

MODELING DIRECT RECHARGE OF SURFICIAL AQUIFERS

By

Brian C. Knoch

Donald C. Slack  
and

Curtis L. Larson

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Principal Investigators:  
Donald C. Slack and Curtis L. Larson

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## ABSTRACT

A one-dimensional, physically-based computer model was developed for predicting direct groundwater recharge. The model was verified using three years of data from an instrumented site in east central Minnesota.

Although the processes of infiltration and redistribution during frozen soil periods were not modeled, the model is capable of operating during both frozen and non-frozen soil periods. The model includes submodels for evapotranspiration, soil water extraction, snowmelt, surface depressional storage, infiltration and redistribution. The model predicts water table level and soil moisture. Water extraction may also be modeled.

The model predicted both water table levels and soil moisture with reasonable accuracy over the three year period modeled.

KEY WORD DESCRIPTORS: \*Groundwater, \*Groundwater Recharge, \*Recharge Modeling, Soil Moisture, Infiltration, Evapotranspiration.

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A complete listing of the computer program developed in this study and the data used to verify the model are available on request.

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Symbols Used

Symbol		
a	i)	coefficient for the Thornthwaite (1948) equation
	ii)	depth storage parameter for the Mitchell and Jones (1976) equation
	iii)	empirical constant for the Holtan (1961) equation
	iv)	constant for the Philip (1957) equation
	v)	constant for Gardner's (1970) redistribution equation
A		albedo
AET		evapotranspiration to extract from a given soil layer for a given time step (inches)
b	i)	depth storage parameter for the Mitchell and Jones (1976) equation
	ii)	absolute slope of the suction versus moisture content curve plotted on a log-log scale
	iii)	constant for Gardner's (1970) redistribution equation
c	i)	constant for the Thornthwaite (1948) equation
CET1		daily input parameter for the proposed recharge model
CET2		daily input parameter for the proposed recharge model
CH		correction coefficient for relative humidity Hargreaves (1974) equation
d		saturation vapor pressure at the mean dew point (mb)
DELTA		time step (hours)
Dm		maximum soil surface depth (inches)
D1		thickness of the upper of a pair of soil layers (feet)
D2		thickness of the lower of a pair of soil layers (feet)
e	i)	monthly evaporation for the Thornthwaite (1948) equation
	ii)	natural exponent

E		evaporation flux ( $\text{cal}/\text{cm}^2$ ) Jensen et al. (1971)
EI		interception loss
EK		fraction of the daily evapotranspiration occurring in a given four hour period (Anderson et al, 1978)
ENT		ending time of precipitation (24 hour clock)
EPAN		daily pan evaporation (inches)
ES		evaporation from open water, bare soil, and surface storage
ET		daily evapotranspiration for a given crop not limited by water (inches)
ETR		evapotranspiration ratio (Moore and Larson, 1979)
F	i)	forest coverage coefficient (Riley et al, 1972 )
	ii)	accumulated infiltration volume (inches)
fc		constant infiltration rate (in/hr) (Holtan, 1961)
fp		infiltration capacity (in/hr)
Fs		infiltration volume to the time of surface ponding (inches) (Mein and Larson; 1971,1973)
G	i)	heat flux to or from soil ( $\text{cal}/\text{cm}^2$ )(Jensen et al, 1971)
	ii)	energy transferred between the surface and air
GF		net groundwater flow
GW		change in groundwater storage
H		energy used for evapotranspiration
hfg'		latent heat of vaporization of water, at wet bulb temperature
I		rainfall intensity (in/hr)
IET		indicator for the method of calculating the daily evapotranspiration in the proposed recharge model
IMD		initial moisture deficit
JDAY		julian day
k		degree day factor

km		constant = .75 (Riley et al, 1972)
kv		$e^{*(-4F)}$ (Riley et al, 1972)
K		hydraulic conductivity (in/hr) a function of the soil moisture content
KC		crop coefficient
KP		pan coefficient (Doorenbuis and Pruitt, 1975)
KPC		combined pan-crop coefficient
Kr		relative hydraulic conductivity (Moore, 1979) a function of moisture content (in/hr)
Ks		saturated hydraulic conductivity (in/hr)
ln		natural logarithm
M	i)	snowmelt (inches)
	ii)	miscellaneous energy term (photosynthesis)
Ma		snowmelt for a given time step (inches)
MF		day length factor (Hargreaves, 1974)
Mr		snowmelt due to rainfall (inches)
Mo		initial soil moisture content at the soil surface (percent)
OF		net overland flow of water
P		rainfall (inches)
PATTERN		extraction pattern
Pcl		percent clay in the soil
PET		potential evapotranspiration (Penman, 1948)
POT		gravity potential (ft)
PR		daily precipitation (inches)
PREDAY		daily precipitation (inches)
Pswb		saturation vapor pressure at wet bulb temperature (psi)
Pv		vapor pressure (psi)

$\Delta S$		change in surface depression storage (inches)
$t$		time
$T$	i)	mean daily temperature (Deg F)
	ii)	mean monthly temperature (Deg F)
$T_a$		air temperature (Deg F)
$T_A$		air temperature (Deg F)
$T_{db}$		dry bulb temperature (Deg R)
$T_e$		equilibrium temperature (Deg F)
$TINC$		time increment (hours)
$t_p$		time to ponding (hours)
$t_p'$		the equivalent time to infiltrate volume $F_s$ under ponded conditions
$TPMNP1$		minimum daily temperature for the next day (Deg F)
$TPMXP1$		maximum daily temperature for the next day (Deg F)
$T_{wb}$		wet bulb temperature (Deg R)
$W$	i)	soil water content in the redistribution zone
	ii)	total daily wind run (miles)
$z$		distance below the soil surface (feet)
$\Delta$		slope of the saturation vapor pressure-temp curve
$\Psi$		soil water potential
$\theta$		volumetric moisture content
$\gamma$		the psychrometric constant

Chapter 1INTRODUCTION

A large percentage of Minnesota's 500,000 acres of irrigated farmland is located in areas of shallow surficial aquifers. These areas are characterized by sandy surface soils which have high potential infiltration rates. As a result, a significant amount of direct recharge by percolation can occur depending on rainfall. Due to an increase in irrigated acreage, however, concern has developed about excessive groundwater withdrawals.

The Minnesota Department of Natural Resources, which has the responsibility for granting permits for irrigation wells, generally lacks sufficient information concerning recharge and aquifer characteristics. Until recently, groundwater had been neglected in water resource planning because it was not believed that it could be adequately evaluated (More, 1980). But due to the extensive work which has been done in the areas of soil water movement and groundwater flow, it should be possible to model soil moisture flow to and from the water table. Such a model, then, could be used by the Department of Natural Resources or consulting firms to predict direct recharge to surficial aquifers. This could aid in the decision of issuing well permits and in the evaluation of methods to increase recharge.

Movement of water from the soil surface to the water table involves (1) the penetration of the soil surface (infiltration) (2) the downward movement of water through the zone of aeration or partially saturated soil (redistribution), and (3) the accumulation of the water at the zone of saturation, which causes a rise of the watertable (groundwater

recharge).

Groundwater recharge occurs when the soil profile is fully replenished with water. Any additional water which flows into the soil is transferred down through the profile in response to gravity and eventually reaches the water table. Recharge can occur both as a result of precipitation or irrigation and from a water body, such as a stream which is above the water table of an aquifer.

#### Objectives of study

In order to predict direct recharge of surficial aquifers the following objectives were set up:

- 1) To develop a one-dimensional mathematical model which can predict direct recharge on a daily basis and which uses input parameters which can be readily measured or obtained.
- 2) To verify the model by instrumenting a test site and applying the model to the test site.
- 3) To apply the model to a hypothetical irrigation situation and predict the effect of irrigation on direct recharge.

## Chapter 2

### LITERATURE REVIEW

#### General

Groundwater is but one part of the earth's hydrologic cycle. Linsley et al. (1949) give a schematic representation of this cycle which is shown in Figure 2.1. The role groundwater plays in this dynamic system is described by Chow(1964):

Groundwater originates for all practical purposes as surface water. Water infiltrates into the ground from natural recharge of precipitation, streamflow, lakes, and reservoirs. In addition, efforts by man constitute artificial recharge. Once underground, the water moves downward, under the action of gravity. When a zone of saturation is reached, the water flows in a direction controlled by the hydraulic boundary conditions. Discharge of groundwater represents a return of the water to the earth's surface. Most discharge is into surface-water bodies. Spring flow, evaporation, and transpiration are other modes of discharge. Pumping of wells is the primary artificial discharge method.

After examining seventeen years of soil water data at Lamberton, Minnesota, Baker et al. (1979) concluded that there are four stages of soil water which can be generalized to any part of the world having a continental climate with a frozen soil period and a major portion of the precipitation occurring during the growing season. These four stages are :

1. Grand consumption stage - a period of relatively rapid and steady drawdown of soil water. (crop use)
2. Fall recharge stage
3. Frozen stage - little water enters the soil because it is frozen.
4. Spring recharge stage - precipitation generally exceeds water loss to the atmosphere.

Holt and Van Doren (1961) found that the fall recharge stage is the major and most efficient of the soil recharge periods. Baker et

al. (1979) confirmed this but indicate that because soil water is seldom in excess in the fall, additions to the groundwater are generally limited to the spring.

Table 2.1 (Freeze and Cherry, 1979) summarized the mechanisms that lead to fluctuations in the groundwater level. Bianchi and Haskell (1966) observed large rises in observation wells in shallow unconfined aquifers during heavy rainstorms. They explained that if the rainfall is intense enough, an inverted zone of saturation is formed at the ground surface and the advancing wetting front traps air between itself and the water table. This results in air pressures greater than atmospheric just above the water table which drives the water level temporarily up in the observation well. Meyboom (1967) examined the water table record in a river valley in western Canada. He found a diurnal fluctuation with drawdown occurring during the day as a result of phreatophytic consumption and recovery occurring at night when the plant stomata are closed. Peck (1960) studied gaseous bubbles entrapped in unsaturated soil and developed the theory of water table fluctuations due to atmospheric pressure change. Chow (1964) states, however, that changes in atmospheric pressure have no effect on water table levels if air entrapped below the water table can be neglected.

Stephenson and Zuzel (1981) studied natural groundwater recharge characteristics for a semi-arid rangeland environment in southwest Idaho. Recharge to the groundwater occurred via infiltration through

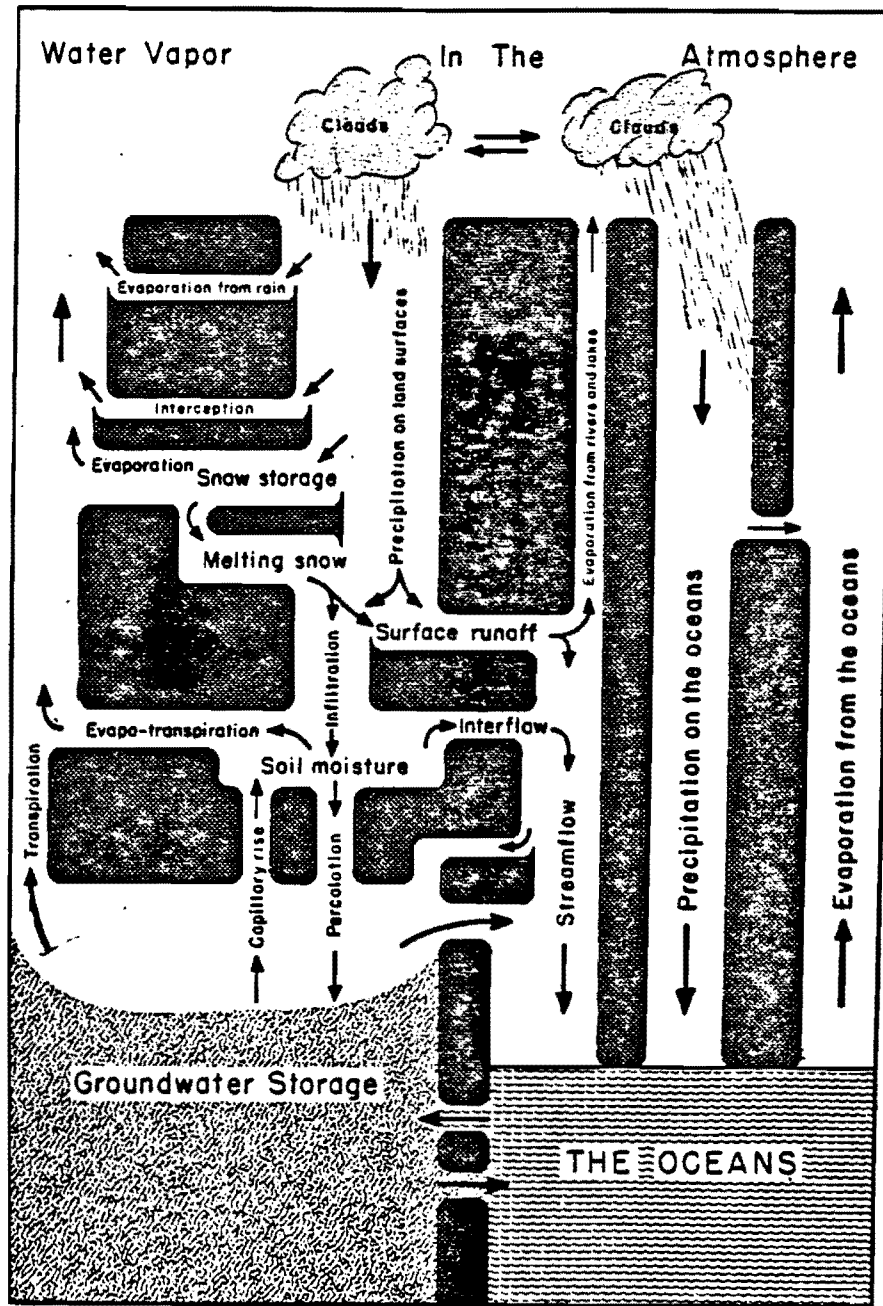


Figure 2.1 The hydrologic cycle. (after Linsley et al. 1949)

Table 2.1 Summary of mechanisms that lead to fluctuations in groundwater levels. (after Freeze and Cherry, 1979)

	Uncon- fined	Confined	Natural	Man- induced	Short- lived	Diurnal	Seasonal	Long- term	Climatic influence
Groundwater recharge (infiltration to the water table)	✓		✓				✓		✓
Air entrapment during groundwater recharge	✓		✓		✓				✓
Evapotranspiration and phreatophytic consumption	✓		✓			✓			✓
Bank-storage effects near streams	✓		✓				✓		✓
Tidal effects near oceans	✓	✓	✓			✓			
Atmospheric pressure effects	✓	✓	✓			✓			✓
External loading of confined aquifers		✓		✓	✓				
Earthquakes		✓	✓		✓				
Groundwater pumpage	✓	✓		✓				✓	
Deep-well injection		✓		✓				✓	
Artificial recharge; leakage from ponds, lagoons, and landfills	✓			✓				✓	
Agricultural irrigation and drainage	✓			✓				✓	✓
Geotechnical drainage of open pit mines, slopes, tunnels, etc.	✓			✓				✓	

low-relief rubbly basalt outcrops, infiltration through shallow surface soils, and transmission through bedrock channels during runoff and channel flow. They reported that the time from the end of a precipitation event to the peak of the groundwater hydrograph was independent of season and depended only on the soil depth.

### Modeling

A watershed model must satisfy the principles of mass and energy conservation. Mass conservation commonly is expressed in the form of a water balance equation. Hewlett and Nutter (1969) express the soil water balance as:

$$P = EI + ES + ET + SM + GW + S + SN + OF + GF + SF \quad (1)$$

where P = precipitation

EI = interception loss  
 ES = evaporation from open water, bare soil, and surface storage  
 ET = transpiration  
 SM = change in soil moisture storage  
 GW = change in groundwater storage  
 S = change in surface storage  
 SN = change in snow storage  
 OF = net overland flow of water  
 GF = net groundwater flow  
 SF = net lateral subsurface flow: interflow

The energy budget can be written as follows (Rose, 1966):

$$R_s *(1 - A) = R_l + G + H + LE + M \quad (2)$$

where  $R_s$  = incoming shortwave radiation  
 A = albedo of the surface  
 $R_l$  = net longwave radiation  
 G = energy transferred between surface and air  
 H = energy used for evapotranspiration  
 M = miscellaneous energy terms such as photosynthesis

Use of the energy balance concept has not been used much in watershed modeling due to the lack of adequate data recording networks and the

lack of experimental work (Fox,1976).

Snyder and Stall (1965) indicate two general methods by which hydrologic models are developed: stochastic and deterministic modeling. Stochastic modeling relies on the use of statistics and often is used when the process to be modeled is not well understood or is too difficult to be modeled using mathematical methods. Deterministic modeling uses mathematical methods or theory to develop an equation or set of equations to model a process. For a given input, a deterministic model always produces the same output.

Ali et al. (1980) used probability theory to predict the flow of water through stratified soils. Rennolls et al.(1980) developed a first order autoregressive model to describe the response of the water table level in a borehole to a series of rainfall events. Jackson et al. (1973) used time series analysis to examine climatologic and hydrologic variables associated with a groundwater discharge area in Manitoba, Canada. They were able to adequately model daily groundwater evapotranspiration and inflow rate with a first-order Markov process.

Freeze (1969) reviewed sixteen papers written between 1952 and 1968 which develop mathematical methods for modeling one-dimensional vertical, unsaturated, unsteady flow. Models of this type have also been developed by Hanks et al. (1969) and Nimah and Hanks (1973) to predict one-dimensional evapotranspiration, infiltration, redistribution, and drainage.

King and Lambert (1976), using an IBM Continuous Systems Modeling Program, developed a dynamic simulation model to trace the movement of precipitation to the water table. The model was successfully applied

to a Piedmont watershed with a water table at approximately 66 feet.

Skaggs (1978) developed and tested a water management model for shallow water table soils. The model was verified at three field sites with a total of five water management treatments which were applied over a five year period. The model can simulate on a day-to-day, hour-by-hour basis the water table position, soil water content, evapotranspiration, and surface runoff in terms of climatologic data, soil properties, crop parameters, and the water management system design.

#### Evapotranspiration

Evapotranspiration is the combined loss of soil water due to evaporation from the soil and transpiration from plants. The concept of potential evapotranspiration, PET, is defined by Penman (1948) as the rate of evapotranspiration from a 3 to 6 inch tall green grass crop of uniform height, actively growing, completely shading the ground, and not short of water. Other definitions of potential evapotranspiration have been given by Jensen (1973) and Miller (1977). These definitions are similar to Penman's except they refer to a "short reference crop" rather than to grass.

Schwab et al. (1966) groups the basic methods of predicting evaporation and evapotranspiration:

- 1) Mass Transfer. This method is based on the concept that moisture moves away from evaporating and transpiring surfaces in response to turbulent air and the vapor pressure gradient. Thornthwaite and Holzman (1939) and Pasquill (1949) have proposed models of this type. The measurement of wind velocity and

humidity for at least two elevations is often required which tends to make models of this type impractical.

2)Energy Balance. Since energy is necessary for evaporation of water, radiation or heat supplied is used as a measure of evaporation. The Penman (1956) equation uses this approach.

3)Empirical Methods. These methods are based on field research or experience and generally make use of the assumption that the energy available for evaporation is proportional to the temperature. Thornthwaite (1948), Blaney and Criddle (1950), Hargreaves (1974), and Tan and Fulton (1980) use equations of this type.

The empirical relationship of Thornthwaite (1948) can be stated as:

$$e = c*(T**a) \quad (3)$$

where e = monthly evaporation  
 T = mean monthly temperature  
 a,c = coefficients which vary according to the site.

Jensen et al. (1971) developed an energy balance method to estimate potential evapotranspiration by modifying an equation by Penman (1958).

$$E = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} (15.36)(1.0 + 0.01W)(e_s - e_d) \quad (4)$$

where E = evaporative flux (latent heat) (cal/cm\*\*2)  
 R<sub>n</sub> = daily net radiation (cal/cm\*\*2)  
 G = heat flux to or from soil (cal/cm\*\*2)  
 Δ = slope of the saturation vapor pressure-  
 temperature curve  
 γ = the psychrometric constant  
 s = mean saturation vapor pressure (mb)  
 d = saturation vapor pressure at the mean dew point  
 temperature (mb)  
 W = total daily wind run (miles)

Hargreaves (1974) did a regression analysis on a number of climatic data measurements (dewpoint, solar radiation, day length, mean temperature, etc.) and came up with an equation to estimate evapotranspiration based on mean daily temperature, mean daily relative humidity, and day length. The Hargreaves equation can be written as follows:

$$PET = MF * T * CH \quad (5)$$

where PET = potential evapotranspiration as defined by Penman (1948) (inches/day)  
 MF = day length factor dependent on latitude and time of year  
 T = mean daily temperature (degrees F)  
 CH = correction coefficient for relative humidity  
 CH = 0.166(100 - RH)\*\*0.5 for RH.LT.64  
 CH = 1.00 for RH.GE.64  
 RH = mean daily relative humidity (%).

Evapotranspiration also has been related to pan evaporation. Tan and Fulton (1980) give the pan equation as:

$$PET = KP * EPAN \quad (6)$$

where PET = potential evapotranspiration as defined by Penman (1948)(inches/day)  
 KP = pan coefficient  
 EPAN = daily pan evaporation (inches)

For a given crop not limited by water, the evapotranspiration is often given by:

$$ET = KC * PET \quad (7)$$

where ET = evapotranspiration for a given crop not limited by water (inches/day)  
 KC = crop coefficient  
 PET = as defined in equation (6)

A number of researchers, Denmead and Shaw (1962); Doorenbuis and Pruitt (1975); Baker et al. (1979); Sharrett(1982), found the crop coefficient to be a function of the stage of the crop.

As the soil dries due to evaporation and plant water uptake, the actual evapotranspiration rate falls below that for a crop not limited by water (Denmead and Shaw, 1962). A number of different theories exist regarding the reduction of evapotranspiration as soil moisture decreases.

Viehmeyer and Hendrickson (1955) assumed that the crop had adequate moisture down to the wilting point. At wilting point the evapotranspiration dropped to zero. Thornthwaite (1948) suggested field capacity as the "break point" and then assumed the actual evapotranspiration to decrease steadily to zero at wilting point. Moore and Larson (1979) used the linear depletion model shown in Figure 2.2. Idike (1981) found the linear depletion scheme to be valid but used one of three depletion lines depending on whether the day was judged to be a high, moderate, or low evaporative demand day.

Anderson et al. (1978) found evapotranspiration to vary with the time of day. Table 2.2 shows the percentage of daily evapotranspiration which they found to occur during the six four-hour periods for a watershed in west central Iowa.

Gardner (1964) developed a mathematical theory describing water uptake by non-uniform root systems. Warrick and Lomen (1981) assumed plant water uptake to decrease exponentially with depth. Saxton et al. (1974) and Baier and Robertson (1965) divided the rooting zone into a number of layers and then allowed a percentage of evapotranspiration to be extracted from each layer. The percentage extracted from each layer was a function of the time of year, thus simulating the growth of roots into the soil.

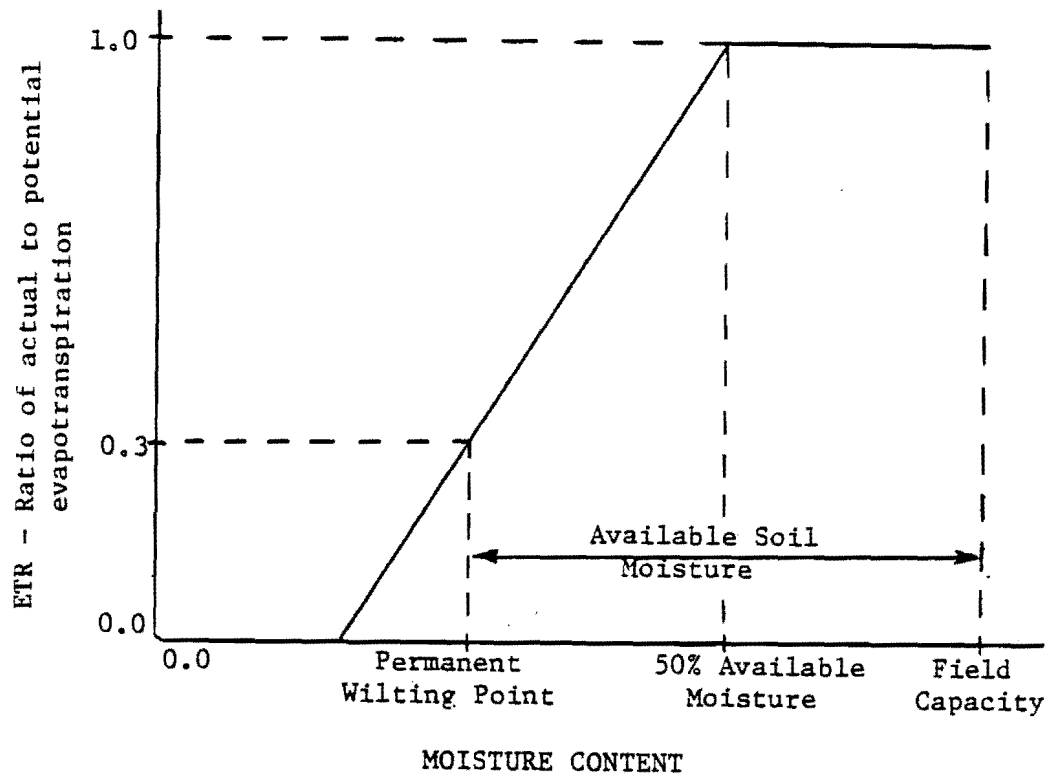


Figure 2.2 Evapotranspiration ratio versus moisture content (after Moore and Larson, 1979).

Table 2.2 Percent evapotranspiration for 4-hour time intervals for a day divided into six periods (after Anderson et al., 1978).

Time interval	Percent of daily Evapotranspiration
12am-4am	2.4
4am-8am	4.8
8am-noon	29.0
noon-4pm	39.7
4pm-8pm	19.5
8pm-12am	4.6

Most of the existing evapotranspiration models were developed for application to irrigation scheduling or for water management to optimize plant growth (Pierce, 1958; Jensen and Haise, 1963; Stegman et al., 1977 ; etc.). Federer (1979) developed a model to simulate evapotranspiration from a layered soil which is based on theory developed by Cowan (1965) for uptake of water by roots and Monteith's combination equation for water flow in the atmosphere (Monteith, 1964). Other evapotranspiration models have been developed by: Saxton et al. (1974), Shaw (1963, 1964), Ritchie (1972), Van Bavel and Ahmed (1976), Kanemasu et al. (1976), etc.

#### Interception

Interception, as defined by McMillan and Burgy (1960), is the process of aerial redistribution of precipitation by vegetation. Generally interception or interception loss has been taken to mean the precipitation that fails to reach the ground beneath a vegetative canopy. Horton (1919) classified interception loss into 2 elements, interception storage and evaporation, thus recognizing the role evaporation plays in the interception process.

Noting the effect of interception on soil moisture depletion, Christiansen (1942) stated that water on foliage should temporarily reduce evaporation from the soil surface and transpiration from the vegetation. Burgy and Pomeroy (1958) studied the use of water by grass and found the evapotranspiration from wetted and unwetted grass to differ little. These results were again confirmed by McMillan and Burgy (1960) leading them to conclude that transpiration was reduced when leaf surfaces were wet.

In reviewing interception modeling, Fox (1976) found that most watershed models use a fixed maximum interception storage capacity which is filled before rain reaches the ground. Evapotranspiration occurs first from interception storage and, if the evapotranspiration demand exceeds the storage, then from the soil moisture root zone.

#### Snowmelt

Khanjani and Molnau (1982) list seven parameters which have major effects on the rate of snowmelt. They are:

1. Net short and long wave radiation
2. Air and snow temperature
3. Snow surface and air vapor pressure
4. Wind speed
5. Type and intensity of precipitation
6. Watershed location (aspect, slope, latitude, and elevation)
7. Watershed vegetation coverage and pattern.

The energy balance is one method of predicting snowmelt rate. All energy and mass exchanges across the boundaries of the snowpack are estimated. Net radiation flux, heat transfer by conduction from the soil, turbulent transfer of latent heat, energy associated with the flux of melt water, and latent energy associated with precipitation are some of the necessary parameters which may be needed for a model of this type. As a result, this method demands much detailed data which sometimes are not available. Anderson (1976), Oblad and Rosse (1977), Granger and Male (1978), Moore and Larson (1979), Fitzgibbon and Dunne (1980), and Kuusisto (1980) discussed and applied the energy

balance method.

Another method to estimate snowmelt rate is the semi-empirical model. In this type of modeling the rate of snowmelt is computed using equations which have theoretical basis but which are simplified for field use. Model parameters may be correlated to one or more meteorological and watershed parameters such as mean air temperature, wind speed, and forest cover. The Corps of Engineers (1956,1960) developed and have heavily tested models of this type. Hendrick and Filgate (1971) also applied a semi-empirical model to a number of different watersheds.

One type of semi-empirical model which has received much attention is the degree-day-model. This model predicts snowmelt by correlating melt with degree-days or degree-hours. Garstka (1964) defines a degree-day as "a unit expressing amount of heat in terms of the persistence of a temperature for a 24 hour period for one degree Fahrenheit departure from a reference temperature." The general equation for a degree-day or degree-hour model is:

$$M = k( T_a - T_e) \quad (8)$$

where M = snowmelt rate

$T_a$  = air temperature

$T_e$  = base temperature or equilibrium temperature

k = degree-day factor

Equilibrium or base temperature is defined by Bengtsson (1976) as "the temperature at which no net transfer of heat takes place between air and snow". Bengtsson (1976) developed an equation to estimate equilibrium temperature as a function of albedo, wind speed, solar radiation, and forest coverage coefficient. Riley et al. (1972)

assumed the equilibrium temperature as a constant, 32 degrees Fahrenheit. King (1976) determined the equilibrium temperature as a function of the julian day.

Kuusisto (1980) states that the degree-day factor is not constant throughout the snowmelt season. It usually increases when the snow ripens and solar radiation becomes more intensive. King (1976) assumed the degree-day factor to be a function of the sum of degree days after snowfall, vegetation cover, and a constant which is calculated from the watershed slope, aspect and latitude. Riley et al. (1972) determined the degree-day factor,  $k$ , as:

$$k = k_m * k_v ( R_{Is}/R_{In} ) ( 1 - A ) \quad (9)$$

where  $k_m$  = constant = .75

$k_v = \exp(-4F)$

$F$  = forest coverage coefficient

$(R_{Is}/R_{In})$  = solar radiation ratio

$R_{Is}$  = insolation on the snowmelt surface

$R_{In}$  = insolation on a horizontal surface

$A$  = albedo of the surface

Anderson (1973) used the degree-day method to predict clear weather melt periods. Riley et al.(1972), Bergstrom (1975), Hendrick and DeAngelis (1976), King (1976), Bengtsson (1976), and Khanjani and Molnau (1982) all used various degree-day methods to estimate snowmelt.

#### Surface storage

Water reaching the soil surface, if it does not immediately infiltrate or runoff, goes into surface storage. Various surface treatments have been examined in order to alter the available surface storage in hope of decreasing runoff (Allmaras et al,1966,1967; Allmaras, 1967;Burwell et al.,1963,1966,1968;Mannering and

Burwell, 1968; etc.).

Mitchell and Jones (1976) express the equation for micro-relief storage as:

$$S_m = a * (D_m^{**b}) \quad (10)$$

where  $S_m$  = maximum surface storage

$D_m$  = maximum soil surface depth

$a, b$  = depth storage curve parameters

$$\log a = -0.6584 - 0.12877 * D_m$$

$$\log b = 0.46046 - 0.38039 * a + 0.18921 * \log(a) - 0.33797 * \log(a * D_m)$$

Mitchell and Jones (1978) quantified the effect of rainfall intensities and duration on the micro-relief surface depression storage. They presented a number of equations for predicting the change in micro-relief surface storage during a rainfall event. Each predictor equation is given as a function of a variety of combinations of the following parameters: rainfall intensity, rainfall duration, peak rate of runoff, peak rate of percolation, initial soil moisture content, percent sand, and percent clay.

#### Infiltration into non-frozen soils

Infiltration is the process by which water enters the soil. Description of the process and theory of infiltration has been presented by: Philip (1957a, 1957b, 1957c, 1969), Horton (1940), Hillel (1971, 1980), Holtan (1961), Baver et al. (1972), and others. Generally, infiltration is modeled either empirically or physically.

The empirical models have parameters which need to be fitted to existing data. Thus care must be used in applying parameters to soils which have not been run through infiltration tests. Holtan (1961) presented an infiltration equation of this type which describes

infiltration as a function of the remaining volume of potential storage in a specified soil depth. Holtan's equation is:

$$f_p = f_c + a*(S_p - F)**n \quad (11)$$

where  $f_p$  = infiltration capacity (in/hr)  
 $S_p$  = storage potential of the soil above the control depth (inches)  
 $F$  = accumulated infiltration volume (inches)  
 $f_c$  = constant infiltration rate (in/hr)  
 $a, n$  = empirical constants

Modifications of Holtan's equation have been proposed by Overton (1964), Huggins and Monke (1967), and Holtan and Lopez (1971).

Physical models use parameters which are measurable physical characteristics of the soil. Most of the physical models of infiltration are based on Darcy's law, continuity of flow, or theory of capillarity.

Richards (1931) proposed a second order non-linear partial differential equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( K(\theta) \frac{\partial \Psi}{\partial z} \right) - \frac{K(\theta)}{\partial z} \quad (12)$$

where  $\theta$  = volumetric moisture content  
 $t$  = time  
 $z$  = distance below the soil surface  
 $\Psi$  = soil water matric potential  
 $K(\theta)$  = is the unsaturated hydraulic conductivity

The Richards equation can be solved by numerical methods using small time and depth increments. The infiltration rate is given as  $\frac{\partial \theta}{\partial t}$  for the uppermost soil layer.

