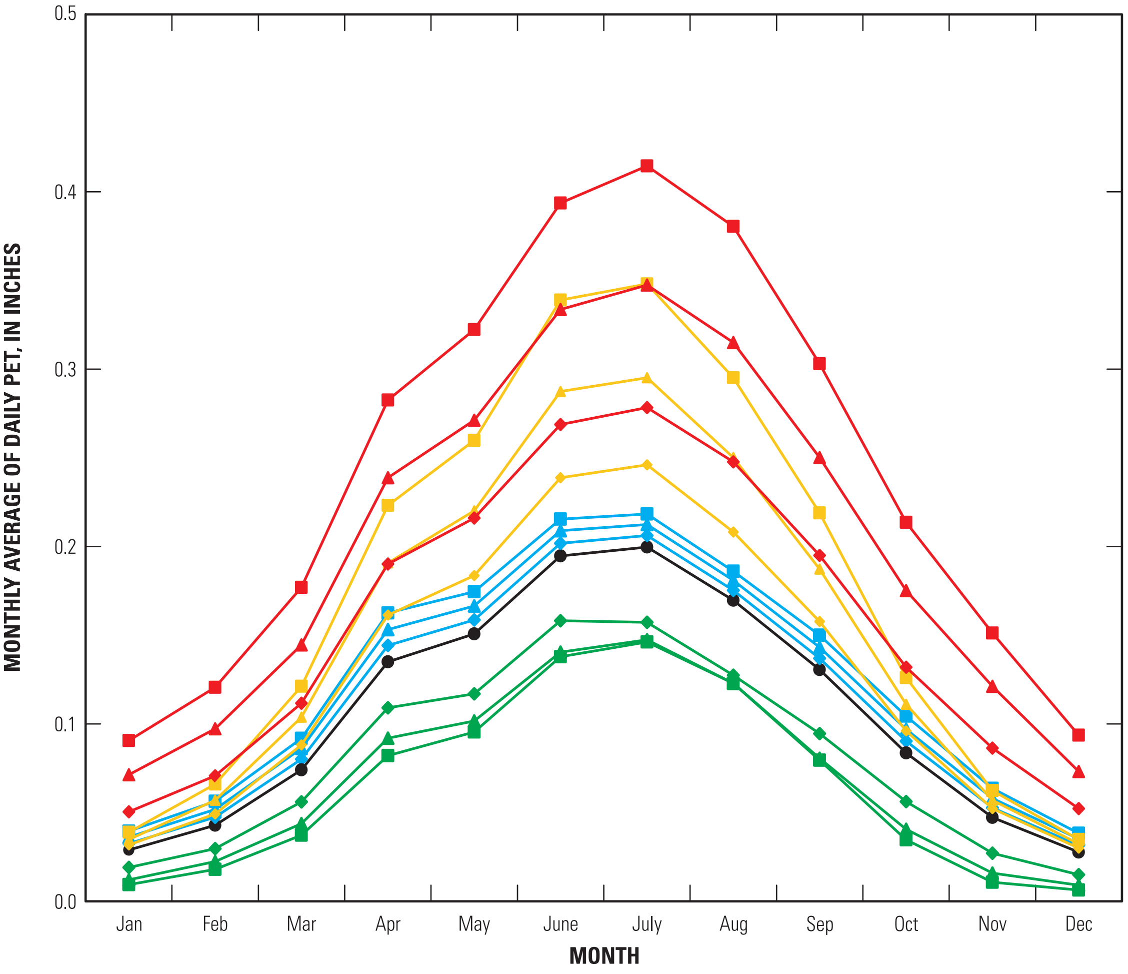
In cooperation with DuPage County Stormwater Management Division

Sensitivity of Potential Evapotranspiration and Simulated Flow to Varying Meteorological Inputs, Salt Creek Watershed, DuPage County, Illinois



Open-File Report 2005-1430

U.S. Department of the Interior
U.S. Geological Survey

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By David E. Whitbeck

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2005

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CONVERSION FACTORS AND SYMBOLS

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per day (in/d)	0 .6096	meter per day (m/d)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
mile per day (mi/d)	38.616	kilometer per day (km/d)
	Pressure	
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
	Energy	
Langleys per day (Lg/d)	279.12	Watts per square meter (W/m^2)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)

List of Symbols

Variables:

A coefficient representing numerator of PET computation [in Hg·in/°F/d]

A_1 expression for PET dependence on net radiation [in Hg·in/°F/d]

A_2 expression for PET dependence on pan evaporation [in Hg·in/°F/d]

A_h energy advected to water body [mm/d]

B coefficient representing denominator of PET computation [in Hg/°F]

C coefficient representing vapor-pressure deficit [dimensionless]

D average vapor pressure deficit (e_s-e_o) [in Hg]

E potential evapotranspiration [in/d]

E_a pan evaporation [in/d]

e_a	saturation vapor pressure at dewpoint T_{dp} [in Hg]
e_o	saturation vapor pressure at temperature T_o [in Hg]
e_s	saturation vapor pressure at temperature T [in Hg]
Q_n	net radiation exchange [mm/d]
R	daily total solar radiation [Lg/d]
T	temperature [°F]
T_a	air temperature [°F]
T_{dp}	dewpoint temperature [°F]
T_o	reference temperature [°F]
U_p	daily total wind movement [mi]
U_2	wind speed measured at 2 meters elevation [m/s]
γ	psychrometric consant [in Hg/°F]
Δ	slope of saturation vapor-pressure curve [in Hg/°F]
λ	latent heat of vaporization
PET	potential evapotranspiration [in/d]

Dimensional Units:

E	energy [$m/L^2/t^2$]
L	length
M	mass
P	pressure [$m/L/t^2$]
t	time
T	temperature

Sensitivity of Potential Evapotranspiration and Simulated Flow to Varying Meteorological Inputs, Salt Creek Watershed, DuPage County, Illinois

