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D. Yates

Abstract

A water balance model combined with the Priestly-Taylor method for computing potential evapotranspiration has been developed as an integrated tool for modeling the response of river basins to potential climate change. The system was designed within the EXCEL 5.0 spreadsheet environment making use of the Visual Basic programming language. The model is simple to use and takes advantage of IIASA's mean monthly hydrologic data base (Leemans and Cramer, 1992). The model environment is described and two case studies are shown using the model.

Introduction

A number of modeling approaches have been developed and previous models modified for studying the impact of a potentially altered climate on river basin runoff (Nemec and Shaake, 1982; Gleick, 1987; Lettenmaier and Gan, 1990; Mimikou and Kouvopoulos, 1991; McCabe and Wolock, 1992; Nash and Gleick, 1993, Kaczmark 1993, Reibsame, et. al 1994; Skiles and Hanson, 1994; Yates and Strzepek, 1994). These methods have used different models and assumptions to derive the potential impact of a changed climate on river basin discharge. Generally there is no accepted method or approach for proper assessment and often simply using different models, assumptions, and methods can lead to different conclusions regarding the impact of climate change on water resources. Proper evaluation of the water balance and evapotranspiration are important components of the hydrologic cycle, as evapotranspiration can be considered a key "link" between the atmosphere and the soil matrix within the hydrologic cycle. The importance of this link has been observed by Dooge (1992) who states that any estimate of climate change impacts on water resources depends on the ability to relate changes in actual evapotranspiration to predicted changes in precipitation and potential evapotranspiration (E_p). To predict proper *changes* in evapotranspiration it is obviously important to begin with good *estimates* of the mechanisms of that change which are the water balance and potential evapotranspiration.

This motivates the need to arrive at a consistent and sound method for assessing the impact of climate change on a river basin. The model described here is an attempt to use simple yet widely accepted assumptions regarding the water balance and sound physical approaches to estimating potential evapotranspiration. Kaczmarek (1993) developed a DOS based meso-scale water balance model known as CLIRUN for studying the impact of climate change on river basin discharge. The CLIRUN model takes as input, effective precipitation, potential evapotranspiration and historic discharge and produces the runoff response of a river basin as well as changes in other variables such as storage and evapotranspiration. Because the model requires effective precipitation and potential evapotranspiration as inputs, it is difficult to find a consistent method for the proper assessment of climate impact on river basins with this model. Simply choosing a different set of criteria for determining effective precipitation or choosing an empirical method over a physically based method for the determination of potential evapotranspiration will likely produce significantly different impact results (Yates and Strzepek, 1994).

This model could be viewed as simply another, slightly modified approach in a long line of hydrologic models. However Kundzewicz and Somlyódy (1993) have observed a recent trend toward simpler, classical modeling approaches especially with the new challenges which climate change brings. More sophisticated rainfall-runoff models have been developed over the past thirty years, but these are usually aimed at short-term flood forecasting on time scales of days or even hours. These distributed models have been used for analyzing climate impacts (Lettenmaier and Gan, 1990; Nash and Gleick, 1993). Yet Franchini and Pacciani (1991) comment on event scale models such as the STANFORD IV and SACRAMENTO models. They state that the interaction of the various phases of rainfall-runoff transformation within the soil is not advantageous for computational purposes, resulting in overparamaterization which leads to difficulty in the calibration procedure. Beven (1989) states that three to five parameters should be sufficient to reproduce most of the information in a hydrological record.

So with these issues in mind, this model makes use of a small number of parameters and incorporates a physically sound and widely accepted method for computing potential evapotranspiration in an attempt to draw attention to simple approaches using physically sound assumptions which are appropriate for climate impact assessment on river basin runoff.

Modeling elements within WatBal

There are essentially two main modeling components within the WatBal model. The first is the water balance component that uses continuous functions to describe water movement into an out of a conceptualized basin. The second component is the calculation of potential evapotranspiration using the well known Priestly-Taylor radiation approach. These two components are described below.

Soil Moisture

The common link in most water balance approaches is the computation of a mass balance within the soil moisture zone. There are many ways of representing the infiltration, discharge and storage behavior of the soil moisture zone (Eagelson, 1978; Shaw, 1982; Chow et. al. 1988, Todini, 1988). WatBal accounts for changes in the soil moisture by taking into account precipitation, runoff, actual evapotranspiration (Ev), while using potential evapotranspiration (PET) to drive the extraction of water from the soil moisture (Figure 1).

Kaczmarek (1991) developed the framework for the WatBal model. Elements of this approach were adapted and then implemented using the Visual Basic programming language within the Excel-5.0 spreadsheet environment. A model of PET was also included within the modeling systems, creating an integrated tool for climate change impact assessment on river basins. The uniqueness of this lumped conceptual model to represent water balance is the use of continuous functions of relative storage to represent surface outflow, sub-surface outflow, and evapotranspiration. In this approach the mass balance is written as a differential equation and storage is lumped as a single, conceptualized "bucket" (Figure 1) with the components of discharge and infiltration being dependent upon the state variable, relative storage (1) The water balance component of the model contains five parameters related to: 1) direct runoff; 2) surface runoff; 3) subsurface runoff; 4) maximum catchment water-holding capacity; and 5) base flow

Because of the differential approach of the model, varying time steps can be used depending on data availability and basin characteristics. For larger basins with long times to concentration, longer time steps are recommended. For the computation of effective precipitation in regions where snowmelt makes up a substantial portion of the runoff water, a temperature index model was used with the upper and lower temperature bounds defined by trial and error (Ozga-Zielinska, 1993; Gray and Prowse, 1993)

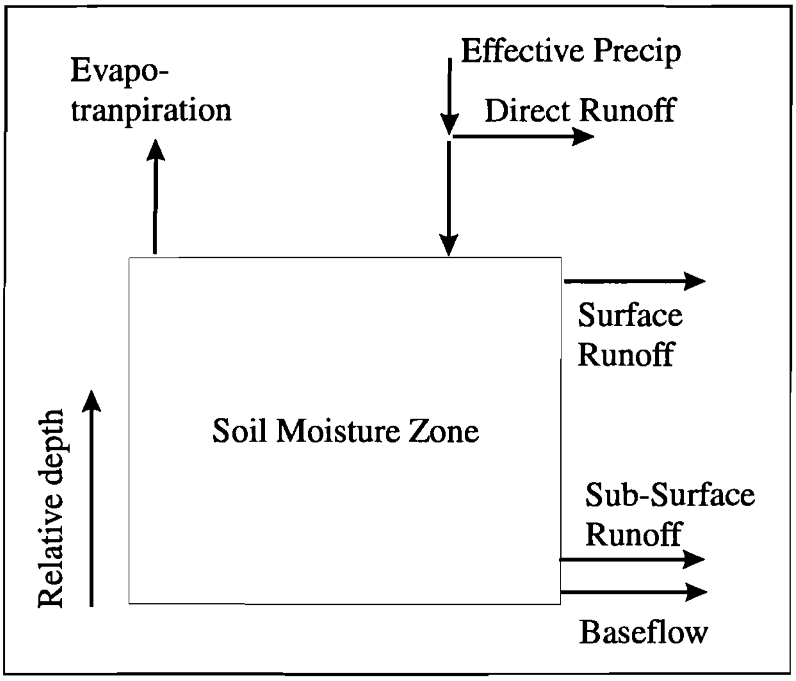

Figure 1. Conceptualization the water balance for the WatBal model

Direct runoff (R_d) is given as:

$$R_d = \beta P_{eff} \tag{1}$$

The soil moisture balance is written as:

$$S_{\max} \frac{dz}{dt} = \left(P_{peff}(t)(1-\beta)\right) - R_s(z,t) - R_{ss}(z,t) - Ev(PET,z,t) - R_b \tag{2}$$

$$\begin{aligned} P_{eff} &= \text{Effective Preciptation (length / time)} \\ R_s &= \text{Surface runoff (length / time)} \\ R_{ss} &= \text{Sub - Surface runoff (length / time)} \\ Ev &= \text{Evaporation (length / time)} \\ R_b &= \text{baseflow (length / time)} \\ S_{max} &= \text{Maximum storage capacity (length)} \\ z &= \text{relative storage } (0 \le z \le 1) \end{aligned}$$

The Continuous functional forms that are used in equation 2 are:

1. Evapotranspiration - E_V:

Evapotranspiration is a function of Potential Evapotranspiration (PET) and the relative catchment storage state. A number of expressions have been given that describe evapotranspiration as a function of the soil moisture state (Kaczmarek, 1991). Shown are a linear and a non-linear expression. A simple-linear expression might be given by;

$$Ev(z,PET,t) = PET\ z \tag{3}$$

A non-linear relationship has been used to describe evpotranspiration (Kaczmarek, 1993).

$$Ev(z,PET,t) = PET()\left(\frac{5z-2z^2}{3}\right) \quad \begin{cases} \text{PET}(z) \text{ albedo is a function of soil mositure} \\ \text{PET}_c \text{ fixed albed} \end{cases} \tag{4}$$

Potential evapotranspiration is modeled using the Priestly-Taylor method (described below). This method was chosen due to its simplicity and the evidence supporting such an empirical relationship on a regional basis, which is the case for river basin modeling (Shuttelworth, 1993). The Priestly-Taylor method is a radiation-based approach to modeling PET, where the net radiation is taken from observed data (in equivalent water depth, mm/day) or is computed based on analytical methods. The albedo, a measure of surface reflectivity incorporated into the compuation of net radiation, can be given as monthly mean values, or can be computed based on the soil moisture content of the soil as well as the predominant surface cover (grass or forest, snow, and fraction of bare ground).