Philip (1957a, 1957c) solved the Richards equation for an infinitely deep soil of uniform initial moisture content. The solution

takes the form of a power series which retains only the first two terms to approximate the cumulative infiltration:

$$F = s * (t)^{0.5} + a * t \quad (13)$$

where F = cumulative volume of infiltration to time t  
 s, a = constants dependent on soil type and initial moisture content

Green and Ampt (1911) developed an equation for infiltration based on the concept that the soil may be represented as a bundle of tiny irregular capillary tubes and assuming a homogeneous deep soil, uniform initial moisture content, and a ponded surface. Mein and Larson (1971, 1973) modified the Green and Ampt equation to allow for delayed surface ponding and obtained the following equations to predict infiltration:

$$F_s = \frac{S_{av} * (IMD)}{I/K_s - 1} \quad (14)$$

$$t_p = \frac{F_s}{I} \quad (15)$$

$$f_p = K_s * \left( 1 + \frac{S_{av} * (IMD)}{F} \right) \quad (16)$$

where  $F_s$  = infiltration volume to the time of surface ponding (inches)  
 $S_{av}$  = capillary suction at the wetting front (inches water)  
 IMD = initial moisture deficit  
 I = rainfall intensity (in/hr)  
 $K_s$  = saturated hydraulic conductivity  
 $t_p$  = time to ponding (hr)  
 $f_p$  = infiltration capacity at time t (in/hr)  
 F = cumulative infiltration volume at time t (in.)  
 $t_p'$  = the equivalent time to infiltrate volume  $F_s$  under ponded surface conditions

The original Green and Ampt equation (Equation 16) applies for delayed ponding with  $F$  equal to the cumulative infiltration at time zero (Mein and Larson, 1971, 1973). In the integrated form the equation is:

$$K_s(t-t_p+t_p') = F - (IMD) * S_{av} * \ln\left(\frac{F}{(IMD)*S_{av}}\right) \quad (17)$$

Mein and Larson (1971,1973) suggested that  $S_{av}$  can be calculated by taking the area under the capillary suction-relative conductivity curve for the range of relative conductivity between 0.01 and 1.0. Relative conductivity is given by the ratio  $K(\theta)/K_s$ . Moore (1979) developed the following relationship for determining  $S_{av}$ :

$$S_{av} = \frac{\int_{K_r(\theta_i)}^{K_r(\theta_{fs})} S(K_r) d(K_r)}{K_r(\theta_{fs}) - K_r(\theta_i)} \quad (18)$$

where  $S(K_r)$  = matric suction ( a function of relative conductivity

$K_r(\theta_i)$  = relative conductivity corresponding to initial moisture content

$K_r(\theta_{fs})$  = relative conductivity corresponding to the maximum volumetric moisture content attained in the wetted zone (at field saturation)

Clapp and Hornberger (1978) suggested the following expression for estimating  $S_{av}$ :

$$S_{av} = ((2b + 3)/(b + 3)) * s \quad (19)$$

where  $b$  = absolute slope of the suction versus theta curve plotted on log-log scale

$s$  = saturation suction

In a comment, Brakensiek (1979) felt that Equation (19) should use the air exit pressure, which could be estimated as  $s/2$ , rather than

saturation suction.

Campbell (1974) developed an equation for predicting unsaturated hydraulic conductivity:

$$K(\theta) = K_s (\theta / \theta_s)^{2b+3} \quad (20)$$

where  $K(\theta)$  = unsaturated hydraulic conductivity  
 $K_s$  = saturated hydraulic conductivity  
 $\theta$  = volumetric moisture content  
 $\theta_s$  = saturated volumetric moisture content  
 $b$  = as defined in equation (19)

Brooks and Corey (1964) proposed a slightly different equation for unsaturated hydraulic conductivity:

$$K(\theta) = K_s * (S_e)^{2/b+3} \quad (21)$$

where  $K(\theta)$  = as defined in equation (20)  
 $K_s$  = as defined in equation (20)  
 $b$  = as defined in equation (19)  
 $S_e$  = effective saturation =  $(S - S_r) / (1 - S_r)$   
 $S = \theta / \theta_s$   
 $S_r$  = residual saturation (point of saturation where the hydraulic conductivity is assumed to be zero)

The Green and Ampt equation as modified by Mein and Larson (GAML model) has received attention since its development in 1971. Chu (1977) and Slack and Larson (1981) showed how the GAML model could be extended to model infiltration during variable rainfall. Idike et al. (1980) found the GAML model to agree well with experimental data. Moore (1981) modified the GAML model to include surface effects such as sealing.

#### Infiltration in frozen soil

Kane (1980) states that infiltration of water into seasonally frozen soils is controlled in part by the amount of ice in the soil pores. He reports that the higher the moisture content, the greater

the amount of ice present in the frozen soil and thus the infiltration rate and the hydraulic conductivity are reduced.

Lee and Molnau (1982) used a rainfall simulator for infiltration studies in a frozen soil. For frozen soils with a high moisture content, infiltration rates as low as 0.002 in/hr were measured. Sartz (1969) measured soil water in both sandy and silty soils for four winters at a watershed in southwestern Wisconsin and found that water may infiltrate and percolate through more than 23 inches of hard-frozen ground. Harris (1972) measured infiltration rate in a frozen Fayette loam in areas of natural deciduous forest, 25-year-old coniferous plantation, and 6-year-old abandoned field vegetation. In the deciduous forest and the abandoned field, soil freezing did not change the infiltration rate sharply until late winter when infiltrating snowmelt and rainfall froze and closed the soil pores. This was attributed to large macropores. The infiltration rate was nearly zero throughout the winter in the conifer plantation due to an impermeable snow-ice layer on the ground surface caused by snowmelt dripping from the conifer canopy.

At present there does not appear to be any models for predicting infiltration into frozen soil (Steenhuis et al. 1977). This is due in part to the complexity of the process which involves phase changes and the difficulty in taking quantitative measurements.

Since soil freezing affects infiltration, knowing whether or not the soil is frozen is important. Baker (1971) developed an equation which predicts the maximum freezing depth in the soil based on the cumulative growing degree-days and the type of winter. Cary et

al.(1978) uses two relationships, one based on the soil atmosphere energy budget and the other on the heat flux across the soil surface layer, to predict whether the soil is frozen or not. Daily maximum and minimum temperatures, solar radiation, and snowfall were used in the model to give fair prediction of soil freezing at five diverse sites in the Palouse region of eastern Washington.

#### Redistribution in non-frozen soil

In a non-frozen soil redistribution, movement of soil water within the soil profile, primarily occurs in response to matric and gravitational gradients (Moore and Larson, 1979). Hillel (1971) cites a number of factors which affect redistribution: pre-infiltration moisture content, soil texture, type of clay present, organic matter content, the presence of impeding layers in the profile, and the pattern of evapotranspiration.

Few redistribution models exist in the literature. James and Larson (1976) note that those existing models are either based on the Richards equation for unsaturated flow or empirical relationships between infiltration rate and time.

Gardner et al. (1970) developed an empirical expression for redistribution which for times sufficiently large reduces to:

$$W = a * (t^{**(-b)}) \quad (22)$$

where W = soil water content in the redistribution zone

t = time

a,b = constants which can be related to capillary conductivity and soil water diffusion

Saxton (1972) uses the one-dimensional Darcy equation for unsaturated flow to predict redistribution in a layered profile. The

one-dimensional Darcy equation can be stated as:

$$q = -K(\theta) \frac{\partial \psi}{\partial x} \quad (23)$$

where  $q$  = flow rate or flux

$K(\theta)$  = hydraulic conductivity at the prevailing  
moisture content

$\frac{\partial \psi}{\partial x}$  = the potential energy gradient

Precipitation becomes available for redistribution as a result of infiltration. Shanholtz and Lillard (1970) and Saxton et al. (1974) both allow the infiltrated water to be stored in the top soil layer until an excess moisture content is reached. Shanholtz and Lillard (1970) considered anything above field capacity as excess. Saxton et al. regarded excess as greater than 90% of saturation. The excess water is then cascaded into the underlying soil layers subject to the excess moisture restriction.

Redistribution models have also been developed by: Gardner(1962), Bybordi(1969), Hanks et al. (1969), Peck (1971), Idike (1981), etc.

#### Redistribution in frozen soils

As noted earlier, the presence of ice in the soil has a significant influence on hydraulic conductivity. Experiments by Dirksen and Miller (1966) and Hoesktra (1966) indicate that as a soil freezes the thermal gradient begins to play a significant part, along with the matric and gravitational gradients, in the movement of soil water. Perfect and Williams (1980) ran experiments on freezing soil columns and found that the unfrozen soil water tended to migrate towards the cooler frozen soil.

Harlan (1971) was among the first to develop a model for soil

moisture redistribution in freezing soils by making an analogy between the mechanisms of water movement in unsaturated unfrozen soil and those in frozen soil. He developed heat and mass transfer equations coupled by change in ice content. Harlan (1973) applied the equations to simulate freezing moisture redistribution in a hypothetical soil. Although he concluded that the mathematical model gave reasonably good simulation results, he did not verify his model with experimental data.

Jame and Norum (1980) used the Crank-Nicolson scheme to solve Harlan's equations. After comparing the model simulation with experimental data, they found that if modifications were made in the hydraulic conductivity of the frozen medium, Harlan's model could be used successfully to numerically simulate the coupled heat and mass transfer processes of a freezing soil.

Bresler and Miller (1975) developed a capillary sink model which is based on the idea of a series of parallel transport mechanisms involving pore-ice and film water movement. The purpose of the model was to simulate the formation of ice lenses in saturated soils.

King and Steenhuis (1982) developed a finite difference computer model based on the irreversible processes of thermodynamics which were introduced by deGroot (1959). After comparing the simulation results of the model with experimental data, they concluded that their computer model could acceptably simulate coupled heat and mass transfer in partly frozen soils.

### Chapter 3

#### MODEL DEVELOPMENT AND OPERATION

##### General description of the recharge model

The groundwater recharge model is a one-dimensional Fortran computer program which simulates evapotranspiration, interception, snowmelt, surface storage, infiltration, and redistribution in the soil-plant-water system. Figure 3.1 shows a schematic representation of the processes involved for both frozen and non-frozen soil. Redistribution in frozen soil is not modeled because development of a suitable model was beyond the scope of the project. Inherent to the model is a water balance which requires that the inflow minus the outflow equal the change in storage. Inflow is represented by infiltration from rainfall or irrigation and outflow by evapotranspiration, runoff, and lateral flow (seepage).

The model requires the division of the soil profile into a number of soil layers. Within each layer the soil is assumed to be homogeneous and of uniform moisture content. Three time steps are used in the model. The first time step, 24-hours, reads the daily input data. The second time step, (TINC2) which is variable but suggested as one or two hours, reads precipitation data and is the basis for the time loop for extraction of evapotranspiration and redistribution when there is no rainfall or surface storage. The third time step, (TINC3) also variable but less than or equal to TINC2, is the basis for the time loop for infiltration, extraction of evapotranspiration, and redistribution during a rainfall event or when there is surface storage.

The program consists of a main program (RECHARG) which reads the

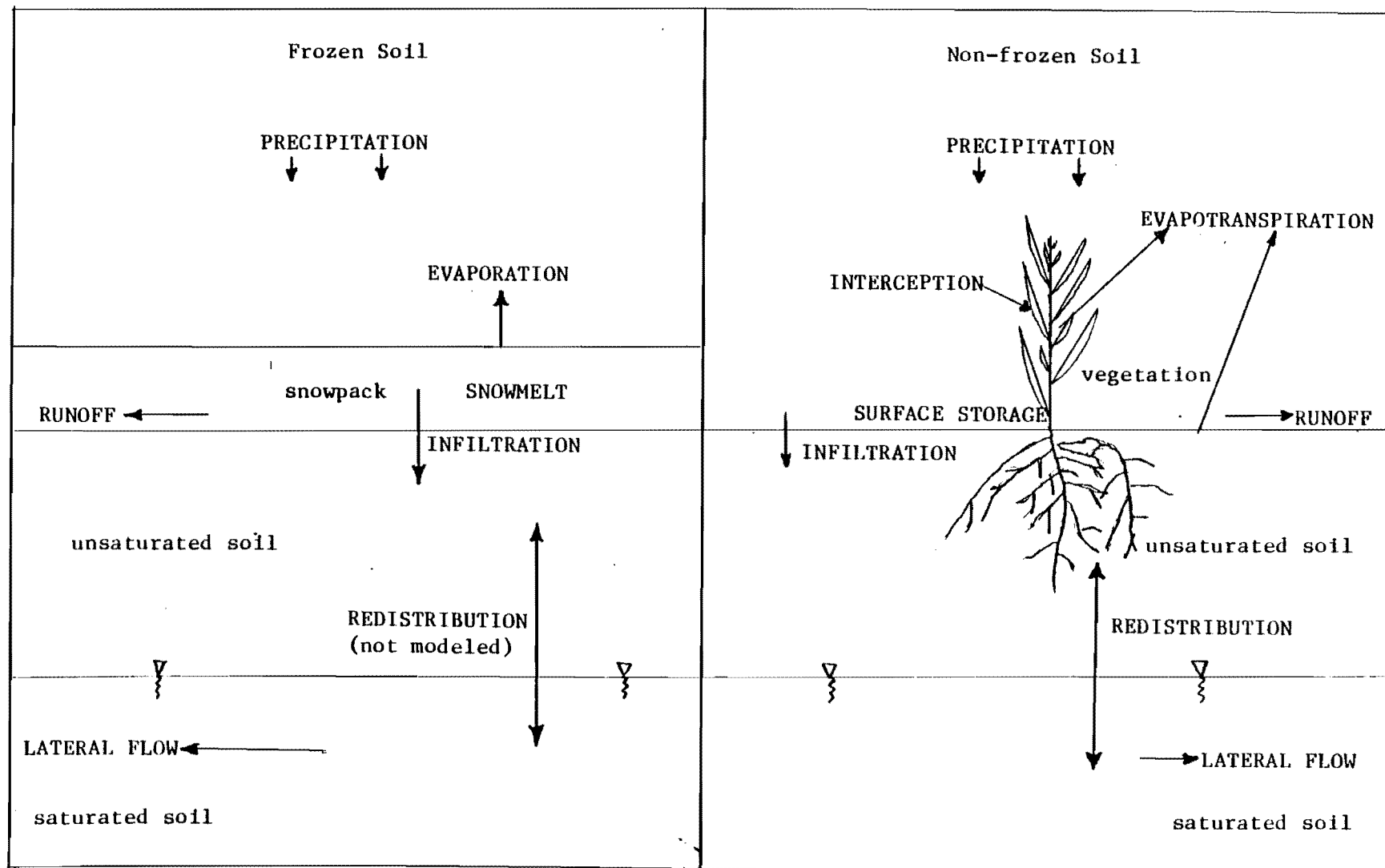


Figure 3.1 Schematic representation of the soil-plant-water system.

soil and crop parameters and initializes the soil moisture profile.

The main program accesses four subprograms which are :

1.) EXTRACT- extracts evapotranspiration from the rooting zone of the profile.

2.) SNOWMEL- computes snowmelt and determines soil moisture storage, surface storage, and runoff of meltwater and precipitation.

3.) IFIL- computes interception, infiltration, surface storage, and runoff of precipitation.

4.) REDIST- redistributes the soil moisture profile.

There are also fourteen subroutines which support the program. These are shown in detail in the listing of the computer program in Appendix C.

#### Evapotranspiration

For conditions where soil water is not limiting, evapotranspiration is calculated on a daily basis using either the pan equation (Equation (6)) or Hargreaves formula (Equation (5)). The form of the pan equation used combines the pan coefficient with the crop coefficient (Equations (6) and (7)):

$$ET = KPC * EPAN \quad (24)$$

where ET = evapotranspiration for a given crop not limited by water (in./day)  
 KPC = combined pan-crop coefficient  
 EPAN = daily pan evaporation (inches)

Hargreaves formula is used in the form:

$$ET = MF * T * CH * KPC/KP * 0.00127 \quad (25)$$

where ET = as defined in Equation (25)  
 MF = Hargreaves monthly factor (mm/month)  
 (values for latitudes in the Midwest are

given in Table 3.1)  
 T = average daily temperature (deg F)  
 CH = correction coefficient for relative humidity  
 (given in Equation (25))  
 KPC = combined pan-crop coefficient  
 KP = pan coefficient (values are shown in Table 3.2,  
 from Doorenbos and Pruitt, 1975)  
 0.00127 = conversion from mm/month to inches/day

Evaporation which occurs from surface storage is assumed to occur at the same rate as pan evaporation. Based on the findings of Burgy and Pomeroy (1958) and McMillan and Burgy (1960), evapotranspiration (ET) is first taken from the available interception storage. Any remaining ET is then available for extraction from the soil. The extraction pattern (i.e. fraction extracted from each soil layer) is a function of the rooting depth, which varies with the time of year and the type of vegetation.

Moore and Larson (1979) present a linear depletion curve (Figure 2.2) to allow for the effect of soil moisture limiting evapotranspiration. ETR, the ratio of actual to potential evapotranspiration, has a value of 1.00 for soil moisture contents ranging from field capacity to that corresponding to 50 percent available moisture. The ETR then decays linearly to 0.3 at permanent wilting point.

Anderson et al (1978) found evapotranspiration to vary with the time of day as shown in Figure 2.2. The equation, then, for evapotranspiration to extract from a given soil layer during a given time step is given by:

$$AET = PATTERN(I,J) * ETR * EK/4.0 * ET/TINC \quad (26)$$

where AET = evapotranspiration to extract from a given

Table 3.1 Hargreaves MF (mm/month) for latitudes in the Midwest (after Hargreaves, 1974).

North Latitude  (Degrees)	<u>MONTH</u>											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
0	.300	.493	1.012	1.605	2.288	2.548	2.485	1.932	1.274	.703	.351	.242
50	.333	.531	1.063	1.657	2.336	2.589	2.531	1.985	1.276	.749	.386	.272
49	.367	.570	1.115	1.709	2.363	2.628	2.574	2.036	1.327	.796	.422	.304
48	.404	.610	1.167	1.760	2.429	2.665	2.616	2.086	1.379	.844	.460	.337
47	.441	.651	1.219	1.810	2.473	2.702	2.656	2.136	1.430	.892	.499	.372
46	.481	.693	1.271	1.859	2.515	2.736	2.695	2.184	1.481	.942	.539	.409
45	.521	.736	1.324	1.908	2.557	2.769	2.733	2.231	1.532	.992	.580	.447
44	.563	.740	1.376	1.956	2.597	2.801	2.769	2.277	1.583	1.042	.623	.487
43	.607	.824	1.429	2.003	2.636	2.811	2.808	2.323	1.633	1.094	.667	.528
42	.651	.869	1.482	2.050	2.674	2.860	2.837	2.367	1.684	1.145	.712	.571
41	.697	.915	1.535	2.096	2.710	2.887	2.869	2.410	1.734	1.198	.758	.615
40												

Table 3.2 Pan coefficients (KPAN) used in the recharge model (after Doorenbos and Pruitt, 1975).

<u>MONTH</u>	<u>KPAN</u>
JAN	.70
FEB	.70
MAR	.70
APR	.70
MAY	.75
JUN	.85
JUL	.85
AUG	.85
SEPT	.85
OCT	.75
NOV	.70
DEC	.70

soil layer for a given time step (inches)  
 PATTERN(I,J) = extraction pattern - the fraction  
                   of the evapotranspiration to extract  
                   from soil layer (I).  
                   J = the extraction pattern number  
                   (a function of the julian day)  
 ETR = ratio of actual to potential evapotranspiration  
 EK = fraction of the daily evapotranspiration  
       which occurs in a given four hour period  
       (see Figure 2.2)  
 ET = daily evapotranspiration for a crop not  
       limited by water (inches)  
 TINC = time increment (hours)

Allowances are made so that soil moisture is not extracted below a soil layer's wilting point. also, if soil moisture is limiting (less then 50 percent available water) in any of the soil layers in the rooting zone, the extraction pattern is altered to allow a larger fraction of the evapotranspiration to be extracted from the soil layers which are not limited by moisture. This ensures that the rooting zone is not treated as being soil moisture limited until all of the soil layers in the rooting zone are soil moisture limited.

#### Interception

The storage capacity of vegetation for interception varies with plant growth, leaf development, surface tension between water and leaf surface, wind velocity, rain intensity, and rain drop size (Linsley et al., 1949). Interception estimation can vary from a simple constant value throughout the growing season to a rather detailed vegetation canopy model. The latter is often used in forested areas. The recharge model developed is best suited for an interception model which predicts maximum interception as a function of julian day. As noted earilier, interception storage is depleted by evapotranspiration. For example, interception for a corn crop might be estimated by assuming that the available interception storage is zero

until the julian day of crop emergence, a second order polynomial as a function of julian day during the growing and harvest seasons, and zero after fall plowing.

### Snowmelt

A necessary component of a recharge model for Minnesota is a snowmelt model. An acceptable method for predicting snowmelt is the degree-day equation (Equation (8)).

The snowmelt model used in the recharge model is one developed by Khanjani and Molnau (1982). Their snowmelt model was tested at sites in Vermont and Michigan with favorable results. The snowmelt model reads daily input and calculates snowmelt on an hourly basis. Hourly air temperatures are generated by fitting a sine function to daily maximum and minimum temperatures. It is assumed that the daily minimum temperature occurs 1/2 hour before sunrise, which is calculated, and the daily maximum temperature occurs at 4:30 pm.

The degree-day factor, K, is calculated on an hourly basis using equation (9). The forest cover coefficient, F, is the fraction of the ground surface which is shaded during the winter. It varies from 0.0 for a bare field to almost 1.0 for a dense pack conifer stand. The albedo, A, which tends to decline as the snow "ripens", is estimated using the equation:

$$A = 0.40 * (1 + (1.25 / ((0.0028 * SD) + 1))) \quad (28)$$

where A = albedo  
SD = sum of degree-hours since the last freezing period (degree F - hours)

The maximum albedo is assumed to be 0.9 and the minimum 0.4. Equilibrium temperature, the temperature at which no net transfer of

heat takes place between the air and snow, is given as a function of julian day but is assumed to never exceed 35.6 F (2 C). It is calculated from the equation:

$$\text{TEQUIL} = \text{JDAY} * 0.036 + 32 \quad (28)$$

where TEQUIL = equilibrium temperature (degrees F)  
JDAY = julian day

Melt due to rainfall is estimated by:

$$\text{Mr} = 0.00027 * (\text{Ta} - 32) * \text{P} \quad (29)$$

where Mr = snowmelt due to rainfall (inches)  
Ta = air temperature (degrees F)  
P = rainfall (inches)

One modification made to the snowmelt model of Khanjani and Molnau was the determination of whether precipitation is in the form of rain or snow. Since the phase change from rain to snow represents a considerable change in energy state of the precipitation, it is important to be able to determine which state it is in. Khanjani and Molnau (1982) determined the precipitation to be rain or snow based on the air dry bulb temperature. As precipitation forms and falls to the ground, however, its temperature approaches the wet bulb temperature of the surrounding air. Thus, determining the state of the precipitation as either rain or snow, might be better based on wet bulb temperature. Brooks (1967) presents a mathematical model of the psychrometric chart. He presents equations for determining wet bulb temperature based on air dry bulb temperatures and relative humidity:

$$\text{Pv} = \text{RH} * e^{(54.6329 - (12301.688/\text{Tdb}) - (5.16923 * \ln(\text{Tdb}))} \quad (30)$$

$$\text{Pv} = \text{Pswb} - ((0.2405 * (\text{Pswb} - 14.6996) * (\text{Tdb} - \text{Twb})) / (.6219 * \text{hfg}')) \quad (31)$$

$$\text{Pswb} = e^{(54.6329 - (12301.688/\text{Tdb}) - (5.16923 * \ln(\text{Tdb}))} \quad (32)$$

where Pv = vapor pressure (psi)

RH = relative humidity (decimal)  
 Tdb = dry bulb temperature (degrees R)  
 Twb = wet bulb temperature (degrees R)  
 Pswb = saturation vapor pressure at Twb (psi)  
 hfg' = latent heat of vaporization of water at Twb  
 e = natural exponent  
 ln = natural logarithm

Since equations (30)-(32) are solved for vapor pressure, an iterative technique would be necessary to solve for wet bulb temperature. It is only necessary, however, to know whether wet bulb is greater than or less than 32 F to determine if precipitation is rain or snow.

If wet bulb is assumed as 32 F then equation (31) becomes:

$$Pv1 = 0.08853 - 0.00525 * (Tdb - 491.69) \quad (33)$$

where Pv1 = vapor pressure at Tdb with Twb = 32 F (491.69 R)  
 Tdb = as defined in Equation (30)

If the relative humidity and air dry bulb temperature are available, then they can be used in equation (30) to solve for the actual vapor pressure. This actual vapor pressure can be compared to PV1. If the actual vapor pressure is less than PV1 then the wet bulb temperature is less than 32 F, and the precipitation is in the form of snow. If the actual vapor pressure is greater than PV1, then the wet bulb temperature is greater than 32 F, and the precipitation is in the form of rain.

To handle this modification for determining the form of precipitation, relative humidity was added to the snowmelt model. The hourly relative humidity was computed applying a sine function to the daily maximum and minimum relative humidity.

The cold content of the snowpack in equivalent water requirement to raise the temperature of the snowpack to 32 F is estimated as:

$$WC = SWE * (5/9 * (Tdb - 32))/160 \quad (34)$$

where WC = snowpack cold content (inches of melt water)  
 SWE = amount of water in the snowpack (inches)  
 Tdb = air dry bulb temperature (degrees F)

Snowmelt for a given time step is computed from:

$$Ma = M + Mr - WC \quad (35)$$

where M = actual snowmelt (inches)  
 Mr = snowmelt due to rainfall (inches)  
 WC = melt water requirement to raise the  
 temperature of the snowpack to 32 F (inches)

### Surface Storage

Precipitation or snowmelt which does not infiltrate into the soil is available for surface storage. Equation (10) is used to calculate the maximum surface storage (SM). An equation developed by Mitchell and Jones (1976) was chosen to predict the change in the surface depression storage resulting from precipitation impact effects. The prediction equation was developed using pooled data from four soil types and eighty-eight experimental runs and can be expressed as:

$$\Delta S/S_m = -0.11705 + 7.0*(10^{**}(-5))*Mo*Pcl - 0.02429*I + 4.7*(10^{**}(-4))*I*Pcl \quad (36)$$

where  $\Delta S$  = change in surface depression storage (inches)  
 $S_m$  = maximum surface depression storage (inches)  
 Mo = initial soil moisture content (percent)  
 Pcl = percent clay  
 I = rainfall intensity (in./hr.)

When a new rainfall event occurs the change in maximum surface storage is calculated and this is subtracted from the present maximum surface storage. In this manner maximum soil surface storage is degraded throughout the rainfall season.

### Infiltration

The precipitation in excess of the available storage is available

for infiltration. The infiltration process is modeled using the Green and Ampt (1911) equation as modified by Mein and Larson (GAML model). The integrated form of the GAML equation (equation 17) is used with a time increment (TINC3). Infiltration volume,  $F_s$ , at the time of ponding is obtained from equation (14); while  $TP'$ , the equivalent time to infiltrate volume  $F_s$  under ponded surface conditions is calculated from equation (17) by replacing  $(T-TP+TP')$  with  $TP'$ . Field saturated conductivity,  $K_s$ , is computed from the moisture content at field saturation for the top soil layer.

The average capillary suction at the wetting front,  $SAV$ , is determined from equation (19) using the  $S/2$  as suggested by Brakensiek (1979). The saturated suction,  $S$ , is determined as the intercept of the suction versus theta curve plotted on a log-log scale.

Infiltration volume is stored in the top soil layer where it is subject to redistribution. Any ponded water fills the available surface storage to be available for infiltration during the next time step. Any ponded water in excess of this is assumed to run off.

Although precipitation is assumed constant during a given time step, allowance is made for intermittent application. A new rainfall event is assumed to occur if there is no precipitation or surface storage of water for one time step, TINC2 (suggested as one hour).

#### Redistribution

Redistribution of soil water within the profile is calculated by applying Darcy's law for flow in unsaturated soils to successive pairs of soil layers from the soil surface down to the unsaturated soil layer above the water table. Darcy's equation in finite difference form for flow between two soil layers for a given time may be stated

as:

$$Q = ((K1+K2)/2.0)*(SUC1-SUC2-POT)/((D1+D2)/2.0)*DELTA \quad (37)$$

where

- Q = flow of water (ft of water) (positive upwards)
- K1 = effective hydraulic conductivity of the upper of the pair of soil layers(ft/hr)
- K2 = effective hydraulic conductivity of the lower of the pair of soil layers(ft/hr)
- SUC1 = the matric suction (positive number) of the upper of the pair of soil layers
- SUC2 = the matric suction (positive number) of the lower of the pair of soil layers
- POT = gravity potential (ft) = (D1+D2)/2.0
- D1 = thickness of the upper of the pair of soil layers
- D2 = thickness of the lower of the pair of soil layers
- DELTA = time step (hours)

The effective hydraulic conductivity of a soil layer is calculated using the Brooks and Corey (1969) equation (equation (21)). The conductivity of the soil layer is calculated using the average of the moisture content before redistribution of the preceding soil layer and the moisture content after redistribution of the preceding soil layers.

During redistribution the amount of moisture which can be removed from a soil layer is restricted by the wilting point. If redistribution of water causes a soil layer to go above field saturation, the excess water is passed along to the next soil zone in direction of flow. Transfer of water from the saturated zone to the unsaturated zone (water table movement) is effected by maintaining the unsaturated soil layer just above the water table at field capacity. If after redistribution the unsaturated soil layer above the water table is above the field capacity, the excess water causes a rise in the water table. If the unsaturated soil layer is below field

capacity, the water table is lowered to bring the soil layer up to field capacity.

#### Model Operation

The first step in operating the model is to modify the necessary program statements to fit the site to be modeled. This might include insertion of an interception equation, insertion of a crop coefficient equation for evaporation, or changing the Hargreaves MF value to correct for a latitude change.

After the soil profile has been divided into a number of soil layers the following soil parameters must be entered for each soil layer: the thickness of the layer (ft), the saturation suction, the slope of the log-log plot of suction versus moisture content, saturated hydraulic conductivity (ft/hr), initial moisture content (vol/vol), saturated moisture content, field saturated moisture content (vol/vol), wilting point (vol/vol), and residual moisture content (vol/vol) (the moisture content at which the hydraulic conductivity is considered to be zero (see Brooks and Corey, 1969)). Then the number of the soil layers containing the water table, the thickness of the saturated zone within that soil layer (ft), the elevation of the ground surface (ft), the moisture content of the unsaturated layer next to the water table, and the lateral flow (ft/min) (includes seepage, irrigation withdrawal, etc.) must be entered. The following must then be entered: the number of time steps (N2) in the day (for reading rainfall data and operating the time loop for a period when there is no precipitation or surface storage), the number of time steps (N3) within each time loop N2 (time loop for a period when there is precipitation or surface storage), the

convergence criteria for calculating infiltration, the initial maximum soil surface depth (in), initial soil moisture content at the soil surface, percent clay in the soil, julian day of frost into the soil, julian day of frost out of the soil, and the extraction patterns for soil layers.

After initialization, the program follows an operational procedure as shown in Figure 3.2. The program reads input on a daily basis. For A day with non-frozen soil, the necessary input is:

JDAY,IET,CET1,CET2

where JDAY = julian day  
 IET = 1 for calculating evapotranspiration using the pan equation  
 IET = 2 for calculating evapotranspiration using Hargreaves formula  
 CET1 = pan evaporation (in/day) if IET=1  
 CET1 = average daily temperature ( F) if IET=2  
 CET2 = dummy argument if IET=1  
 CET2 = average daily relative humidity (%) if IET=2  
 PREDAY = daily precipitation (in).

If PREDAY is greater than zero, then the rainfall intensities (in/hr) are read for each hour of the day (or other specified time interval). The daily output (at midnight) includes: julian day, daily precipitation, present interception storage, present surface storage, total runoff for the day, total infiltration for the day, total evapotranspiration extracted from the soil, maximum possible

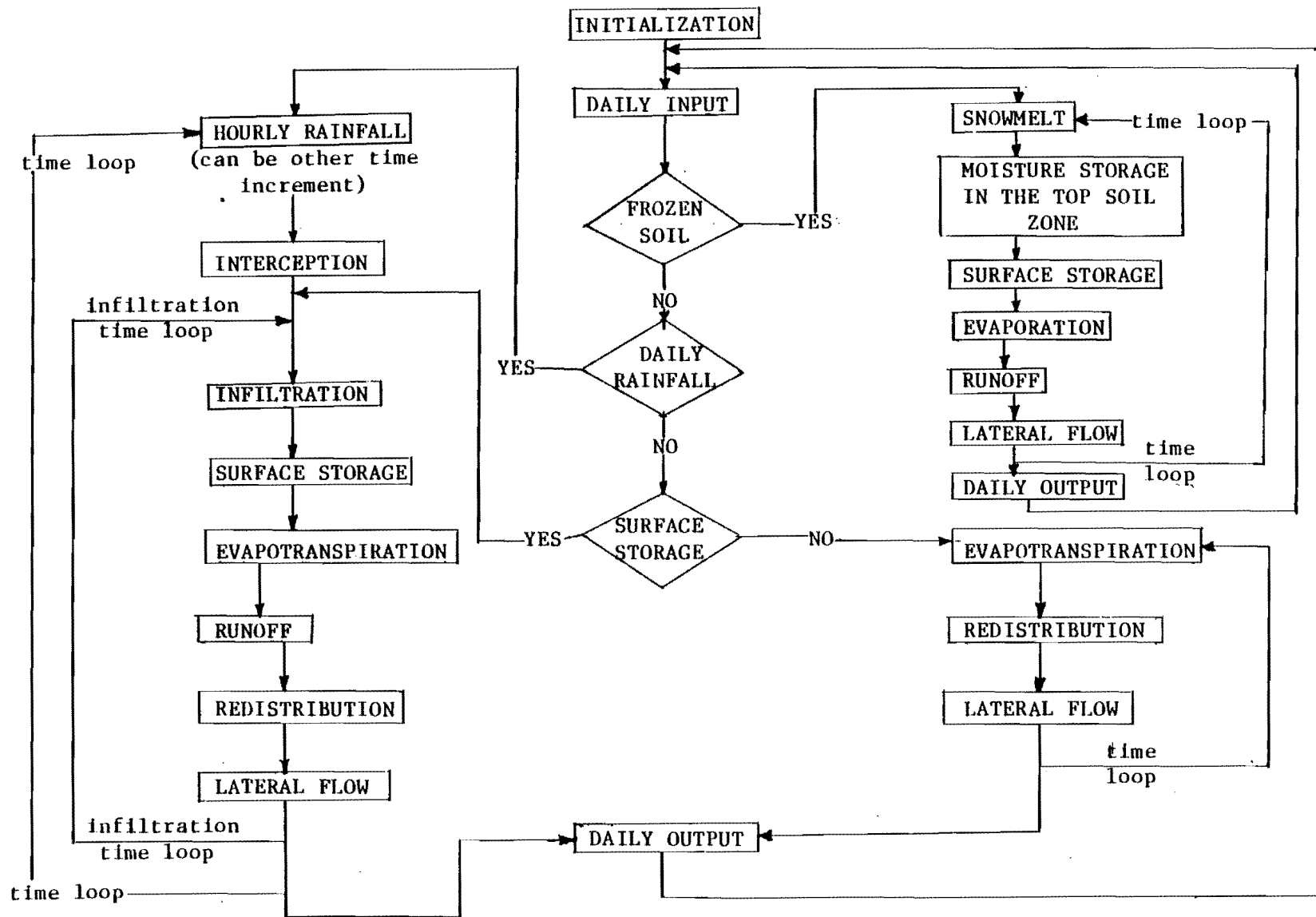


Figure 3.2 Operational flowchart for the recharge model.

evapotranspiration for the day (soil water not limiting), and the water table elevation (calculated at noon).