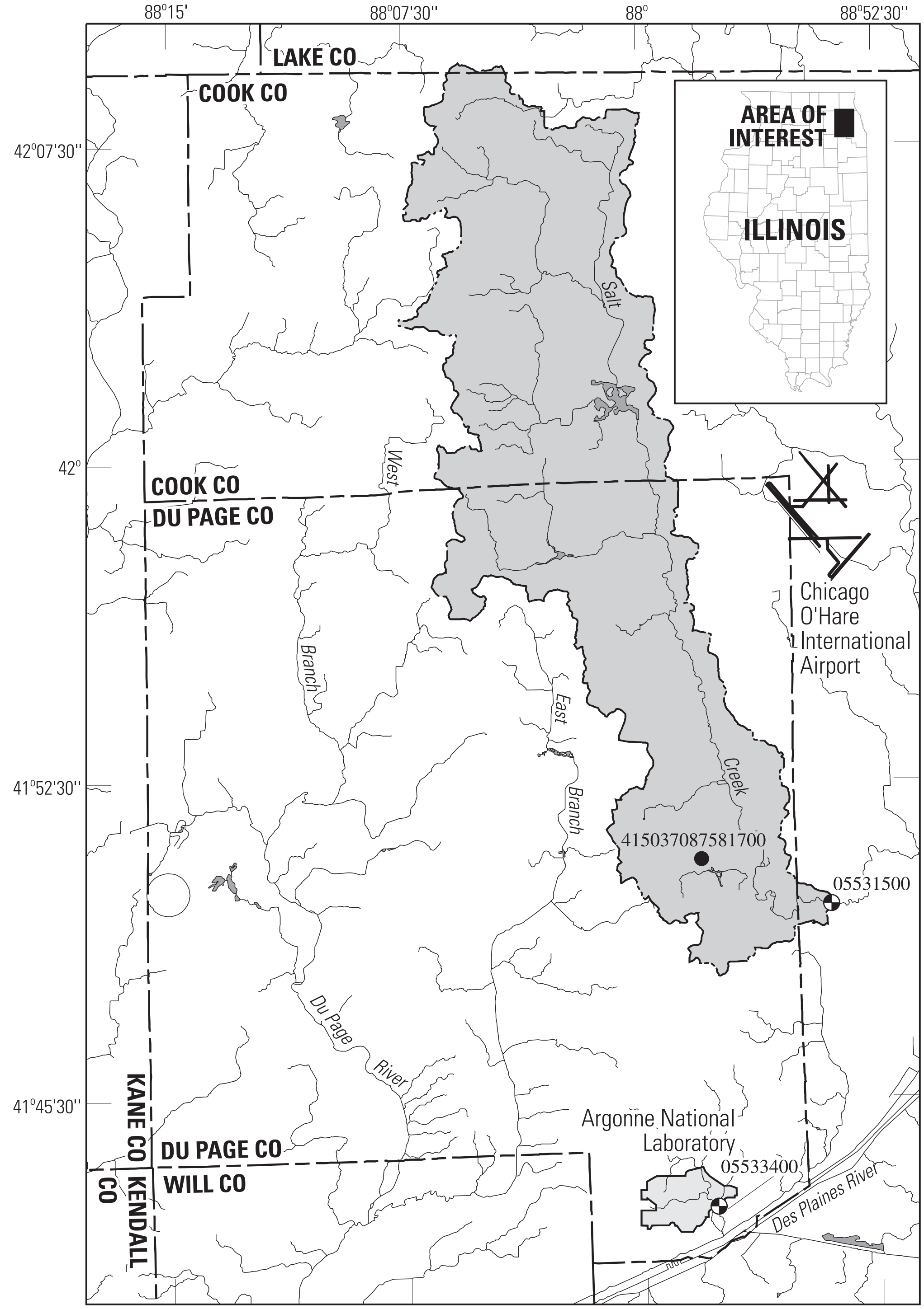
By David E. Whitbeck

Abstract

The Lamoreux Potential Evapotranspiration (LXPET) Program computes potential evapotranspiration (PET) using inputs from four different meteorological sources: temperature, dewpoint, wind speed, and solar radiation. PET and the same four meteorological inputs are used with precipitation data in the Hydrological Simulation Program–Fortran (HSPF) to simulate streamflow in the Salt Creek watershed, DuPage County, Illinois. Streamflows from HSPF are routed with the Full Equations (FEQ) model to determine water-surface elevations. Consequently, variations in meteorological inputs have potential to propagate through many calculations. Sensitivity of PET to variation was simulated by increasing the meteorological input values by 20, 40, and 60 percent and evaluating the change in the calculated PET. Increases in temperatures produced the greatest percent changes, followed by increases in solar radiation, dewpoint, and then wind speed. Additional sensitivity of PET was considered for shifts in input temperatures and dewpoints by absolute differences of ±10, ±20, and ±30 degrees Fahrenheit (°F). Again, changes in input temperatures produced the greatest differences in PET. Sensitivity of streamflow simulated by HSPF was evaluated for 20-percent increases in meteorological inputs. These simulations showed that increases in temperature produced the greatest change in flow. Finally, peak water-surface elevations for nine storm events were compared among unmodified meteorological inputs and inputs with values predicted 6, 24, and 48 hours preceding the simulated peak. Results of this study can be applied to determine how errors specific to a hydrologic system will affect computations of system streamflow and water-surface elevations.

INTRODUCTION

Meteorological data collected on a real-time basis from Argonne National Laboratory in Argonne, IL (fig. 1), have been used by the U.S. Geological Survey (USGS), in cooperation with the DuPage County Stormwater Management Division, to develop a database for historic and real-time continuous simulation hydrologic modeling. The database, which includes the period from 1948 to 2004, is used in the computation of potential evapotranspiration (PET) and for simulation of streamflow with the Hydrological Simulation Program–Fortran (HSPF) for the Salt Creek watershed, DuPage County, IL (fig. 1). In a previous study, Murphy (2005) reported on the development of the program Lamoreux Potential Evapotranspiration (LXPET), based on the methods of Lamoreux (1962) and Kohler and others (1955) to calculate potential evapotranspiration. Four meteorological time series are input to LXPET: temperature, dewpoint, wind speed, and solar radiation. Whereas the quality-assured (QA'd) data supplied by the Argonne National Laboratory (Cutshaw and others, 2004) are assumed to be accurate, all measurements inherently include a certain amount of error depending on instrumentation and other issues, such as location with respect to the watershed and the methods or data used to fill missing periods. The usage of data may also include errors. These errors have the potential to propagate through calculations of the PET and flow simulations and appreciably modify the output results. In addition, on a real-time simulation basis, similar errors in



Base from U.S. Geological Survey 1:100,000-scale digital data.
Albers Equal-Area Conic projection, standard parallels 33° and 45°, central meridian -89°.

EXPLANATION

SALT CREEK WATERSHED BOUNDARY

05531500 U.S. GEOLOGICAL SURVEY STREAMFLOW-GAGING STATION SALT CREEK AT WESTERN SPRINGS AND NUMBER

05533400 U.S. GEOLOGICAL SURVEY STREAMFLOW-GAGING STATION SAWMILL CREEK NEAR LEMONT AND NUMBER

415037087581700 U.S. GEOLOGICAL SURVEY PRECIPITATION STATION AT THE OAK BROOK PRODUCTION WELL AND NUMBER

Figure 1. Salt Creek watershed, DuPage County, Illinois.

forecasted time series may produce differences in water-surface elevation that may affect peak flows and elevations.

Previous to 1996, meteorological data used for long-term streamflow simulation were obtained from a meteorological station at Chicago O'Hare International Airport. In November 1996, the replacement of instrumentation at O'Hare Airport resulted in an evaluation of whether Argonne National Laboratory could provide an alternative meteorological data series and a comparison of Argonne and O'Hare data (T.H. Price, Northeastern Illinois Planning Commission, written commun., 1998). In his study of meteorological data from October 1990 through September 1995, Price found that temperature and dewpoint between the two stations had very high correlations (with a slope of 0.99 for lines relating the two data series), but the correlation between solar-radiation data was not as high and wind speed averaged 28 percent lower at Argonne than O'Hare. Subsequent computations of PET resulted in a 9 percent lower estimation of PET at Argonne than O'Hare and flow simulations resulted in a 14-percent increase in average annual runoff (Price, 1998). In 2006, errors or deviations in meteorological data could still have appreciable effects on forecasting models used in DuPage County to simulate flow and water-surface elevations.

Purpose and Scope

This report presents the findings of a sensitivity analysis performed on calculations of potential evapotranspiration and the corresponding effects on simulated flow and forecasted data in the Salt Creek watershed, DuPage County, Illinois. Data used for hydrologic analysis have potential to include error that may originate from many sources, including instrumentation error, bias errors related to dataset location, missing data, and forecast errors. In this study, the effect of data variation is explored to determine how varying meteorological inputs affects PET, streamflow, and water-surface elevations over time. Meteorological data from Argonne National Laboratory were acquired for the 4-year time span from January 1, 2000, through December 31, 2003. These data are available in a USGS Water-Data Report by Cutshaw and others (2004). New datasets were created by calculating either percent increases or absolute shifts from the original meteorological data. Using these new modified datasets, potential evapotranspiration was calculated using LXPET and flow was simulated using the HSPF model in the program Generation Analysis of Model Simulation Scenarios (GenScn). The absolute errors in peak-flow simulation and water-surface elevations introduced by time series with data predicted by repeating data from the previous day at 6, 24, and 48 hours before the peak were also examined by routing the HSPF runoff with the Full Equations (FEQ) model. The results can be useful for long-term calibration of flow in the Salt Creek watershed and for understanding potential sources of error in real-time simulation.

Background

The evaporation from a land surface is often referred to as evapotranspiration (ET) to emphasize that it includes that portion of evaporation that is mediated by the vascular systems of plants (transpiration). PET refers to the rate at which evapotranspiration would occur in an ideal environment, one with uniform vegetation cover, unlimited soil-water supply, and negligible advection or heat-storage effects (Dingman, 1994). A common method of estimating PET is to compute the theoretical evaporation from a lake based on meteorological variables. The Penman equation (or Combination equation) computes evapotranspiration from meteorological inputs using a relation of the following form (Penman, 1948):

$$E = \frac{\Delta}{\Delta + \gamma}(Q_n + A_h) + \frac{\gamma}{\Delta + \gamma}\,\frac{6.43\,(1 + 0.536U_2)D}{\lambda}\ , \qquad (1)$$

where E is the rate of potential evapotranspiration [L/t]; Δ is the slope (or derivative) of the curve of saturation vapor pressure against temperature [P/T]; γ is termed the "psychrometric" constant [P/T]; Q_n is the net surface radiation flux [L/t] expressed as an equivalent water flux; A_h is the energy advected to the water body [L/t], also expressed as an equivalent water flux; U_2 is the wind speed [L/t]; $D = e_s - e_a$ is the vapor-pressure deficit [P], where e_s and e_a are the saturation vapor pressures of the air and dewpoint, respectively; and λ is the latent heat of vaporization of water [E/M].

