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REGIONAL RUNOFF SIMULATION FOR SOUTHEAST MICHIGAN[1]

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ABSTRACT: The feasibility of simulating monthly runoff for southeast Michigan, which comprises four major river basins, was evaluated with the Streamflow Synthesis and Reservoir Regulation watershed model. The evaluation covered a 13-year period (1961-73), which encompassed a complete runoff cycle. Results indicate it is feasible to simulate monthly runoff volumes on a regional scale with a single equivalent watershed by using daily precipitation and temperature data. Simulation of regional flows appears particularly attractive for the Great Lakes basin, since the basin consists of many relatively small watersheds. This method also appears promising for development of monthly runoff forecasts by employing average monthly meteorological data distributed on a daily basis. Tests of six-month runoff forecasts show relatively small deterioration with time and offer considerable improvement over climatology.
(KEY TERMS: runoff simulation; regional drainage; soil moisture; Lake Michigan basin.)

INTRODUCTION

Conceptual watershed models have been directed primarily toward reproduction of event hydrographs and peak flows for flood forecasting and reservoir design. However, the principles of simulating continuous soil moisture from climatologic data should be applicable for determining the volume of runoff on a regional scale. Simulation and forecasts of regional runoff into the Great Lakes have a wide range of practical applications. Because there are long delays in obtaining observed streamflow records (1 to 2 years), simulated runoff could be employed in a variety of water budget studies on a more timely basis. This is particularly true for the Great Lakes basin, since it consists of a large area with multiple watersheds. Thus runoff could be simulated by applying a single equivalent basin for each of the lakes or major regions of their basin. Another important application for simulated runoff is in the hindcasting of flows for hydrologic studies requiring long periods of record preceding the last two or three decades. Observed streamflow data for that period are generally sparse. Development of successful runoff forecasting procedures would be of great value in improving water level forecasts and lake level regulation. For the volumetric simulation of regional runoff, practical considerations suggest selection of monthly periods as a basic unit of time.

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The present study consists of testing the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U. S. Army Corps of Engineers, North Pacific Division, 1972) for simulation of monthly runoff from large regions consisting of multiple watersheds; such regions are common within the Great Lakes basin. The area selected for the test is the southeastern Lake Michigan drainage basin. The feasibility of monthly runoff forecasts is also examined briefly for the possibility of a more comprehensive followup study. Since the SSARR model operates on an input of daily precipitation and temperature data, the daily values were used in the calibration of the model and simulation of the monthly runoff volumes. Because the daily distribution of the input data would not be available a month in advance, the average monthly data distributed on a daily basis were used for testing the feasibility of monthly runoff forecasts.

The period of record for this study consisted of 13 water years, from 1961 to 1973 (October 1960 through September 1973). This period includes both the low (1964) and the high (1973) lake levels. Because it includes a complete long-term runoff cycle, spanning both low and high flows, the period is sufficient to permit unbiased model calibration for the whole range of flows.

DESCRIPTION OF WATERSHED

The southeastern portion of the Lake Michigan drainage basin covers a total area of 41,320 km^2 (15,950 mi^2), consisting of the St. Joseph, Kalamazoo, Grand, and Muskegon Rivers watersheds (Figure 1). This equivalent watershed represents 35 percent of the Lake Michigan drainage basin (118,000 km^2 or 45,600 mi^2) and has maximum north-south and east-west dimensions of 370 and 195 km (230 and 120 mi), respectively. Elevation of the watershed is gentle, rising gradually eastward from 176 m (579 ft) along the lake to over 300 m (985 ft) in the northern and southeastern extremities of the basin, with a central trough at approximately 230 m (755 ft) along the Grand River.

The watershed has an average annual precipitation of 82 cm (32 in), distributed fairly uniformly throughout the year, and a mean annual air temperature of 9°C (48°F). The mean monthly temperatures range from −5°C (23°F) in January to 21°C (70°F) in July. Winter precipitation is predominantly snowfall, with intermittent snowmelts throughout the season. The region has a well developed drainage network producing a total runoff of 360 m^3/sec (12,700 cfs), which is equivalent to 8.7×10^{-3} m^3/sec/km^2 (8.0×10^{-1} cfs/mi^2) or an annual volume of 27 cm (11 in) over the drainage area (33 percent of precipitation). Monthly distribution of the annual runoff varies from approximately 15 percent in early spring (March and April) to about 5 percent during late summer (August and September). All major rivers in the region have some degree of regulation, normally classified as moderate, associated with the operation of power plants or paper mills.

The hydrologic and climatologic data for the study were obtained from pertinent U.S. Geological Survey and National Weather Service publications. The regional runoff was determined from gaged streamflow records at the lowest gaging stations on the four main rivers (St. Joseph, Kalamazoo, Grand, and Muskegon), plus five minor downstream tributaries with gaged streamflow (Dowagiac, Paw Paw, Rabbit, and two Black Rivers). The total gaged area represents 34,640 km^2 (13,370 mi^2) or approximately 84 percent of the total regional watershed. Because the study involved simulation of runoff to Lake Michigan, the gaged streamflow records were expanded to cover the entire regional watershed by straight areal extrapolation, producing an average runoff expansion factor of 1.193. The regional precipitation and temperature (maximum) were determined from five meteorological stations located at Houghton Lake, Muskegon, East Lansing, and Benton Harbor, Michigan, and Fort Wayne, Indiana. Selection of the stations was governed by the availability of long periods of reliable records, the representation of the overall regional climate, and the distribution of climatic conditions within the basin.

