2.28 inches). The Eau Pleine River's response to the melt was somewhat delayed. Flows started increasing March 20 and peaking March 25. This would be expected since there was still a deep snow cover which would delay the infiltration and runoff processes.

There was a similar four-day delay in the river's response to the second spring melt. This melt started April 3 and ended with a complete melting of the snowpack by April 21. River flows started increasing April 7 and reached a maximum flow of 1900 cfs by April 16. Additional increases thereafter were due to heavy rains.

Average minimum and maximum air temperature were for the first melt 27 and 42 degrees F. and for the second melt 26 and 44 degrees F respectfully (Figure 8). While average minimum and maximum air temperatures for the two melts were similar, in addition to longer duration, the second melt had

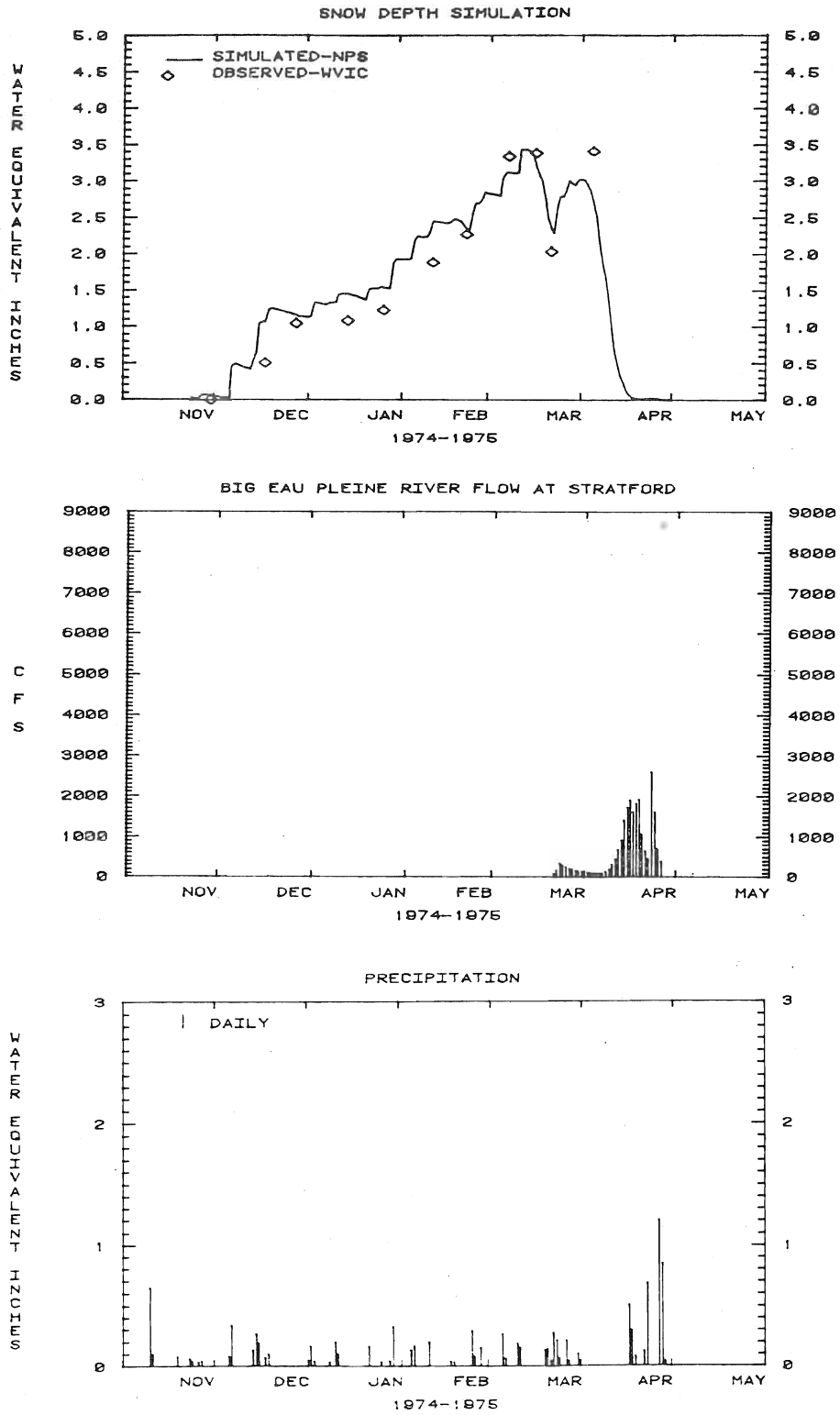


Figure 7. Basin snow depth simulation, river flow and precipitation for 1975.

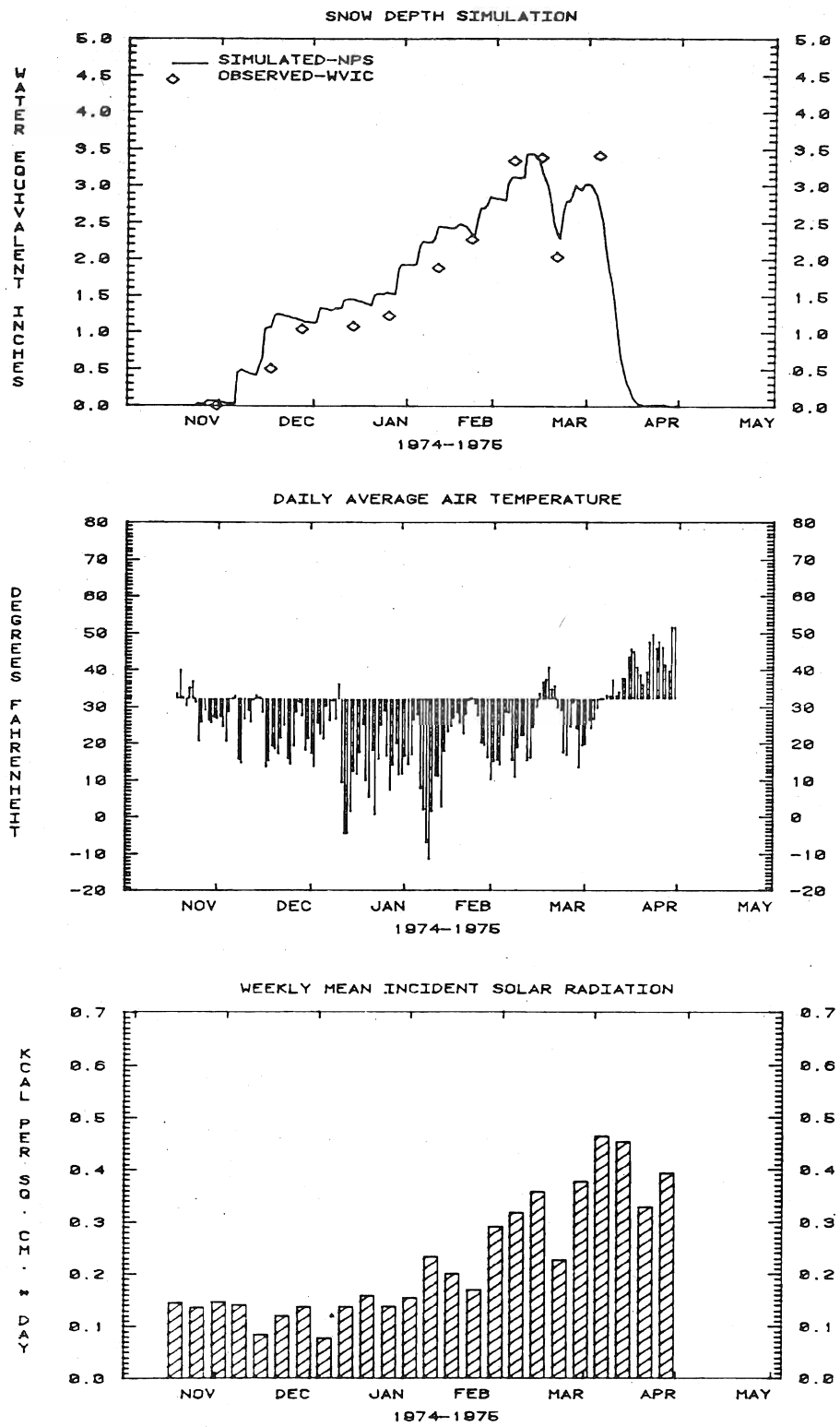


Figure 8. Basin snow depth simulation, average air temperature and mean incident solar radiation for 1975.

both higher average daily temperatures and higher average levels of incident solar radiation. Solar radiation levels averaged only .273 kcal/cm^2·day for the first melt in comparison to .405 kcal/cm^2·day for the second melt. Both the higher average air temperatures and solar radiation levels in the second melt produced a more rapid depletion of the snow cover while the longer duration made the depletion complete.

1976

The 1976 winter simulation produced a good correlation between spring snowmelt and river flow (Figure 9). Similar to 1975 two major melts occurred in 1976. The first melt, extending between February 4 and February 29 was a combination of two small melt periods separated by a snow event. Overall, there was a .9 inch water equivalent reduction in the snowpack. During this period the largest melt occurred February 26, producing a .34 inch ablation in the snowpack. In relation to spring melt, river flows started increasing February 10 and produced peak flows on February 20 and March 1.