Lamoreux (1962) simplified equation 1 by assuming energy advected to the water body (A_h) to be negligible and by grouping the vapor-pressure deficit and latent heat relation into a variable E_a, representing the pan evaporation:

$$E = \frac{Q_n \Delta + E_a \gamma}{\Delta + \gamma} \quad . \tag{2}$$

Lamoreux used data from the study by Kohler and others (1955) of Lake Hefner in Oklahoma to obtain a relation between lake and pan evaporation and to fit empirical relations to E_a and $Q_n\Delta$. In particular, Lamoreux expressed E_a as

$$E_a = (e_s - e_a)^{0.88}\,(0.37 + 0.0041 U_p) \quad , \tag{3}$$

where e_s and e_a are the same as before, expressed in inches of mercury (in Hg), and U_p is wind movement in miles per day. Making use of the Clausius-Clapeyron equation,

$$e_s = e_o \exp\left[\frac{\lambda}{RT_o}\right] \exp\left[\frac{-\lambda}{RT_a}\right] \quad , \tag{4}$$

where e_s is the saturated vapor pressure at the air temperature T_a , R is the universal gas constant, λ is the latent heat of vaporization, T_o is a reference temperature (T_d if dewpoint), and e_o is the saturated vapor pressure at the reference temperature, T_o (Stull, 2000). It follows that

$$e_a = e_o \exp\left[\frac{\lambda}{RT_o}\right] \exp\left[\frac{-\lambda}{RT_{dp}}\right] \quad . \tag{5}$$

Lamoreux expresses $e_s - e_a$ as

$$e_s - e_a = 6{,}413{,}300 * \left[\exp\left(\frac{-7{,}482.6}{T_a + 398.36}\right) - \exp\left(\frac{-7{,}482.6}{T_{dp} + 398.36}\right)\right] \quad , \tag{6}$$

where T_a is in °F. It follows that

$$\Delta = \frac{de_s}{dT_a} = \frac{7{,}482.6}{(T_a + 398.36)} * \exp(15.674) \exp\left(\frac{-7{,}482.6}{T_a + 398.36}\right) \quad . \tag{7}$$

The coefficients in the wind-movement term, $0.37 + 0.0041U_p$, come from Lamoreux's (1962) empirical fit of evaporation from the water to the thin laminar sublayer of air next to the water, given a vapor-pressure deficit and wind speed (Penman, 1948). Lamoreux expressed $Q_n\Delta$ as

$$Q_n\Delta = \exp[(T_a - 212)(0.1024 - 0.01066 \ln R)] - 0.0001 \quad , \tag{8}$$

where R is solar radiation in Langleys per day (Lg/d), and determined this relation by fitting an equation to the graphical results of data from Kohler and others (1955) study of Lake Hefner, Oklahoma. Equation 8 expresses the dependence of $Q_n\Delta$ on solar radiation and air temperature, but because these terms depend on surface properties, this relation only approximates estimation of PET over land surfaces. Combining the relations in equations 3, 7, and 8 with equation 2 gives the equations used by LXPET (Murphy, 2005). Using the variable names used in LXPET, PET is computed in LXPET following Lamoreux (1962) as

$$PET = B * A * 1{,}000 \quad , \tag{9}$$

where

$$B = [\gamma + \Delta]^{-1}\left[0.015 + ((T_a + 398.36)^{-2})) * (68.554 * 10^9) * \exp\left(\frac{-7{,}482.6}{(T_a + 398.36)}\right)\right]^{-1} \quad , \tag{10}$$

and

$$A = A_1 + A_2 \ , \tag{11}$$

where

$$A_1 = Q_n\Delta = \exp[-0.1024(212 - T_a)]R^{.01066(212-T_a)} - 0.0001 \tag{12}$$

$$A_2 = \gamma E_a = 0.0105 * C^{0.88} * (0.37 + 0.0041 * U_p) \ , \tag{13}$$

where

$$C = e_s - e_a = 6{,}413{,}300 * \left[\exp\left(\frac{-7{,}482.6}{(T_a + 398.36)}\right) - \exp\left(\frac{-7{,}482.6}{(T_{dp} + 398.36)}\right)\right] \ , \tag{14}$$

where T_a is the air temperature in degrees Fahrenheit (°F), R is the daily total solar radiation in Langleys per day (Lg/d), U_p is the total daily wind movement in miles (mi), and T_{dp} is the dewpoint temperature in °F. LXPET takes the meteorological inputs and combines them into a dataset of daily values. Hourly values are computed by disaggregating the dataset using a fixed distribution (Murphy, 2005).

HSPF was developed by the U.S. Environmental Protection Agency (USEPA) and USGS. Precipitation data and potential evapotranspiration are used in HSPF as the primary meteorological inputs, along with calibrated parameters representing land use, soils, and vegetation data, to simulate streamflow hydrographs in a continuous-time mode. PET is important in the simulation of flow in HSPF because, in most hydrologic regimes, the volume of water leaving the watershed from evapotranspiration exceeds the total volume of streamflow (Bicknell, 2004). Actual evapotranspiration is estimated as a function of PET and moisture present in storage that includes ground-water outflow or base flow, interception storage, and lower zone storage. HSPF can be downloaded from the USGS at *http://water.usgs.gov/software/hspf.html*.

Full Equations (FEQ) is a dynamic-wave model that can route the HSPF rainfall-runoff time series through channels and control structures (Franz and Melching, 1996). This model is used in real-time simulation to predict peak flows and elevations at many points along the Salt Creek in Illinois (Ishii and others, 1998). Water-surface elevations and peak flows are generated, from which comparisons can be drawn between the runoff generated by modified meteorological inputs and the unmodified base case. FEQ can be downloaded from the USGS at *http://water.usgs.gov/software/feq.html*.

Methodology

Meteorological data collected at the Argonne National Laboratory including temperature, dewpoint, wind speed, and solar radiation are available from 1948 to 2004 (Cutshaw, 2004). This study used data from a 4-year time span of these longer datasets: January 1, 2000, through December 31, 2003. The data had been previously filled and adjusted for statistical inconsistencies (T.M. Over and others, U.S. Geological Survey, written commun., 2005) and a spreadsheet program was used to convert units to insure that temperature and dewpoint inputs were in degrees Fahrenheit (°F), wind speed was in miles per hour (mph), and solar radiation was in Langleys per day (Lg/d). New datasets were created for each of the four meteorological inputs that increased the original data by 20, 40, and 60 percent. Increases rather than decreases were considered here for simplification and because evaluation of the underlying calculations in PET showed that equivalent results would be expected from decreases in meteorological variables, but shifted in the opposite direction. Next, for the temperature and dewpoint time series, additional files were created that shifted the original data by ±10, ±20, and ±30°F. Additional datasets of wind speed were created that summed the hourly values into daily values for use in LXPET, which requires daily totals of hourly wind speed. The datasets of hourly wind-speed totals (in miles per hour) were used in the input to HSPF. Precipitation is also a potential meteorological input, but because this study focuses on PET, precipitation was used only in generation of streamflow using HSPF and not as a varying input. The magnitudes of the errors considered in this study are not necessarily within an order of magnitude of what is commonly found in the field nor are the errors limited to a feasible range (such as dewpoint always less than temperature). Errors were instead varied to examine a more formal sensitivity of PET with the knowledge that errors associated with measurements, bias and location variation, can deviate by high percentages from reality and, depending on instrumentation bias or location errors, even appear to defy normal physical constraints. For example, dewpoint and temperature are measured using independent instruments and, therefore, temperature may be reported to be lower than dewpoint. In Price's 1998 review of meteorological data at O'Hare Airport, the average wind speed was 39 percent higher than at Argonne National Laboratory (T.H. Price, Northeastern Illinois Planning Commission, written commun., 1998).

The LXPET program requires a dataset of each of the four meteorological inputs to calculate PET. A series of new PET datasets were produced by modifying one input at a time. These new PET datasets, the original and modified meteorological datasets, and precipitation data from the station at Oak Brook production well, Oak Brook, Illinois (USGS precipitation station 4150370875811700; fig. 1), were loaded into a Watershed Data Management (wdm) file using the USGS program Input/Output for WDM (IOWDM). The program WDMUtil reads the time-series data and stores them as a dataset termed a watershed data management file (.wdm) for access and analysis. The file is also readable by the program GenScn, which can be used to calculate monthly averages over the entire 4-year span and produce plots for comparisons. IOWDM and GenScn are available for download at *http://water.usgs.gov/software/surface_water.html* .

GenScn also contains a module that will run HSPF when supplied with a User-Control Input file (UCI) and initial conditions. This model was calibrated for Salt Creek at Western Springs in 1994 (T.H. Price, Northeastern Illinois Planning Commission, written commun., 1994). Initial conditions for the beginning of the study (January 1, 2000) were produced by running the HSPF model starting in 1997 and ending on January 1, 2000. It is assumed with this method that any errors in initial condition storage factors present before 1997 have become negligible with time. Flow datasets were generated by entering the four original input data series (wind speed, temperature, dewpoint, and solar radiation), precipitation data, and calculated PET data and running this file with the HSPF utility. Each of the four datasets contained hourly data and the HSPF model was simulated using an hourly time step for runoff generation. With these initial conditions, flow was simulated at Salt Creek at Western Springs using the HSPF utility in GenScn for the original data and for meteorological data values that had been increased by 20 percent. Increases only were considered because equivalent results would be expected for increases or decreases.

In real-time simulation, meteorological time series must be predicted for time steps beyond the current time. The magnitude of error in meteorological inputs of temperature, dewpoint, wind speed, solar radiation, and computed PET is normally expected to be small, but may be large during forecasts into the future. Additional sources of real-time errors may occur due to the use of data that have not been quality assured

(QA'd) or quality controlled (QC'd). These errors would include biased and/or missing data. Using non-QA/QC'd data would likely produce results similar to a biased dataset, which would act similar to a dataset that is shifted by either percentage or absolute values. Processing of the raw data using regressions and filling techniques has produced the data used in this sensitivity study (T.M. Over and others, U.S. Geological Survey, written commun., 2005).