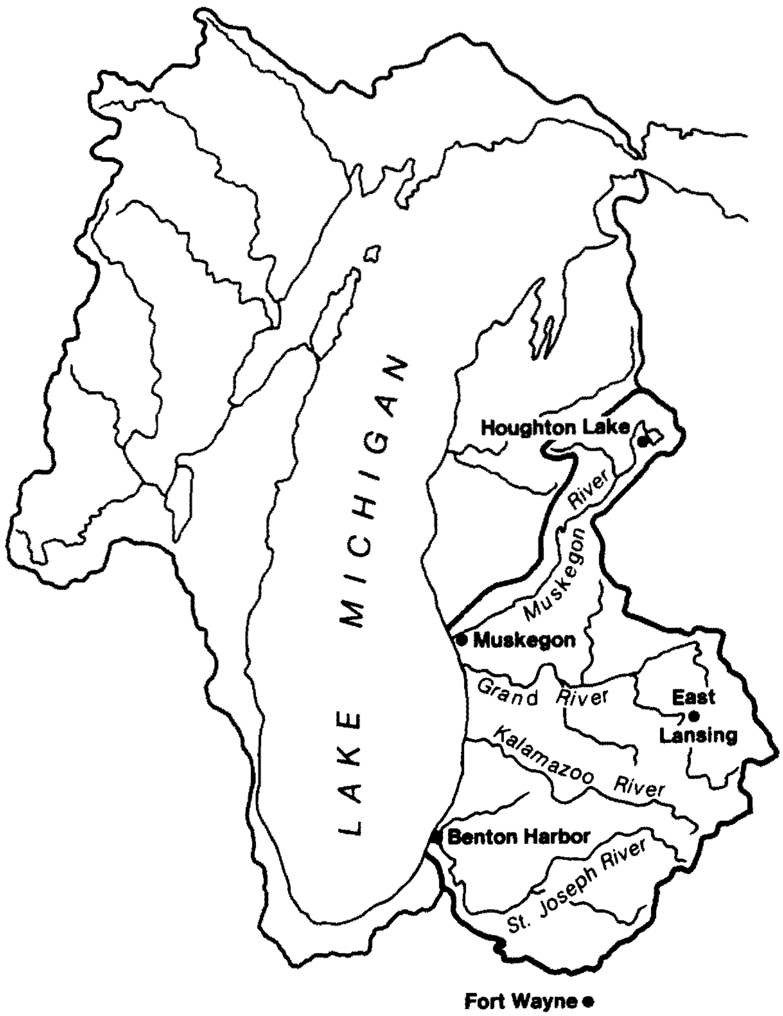

Figure 1. Lake Michigan Drainage Basin.

MODEL CALIBRATION

Operation of the model with daily time increments requires input of daily data from a limited number of meteorological stations to develop a series of index relationships for precipitation, temperature, evapotranspiration, and soil moisture. The evaluation of model results was based on the comparison between simulated and recorded runoff, primarily on a monthly basis, although seasonal and annual volumes were also considered. The model operates in either English or metric units.

Initial calibration of the model for the southeast Lake Michigan drainage basin was conducted over a five-year period, from 1967 to 1971 (Derecki and Potok, 1978). These preliminary calibration results were reevaluated because of slight changes in the meteorological network, modified somewhat and applied to the expanded 13-year period. Initial estimates of the index relationships between areal precipitation, temperature, evapotranspiration, soil moisture, and runoff were adjusted by trial and error to obtain improved runoff simulation.

Because the primary purpose of the study was the long-term simulation of runoff into the Great Lakes, simulating monthly flow volumes, rather than reproduction of flow hydrographs, was emphasized in model calibration. In the case of runoff forecasts based on average monthly meteorological data distributed in equal daily increments throughout the month, the reproduction of flow hydrographs is not possible.

The SSARR model was modified slightly during calibration by adding a snow catch deficiency factor of 1.20, which increased solid precipitation measurements by 20 percent. The rain gage deficiency for measuring snowfall is well documented in the literature and the 20 percent snow catch deficiency appears conservative in view of recent findings (Larson and Peck, 1974). The inclusion of the snow catch deficiency factor was prompted by consistent deficiency of precipitation during winter.

DISCUSSION OF RESULTS

Figures 2 and 3 show monthly relationships between observed and simulated values for January-June and July-December, respectively. Each monthly graph also shows a 45° line with zero intercept representing perfect simulation. Statistics for the simulation results are summarized in Table 1. The correlation coefficients for simulation of monthly runoff volumes range from 0.96 to 0.55, but are reasonably high for most months, indicating good to fair accuracy of the simulation with respect to a best fit line (which does not necessarily correspond to the 45° line). To obtain simulation results with an accuracy indicated by the correlation coefficient requires an adjustment based on the regression equation of the best fit line.