This melt is of particular interest since there appears to be a conflict between WVIC data and flow in the Eau Plaine River. The January 31 and February 28 WVIC sampling dates suggest that the snowpack increased 1.05 inches water equivalent (from 1.76 to 2.81 inches). During this time period precipitation amounted to 1.19 inches, hence, a net contribution of only .14 inches to river flow in comparison to the NPS model's prediction of .92 inches. Both of these values

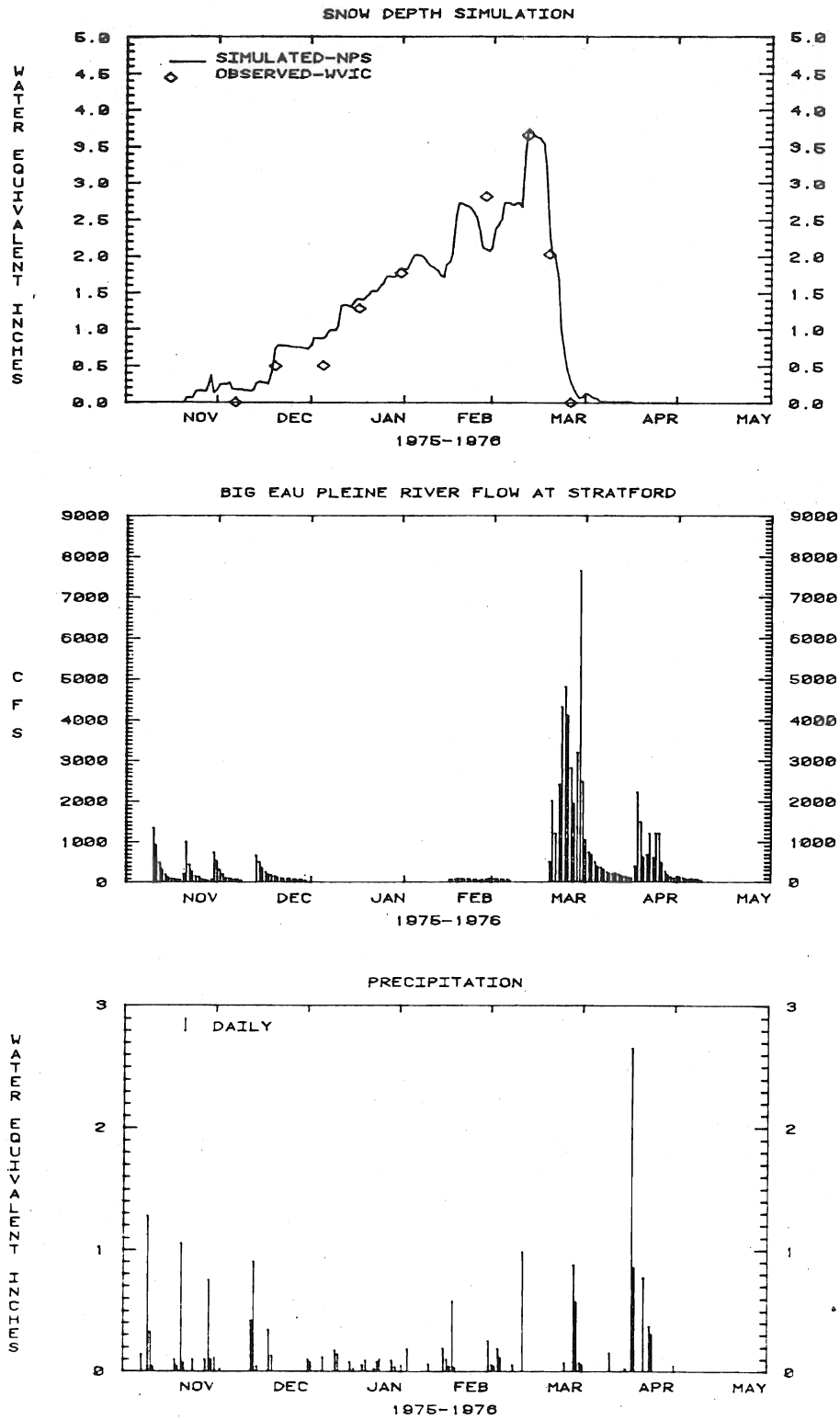


Figure 9. Basin snow depth simulation, river flow and precipitation for 1976.

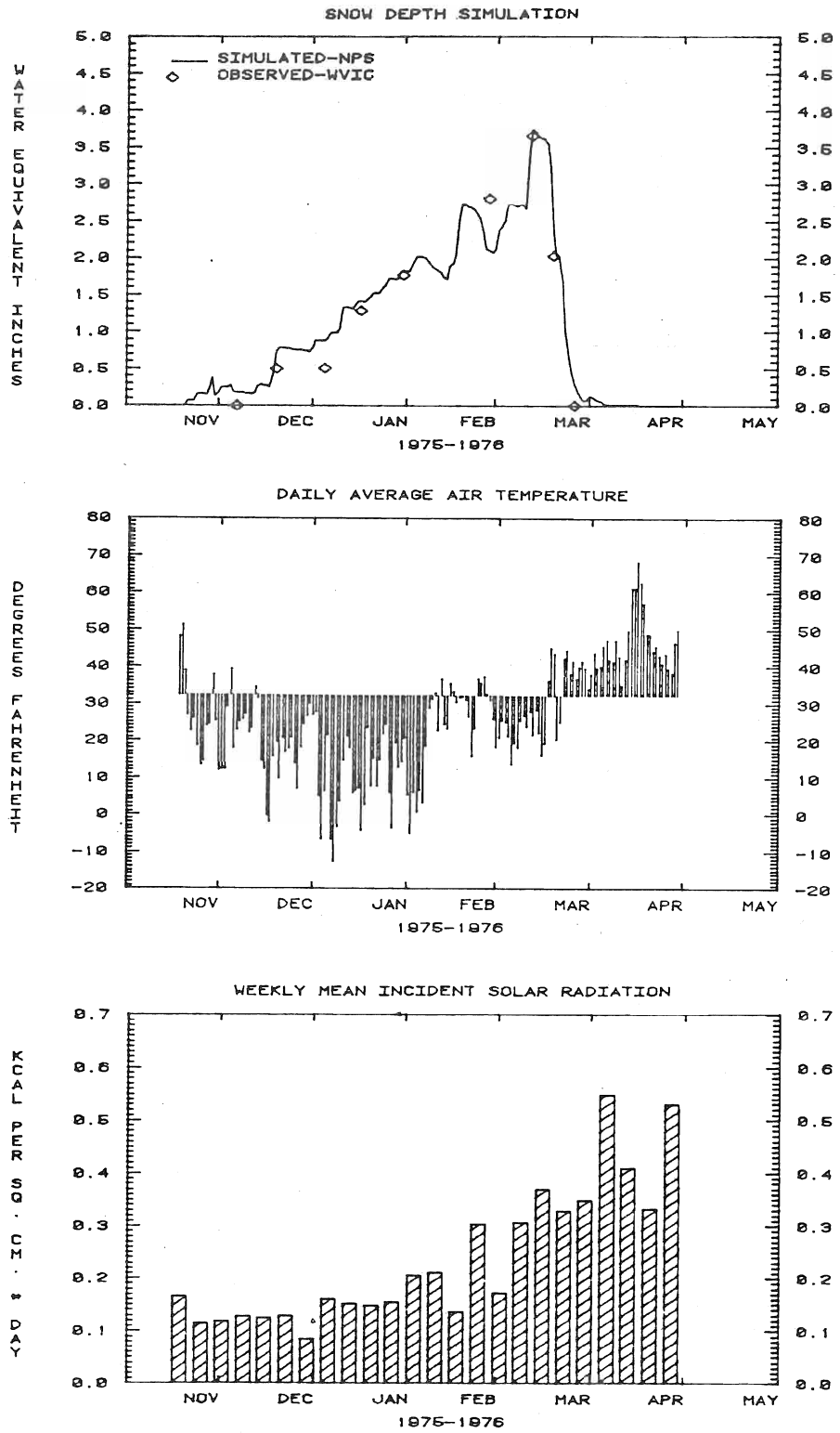


Figure 10. Basin snow depth simulation, average air temperature and mean incident solar radiation for 1976.

would be reduced when considering that sublimation and snow evaporation were occurring during this time period.

Daily evaporation-sublimation is usually small (Donigian and Crawford, 1976), although it could be significant over a 28-day period. Meiman and Grant (1974) in comparing evaporation and sublimation between mountainous open and forested areas obtained average daily values of .051 and .035 inches per day respectively (minimum = .004 inches per day). Since evaporation-sublimation is a function of vapor pressure and temperature of both the air and snowpack, wind speed and solar radiation, these values cannot be compared directly to the Eau Pleine Basin.

The NPS model typically calculates evaporation and sublimation in the range of .003 to .011 inches per day. The lower magnitude of these values, in comparison to Meiman and Grant, is expected since the meterological regime in Wisconsin is very moderate compared to mountainous regions. However, even using an average evaporation-sublimation rate of .007 inches per day, approximately .2 inches of water would be lost from the snowpack within this time period. Assuming this value is accurate within $\pm$ .1 inches then based on WVIC's measurements, it would be improbable to have the increased flow that occurred within the Eau Pleine River.