2. Surface Runoff - R_S:

A variation of the surface runoff term has been used in the WatBal model. approach. Surface runoff is described in terms of the storage state, z, the effective precipitation, P_{eff}, and the baseflow. If the precipitation exceeds the predefined baseflow, then surface runoff is zero. Kaczmarek (1993) defines surface runoff as;

$$R_s(z,P,t) = \frac{\varepsilon}{1+\varepsilon-z}(P_{eff} - R_b) \tag{5}$$

Investigation of this expression led to a reformulation that gave a more robust solution to basins with large variations in storage due to extreme seasonality. The above expression has been changed to,

$$R_s(z,P,t) = \begin{cases} z^{\varepsilon}(P_{eff} - R_b) & \text{for } P_{eff} > R_b \\ 0 & \text{for } P_{eff} \le R_b \end{cases} \tag{6}$$

Equation 6 allows the surface runoff term to approach zero as the relative storage becomes very small. This has been found to be important in a basin such as the Mulberry River, Arkansas. If there is a large contribution from direct runoff, then this can be described with the parameter β (1).

3. Sub-Surface Runoff - R_{SS}:

Sub-surface discharge is a function of the relative storage state times a coefficient, α (7). In most cases, the value of γ is 2.0, however it was observed that for some basins (East) it appears that the value is smaller than 2.0. As γ approaches 1.0 the sub-surface discharge responds more linearly with relative storage, indicating a decrease in the holding or retention capacity of the soil. A value of γ less than 2.0 might be for gravel dominated basins such as that found in the East River.

$$R_{ss} = \alpha z^{\gamma} \tag{7}$$

The 4th model parameter is the maximum catchment holding capacity, S_{max}. The storage variable, Z, is given as the relative storage state: $0 \le Z \le 1$. Referring to figure 1, S_{max} is defined as the maximum storage volume, so when S_{max} is multiplied by z, the current storage volume for the period is given.

Total runoff, for each time step, is the sum of the four components:

$$R_t = R_s + R_{ss} + R_b + R_d \tag{8}$$

The differential equation (2) is solved using a predictor-corrector method (Carnale and Chapra, 1988). The model is calibrated using a unconstrained heuristic algorithm which finds an optimal set of model parameters while meeting the criteria of minimizing the root mean square error between the observed and predicted monthly runoff value. The direct runoff coefficient, β, and the power term on sub-surface runoff, γ, are not part of the optimization routine.

Time series inputs to this model include: Effective Precipitation (adjustments for seasonal interception, elevation adjustments, and gauge error must be predefined using the worksheet), potential evapotranspiration, and for calibration and validation purposes - runoff in the units of (length/time). Potential evapotranspiration can be estimated using the Priestly-Taylor subcomponent in which case a temperature time series is also required (see below). For basins with a large portion of runoff from snowmelt, a temperature index snowmelt model is used with temperature thresholds for melting and freezing (see below), creating an "adjusted" effective precipitation. The snowmelt model is also used to calculate winter albedo in those basins where winter precipitation in the form of snow is significant (20).

Effective Precipitation

A sub-component of WatBal is the computation of an "adjusted" effective precipitation based on snowmelt processes. Precipitation must first be corrected for elevation affects, gauge error, seasonal interception, etc.; the snowmelt model will then compute an "adjusted" effective precipitation to the water balance component. The following relationships are used to derived this "adjusted" effective precipitation based on the snowmelt process.

$$Peff_i = mf_i(A_{i-1} + Pm_i) \tag{9}$$

where,

$$mf_i = \begin{cases} 0 & \text{for} \quad T_i \le T_s \\ 1 & \text{for} \quad T_i \ge T_l \\ \dfrac{(T_i - T_s)}{(T_l - T_s)} & \text{for} \quad T_s < T_i < T_l \end{cases} \qquad (10)$$

and snow accumulation is written as,

$$A_i = (1 - mf_i)(A_{i-1} + Pm_i) \qquad (11)$$

where,

mf_i = melt factor in month i
A_i = snow accumulation in month i
Pm_i = "observed" precipitation in month i
$Peff_i$ = effective precipitation in month i

Priestly Taylor Method for Potential Evapotranspiration

Penman (1948) was one of the first to describe evaporation in terms of the two main micrometerological components: energy for the conversion of water to a vapor phase and aerodynamic processes for the removal of saturateed air away from the surface. The Penman equation is the most widely known combined method of estimating evaporation.

$$E = \frac{\Delta}{\Delta + \gamma} E_r + \frac{\gamma}{\Delta + \gamma} E_a \qquad (12)$$

where:

E = Combined evaporation estimate [mm/day]
E_a =Evaporation estimate which assumes an unlimited availability of energy.
E_r =Evaporation estimate which assumes the ability of the system to remove moist air is not limiting.
D = slope of the saturated vapor pressure curve
γ = psychometric constant = $C_p\, p\, K_h / (0.622\, l\, K_w)$
where, Cp = specific heat at constant temperature
Kh, Kw = diffusivity [L^2/t]

Priestley and Taylor (1972) found that for very large areas the second term of the Penman equation is approximately thirty percent that of the first. Thus an approximation to the Penman equation which gives an estimate of referernce crop evapotranspiration may be written as:

$$E_{rc} = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \qquad (13)$$

where α has been given the value of 1.26 in humid climates (relative humidity greater than 60 percent in the month with the maximum evaporation) and 1.74 for arid climates (relative humidity less than 60 percent in the month with the maximum evaporation). G is the soil heat flux which for regional estimates can be assumed to be zero, all other terms have been defined. This is a *reference crop* evapotranspiration estimate (referred in this paper as potential evapotranspiration), which should show lower values than similar estimates which give free surface or *potential* evapotranspiration.

Radiation

Because net radiation data is often scarce, an equation to derive its value was used. Aside from temperature, the equation uses two additional climate variables; relative humidity and bright sunshine hours per day. These were taken as monthly mean values from the IIASA database, given on a 0.5 x 0.5° basis (Leemans and Cramer., 1992). The value for net radiation can be calculated with the following equation.

$$R_n = \left((1-alb)\left(0.25+0.5\frac{n}{N}\right)R_a \right) - (f)\left(0.34-0.14\sqrt{e_d}\right)\sigma(T+273.2)^4 \qquad (14)$$

n = bright sunshine hours per day (h)
N = total day length (h)
R_a = extraterrestrial radiation (MJ $m^{-2}day^{-1}$)
σ = Stefan-Boltzmann constant ($4.903x10^{-9}$ MJ $m^{-2}{}^{\circ}K^{-4}day^{-1}$)
T = mean air temperature (°C)
e_d = vapor pressure (kPa)
R_n= net radiation (MJ $m^{-2}day^{-1}$)
alb = albedo (short-wave radiation reflection coefficient)
f = cloudiness factor, given by

$$f = \left(a_c \frac{b_s}{a_s + b_s} \right)\frac{n}{N} + \left(b_c + \frac{a_s}{a_s + b_s} a_c \right) \qquad (15)$$

where
a_s= 0.25 and b_s= 0.50
a_c= 1.35 and b_c= -0.35 (arid climates)
a_c= 1.0 and b_c= 0.0 (humid climates)

If it is assumed that the density of water is constant (1000 kg m^{-3}) then R_n (14) can be converted from MJ $m^{-2}day^{-1}$ to mm/day by diving R_n by the latent heat of vaporization (in MJ kg^{-1}). Actual vapor pressure is estimated using data of mean monthly relative humidity values. Relative humidity, taken from the IIASA data base, is estimated by multiplying the saturated vapor pressure by the relative humidity data. To compute the extraterrestrial radiation and total day length the following equations were used.

$$R_A = 15.392\ d_r\ (w_s \sin f \sin d + \cos f \cos d\ \sin w_s) \qquad (16)$$

where;

R_A = extra-terrestrial radiation (mm/day)
N = maximum possible daylight hours, equation (9)
d_r = relative distance earth-sun, equation (10)
w_s = sunset hour angle [radians], equation (11)
f = latitude of site (+ for Northern Hemisphere, - for Southern Hemisphere) [radians]
d = solar declination [radians], equation (12)
J = Julian day

and:

$$N = \frac{24}{\pi}\omega_s \qquad (17)$$

$$d_r = 1 + 0.033 \cos(2p\, J / 365) \quad (18)$$

$$w_s = \arc\cos(-\tan f \tan d) \quad (19)$$

$$d = 0.4093 \sin(2p\, J / 365 - 1.405) \quad (20)$$

Albedo

The albedo is a measure of the surface's capacity to reflect incoming short-water solar radiation. Albedo can be given exogenously as monthly mean values or it can be computed based on land cover conditions as well as the soil moisture state. Two broad land cover classes have been used within WatBal, where one is tall forest and the other is grass and pasture. Shuttelworth (1993) suggested the following coefficients for short water radiation reflection (albedo); these have been used within WatBal to compute albedo based on equation 21.