For a day with frozen soil, the necessary input is:

JDAY,TPMXP1,TPMNP1,PR,STT,ENT,RHMXP1,RHMNP1

where: JDAY = julian day  
TPMXP1 = maximum temperature for the next day ( F)  
TPMNP1 = minimum temperature for the next day ( F)  
PR = daily precipitation (in)  
STT = starting time of the precipitation (24 hour clock)  
ENT = ending time of the precipitation  
RHMXP1 = maximum relative humidity (%) for the next day  
RHMNP1 = minimum relative humidity (%) for the next day.

Daily output (at midnight) for when the soil is frozen includes: julian day, daily precipitation, present water equivalent of snow on the ground, total water available for infiltration for the day (rainfall plus snowmelt), present surface storage, total runoff for the day, total evaporation for the day, maximum allowable surface storage evaporation for the day, and water table elevation calculated at noon.

CHAPTER 4MODEL VERIFICATIONSite Description

In order to verify the recharge model a site with the following characteristics was desired:

- 1) Sandy surface soil
- 2) Shallow water table
- 3) No nearby wells which could affect the water table level
- 4) No or measurable lateral flow or seepage of groundwater
- 5) Uniform topography, preferably flat

Such a site was found in Andover, Minnesota (Anoka county) located at latitude North 45 15' and longitude West 93 18'. The Andover site is part of the Anoka sand-plain aquifer which has an area of approximately 1,300 square miles. At the site the saturated thickness of the aquifer is near 50 feet with the water table ranging from about 4.5 feet to almost 7.5 feet below the ground surface. The underlying impermeable layer consists of either red-brown sandy till or red-brown lake deposits (Helgeson and Lindholm, 1977) the soil profile is of the Sartell fine sand series. The topography is flat and vegetation is sparse (20 to 50 percent cover) consisting primarily of perennial grasses and weeds.

Instrumentation

A field plot was laid out as shown in Figure 4.1 A standard weather instrument shelter was set up to house a drum type continuous water level recorder (Belfort Instrument Well

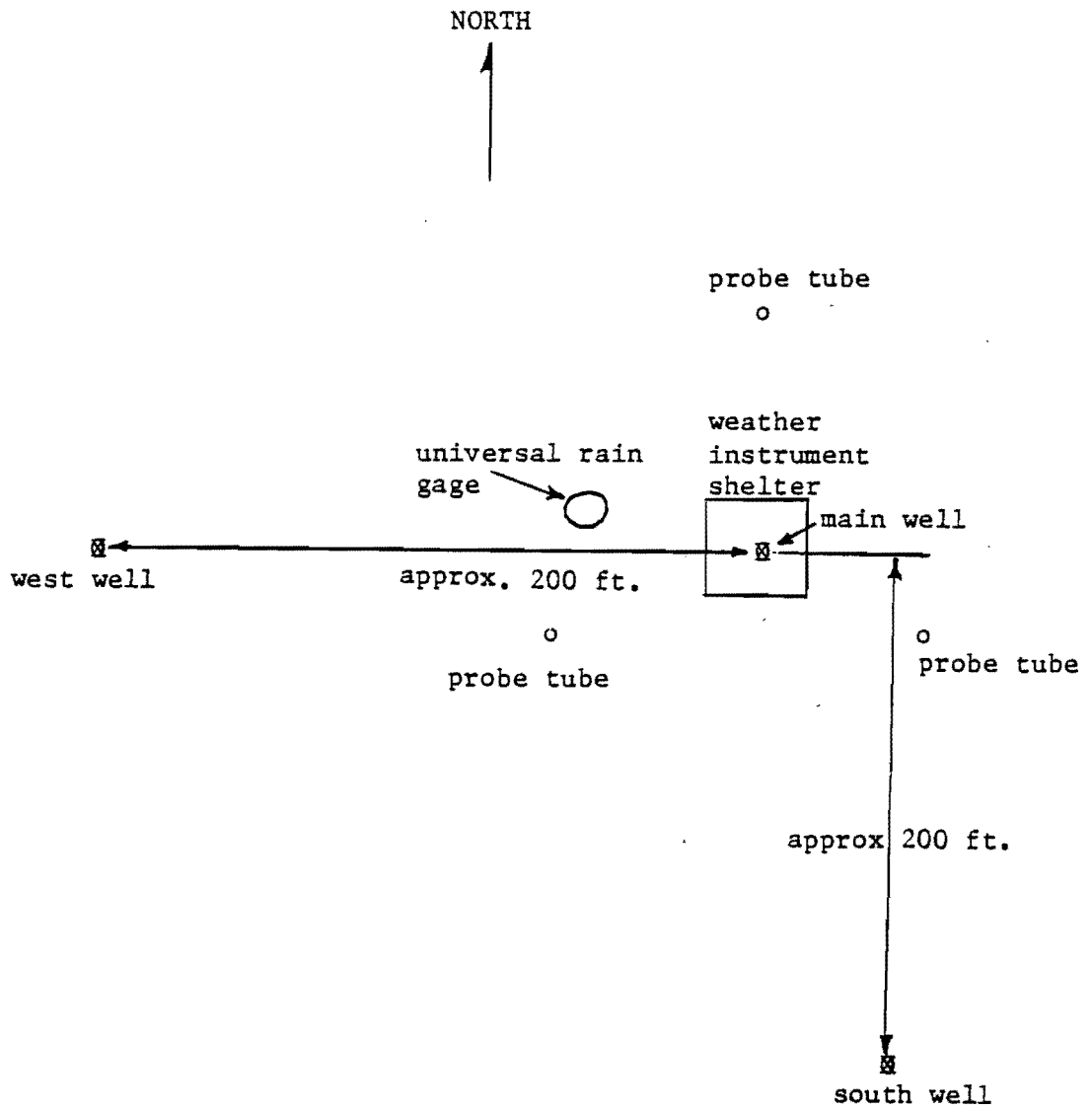


Figure 4.1 Layout of the Andover field site.

Level Recorder serial no. 1466) and a drum type continuous temperature-relative humidity-barometric pressure recorder (Weathertronics 5010 Hi-Q meteorograph serial no. 365) A universal rain gauge (Belfort Instruments Rain Gauge serial no. B-9817) was also set up near the instrument shelter. Three wells, a four inch main well and 2 two inch wells, were drilled to measure the water table elevation. The water table elevation in the main well was measured continuously while the other 2 wells were measured on a weekly basis. Weekly soil moisture measurements were taken with a neutron probe (Troxler model 3210) at one foot intervals down to nine feet in three probe tubes located near the weather shelter. Data were gathered from April 18, 1980 through December 31, 1982.

#### Input data and run descriptions

Pan evaporation, which was used for predicting evapotranspiration, was taken from the St. Paul campus weather station at the University of Minnesota.

Saturated hydraulic conductivity and bulk density measurements were conducted on soil samples at: 6 inches, 28 inches, 34 inches, 42 inches, 48 inches, and 60 inches. Moisture release tests were run on soil samples taken at: 6-12 inches, 12-16 inches, 20-24 inches, 36-40 inches, 62-66 inches, and 72-76 inches. Using the above measurements soil parameters for a ten foot soil profile were calculated. It was assumed that field saturation was 90 percent of porosity. Wilting point was calculated for a suction of 15 bars. Table 4.1 gives: saturation

Table 4.1 Soil parameters for the Andover site.

soil layer	S	b	Ks	$\theta_s$	$\theta_{fs}$	$\theta_r$	$\theta_{fc}$	$\theta_{wp}$
	Saturation suction (ft-water)	slope of log-log plot of $\Psi$ vs $\theta$	saturated hydraulic conduct. (ft/hr)	moisture content at sat.	moisture content at field saturation	moisture content at which conductivity is taken as zero	field capacity	wilting point
1 0-1ft	0.000036	3.9535	0.8080	0.396	0.356	0.0154	0.15	0.0155
2 1-2ft	0.000048	3.7772	1.2202	0.394	0.355	0.0138	0.15	0.0139
3 2-3ft	0.000048	3.7772	1.4173	0.390	0.351	0.0138	0.15	0.0139
4 3-4ft	0.000283	2.4735	0.9898	0.383	0.345	0.0079	0.15	0.0080
5 4-5ft	0.000978	2.6644	1.7303	0.430	0.387	0.0071	0.15	0.0072
6 5-6ft	0.003389	2.6519	1.5000	0.445	0.400	0.0111	0.15	0.1120
7 6-7ft	0.001188	2.8476	1.5000	0.445	0.400	0.0104	0.15	0.0106
8 7-8ft	0.001188	2.8476	1.5000	0.445	0.400	0.0104	0.15	0.0106
9 8-9ft	0.001188	2.8476	1.5000	0.445	0.400	0.0104	0.15	0.0106
10 9-10ft	0.001188	2.8476	1.5000	0.445	0.400	0.0104	0.15	0.0106

suction, slope of the log-log plot of the moisture release curve, saturated hydraulic conductivity, saturated moisture content, moisture content at which the suction is assumed to be zero, field capacity, and wilting point; for a 10 layer soil profile at the Andover site.

Since an evapotranspiration crop curve for the type of vegetation at the Andover site could not be located in the literature, soil moisture data at the site was examined. By comparing the change in soil moisture storage with pan evaporation a crop curve for the site was developed. It can be stated as:

$$KPC = 0.35 \quad \text{for } JDAY < 98, JDAY > 289$$

$$KPC = 0.0076 * JDAY - 0.397 \quad \text{for } 98 < JDAY < 138$$

$$KPC = 0.655 \quad \text{for } 138 < JDAY < 244$$

$$KPC = -0.0068 * JDAY + 2.309 \quad \text{for } 244 < JDAY < 289$$

where KPC = combined pan- crop coefficient

JDAY = julian day

From examining the soil moisture data at the Andover site it appeared that the vegetation did not extract water below the three foot depth. Thus the maximum rooting depth was assumed to be three feet. The extraction pattern takes the form suggested by Shaw(1964) for a pasture. The Andover site extraction pattern is given in Table 4.2.

The measured water table elevation records were examined to determine the loss of water due to either lateral flow or seepage and the dates of frost into and out of the soil. Loss of water to

Table 4.2 Fraction of the maximum evapotranspiration extracted from a soil layer depending on the time of year for a sparse vegetative cover of grass and weeds at the Andover site.

JULIAN DAY	SOIL LAYER		
	1	2	3
Less than 121	1.00	0.0	0.0
121 to 151	0.70	0.30	0.0
Greater than 151	0.60	0.20	0.20

lateral flow or seepage was determined by taking the average slope of the water table change during the winter when the soil is assumed to be impermeable to infiltration of water. This water flow was determined to be 0.0001 feet/hour. Dates of frost into and out of the soil were figured to occur in the fall and spring when the water table elevation took a continuous fall (frost in) or a large abrupt rise (frost out). Table 4.3 gives the dates of frost into and out of the soil at the Andover site for 1980, 1981, and 1982.

To verify the recharge model, a number of runs were done in order to see the response of the model to changes in: the time increment for calculating infiltration, the number of soil layers that the profile is divided into, and the number of days of simulation. To do this the following runs made:

Run 1a- the time increment for infiltration (TINC3)  
= 0.1 hours, 10 soil layers, 365 days (Jan  
-Dec 1981)

Run 1b- this run was made because Run 1a greatly overpredicted the water table rise at the time of frost out in the spring. This was due to the amount of snowmelt which had been allowed to be stored in the soil. ( Melt water had been allowed to flow into the top soil layer until the layer reached field saturation. This allowed up to 4.2 inches of melt water to move into the soil) It was then realized that the amount of allowable amount of melt water to infiltrate into the soil must be specified. Run 1b, then, has the same conditions as Run 1a except that the allowable melt water infiltration is 1.2 inches. ( 1.2 inches corresponds to field capacity in the top one foot soil layer)

Run 2 - the time increment for infiltration (TINC3)=  
1.0 hours, 10 soil zones, 365 days (Jan-

Table 4.3 Assumed dates of frost-out and frost-in to the soil.

YEAR	FROST-IN (Julian Day)	FROST-OUT (Julian Day)
1980*	336 (Dec. 1)	90 (Mar. 30)
1981	336 (Dec. 2)	90 (Mar. 31)
1982	336 (Dec. 2)	84 (Mar. 25)

\* 1980- Leap Year

Dec 1981), snow infil = 1.2 inches

Run 3 - the time increment for infiltration (TINC3)  
= .1 hours, 2 soil zones, 365 days (Jan-  
Dec 1981), snow infil. = 1.2 inches

Run 4 - the time increment for infiltration (TINC3)  
= .1 hours, 10 soil zones, 974 days (May  
1980 - Dec 1982), snow infil= 1.2 inches

The elevation of the ground surface, surveyed from a USGS benchmark, was 898.94 feet above mean sea level.

### Results and Discussion

Appendix A gives plots of: simulated and measured water table elevation versus julian day (runs 1-4), precipitation versus julian day (runs 1-4), simulated water table elevation versus measured water table elevation (runs 1-3), soil moisture versus julian day for one foot, two foot, three foot, and four foot soil depths (runs 1-2). Table 4.4 lists the cost of each run and the maximum overprediction and underprediction of the water table elevation. The main criteria for evaluating the performance of the model was its ability to predict the water table elevation, although the soil moisture profile in the unsaturated zone was also examined.

The error in prediction of the water table elevation in Run 1a was skewed towards overprediction (shown in Figure A1.2 simulated versus predicted water table elevation). This was a result of over estimating the amount of snowmelt water

Table 4.4 Summary results of the verification runs for the recharge model.

Run	Time Increment for Infiltration (Hrs)	No. of Soil Zones	Maximum Snowmelt Infiltration (Inches-Water)	Duration of Run	Cost of Run (\$)	Maximum Underprediction of Water Table	Maximum Overprediction of Water Table
1a	0.1	10	4.2	Jan-Dec 1981	8.31	0.07 ft (.21 in. water)	1.27 ft (3.81 in. water)
1b	0.1	10	1.2	Jan-Dec 1981	8.25	0.51 ft (1.53 in. water)	0.78 ft (2.34 in. water)
2	1.0	10	1.2	Jan-Dec 1981	6.59	0.39 ft (1.17 in. water)	0.78 ft (2.34 in. water)
3	0.1	2	1.2	Jan-Dec 1981	3.07	1.07 ft (3.21 in. water)	0.77 ft (2.31 in. water)
4	0.1	10	1.2	May 1980 -Dec 1982	31.18	0.53 ft (1.59 in. water)	0.78 ft (2.34 in. water)

which infiltrated into the soil. After a new estimate is made, (Run 1b) the error becomes uniformly distributed. This indicated that after snowmelt infiltration was accounted for, the model did a reasonable job of predicting the water table elevation.

The error in prediction of the water table elevations in runs 1b and 2 ranged from -0.51 feet to 0.78 feet. Although this may seem to be a rather large error, when calculated in terms of actual depth of water the range is -1.53 to 2.34 inches of water. Considering the number of estimated parameters and the accuracy of the modeling equations, the results appear very good. Run 1b for example predicts the water table elevation for 66 percent of the days in a year to within .1 feet (0.3 inches of water).

Soil moisture was reasonably well predicted for the two and three foot depths (usually within 0.02 of the actual values). The moisture content in the top foot was generally overpredicted. This could be due in part to surface evaporation which may extend into the soil due to its loose structure. The soil moisture at the four foot depth was consistently underpredicted. Considering the proximity of the water table to the four foot depth, this could be due to the capillary rise or the inaccuracy of the neutron probe when used in saturated soil.

The effect of changing the infiltration time step by a factor of ten (0.1 to 1.0) resulted in slightly better prediction of water table elevation. Prediction of soil moisture content, however, became rather poor. If one were looking only for prediction of the water table elevation, then the infiltration

time step of one hour would probably work and definitely would save computer time.

Changing from ten to two soil layers reduced the cost of computer time by almost 63 percent. Although the error of predicting the water table elevation increased, the general trends were still modeled fairly well.

Changing the number of days of simulation from 365 to 974 (Run 4) had no significant affect on the error in predicting the water table elevation. It can be seen, however, that the evapotranspiration model tended to overpredict evapotranspiration during the growing season and slightly under predict evapotranspiration during the off season. This is probably due to the crop curve, which was estimated from soil moisture data, being somewhat incorrect. ( The crop curve was determined by examining the change in soil moisture content in the top three feet of the soil. Pan-crop coefficients were then determined by comparing the change in soil moisture with pan evaporation data from the St. Paul campus weather station. Comparison was done only for days where soil moisture did not appear to be limiting in the soil at Andover.)

Storage of snowmelt water in the soil does not appear to be the same each year. 1.2 inches was assumed as the maximum amount of snowmelt infiltration for each winter. This value was a slight over estimation in the winter of 1981-1982, but an under estimation of total snowmelt infiltration during the winter of 1981-1982. This could be due to the type of winters which

occurred. The winter of 1980-1981 had little snow, while the winter of 1981-1982 set a snowfall record. Baker (1971) showed that freezing and thawing of the soil is greatly affected by the depth and persistence of snow cover. This in turn could affect the formation of ice lenses which restrict the flow of melt water into the soil. Since the freezing and thawing process is not modeled it seems that operation during a frozen period is a weak point of the recharge model.

Generally, the model gives good prediction of the water table elevation and soil moisture content in the unsaturated zone. Run 1b ( time step infiltration = 0.1 hours , 10 soil layers) gives the best overall prediction of soil water movement and is thus favored for modeling using natural precipitation. In the case of irrigation, however, much infiltration occurs causing an increase in computer time. In this instance it may be more cost effective to use a longer time step for infiltration.

CHAPTER 5Model Application

It should be possible to apply the recharge model to a variety of cropping and soil conditions. This could be achieved by either modifying existing routines in the program (such as modifying the lateral flow subroutines (BASEQ) to allow for pumping) or adding additional ones. To test such an application, a hypothetical irrigation situation was derived:

The Andover site was considered as an irrigated corn field. Irrigation was applied continuously and constantly at a rate of 1 inch/week between June 15 and September 15 (irrigation water was applied even during precipitation). The following assumptions were made:

1.) The water withdrawal for irrigation caused a uniform drop in the water table.

2.) The application of the irrigation water is uniform over the crop and application efficiency is 100 percent (ie. all water applied reaches the soil surface.)

In order to model the situation, the following program modifications were necessary:

1.) The crop curve equation was changed to one for corn and was taken from Idike, 1980. It can be written as:

$$KPC=0.152 + 0.0164 * (JDAY - 120) - 0.00012 * (JDAY - 120) ** 2$$

2.) An equation was added to provide a constant loss of water from the water table to of 0.000496 ft/day (1 in./week) in

addition to existing lateral flow. This represents the amount of water pumped for irrigation.

3.) Precipitation of 0.00595 in/hr (1 in./week) was added for each day within the irrigation season. This represents irrigation applied.

The extraction patterns and interception storage were left as they were in Run 1b because it was felt that changes would not greatly alter the results.

The application run cost was 23.14 dollars. This comparatively high cost resulted from the fact that infiltration was occurring mostly due to the irrigation and the time step for infiltration was 0.1 hour. In retrospect, the use of a longer time step (1 hour) would probably give similar results and cost only about one third as much.

On any given day during the irrigation season, at least one third of the applied water went back to the water table as recharge. This suggests that the irrigation rate is excessive, which is not surprising since irrigation continued even when precipitation was occurring.

Figure 5.1 shows a plot of the simulated water table elevation versus julian day. The model predicts the same general trends as the case without irrigation.

In comparing Figure 5.1 with Figure A1.1, which shows the simulated water table elevation from verification run 1b, the effect of irrigation on the water table seems to be minimal as there appears to have been enough precipitation to allow recovery of the water table from its loss due to pumping.

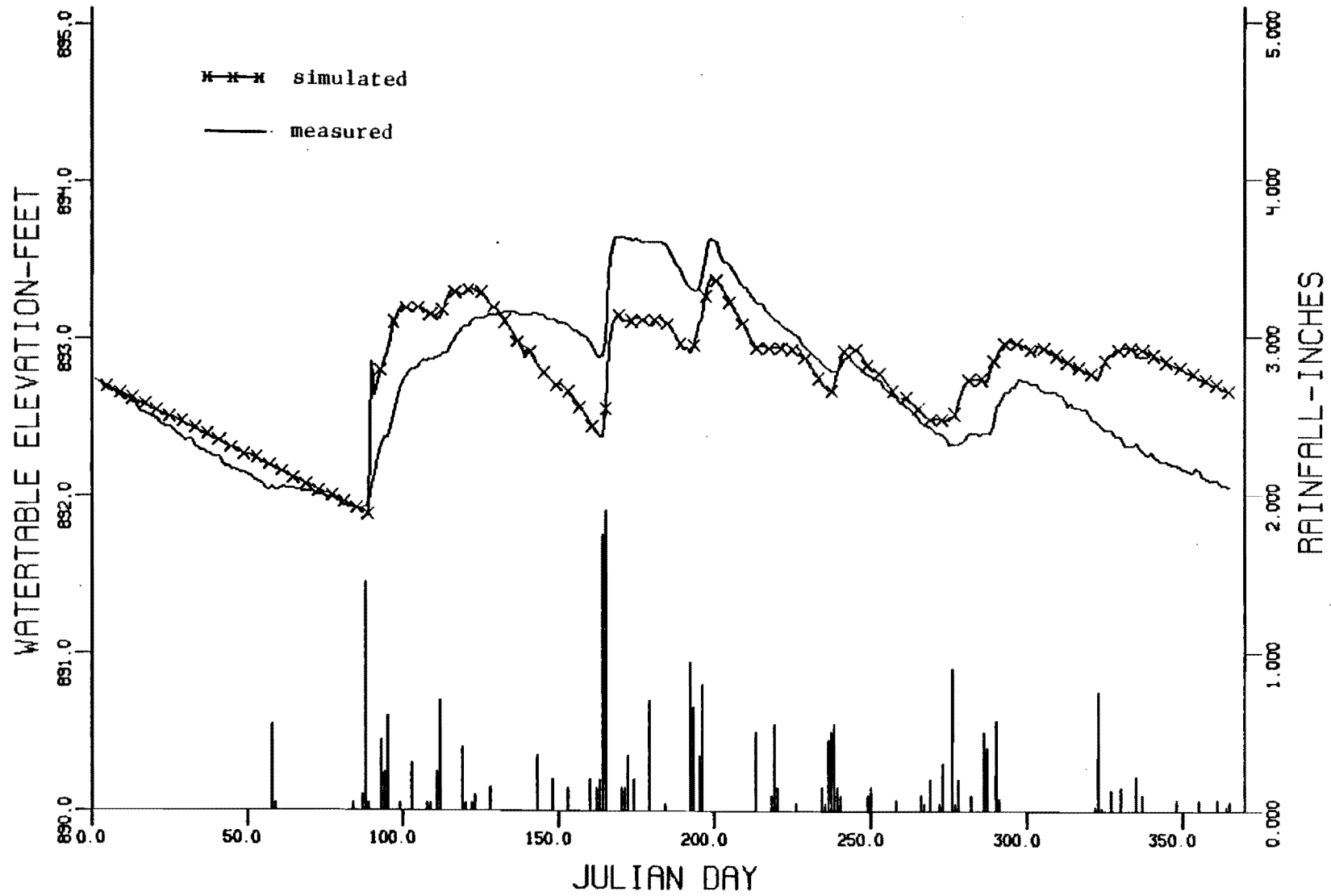


Figure 5.1 Simulated watertable elevation for a hypothetical irrigation situation and measured watertable elevation versus julian day. Andover MN. JAN-DEC 1981.

Chapter 6SUMMARY AND CONCLUSIONS

A one-dimensional, physically-based computer model was developed for predicting direct groundwater recharge. Although the processes of infiltration and redistribution are not modeled during frozen soil periods, the model is capable of operating during frozen and non-frozen conditions. Evapotranspiration for a crop not limited by water is calculated using either the pan equation or a formula developed by Hargreaves (1974) which is based on relative humidity and temperature. A linear depletion equation given by Moore and Larson (1980) is used to extract evapotranspiration from a soil with moisture limiting. Snowmelt is computed on an hourly basis using a degree-day method developed by Khanjani and Molnau (1982).

Change in the surface depression storage is modeled using a method developed by Mitchell and Jones (1978). Infiltration, which is stored in the top soil moisture layer, is modeled by the Green and Ampt equation as modified by Mein and Larson (1971,1973). Rainfall is assumed constant during a time step but allowance is made for intermittent application. Redistribution is calculated by dividing the soil profile into a series of layers and then applying Darcy's law between pairs of soil layers. Water table movement occurs by maintaining the soil layer above the water table at field capacity. Any soil water in excess of field capacity causes a rise in the water table while a deficit is made up by lowering the water table.

The model was verified using soil moisture and climatologic data from a sandplain site in Andover, Minnesota for the period May 1980

through December 1982. A hypothetical irrigation situation was also modeled to illustrate an application of the model.

Conclusions from the study are:

- 1) The proposed recharge model gives reasonable prediction of the water table elevation at a sandplain site.
- 2) The proposed recharge model is capable of predicting soil moisture profile at a sandplain site.
- 3) The model can be used to study the effects of water withdrawal on the water table elevations in the Anoka sand plain aquifer.
- 4) It is necessary to consider the type of winter which occurs during the frozen period in order to make a useful estimate of the amount of snowmelt infiltration.
- 5) During the non frozen period at the Andover site, there was an almost immediate rise in the water table in response to precipitation of one inch or more per day.
- 6) Pumping of water at the test site, for purposes of irrigation, does not appear to have a significant effect on the water table elevation.

Suggestions for further study:

- 1) Verification of the model at additional sites.
- 2) Application of the model to predict the usefulness of tillage practices on groundwater recharge.
- 3) Development of a model for infiltration and redistribution of snowmelt during frozen soil conditions.

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APPENDIX A

Plotted results of the Andover verification runs

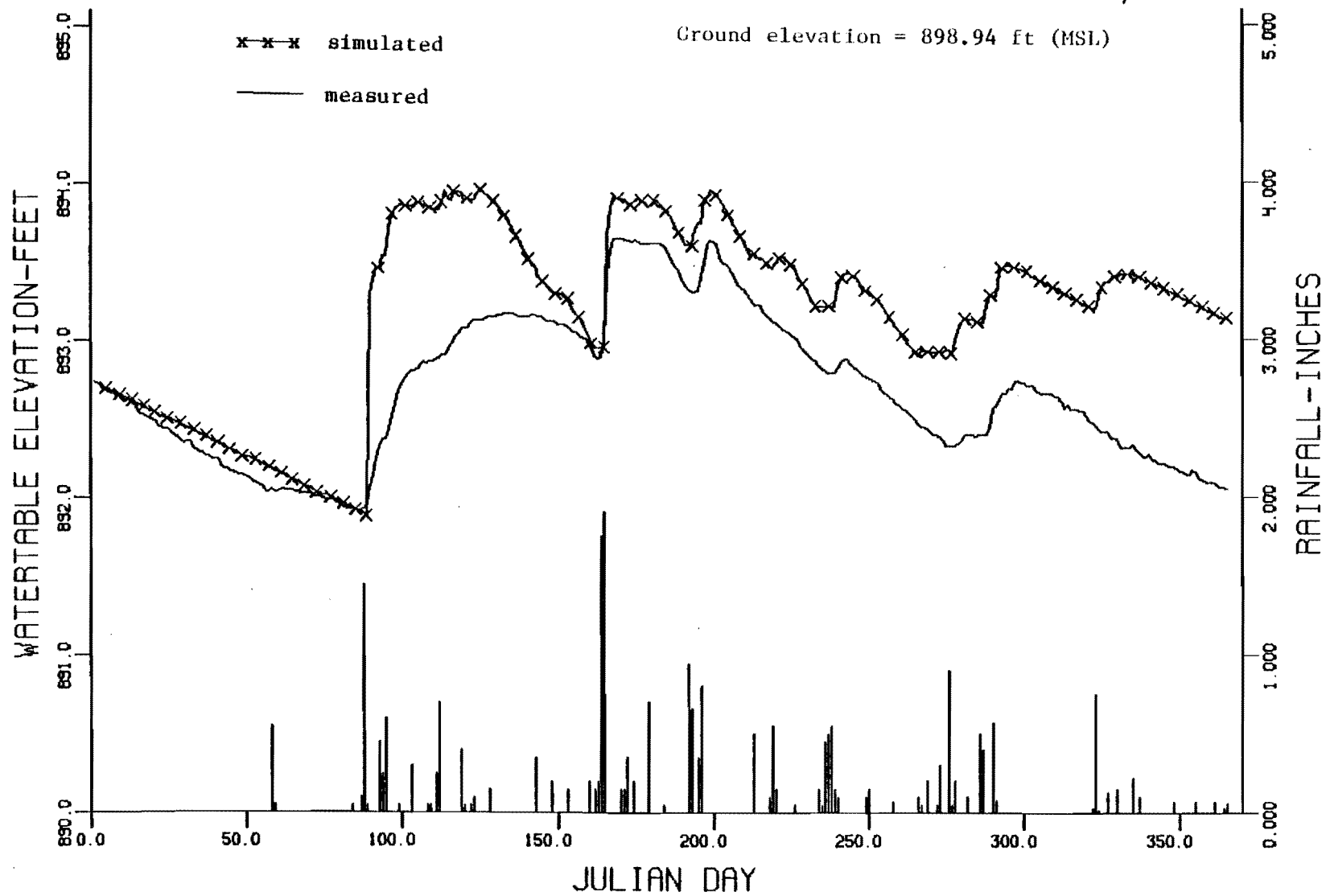


Figure A1.1 Simulated and measured watertable elevations versus julian day and precipitation versus julian day. RUN 1a: tinc3=.1 hr, 10 zones, snow infil= 4.2 in. Jan-Dec 1981

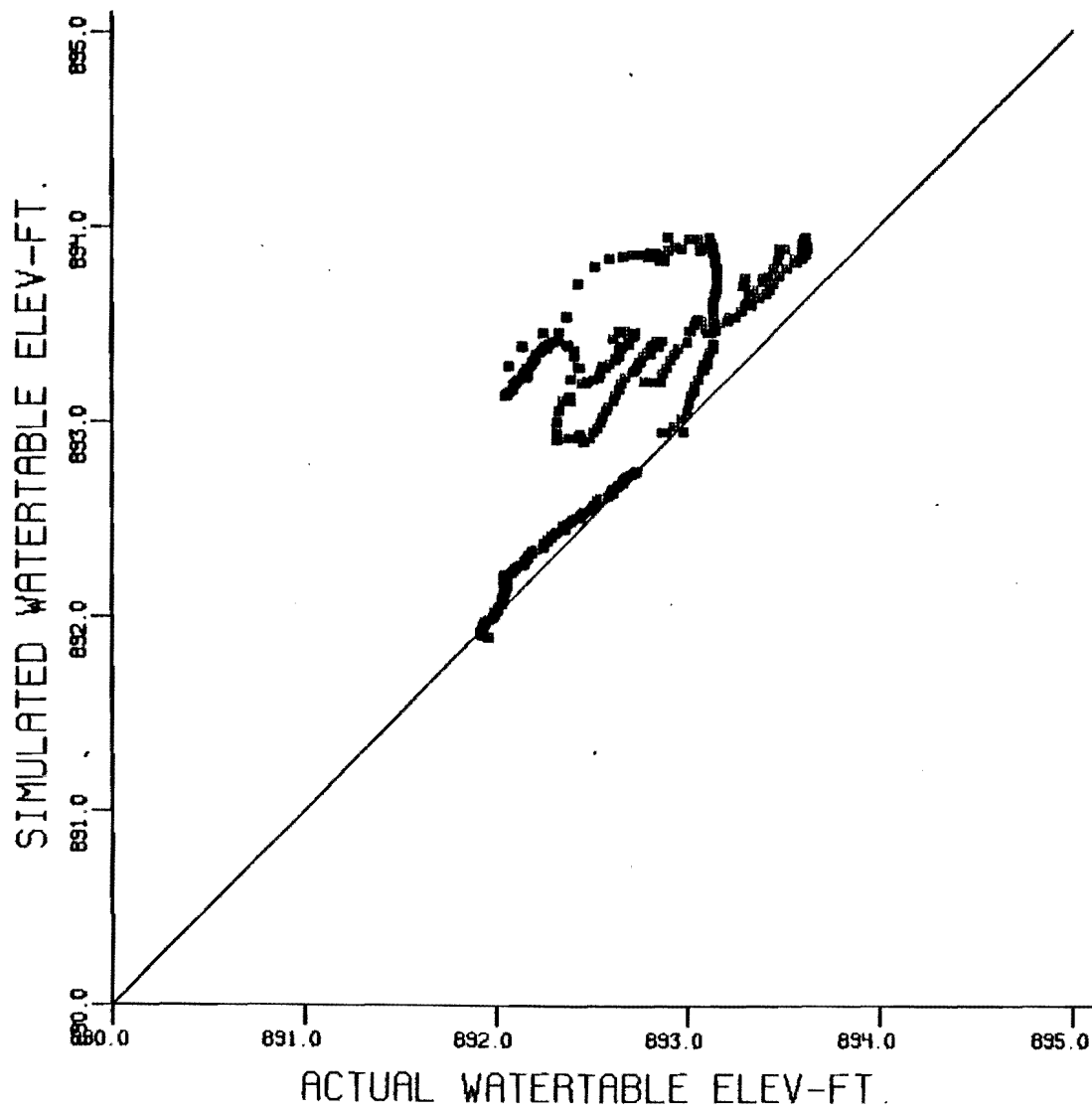


Figure A1.2 Simulated versus actual watertable elevation. RUN 1a: tinc3=.1 hr, 10 zones, snow infil= 4.2 in. Jan-Dec 1981