To test the effect of meteorological errors due to missing data on simulated peak flows and water-surface elevations, meteorological data from nine storm events between 2000 and 2003 were predicted for hours preceding the simulated peak water-surface elevation. Predictions were performed by repeating data from the previous day beginning either 6, 24, or 48 hours before the simulated peak and repeating until after the peak. This repetition could represent a rudimentary forecast when better forecasts are not available. The data were input to GenScn and the resulting rainfall runoff was routed with FEQ. Results using repeated meteorological data were compared with unmodified published data to determine magnitude of errors.

SENSITIVITY OF POTENTIAL EVAPOTRANSPIRATION AND SIMULATED FLOW TO VARYING METEOROLOGICAL INPUTS

A series of analyses were performed to evaluate the sensitivity to inputs of potential evapotranspiration calculated from LXPET and streamflow simulated by HSPF. PET was calculated from temperature, dewpoint, wind speed, and solar-radiation data for cases in which a single meteorological input dataset was increased by 20, 40, and 60 percent. Additionally, PET was calculated for cases in which dewpoint or temperature inputs were modified by absolute shifts of ±10, ±20, and ±30°F. Finally, a sensitivity analysis was done simulating the streamflow in HSPF using the calculated PET, as well as the temperature, wind-speed, dewpoint, and solar-radiation meteorological data to simulate streamflow changes resulting from individual datasets increased by 20 percent. Following is a comparison of the calculated PET and streamflow to the original data and a discussion of the sensitivity of the outputs.

Sensitivity of Potential Evapotranspiration

The changes resulting from varying input factors on potential evapotranspiration were evaluated using both percent changes and absolute shifts of the input data. Percent changes increased the original meteorological data values by 20, 40, and 60 percent and new PET datasets were created with LXPET for modifications of all four inputs: temperature, dewpoint, wind speed, and solar radiation (fig. 2a). Theoretical considerations indicate that absolute shifts should also be considered for temperature and dewpoint inputs to eliminate the relative effects of a non-absolute temperature scale, but percent changes are included in this analysis to provide an indication relative to percent change in the other variables. As a result, additional PET inputs for temperature and dewpoint were computed using absolute shifts of ±10, ±20, and ±30°F.

Percent Changes in Inputs

Changing one input dataset by a specified amount (20, 40, or 60 percent) was shown to greatly affect the calculated PET (fig. 2b). Two patterns were observed in the PET comparisons. First, increases in temperature, solar-radiation, and wind-speed inputs increased the calculated PET, whereas an increase in dewpoint resulted in a decrease in PET. Physically, the three inputs causing increases do so for different reasons. Increasing the temperature reduces the vapor-pressure deficit for a given amount of atmospheric moisture. The magnitude of this effect is expressed in LXPET as coefficient C. Increasing the solar radiation increases the amount of surface energy that must be dissipated by evaporation or sensible heat flux. This effect is expressed in LXPET in the coefficient B. Increasing the wind speed increases the efficiency of water-vapor transport away from the surface. This effect is expressed in LXPET in the term A_2.

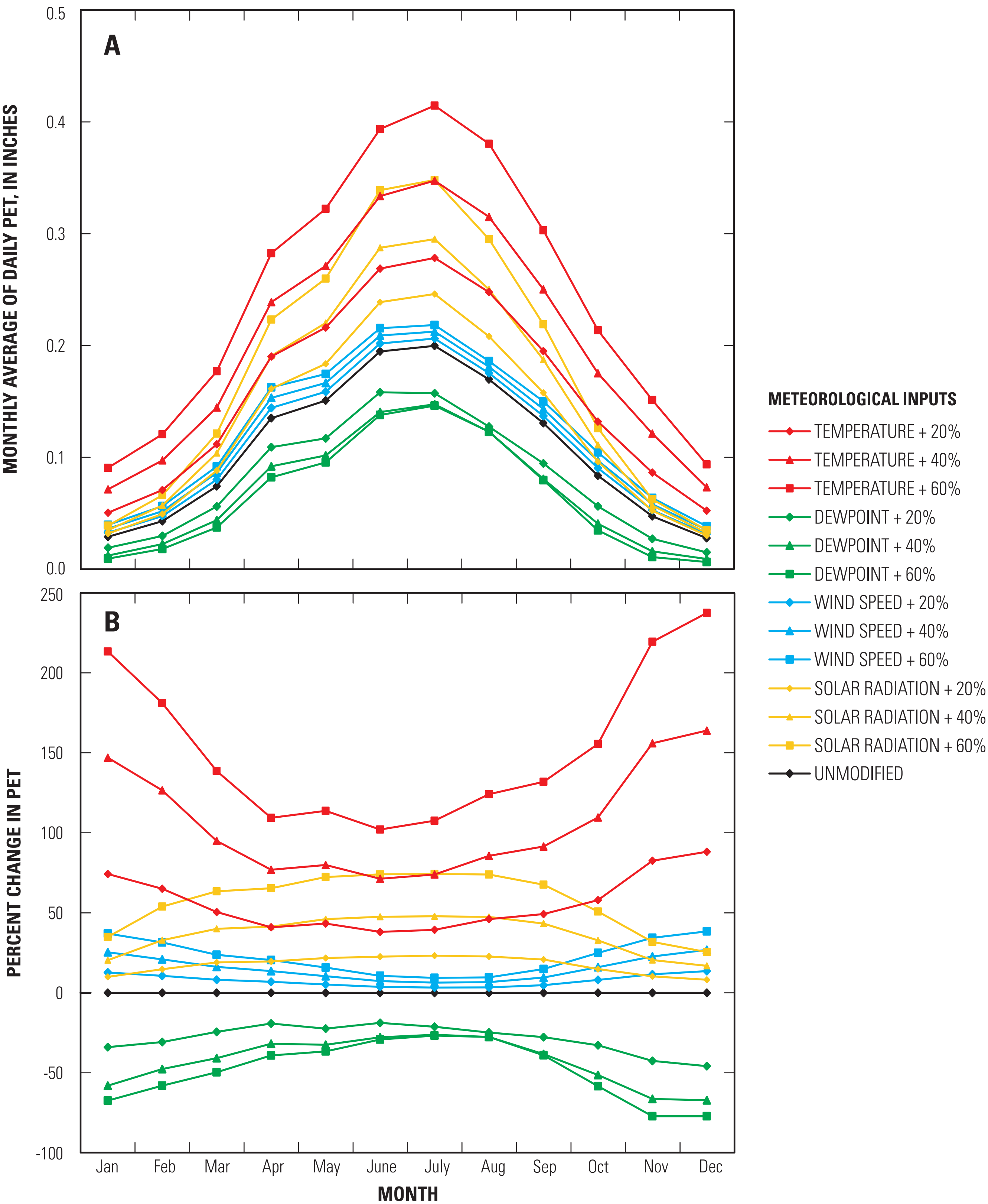


Figure 2. A) Monthly average of daily potential evapotranspiration (PET), and B) percent changes in monthly average values of PET, for Salt Creek watershed, DuPage County, Illinois, from 2000 to 2003, calculated by LXPET (Lamoreux Potential Evapotranspiration) for meteorological inputs of temperature, dewpoint, wind speed, and solar radiation increased by 20, 40, and 60 percent (%).

A second pattern observed was that temperature, dewpoint, and wind speed showed a larger percent change during the winter than during the summer, whereas solar radiation showed the opposite pattern. From theory, the Clausius-Clapeyron equation (eq. 4) states that the saturation vapor pressure has an exponential relation with temperature. This relation means that an increase in temperature or dewpoint for colder temperatures, as during the winter, should result in a greater percent change in computed PET than an increase observed during the summer. This exponential factor is also present in the calculations of LXPET, and evaluation of the derivative of equation 5 demonstrates greater rates of change in the winter than in the summer. Percent changes in wind speed are greater in the winter because the average observed wind speed is greater in those months and, thus, percent increases of these higher values result in greater changes than during the summer. Also, wind enters the computations in LXPET as part of the coefficient E_a. Equation 2 can be broken into two terms with a common denominator as

$$E = \left(\frac{\Delta}{\Delta + \gamma}\right) Q_n + \left(\frac{\gamma}{\Delta + \gamma}\right) E_a \quad . \tag{15}$$

It follows that the coefficients of these two terms add up to 1, and because Δ is a function of temperature, there will be a seasonal shift in the importance of the term with E_a. Because γ is a constant, as the temperature gets colder, the term with E_a will increase and, hence, the sensitivity of PET to wind speed will increase.

Solar radiation, opposite to temperature, dewpoint, and wind speed had lesser increases during the winter than in the summer. An increase in solar radiation (R) increases the coefficient A_1 (eq. 12) and results in a greater calculated PET. During the colder months, there is a two-fold effect that diminishes the sensitivity of PET to solar radiation. First, the smaller range in the winter probably results from effects of the season, such as a greater angle of incidence of the sun, fewer hours of light each day, and increased cloudiness during the winter. Second, as solar radiation is involved in $Q_n\Delta$, the first term in equation 15, cold temperature effects will result in diminished importance of solar radiation.