Table 1 Albedo values for different land covers included within WatBal.

Land Cover Class	Albedo Value, alb
Forest	0.11-0.16
Grass and Pasture	0.20-0.26
Bare Soil	0.10 (wet) - 0.35 (dry)
Snow and Ice	0.20 (old) - 0.80 (new)

$$alb_i = \begin{cases} ([1-mf_i)0.8] + mf_i[(1-GC)(a_1-(z*a_2)) + GC(a_d-(z*a_w))] & \text{if } mf_i < 1.0, \text{ new snow} \\ [(1-mf_i)0.2] + mf_i[(1-GC)(a_1-(z*a_2)) + GC(a_d-(z*a_w))] & \text{if } mf_i < 1.0, \text{ old snow} \\ (1-GC)(a_1-(z*a_2)) + GC(a_d-(z*a_w)) & \text{if } mf_i = 1.0 \end{cases} \quad (21)$$

where for each month,

GC =ground cover index (0.0 £ GC £ 1.0; GC =0.0 completely covered, GC = 1.0 completely bare)

mf_i = melt factor; (0.0 £ mf_i £ 1.0) (20)

z = relative soil moisture; (0.0 £ z_i £ 1.0) (2)

a_1, a_2 = albedo bounds based on land cover type (grass/pasture or forest)

a_d, a_w = albedo bounds for bare soil (dry and wet)

Case Studies

Two case studies have been selected for testing the WatBal model. They are intended to show the range of the models applicability by selecting a basin in a more humid climate that is dominated by winter rainfall and warm summers and a basin in a semi-arid region that is dominated by snowfall and colder temperatures. A split sample test was used on both basins to evaluate the hydrologic model. In this test the historic record is broken into two segments, one used for calibration and the other for validation. If the statistical values derived from the calibration and validation procedure are similar (correlation coefficient and monthly error) then the model can be deemed acceptable. Two simple statistical measures were used here: The correlation coefficient and the average monthly error. The correlation coefficient is given by:

$$\rho_{Q_o,Q_p} = \frac{Cov(Q_o,Q_p)}{\sigma_{Q_o}\sigma_{Q_p}} \tag{22}$$

$Cov(Q_o, Q_p)$ is the covariance of the observed and modeled discharge and σ_{Qo} and σ_{Qp} are the standard deviation of the observed and modeled series. The average monthly error between the predicted and observed discharge is given by

$$E_{p,o} = \frac{\sum abs(Q_p - Q_o)}{n} \tag{23}$$

where;

Q_o = Observed monthly discharge
Q_p = Model prediction of monthly discharge

Because of the short record for the East river, the first 7 years were used for calibration and the reaming three year were used for validation (calibration: 1979-1985; validation 1986-1988). For the Mulberry river, 40 years of data were available from 1948 to 1987; the first 20 years were used for calibration and the second 20 for validation.

Scenario development for climate change impact assessment is usually performed in one of four ways (Niemann, et. at, 1994).

1. GCM based scenarios. GCM derived adjustments to base climates.
2. Hypothetical scenarios. Usually put in the framework of sensitivity analysis by applying an ensemble of potential climates.
3. Historical scenarios. Data from historic periods that "mimic" a changed climate (if available)
4. Analog scenarios. The changed climate in one location could be potentially similar to the climate in another location.

Since the focus of this work is on assessing the applicability of WatBal as a water balance model for climate impact assessment on a river basin, the second method was chosen for its simplicity. In this approach, hypothetical scenarios are cast as a set of plausible future climates. These scenarios will enable the generation of a family of tables that will give insight into the sensitivity of the basins and the model to climate variations. The scenarios chosen give uniform, annual changes in temperature (ΔT) and precipitation (%P) in the following combinations, with the expectation that they cover the range of plausible future climates (Table 3).

Table 2. Uniform Climate Scenarios Used. (base*)

T +0 P+0*	T +0 P+10	T +0 P+20	T +0 P-10	T +0 P-20
T +2 P+0	T +2 P+10	T +2 P+20	T +2 P-10	T +2 P-20
T +4 P+0	T +4 P+10	T +4 P+20	T +4 P-10	T +4 P-20

Mulberry River

The Mulberry basin in Arkansas U.S.A. is found at Lat 35°N Long 94 °W. This is a moderately temperate climate, with a mean annual air temperature of approximately 16°C and only a few incidents of winter mean monthly air temperatures dropping below 0°C. The region is characterized by dense ground cover and has little variation in elevation, with the gauging station located at 342 m above sea level. The basin area is a little less than 1000 km^2. Although Nemec and Shaake (1982) state that modeling such basins should produce minimum error, the climate of this basin produces an interesting runoff characteristic that can be observed in Figure 2. Although the overall runoff coefficient is approximately 0.44; the winter season coefficient is as high as 0.70, while the summer season's runoff coefficient drops to below 0.20. This large seasonal change is difficult to model when using models with a limited number of parameters.

A first modeling attempt of the Mulberry basin gave considerable error when attempting to match the historic runoff. It was assumed that the Mulberry precipitation record was given as gauge precipitation, therefore a interception value of 0.20 was used for the months, June, July, August, and September. This procedure produced an "effective precipitation" that was used for all model runs. Albedo was not endogenous but was given as monthly mean values, with summer albedo of 0.15 (to reflect dense forest growth) and a winter albedo of 0.23 (the recommended average from Shuttelworth, 1993). Figure 2 is a plot of the mean monthly discharge for the calibration and validation series, while Figure 3 is a plot of the annual values over the 40 year record for observed discharge, precipitation and potential evapotranspiration.

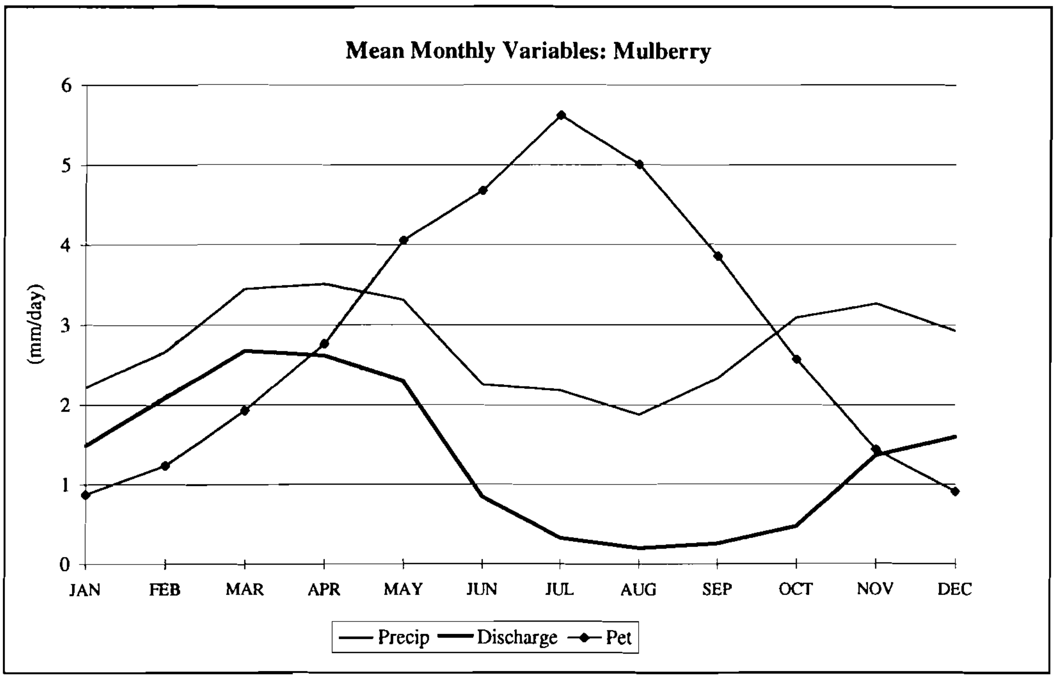

Figure 2. Mulberry River mean monthly values of precipitation, runoff and potential evapotranspiration by Priestly-Taylor.