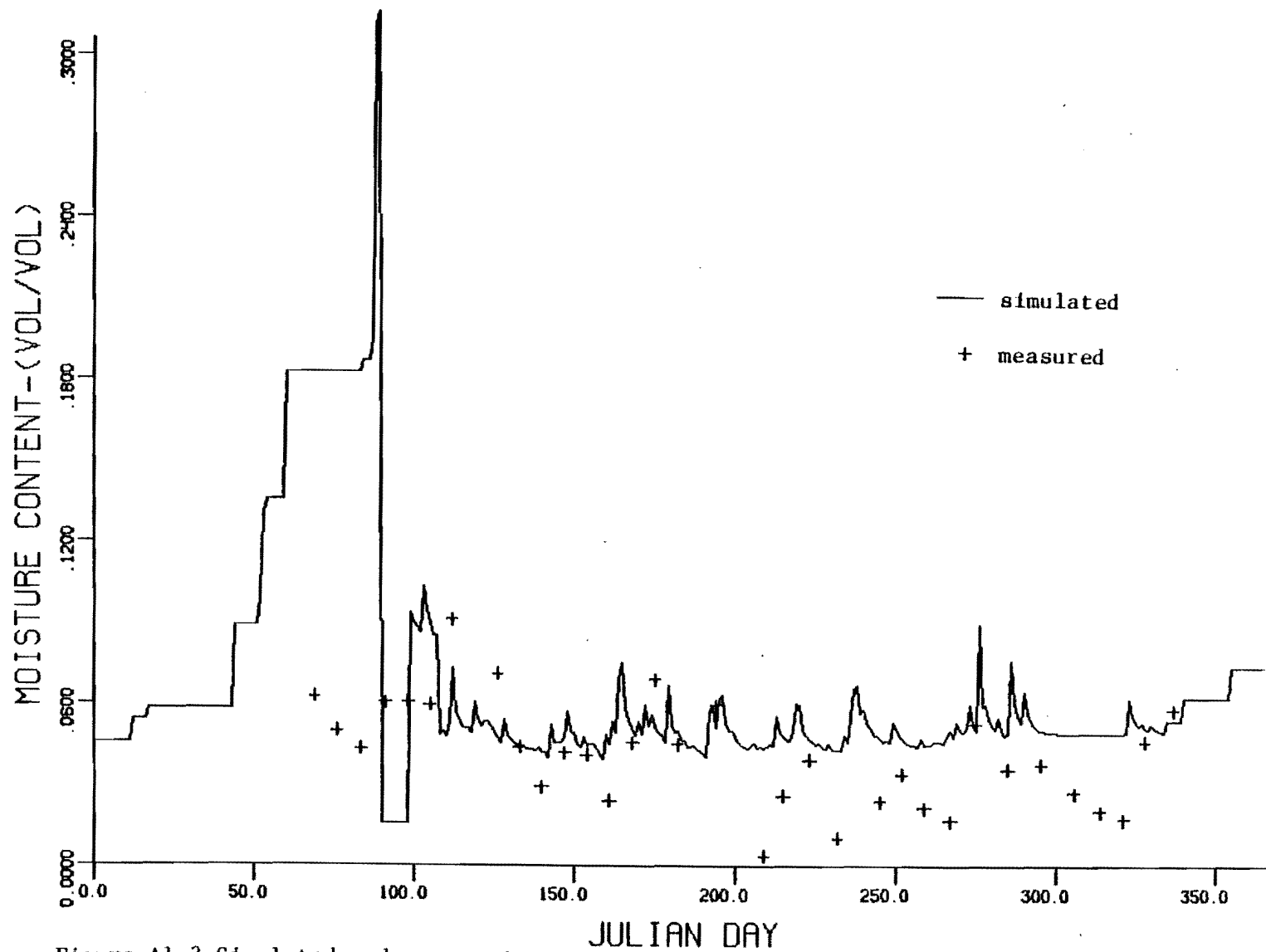


Figure A1.3 Simulated and measured moisture content versus julian day. Run 1a: tinc3= .1 hr., 10 zones, snow infil= 4.2 in. Jan-Déc 1981 ONE FOOT DEPTH

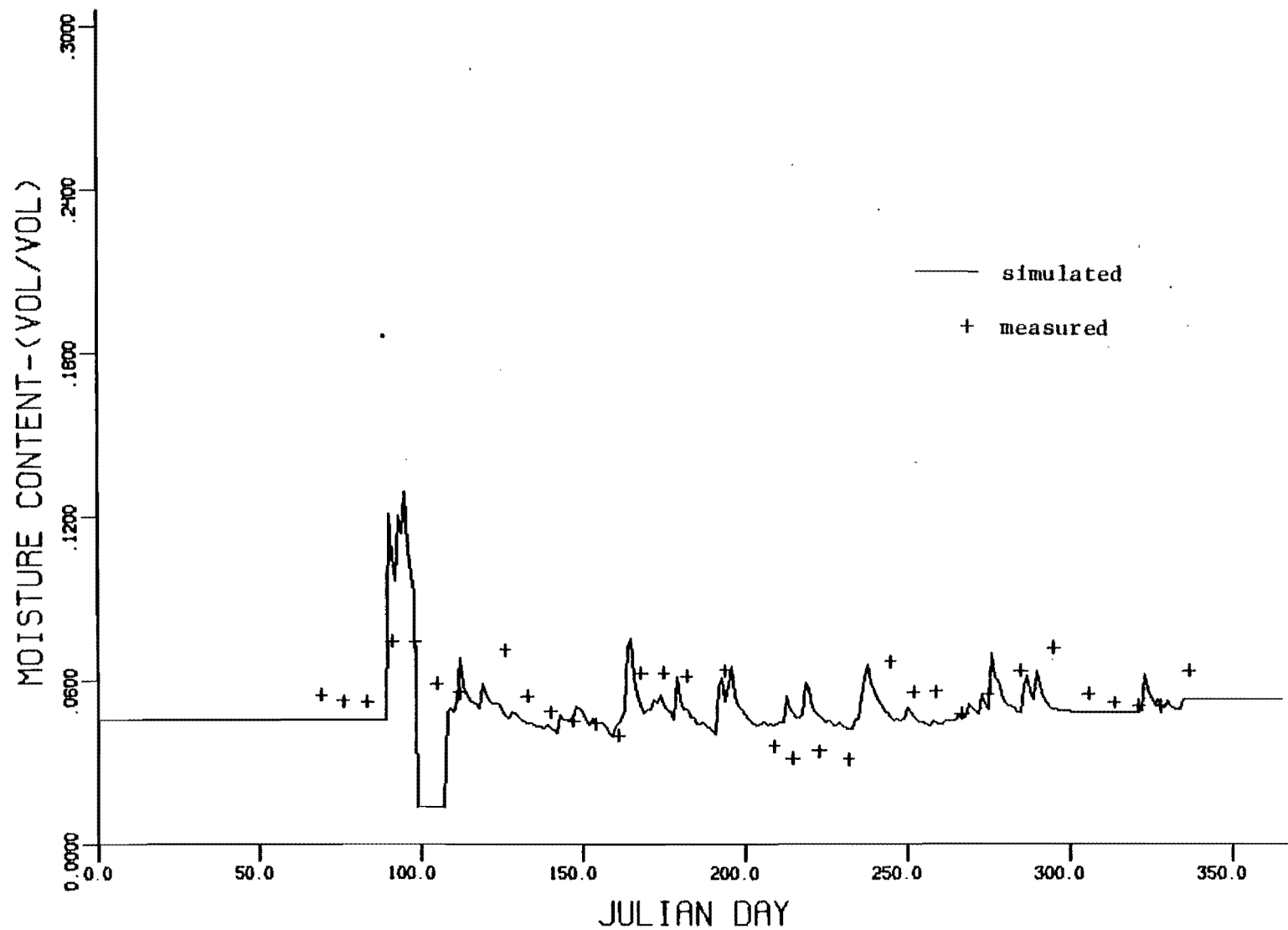


Figure A1.4 Simulated and measured moisture content versus Julian day. Run 1a: tinc3= .1 hr. 10 zones, snow infil= 4.2 in. Jan-Dec 1981 TWO FOOT DEPTH

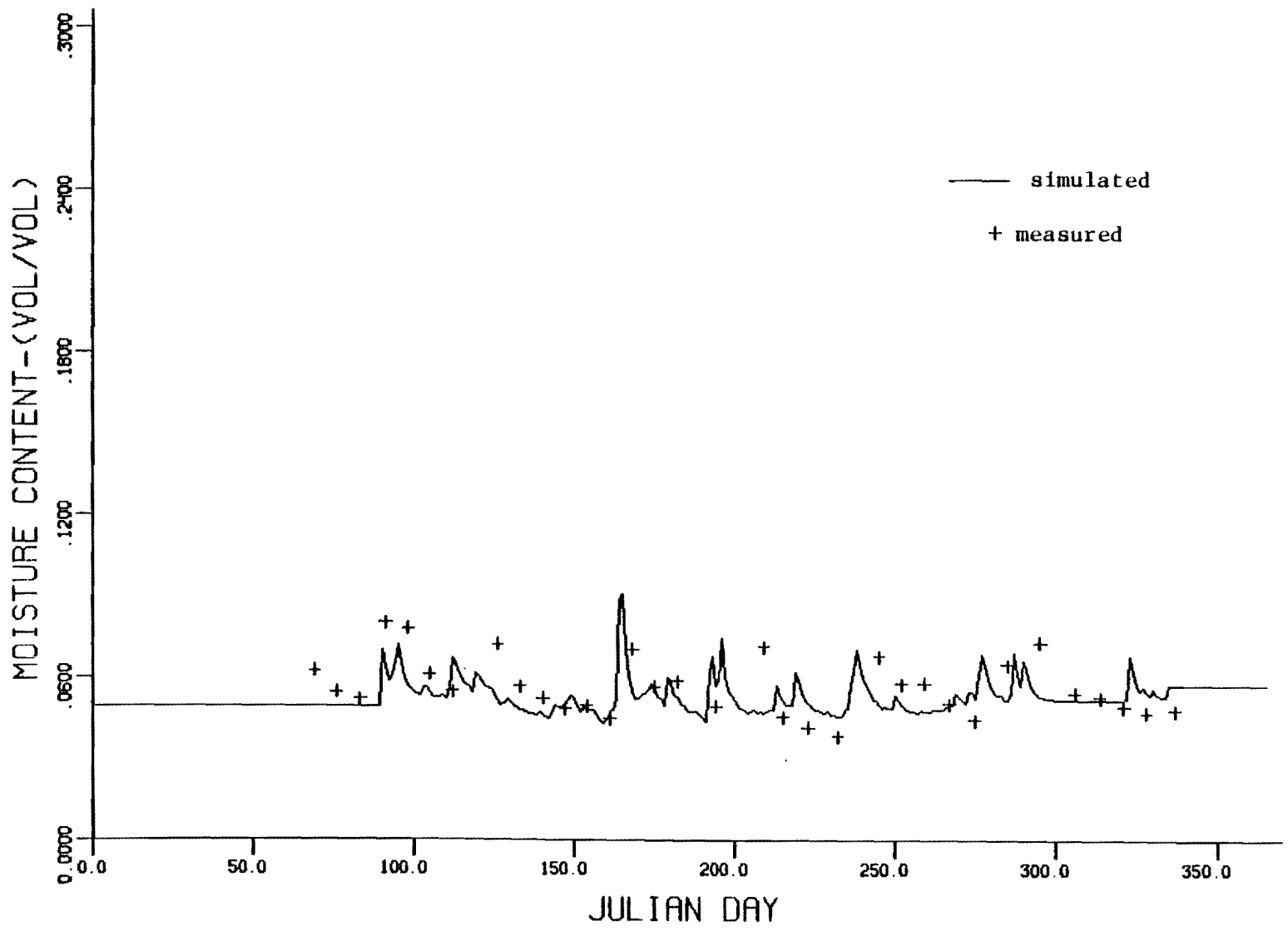


Figure A1.5 Simulated and measured moisture content versus julian day. Run 1a: tinc3= .1 hr.  
 10 zones, snow infil= 4.2 in. Jan-Dec 1981      THREE FOOT DEPTH

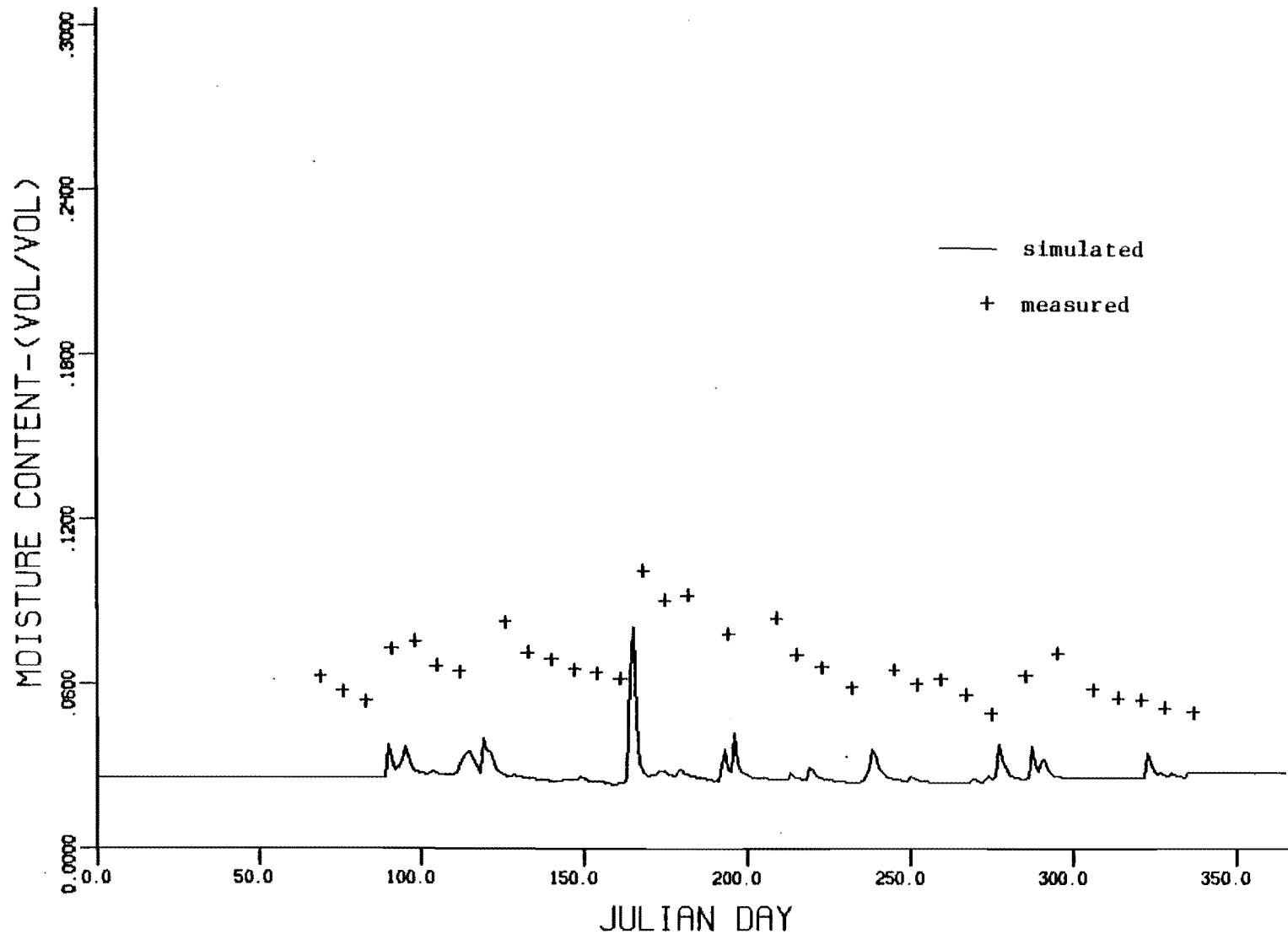


Figure A1.6 Simulated and measured moisture content versus julian day. Run 1a: tinc3= .1 hr. 10 zones, snow infil= 4.2 in. Jan-Dec 1981 FOUR FOOT DEPTH

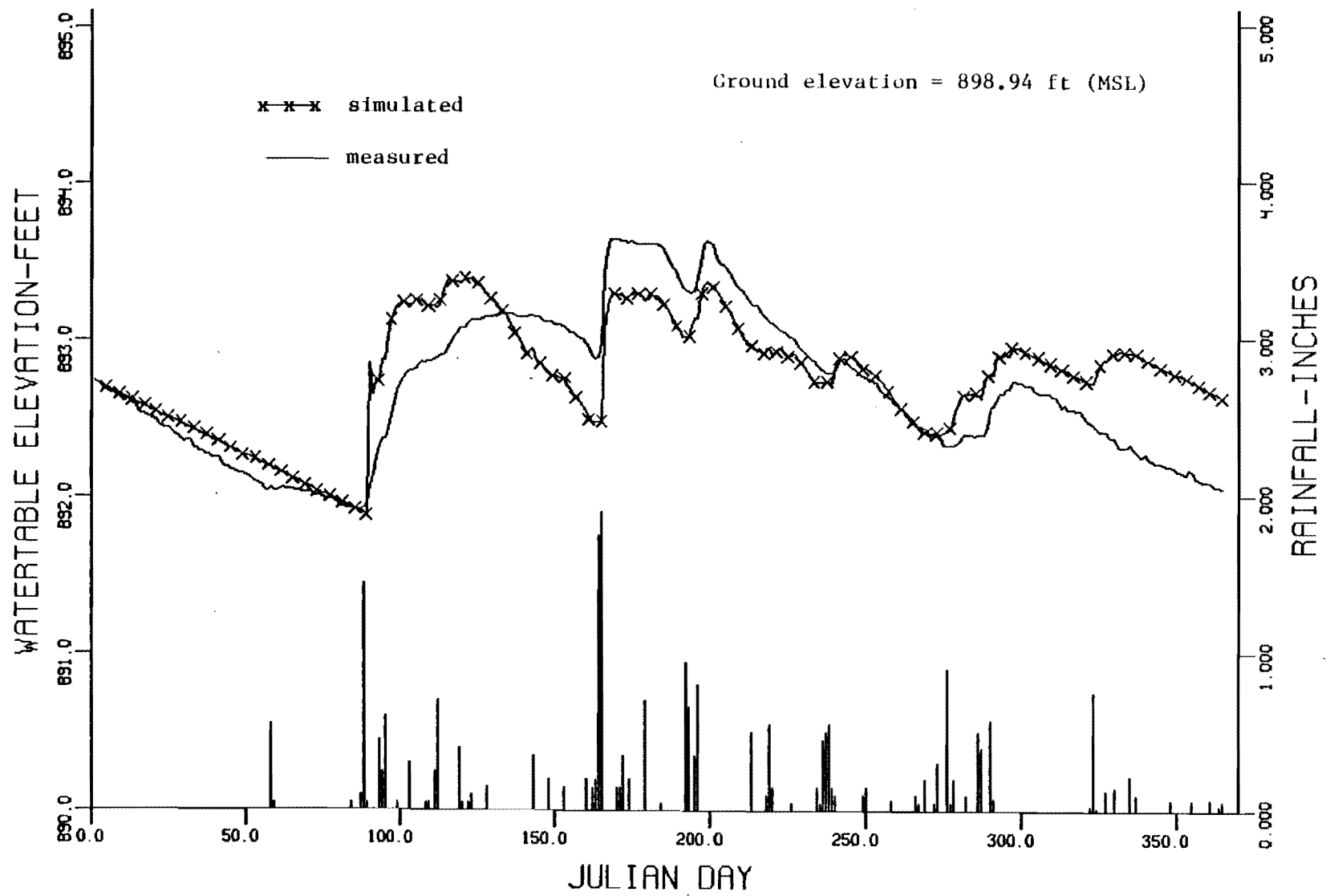


Figure A2.1 Simulated and measured watertable elevations versus julian day and precipitation versus julian day. RUN 1b: tinc3= .1 hr, 10 zones, snow infil= 1.2 in. Jan-Dec 1981

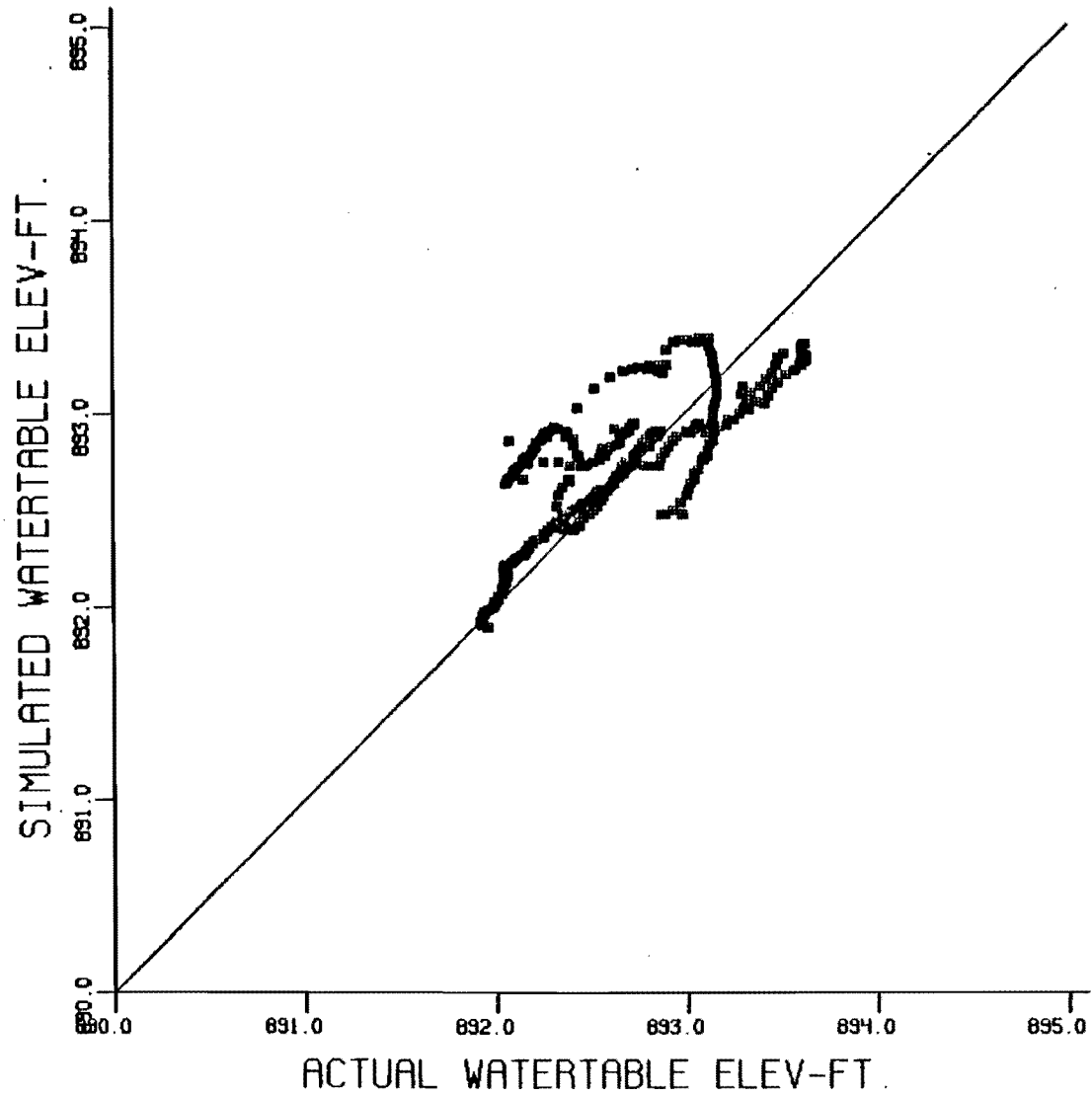


Figure A2.2 Simulated versus actual watertable elevation. RUN 1b: tinc3= .1 hr, 10 zones  
snow infil= 1.2 in. Jan-Dec 1981

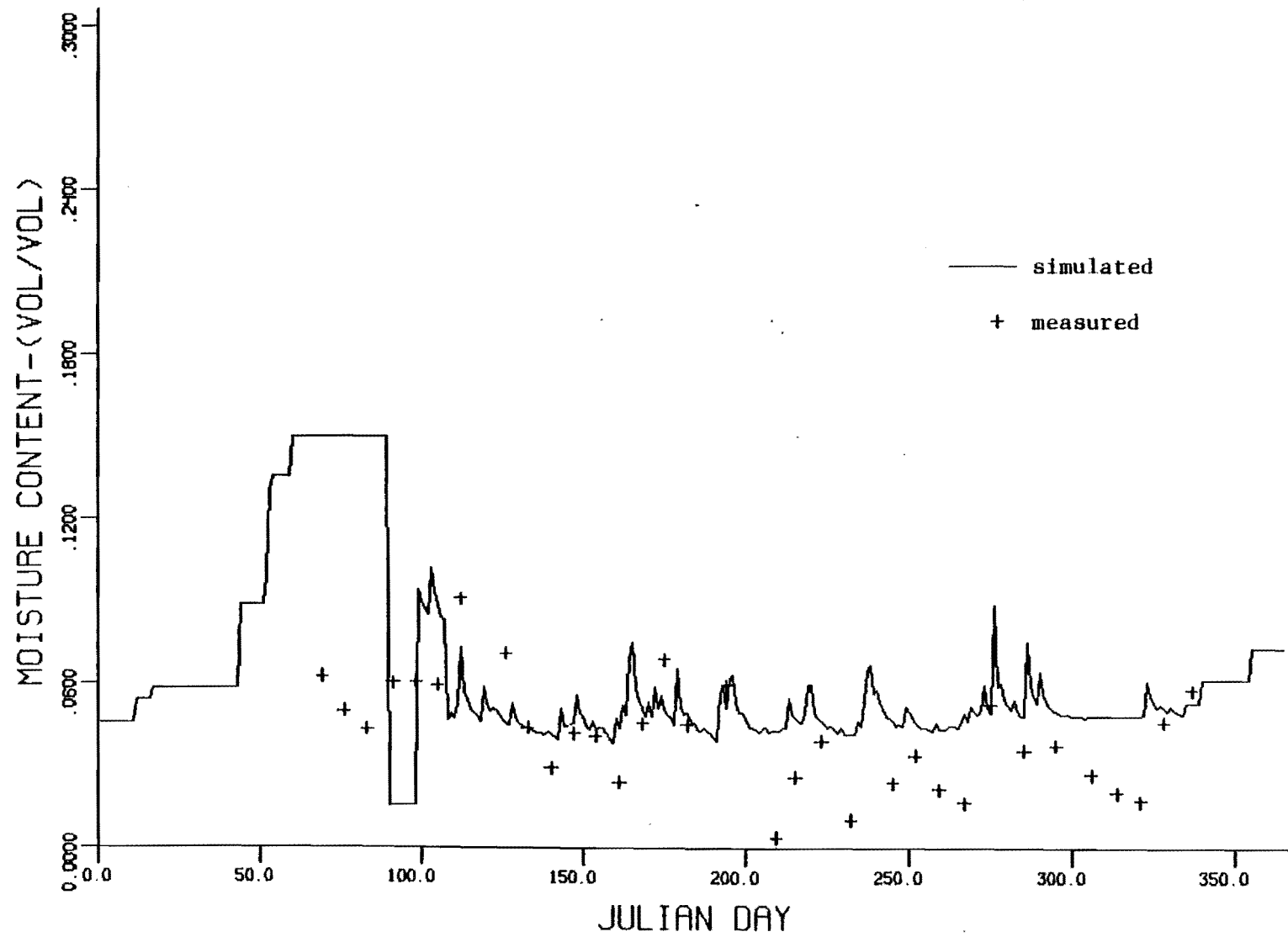


Figure A2.3 Simulated and measured moisture content versus julian day. Run 1b: tinc3= .1hr  
 10 zones, snow infil= 1.2 in. Jan-Dec 1981 ONE FOOT DEPTH

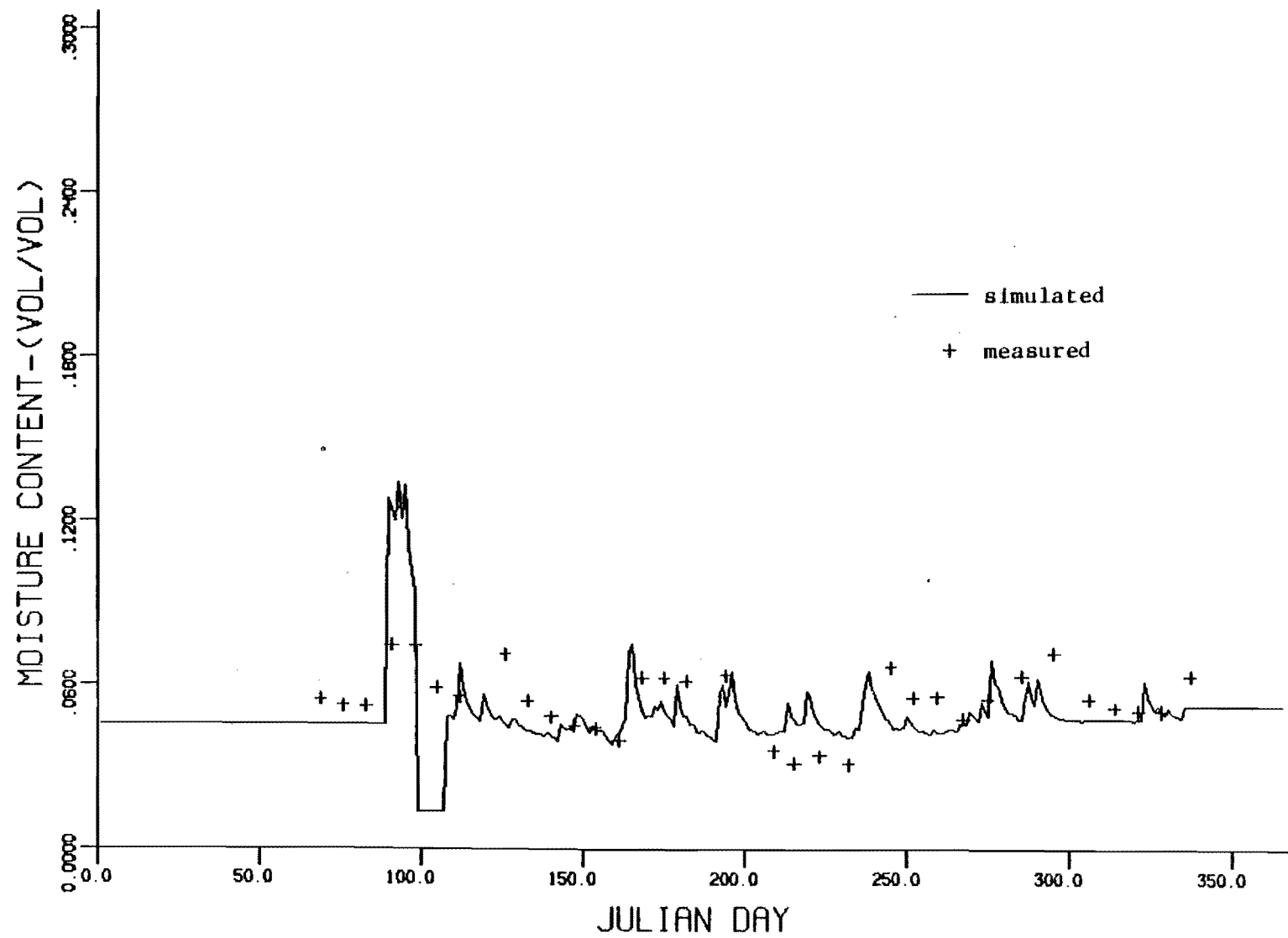


Figure A2.4 Simulated and measured moisture content versus julian day. Run 1b: tinc3= .1 hr  
10 zones, snow infil= 1.2 in. Jan-Dec 1981 TWO FOOT DEPTH

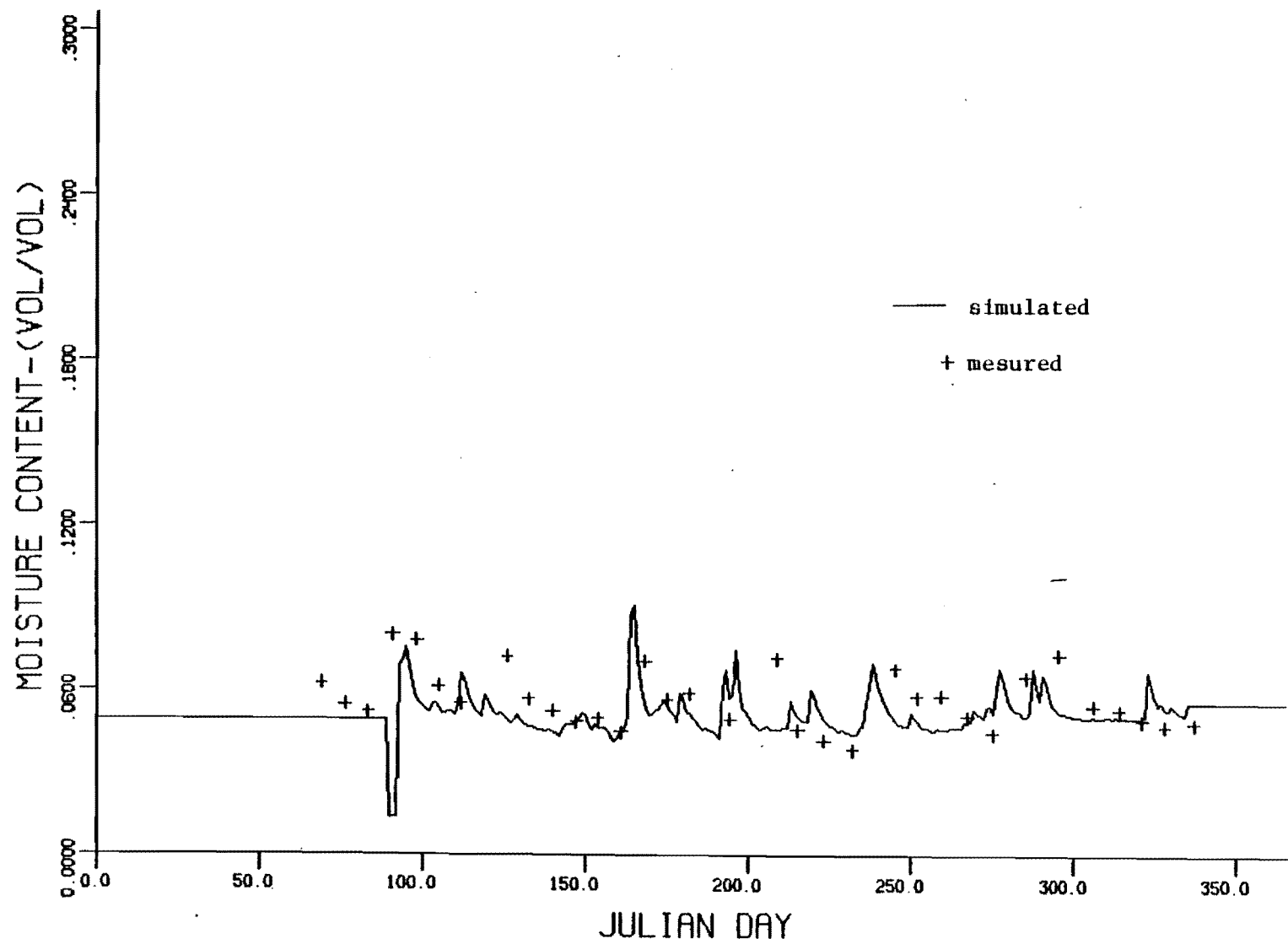


Figure A2.5 Simulated and measured moisture content versus julian day. Run lb: tinc3= .1 hr  
10 zones, snow infil= 1.2 in. Jan-Dec 1981 THREE FOOT DEPTH