PET calculated by increasing the temperature inputs produced the greatest percent changes. An increase of 60 percent modified the output by greater than 200 percent during parts of the year. Variation in solar-radiation and wind-speed inputs also produced increases in the PET, but variation in dewpoint inputs resulted in decreases in PET as low as -67 percent. These patterns are in agreement with analysis of the equations developed by Kohler (1995) and scientific principles behind PET.

Absolute Shifts

PET was calculated for varying temperature inputs by absolute shifts of ±10, ±20, and ±30°F (fig. 3a). Temperature had a great effect on the output PET, producing shifts in PET near linear with proportion to the shift in temperature. At its maximum in July, an increase in temperature by 30°F produced an increase of 0.15 inch in PET, a 75-percent increase. Decreases in temperature had diminishing linearity in shift and peak values, probably for two reasons. First, during the winter months, the PET values are near zero and, because PET cannot be a negative value, shifts resulting from decreasing temperature do not produce large changes. Second, as ambient temperature approaches dewpoint temperature, the saturated vapor-pressure deficit approaches zero (eq. 6). If the vapor-pressure deficit (eq. 6) drops below 0.00001, LXPET replaces it with this value, essentially "saturating" the effects of air temperature when it reaches the dewpoint temperature.

The dewpoint inputs were varied in a similar fashion as the temperature and the resulting shifts were evaluated (fig. 4a). Decreasing the dewpoint resulted in an increase in the PET, whereas increasing the dewpoint resulted in a decrease. Similar but opposite to the temperature effects, the dewpoint inputs are limited in the LXPET program because it does not allow for a vapor-pressure deficit less than 0.00001. As a result, if the dewpoint has been increased to the point where it has reached or exceeded air temperature, the effects have essentially "saturated" and, no matter the increase in dewpoint, the vapor-pressure deficit remains at 0.00001.

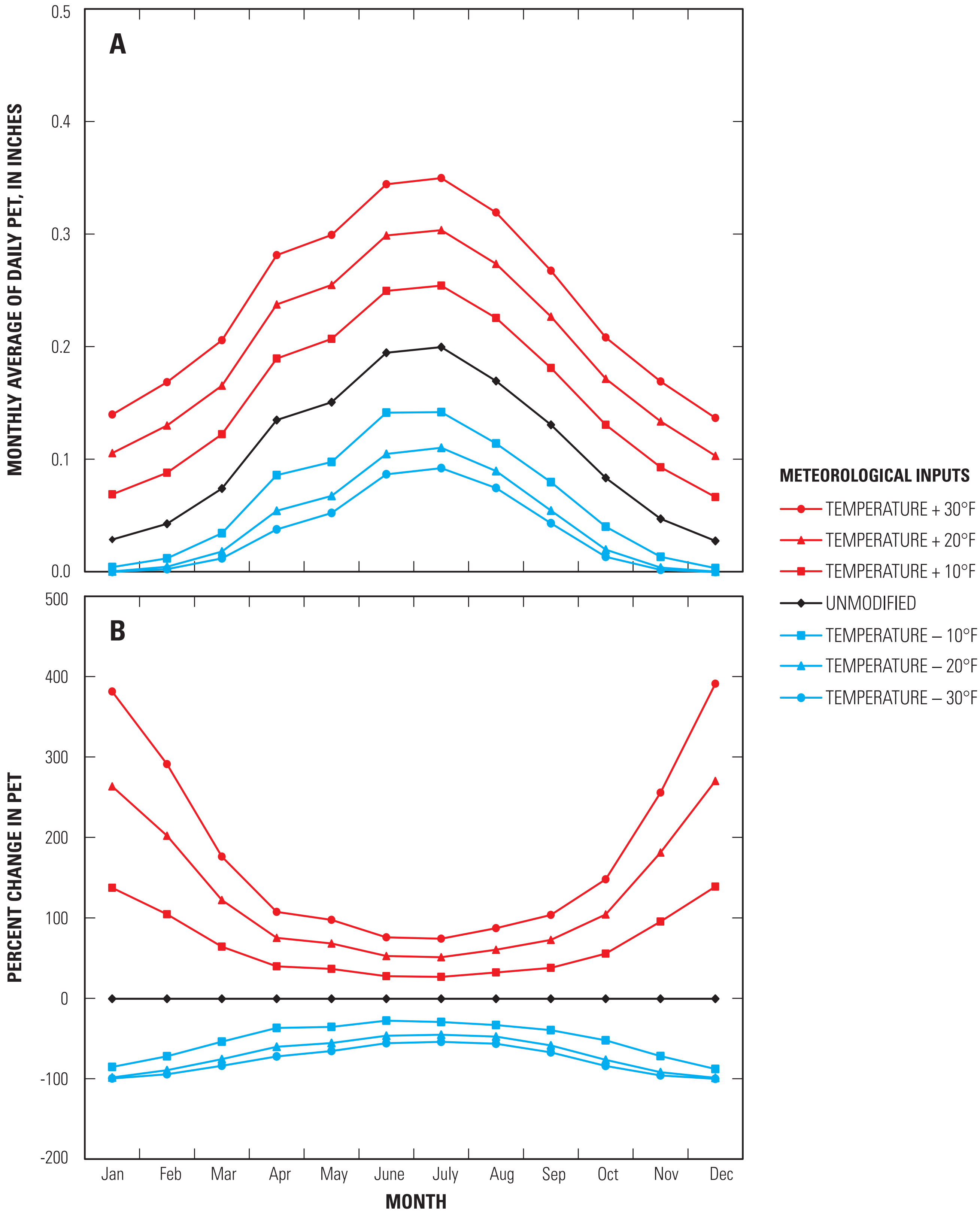


Figure 3. A) Monthly average of daily computed potential evapotranspiration (PET), and B) percent changes in PET for Salt Creek watershed, DuPage County, Illinois, from 2000 to 2003 as calculated by LXPET (Lamoreux Potential Evapotranspiration) for varying temperature inputs at intervals of ±10, ±20, and ±30 degrees Fahrenheit (°F).

To determine which meteorological input (temperature or dewpoint) causes greater shifts, comparisons of the PET for the summer months are most accurate, when minimal errors from “saturated” values result (fig. 5). At these times, temperature had a greater effect on the computed PET than dewpoint. At its maximal increases in July, an increase in temperature of 30°F produced an increase of 0.15 inch PET (fig. 3a), whereas a similar shift in dewpoint only decreased PET by 0.066 inch (fig. 4a). For reasons discussed previously, the linearity of response to absolute shifts in PET produced higher percent changes in winter than in summer (figs. 3b, 4b) It is apparent that temperature produced the greater shift, as the ± 30°F shifts in dewpoint were within the bounds of the 30°F shifts in temperature for both the increasing and decreasing case.

Flow Sensitivity

An analysis of the sensitivity of flow to variation in PET and the meteorological input values was performed for additional comparison that demonstrates the effect of variation in PET on simulated flow. Two studies were considered, the first involving modified PET datasets and determining how the simulated flow in HSPF is affected. The second involved examining the differences produced from predicted data in relation to observed data on peak flows and water-surface elevations.

Simulated Flow

Precipitation data collected at the station at Oak Brook production well, Oak Brook, Illinois (fig. 6), was used to simulate the flow in the Salt Creek watershed for both an unmodified base case (fig. 7) and a case where meteorological input values were increased by 20 percent (fig. 8a). This station was selected because the precipitation gage was heated throughout the period. Only increases in meteorological variables were considered on reasoning that analysis of the underlying equations determined that similar ranges in results are expected for increases or decreases in flow. Increases were selected as opposed to decreases mostly for simplification in presentation. The HSPF simulation used meteorological inputs of hourly values and output an hourly time series of flow. The hourly flows were averaged over days or months to characterize the sensitivity over time. Whereas daily average flows might be more erratic, average monthly flows were used to illustrate the differences in flow so that seasonal trends and long-term effects might be identified.

Increases in dewpoint were observed to increase the flow, whereas an increase in the other three inputs decreased the flow (fig. 8a). The direction of these shifts was expected because flow is a monotonically increasing function with the inverse of PET. Conceptually, this dependence means the greater the PET, the greater the actual evapotranspiration and the less water there will be available in the river for flow. Analysis of the differences between streamflow simulated with modified input variables (increased by 20 percent) and the unmodified case showed that there was not an increasing or decreasing trend of errors over time (fig. 8b). Seasonal patterns of higher flows during the spring and fall were observed and, as a result, monthly averages were computed to normalize the effects over an entire year (fig. 9). Data analysis determined that increases in temperature input values produced the greatest changes, decreasing the simulated flow by an average of 21 percent per month. Changing dewpoint increased the flow by an average of 17 percent, solar radiation decreased flow by 7.7 percent, and wind speed decreased flow by an average of only 2.7 percent. Because the resulting shifts in the input data are temporally consistent and not bounded in either the positive or negative direction, the effect for a 20-percent decrease in meteorological data values would produce results of similar magnitude though opposite in sign.