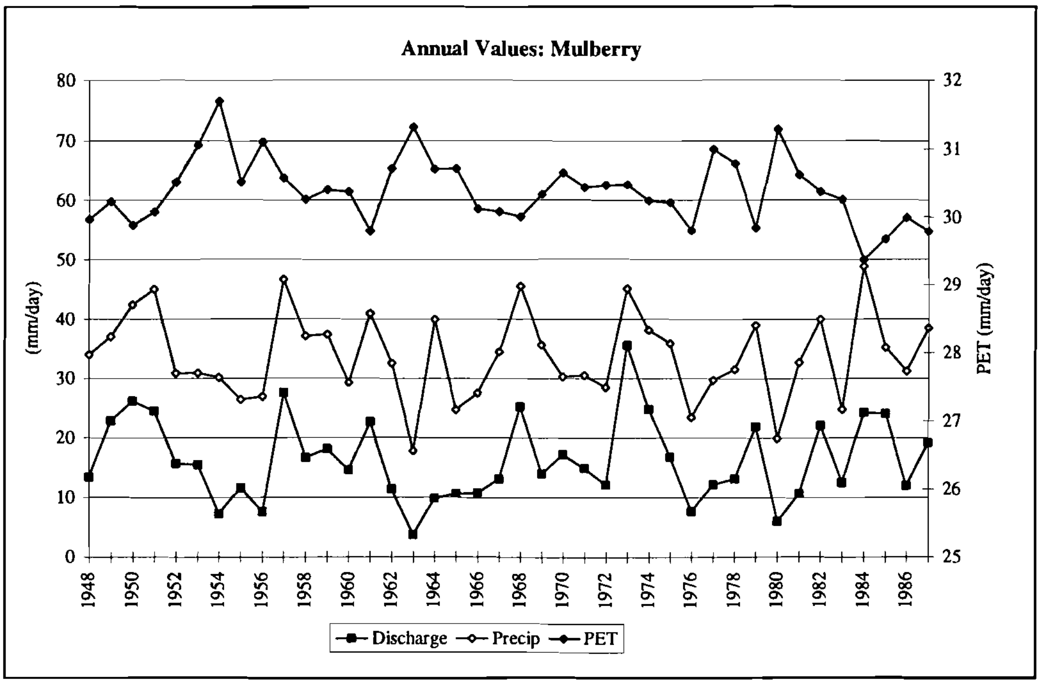

Figure 3. Annual totals of observed discharge, precipitation and potential evapotranspiration for the Mulberry Basin.

Calibration and Validation

The climatological record used for the Mulberry River spans the years 1948 - 1987. The basin shows strong runoff response to moderate changes in precipitation and temperature (Figure 3). Temperature is negatively correlated to runoff (-0.32), while precipitation, not surprisingly, is positively correlated (0.70). The annual precipitation, temperature and discharge record seems to indicate that the basin is possibly sensitive to even small temperature variations, as the two driest portions in the record are also the warmest (1954-1958 and 1964-1969). One portion of the record (1973 to 1977) has a large increase in basin discharge without a significant increase in precipitation or a substantial decrease in temperature which the model failed to capture (Figure 3). Figure 4 is a plot of the the mean monthly observed and modeled discharge for the calibration and validation period. The model appears to consistenly underpridct the winter runoff and tends to under estimate the transition period when the flow diminishes greatly from May to June. This kind of result might point to the strength of seasonal model parameters.

Calibration and validation values used in the WatBal model for the East River include the following:

- Sub-surface coefficient, $\gamma = 2.0$
- Sub-surface coefficient, $\alpha = 2.5$
- surface runoff coefficient, $\varepsilon = 1.7$
- Maximum Storage, $S_{max} = 295$ mm
- Initial storage, $Z_i = 0.4$
- Direct runoff coefficient, DRC = 0.0
- Latitude = 34.0°N
- Upper temperature, T_l = - (not used)
- Lower temperature, T_s = - (not used)
- Priestly Taylor coefficient, P.T. = 1.26
- Ground cover index, G.C. = 0.1
- base flow = 0.005 mm/day (0.95 percentile low flow)

Table 3. Calibration and Validation values for the Mulberry River. Average error is given in mm/day based on the monthly time step.

	Correl	Avg Err
Calib	0.90	0.47
Valid	0.88	0.53

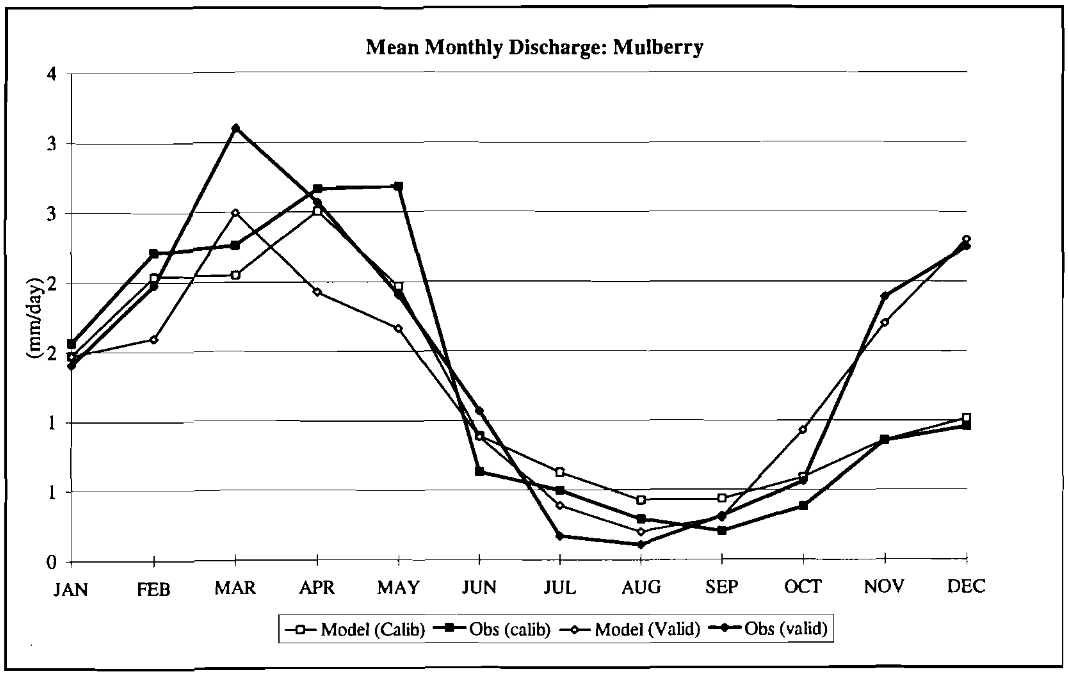

Figure 4. Observed discharge vs. model prediction for calibration and validation series.

Climate Change Scenarios: Mulberry

The ten climate change scenarios are shown in Table 4. These reveal the sensitivity of the basin to precipitation change where a 20 percent increase or decrease in precipitation leads to at least a 30 percent increase or decrease in discharge. An approximate 1.5% decrease in flow is observed for each °C increase (Table 4).

Table 4. Climate change scenarios

	P0	P10	P20	P-10	P-20
T0	0%	17%	34%	-16%	-32%
T2	-3%	14%	31%	-19%	-34%
T4	-6%	11%	28%	-21%	-36%

East River

The East river in Colorado (Lat 40°N Long 105°W) U.S.A. is a tributary of the Gunnison River basin (750 km^2). This basin resides within the Rocky Mountain Range, with most of the basin above 3000m. Although considered a semi-arid region, the runoff coefficient for this basin is high due runoff from spring snowmelt. The climate station for this basin is located in the Gunnison Valley (elevation 2500m), and so the precipitation records were adjusted to reflect the effect of elevation on precipitation by multiplying the precipitation record by 1.15 in the winter months, November to March (Gray and Prowse, 1993).

The climatological record for the East River spans the years 1979 - 1988. The hydrologic year begins in October, when it is assumed that snow accumulation is zero. Because the basin is located in mountainous regions, it is assumed that the gauging station underpridicts basin precipitation. For this reason winter precipitation values were increased by 15%. Figure 6 is the annual temperature, precipitation, and runoff for this basin over the 10 year record.

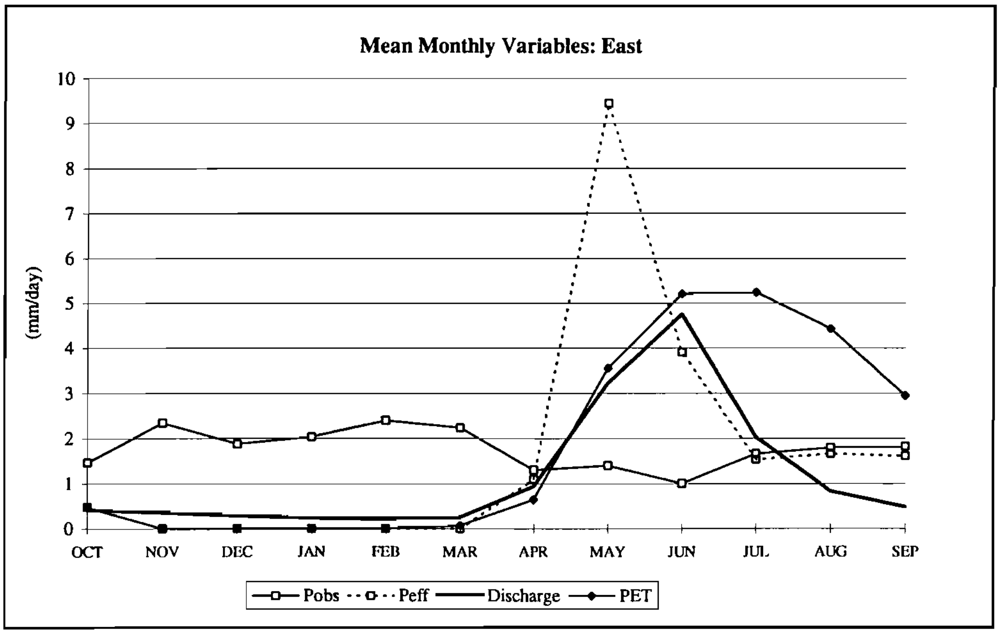

Figure 5. East River mean monthly values of precipitation, runoff and potential evapotranspiration by Priestly-Taylor.