Similar to the discrepancy discussed in the 1974 simulation, this situation provides an additional example of the limitations in computer modeling when the modeling efforts are based solely on one data set or one source for data.

The fact that the increased flow in the Eau Pleine River was seven times greater than the normal base flow definitely indicates that a melt or rain event transpired. The inability in WVIC's measurements to show that event implies there is a data error, misrepresentation of the basin or simply a localized occurrence such as snow drifting that is masking the origin for river flow. Without additional sources of data it is not possible to completely ascertain the above implication, however later within this report further attention is given to this problem.

With respect to the second melt, March 13 to April 8, river flow shows a strong correlation to both the NPS simulation and WVIC measurements. This melt was relatively slow the first three days, increasing slightly the next three days. A very rapid melt, in excess of .7 inches per day, occurred March 19 and 20. The rapid melt was followed by a two-day cold spell where the average air temperature was less than 25 degrees F. (Figure 10). After the cold spell, the melt continued at an accelerated rate so that by March 30 the snowpack contained less than .1 inch water equivalent.

An inspection of river flow shows peaks similar to the snowmelt process. The first peak occurred March 21 with river flow amounting to 2000 cfs, while the second peak occurred March 25 with a flow of 4800 cfs. River flow gradually declined until a rainstorm in excess of 1.5 inches occurred. Response to the storm produced the major river flow of 7600 cfs March 30. Subsequent river fluctuations were due to

mixed rain-snow events with rain being the predominant form of precipitation.

1977

The 1976-77 winter was difficult to simulate (Figure 11). There was .61 inches of precipitation during the month of December. Since solar radiation levels were low and average daily air temperatures did not exceed 30 degrees F. (Figure 12) very little snowmelt should have occurred. Still, by the end of December the snowpack contained only .16 inches of water based on WVIC data. Even using an evaporation sublimation rate of .011 inches per day it would be expected that the snowpack should contain minimally almost twice as much water as WVIC has recorded.

Additional differences arise in examining the time period of January 14 to January 28. There was .14 inches of precipitation within this period, yet based on WVIC's measurements, the snowpack increased .35 inches (from .65 to 1.00 inches). Similarly, WVIC recorded the snowpack as increasing .15 inches from January 28 to February 12 but in contrast precipitation was not recorded at either the Eau Pleine dam or Wausau SS7 during this period.

The summer and fall of 1976 were abnormally dry producing low water levels in the reservoir and inflowing tributaries. The low water concentration in the surrounding basin soils prior to winter is evident in the Big Eau Pleine River response to the 1977 spring melt.

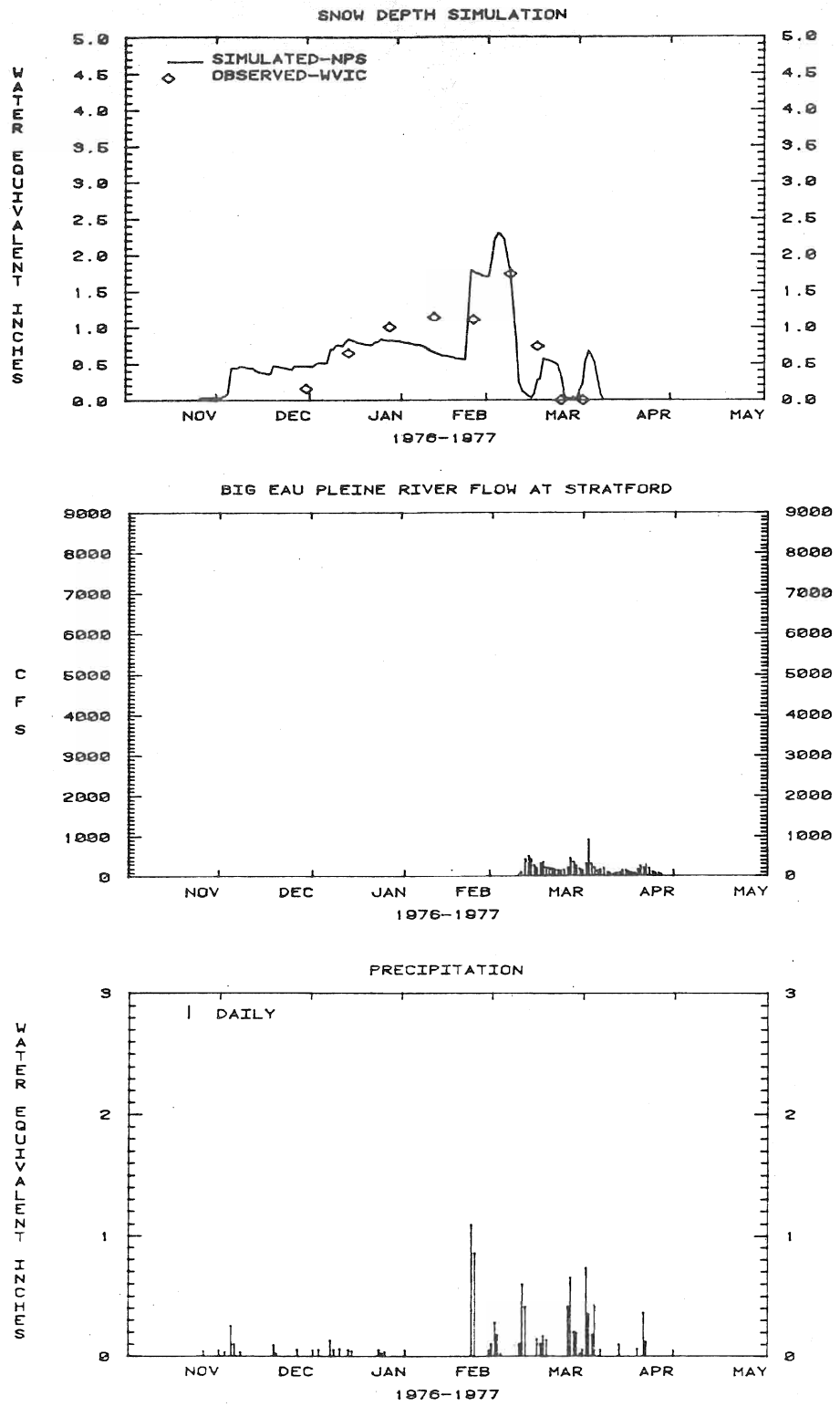


Figure 11. Basin snow depth simulation, river flow and precipitation for 1977.

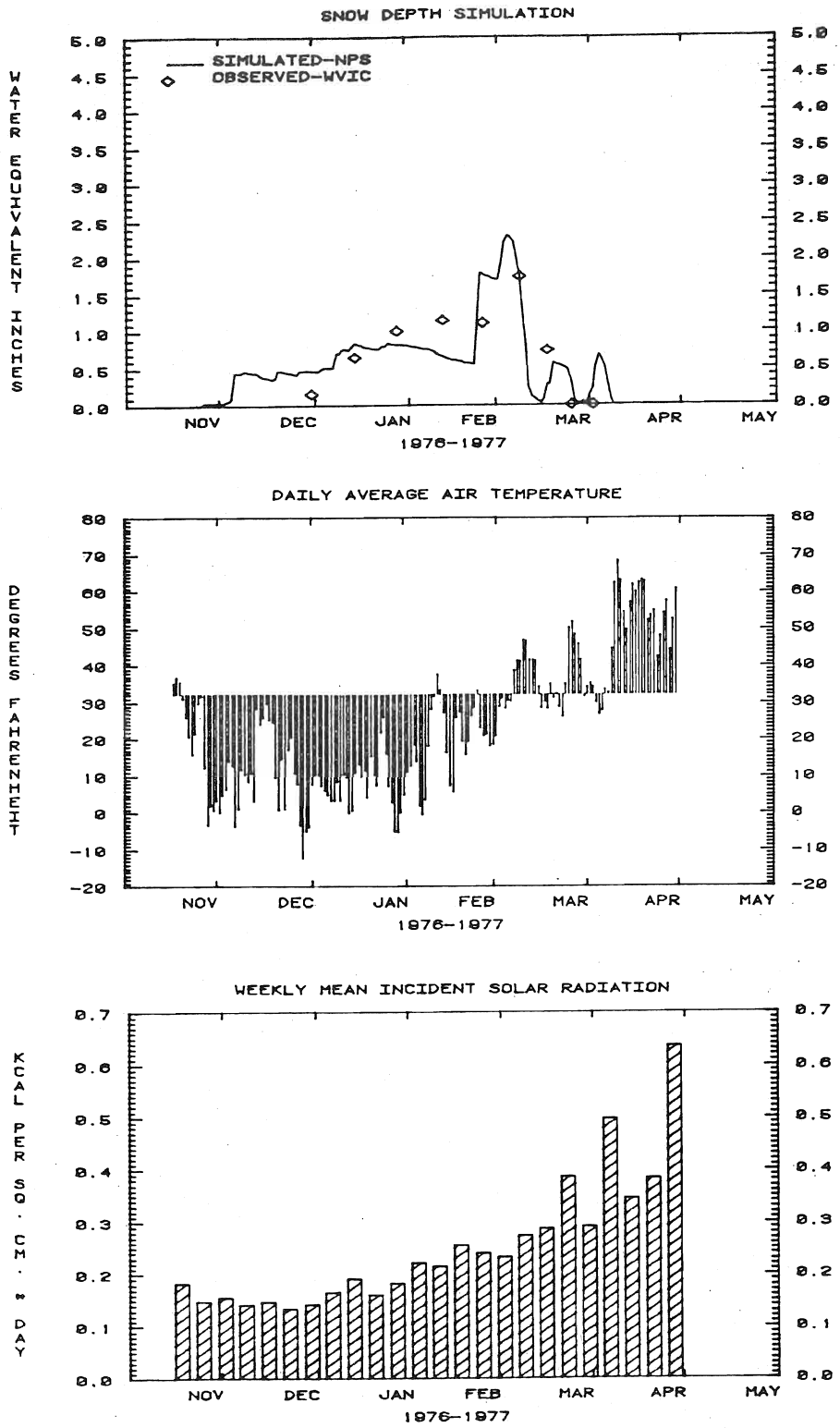


Figure 12. Basin snow depth simulation, average air temperature and mean incident solar radiation for 1977.