Comparison of Peak Flows and Water-Surface Elevations

In real-time simulation, meteorological time series must be predicted for time steps beyond the current time. To test the potential error resulting from predicted data, datasets from nine storm events between 2000 and 2003 were predicted by repeating meteorological data from the previous day beginning 6, 24, and

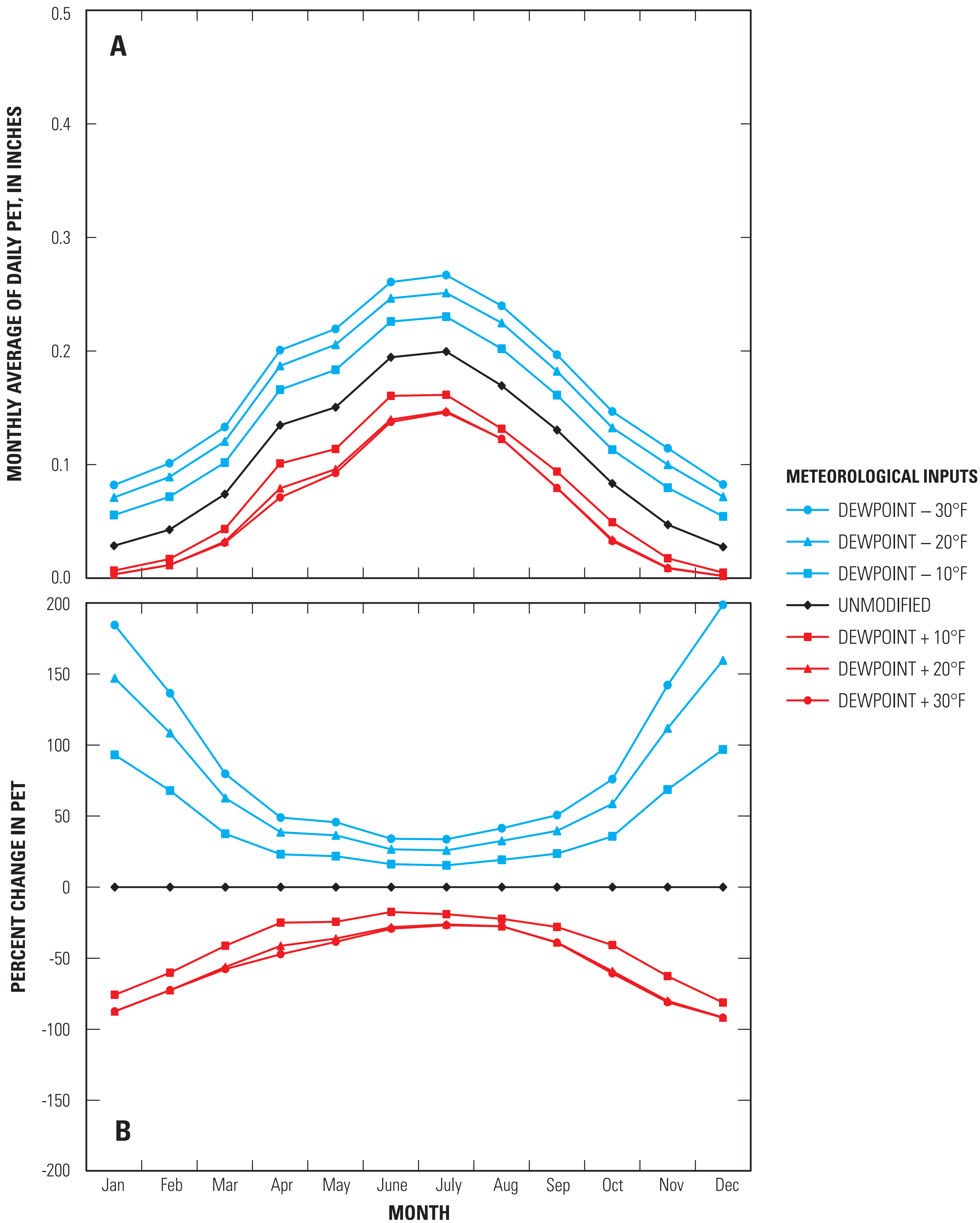


Figure 4. A) Monthly average of daily computed potential evapotranspiration (PET), and B) percent changes in PET, for Salt Creek watershed, DuPage County, Illinois, from 2000 to 2003 as calculated by LXPET (Lamoreux Potential Evapotranspiration) for varying dewpoint inputs at intervals of ±10, ±20, and ±30 degrees Fahrenheit (°F).

48 hours previous to the storm's simulated peak water-surface elevation and repeating the data until past the simulated peaks. The predicted meteorological data and the actual precipitation recorded at Oak Brook production well, Oak Brook, Illinois, were input to GenScn and the resulting rainfall runoff was routed with FEQ. The routed peak flow and water-surface elevations at one location on the upper Salt Creek and one on the lower Salt Creek were compared with a simulated base case of unmodified published data for the same storm events. The effect of repeating data from 6 hours ahead of the simulated peak was found to produce an average difference of 0.002 ft with a maximum of 0.005 ft on the lower Salt Creek and an average of 0.001 ft with a maximum of 0.004 ft on the upper Salt Creek. These differences in water-surface elevation corresponded to a 0.07 percent average and 0.13 percent maximum difference in peak flow in the lower Salt Creek and a 0.13 percent average and 0.68 percent maximum difference in the upper Salt Creek. For predicting 24 hours ahead, the average difference was 0.05 ft (a peak flow difference of 2.1 percent) with a maximum of 0.251 ft (10.4 percent peak flow difference) on the lower salt and an average of 0.01 ft (1.1 percent peak flow difference) with a maximum of 0.081 ft (7.5 percent peak flow difference) on the upper Salt Creek. Finally, for predictions starting 48 hours ahead, the average difference was 0.05 ft (1.9 percent peak flow difference) with a maximum of 0.178 ft (7.3 percent peak flow difference) on the lower salt and an average of 0.02 ft (2.1 percent peak flow difference) with a maximum of 0.061 ft (5.5 percent peak flow difference) on the upper Salt Creek. The maximum differences between water-surface elevation and peak flow occurred during an event that had an observed large decrease in temperature at the beginning

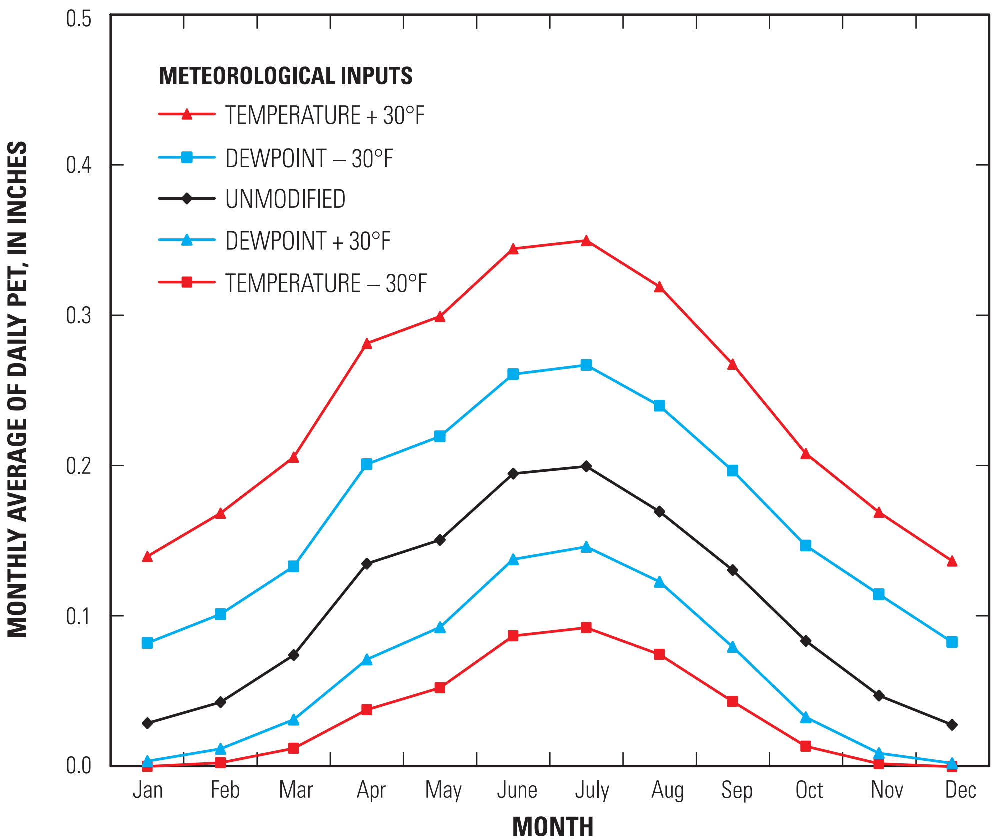


Figure 5. A comparison of monthly averages of daily computed potential evapotranspiration (PET) for Salt Creek watershed, DuPage County, Illinois, from 2000 to 2003 as calculated by LXPET (Lamoreux Potential Evapotranspiration) for varying temperature and dewpoint inputs at intervals of +30 and -30 °F.