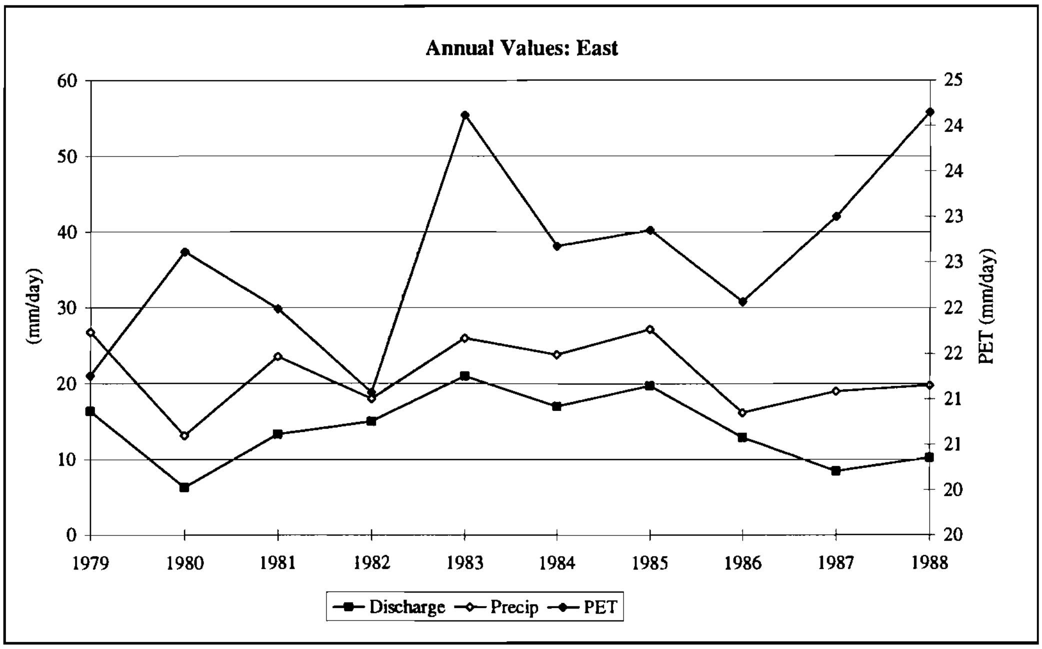

Figure 6. Annual totals of observed discharge, precipitation and potential evapotranspiration for the Mulberry Basin.

Calibration and Validation: East

The climatological record for the East River spans the years 1979 - 1988. The hydrologic year begins in October, when it is assumed that snow accumulation is zero. WatBal proved to be very sensitive to the definition of effective precipitation, where a one or two degree variation can be significant in the representation of snow melt, which is used to derive the effective precipitation. Also, representation of the melting rate produces a significantly different runoff regime as represented by changes in model parameters. A likely weaknesses of a lumped approach such as that used in WatBal is the inadequate representation of seasonal variability in the soil moisture holding capacity. Spring runoff occurs over predominantly frozen soils, which has less holding capacity than the dryer summer soils. For the WatBal model, a single maximum holding capacity is specified, so in order to observe the high spring discharge, a smaller soil moisture capacity value must be given at the expense of high summer runoffs. Although the lumped model parameters loose some of their physical meaning, it is possible to achieve similar calibration results with significantly different calibration parameters. A large soil moisture holding capacity (S_{max}), combined with a large value for the sub-surface flow parameter, α, will give similar results to a smaller values of these parameters. When larger precipitaiton changes are prescribed, then the smaller values of S_{max} will give substantially more discharge due to the non-linearity. Therefore, understanding the mechanisms of runoff when using a lumped model with automated calibration is important in a basin such as the East.

Calibration and validation coefficients used in the WatBal model for the East River include the following:

- Sub-surface coefficient, γ= 2.0
- Sub-surface coefficient, α= 12.3
- surface runoff coefficient, ε= 1.05
- Maximum Storage, S_{max}= 400 mm
- Initial storage, Z_i= 0.10
- Direct runoff coefficient, DRC = 0.10
- Latitude = 40.0°N
- Upper temperature, T_l = 6.0°C
- Lower temperature, T_s = -3.0°C
- Priestly Taylor coefficient, P.T.= 1.6
- Ground cover index, G.C. = 0.25
- base flow = 0.19 mm/day (0.95 percentile low flow)

Table 5. Calibration and Validation values for the East River on a monthly time step. Average error is given in mm/day based on the monthly time step.

	Correl	Avg Err
Calib	0.95	0.33
Valid	0.92	0.29

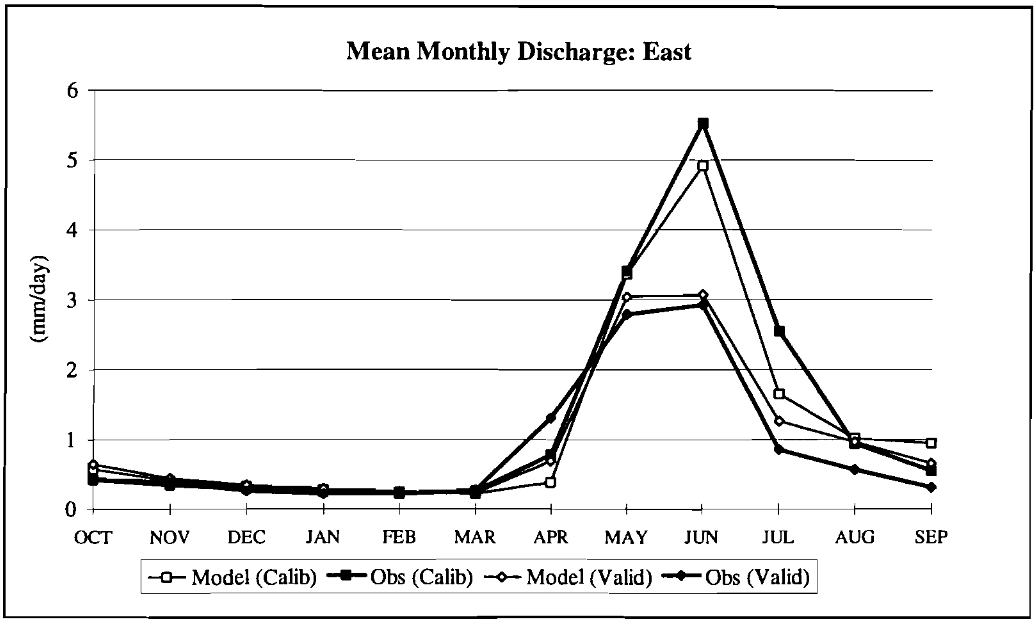

Figure 7. Mean monthly calibration and validation series for the East River with WatBal on a monthly time step

WatBal, was used with a daily time step for the East River to examine the difference between the results found on a monthly time step (Figures 7 and 8). A modified daily snow melt function (24) was used, whose parameters proved to be very sensitive during the calibration procedure of the lumped model (Gray and Prowse, 1993). A shift of 1°C or 2°C in the value of T_b drastically shifts the runoff regime and requires recalibration to match the discharge record. This sensitivity pointed out the importance of properly representing the snow melt process, which is one of the keys to understanding climate change for a basin such as the East.

$$M_f = (A_{i-1} / A_{max}) * M_r (T_i - T_b) \tag{24}$$

where,

M_f = melting rate (mm/day)

M_r = melting rate constant (≈ 5.5mm / °C day)

T_i = daily mean temperature °C

T_b = temperature threshold (≈ 0 °C)

A_i = accumulation (mm)

Observing the daily runoff hydrograph of figure 8 and understanding the mechanisms that create the effective precipitation which was computed using the simple snow melt model, it is possible to "predict" the primary mechanisms of runoff with the lumped integral model. The basin is not an "event" driven basin, as the slower snow melt process produces an effective uniform precipitation that is discharged primarily as sub-surface flow (as defined by the daily model). This is contrast to the monthly time step, where a larger portion of runoff is attributed to surface runoff. The calibration and validation with the daily time step reveals the tendency of the model to under-estimate winter runoff and over-estimate summer runoff. In spite of this, the calibration and validation statistics were quite good (Figure 8). The rapid decrease in discharge in June is followed by relatively large summer precipitation's that do not show up in the observed runoff hydrograph (this was one reason winter precipitations were assumed to be underestimated). This is possibly due to large interception by plants as well as changes in the soil moisture holding capacity when the soil matrix undergoes thawing. In order to account for this discrepancy the summer precipitation (June - Sept.) was reduced by 20%. Potential evapotranspiration was also reduced based on snow cover extent, where $PET_i = PET_i(1-(A_i/A_{max}))$