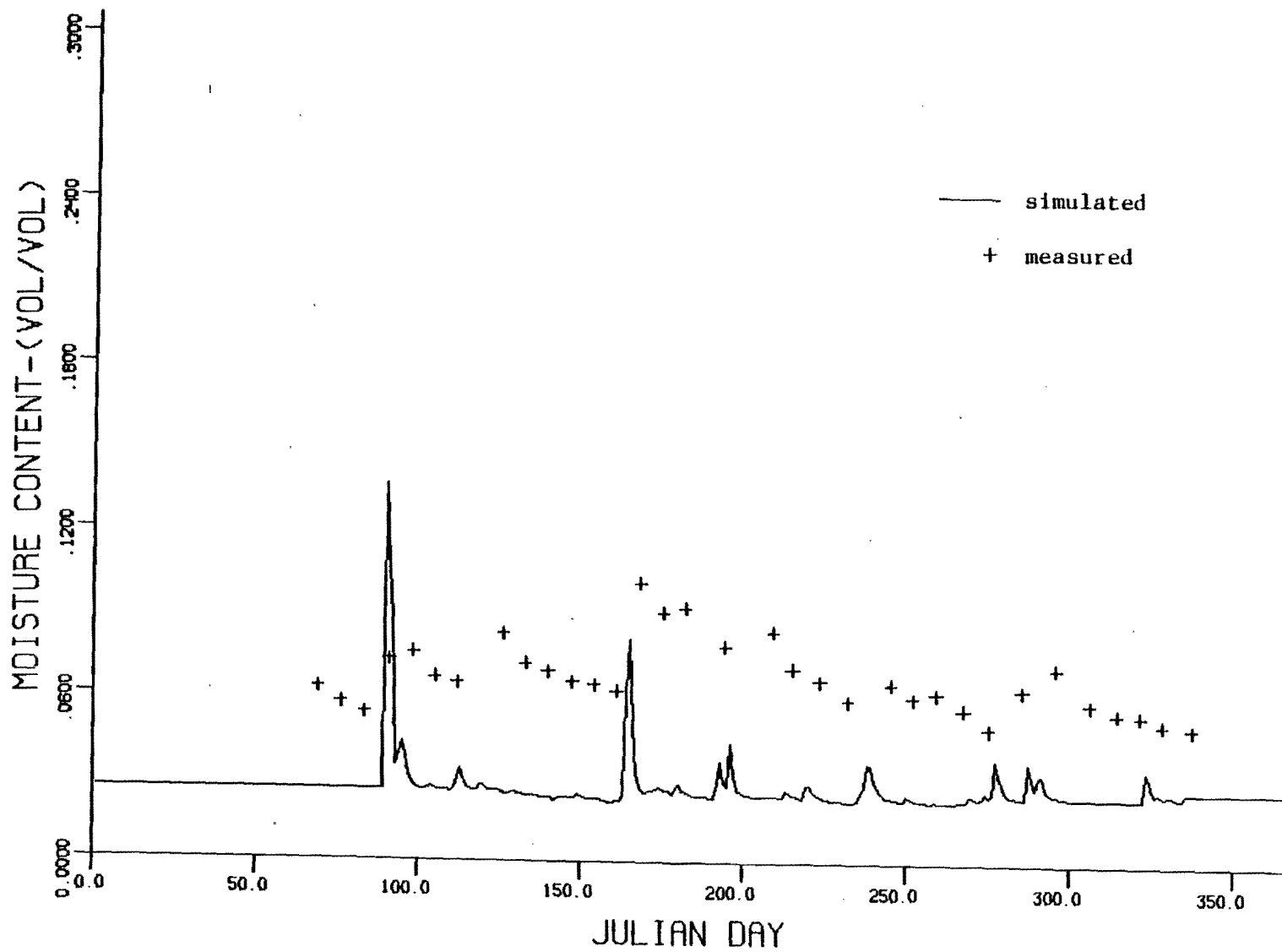


Figure A2.6 Simulated and measured moisture content versus julian day. Run 1b: tinc3= .1 hr  
 10 zones, snow infil= 1.2 in. Jan-Dec 1981      FOUR FOOT DEPTH

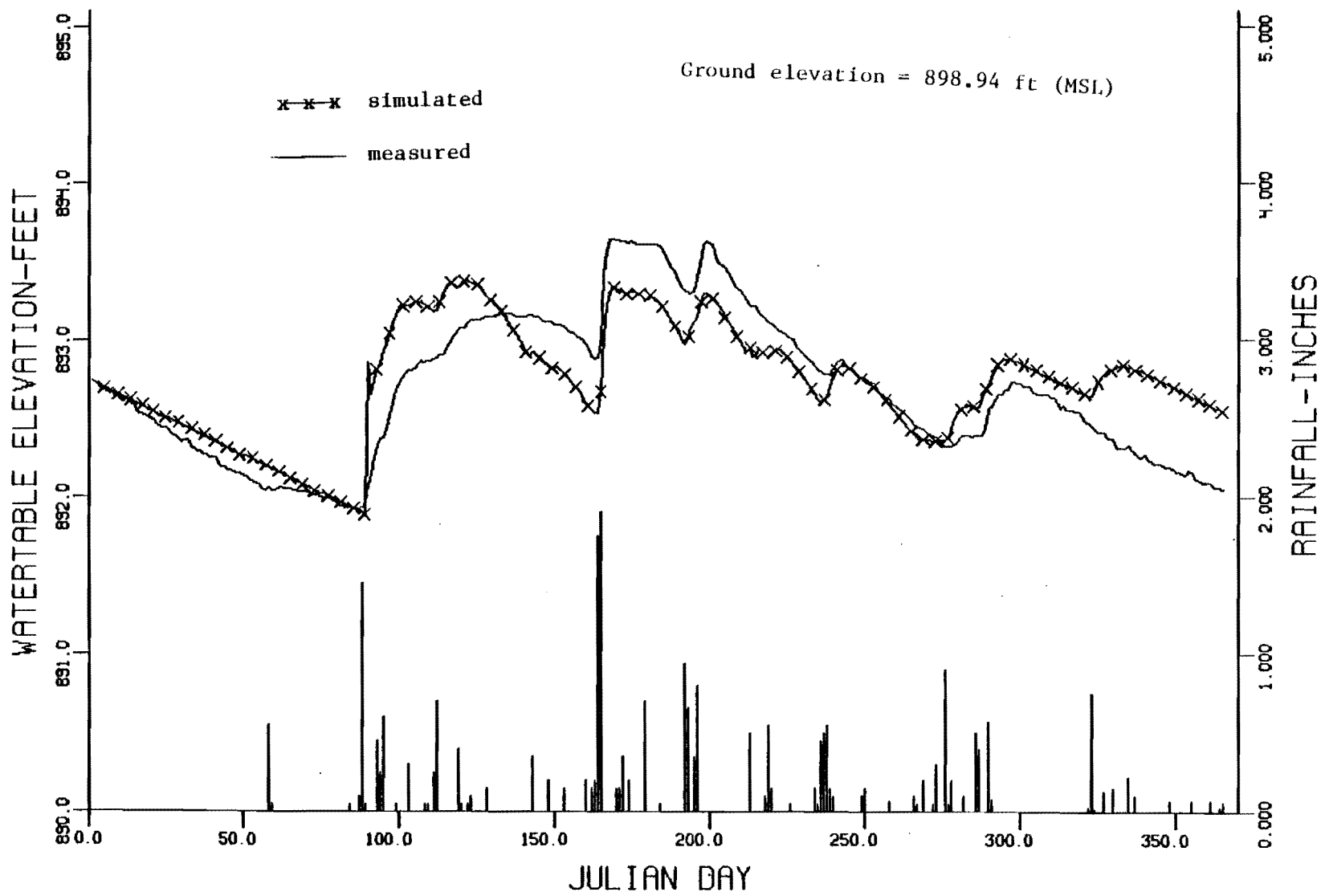


Figure A3.1 Simulated and measured watertable elevation versus julian day and precipitation versus julian day. Run 2: tinc3= 1.0, 10 zones, snow infil= 1.2 in. Jan-Dec 1981

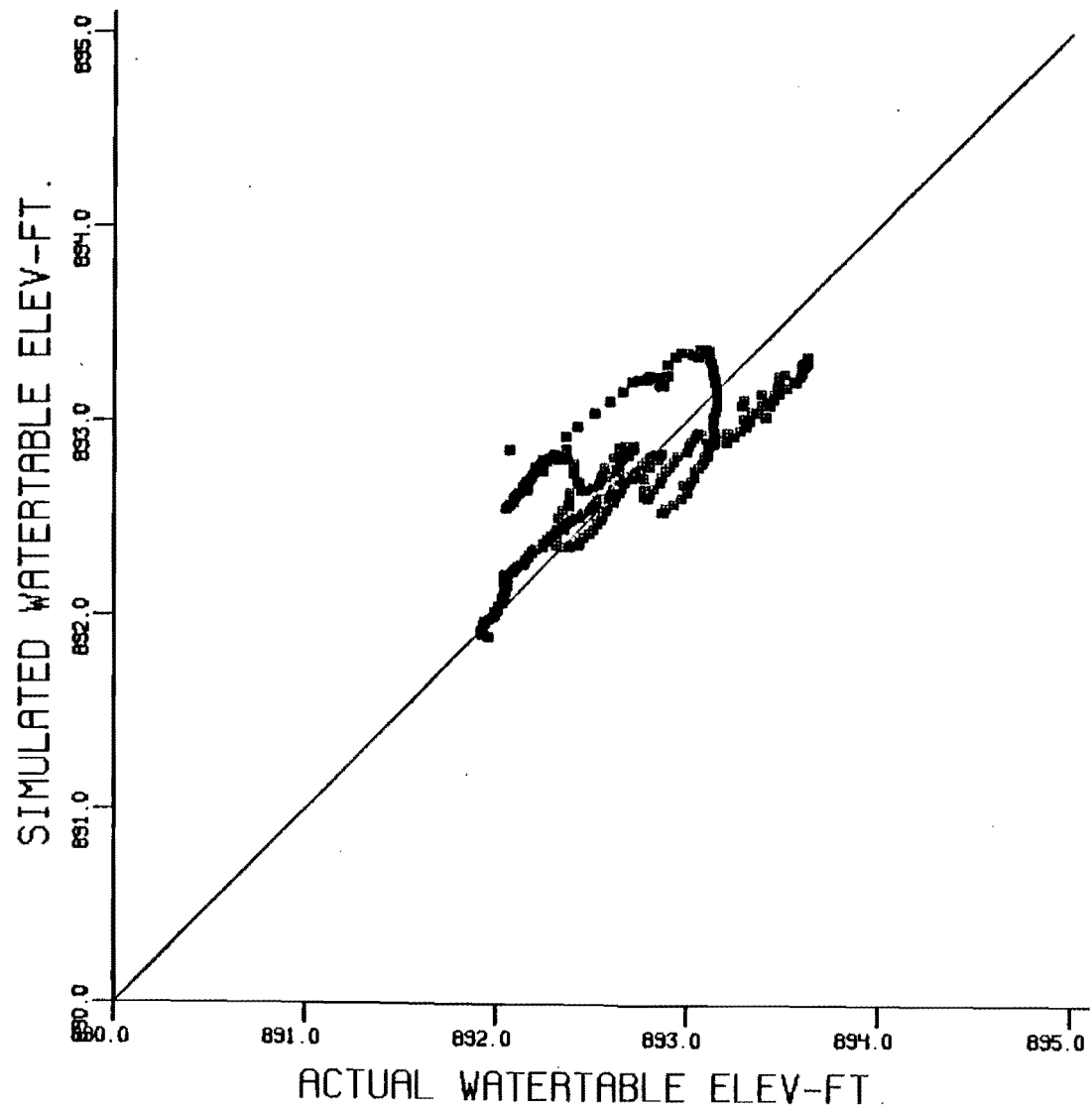


Figure A3.2 Simulated versus actual watertable elevation. Run 2: tinc3= 1.0 hr, 10 zones, snow infil= 1.2 in. Jan-Dec 1981

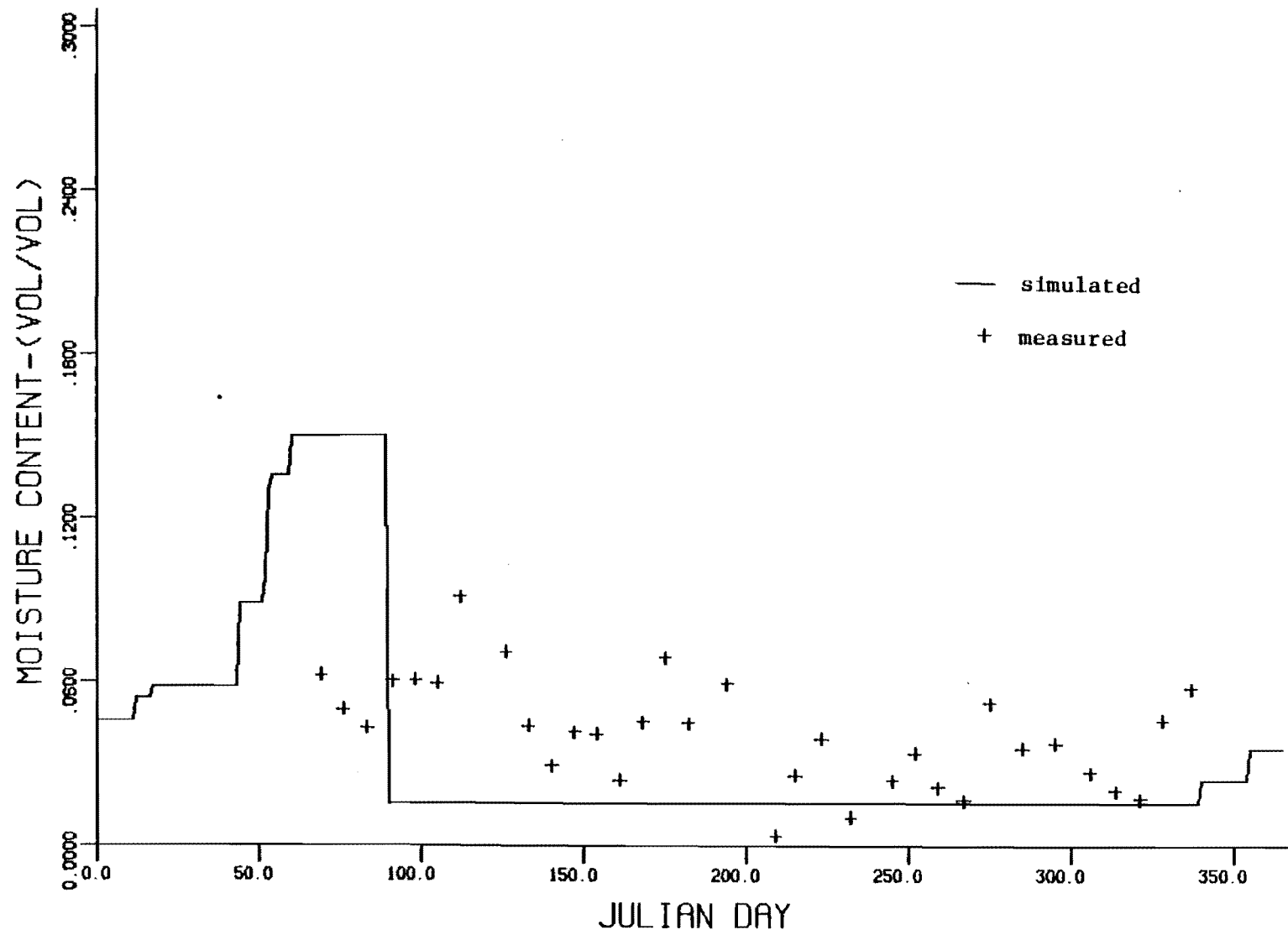


Figure A3.3 Simulated and measured moisture content versus julian day. Run 2: tinc3= 1.0 hr.  
10 zones, snow infil= 1.2 in. Jan-Dec 1981 ONE FOOT DEPTH

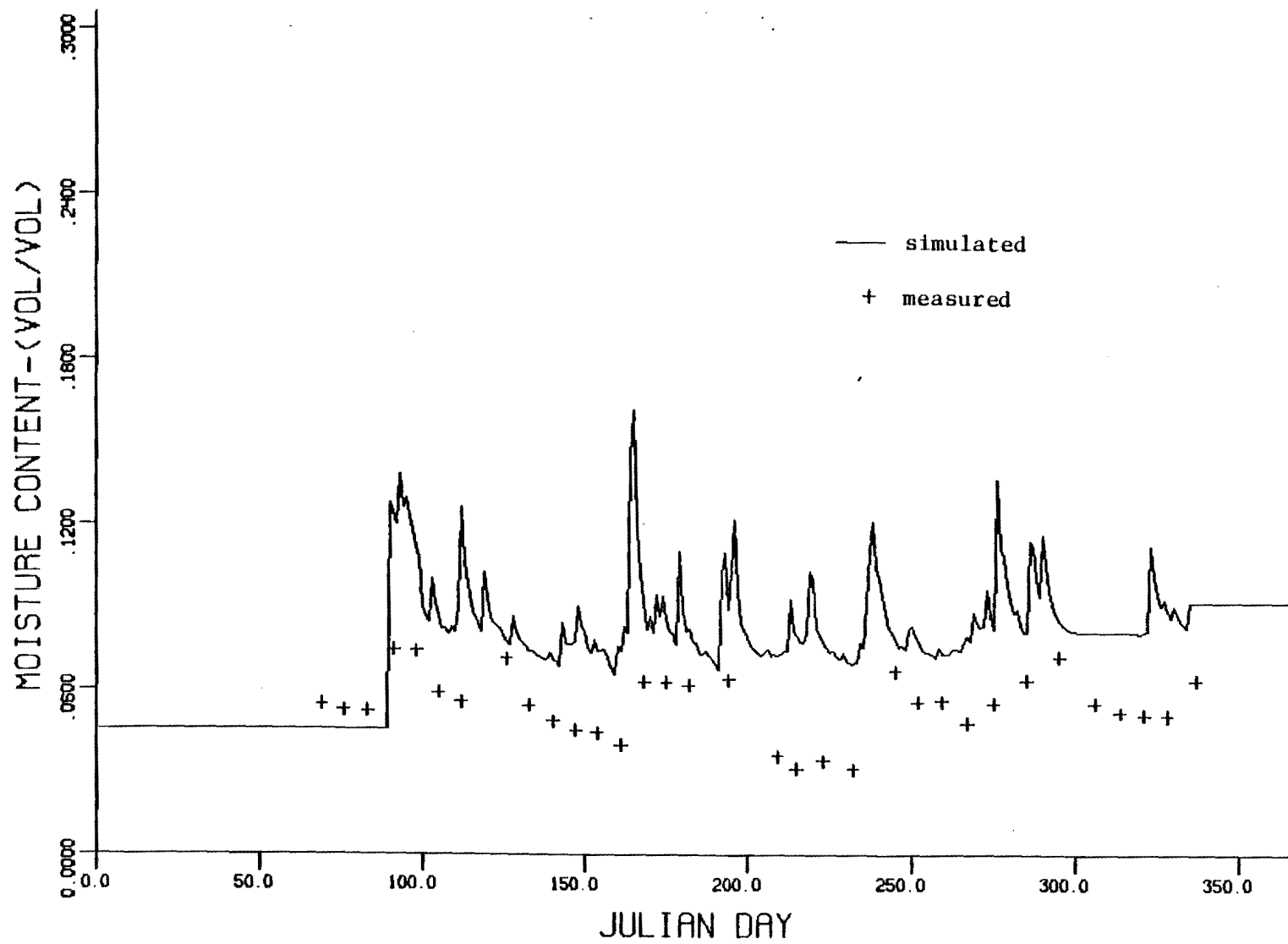


Figure A3.4 Simulated and measured moisture content versus julian day. Run 2: tinc3= 1.0hr.  
 10 zones, snow infil= 1.2 in. Jan-Dec 1981 TWO FOOT DEPTH

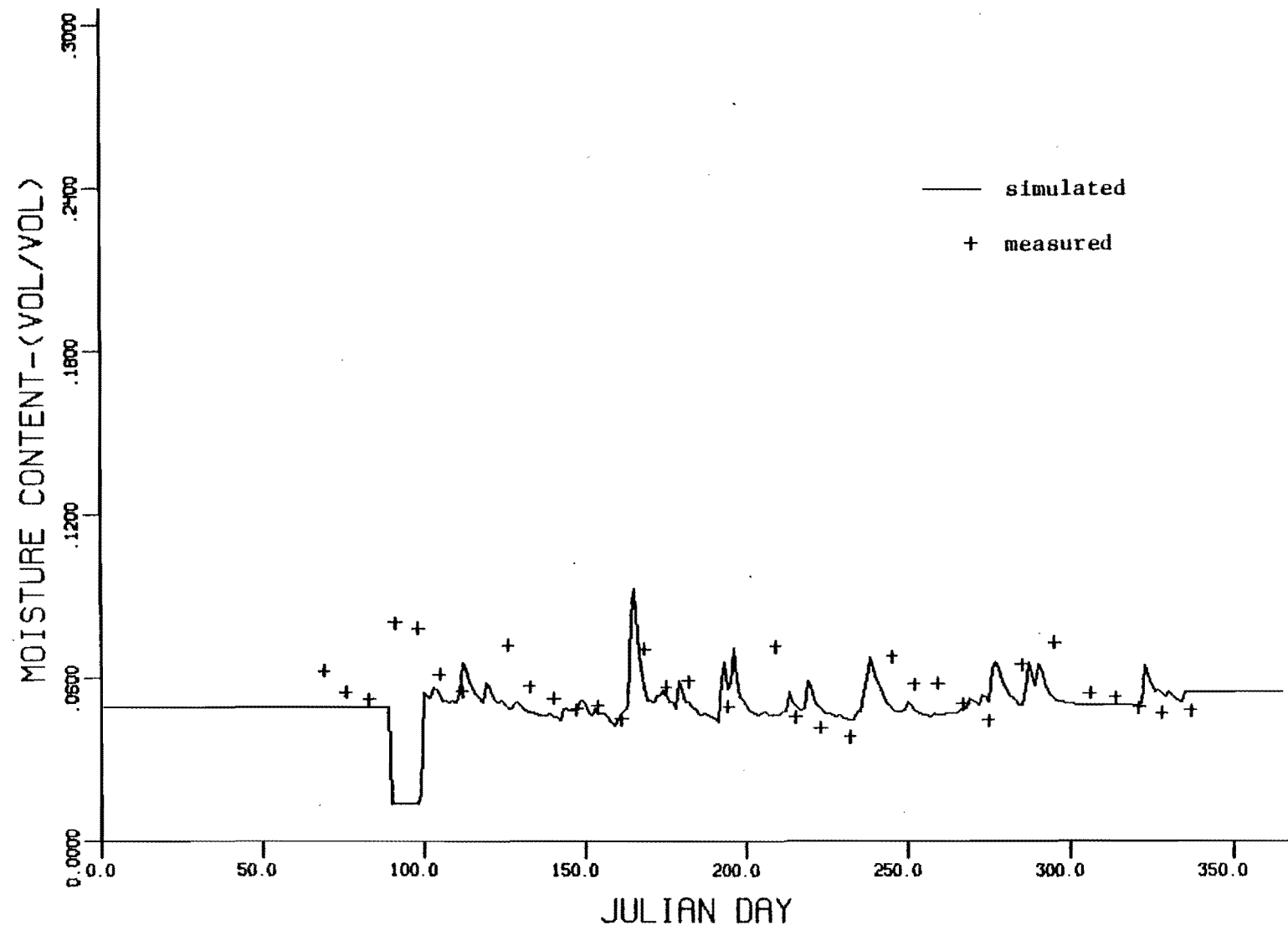


Figure A3.5 Simulated and measured moisture content versus julian day. Run 2: tinc3= 1.0 hr. 10 zones, snow infil= 1.2 in. Jan-Dec 1981 THREE FOOT DEPTH

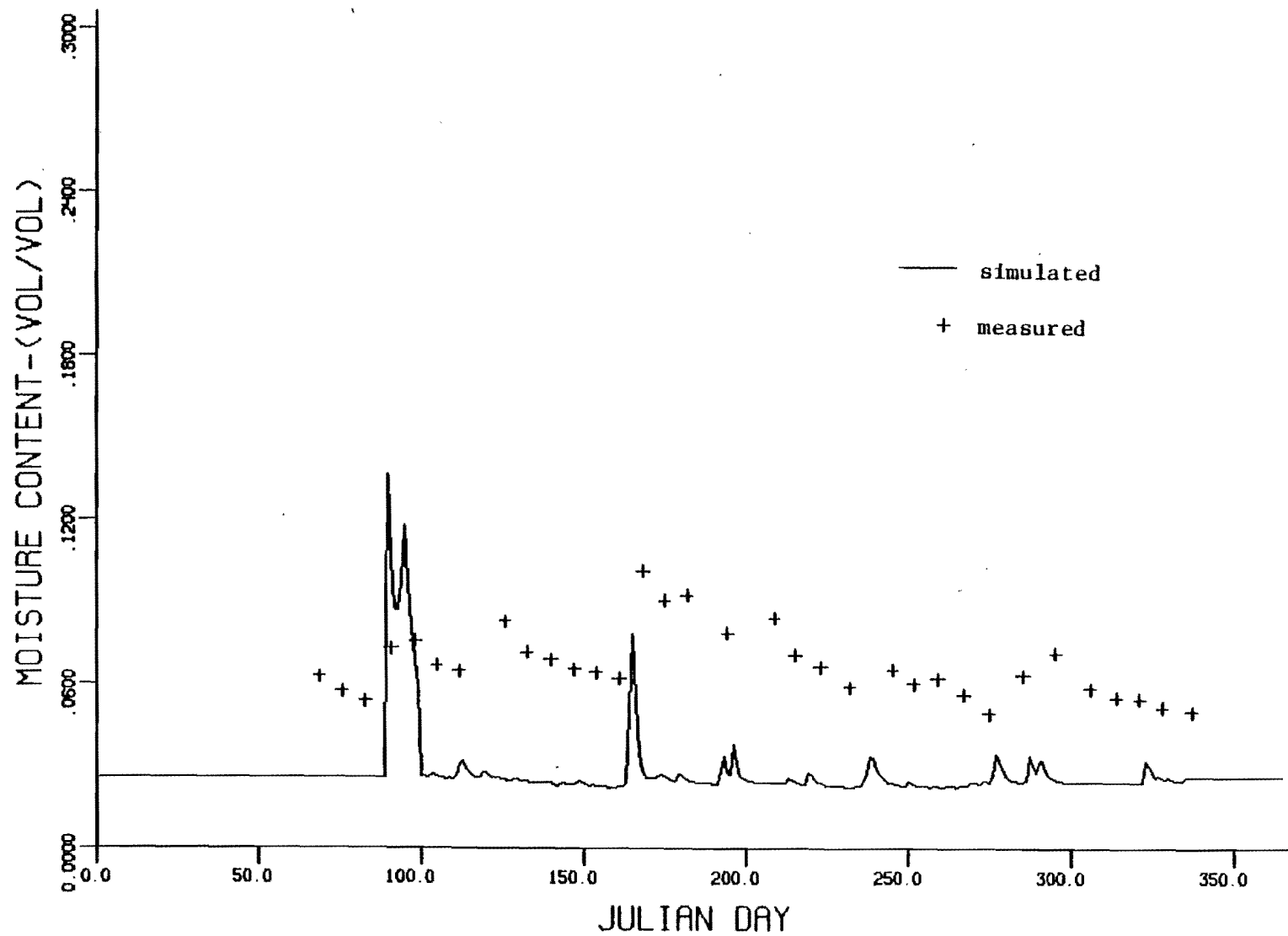


Figure A3.6 Simulated and measured moisture content versus julian day. Run 2: tinc3= 1.0 hr.  
 10 zones, snow infil= 1.2 in. Jan-Dec 1981 FOUR FOOT DEPTH

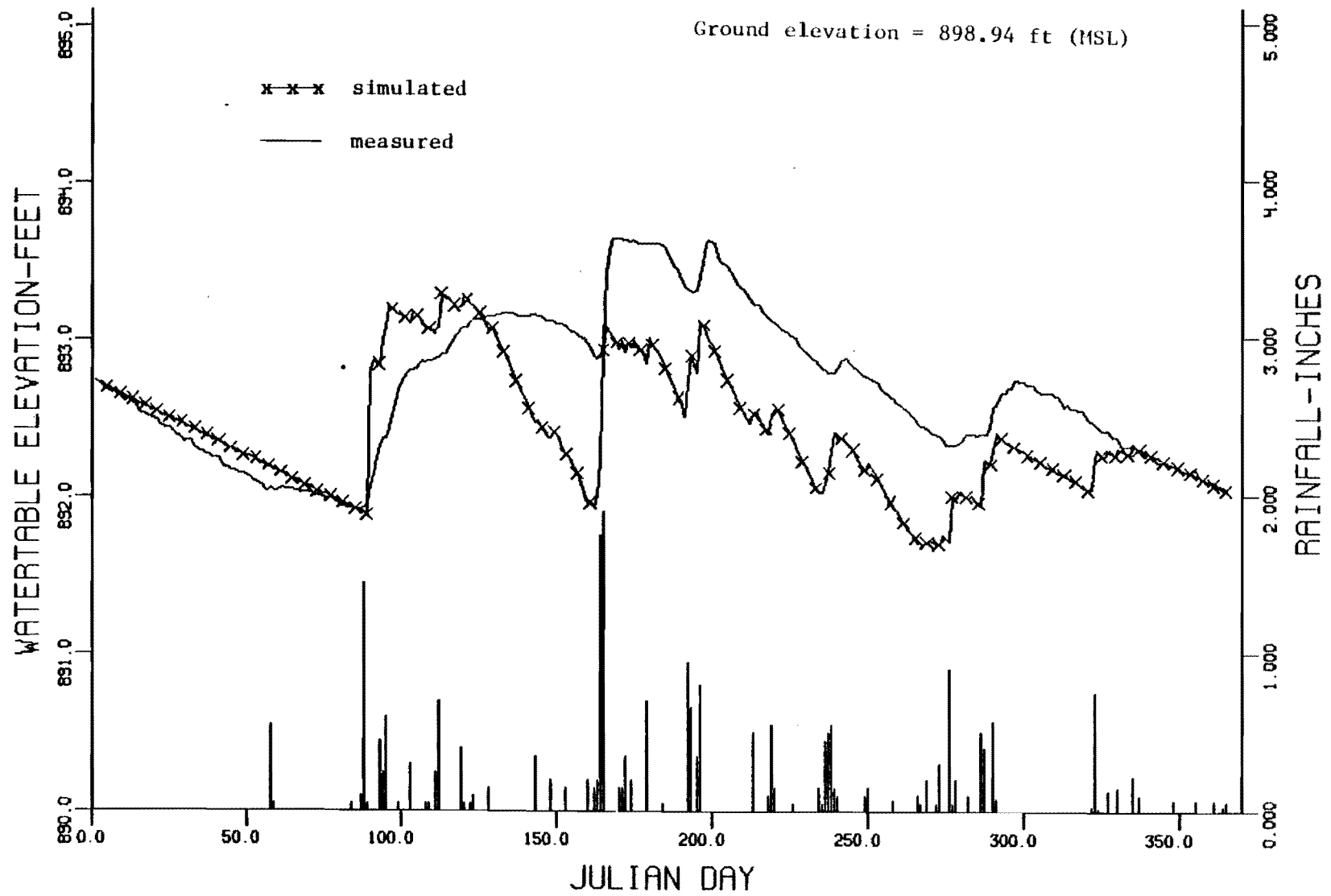


Figure A4.1 Simulated and measured watertable elevation versus julian day and precipitation versus julian day. Run 3: tinc3=0.1, 2 zones, snow infil= 1.2 in. Jan-Dec 1981

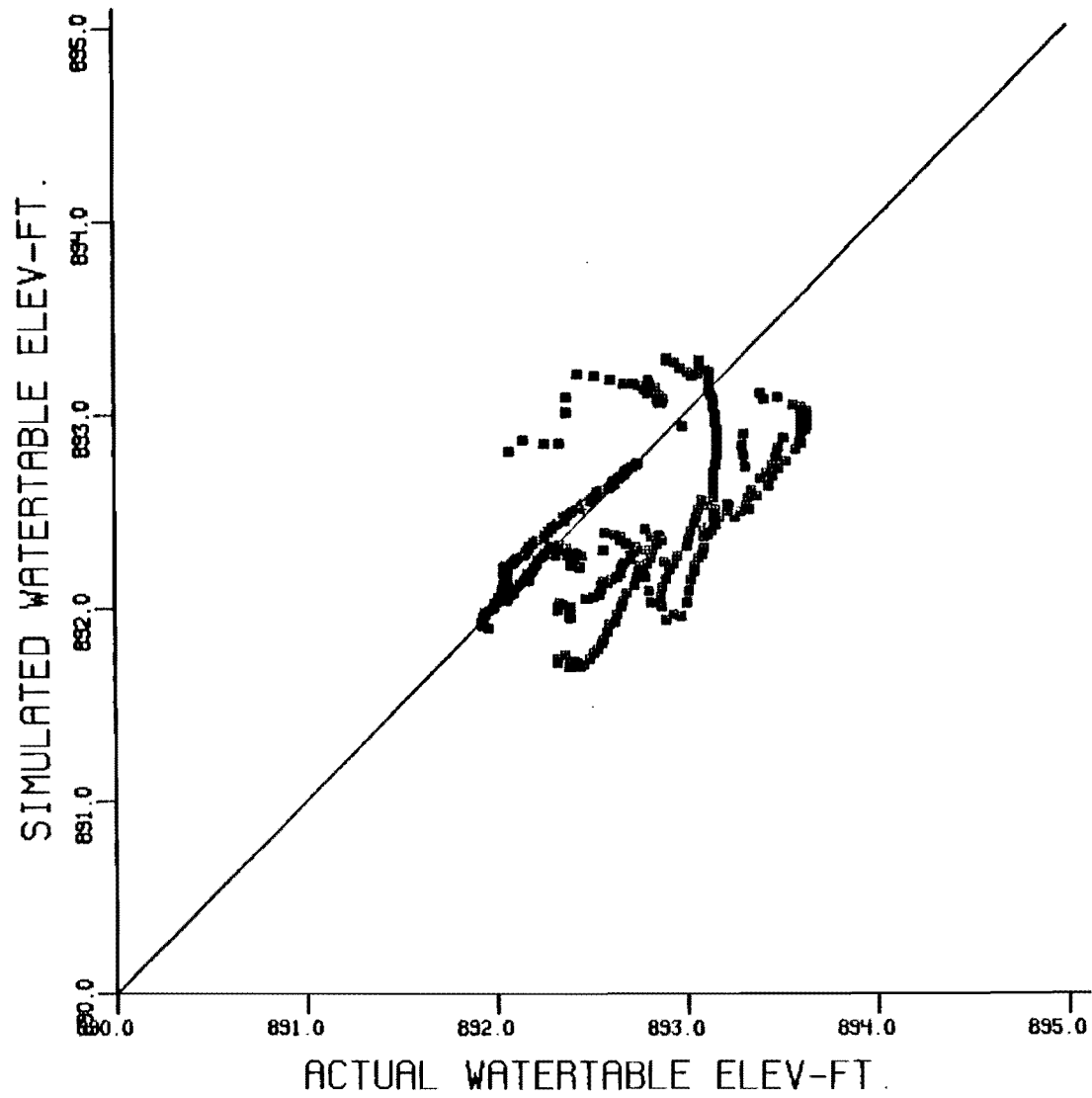


Figure A4.2 Simulated versus actual watertable elevation. Run 3:  $tinc3 = 0.1$ , 2 zones, snow infil = 1.2 in. Jan-Dec 1981