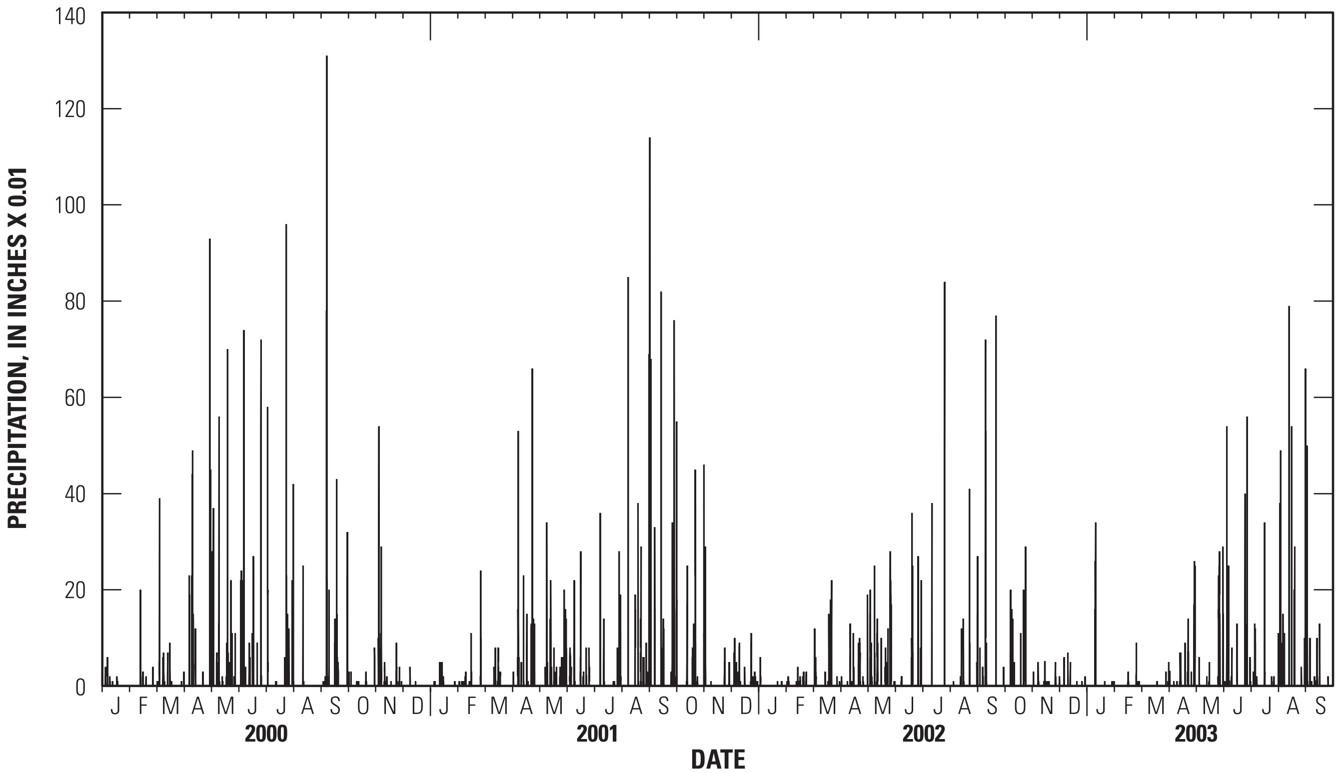


Figure 6. Hourly precipitation recorded at Oak Brook production well, Oak Brook, Illinois, from January 1, 2000, through September 30, 2003.

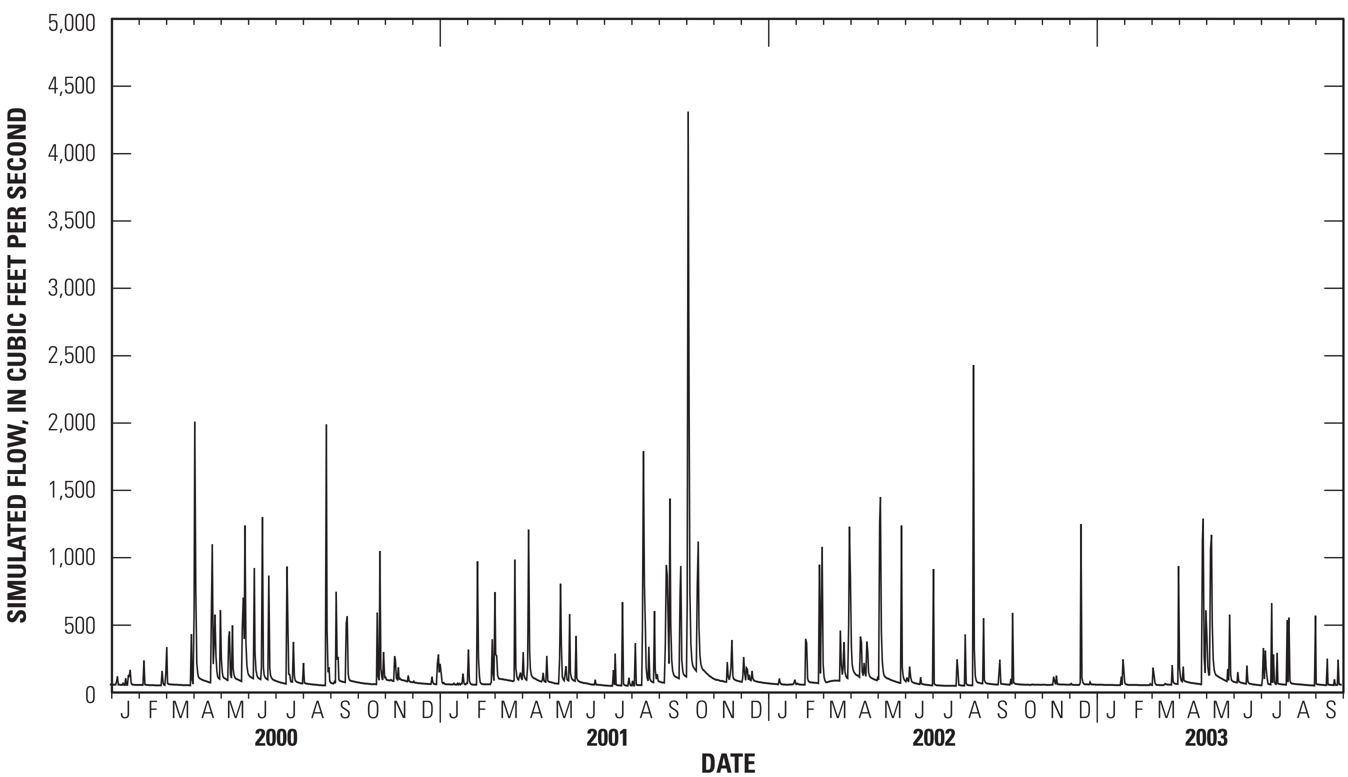


Figure 7. Daily mean streamflow simulated with the Hydrologic Simulation Program-Fortran (HSPF) for precipitation data from Oak Brook production well, Oak Brook, Illinois, and with unmodified meteorological data from Argonne National Laboratory from January 1, 2000, through September 30, 2003.