Computer Modeling the Reservoir Snow Cover

Calibration

Although there were limitations associated with the use of either snow model, the magnitude of those limitations were insufficient to prevent utilizing the NPS model as a predictive tool. Therefore, the NPS model was recalibrated for a reservoir situation based on the field data collected during the 1977 winter (Table 7). For comparative purposes, the values for the NPS calibration coefficients used in the simulations for the BEP reservoir and watershed and the Manitou Way watershed (Wisconsin) are shown in Table 8. It should be noted that the values of the coefficients used in simulating the Manitou Way watershed were obtained from the work of Donigian and Crawford (1976).

The reservoir calibration results for both snow depth and water equivalent are presented in Figure 13 (Table 7). Overall the simulations were in good agreement with the measured field data. In particular there was a strong correlation (r= .978) associated with the water equivalent data (Table 9), while the snow depth data had a slightly lower correlation (r= .964). The lower correlation for snow depth was primarily due to the model's inability to simulate the rapid compaction that occurred between January 14 and January 21.

Table 7. A summary of the 1977 winter field measurements and comparison with the NPS model simulation.

Date	Observed Measurements					Simulated-NPS Model		
Mn Dy Yr	Depth In.	S. D. Depth	Water In.	S. D. Water	Density Percent	Depth In.	Water In.	Density Percent
12/ 1/76	0.00	0.00	0.00	.000	0.0	0.00	0.00	0.0
12/ 4/76	0.59	1.00	0.06	.110	11.0	0.29	0.05	15.7
12/19/76	1.53	1.08	0.54	.390	35.0	1.66	0.61	36.9
12/22/76	2.34	1.35	0.75	.432	32.0	2.31	0.75	32.6
12/30/76	2.18	1.47	0.65	.442	30.0	2.84	0.83	29.2
1/ 4/77	2.87	1.37	0.86	.411	30.0	3.32	0.90	27.1
1/ 8/77	5.30	1.43	1.17	.314	22.0	5.39	1.16	21.6
1/14/77	6.67	1.86	1.40	.390	21.0	6.79	1.38	20.3
1/21/77	4.50	1.46	1.30	.422	28.8	6.28	1.38	22.0
1/30/77	5.24	2.48	1.59	.754	30.4	6.57	1.53	23.3
2/ 5/77	5.18	2.60	1.53	.768	29.5	6.17	1.53	24.8
2/10/77	4.51	2.58	1.46	.836	32.4	4.49	1.46	32.6
2/11/77	2.97	3.12	1.10	1.157	37.1	2.44	0.88	36.0
2/12/77	2.08	2.53	0.82	.997	39.4	1.53	0.55	36.0
2/17/77	1.79	2.24	0.64	.797	35.6	1.34	0.49	37.0
2/25/77	3.62	2.26	1.04	.650	28.8	3.53	0.99	28.1
3/ 5/77	5.28	1.34	1.36	.345	25.8	4.76	1.46	30.8
3/ 9/77	1.15	1.66	0.38	.549	33.0	1.04	0.33	31.4
3/12/77	0.00	0.00	0.00	.000	0.0	0.00	0.00	0.0

Table 8. Calibration values for the coefficients used in the NPS snow model.

Coefficient	*Manitou Way Watershed	Eau Pleine Watershed	Eau Pleine Reservoir
RADCON	.250	.684	2.844
CCFAC	.250	.594	2.000
EVAPSN	.600	.640	.002
TSNOW	33.000	33.765	28.856
MPACK	.100	1.000	.864
DGM	.001	.001	.001
IDNS	.100	.274	.122
SCF	1.100	1.100	1.400
WMUL	1.000	1.000	1.800
F	.500	.500	.681
KUGI	8.000	3.000	9.576
RMUL	1.000	.990	.600
WC	.050	.117	.011

*Donigian and Crawford, 1976.

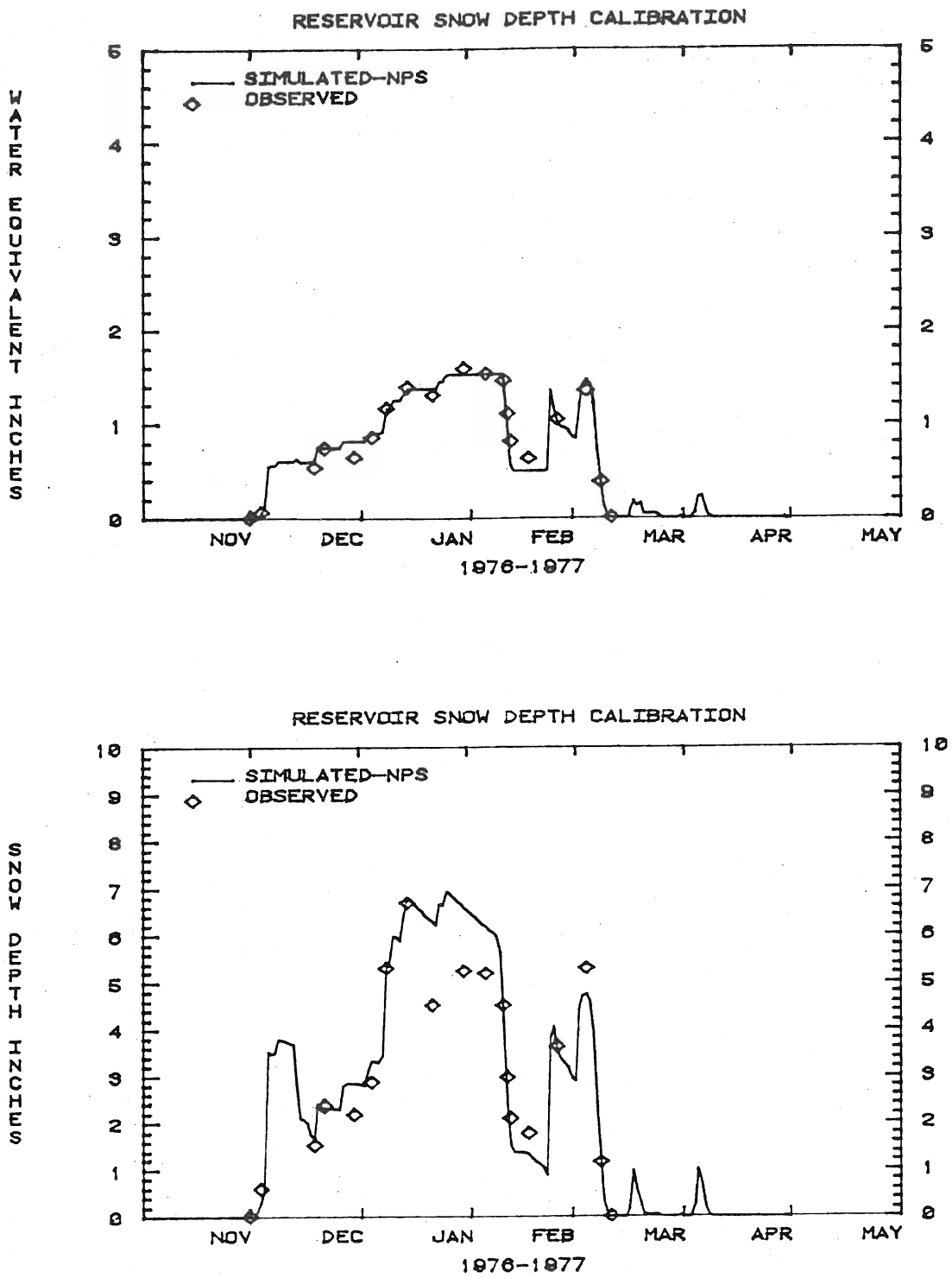


Figure 13. Comparison of observed and simulated reservoir snow water equivalent and snow depth.

Table 9. A statistical comparison between output from the NPS snow model and field data for the 1977 calibration period (inches).

	Sample Size	Intercept	Slope	Correlation Coefficient	Standard Error of Estimate
Water Equivalent	19	-0.018	0.999	.978	0.109
Snow Depth	19	-0.020	1.116	.964	0.611
Snow Density %	19	1.170	0.923	.957	3.160

High winds and frigid air temperatures which increase the settling rate of snow, typify this period of rapid compaction. Since the NPS model calculates compaction through an empirical formula where the increase in densification is constant with time, the discrepancy in simulating snow depth was expected. However, as the densification progresses from compaction to melt metamorphism the NPS model produces improved simulated snow depths. This relationship is evident in Figure 13. When a rapid melt occurred between February 5 and February 17, the model was in good agreement with the measured data.