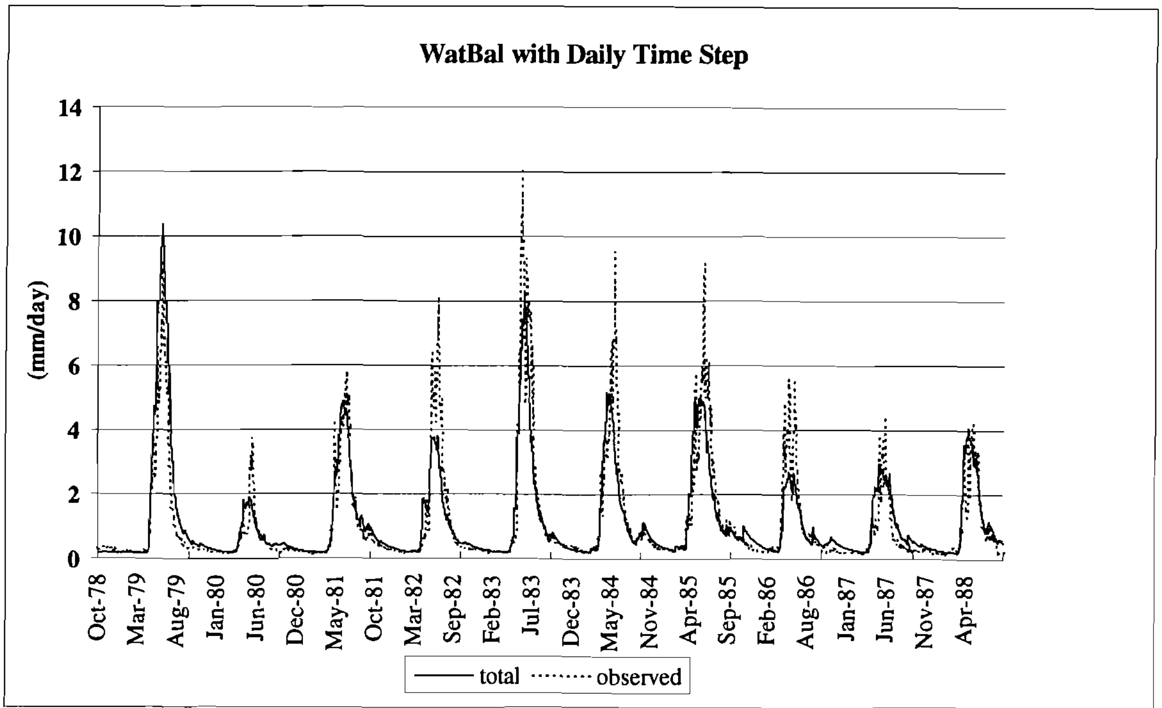

Figure 8. East River Daily runoff hydrograph (WatBal) vs. observed discharge. The model was calibrated over the first 5 years of data (1979-1983) and validated over remaining 5 years (1984-1988). Calibration: correlation: 0.90, average daily error 0.40; Validation: correlation :0.89, average daily error 0.37

Climate Change Scenarios: East

The ten climate scenarios for the East river are shown in Table 5. This basin produces interesting climate change results indicating that the snowmelt process is very sensitive to the freezing and melting temperature thresholds (10) and the definition of temperature. Figure 8 is a plot of the $\Delta T°2C$ and $\Delta T°4C$ scenarios, where a one month shift in the runoff regime is observed for both scenarios. Generally a 1°C increase in temperature reduces flow by 2 percent. Precipitation behaved quite linearly when compared to the Mulberry basin, where a ±10 and ±20 percent precipitation change produced a ±12 and ± 23 percent change in runoff respectively.

Table 6. Climate change scenarios: East

Monthly	PO	P10	P20	P-10	P-20
TO	0%	12%	23%	-12%	-23%
T2	-4%	7%	17%	-15%	-25%
T4	-7%	4%	15%	-18%	-28%
Daily	PO	P10	P20	P-10	P-20
TO	0%	13%	25%	-12%	-24%
T2	-6%	5%	17%	-18%	-29%
T4	-6%	7%	19%	-17%	-28%

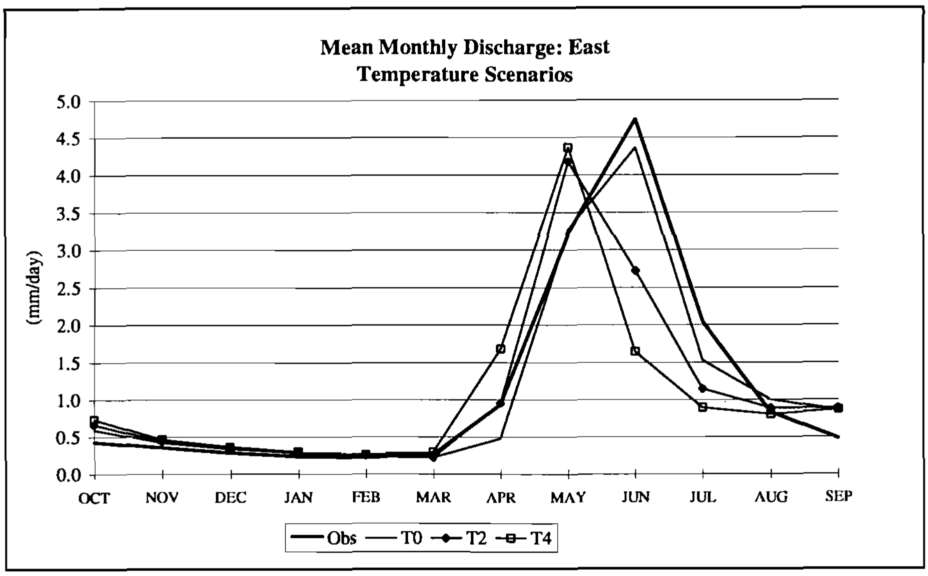

Figure 9. Mean monthly discharge for the East basin under uniform temperature increases of 2°C and 4°C. on a monthly time step. The peak discharge shifts to the left under both scenarios. The two degree shift shows a sustained large May flow while the four degree change shifts the peak runoff one month to the left (May).

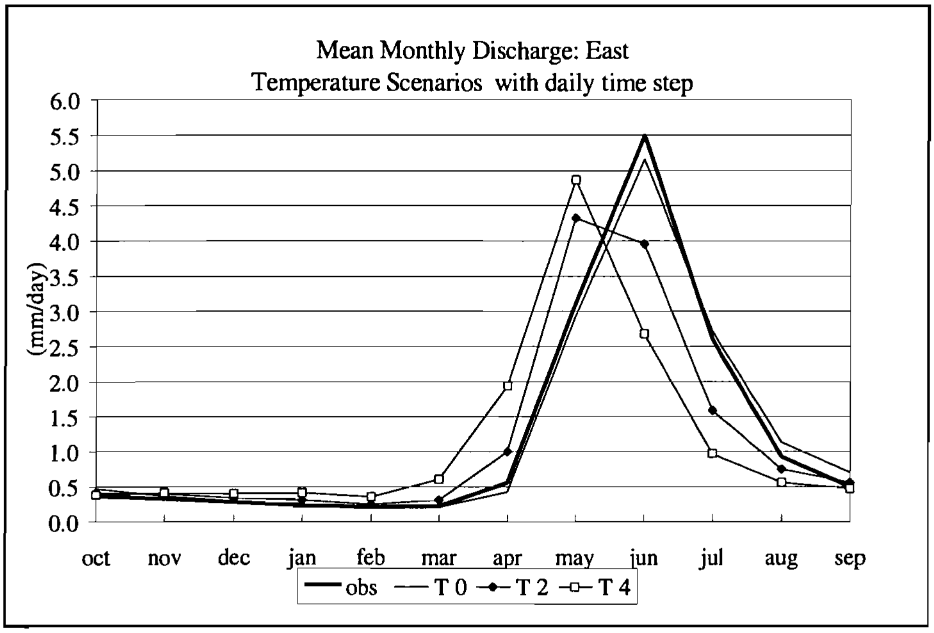

Figure 10. Mean monthly discharge for the East basin under uniform temperature increases of 2° C and 4°C. on a daily time step. Under the 2°C there is an effective double peak in May and Juane. The 4°C. scenario shifts the peak runoff to May.

Conclusions

WatBal was designed to be a simple to use water balance model for assessing the impact of climate change on a river basin. The above description of the model, combined with the two case studies shows that the model behaves fairly well given its simplicity. In the Mulberry basin the model appears to reveal the sensitivity of the basin to precipitation change, which follows the conclusion of Nemec and Shaake (1982) for a similar basin in the Eastern U.S. The strong seasonal variation in runoff in the Mulberry basin points to the need for possible seasonal parameters within WatBal. However Yates and Strzepek (1994) point out that emperically based potential evapotranspiration models that have been regionally developed and calibrated (Thornthwaite) can give superior results over a physically based model such as Priestly-Taylor, which might eliminate the need for additional model parameters. However, emperically based methods of PET can be very misleading when performing climate change studies in river basins (Yates and Strzepek, 1994). WatBal performed well on a monthly time step for the Mulberry, where precipitation was relatively uniform over the year (snowmelt processes were not important) and dramatic runoff changes were largely attributable to evapotranspiration.