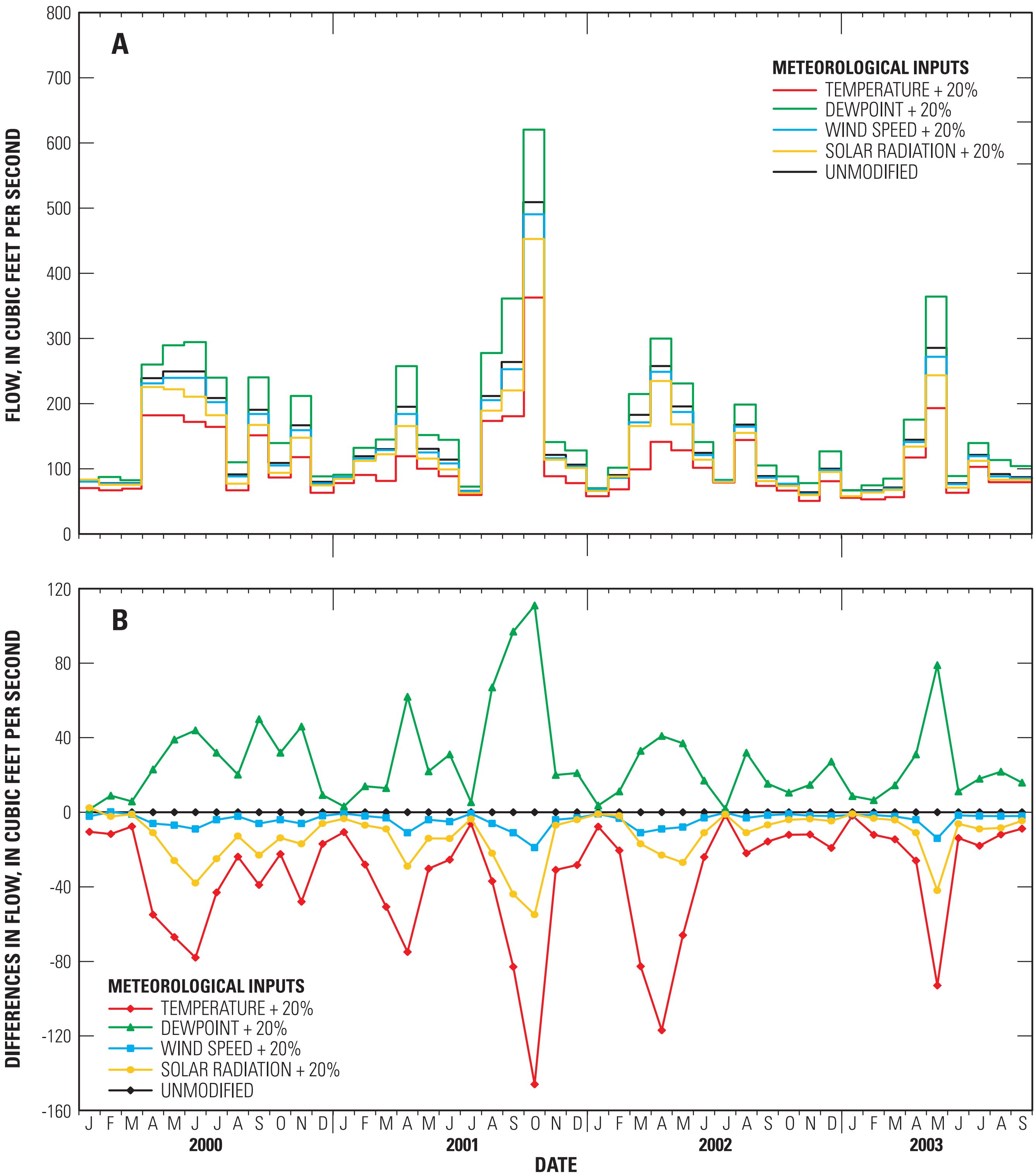


Figure 8. A) Monthly mean streamflow, and B) differences in streamflow from unmodified monthly mean streamflow, simulated with the Hydrologic Simulation Program-Fortran (HSPF) for precipitation data for Salt Creek at Western Springs, Illinois, and for meteorological inputs (temperature, dewpoint, wind speed, and solar radiation) that were either unmodified or increased by 20 percent (%) from January 1, 2000, through September 30, 2003.

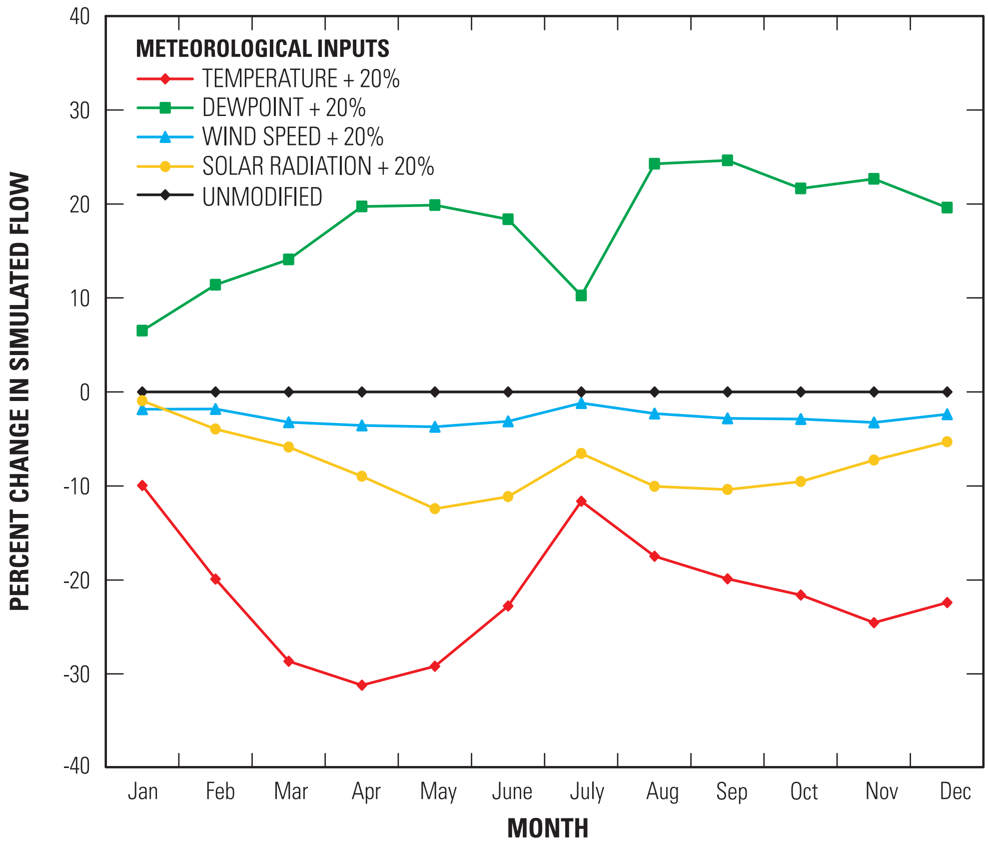


Figure 9. Percent changes in the monthly average simulated streamflow from January 1, 2000, through September 30, 2003, for Salt Creek at Western Springs, Illinois, produced by the Hydrologic Simulation Program-Fortran (HSPF) and resulting from 20-percent (%) increases in meteorological inputs of temperature, dewpoint, wind speed, and solar radiation.

of the storm that was not reflected in the repeated data and, therefore, resulted in overestimation of peak flow and water-surface elevation. The error could be much larger for events where freeze-thaw conditions occur because of the effect on rainfall runoff in addition to the effect on PET. The small flow and elevation differences observed for most large storm events are reasonable because the amount of rain and resulting volume of surface runoff will usually tend to overwhelm the effects of evapotranspiration during these conditions.

SUMMARY AND CONCLUSIONS

Meteorological data from Argonne National Laboratory in Argonne, Illinois, have been used by the USGS, in cooperation with DuPage County Stormwater Management Division, to develop a database for continuous simulation hydrologic modeling. This report presents the results of a sensitivity analysis of calculated potential evaporation and simulated flow resulting from varying meteorological inputs in the Salt Creek watershed, DuPage County, Illinois. Meteorological quality-assured data were acquired from the Argonne National Laboratory for temperature, dewpoint, wind speed, and solar radiation from January 1, 2000, through December 31, 2003. New datasets were created for each of the four meteorological input values that increased the original data by 20, 40, and 60 percent. For the temperature and dewpoint time-series inputs, additional files were created that shifted the original data by ±10, ±20, and ±30°F. A series of new PET datasets was produced using LXPET by modifying individual inputs one at a time and an analysis was performed to determine the sensitivity of PET to varying input factors. Additionally, flow datasets were generated using the HSPF utility in GenScn by modifying a UCI to use the four original input data series (wind speed, temperature, dewpoint, and solar radiation), precipitation data from Salt Creek, and calculated evapotranspiration data. With these initial conditions, sensitivity of simulated flow was evaluated for a 20-percent increase in input data values.

The changes resulting from varying input factors on potential evapotranspiration in the Salt Creek watershed were evaluated using both percent changes and absolute shifts of the input data. For sensitivity to percent changes in the meteorological input values, two patterns were observed. Wind speed, temperature, and solar radiation acted to increase the calculated PET, whereas an increase in dewpoint resulted in a decrease in PET. Additionally, wind speed, temperature, and dewpoint had higher percent changes during the winter than during the summer, whereas solar radiation had the opposite pattern. Finally, PET calculated by increasing the air temperature produced the greatest percent changes in PET, modifying the output by greater than 200 percent during parts of the year.

PET calculated by absolute shifts in the input data demonstrated that temperature again had a greater effect on the computed PET than dewpoint. At its maximum in July, an increase in temperature of 30°F produced an increase in PET of 0.15 inch, a 75-percent increase, whereas a similar shift in dewpoint only decreased PET by 0.066 inch, only a 33-percent decrease.

Analysis of the sensitivity to flow to varying meteorological inputs demonstrated the effect of variation on the simulated flow. Increases in dewpoint were observed to increase the flow over time, whereas an increase in the other three inputs decreased the flow over time. The direction of these shifts, although opposite of PET, was expected because the effects of meteorological inputs on flow is proportional to the inverse of PET. Changes in temperature inputs resulted in the greatest changes in flow, decreasing the simulated flow by an average of 21 percent per month.

Finally, absolute errors in simulated peak flows and water-surface elevations resulting from predictions by repeating meteorological data for 6, 24, and 48 hours before the simulated peak were investigated for nine storm events at two locations. The effect of using repeated data was found to produce an average difference of 0.03 ft with a maximum of 0.25 ft on the lower Salt Creek and an average of 0.01 ft with a maximum of 0.08 ft on the upper Salt Creek. These differences in water-surface elevation corresponded to a 1.4 percent average and 10.4 percent maximum difference in peak flow in the lower Salt Creek and a 1.1 percent average and 7.3 percent maximum difference in the upper Salt Creek.

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