Simulation and Application

Once calibrated the NPS model was used to simulate the winter periods extending from January 1974 through May 1976. Following the procedure used in the watershed predictions to simulate the 1974 winter the model was initialized with WVIC's December 31, 1973 snow measurements. Finally output from the four winter simulations were used in conjunction with Anderson's (1976) equations to predict the amount of solar

radiation present at the snow-ice interface.

Comparing the melt periods for the basin and reservoir simulations (Figure 14 to 17) shows a shallower snowpack being predicted for the reservoir during all four winters. This would be expected since the reservoir calibration amplified the NPS models melt components and phase dynamics. In particular the effectiveness of radiation, condensation and convection melt were notably increased for the reservoir simulation while only evaporation melt was reduced. To compensate for the reduction in evaporation the effectiveness of wind was increased thereby maintaining if not increasing the overall rate of evaporation and at the same time increasing the potential rate of condensation and convection.

Additional similarity during the four winters is the presence of an intermittent snowpack usually occurring by the end of March. This results in typically a two cycle melt season with the first melt being generally more prominent. Since significant snow accumulation commonly occur by January, the duration of the snow accumulation period prior to the first melt produces photosynthetically limiting solar radiation levels for approximately two months of the various winters (Figure 14 to 17).

While the melt seasons were similar during the four winters, differences occurred among the snow accumulation periods with dynamic variation demonstrated between the reservoir and basin simulations. The presence of a notable

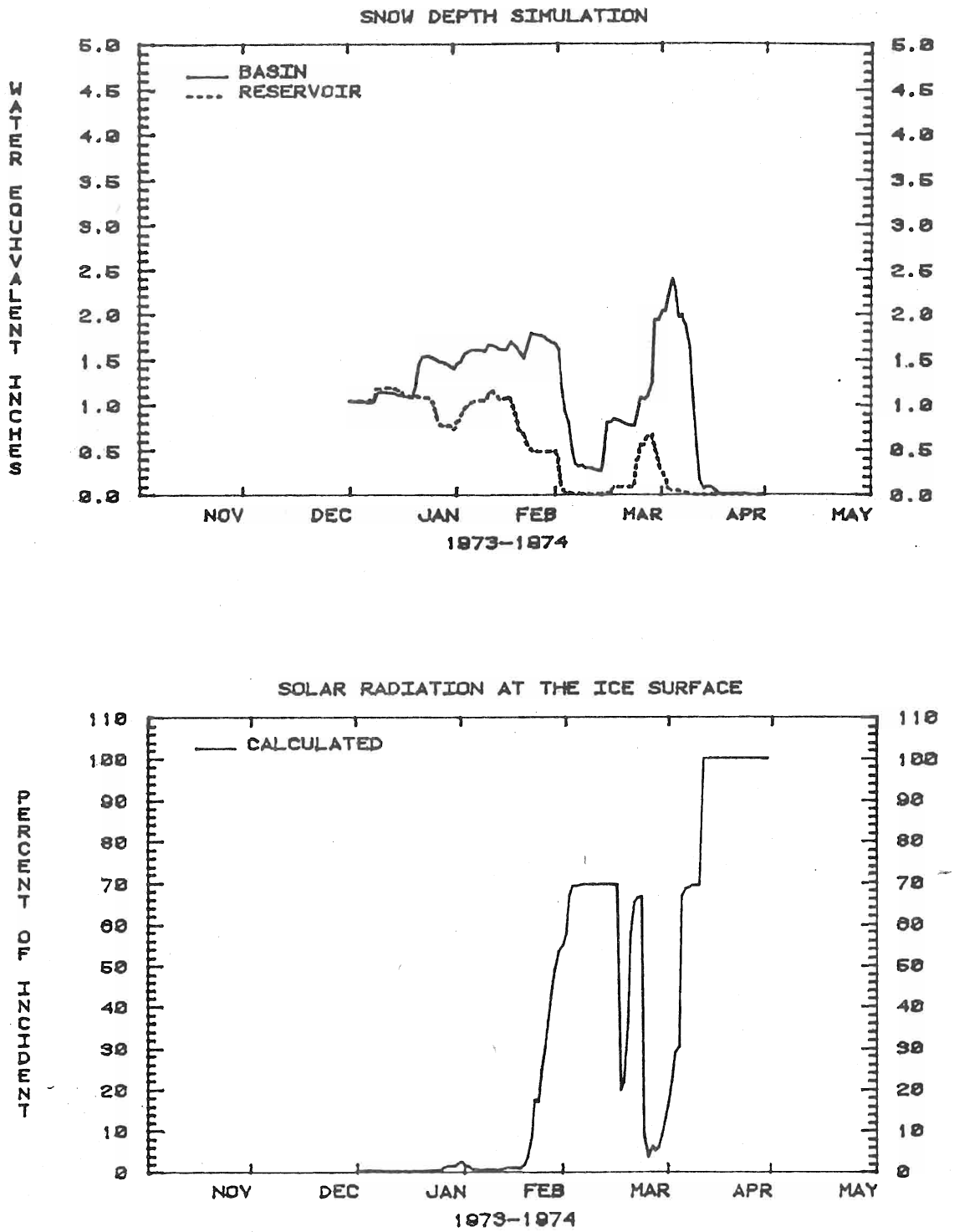


Figure 14. Comparison of the 1974 basin and reservoir snow simulations along with predicted incident solar radiation at the snow-ice interface.

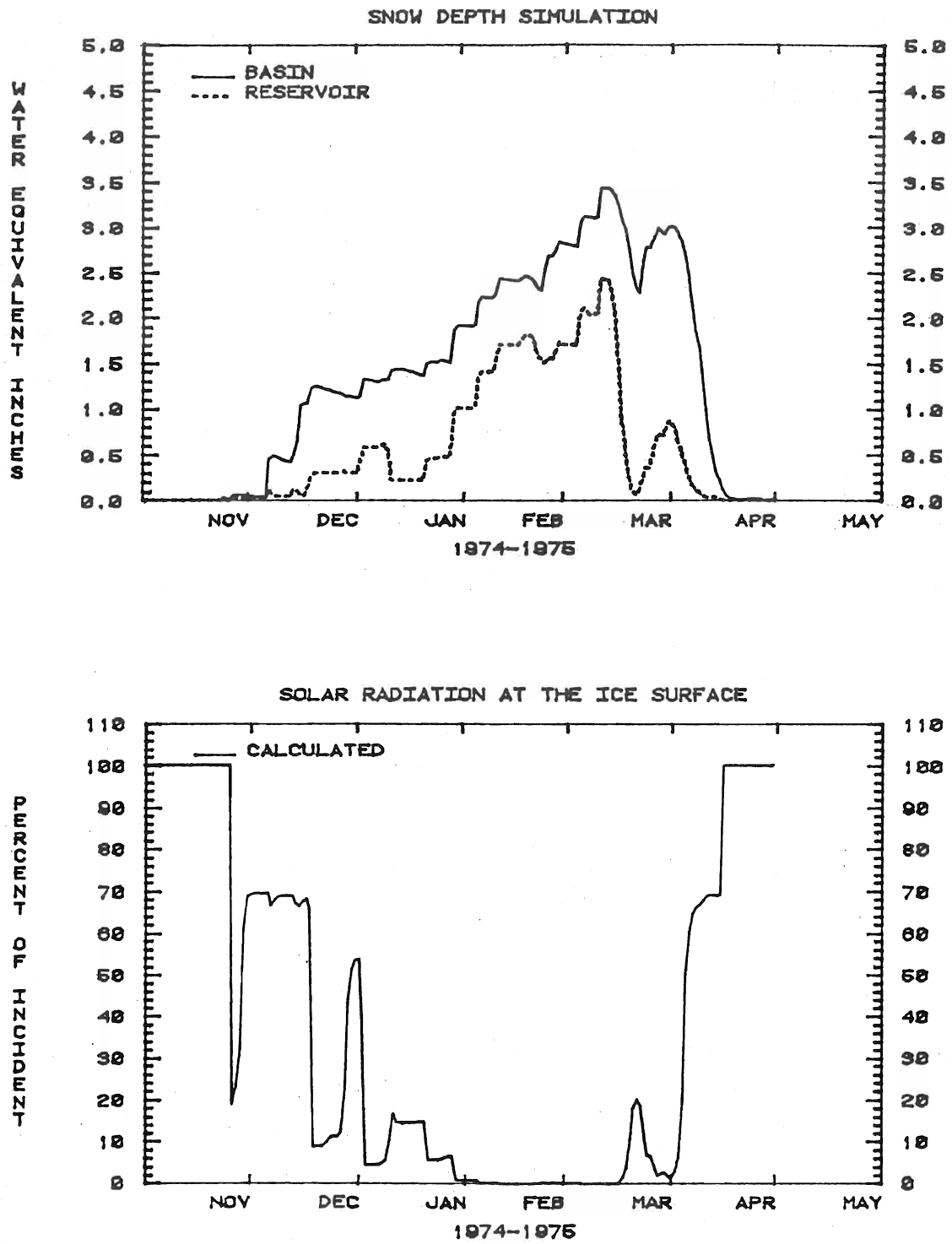


Figure 15. Comparison of 1975 basin and reservoir snow simulation along with predicted incident solar radiation at the snow-ice interface.