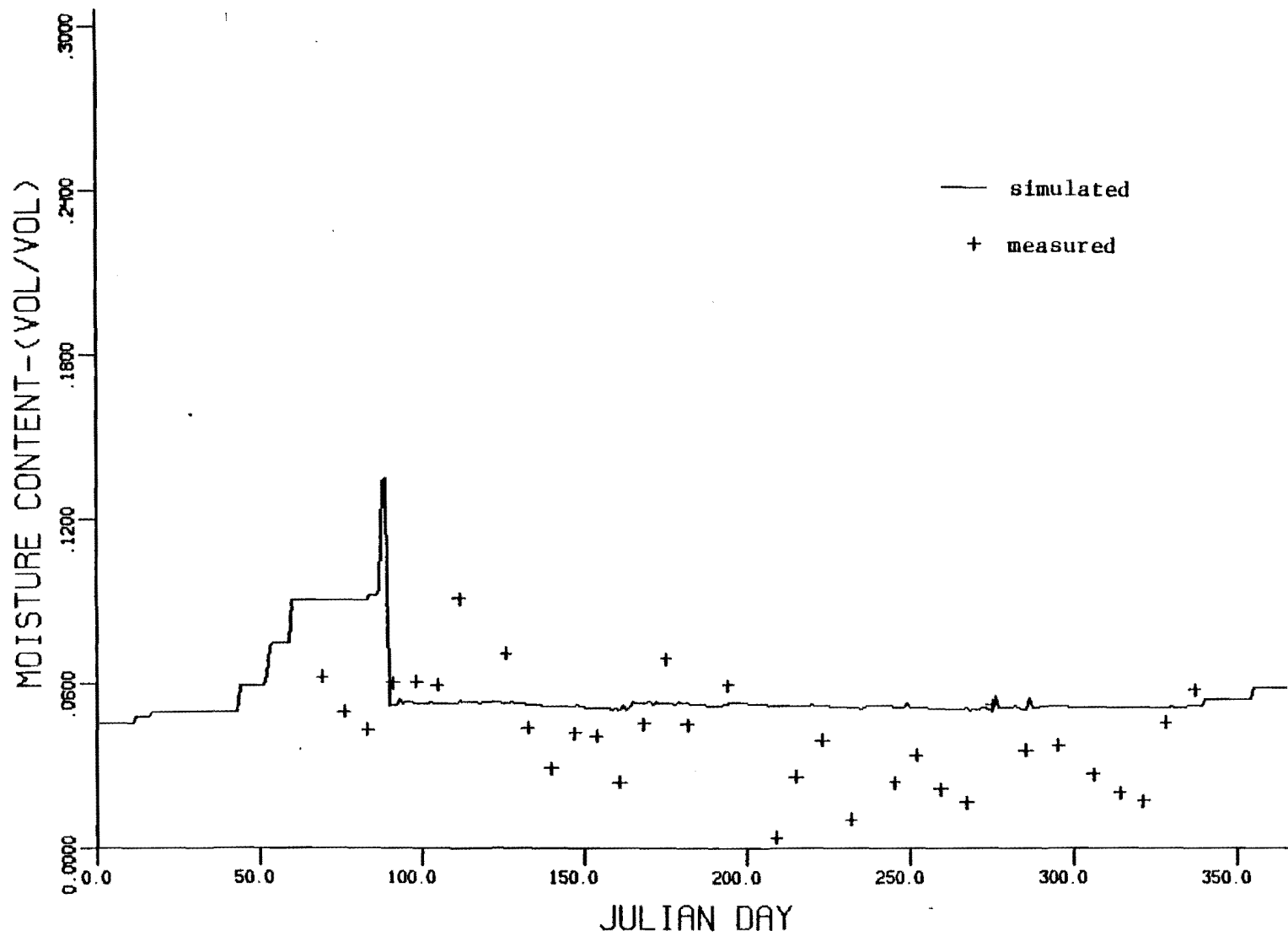


Figure A4.3 Simulated and measured moisture content versus julian day. Run 3: tinc3= .1 hr.  
 2 zones, snow infil= 1.2 in. Jan-Dec 1981 ONE FOOT DEPTH

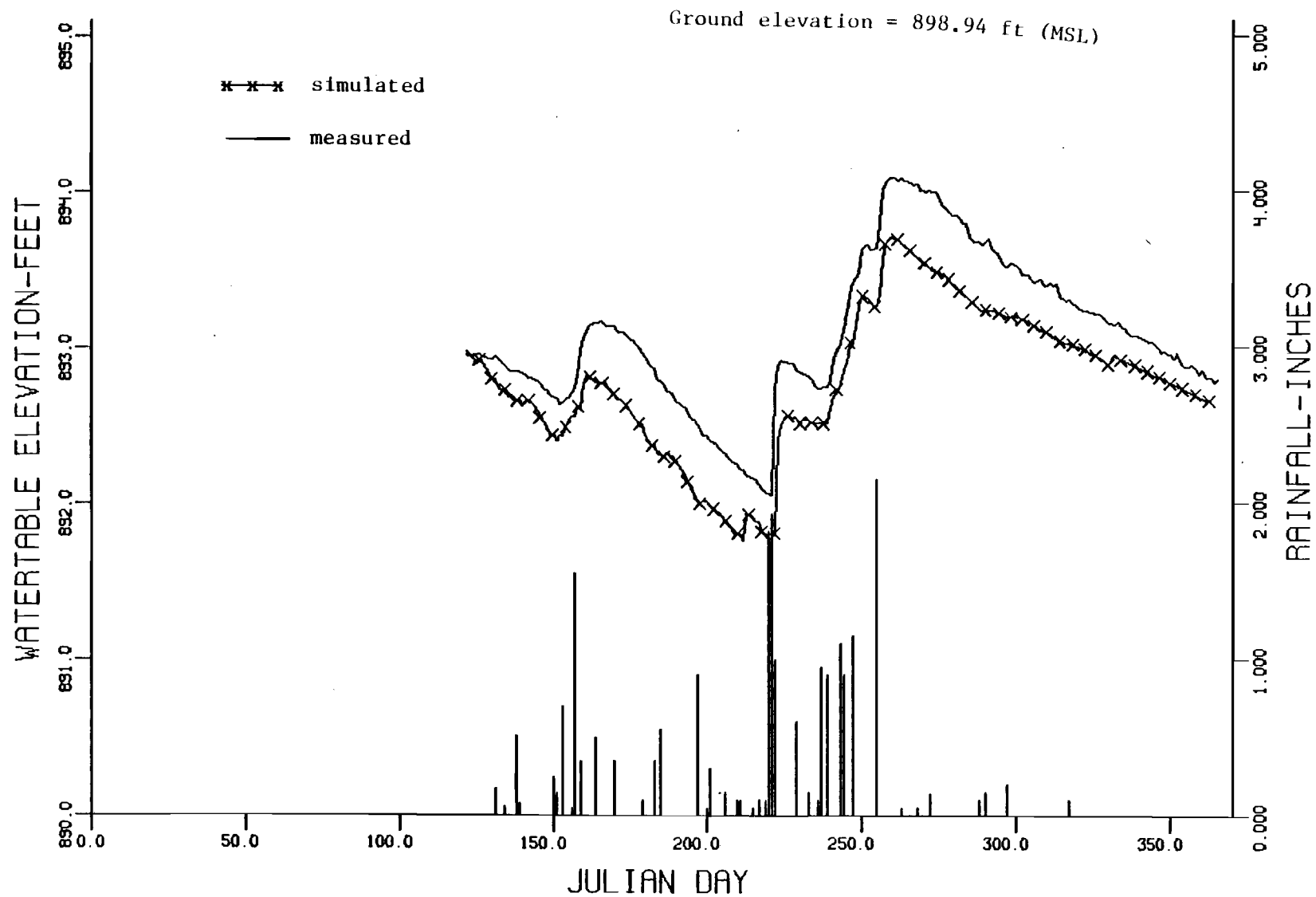


Figure A5.1 Simulated and measured watertable elevation versus Julian day and precipitation versus Julian day. Run 4:  $tinc3 = 0.1$  hrs., snow infil= 1.2 in. MAY-DEC 1980

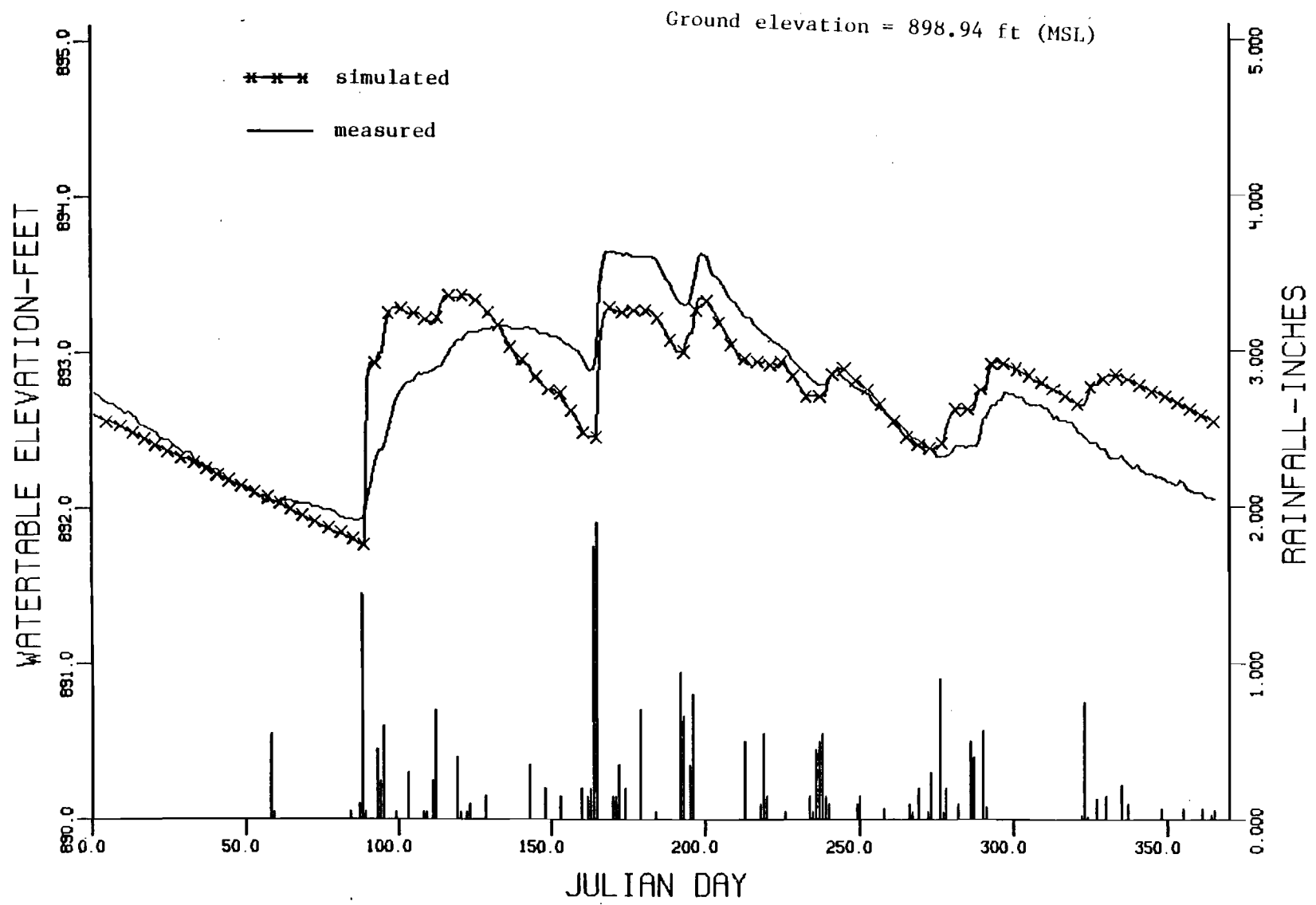


Figure A5.2 Simulated and measured watertable elevation versus julian day and precipitation versus julian day. Run 4: tinc3 = 0.1 hrs., snow infil= 1.2 in. JAN-DEC 1981

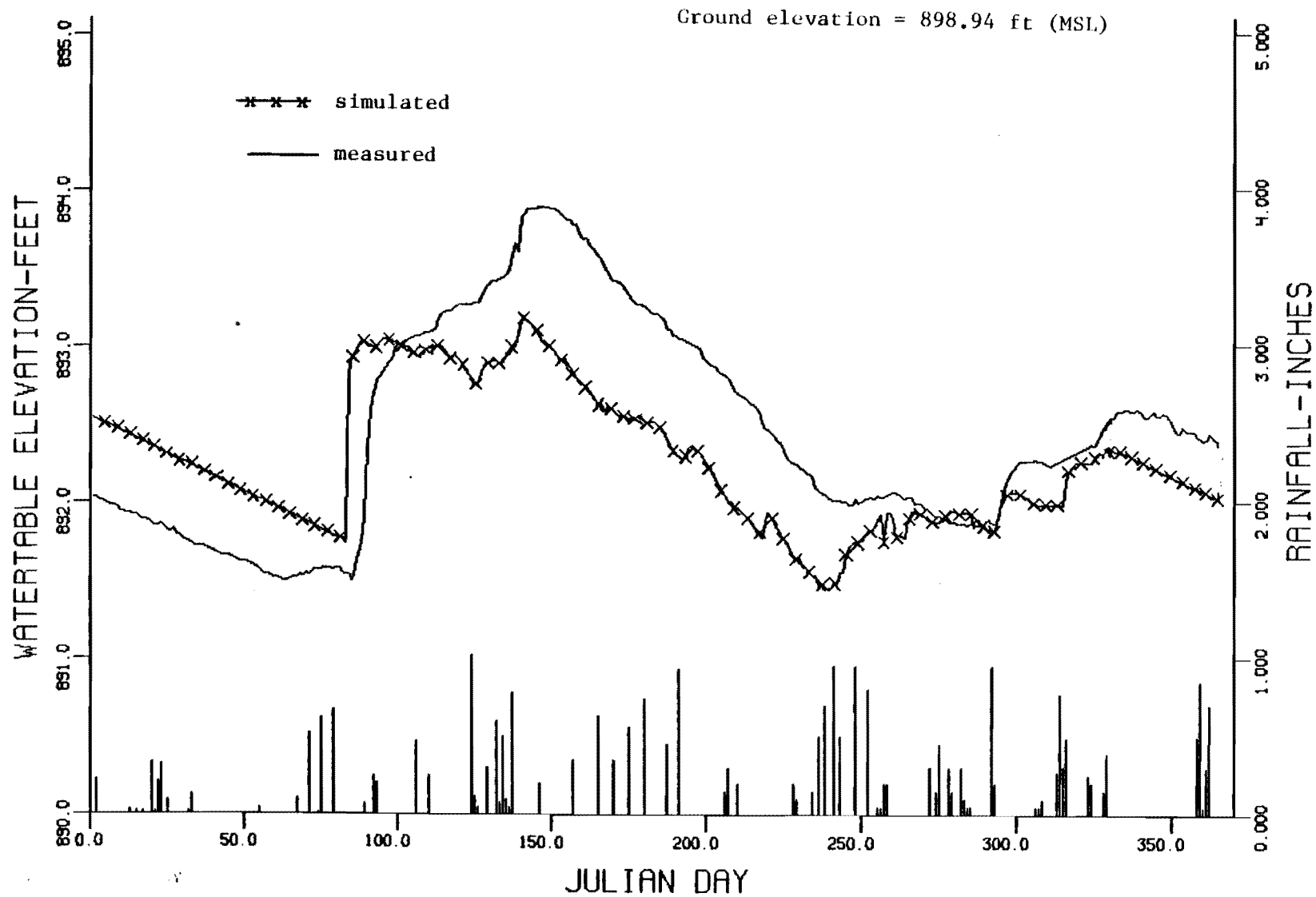


Figure A5.3 Simulated and measured watertable elevation versus julian day and precipitation versus julian day. Run 4:  $t_{inc3} = 0.1$  hrs, snow infil = 1.2 in. JAN-DEC 1982

APPENDIX B

List of the input data for the Andover site  
May 1980 - December 1982

10

1.0,.000036,3.9535,0.808,0.0456,.396,.356,.15,.0155,.0154  
1.0,.000048,3.7772,1.2202,.0453,.394,.355,.15,.0139,.0138  
1.0,.000048,3.7772,1.4173,.049,.39,.351,.15,.0139,.0138  
1.0,.000283,2.4735,.9898,.0259,.383,.345,.15,.008,.0079  
1.0,.000978,2.6644,1.7303,.0696,.43,.387,.15,.0072,.0071  
1.0,.00389,2.6519,1.5,.070,.445,.4,.15,.0112,.0111  
1.0,.001188,2.8476,1.5,.4,.445,.4,.15,.01057,.0104  
1.0,.001188,2.8476,1.5,.4,.445,.4,.15,.01057,.0104  
1.0,.001188,2.8476,1.5,.4,.445,.4,.15,.01057,.0104  
1.0,.001188,2.8476,1.5,.4,.445,.4,.15,.01057,.0104  
6,.01,898.94,.15,.0001  
24,10,.01  
.1,.1,0.  
336,90  
3,3  
1,121  
121,151  
151,366  
1.00,0.0,0.0  
.70,.30,0.0  
.60,.20,.20  
122,1,.27,0.,0.  
123,1,.27,0.,0.  
124,1,.32,0.,0.  
125,1,.31,0.,0.  
126,1,.35,0.,0.  
127,1,.39,0.,0.  
128,1,.21,0.,0.  
129,1,.24,0.,0.  
130,1,.21,0.,0.  
131,1,.24,0.,.27  
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.07,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
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133,1,.18,0.,0.  
134,1,.14,0.,.09  
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136,1,.12,0.,0.  
137,1,.25,0.,0.  
138,1,.11,0.,.10  
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141,1,.24,0.,0.  
142,1,.28,0.,0.  
143,1,.37,0.,0.  
144,1,.30,0.,0.  
145,1,.36,0.,0.

10

1.0,.000036,3.9535,0.808,0.0456,.396,.356,.15,.0155,.0154  
1.0,.000048,3.7772,1.2202,.0453,.394,.355,.15,.0139,.0138  
1.0,.000048,3.7772,1.4173,.049,.39,.351,.15,.0139,.0138  
1.0,.000283,2.4735,.9898,.0259,.383,.345,.15,.008,.0079  
1.0,.000978,2.6644,1.7303,.0696,.43,.387,.15,.0072,.0071  
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6,.01,898.94,.15,.0001  
24,10,.01  
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336,90  
3,3  
1,121  
121,151  
151,366  
1.00,0.0,0.0,0  
.70,.30,0.0  
.60,.20,.20  
122,1,.27,0.,0.  
123,1,.27,0.,0.  
124,1,.32,0.,0.  
125,1,.31,0.,0.  
126,1,.35,0.,0.  
127,1,.39,0.,0.  
128,1,.21,0.,0.  
129,1,.24,0.,0.  
130,1,.21,0.,0.  
131,1,.24,0.,.27  
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134,1,.14,0.,.09  
0.,0.,0.,0.,0.,.05,.04,0.,0.,0.,0.,0.  
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
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136,1,.12,0.,0.  
137,1,.25,0.,0.  
138,1,.11,0.,.10  
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141,1,.24,0.,0.  
142,1,.28,0.,0.  
143,1,.37,0.,0.  
144,1,.30,0.,0.  
145,1,.36,0.,0.

146,1,.28,0.,0.  
 147,1,.44,0.,0.  
 148,1,.39,0.,0.  
 149,1,.33,0.,0.  
 150,1,.37,0.,1.08  
 .05,.05,.05,.05,.05,.05,.05,.05,.05,.05,.05  
 .05,.05,.05,.05,.05,.05,.05,.05,.05,.03,0.,0.  
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 .07,.08,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
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 153,1,.24,0.,.70  
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 155,1,.10,0.,0.  
 156,1,.27,0.,.05  
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 162,1,.27,0.,0.  
 163,1,.40,0.,0.  
 164,1,.11,0.,.50  
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 166,1,.37,0.,0.  
 167,1,.25,0.,0.  
 168,1,.26,0.,0.  
 169,1,.31,0.,0.  
 170,1,.27,0.,.35  
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 174,1,.24,0.,0.  
 175,1,.24,0.,0.  
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 177,1,.13,0.,0.  
 178,1,.31,0.,0.  
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 181,1,.50,0.,0.

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 183, 1, .26, 0, ., .35  
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 185, 1, .27, 0, ., .55  
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 189, 1, .38, 0, ., 0.  
 190, 1, .27, 0, ., 0.  
 191, 1, .27, 0, ., 0.  
 192, 1, .43, 0, ., 0.  
 193, 1, .30, 0, ., 0.  
 194, 1, .36, 0, ., 0.  
 195, 1, .21, 0, ., 0.  
 196, 1, .21, 0, ., 0.  
 197, 1, .32, 0, ., .90  
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 199, 1, .36, 0, ., 0.  
 200, 1, .28, 0, ., .05  
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 203, 1, .12, 0, ., 0.  
 204, 1, .27, 0, ., 0.  
 205, 1, .26, 0, ., 0.  
 206, 1, .26, 0, ., .15  
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 208, 1, .27, 0, ., 0.  
 209, 1, .27, 0, ., 0.  
 210, 1, .28, 0, ., .10  
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 213, 1, .24, 0, ., 0.  
 214, 1, .33, 0, ., 0.  
 215, 1, .31, 0, ., .05  
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 0, ., 0, ., 0, ., 0, ., 0, ., 0, ., 0, ., 0, ., 0, ., 0, ., 0.  
 216, 1, .23, 0, ., 0.  
 217, 1, .26, 0, ., .10

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 219,1.,28,0.,.10  
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 0.,0.,0.,0.,0.,0.,0.,0.,.26,.26,.10,.09  
 221,1.,55,0.,1.93  
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 222,1.,23,0.,1.0  
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 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
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 224,1.,11,0.,0.  
 225,1.,22,0.,0.  
 226,1.,20,0.,0.  
 227,1.,11,0.,0.  
 228,1.,25,0.,0.  
 229,1.,36,0.,.60  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,.05,  
 .1,.1,.05,.05,.05,.1,.05,.05,0.,0.,0.,0.  
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 231,1.,02,0.,0.  
 232,1.,23,0.,0.  
 233,1.,23,0.,.15  
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 0.,0.,0.,0.,0.,0.,.05,0.,0.,0.,0.,0.  
 234,1.,16,0.,0.  
 235,1.,29,0.,0.  
 236,1.,29,0.,.10  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,.05,.05  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
 237,1.,30,0.,.95  
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 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
 238,1.,18,0.,0.  
 239,1.,21,0.,.90  
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 .05,.05,.15,.15,.10,.10,.05,.05,0.,0.,0.,0.  
 240,1.,12,0.,0.  
 241,1.,09,0.,0.  
 242,1.,06,0.,0.  
 243,1.,42,0.,1.1  
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 .30,.30,.10,.10,.05,.05,0.,0.,0.,0.,0.,0.  
 245,1,0.,0.,0.  
 246,1.,14,0.,0.  
 247,1.,28,0.,1.15

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 249,1.,31,0.,0.  
 250,1.,18,0.,0.  
 251,1.,22,0.,0.  
 252,1.,18,0.,0.  
 253,1.,34,0.,0.  
 254,1.,27,0.,0.  
 255,1.,30,0.,2.15  
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 .1.,1.,05.,1.,2.,25.,3.,3.,1.,05.,15.,15  
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 258,1.,09,0.,0.  
 259,1.,06,0.,0.  
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 261,1.,11,0.,0.  
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 263,1.,11,0.,05  
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 0.,0.,0.,05,0.,0.,0.,0.,0.,0.,0.,0.  
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 266,1.,05,0.,0.  
 267,1.,21,0.,0.  
 268,1.,13,0.,05  
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 270,1.,10,0.,0.  
 271,1.,09,0.,0.  
 272,1.,15,0.,14  
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 274,1.,03,0.,0.  
 275,1.,14,0.,0.  
 276,1.,21,0.,0.  
 277,1.,07,0.,0.  
 278,1.,05,0.,0.  
 279,1.,05,0.,0.  
 280,1.,12,0.,0.  
 281,1.,13,0.,0.  
 282,1.,22,0.,0.  
 283,1.,15,0.,0.  
 284,1.,25,0.,0.  
 285,1.,16,0.,0.  
 286,1.,06,0.,0.  
 287,1.,09,0.,0.  
 288,2,43.,88.,10  
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 289,2,50.,70.,0



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 70.0,80.0,69.0  
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 337,32.,20.,0.,1.,2.,82.,64.  
 338,37.,22.,0.,1.,2.,95.,77.  
 339,36.,32.,0.,1.,2.,93.,81.  
 340,32.,22.,0.,1.,2.,89.,78.  
 341,24.,06.,0.,1.,2.,83.,48.  
 342,24.,6.,0.,1.,2.,80.,58.  
 343,10.,-6.,0.,1.,2.,72.,48.  
 344,16.,-8.,0.,1.,2.,80.,52.  
 345,49.,12.,0.,1.,2.,79.,43.  
 346,22.,0.,0.,1.,2.,83.,42.  
 347,24.,17.,0.,1.,2.,87.,35.  
 348,30.,14.,0.,1.,2.,78.,50.  
 349,30.,22.,0.,1.,2.,84.,58.  
 350,45.,23.,0.,1.,2.,90.,38.  
 351,25.,01.,0.,1.,2.,51.,34.  
 352,04.,-4.,0.,1.,2.,65.,44.  
 353,08.,-8.,0.,1.,2.,76.,51.  
 354,20.,-7.,0.,1.,2.,83.,54.  
 355,28.,19.,0.,1.,2.,86.,51.  
 356,26.,10.,0.,1.,2.,81.,66.  
 357,10.,-4.,0.,1.,2.,74.,46.  
 358,17.,-10.,0.,1.,2.,79.,55.  
 359,20.,06.,0.,1.,2.,83.,54.  
 360,29.,14.,0.,1.,2.,81.,64.  
 361,34.,18.,0.,1.,2.,92.,68.  
 362,32.,12.,0.,1.,2.,96.,52.  
 363,42.,26.,0.,1.,2.,97.,64.  
 364,34.,30.,0.,1.,2.,94.,73.  
 365,32.,12.,0.,1.,2.,93.,44.  
 366,20.,09.,0.,1.,2.,66.,33.  
 001,20.,9.,0.,1.,2.,66.,33.  
 002,4.,-3.,0.,1.,2.,72.,48.  
 003,7.,-12.,0.,1.,2.,72.,39.  
 004,27.,-5.,0.,1.,2.,69.,41.  
 005,26.,2.,0.,1.,2.,89.,42.  
 006,8.,-9.,10.,1.,12.,78.,53.  
 007,13.,-5.,0.,1.,2.,83.,55.  
 008,4.,-3.,0.,1.,2.,84.,51.  
 009,7.,-11.,0.,1.,2.,79.,58.  
 010,18.,-11.,0.,1.,2.,87.,55.  
 011,40.,3.,0.,1.,2.,89.,51.  
 012,25.,8.,0.,1.,2.,97.,77.  
 013,29.,15.,0.,1.,2.,97.,71.  
 014,16.,1.,05,1.,12.,78.,57.  
 015,16.,-3.,0.,1.,2.,85.,53.  
 016,39.,1.,0.,1.,2.,86.,41.  
 017,46.,9.,0.,1.,2.,96.,41.  
 018,44.,8.,0.,1.,2.,98.,46.  
 019,37.,6.,0.,1.,2.,97.,62.  
 020,44.,15.,0.,1.,2.,100.,42

021,47.,12.,0.,1.,2.,99.,37.  
022,49.,16.,0.,1.,2.,97.,33.  
023,52.,20.,0.,1.,2.,99.,40.  
024,51.,32.,0.,1.,2.,96.,43.  
025,34.,24.,0.,1.,2.,85.,66.  
026,24.,7.,0.,1.,2.,92.,58.  
027,21.,1.,0.,1.,2.,90.,50.  
028,22.,-6.,0.,1.,2.,92.,48.  
029,29.,-10.,0.,1.,2.,90.,43.  
030,30.,22.,0.,1.,2.,98.,49.  
031,24.,0.,0.,1.,2.,98.,50.  
032,4.,-8.,.18,1.,12.,77.,57.  
033,14.,-18.,0.,1.,2.,81.,53.  
034,12.,-10.,0.,1.,2.,82.,53.  
035,26.,4.,0.,1.,2.,90.,65.  
036,28.,7.,0.,1.,2.,95.,60.  
037,25.,12.,0.,1.,2.,95.,81.  
038,25.,2.,.10,1.,12.,90.,55.  
039,6.,-9.,0.,1.,2.,88.,60.  
040,0.,-9.,.02,1.,12.,78.,58.  
041,1.,-20.,.07,1.,12.,80.,60.  
042,18.,-18.,0.,1.,2.,81.,56.  
043,33.,-11.,0.,1.,2.,96.,53.  
044,42.,7.,0.,1.,2.,99.,59.  
045,49.,38.,0.,1.,2.,90.,61.  
046,56.,32.,0.,1.,2.,95.,44.  
047,54.,30.,0.,1.,2.,98.,50.  
048,58.,29.,0.,1.,2.,97.,47.  
049,57.,29.,0.,1.,2.,99.,42.  
050,56.,24.,0.,1.,2.,99.,47.  
051,45.,34.,0.,1.,2.,96.,83.  
052,41.,34.,.12,1.,12.,96.,61.  
053,44.,28.,.38,1.,12.,97.,43.  
054,48.,21.,.06,1.,12.,97.,32.  
055,38.,18.,0.,1.,2.,96.,49.  
056,37.,20.,0.,1.,2.,97.,57.  
057,34.,30.,0.,1.,2.,80.,68.  
058,32.,24.,.55,0.,14.,93.,73.  
059,40.,27.,.05,6.,8.,82.,46.  
060,30.,15.,0.,1.,2.,80.,43.  
061,44.,7.,0.,1.,2.,91.,47.  
062,35.,20.,0.,1.,2.,98.,35.  
063,39.,7.,0.,1.,2.,95.,29.  
064,31.,14.,0.,1.,2.,87.,40.  
065,40.,6.,0.,1.,2.,96.,38.  
066,46.,10.,0.,1.,2.,96.,35.  
067,42.,24.,0.,1.,2.,96.,30.  
068,38.,17.,0.,1.,2.,95.,55.  
069,54.,13.,0.,1.,2.,98.,33.  
070,54.,25.,0.,1.,2.,91.,27.  
071,42.,20.,0.,1.,2.,88.,37.  
072,62.,11.,0.,1.,2.,100.,25.  
073,54.,27.,0.,1.,2.,90.,26.  
074,53.,10.,0.,1.,2.,100.,31.

075,39.,16.,0.,1.,2.,88.,31.  
 076,38.,23.,0.,1.,2.,73.,43.  
 077,43.,21.,0.,1.,2.,87.,41.  
 078,47.,12.,0.,1.,2.,100.,31.  
 079,51.,14.,0.,1.,2.,100.,30.  
 080,59.,16.,0.,1.,2.,100.,25.  
 081,59.,17.,0.,1.,2.,100.,25.  
 082,55.,23.,0.,1.,2.,95.,26.  
 083,59.,33.,0.,1.,2.,100.,57.  
 084,50.,26.,.05,12.,14.,98.,51.  
 085,59.,31.,0.,1.,2.,93.,33.  
 086,75.,50.,0.,1.,2.,90.,41.  
 087,60.,44.,.10,18.,22.,92.,67.  
 088,50.,38.,1.45,0.,22.,92.,57.  
 089,62.,40.,.05,20.,22.,93.,48.  
 336,84  
 090,2,51.,71.,0.  
 091,2,42.,61.,0.  
 092,2,56.,62.,0.  
 093,2,47.,73.,.45  
 0.,0.,.03,.02,0.,0.,0.,0.,0.,0.,0.,0.  
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 094,2,35.,80.,.25  
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 096,2,41.,63.,0.  
 097,2,57.,54.,0.  
 098,2,45.,54.,0.  
 099,2,47.,65.,.05  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
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 100,2,56.,58.,0.  
 101,2,44.,64.,0.  
 102,2,53.,66.,0.  
 103,1.,18,0.,.30  
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 104,1.,12,0.,0.  
 105,1.,16,0.,0.  
 106,1.,31,0.,0.  
 107,1.,05,0.,0.  
 108,1.,38,0.,.05  
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 111,1.,24,0.,.25  
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112,1,.02,0...70  
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 114,1,0.0,0.,0.  
 115,1,.14,0.,0.  
 116,1,.11,0.,0.  
 117,1,.11,0.,0.  
 118,1,.21,0.,0.  
 119,1,.01,0...40  
 0.,0.,0.,0...08,.07,0.,0.,0.,0.,0.,0.  
 0.,0...13,.12,0.,0.,0.,0.,0.,0.,0.,0.  
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 0.,0.,0.,0...03,.02,0.,0.,0.,0.,0.,0.  
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 122,1,.22,0...05  
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 124,1,.04,0.,0.  
 125,1,.20,0.,0.  
 126,1,.23,0.,0.  
 127,1,.24,0.,0.  
 128,1,.17,0...15  
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 0.,0.,0.,0.,0.,0.,0...08,.07,0.,0.  
 129,1,.19,0.,0.  
 130,1,.22,0.,0.  
 131,1,.22,0.,0.  
 132,1,.21,0.,0.  
 133,1,.28,0.,0.  
 134,1,.20,0.,0.  
 135,1,.27,0.,0.  
 136,1,.27,0.,0.  
 137,1,.24,0.,0.  
 138,1,.27,0.,0.  
 139,1,.12,0.,0.  
 140,1,.32,0.,0.  
 141,1,.27,0.,0.  
 142,1,.38,0.,0.  
 143,1,.44,0...35  
 .03,.02,0.,0...03,.02,0.,0.,0.,0.,0.,0.  
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 145,1,.13,0.,0.  
 146,1,.11,0.,0.  
 147,1,.01,0.,0.  
 148,1,.09,0...20  
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 0.,0.,0.,0.,0.,0...05,.05,.05,.05,0.,0.  
 149,1,.09,0.,0.