The snowmelt dominated East basin showed less sensitivity to precipitation change, however it is felt that snowmelt dominated basins are difficult to model without detailed understanding of the climatological and hydrological elements of a basin. The monthly and daily snowmelt models proved quite sensitive to the temperature threshold values, where changes in temperature parameters produced significantly different results. WatBal run with a daily time step in the East basin produced similar calibration and validation statistics when compared to the monthly results. Climate change results did not differ greatly between the model run with a daily or monthly time step.

Appendix: Model Environment and Use

WatBal consists of only two dialog boxes (along with two help screens) within an Excel5.0 worksheet. Below is a description of how to load the model as an Excel5.0 add-in as well as descriptions of the dialog boxes. The water balance component of WatBal has the capability to run on any time step (seasonal, monthly, daily, hourly), however the PET model has been developed to work on a monthly time-step only. If other time scales are desired (other than monthly), then a PET model should be developed within a Excel5.0 worksheet. If run in daily mode, it is recommended to not use more than 5 years of data at a time (approximately 1850 rows in an Excel worksheet). Five years of daily data should be adequate for calibration, so if there are more than five years of data available, this series should be broken into five year increments. There should be no limitation on the number of years when performing analysis on a monthly time scale or longer (more than 100 years).

Loading the Model within an Excel 5.0 worksheet

WatBal was written in Excel5.0's Visual Basic macro language. Although simply a detailed macro it is possible to create an "executable" version of the program. A macro like WatBal is written within an excel5.0 worksheet as a macro sub-component (module), so the "source code" (an Excel5.0 macro) is a file with a *.xls* extension (for example, wb_svga.xls). To allow for model portability and to increase speed, it is possible to "compile" an Excel5.0 macro into machine-only readable code referred to as an "add-in". This produces a file with the extension .xla (for example, wb_svga.xla). In summary, a macro is written and then saved as an Excel5.0 worksheet (.xls) which can subsequently be compiled as a add-in (.xla).

This procedure was used to create a compiled version of WatBal. Because it is compiled, it is now ready to be loaded as an add-in within a Excel worksheet. This is done by selecting the *Tools/Add-Ins* from the main tool bar of Excel. If WatBal has been previously loaded, it will appear in the *Add-Ins Available* list within the Add-Ins dialog box (Figure 11). If the check box is selected then the add-in is loaded and *Runoff* should appear in the main tool bar menu of Excel. If the check box is not selected, then the user simply selects this box and the add-in will load into memory. If the "Water balance model" does not appear within the "Add-Ins Available:" scroll edit box or an error message appears that says it can not find that add-in, then select the Browse button within the Add-Ins dialog box and search for one of the compiled WatBal add-ins. Because different video drivers interpret different screen sizes it is necessary to select the appropriate compiled WatBal model to fit a specific screen. The version that works well with Super VGA is wb_svga.xla

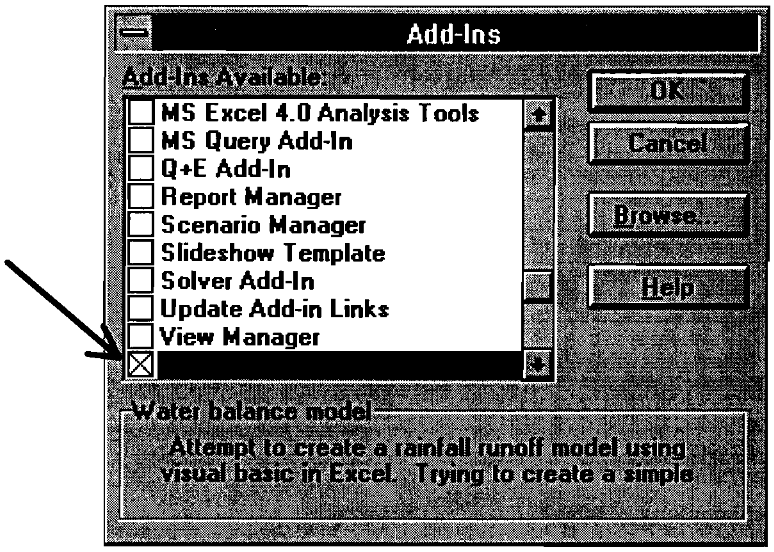

Figure 11. Add in selection box from Tools/Add-Ins on the Menu Bar of Excel 5.0

WatBal Dialog Box

Once the WatBal dialog is loaded into memory it can be selected from *runoff* on the toolbar. The **WatBal - Water Balance Model** dialog will appear (figure 12). This module contains both the water balance component as well as the Priestly-Taylor potential evapotranspiration model (the **PET** button on the bottom of the initial dialog will open the PET portion of the dialog).

Water Balance Component

Title - Title string for identification of model run

Precip - Effective precipitation, entered as a range of cells from an Excel worksheet. Effective precipitation might include altering the precipitation record for seasonal effects such as the Leaf Area Index (LAI) or altering the record for precipitation changes due to elevation or gauge error. Within the PET sub-module is a check box which implements the temperature index snowmelt model to derive a "new" effective precipitation based on snowmelt.

PET - Potential Evapotranspiration, entered as a range of cells from an Excel worksheet. PET can be calculated using an Excel worksheet allowing alternative methods than the Priestly-Taylor which is a component of WatBal. If the PET range is selected then the relative humidity or sunshine hours should not be selected within the PET subcomponent (Figure 12).

Runoff - Runoff is entered as a range of cells from an Excel worksheet. This range is necessary during calibration, when the number of iterations is 1 or more. After finding the best set of model parameters it might be necessary to validate the model using a different portion of the historic record. The validation phase is performed by selecting the appropriate range and setting the number of iterations (iter) equal to zero.

Output Cell ( )totals? - If immediate output of the observed and computed discharge are wanted then select the appropriate cell using this range selector. The ( )**totals?** check box will display summed values of the observed and computed discharge.

ssrc - In the sub-surface runoff equation (7), $R_{ss} = \alpha z^{\gamma}$, the ssrc coefficient is the power term, g, of this equation. This value is not part of the automated calibration routine and is normally set at a value of 2.0 (sub-surface runoff occurs as the square of relative storage). For some basins this relationship might not hold and the user can manually change this value, however it must be done by trial and error since its value remains unchanged during the calibration routine.

Zi - Initial relative storage at the beginning of the calibration, validation, or simulation. Must be predefined by the user and is not part of the calibration phase.

eps - Epsilon, e, is the power term on the surface runoff expression (6), whose value changes during the calibration phase in order to find the best value.

$$R_s(z,P,t) = \begin{cases} z^{\varepsilon}(P_{eff} - R_b) & \text{for } P_{eff} > R_b \\ 0 & \text{for } P_{eff} \le R_b \end{cases}$$

alpha - Alpha, a, is the coefficient in front of the sub-surface runoff expression (7), $R_{ss} = \alpha z^{\gamma}$, whose value changes during the calibration phase in order to find the best value.

Smax - S_{max} is the maximum catchment holding capacity whose value changes during the calibration phase in order to find the best value.

drc - Direct runoff coefficient, b, is used in the expression $R_d = \beta P_{eff}$ (1). Its value is not part of the calibration phase and must be predefined by the user.

bs flw - Base flow is predefined by the user. A good estimate of baseflow is the 95 percentile low flow (use the percentile function in Excel over the observed discharge series).

T.S. - Time step used in the model. Properly specifying the time step is important. For example, if data is specified in mm/day and the time horizon is in months, then the time step can be given as 30.4 days/month. If the time horizon is in days and the data is given in mm/day then the time step should be 1 day/day.

pc err - Predictor corrector error tolerance value used to numerically solve equation 2. A value of 0.005 is the default but can be made larger to decrease the amount of time spent running the model.

iter - Iteration number for calibration routine. The calibration routine is a simple unconstrained heuristic algorithm that finds the minimum residual error between the observed and predicted discharge. More than 3 iterations are probably not advantageous. After iterating, enter the new values for a, e, and S_{max} into the WatBal dialog and reiterate. It is highly probably that the model parameters found during calibration are sub-optimal, so it might be advantageous to select different initial starting values of a,e, and S_{max} to see if there is a different portion of hyperspace with a lower value. Validation and simulation runs can be made by setting the number of iterations to zero.

( ) Calib w/e & a - Selecting this check box will cause the model to only calibrate e and a, while S_{max} is held constant.

( ) use mean - The model can run in two different modes to compute the relative storage state variable. Use mean z is the default, where model components (surface discharge, sub-surface discharge, evapotranspiration, etc.) are computed from the mean value between the Z_i and Z_{i-1}. Unchecking this box forces the model to compute variables based on the storage state of that time period, Z_i. This check box allows the user to define if the input variables are the mean monthly values or beginning and end of month values.