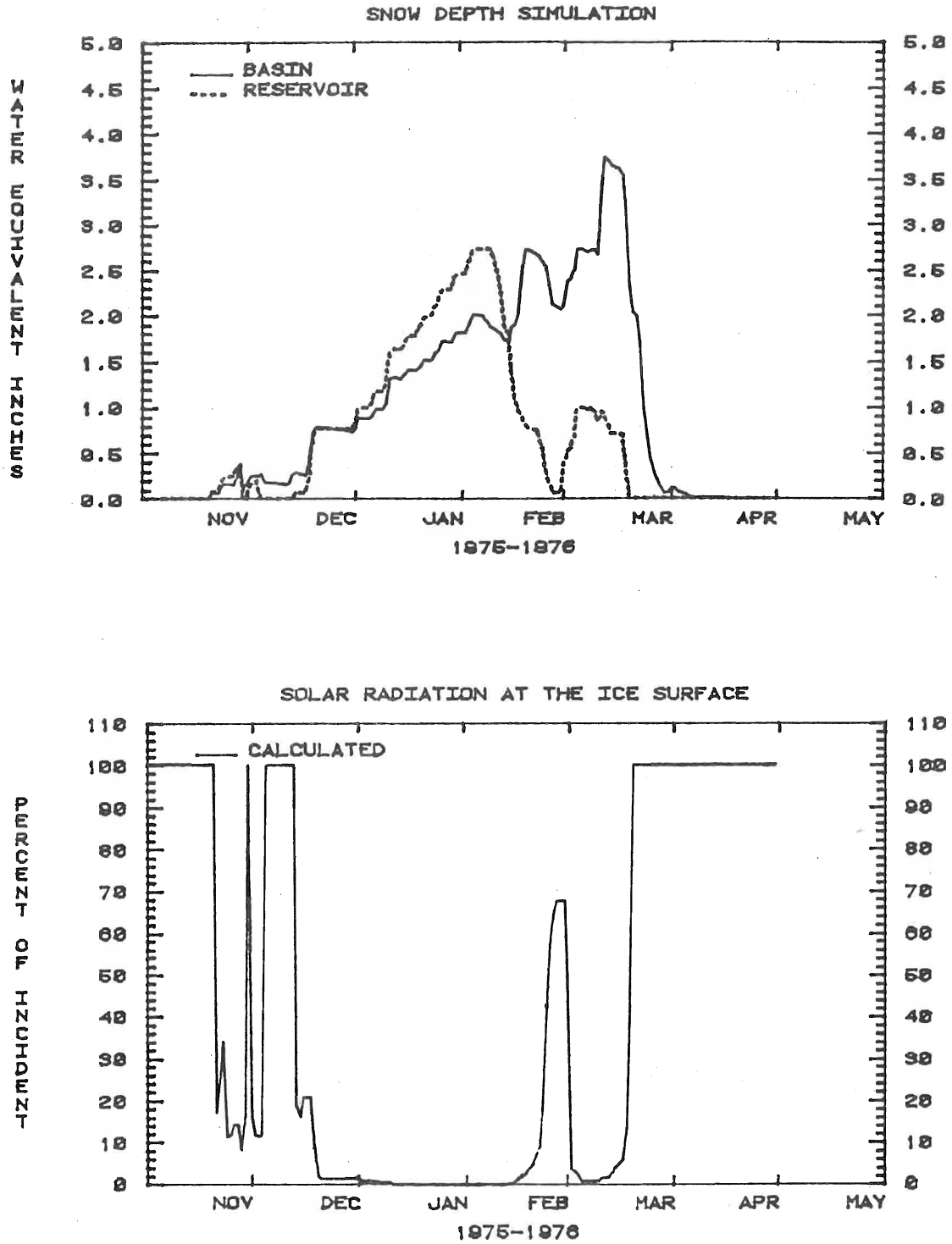


Figure 16. Comparison of the 1976 basin and reservoir snow simulation, along with predicted incident solar radiation at the snow-ice interface.

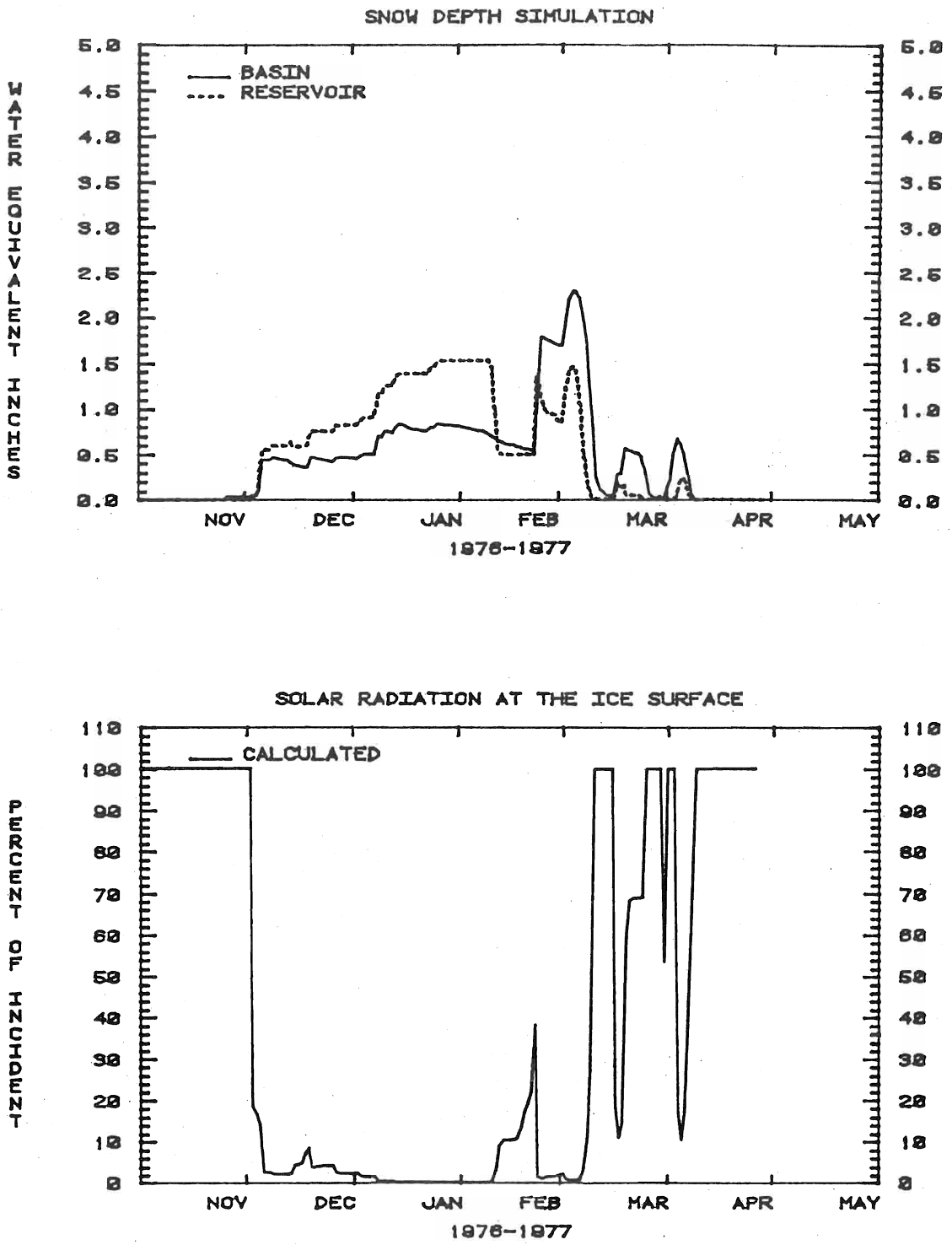


Figure 17. Comparison of the 1977 basin and reservoir snow simulation, along with predicted incident solar radiation at the snow-ice interface.

deviation between the reservoir and basin simulation was anticipated since one prediction is for a completely open area and the other for a partly forested area. In general greater snow accumulation during non-melt periods would occur in the open areas (Army Corps of Engineers, 1956) rather than the forest areas. Although sublimation-evaporation is greater for an open area, snow drifting also occurs to a greater extent. Since the reservoir is essentially at the base of the watershed, snowdrift from the surrounding watershed would cause a net increase in the snowpack.

Similarly, the reservoir does not experience snow loss due to interception as the forest area would. Although interception loss is of short duration, occurring up to about three days after a precipitation event, snow located on vegetation has an effectively large amount of surface area readily exposed promoting sublimation-evaporation processes. While the WVIC site is not heavily forest, Rowe and Hendrix (1951) have reported significant interception loss occurring in the order of 17% for a moderate forest stand with 40% cover density. Willen (et al, 1969) using snow hydrology data (Army Corps of Engineers, 1956) calculated a 14.7% interception loss for a stand of similar canopy density. Likewise, Leaf and Brink (1973B) utilized rates for interception loss ranging from 10 to 15% in their hydrologic simulation model. Additionally, Chow (1964) suggests interception loss for northern hardwoods of approximately 10%.