150,1,.06,0.,0.  
 151,1,.35,0.,0.  
 152,1,.26,0.,0.  
 153,1,.27,0.,.15  
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 0.,0.,.03,.02,0.,0.,0.,0.,0.,0.,0.,0.  
 154,1,.30,0.,0.  
 155,1,.13,0.,0.  
 156,1,.13,0.,0.  
 157,1,.31,0.,0.  
 158,1,.42,0.,0.  
 159,1,.39,0.,0.  
 160,1,.34,0.,.2  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
 0.,0.,0.,0.,.03,.02,.03,.02,.05,.05,0.,0.  
 161,1,.15,0.,0.  
 162,1,.16,0.,.15  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
 0.,0.,0.,0.,.03,.02,0.,0.,0.,0.,.05,.05  
 163,1,.30,0.,.20  
 .05,.05,.05,.05,0.,0.,0.,0.,0.,0.,0.,0.  
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 164,1,.14,0.,1.75  
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 0.,0.,0.,0.,.1,.2,.03,.02,0.,0.,0.,0.  
 166,1,.14,0.,0.  
 167,1,.17,0.,0.  
 168,1,.14,0.,0.  
 169,1,.24,0.,0.  
 170,1,.20,0.,.15  
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 0.,0.,.03,.02,0.,0.,.03,.02,0.,0.,.03,.02  
 171,1,.40,0.,.15  
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 .03,.02,.05,.05,0.,0.,.08,.07,0.,0.,.03,.02  
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 174,1,.08,0.,.20  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
 .03,.02,.07,.08,0.,0.,0.,0.,0.,0.,0.,0.  
 175,1,.13,0.,0.  
 176,1,.13,0.,0.  
 177,1,.08,0.,0.  
 178,1,.33,0.,0.  
 179,1,.34,0.,.70  
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 180,1,.30,0.,0.  
 181,1,.22,0.,0.

182,1,.00,0.,0.  
 183,1,.27,0.,0.  
 184,1,.29,0.,.05  
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 186,1,.26,0.,0.  
 187,1,.15,0.,0.  
 188,1,.28,0.,0.  
 189,1,.29,0.,0.  
 190,1,.37,0.,0.  
 191,1,.40,0.,0.  
 192,1,.36,0.,.94  
 .1,.1,.1,.1,.1,.1,.1,.1,.1,.04,0.,0.  
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 195,1,.16,0.,.35  
 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.  
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 196,1,.08,0.,.80  
 0.,0.,0.,0.,.35,.35,.05,.05,0.,0.,0.,0.  
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 198,1,.27,0.,0.  
 199,1,.06,0.,0.  
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 205,1,.16,0.,0.  
 206,1,.14,0.,0.  
 207,1,.32,0.,0.  
 208,1,.20,0.,0.  
 209,1,.24,0.,0.  
 210,1,.18,0.,0.  
 211,1,.12,0.,0.  
 212,1,.18,0.,0.  
 213,1,.28,0.,.50  
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 216,1,.18,0.,0.  
 217,1,.12,0.,0.  
 218,1,.22,0.,.10  
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220,1,.13,0.,.15  
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 231,1,.24,0.,0.  
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 233,1,.22,0.,0.  
 234,1,.23,0.,.15  
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 244,1,.07,0.,0.  
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 247,1,.09,0.,0.  
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 249,1,.13,0.,.10  
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 261,1,.19,0.,0.  
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 265,1,.18,0.,0.  
 266,1,.19,0.,.10  
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 272,1,.15,0.,.05  
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 276,1,.09,0.,.90  
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 281,1,.02,0.,0.  
 282,1,.12,0.,.10  
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 285,1,.00,0.,0.

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 317,2,48.,59.,.0.  
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 319,2,50.,79.,.0.  
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 322,2,36.,80.,.03  
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 325,2,14.,86.,.0.

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 329,2,33,,84,,0.  
 330,2,34,,85,,15  
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 332,2,28,,76,,0.  
 333,2,30,,76,,0.  
 334,2,27,,78,,0.  
 335,2,31,,82,,22  
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 30,0,25,0,18,0,0,0  
 71,0,93,0,72,0  
 336,28,,20,,0,,1,,2,,93,,48.  
 337,32,,2,,10,1,,12,,92,,66.  
 338,24,,-2,,0,,1,,2,,90,,78.  
 339,40,,23,,0,,1,,2,,93,,63.

340,39,,26,,0,,1,,2,,94,,62.  
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 342,27,,2,,0,,1,,2,,81,,49.  
 343,29,,-1,,0,,1,,2,,90,,48.  
 344,30,,23,,0,,1,,2,,93,,43.  
 345,34,,29,,0,,1,,2,,92,,41.  
 346,31,,23,,0,,1,,2,,90,,43.  
 347,16,,-10,,0,,1,,2,,86,,48.  
 348,15,,-12,,07,1,,12,,85,,51.  
 349,9,,-5,,0,,1,,2,,87,,49.  
 350,7,,-4,,0,,1,,2,,90,,43.  
 351,5,,-5,,0,,1,,2,,92,,41.  
 352,12,,-8,,0,,1,,2,,87,,37.  
 353,26,,-3,,0,,1,,2,,87,,33.  
 354,37,,27,,0,,1,,2,,92,,40.  
 355,29,,16,,07,1,,12,,92,,42.  
 356,21,,8,,0,,1,,2,,93,,43.  
 357,24,,7,,0,,1,,2,,81,,43.  
 358,22,,12,,0,,1,,2,,76,,48.  
 359,29,,18,,0,,1,,2,,79,,51.  
 360,28,,10,,0,,1,,2,,82,,46.  
 361,8,,1,,07,1,,12,,83,,50.  
 362,7,,-8,,0,,1,,2,,83,,44.  
 363,21,,-8,,0,,1,,2,,90,,42.  
 364,26,,9,,03,1,,12,,92,,38.  
 365,12,,-14,,06,1,,12,,93,,43.

005,7.,-9.,0.,1.,12.,90.,50.  
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008,-3.,-21.,0.,1.,12.,90.,50.  
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013,2.,-21.,03,1.,12.,90.,50.  
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023,4.,-22.,32,1.,12.,90.,50.  
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 087,2,37.,60.,0.  
 088,2,42.,57.,0.  
 089,2,46.,70.,0.0  
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 092,2,46.,67.,.25  
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 093,2,25.,72.,.20  
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 096,2,19.,59.,0.  
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 105,2,56.,58.,.10



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 362,21.,6.,.7,0.,8.,88.,66.  
 363,12.,-4.0,0.,1.,2.,85.,65.  
 364,23.,1.,0.,1.,2.,80.,70.  
 365,28.,16.,0.,1.,2.,84.,65.  
 999,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0  
 336.90  
 999,1,0.0,0.0,0.0

APPENDIX C

Computer program listing

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00050 PROGRAM RECHARG(OUTPUT,TAPE6,TAPE1,TAPE4)
00100C
00150C
00200C
00250C
00300C *****
00350C TITLE: PREDICTING DIRECT RECHARGE OF SURFICIAL AQUIFERS
00400C A ONE-DIMENSIONAL COMPUTER PROGRAM TO SIMULATE CHANGE IN
00450C WATERTABLE ELEVATION AND THE SOIL MOISTURE PROFILE
00500C QWRT PROJECT NO.: A-043-MINN.
00550C
00600C
00650C THE SOIL PROFILE MUST BE DIVIDED INTO A SERIES OF SOIL LAYERS
00700C SOIL PROPERTIES FOR EACH SOIL LAYER ARE READ AND ALL
00750C CONDITIONS WITHIN A LAYER ARE ASSUMED TO BE UNIFORM
00800C WITHIN THAT LAYER (IE. MOISTURE CONTENT, HYDRAULIC
00850C CONDUCTIVITY,). THE PROGRAM CONSISTS OF A MAIN PROGRAM
00900C CALLED RECHERG AND AFOUR SUBPROGRAMS: EXTRACT,IFIL,
00950C REDIST, AND SNOWMEL. THESE SUBPROGRAMS MODEL THE
01000C PROCESSES OF ET EXTRACTION, INFILTRATION, REDISTRIBUTION,
01050C AND FROZEN SOIL WATER STORAGE. IN ADDITION THERE ARE
01100C 14 SUBROUTINES WHICH SUPPORT THE MAIN PROGRAM AND
01150C ITS SUBPROGRAMS.
01200C *****
01250C
01300C
01350C
01400C
01450C
01500C
01550C
01650 COMMON/BLOCK22/TINT,STOINT,CROPET
01700 COMMON/BLOCK3/N,N2,N3,PREDAY,TIN2,TIN3,ETIME,CONVRG
01750 COMMON/BLOCK4/SRATIO,AM,BM,SM,DM,XMO,PCL,TSHIFT,FAN,EVAP,APPLY
01800 COMMON/BLOCK5/ASTORE,RUNOFF
01850 COMMON/BLOCK10/TRO,TBASE,TAET,TIFIL,TLAST,TN,AET,FIL

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01900 COMMON/BLOCK1/SAV, IPOND, INEW, XKFS  
 01950 COMMON/BLOCK2/R(24), XMD, FBIG, F, FP, TP, TPP  
 02000 COMMON/BLOCK30/THEI(50), D(50), THE2(50), THE3(50), FC(50), THEFS(50)  
 02050 COMMON/BLOCK31/WP(50)  
 02100 COMMON/BLOCK32/A(50), B(50), XKS(50), THER(50), THES(50)  
 02150 COMMON/BLOCK33/NH20, THEUN, DH20, BASE, STORAGE, WTABLE  
 02200 COMMON/BLOCK20/PATTERN(10, 50), LQ(10), LHI(10), BREAK(10), SL1(10),  
 02250+B1(10)  
 02300 COMMON/BLOCK21/NROOT, INT1  
 02350 COMMON/BLOCK42/ELEV  
 2351C  
 2352C  
 2353C TINT= TOTAL POSSIBLE INTERCEPTION STORAGE (INCHES)  
 2354C STOINT= PRESENT INTERCEPTION STORAGE (INCHES)  
 2355C CROPET= THE DAILY ET FOR A GIVEN CROP NOT  
 2356C LIMITED BY WATER  
 2357C N = THE NUMBER OF SOIL LAYERS IN THE PROFILE  
 2358C N2= THE NUMBER OF TIME STEPS IN A DAY (USED FOR  
 2359C THE TIME LOOP WHEN THERE IS NO PRECIPITATIOB  
 2360C OR SURFACE STORAGE  
 2361C N3 = THE NUMBER OF TIME STEPS TO DIVIDE N2 INTO  
 2362C (USED FOR PERIODS WHEN THERE IS PRECIPITATION  
 2363C OR SURFACE STORAGE  
 2364C PREDAY= THE DAILY PRECIPITATION (INCHES)  
 2365C TIN2 = THE TIME STEP CORRESPONDING TO N2 (HOURS)  
 2366C TIN3 = THE TIME STEP CORRESPONDING TO N3 (HOURS)  
 2367C ETIME = THE CLOCK TIME OF THE FRESNET TIME STEP (HOURS)  
 2368C CONVRG = THE CONVERGEANCE CRITERIA FOR THE ITERATION  
 2369C SCHEME USED IN CALCULATING INFILTRATION  
 2370C SRATIO =  
 02400C  
 02450C  
 02500C ++++++  
 02550C INITIALIZATION OF THE PROGRAM  
 02600C  
 02650C

```

02700C
02750 READ(1,*) N
02800 DO 600 I=1,N
02850 READ(1,*) D(I),A(I),B(I),XKS(I),THEI(I),THES(I),THEFS(I),FC(I),
02900+WP(I),THER(I)
02950 THE3(I)=THEI(I)
03000 THE2(I)=THEI(I)
03050 600 CONTINUE
03100 READ(1,*) NH20,DH20,ELEV,THEUN,BASE
03150 READ(1,*) N2,N3,CONVRG
03200 READ(1,*) DM,XMO,FCL
03250 IPOND=0
03300 TINT=0.01
03350 STOINT=0.0
03400 INEW=1
03450 STORAGE=0.0
03500 TAET=TIFIL=TBASE=TRO=0.0
03550 X2=N2
03600 X3=N3
03650 TLAST=0.0
03700 DO 48 IX=1,NH20-1
03750 48 TLAST=TLAST+THEI(IX)*D(IX)
03800 TLAST=TLAST+THEUN*(D(NH20)-DH20)
03850 TLAST=TLAST+THEI(NH20)*DH20
03900 DO 49 IX=NH20+1,N
03950 49 TLAST=TLAST+THEI(IX)*D(IX)
04000 TIN2=24.0/X2
04050 TIN3=TIN2/X3
04100 SAV=(2.0*B(1)+3.0)/(B(1)+3.0)*A(1)*12.0/2.0
04150 AM=10.0**(-0.6584-0.12877*DM)
04200 BM=10.0**(0.46046-0.38039*AM+0.18421*LOG(AM)-0.33797*LOG(AM*DM))
04250 SM=AM*(DM**BM)
04300 XKFS=XKS(1)*12.0*((THEFS(1)-THER(1))/(THES(1)-THER(1)))**
04350+(2.0/B(1)+3.0)
04400 READ(1,*) JIN,JOUT
04450 READ(1,*) INT1,NROOT

```

```

02700C
02750 READ(1,*) N
02800 DO 600 I=1,N
02850 READ(1,*) D(I),A(I),B(I),XKS(I),THEI(I),THES(I),THEFS(I),FC(I),
02900+WP(I),THER(I)
02950 THE3(I)=THEI(I)
03000 THE2(I)=THEI(I)
03050 600 CONTINUE
03100 READ(1,*) NH20,DH20,ELEV,THEUN,BASE
03150 READ(1,*) N2,N3,CONVRG
03200 READ(1,*) DM,XMO,FCL
03250 IPOND=0
03300 TINT=0.01
03350 STOINT=0.0
03400 INEW=1
03450 STORAGE=0.0
03500 TAET=TIFIL=TBASE=TRO=0.0
03550 X2=N2
03600 X3=N3
03650 TLAST=0.0
03700 DO 48 IX=1,NH20-1
03750 48 TLAST=TLAST+THEI(IX)*D(IX)
03800 TLAST=TLAST+THEUN*(D(NH20)-DH20)
03850 TLAST=TLAST+THEI(NH20)*DH20
03900 DO 49 IX=NH20+1,N
03950 49 TLAST=TLAST+THEI(IX)*D(IX)
04000 TIN2=24.0/X2
04050 TIN3=TIN2/X3
04100 SAV=(2.0*B(1)+3.0)/(B(1)+3.0)*A(1)*12.0/2.0
04150 AM=10.0**(-0.6584-0.12877*DM)
04200 BM=10.0**(0.46046-0.38039*AM+0.18421*LOG(AM)-0.33797*LOG(AM*DM))
04250 SM=AM*(DM**BM)
04300 XKFS=XKS(1)*12.0*((THEFS(1)-THER(1))/(THES(1)-THER(1)))**
04350+(2.0/B(1)+3.0)
04400 READ(1,*) JIN,JOUT
04450 READ(1,*) INT1,NROOT