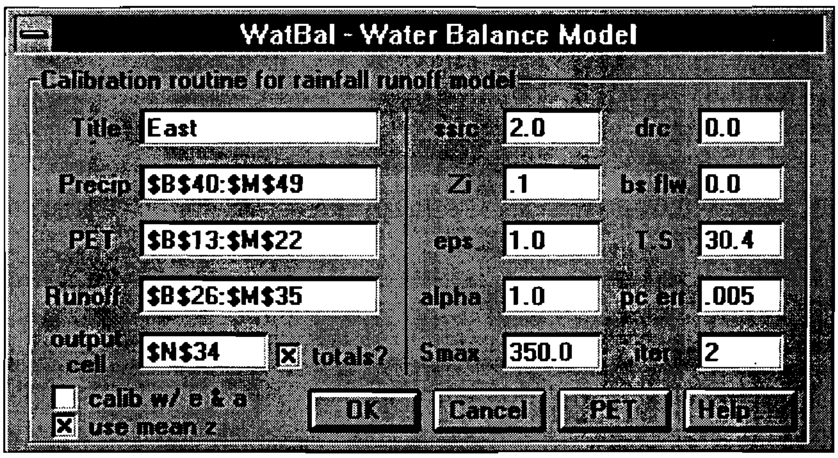

Figure 12. Initial WatBal dialog box for entering data. This example uses values of potential evapotranspiration taken from calculation from within a worksheet. The output cell has been selected and the totals along with other information will appear in the region of cell N34. The model will calibrate the three calibration parameters, a, e, and S_{max} using the mean z values. Two iterations will be performed with an predictor corrector tolerance of 0.005. Data is given in mm/day on a monthly time step so the T.S. value is 30.4 days/month.

Priestly-Taylor Potential Evapotranspiration Component

The Priestly-Taylor method is used to compute Potential Evapotranspiration in mm/day on a monthly time step. The lower portion of Figure 13 details the elements of the Priestly-Taylor method for PET.

Temp - Range of mean temperatures in °C for computing effective precipitation and potential evapotranspiration based on the Priestly-Taylor method.

Sun (h) - Mean monthly sunshine hours. If the data is given in, for instance, mm/day and a monthly time step is used then the sunshine hours are in hours/day.

Rn - Net radiation can be entered as a time series or the PET submodule can compute it based on equations 10-16. R_n is computed within WatBal in mm/day so when the model computes PET the time step will be 30.4 days/month since it is required to run on a monthly time step.

( ) cmp Rn - When the *compute net radiation* check box is checked then net radiation is computed internally.

albedo - Albedo can be entered as a set of 12 mean monthly values from the Excel5.0 worksheet or it can be computed internally based on the land cover class and the soil moisture state (Equation 20 and Table 1).

( ) cmp alb; gras(x), forst( ) - Check boxes for the albedo. If cmp alb (compute albedo) is checked, then the model will compute the albedo internally. If the albedo is computed internally, then the user must select the predominant land cover class (either forest or grass/pasture). The GC (ground cover index) is also used in computing the albedo.

RH - Mean monthly values of relative humidity entered from the worksheet.

Tl,Ts - The liquid temperature (Tl) and the solid temperature (Ts) thresholds for the snowmelt index model. The values are computed by trial and error with a default value of +3°C and -3°C respectively. Some basins are very sensitive to the threshold values so a trial and error procedure is sometimes necessary to find appropriate values since these are not part of the optimization routine during the calibration phase.

( ) Cmp Peff - This checkbox will implement the snowmelt model for computation of effective precipitation. This also computes a snow extent factor for computation of albedo in snow dominated basins.

mnth - This is the starting month of the monthly time series. Jan =1, Feb =2, March =3, ... Dec =12. This is necessary for properly estimating net radiation

P.T. - Priestly-Taylor coefficient. For humid basins (relative humidity greater than 60% in the month of peak evapotranspiration), this value has been estimated to be approximately 1.26±15 percent. For arid basins (relative humidity less than 60% in the month of peak evapotranspiration), this value has been estimated to be approximately 1.74±15 (Shuttelworth, 1993). Values between these two numbers may be used if the calibration improves.

hmd(x), arid( ) - In order to define a cloudiness factor to compute net radiation (11) a distinction between a predominately arid or humid basin type is required.

Lat - To compute extra-terrestrial solar radiation (12) the mean latitude of the basin is required. The functional relationships will work from latitudes of 55°N to 55° S, with positive northern latitudes and negative southern latitudes.

GC - Ground cover index (0.0 £ G.C £ 1.0) is a component of the endogenous albedo, not the direct runoff. A value of 0.0 indicates that the surface is completely covered by the specified land cover type (grass/pasture or forest), while a value of 1.0 indicates that the surface is completely bare soil.

Dismiss - This button simply dismisses the PET component of the WatBal model.

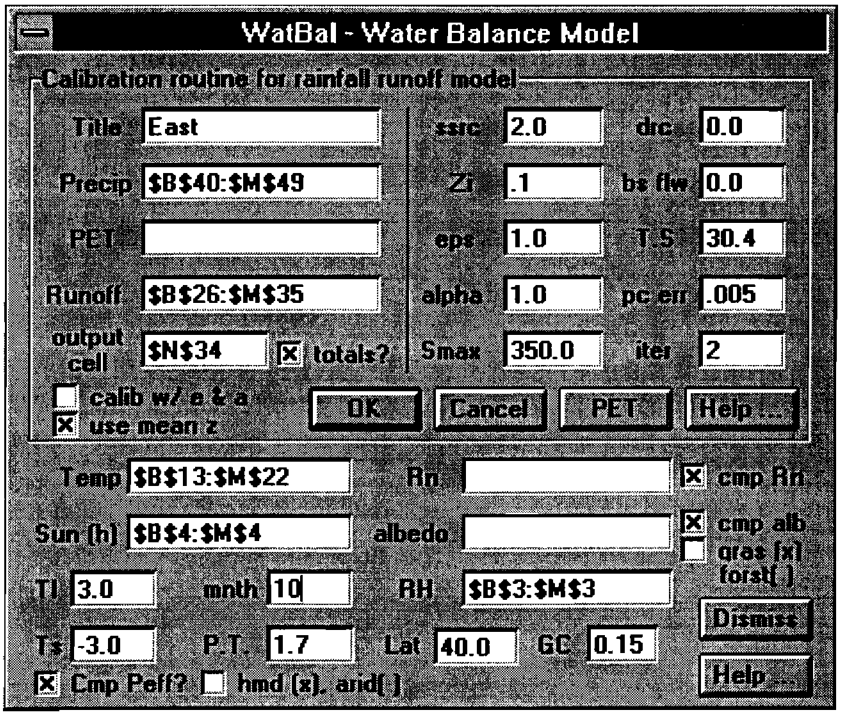

Figure 13. WatBal dialog box with Priestly-Taylor PET sub-component. Net radiation and albedo are computed internally (no range appears in their cell reference box and the Cmp boxes are checked). Effective precipitation will be computed with +3°C and -3°C thresholds. The starting month is October, with a value of 10. The basin is generalized as arid with a Priestly-Taylor coefficient of 1.7.

View Output Dialog

This dialog box is the second option on the main tool bar menu. This dialog can only be run once model results become available. The user is asked which variables are to be displayed and the location on the spreadsheet where the output will begin to be printed. Below is a brief description of the elements of this dialog.

Cell - Selection of a single cell where output results will be placed.

Horiz - This selection outputs the results across the worksheet horizontally (only works when model is run on a monthly time step).

total - Total of all month for mass variables such as precipitation and runoff and average values for other variables such as temperature, albedo, relative storage, etc.

annual - Sums the monthly values to find the total annual values (only works when model is run on a monthly time step.

Variable selectors - Check box selection of those variables that are wanted in the output that goes to the worksheet.

Chart results - When the results are plotted vertically on the excel spreadsheet, then this selection box will immediately chart the results.

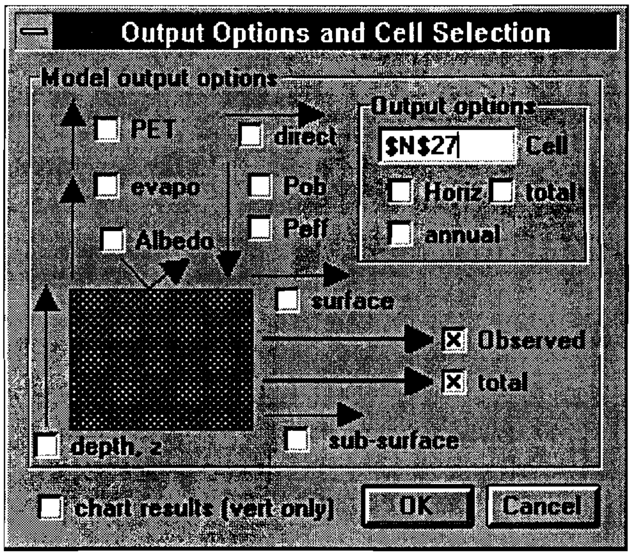

Figure 14. Output selection dialog box. Output will begin in cell N27 on the currently selected worksheet and only the observed and total discharge will be displayed in a vertical fashion.

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