Only the 1976 and 1977 simulations show the greater snow accumulation for the reservoir compared to the forest situation. Significant melts were predicted during the accumulation periods for both 1974 and 1975. Since the amplified melt equations predicted even greater melt rates for the reservoir than the basin, the magnitude of the melts obscured the above processes during these two winters.

Verification

Ganf (1972) has shown that light attenuation and chlorophyll a concentrations in a column of lake water are directly related. Additionally, Wright (1964), studying the dynamics of a phytoplankton community in an ice cover lake, has reported that the development of a heavy snow cover effectively terminated photosynthesis due to low light conditions producing a decline in chlorophyll a concentrations and phytoplankton numbers. As such, a similar relationship would be expected in the reservoir during the gradual snow accumulation season when light conditions become limiting.

Sullivan (1978) has summarized chlorophyll a data collected from the Eau Pleine reservoir. Ten average surface measurements were obtained from his study for the time period of November 18, 1975 through March 15, 1976 (Table 10). Ignoring the minor effects of an ice cover, solar radiation predictions calculated by CLIMA from cloud cover observations made at Wausau FAA and attenuated through snow based on Anderson's equations and the NPS model's output,

were then compared to these measurements. Although this was a limited sample collected on the average bi-weekly, a significant correlation (alpha = .01) was obtained (r = .882).

Table 10. A comparison between solar radiation predictions and average surface chlorophyll a concentrations in the Big Eau Pleine Reservoir

Date Mn Dy Yr	Solar Radiation Langley/Day	*Chlorophyll a (ug/l) Sample Size	Mean	Standard Deviation
11/18/75	49.45	7	17.8	9.9
12/18/75	37.64	4	9.4	10.0
1/ 6/76	0.55	6	7.4	5.6
1/20/76	0.05	5	3.1	1.5
2/ 3/76	0.01	3	1.8	1.5
2/ 4/76	0.01	3	1.8	0.3
2/16/76	1.62	3	4.2	2.2
2/17/76	2.28	3	4.2	2.2
3/ 4/76	3.65	5	5.3	0.8
3/15/76	11.79	5	8.3	4.4

* Sampled at 0.5 meters (Sullivan, 1978)

Y (ug/l) = 3.48 + 0.248 X (ly)

r = .882, s = 2.33

Chlorophyll a concentrations decreased from November 18 to February 4 and increased from February 4 to March 15, paralleling predicted solar radiation levels. After March 15 the reservoir had been resampled April 5 showing a decrease in chlorophyll a concentrations. But, since Wausau FAA had last reported snow on the ground as of March 23 and the reservoir had completely refilled this decrease was probably due to diluation and therefore not used in the correlation.

Since chlorophyll a data parallels the predicted solar radiation levels showing a reasonable correlation supports

the validity of this study. Additional support is the fact that calibration procedures for the NPS model and the coefficients in Anderson's equations were based totally on data obtained during the 1977 winter, hence, 1976 represents a completely predicted winter.

Data and Modeling Limitation

WVIC Data

Previous discussion has shown that in some cases discrepancies arise between WVIC's measured data and conditions within the watershed. Although the data used in this report are the averages of 48 separate measurements, all of the measurements were made in a relatively small area. The large standard deviation associated with these measurements demonstrates the high variability in the snow cover.

Part of this variability could be an unintentional bias in response to the uneven terrain in the area. A large number of stones, due to both glacial erratic and float from bedrock were present in the sample area and could have influenced snow measurements. In particular, stones would interfere with the snow sampler, hence preferential site selection may occur.

The large amount of samples (48) in comparison to the recommended five (Army Corps of Engineers, 1956) indicate that the variability of the snow course has been recognized and an attempt is being made to obtain a "true" mean snow water equivalent by increased sample size. A potential drawback to this procedure is the possibility that increased sample size may increase sample variability without improving the attainment of a true mean. Presently the variability is such that for a statistical difference (alpha = .05) to occur between two consecutive sample dates, there must be approximately .25 inch difference in mean water equivalent for those

dates.

Alternatives to the above procedure include relocation of the snow course, statistical comparison of each of the 12 stations with respect to time to determine if one or more stations are continuously bias, and thirdly, installation of an additional snow course. If feasible, the combination of the statistical test, such as analysis of variance, to eliminate bias stations and the installation of a second snow course would provide the best solution. Considering that the present snow course is located in a wooded area and that only 14% of the Eau Pleine watershed is classified as woodland (Hansen, 1979), a second snow course located in a relatively open area would provide valuable data. Following this procedure, sampling at one snow course may be reduced while data obtained from the second course could be used to counter-check the first snow course and provide correction factors for past data.

Precipitation Data

The utilization of precipitation measurements made at Wausau 7SSW station (eight miles NE of BEP dam) for snow accumulation was based on the assumption that these measurements were representative of conditions existing in the Eau Pleine Basin. Discrepancies between simulated and observed water equivalent data could have occurred if this assumption was not correct or if errors exist in the weather data.

An apparent source of error in the precipitation data is the tendency for precipitation gauges to underestimate

the amount of precipitation during snow events (Army Corps of Engineers, 1956). The placement of a gauge relative to above ground obstructions, type of gauge and wind speed and direction all affect the accuracy a precipitation gauge has in measuring the actual precipitation (Larson, 1972). To reduce this problem, the two snow models use a procedure similar to other snow models (Anderson and Crawford, 1964; Crawford and Linsley, 1966; NWSRFS, 1972; Striffler, 1973). The procedure used involves adjusting a coefficient through calibration to increase all precipitation by a constant percentage. This percentage amounts to approximately a 10% increase in precipitation for the Eau Pleine watershed.

An additional source for error in the precipitation data is related to the amount of localization occurring in the overall snowfall period. Fortunately, the winter equivalent of a summer thunderstorm is relatively improbable and therefore not an influencing factor towards localized precipitation patterns. More important factors could be either measurement errors or the influence exerted by topographic features between the weather station and the Eau Pleine Basin.

A practical procedure for testing the continuity of a precipitation gauge or the presence of localized weather patterns is to compare that gauge with other precipitation gauges within the immediate area (NWSRFS, 1972). To use this procedure, winter monthly total precipitation data was obtained for precipitation gauges located at the Big Eau

Pleine dam, Marshfield (20 miles WSW of BEP dam), and Wausau FAA airport (15 miles NNE of BEP dam).

Utilizing the data for the four winters a statistical difference was not detected between the various precipitation stations (alpha = .05). Lack of a statistical difference demonstrates that strong localized precipitation patterns do not exist between the various stations and that overall if errors are occurring periodically in measuring precipitation at one station, similar errors are occurring at the other stations. This does not imply that all four stations are intermittently inaccurate in measuring precipitation, only that if errors do exist they are compensating type errors or errors not large enough to affect the statistical test.

Although a statistical difference was not detected in comparing the means of the precipitation stations, comparing each station separately with Wausau SS7 shows some differences. Using matched student's t tests statistical differences (alpha = .05) were not detected between the various stations but the results of regression and correlation analysis (Table 11) while showing strong correlations also have a relatively high standard error of estimate associated with those regressions. In particular, if either the Eau Pleine Dam or Wausau SS7 station were used in determining the "true" amount of precipitation and this data was then compared to actual events occurring within the basin, it would be possible that the measurements could be

on the average ± .165 inches in disagreement.

Table 11. A statistical comparison of winter monthly total precipitation for Wausau SS7 and nearby weather stations.

Weather Station	Sample Size	Intercept	Slope	Correlation Coefficient	Standard Error of Estimate
Wausau FAA	22	-.043	1.013	.959	.412
Eau Pleine Dam	22	-.068	1.033	.993	.165
Marshfield	22	-.083	0.992	.972	.333

The slope and intercept for the Wausau SS7 - Eau Pleine Dam regression are so close to ideality that the differences between the two stations must be compensating, therefore difficult to detect.

In regards to snow modeling the statistical tests demonstrate that any of four stations would provide compatible precipitation data. Since the Wausau SS7 station is the only one of the four stations to publish hourly data consistently, precipitation data from that station was used in this study. Even using data from this station calibration techniques have shown that, based on WVIC snow data, the precipitation data is on the average underestimated by 10%. Regression analysis between the Eau Pleine Dam and Wausau SS7 shows the potential for an error when using either stations precipitation data and that the error would be on the average a monthly maximum of ± .165 inches. Since this value is approximately one-half of the average standard deviation associated with WVIC measurements, its relative importance is reduced, but not eliminated.

Previous discussion has shown that there are limitations in the WVIC data while the present discussion demonstrates the limitations in precipitation data. Without an additional snow course and more consistent precipitation, measurements at other weather stations overcoming these limitations is improbable. Since this problem is not unique to this study, but rather common in hydrological modeling attempts, two remedial procedures occasionally used are further discussed.

Aerial analysis procedures, such as isohyets, Thiessen weights, or grid point weights are useful in calculating precipitation at a point where a gauge does not exist. In particular, these procedures are beneficial if the surrounding weather stations show diversity in their precipitation measurements (NWSRFS, 1972). Fundamentally none of these methods can result in a point estimate that is greater than the largest amount observed. Since calibration shows precipitation as being underestimated and statistics indicated the lack of diversity in the precipitation gauges, these procedures would not influence the simulations.