```

```

04500 READ(1,*) (LO(I),LHI(I),I=1,IN1)
04550 READ(1,*) ((PATTERN(I,J),J=1,NROOT),I=1,INT1)
04600 DO 601 I=1,NROOT
04650 BREAK(I)=((FC(I)-WP(I))/2.0)+WP(I)
04700 SL1(I)=0.70/(BREAK(I)-WP(I))
04750 B1(I)=0.30-SL1(I)*WP(I)
04800 601 CONTINUE
04850 WRITE(6,650)
04900 650 FORMAT(4X,'ZONE',3X,'THICKNESS',6X,'A',9X,'B',8X,'KS',5X,
04950+'INITIAL',5X,'THETA',5X,'THETA',5X,'FIELD',4X,'WILTING',4X,'THETA
05000+')
05050 WRITE(6,651)
05100 651 FORMAT(5X,'NO',7X,'(FEET)',24X,'(FT/HR)',5X,'THETA',6X,'SAT',
05150+7X,'FS',7X,'CAP',6X,'POINT',6X,'RESID')
05200 WRITE(6,652)(I,D(I),A(I),B(I),XKS(I),THEI(I),THES(I),THEFS(I),
05250+FC(I),WP(I),THER(I),I=1,N)
05300 652 FORMAT(1X,I5,5X,10F10.6)
05350 WRITE(6,653)
05400 653 FORMAT(1X,/, 'EXTRACTION PATTERNS')
05450 WRITE(6,654)
05500 654 FORMAT(12X,'INTERVAL')
05550 WRITE(6,655)
05600 655 FORMAT(4X,'DAY TO DAY',8X,'FRACTION EXTRACTED FROM EACH
05650+ ZONE, TOP-BOTTOM')
05700 DO 523 JJ=1,INT1
05750 WRITE(6,656) LO(JJ),LHI(JJ),(PATTERN(JJ,J),J=1,NROOT)
05800 523 CONTINUE
05850 656 FORMAT(4X,I5,5X,I5,2X,3F10.5)
05900 WRITE(6,657)
05950 657 FORMAT(5X,'DM',8X,'AM',8X,'BM',8X,'SM',7X,'XMO',7X,'PCL')
06000 WRITE(6,658) DM,AM,BM,SM,XMO,PCL
06050 658 FORMAT(1X,6F10.5)
06100 WRITE(6,659)
06150 659 FORMAT(1X,'CONVERGEANCE TIME INCREMENT 2 TIME INCRE
06200+MENT 3')
06250 WRITE(6,660)

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08100 READ(1,*) JIN,JOUT
08150 GO TO 100
08200 ENDIF
08250 CALL ET(JDAY,IET,CET1,CET2,CROPET,PAN)
08300 IF(PREDAY.NE.0.0.OR.STORAGE.NE.0.0) THEN
08350 CALL IFIL (JDAY)
08400 GO TO 51
08450 ENDIF
08500 ETIME=0.0
08550 DO 50 J=1,N2
08600 ETIME=ETIME+TIN2
08650 CALL EXTRACT(JDAY,TIN2,ETIME)
08700 CALL REDIST(TIN2)
08750 50 CONTINUE
08800 51 CONTINUE
08850 WRITE(4,333) JDAY,THEI(1),THEI(2),THEI(3),THEI(4),WTABLE
08900 333 FORMAT(1X,I3,4(' ',F6.4),', ',F8.2)
08950 TN=0.0
09000 DO 44 L=1,NH20-1
09050 TN=TN+THEI(L)*D(L)
09100 44 CONTINUE
09150 TN=TN+THEUN*(D(NH20)-DH20)
09200 TN=TN+THEI(NH20)*DH20
09250 DO 45 L=NH20+1,N
09300 TN=TN+THEI(L)*D(L)
09350 45 CONTINUE
09400 CHECK=TN-TLAST-TIFIL/12.0+TAET/12.0+TBASE
09450 335 FORMAT(1X,'(DAY)',2X,'(IN.)',3X,'(IN.) ',2X,'(IN.) ',2X,'
09500+(IN.) ',2X,'(IN.)',2X,'(IN.)',2X,'(IN.)',5X,'FEETH20)',2X,'(FEET
09505+)')
09550 WRITE(6,334)
09600 334 FORMAT(2X,'JDAY',2X,'PREDAY',2X,'STOINT',2X,'STORAGE',2X,
9650+'TRUNOFF',2X,'TINFIL',2X,'TOTAET',2X,'CROPET',2X,'WATBALCHK',2X,
09655+'WTABLELEV')
09700 WRITE(6,335)
09750 WRITE(6,336) JDAY,PREDAY,STOINT,STORAGE,TRO,TIFIL,TAET,CROPET,

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09800+CHECK,WTABLE
09850 336 FORMAT(1X,15,2X,F6.2,2X,F6.3,2X,F6.3,2X,F7.3,2X,F6.2,2X,
09900+F6.3,2X,F6.3,4X,F9.6,2X,F9.2)
09950 TAET=TIFIL=TBASE=TR0=0.0
10000 TLAST=TN
10050 DEP1=DEP2=0.0
10100 WRITE(6,227)
10150 DO 11 I=1,N
10200 IF(I.EQ.NH20) THEN
10250 DEP2=DEP1-D(I)+DH20
10300 WRITE(6,228) I,DEP1,DEP2,THEUN
10350 DEP1=DEP2
10400 DEP2=DEP1-DH20
10450 WRITE(6,228) I,DEP1,DEP2,THEI(I)
10500 GO TO 9
10550 ENDIF
10600 DEP2=DEP1-D(I)
10650 WRITE(6,228) I,DEP1,DEP2,THEI(I)
10700 9 DEP1=DEP2
10750 11 CONTINUE
10800 227 FORMAT(4X,'ZONE',8X,'DEPTH',8X,'THETA')
10850 228 FORMAT(5X,I2,4X,F6.2,' - ',F6.2,3X,F7.4)
10900 GO TO 100
10950 200 STOP
11000 END
11050 SUBROUTINE EXTRACT(JDAY,TINC,TIME)
11100 COMMON/BLOCK33/NH20,THEUN,DH20,BASE,STORAGE,WTABLE
11150 COMMON/BLOCK20/PATTERN(10,50),LO(10),LHI(10),BREAK(10),SL1(10),
11200+B1(10)
11250 COMMON/BLOCK21/NROOT,INT1
11300 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
11350 COMMON/BLOCK31/WP(50)
11400 COMMON/BLOCK22/TINT,STOINT,CROPET
11450 COMMON/BLOCK10/TR0,TBASE,TAET,TIFIL,TLAST,TN,AET,FIL
11500 RESID=0.0
11550 EK=.024

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11600 IF(TIME.GT.4.0) EK=.048
11650 IF(TIME.GT.8.0) EK=.290
11700 IF(TIME.GT.12.0) EK=.397
11750 IF(TIME.GT.16.0) EK=.195
11800 IF(TIME.GT.20.0) EK=.046
11850 PCET=CROPET/4.0*EK*TINC
11900 P2ET=PCET-STOINT
11950 STOINT=0.0
12000 IF(P2ET.LT.0.0) THEN
12050 STOINT=-P2ET
12100 P2ET=0.0
12150 ENDIF
12300 IF(P2ET.EQ.0.0) GO TO 30
12350 DO 5 I=1,INT1
12400 IF(JDAY.LT.LO(I).OR.JDAY.GT.LHI(I)) GO TO 5
12450 KM=I
12500 5 CONTINUE
12550 DO 10 L=1,NROOT
12600 PULL=PATTERN(KM,L)*P2ET
12650 THE=THEI(L)
12700 IF(L.EQ.1) THE=THE2(1)
12750 IF(THE.GT.BREAK(L)) ETR=1.0
12800 IF(THE.LE.BREAK(L)) ETR=SL1(L)*THE+B1(L)
12850 IF(ETR.LT.0.0) ETR=0.0
12900 TAKE=ETR*PULL
12950 AVAIL = (THEI(L)-WP(L))*D(L)*12.0
13000 IF(L.EQ.1) AVAIL=(THE2(1)-WP(1))*D(1)*12.0
13050 IF(L.EQ.NH20) THEN
13100 AVAIL1=(THEUN-WP(L))*(D(L)-DH20)*12.0
13150 AVAIL=AVAIL1+(THEI(L)-WP(L))*(DH20-0.0001)*12.0
13200 IF(TAKE.GT.AVAIL) THEN
13250 THEUN=WP(L)
13300 DH20=0.0001
13350 GO TO 15
13400 ENDIF
13450 IF(TAKE.LE.AVAIL1) THEN

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13500 THEUN=THEUN-TAKE/12.0/(D(L)-DH20)
13550 AVAIL=TAKE
13600 GO TO 15
13650 ENDIF
13700 THEUN=WP(L)
13750 DROP=(TAKE-AVAIL1)/(THEI(L)-WP(L))/12.0
13800 DH20=DH20-DROP
13850 AVAIL=TAKE
13900 GO TO 15
13950 ENDIF
14000 IF(L.EQ.1) THEN
14050 IF(AVAIL.GT.TAKE) THEN
14100 THE2(L)=THE2(L)-TAKE/12.0/D(L)
14150 AVAIL=TAKE
14200 GO TO 15
14250 ENDIF
14300 THE2(L)=WP(L)
14350 GO TO 15
14400 ENDIF
14450 IF(AVAIL.GT.TAKE) THEN
14500 THEI(L)=THEI(L)-TAKE/12.0/D(L)
14550 AVAIL = TAKE
14600 GO TO 15
14650 ENDIF
14700 THEI(L)=WP(L)
14750 15 RESID=RESID+PULL-AVAIL
14800 10 CONTINUE
14850 DO 20 I=1,NROOT
14900 IF(PATTERN(KM,I).EQ.0.0) GO TO 20
14950 IF(I.EQ.1) THEN
15000 IF(THE2(I).LT.BREAK(I)) GO TO 20
15050 E=(THE2(I)-BREAK(I))*D(I)*12.0
15100 IF(E.GT.RESID) E=RESID
15150 THE2(I)=THE2(I)-E/D(I)/12.0
15200 RESID=RESID-E
15250 GO TO 25

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```

15300 ENDIF
15350 IF(I.EQ.NH20) THEN
15400 IF(THEUN.LT.BREAK(I)) GO TO 20
15450 AVAIL1=(THEUN-BREAK(I))*(D(I)-DH20)*12.0
15500 AVAIL=AVAIL1+(THEI(I)-BREAK(I))*(DH20-0.0001)*12.0
15550 IF(RESID.GT.AVAIL) THEN
15600 THEUN=BREAK(I)
15650 DH20=0.0001
15700 RESID=RESID-AVAIL
15750 GO TO 25
15800 ENDIF
15850 IF(RESID.LE.AVAIL1) THEN
15900 THEUN=THEUN-RESID/12.0/(D(I)-DH20)
15950 RESID=0.0
16000 GO TO 30
16050 ENDIF
16100 THEUN=BREAK(I)
16150 DROP=(RESID-AVAIL1)/(THEI(I)-BREAK(I))/12.0
16200 DH20=DH20-DROP
16250 RESID=0.0
16300 GO TO 30
16350 ENDIF
16400 IF(THEI(I).LT.BREAK(I)) GO TO 20
16450 E=(THEI(I)-BREAK(I))*D(I)*12.0
16500 IF(E.GT.RESID) E=RESID
16550 THEI(I)=THEI(I)-E/D(I)/12.0
16600 RESID=RESID-E
16650 25 IF(RESID.EQ.0.0) GO TO 30
16700 20 CONTINUE
16750 30 CONTINUE
16800 AET=P2ET-RESID
16850 TAET=TAET+AET
17000 RETURN
17050 END
17100 SUBROUTINE ET(JDAY, IET, CET1, CET2, CROPET, PAN)
17150 X=JDAY

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17200 C=0.35
17250 IF(JDAY.GE.96) C=0.0076*X-0.397
17300 IF(JDAY.GE.138) C=0.655
17350 IF(JDAY.GE.244) C=-0.0068*X+2.309
17400 IF(JDAY.GE.289) C=0.35
17450 PAN=CET1
17500 IF(IET.EQ.2) THEN
17550 XMF=.481
17600 XKP=.70
17650 IF(JDAY.GT.31) XMF=.693
17700 IF(JDAY.GT.59) XMF=1.271
17750 IF(JDAY.GT.90) XMF=1.859
17800 IF(JDAY.GT.120) THEN
17850 XMF=2.515
17900 XKP=.75
17950 ENDIF
18000 IF(JDAY.GT.151) THEN
18050 XMF=2.736
18100 XKP=.85
18150 ENDIF
18200 IF(JDAY.GT.181) XMF=2.695
18250 IF(JDAY.GT.212) XMF=2.184
18300 IF(JDAY.GT.243) XMF=1.481
18350 IF(JDAY.GT.273) THEN
18400 XMF=.942
18450 XKP=.75
18500 ENDIF
18550 IF(JDAY.GT.304) THEN
18600 XMF=.539
18650 XKP=.70
18700 ENDIF
18750 IF(JDAY.GT.334) XMF=.489
18800 CH=0.166*(100-CET2)**0.5
18850 IF(CH.GT.1.0) CH=1.0
18855 XMF=XMF*0.00127
18900 PET=XMF*CET1*CH
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18950 IF(PET.LT.0.0) PET=0.0
19000 PAN=PET/XKP
19050 ENDIF
19100 CROPET=C*PAN
19150 RETURN
19200 END
19250 SUBROUTINE IFIL (JDAY)
19300 COMMON/BLOCK1/SAV, IPOND, INEW, XKFS
19350 COMMON/BLOCK2/R(24), XMD, FBIG, F, FP, TP, TPP
19400 COMMON/BLOCK30/THEI(50), D(50), THE2(50), THE3(50), FC(50), THEFS(50)
19450 COMMON/BLOCK31/WP(50)
19500 COMMON/BLOCK32/A(50), B(50), XKS(50), THER(50), THES(50)
19550 COMMON/BLOCK33/NH20, THEUN, DH20, BASE, STORAGE, WTABLE
19600 COMMON/BLOCK3/N, N2, N3, PREDAY, TIN2, TIN3, ETIME, CONVRG
19650 COMMON/BLOCK4/SRATIO, AM, BM, SM, DM, XMD, PCL, TSHIFT, PAN, EVAP, APPLY
19700 COMMON/BLOCK5/ASTORE, RUNOFF
19750 COMMON/BLOCK22/TINT, STOINT, CROPET
19800 COMMON/BLOCK10/TRO, TBASE, TAET, TIFIL, TLAST, TN, AET, FIL
19850 ETIME=0.0
19900 IF(PREDAY.EQ.0.0) THEN
19950 DO 15 I2=1,N2
20000 R(I2)=0.0
20050 15 CONTINUE
20100 GO TO 16
20150 ENDIF
20200 READ(1,*) R(1),R(2),R(3),R(4),R(5),R(6),R(7),R(8),R(9),R(10),
20250+R(11),R(12)
20300 READ(1,*)R(13),R(14),R(15),R(16),R(17),R(18),R(19),R(20),
20350+R(21),R(22),R(23),R(24)
20400 16 CONTINUE
20450 DO 20 J=1,N2
20500 IF(R(J).EQ.0.0.AND.STORAGE.EQ.0.0) THEN
20550 INEW=1
20600 ETIME=ETIME+TIN2
20650 CALL EXTRACT(JDAY,TIN2,ETIME)
20700 CALL REDIST(TIN2)

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22650 IF(E2.LT.0.0) THEN
22700 STQINT=STQINT+R(J)*TIN3
22750 E2=0.0
22900 ENDIF
22950 IF(E2.GE.0.0) STQINT=TINT
23000 APPLY=E2+STORAGE
23050 TSHIFT=TSHIFT+TIN3
23100 IF(APPLY.LE.(XKFS*TIN3)) THEN
23150 F=APPLY
23200 FBIG=FBIG+F
23250 GO TO 100
23300 ENDIF
23350 IF(IPOND.EQ.0) THEN
23400 FP=SAV*XMD/((APPLY/TIN3)/XKFS-1.0)
23450 TP=ETIME-TIN3+(FP-F)/(APPLY/TIN3)
23500 IF(TP.GT.ETIME) THEN
23550 F=APPLY
23600 FBIG=FBIG+F
23650 GO TO 100
23700 ENDIF
23750 IPOND=1
23800 TPP=FP/XKFS-SAV*XMD/XKFS*LOG(1.0+FP/(XMD*SAV))
23850 ENDIF
23900 TSHIFT=TP-TPP+(FBIG-XMD*SAV*LOG(1.0+FBIG/(XMD*SAV)))/XKFS+TIN3
23950 FG=FBIG+APPLY
24000 TG=TP-TPP+(FG-XMD*SAV*LOG(1.0+FG/(XMD*SAV)))/XKFS
24050 IF(TG.LE.TSHIFT) THEN
24100 FBIG=FG
24150 F=APPLY
24200 TSHIFT=TG
24250 RUNOFF=0.0
24300 STORAGE=0.0
24350 GO TO 100
24400 ENDIF
24450 FHI=FG
24500 FLO=FBIG

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```
24550 33 FG=(FHI+FLO)/2.0
24600 TG=TP-TPP+(FG-XMD*SAV*LOG(1.0+FG/(XMD*SAV)))/XKFS
24650 DIFF=TSHIFT-TG
24700 IF((ABS(DIFF)).LE.CONVRG) THEN
24750 F=FG-FBIG
24800 FBIG=FG
24850 EXCESS=APPLY-F
24900 E=ASTORE-EXCESS
24950 IF(E.LT.0.0) THEN
25000 STORAGE=ASTORE
25050 RUNOFF=-E
25100 GO TO 100
25150 ENDIF
25200 STORAGE=EXCESS
25250 RUNOFF=0.0
25300 GO TO 100
25350 ENDIF
25400 IF(DIFF.GT.0.0) THEN
25450 FLD=FG
25500 GO TO 33
25550 ENDIF
25600 IF(DIFF.LT.0.0) THEN
25650 FHI=FG
25700 GO TO 33
25750 ENDIF
25800 100 CONTINUE
25850 EVAP=PAN/24.0*TIN3
25900 IF(EVAP.GT.STORAGE) THEN
25950 EVAP=STORAGE
26000 STORAGE=0.0
26050 GO TO 44
26100 ENDIF
26150 STORAGE=STORAGE-EVAP
26200 44 CONTINUE
26250 THE2(1)=THE2(1)+F/12.0/D(1)
26300 FIL=F
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26350 TIFIL=TIFIL+F
26400 TRO=TRO+RUNOFF
26550 RETURN
26600 END
26650 SUBROUTINE REDIST (DELT)
26700 COMMON/BLOCK32/A(50),B(50),XKS(50),THER(50),THES(50)
26750 COMMON/BLOCK33/NH20,THEUN,DH20,BASE,STORAGE,WTABLE
26800 COMMON/BLOCK3/N,N2,N3,PREDAY,TIN2,TIN3,ETIME,CONVRG
26850 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
26900 COMMON/BLOCK31/WP(50)
26950 COMMON/BLOCK42/ELEV
27000 COMMON/BLOCK10/TRO,TBASE,TAET,TIFIL,TLAST,TN,AET,FIL
27050C REDISTRIBUTION FROM TOP OF SOIL TO ZONE ABOVE H2O TABLE
27100 L=NH20-2
27110 IF(L.LT.1) GO TO 890
27150 DO 20 I=1,L
27200 CALL FLOW(THEI(I),THE2(I),THEI(I+1),D(I),D(I+1),DELT,A(I),A(I+1),
27250+B(I),B(I+1),XKS(I),XKS(I+1),Q,THEFS(I),THEFS(I+1),THER(I),
27300+THER(I+1))
27350 CALL LOWLIM (Q,I,THEUN,DH20,NH20)
27400 EXCESS1=(THE3(I)-THEFS(I))*D(I)
27450 EXCESS2=(THE2(I+1)-THEFS(I+1))*D(I+1)
27500 IF(EXCESS1.LT.0.0) EXCESS1=0.0
27550 IF(EXCESS2.LT.0.0) EXCESS2=0.0
27600 IF(EXCESS1.GT.0.0) THE3(I)=THEFS(I)
27650 IF(EXCESS2.GT.0.0) THE2(I+1)=THEFS(I+1)
27700 EXCESS=EXCESS1+EXCESS2
27750 IF(EXCESS.GT.0.0.AND.Q.GT.0.0) CALL UP(I,EXCESS)
27800 IF(EXCESS.GT.0.0.AND.Q.LT.0.0) CALL DOWN(I,EXCESS,THEUN,DH20,NH20)
27850 IF(EXCESS.GT.0.0.AND.Q.GT.0.0) CALL DOWN(I,EXCESS,THEUN,DH20,NH20)
27900 IF(EXCESS.GT.0.0.AND.Q.LT.0.0) CALL UP(I,EXCESS)
27950 20 CONTINUE
27960 890 CONTINUE
28000 DUN=D(NH20)-DH20
28050 M=NH20-1
28100 CALL FLOW(THEI(M),THE2(M),THEUN,D(M),DUN,DELT,A(M),A(NH20),

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28150+B(M), B(NH20), XKS(M), XKS(NH20), Q, THEFS(M), THEFS(NH20), THER(M),
28200+THER(NH20))
28250 CALL LOWLIM(Q,M,THEUN,DH20,NH20)
28300 IF (THE3(M).GT.THEFS(M)) THEN
28350 EXCESS=(THE3(M)-THEFS(M))*D(M)
28400 THE3(M)=THEFS(M)
28450 CALL UP(M,EXCESS)
28500 IF (EXCESS.GT.0.0) THEUN=THEUN+EXCESS/DUN
28550 ENDIF
28600 CALL WATAB(THEUN,DH20,NH20)
28650 CALL BASEQ (NH20,DH20,BASE,THEUN,DELT)
28700 DO 60 J=1,N
28750 THEI(J)=THE3(J)
28800 60 CONTINUE
28850 THE2(1)=THE3(1)
28900 IF (ETIME.EQ.12.0) THEN
28950 EL=0.0
29000 DO 98 J=1,NH20
29050 EL=EL+D(J)
29100 98 CONTINUE
29150 WTABLE=ELEV-EL+DH20
29200 ENDIF
29250 RETURN
29300 END
29350 SUBROUTINE FLOW(THI1,TH21,THI2,D1,D2,TIM,A1,A2,B1,B2,XK1,XK2,Q,
29400+THS1,THS2,THR1,THR2)
29450 W1=(THI1+TH21)/2.0
29500 W2=THI2
29550 X1=2.0/B1+3.0
29600 X2=2.0/B2+3.0
29650 X1=XK1*((W1-THR1)/(THS1-THR1))**X1
29700 X2=XK2*((W2-THR2)/(THS2-THR2))**X2
29750 SUC1=A1*W1**(-B1)
29800 SUC2=A2*W2**(-B2)
29850 POT=(D1+D2)/2.0
29900 Q=(X1+X2)/2.0*(SUC1-SUC2-POT)/((D1+D2)/2.0)*TIM

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29950 RETURN
30000 END
30050 SUBROUTINE LOWLIM (Q,I,THEUN,DH20,NH20)
30100 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
30150 COMMON/BLOCK31/THELOW(50)
30200 DB=D(I+1)
30250 THEIB=THEI(I+1)
30300 IF(I+1.EQ.NH20) THEN
30350 DB=D(NH20)-DH20
30400 THEIB=THEUN
30450 ENDIF
30500 IF(DB.EQ.0.0) THEN
30550 Q=0.0
30600 THE3(I)=THE2(I)
30650 GO TO 30
30700 ENDIF
30750 THE3(I)=THE2(I)+Q/D(I)
30800 IF(THE3(I).GE.THELOW(I)) GO TO 23
30850 Q=-THE2(I)*D(I)+THELOW(I)*D(I)
30900 THE3(I)=THELOW(I)
30950 23 CONTINUE
31000 THE2B=THEIB-Q/DB
31050 IF(THE2B.GE.THELOW(I+1)) GO TO 25
31100 Q=THEIB*DB-THELOW(I+1)*DB
31150 THE2B=THELOW(I+1)
31200 THE3(I)=THE2(I)+Q/D(I)
31250 25 CONTINUE
31300 THE2(I+1)=THE2B
31350 IF(I+1.EQ.NH20) THEUN=THE2B
31400 30 RETURN
31450 END
31500 SUBROUTINE UP (I,EXCESS)
31550 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
31600 DO 10 J=I,1,-1
31650 TAKE=(THEFS(J)-THE3(J))*D(J)
31700 IF(TAKE.GT.EXCESS) THEN

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31750 THE3(J)=THE3(J)+EXCESS/D(J)
31800 EXCESS=0.0
31850 GO TO 20
31900 ENDIF
31950 EXCESS=EXCESS-TAKE
32000 THE3(J)=THEFS(J)
32050 10 CONTINUE
32100 20 RETURN
32150 END
32200 SUBROUTINE DOWN (I,EXCESS,THEUN,DH20,NH20)
32250 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
32300 DO 10 J=I+1,NH20,1
32350 DE=D(J)
32400 TH=THEI(J)
32450 IF(J.EQ.I+1) TH=THE2(J)
32500 IF(J.EQ.NH20) TH=THEUN
32550 IF(J.EQ.NH20) DE=D(NH20)-DH20
32600 TAKE=(THEFS(J)-TH)*DE
32650 IF(TAKE.GT.EXCESS) THEN
32700 TH=TH+EXCESS/DE
32750 THE2(J)=TH
32800 IF(J.NE.I+1.AND.J.NE.NH20) THEI(J)=TH
32850 IF(J.EQ.NH20) THEUN=TH
32900 EXCESS=0.0
32950 GO TO 20
33000 ENDIF
33050 THE2(J)=THEFS(J)
33100 IF(J.NE.I+1.AND.J.NE.NH20) THEI(J)=THEFS(J)
33150 IF(J.EQ.NH20) THEUN=THEFS(J)
33200 EXCESS=EXCESS-TAKE
33250 10 CONTINUE
33300 20 RETURN
33350 END
33400 SUBROUTINE BASEQ (NH20,DH20,BASE,THEUN,TINC)
33450 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
33500 COMMON/BLOCK10/TRO,TBASE,TAET,TIFIL,TLAST,TN,AET,FIL

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33550 BOUT=BASE*TINC
33600 TBASE=TBASE+BOUT
33650 10 CONTINUE
33700 AVAIL=(THEFS(NH20)-FC(NH20))*DH20
33750 IF(AVAIL.GE.BOUT) THEN
33800 DH20=DH20-BOUT/(THEFS(NH20)-FC(NH20))
33850 BOUT=0.0
33900 GO TO 20
33950 ENDIF
34000 THE3(NH20)=FC(NH20)
34050 BOUT=BOUT-AVAIL
34100 NH20=NH20+1
34150 DH20=D(NH20)
34200 THEUN=FC(NH20)
34250 GO TO 10
34300 20 RETURN
34350 END
34400 SUBROUTINE WATAB (THEUN,DH20,NH20)
34450 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
34500 10 CONTINUE
34550 IF(THEUN.EQ.FC(NH20)) GO TO 50
34600 IF(THEUN.GE.FC(NH20)) THEN
34650 EXTRA=(THEUN-FC(NH20))*(D(NH20)-DH20)
34700 TAKE=(THEFS(NH20)-FC(NH20))*(D(NH20)-DH20)
34750 IF(TAKE.GE.EXTRA) THEN
34800 DH20=DH20+EXTRA/(THEFS(NH20)-FC(NH20))
34850 THEUN=FC(NH20)
34900 GO TO 50
34950 ENDIF
35000 EXTRA=EXTRA-TAKE
35050 DH20=0.0
35100 NH20=NH20-1
35150 THEUN=THE3(NH20)+EXTRA/D(NH20)
35200 THE3(NH20)=THEFS(NH20)
35250 GO TO 10

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35300 ENDIF
35350 XNEED=(FC(NH20)-THEUN)*(D(NH20)-DH20)
35400 20 GIVE=(THEFS(NH20)-FC(NH20))*DH20
35450 IF(GIVE.GE.XNEED) THEN
35500 DH20=DH20-XNEED/(THEFS(NH20)-FC(NH20))
35550 THEUN=FC(NH20)
35600 GO TO 50
35650 ENDIF
35700 XNEED=XNEED-GIVE
35750 THE3(NH20)=FC(NH20)
35800 NH20=NH20+1
35850 DH20=D(NH20)
35900 GO TO 20
35950 50 RETURN
36000 END
36050 SUBROUTINE SNOWMEL (JIN,JOUT,JDAY)
36100 COMMON/BLOCK30/THEI(50),D(50),THE2(50),THE3(50),FC(50),THEFS(50)
36150 COMMON/BLOCK42/ELEV
36200 COMMON/BLOCK33/NH20,THEUN,DH20,BASE,STORAGE,WTABLE
36250 STORAGE=RUNOFF=0.0
36252 RUNOFF=0.0
36350 TRO=TEVAP=TGWAT=0.0
36400 WRITE(6,401)
36450 READ(1,*) ALA,SLOP,ASP,SNOW,SUMD,FRC
36500 READ(1,*) TPMX1,TPMX,TPMN,OFFSTOR
36550 READ(1,*) RHMN1,RHMX,RHMN
36600 TPMN1=TPMN
36650 TONEM=0.
36700 99 IF(JDAY+1.LT.JOUT.OR.JDAY+1.GE.JIN) GO TO 111
36750 GO TO 110
36800 111 CONTINUE
36850 READ(1,*) JDAY,TPMXP1,TPMNP1,PR,STT,ENT,RHMXP1,RHMNP1
36900 IF(JDAY.EQ.999) GO TO 110
36902 CET1=(TPMN+TPMX)/2.0
36904 CET2=(RHMN+RHMX)/2.0
36906 CALL ET(JDAY,2,CET1,CET2,CROPET,PAN)

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36950 DO 10 J=1,24
37000 TIM=J
37050 CALL RADRAT(ALA,SLOP,ASP,JDAY,TIM,DXTIMN,RATIO)
37100 CALL TEMPR(TPMX,TPMN,14.5,DXTIMN,TIM,TEMP,TPMX1,TPMNP1)
37150 CALL TEMPR(RHMN,RHMX,14.5,DXTIMN,TIM,RH,RHMN1,RHMX1)
37200 CALL PRCPT(J,PR,STT,ENT,PPX)
37250 CALL ALR(SUMD,PPX,TEMP,ALB,AI,RH)
37300 CALL MELT2(TEMP,PPX,JDAY,FRC,ALB,RATIO,AI,AMELT,COEFF)
37350 M1=DXTIMN
37400C
37450C
37500C   COLD = COLD CONTENT: OR EQUIVALENT WATER REQUIREMENT TO RAISE
37550C   THE TEMPERATURE OF THE SNOWPACK TO 32 DEG. F.
37600C
37650C
37700 COLD=SNOW*(TPMN-32.)*5./9./160.
37750 IF(M1.GT.J) COLD=SNOW*(TPMN1-32.)*5./9./160.
37800 IF(COLD.GT.0.) COLD=0.
37850 TONEM=COLD
37900 CALL ACCT(SNOW,PPX,0.,AMELT,AI,TOTALM,GWAT,TONEM)
38150 EVAP=PAN/24.0
38200 STORAGE=STORAGE-EVAP
38250 IF(STORAGE.LT.0.0) THEN
38350 EVAP=EVAP+STORAGE
38400 STORAGE=0.0
38450 ENDIF
38500 THEI(1)=THEI(1)+GWAT/12.0/D(1)
38550 IF(THEI(1).GT.FC(1)) THEN
38600 XLEFT=(THEI(1)-FC(1))*D(1)*12.0
38650 THEI(1)=FC(1)
38700 STORAGE=STORAGE+XLEFT
38750 ENDIF
38800 IF(STORAGE.GT.OFFSTOR) THEN
38850 RUNOFF=STORAGE-OFFSTOR
38900 STORAGE=OFFSTOR
38950 ENDIF

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38992 RUNOFF=0.0
39000 THE2(1)=THEI(1)
39050 CALL BASEQ(NH20,DH20,BASE,THEUN,1.0)
39100 TRO=TR0+RUNOFF
39150 TEVAP=TEVAP+EVAP
39200 TGWAT=TGWAT+GWAT
39550 IF(TIM.EQ.12.0) THEN
39600 EL=0.0
39650 DO 91 JZ=1,NH20
39700 EL=EL+D(JZ)
39750 91 CONTINUE
39800 WTABLE=ELEV-EL+DH20
39850 ENDIF
39900 10 CONTINUE
39950 TPMX1=TPMX
40000 TPMN1=TPMN
40050 TPMN=TPMNP1
40100 TPMX=TPMXP1
40150 RHMN1=RHMN
40200 RHMN=RHMNP1
40250 RHMN=RHMXP1
40450 401 FORMAT(1X,'JDAY',4X,' PR ',3X,'SNOW',6X,'TGWAT',4X,
40500+'STORAGE',6X,'TR0',5X,'TEVAP',7X,'PAN',5X,'WATELEV')
40550 WRITE(6,402) JDAY,PR,SNOW,TGWAT,STORAGE,TR0,TEVAP,PAN,
40600+WTABLE
40650 402 FORMAT(1X,I4,4X,8F10.5)
40700 TR0=TEVAP=TGWAT=0.0
40702 WRITE(4,405) JDAY,THEI(1),THEI(2),THEI(3),THEI(4),WTABLE
40704 405 FORMAT(1X,I3,4(' ',F6.4),',',',',F8.2)
40706 TR0=TEVAP=TGWAT=0.0
40750 GO TO 99
40800 110 CONTINUE
40850 RETURN
40900 END
40950 SUBROUTINE RADRAT(ALAT1,SLOP1,ASP1,IYDAY,TIM,DXTIMN,RATIO)
41000C

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41050C
41100C THIS SUBROUTINE COMPUTES SOLAR RADIATION RATIO ACCORDING TO
41150C WATERSHED LATITUDE, SLOPE, AND ASPECT.
41200C
41250C
41300C ALAT1 = LATITUDE IN DEGREES
41350C SLOP1 = ANGLE BETWEEN SLOPING SURFACE AND HORIZONTAL
41400C SURFACE IN DEGREES (0 TO 90 DEGREES)
41450C ASP1 = ASPECT IN DEGREES
41500C IYDAY = JULIAN DAY
41550C TIM = ACTUAL MILITARY TIME WHEN PROGRAM IS EXECUTED
41600C DXTIMN = ASSUMED MILITARY TIME OCCUR. OF MIN. TEMP.
41650C RATIO = RATIO OF INCIDENT SOLAR RAD. TO HORIZ. AND
41700C INCLINED SURFACES
41750C SOLCON = SOLAR CONSTANT
41800C DECL = DECLINATION
41850C RS = TIME DEV. FROM NOON OF SUNRISE/SET ON FLAT SURFACE
41900C SUNR, SUNS = SUNRISE/SUNSET TIMES ON FLAT SURFACE
41950C AHR = HOUR ANGLE FROM NOON
42000C ALT = SOLAR ALTITUDE
42050C AZ = SOLAR AZIMUTH
42100C THETA = ZENITH ANGLE OF SUN RELATIVE TO LOCAL SLOPE
42150C
42200C
42250C
42300 SLOP2=SLOP1
42350 ALAT=ALAT1/57.3
42400 SLOP=SLOP2/57.3
42450 ASP=ASP1/57.3
42500 SSLOP=SIN(SLOP)
42550 CSLOP=COS(SLOP)
42600 SALAT=SIN(ALAT)
42650 CALAT=COS(ALAT)
42700 ATRANS=1.0
42750 SOLCON = 1.94+.0645*(COS(0.986*IYDAY/57.3))
42800 DECL=0.4093*SIN(0.9863*(IYDAY+284.)/57.3)

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42850 RS=(ACOS(-TAN(DECL*TAN(ALAT))))/0.262
42900 SUNR=12.-RS
42950 SUNS=12.+RS
43000 SNR=SUNR+1.
43050 SNS=SUNS-1.
43100 DXTIMN=SUNR-.5
43150 TERM1=SALAT*SIN(DECL)
43200 TERM2=CALAT*COS(DECL)
43250 IF(TIM.LE.SNR) GO TO 100
43300 IF(TIM.GE.SNS) GO TO 100
43350 AHR=(12.-TIM)*0.262
43400 SALT=TERM1+(TERM2*COS(AHR))
43450 ALT=ASIN(SALT)
43500 IF(ALT.LE.0.0) GO TO 100
43550 CALT=COS(ALT)
43600 CSCALT=1./SALT
43650 SAZ=-COS(DECL)*SIN(AHR)/CALT
43700 AZ=ASIN(SAZ)
43750 STHETA=(SALT*CSLOP)-(CALT*SSLOP*SIN(AZ+1.571-ASP))
43800 STHET=SALT
43850 SI=60.*SOLCON*(ATRANS**CSCALT)*STHETA
43900 IF(SI.LT.10) SI=0.
43950 SIH=60.*SOLCON*(ATRANS**CSCALT)*STHET
44000 IF(SIH.LT.10) SIH=0.
44050 RATIO=SI/SIH
44100 IF(RATIO.EQ.0.) RATIO=1.
44150 GO TO 200
44200 100 SIH=0.
44250 SI=0.
44300 RATIO=1.
44350 200 CONTINUE
44400 RETURN
44450 END
44500C
44550C
44600C

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44650 SUBROUTINE TEMPR(TPMX,TPMN,DXTIMX,DXTIMN,TIM,TEMP,TPMX1,TPMNP1)
44700C
44750C
44800C
44850C THIS SUBROUTINE DETERMINES HOURLY TEMPERATURE OR RELATIVE
44900C HUMIDITY BASED ON MAXIMUM AND MINIMUM VALUES. A SINE WAVE IS
44950C USED FOR CALCULATION
45000C     TPMX = MAX. DAILY VALUE
45050C     TPMN = MIN. DAILY VALUE
45100C     DXTIMX = ASSUMED MILITARY TIME OCCUR. OF MAX. VALUE
45150C     DXTIMN = ASSUMED MILITARY TIME OCCUR. OF MIN. VALUE
45200C     TIM = ACTUAL MILITARY TIME WHEN PROGRAM IS EXECUTED
45250C     TEMP = COMPUTED VALUR AT TIME TIM
45300C     TPMX1 = MAX. VALUE FOR THE PREVIOUS DAY
45350C     TPMNP1 = MIN VALUE FOR THE PREVOIUS DAY
45400C
45450C
45500C
45550 IF(TIM.LE.DXTIMX.AND.TIM.GE.DXTIMN) ITP=1
45600 IF(TIM.GT.DXTIMX) ITP=2
45650 IF(TIM.LT.DXTIMN) ITP=3
45700 GO TO (100,200,300) ITP
45750 100 DEGR=((TIM-DXTIMN)*180./(DXTIMX-DXTIMN)-90.)*3.14159/180.
45800 TEMP=TPMN+(TPMX-TPMN)/2.*(SIN(DEGR)+1.)
45850 GO TO 400
45900 200 DEGR=((DXTIMX-TIM)*180./(24.-DXTIMX+DXTIMN)+90.)*3.14159/180.
45950 TEMP=TPMX-(TPMX-TPMNP1)/2.*(1.-SIN(DEGR))
46000 GO TO 400
46050 300 ST=TIM+24.
46100 DEGR=((DXTIMX-ST)*180./(24.-DXTIMX+DXTIMN)+90.)*3.14159/180.
46150 TEMP=TPMX1-(TPMX1-TPMN)/2.*(1.-SIN(DEGR))
46200 400 CONTINUE
46250 END
46300C
46350C
46400C

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46450C
46500 SUBROUTINE PRCP(T,J,PREC,STAT,ENDT,PRECIP)
46550C
46600C
46650C THIS SUBROUTINE DISTRIBUTES DAILY PRECIP EVENLY BETWEEN
46700C STARTING HOUR AND ENDING HOUR.
46750C     J = ACTUAL MILITARY TIME WHEN PROGRAM IS EXECUTED
46800C     PREC = DAILY PRECIP- IN.
46850C     STAT,ENDT = STARTING AND ENDING TIME OF DAILY PRECIP.
46900C     PRECIP = HOURLY PRECIP. IN.
46950C
47000C
47050C
47100 XJ=J
47150 TIMINT=ENDT-STAT+1
47160 IF(TIMINT.GT.24.) TIMINT=24.
47200 PRECIP=PREC/TIMINT
47250 IF(XJ.LT.STAT.OR.XJ.GT.ENDT) PRECIP=0.0
47700 RETURN
47750 END
47800C
47850C
47900C
47950C
48000 SUBROUTINE ALR(SUMDEG,PRECIP,PERTEM,ALBEDO,AI,RH)
48050 DATA RAIN,SNOW,DRY /'RAIN','SNOW','-----'/
48100C
48150C
48200C THIS SUBROUTINE DETERMINES TYPE OF PRECIP AND COMPUTES SNOW
48250C SURFACE ALBEDO.
48300C     SUMDEG = SUM OF DEGREE HOURS
48350C     PRECIP = PRECIP. IN.
48400C     PERTEM = AIR TEMP --F
48450C     ALBEDO = SNOW SURFACE ALBEDO
48500C AI = PRECIPITATION INDEX RAIN OR SNOW
48550C     RH = RELATIVE HUMIDITY

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48600C
48650C
48700C
48750 XRH=RH/100.
48800 TEM=PERTEM+459.69
48850 PVR=XRH*(EXP(54.6329-12301.688/TEM-5.16923*LOG(TEM)))
48900 PVL=0.08853-(.00525*(PERTEM-32.))
48950 IF(PVR.LT.PVL) AI=SNOW
49000 IF(PVR.GE.PVL) AI=RAIN
49050 IF(PRECIP.EQ.0.0) GO TO 40
49100 IF(AI.NE.SNOW) GO TO 55
49150 SUMDEG=0.
49200 GO TO 60
49250 40 CONTINUE
49300 PSUMD=PERTEM-32.
49350 IF(PSUMD.LT.0.0) PSUMD=0.0
49400 SUMDEG=SUMDEG+PSUMD
49450 AI=DRY
49500 IF(SUMDEG.LT.0.) SUMDEG=0.
49550 GO TO 60
49600 55 IF(SUMDEG.LT.450.) SUMDEG=450.
49650 60 ALBEDO=.40*(1.+1.25/(SUMDEG*5./9.*.005+1.))
49700 RETURN
49750 END
49800C
49850C
49900C
49950C
50000 SUBROUTINE MELT2(TEMP,PREC,IYDAY,CV,ALB,RATIO,AI,AM,CO)
50050C
50100C
50150C
50200C THIS SUBROUTINE COMPUTES SNOWMELT BY DEGREE-HOUR METHOD
50250C
50300C     TEMP = AIR TEMP --F
50350C     PREC = HOURLY PREC-- IN.

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50400C IYDAY = JULIAN DAY
50450C CV = FOREST COVERAGE COEFF.
50500C KM = COEFF.
50550C ALB = SNOW SURFACE ALBEDO
50600C RATIO = RATIO OF INCID. RADIATION TO HORIZ. AND INCL. SURFACES
50650C AI = PRECIPITATION INDEX RAIN OR SNOW
50700C AM = SNOWMELT -IN.
50750C
50800C
50850C
50900 DATA RAIN/'RAIN'/
50950 CM=.75
51000 RAINF=PREC
51050 C=EXP(-4*CV)
51100 IF(AI.NE.RAIN) RAINF=0.
51150 TEQUIL=FLOAT(IYDAY)*.036+32.
51200 IF(IYDAY.GT.200) TEQUIL=35.6
51210 RATIO=1.0
51250 IF(TEQUIL.GT.35.6) TEQUIL=35.6
51300 CO=CM*C*RATIO*(1.-ALB)
51350 AMLT=CO*(TEMP-TEQUIL)
51400 RMLT=.0126*5./9.*(TEMP-32.)*RAINF
51450 AM=AMLT+RMLT
51500 IF(AM.LT.0.0) AM=0.0
51550 RETURN
51600 END
51650C
51700C
51750C
51800 SUBROUTINE ACCT(WESN,PRECIP,QSUB,AMELT,AI,TOTALM,GWAT,TONEM)
51850 DATA RAIN/'RAIN'/
51900C
51950C
52000C THIS SUBROUTINE COMPUTES WATER BALANCE.
52050C
52100C WESN = WATER EQUIV. OF SNOW ON THE GROUND-IN.

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52150C       PRECIP = HOURLY PRECIPITATION- IN.  
 52200C       QSUB = SUBLIMATION OR CONDENSATION- IN.  
 52250C       AMELT = SNOWMELT - IN.  
 52300C       AI = PRECIPITATION INDEX RAIN OR SNOW  
 52350C       TOTALM = TOTAL SNOW WATER EQUIV. LOSS - IN.  
 52400C       GWAT = WATER AVAILABLE TO THE GROUND - IN.  
 52450C       TONEM = TOTAL NEGATIVE SNOWMELT - IN.  
 52500C  
 52550C  
 52600C  
 52650       TOTALM=AMELT+TONEM+QSUB  
 52700       IF(AI.NE.RAIN) WESN=WESN+PRECIP  
 52750       IF(TOTALM.GT.WESN) TOTALM=WESN  
 52800       IF(TOTALM.LT.0.0) TOTALM=0.0  
 52850       WESN=WESN-TOTALM  
 52900       GWAT=TOTALM  
 52950       IF(AI.EQ.RAIN) GWAT=GWAT+PRECIP  
 53000       RETURN  
 53050       END  
 2370C       SRATIO = CHANGE IN SURFACE STORAGE/PRESENT SURFACE STORAGE  
 2371C       AM = A FOR MITCHELL AND JONES EQUATION (SURFACE STORAGE)  
 2372C       BM = B FOR MITCHELL AND JONES EQUATION (SURFACE STORAGE)  
 2373C       SM = MAXIMUM SURFACE STORAGE (INCHES)  
 2374C       DM = MAX. SURFACE DEPRESSION DEPTH (INCHES)  
 2375C       XMO = INITIAL MOISTURE CONTENT OF THE SURFACE (PERCENT)  
 2376C       PCL = PERCENT CLAY IN THE SOIL  
 2377C       TSHIFT = THE CUMULATIVE TIME DURING AN INFILTRATION  
 2378C               EVENT ( ADJUSTED FOR INTERMITTENT RAINFALL) (HOURS)  
 2379C       PAN = DDAILY PAN   EVAPORATION (INCHES)  
 2380C       EVAP = EVAPORATION DURING A TIME STEP EITHER FROM  
 2381C               SURFACE STORAGE OR INTERCEPTION STORAGE (INCHES)  
 2382C       APPLY = THE TOTAL WATER APPLIED TO THE SOIL SURFACE DURING  
 2383C               A TIME STEP (INCHES)  
 2384C       ASTORE = THE AVAILABLE SURFACE STORAGE (INCHES)  
 2385C       RUNOFF = THE RUNOFF DURING A TIME STEP (INCHES)  
 2386C       TRO = TOTAL RUNOFF FOR A DAY (INCHES)

2387C TBASE = TOTAL BASE FLOW OR SEEPAGE FOR A DAY (FEET)  
 2388C TAET = TOTAL ET EXTRACTED FROM THE SOIL FOR A DAY (INCHES)  
 2389C TIFIL = TOTAL INFILTRATION FOR A DAY (INCHES)  
 2390C TLAST = TOTAL WATER IN THE SOIL PROFILE ON THE PREVIOUS DAY (FT)  
 2391C TN = TOTAL WATER IN THE PROFILE FOR THE PRESENT DAY (FT)  
 2392C AET = THE EVAPOTRANSPIRATION EXTRACTED FROM THE SOIL PROFILE  
 2393C DURING A TIME STEP (INCHES)  
 2394C FIL = THE INFILTRATION DURING A TIME STEP (INCHES)  
 2395C SAV = AVERAGE CAPILLARY SUCTION AT THE WETTING FRONT (FT H2O)  
 2396C IPOND = 1 IF PONDING HAS OCCURRED, 0 IF PONDING HAS NOT  
 2397C INEW = 1 IF THIS IS A NEW RAINFALL EVENT, 0 IF NOT  
 2398C XKFS = HYDRAULIC CONDUCTIVITY AT FIELD SAT (INCHES/HR)  
 2399C R = ARRAY OF THE RAINFALL INTENSITIES (IN/HR) FOR  
 2400C THE PERIODS OF THE DAY  
 2401C XMD = INITIAL MOISTURE DEFICIT AT THE SOIL SURFACE  
 2402C FBIG = CUMULATIVE INFILTRATION DURING AN EVENT (INCHES)  
 2403C F = INFILTRATION DURING A TIME STEP (INCHES)  
 2404C FP = CUMULATIVE INFILTRATION TO TIME OF PONDING (INCHES)  
 2405C TP = TIME TO PONDING (HRS)  
 2406C TPP = TP PRIME (CORRECTION TO ALLOW FOR PONDING NOT OCCURRING  
 2407C INSTANTLY DURING AN EVENT  
 2408C THEI = ARRAY OF THE INITIAL MOISTURE CONTENTS FOR A SOIL LAYER  
 2409C D = ARRAY OF THE THICKNESS OF EACH SOIL LAYER (FT)  
 2410C THE2 = ARRAY OF THE INTERMEDIATE MOISTURE CONTENT OF A SOIL LAYER  
 2411C DURING REDISTRIBUTION  
 2412C THE3 = ARRAY OF THE SOIL MOISTURE CONTENT OF EACH SOIL LAYER  
 2413C AFTER REDISTRIBUTION  
 2414C FC = FIELD CAPACITY FOR EACH SOIL LAYER  
 2415C THEFS = ARRAY OF THE FIELD SATURATION MOISTURE CONTENT OF EACH  
 2416C SOIL LAYER  
 2417C WP = ARRAY OF THE WILTING POINT FOR EACH SOIL LAYER  
 2418C A = SATURATION SUCTION FOR EACH SOIL LAYER (FROM CAMPBELL'S  
 2419C LOG LOG PLOT OF THE MOISTURE RELEASE CURVE)  $SUC=A*\theta^{*-B}$   
 2420C B = ARRAY OF THE SLOPE OF THE LOG LOG PLOT OF THE MOISTURE  
 2421C RELEASE CURVE  
 2422C XKS = ARRAY OF THE SAT HYDR. CONDUCTIVITY OF EACH SOIL LAYER (FT/HR)

2423C THER = ARRAY OF MOISTURE CONTENTS AT WHICH CONDUCTIVITY IS ZERO  
 2424C THES = SATURATED MOISTURE CONTENT OF EACH SOIL LAYER  
 2425C NH20 = NUMBER OF THE SOIL LAYER WHICH CONTAINED THE WATER TABLE  
 2426C THEUN = MOISTURE CONTENT OF THE UNSATURATED LAYER JUST ABOVE THE  
 2427C WATER TABLE  
 2428C DH20 = THE THICKNESS OF THE SATURATED ZONE IN THE LAYER WHICH  
 2429C CONTAINS THE WATER TABLE  
 2430C BASE = BASE FLOW OR SEEPAGE (FT/HR)  
 2431C STORAGE = THE PRESENT SURFACE STORAGE (INCHES)  
 2432C WTABLE = THE ELEVATION OF THE WATER TABLE (FT)  
 2433C PATTERN = THE EXTRACTION PATTERNS (10 IS THE MAX NUMBER OF  
 2434C DIFFERENT EXTRACTION PATTERNS) (50 REFERS TO THE  
 2435C FRACTION EXTRACTED FROM EACH DEPTH - 50 IS THE  
 2436C MAX. NUMBER OF SOIL LAYERS)  
 2437C LO = ARRAY OF THE BEGINNING DAY FOR APPLICATION OF A GIVEN  
 2438C EXTRACTION PATTERN  
 2439C LHI = ARRAY OF THE ENDING DAY FOR APPLYING A GIVEN EXTRACTION  
 2440C PATTERN  
 2441C BREAK = THE MOISTURE CONTENT AT WHICH SOIL MOISTURE BEGINS TO  
 2442C LIMIT ET  
 2443C SL1 = THE ARRAY OF THE SLOPE OF THE LINEAR DEPLETION LINE FOR  
 2444C EXTRACTION OF ET FROM EACH SOIL ZONE (SEE MOORE AND LARSON  
 2445C 1979)  
 2446C B1 = THE X INTERCEPT OF THE LINEAR DEPLETION LINE (MOORE AND  
 2447C LARSON 1979)  
 2448C NROOT = THE NUMBER OF THE SOIL LAYER WHICH IS THE BOTTOM OF THE  
 2449C ROOTING ZONE  
 2450C INT1 = THE NUMBER OF EXTRACTION PATTERNS  
 2451C ELEV = THE ELEVATION OF THE GROUND SURFACE (FEET)  
 7910C 999 IS THE INDICATOR FOR ENDING SIMULATION  
 8060C JIN = THE DAY OF FROST INTO THE SOIL (JULIAN DAY)  
 8061C JOUT = THE DAY OF FROST OUT OF THE SOIL  
 7651C ETIME = THE TIME OF DAY OF THE PRESENT TIME STEP (HOUR)  
 8960C  
 8961C CALC. OF WATER IN THE SOIL PROFILE  
 9410C ABOVE EQUATION CALCULATES WATER BALANCE FOR THE DAY (FT)

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9411C THE WATER BALANCE SHOULD ALWAYS BE ZERO TO WITHIN 10 DECIMAL
9412C OTHERWISE IT INDICATES A PROBLEM IN THE PROGRAM. THERE IS
9413C ONE EXCEPTION HOWEVER THIS IS WHEN THE MODEL SWITCHES
9414C FROM THE FROZEN TO NON-FROZEN PERIOD THEN THE WATER BALANCE
9415C (CHECK) INDICATED THE NET CHANGE IN WATER STORAGE IN THE
9416C PROFILE
9417
11001C THE END OF THE MAIN PROGRAM
11002C#####
11030C #####
11031C THE TOP OF THE SUBROUTINE FOR EXTRACTING
11032C THE ET FROM EACH SOIL LAYER (EXTRACT)
11033C
11034C
11549C EK = THE FRACTION OF ET TO EXTRACT FOR EACH
11548C EK = THE FRACTION OF ET TO EXTRACT FOR EACH 4 HOUR PERIOD
11549C OF THE DAY
11480C RESID = THE ET LEFT AFTER AS MUCH CAN BE EXTRACTED
11481C FROM THE SOIL PROFILE AS IS POSSIBLE (BASED ON LINEAR
11482C DEPLETION CURVE)
11880C P2ET = THE ET TO EXTRACT AFTER INTERCEPTION STORAGE HAS
11881C BEEN DEPLETED
12440C KM = THE NUMBER OF THE EXTRACTION PATTERN TO USE
12580C PULL = THE ET FOR A TIME STEP TO TRY TO EXTRACT FROM A
12581C GIVEN SOIL ZONE (CAN BE LIMITED BY SOIL MOISTURE)
12582C AVAIL = THE AMOUNT OF SOIL MOISTURE WHICH CAN BE
12583C EXTRACTED FROM A GIVEN SOIL ZONE
17051C#####
17052C"#####
17053C THE SUBROUTINE FOR CALCULATING THE ET FOR THE VEGETATION
17054C FOR THE DAY FOR THE CASE OF SOIL MOISTURE NOT LIMITING
17055C
17056C C = THE COMBINED CROP-PAN COEFFICIENT
17057C XMF = HARGREAVES MF FACTOR
17058C XKP = THE PAN COEFFICIENT
17059C CH = CORRECTION FOR RELATIVE HUMIDITY

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