An alternative procedure sometimes justified is to alter the precipitation data so that simulations are comparable to measured field data. Not often recommended, an example where this procedure may be helpful is the situation where total simulated runoff is notably at variance with measured data for one year and previous simulations have verified the model. Since runoff was not being simulated

in this study, it could not be used to validate the altering of precipitation data nor confirm WVIC's snow measurements.

Computer Modeling Considerations

Computer modeling techniques attempt to approximate natural occurring processes through mathematical expressions. In this study the natural process of snow accumulation and melt are being calculated by equations defining both snowpack characteristics and energy transformations along with their corresponding interactions. Past studies show that exceptionally good results have been obtained in modeling the snow cover where extensive meteorological and verification data have been available (Anderson, 1976). Similarly, good results have been obtained in modeling mountainous regions where the snow accumulation and melt season are well defined (Leaf and Brink, 1973). However, modeling results are variable when input data is limited or where an intermittent snowpack is possible (Soloman, et al, 1976). Since both of these conditions are present in this study, some variability in results were expected.

One method of reducing the variability in results is to incorporate additional input data and correspondingly increase the complexity of the model. The superior results of the NPS model to the LEAF model reflect this method. A distinct drawback to this approach is that as the method is extended, the model can reach the complexity of that developed by Anderson in which the cost of obtaining input and supportive

data probably exceeds the value of the model's output. Hence, there is a limit to modeling complexity that is more often than not based on financial criteria. Since realistically this limit exists, it also reflects the amount of variability that is acceptable in the modeling efforts.

Snow accumulation and melt is a complex process which for modeling purposes is broken down into simplified components, relationships, generalities and when necessary, approximations. Literature shows that many of the major components involved in these processes are well understood at point measurements but that areal applications are variable. In particular, often the extensive data used to define these components limits their areal applications requiring instead some form of approximation. The approximations, in turn, since they are general relationships, usually require correction coefficients prior to being representative of the more complex natural mechanism. Unfortunately, correction coefficients are commonly variables requiring some form of calibration procedure. Although justification for calibration is usually based on regional difference, very little work has been conducted to insure that seasonal changes are not more important than regional variations.

Assuming that input and verification data are reasonable, simulations with both the LEAF and NPS model are in good agreement with the WVIC data for any of the four winters provided that the calibration variables are altered. However,

a two-year calibration period followed by two-year simulation period produces variable results. This would indicate that the calibration coefficients are affected to a greater degree by seasonal changes rather than regional variations.

The NPS model has 13 calibration coefficients with one or more coefficients affecting each of the major energy exchange and physical metamorphic processes. The large number of coefficients indicate that many of the equations in the model are only approximations each of which can contribute to the variability in the results. Although the LEAF model has only three coefficients, this study shows that the NPS model is the more stable of the two and that the LEAF model cannot account for annual variations versus regional changes. Therefore, even though the additional coefficients in the NPS model have the potential to increase variation in results, they do help reduce the effect annual variations can have in some of the major modeling components.

This does not imply that the NPS model would be a more accurate model if additional coefficients were incorporated. Incorporation of additional coefficients would statistically reduce the reliability of the model and increase the difficulty in performing calibration since many of the coefficients influence more than one snow process. In particular, within the NPS energy exchange calculations several of the coefficients interact in the equations making isolation of their effects impossible. Introducing additional coefficients to these equations would complicate calibration greatly.

Similar basic mechanisms for snow accumulation and melt are present in both the NPS and LEAF model. Literature shows intensive research has been conducted concerning these mechanisms and principles behind them so that the theory involved is fairly well understood. Major differences between the models arise from the assumptions made to utilize these basic components. Critical assumptions in both models deal with the amount and type of input data that is required. The greater amount of input data for the NPS model reduces the variability in predictions but increases the calibration effort. Similarly, the small amount of input data for the LEAF model allows for rapid calibration but instability during long term predictions. Both models, however, contain numerous assumptions and other approximations in their representation of the natural processes. As such, both models are performing a superficial representation of the natural system and variance from that system should be expected.

Computer Calibration

The calibration procedures used for both models were elaborate since they are designed to provide an objective calibration that could be used to compare the sensitivity of the two models. A serious limitation to this method is the large amount of computer time required before calibration is verified and the absence of familiarity with the model due to computer oriented calibration. Typical calibration procedures usually group and isolate coefficients based on both

the degree they control a model and the internal processes they have in common. With this procedure, gross calibration is first obtained using coefficients that dynamically control a model followed by refined calibration with the coefficients that exert only a small influence.

Conversely, in this study all of the coefficients were calibrated at the same time with the optimization routine controlling the order that the coefficients were adjusted. For the NPS model, three groups of 100 two-year simulations were performed to determine initial values, ranges and degree of adjustment for each of the thirteen coefficients. This was followed by a single run in excess of 1,000 simulations to determine the final values for the coefficients. Finally, a verification run consisting of approximately 500 simulations was performed.

A significant reduction in computer time would occur if manual calibration procedures were followed to provide gross calibration and then utilizing the optimization routine to perform the refined calibration. Similarly, a large portion of the verification run would be eliminated. In addition, incorporating this procedure the user would readily obtain a sensitivity analysis which could be used to evaluate the soundness and accuracy of the input and verification data, models predictions and the calibration procedure.

Predictive Tool for Solar Radiation

There are reservations associated with this procedure for predicting solar radiation penetration through

snow. In particular, the original assumption that the Lambert-Beer law is valid for snow or ice has been questioned in past studies (Yen, 1969 and Shishonin, 1969). Similarly, if the relationship is valid, then it is valid essentially only for a homogeneous snowpack. While the coefficients for Anderson's equations were calculated based on a multi-density snow cover, the NPS model was not designed to calculate such complicated predictions. Instead, the output represents the average snowpack density which calibration results have shown to have some inaccuracy. Furthermore, Anderson's basic equation relating snow density to snow grain size is in itself an empirical approximation. Likewise, previous discussion has already shown the potential sources of error present in modeling and data collection. Therefore, for these reasons this overall procedure has been referred to as calculating an "index" to solar radiation penetration through snow and as such some errors are expected.

Recommendations

Snow, a major component in the hydrologic cycle, is also an important commodity. Significant snow accumulations occur over 50 percent of the continental United States with some areas relying almost entirely on snowmelt for their freshwater supply. Similarly, snow plays an important role in the agricultural and hydroelectric industries. In many areas snow determines the location, timing and extensiveness of both these industries. Yet, the relative importance of

snow is not reflected in the quality of our weather collection system.

The inadequacy of our weather collection system has been the concern of many studies, however, improvements have not been noticeable. While there has been an increase in both the number of stations and amount of data they are collecting, the efforts have been directed mainly towards storm predictions. Although storm predictions provide valuable information, efforts should also be directed towards upgrading and standardizing the present system.

Precipitation gauges should be standardized so that both snow and rain correction factors are not required to determine areal precipitation. The measurement of solar radiation flux, incident and reflected, should be as common as air temperature. Also, measuring evaporation and soil temperature should be as significant as accurately recording wind speed. Similarly, during winter the temperature of the snowpack should be measured daily. Finally, the deficiency in representative snow depth, density and water equivalent measurements should be corrected.

Computer modeling efforts have increased dynamically in the past decade but presently appear to be reaching a crest where efforts are directed more towards providing correction coefficients and procedures for input data rather than restructuring and updating internal processes. With an increase in the quality and diversity of input data modeling efforts could be redirected making reliable predictions more feasible.

CONCLUSIONS

1. Theoretical equations for calculating solar radiation penetration through snow based on snow density showed a strong correlation with field measurements. Field measurements show results similar to other studies that as little as 10cm of low density snow present over ice is sufficient to inhibit photosynthesis by reducing solar radiation levels to less than 1%. However, field experience indicates the need for more durable radiation measuring equipment and a more accurate expression for relating snow grain size to snow density.

2. A comparison of the LEAF and NPS snow models indicate that, while both models show some difficulty in simulating certain conditions based on input weather data, the NPS model is superior to the LEAF model in predicting snow accumulation and melt in the BEP basin. Comparing NPS snowmelt with flow in the Big Eau Pleine River demonstrates a rapid response from the watershed with increasing river flow occurring two to four days after the start of the snowmelt period.

3. Snowmelt in the basin is typically two-phased with the second melt being more prominent, and thereby producing the highest flow. The reservoir tends to have greater snow accumulations than the watershed during non-melt periods. In addition, the process of snowmelt is more rapid on the reservoir than in the watershed. The typical dual melt cycle associated with the watershed occurs similarly

on the reservoir with the first melt usually more prominent.

4. Problems encountered in this study indicate notable improvements are needed in weather and snow data collection procedures and instruments. While computer modeling techniques have changed dynamically, procedures used to supply data for these models have undergone minimal refinement since their development. Clearly modeling efforts have reached a plateau where further advancement is hindered by the quality and quantity of supportive data.

5. This study demonstrates the feasibility of using theoretical relationships to calculate solar radiation penetration through snow and offers a practical application of combining these relationships with a snow model so as to construct a predictive tool. Similarly utilization of the predictive tool indicates solar radiation levels in the reservoir are limiting for algal growth during approximately two months each winter.

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