A more direct measure of the accuracy of simulation is the RMS error between the simulated and the observed values. The RMS errors for most months are substantially smaller than the standard deviation, indicating a significant improvement for the simulation results. The standard deviation of the observed runoff is a rough measure of the errors associated with using the mean runoff value as the most likely to occur. The mean errors for the monthly simulation are generally very small, but the maximum errors for some of the months are rather large, approaching mean monthly values.

The best simulation results were obtained for the mid-winter months of January and February. During early spring simulation deteriorates considerably, showing more scatter of data and poor simulation results. March and April are the peak runoff months, with nearly 30 percent of the annual runoff, reflecting early spring snowmelt, seasonal increase in precipitation, and relatively low losses. The overall deterioration of runoff simulation is due to intermittent snow and rain, and limited ability of the model to estimate snowmelt and its effect on soil moisture. Further deterioration in April is also caused by severe weather, which appears to be responsible for the largest errors. Largest undersimulation of runoff occurred in April 1967, which was dominated by violent storms with an

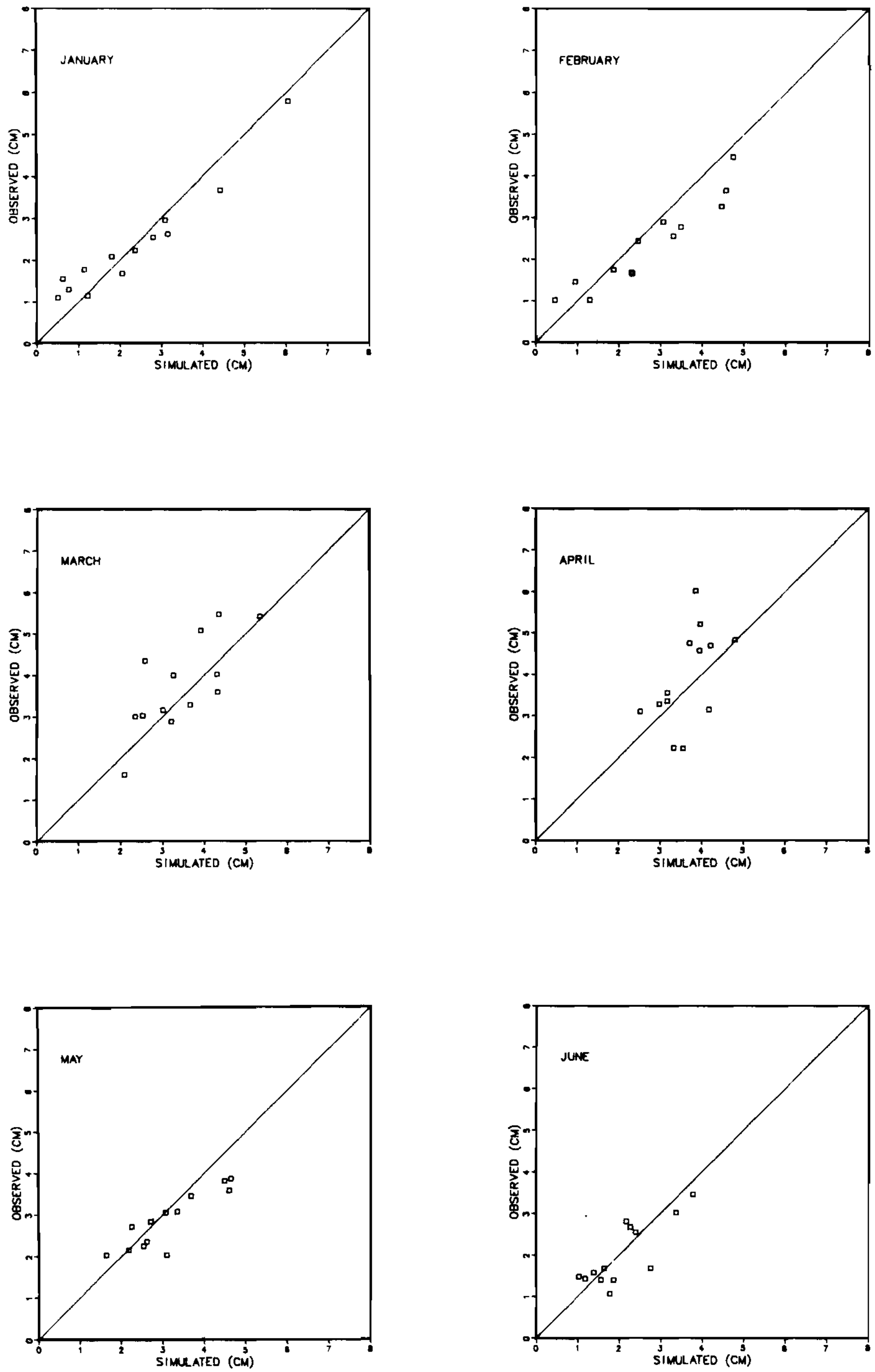

Figure 2. Comparison of Observed and Simulated Runoff for January Through June.

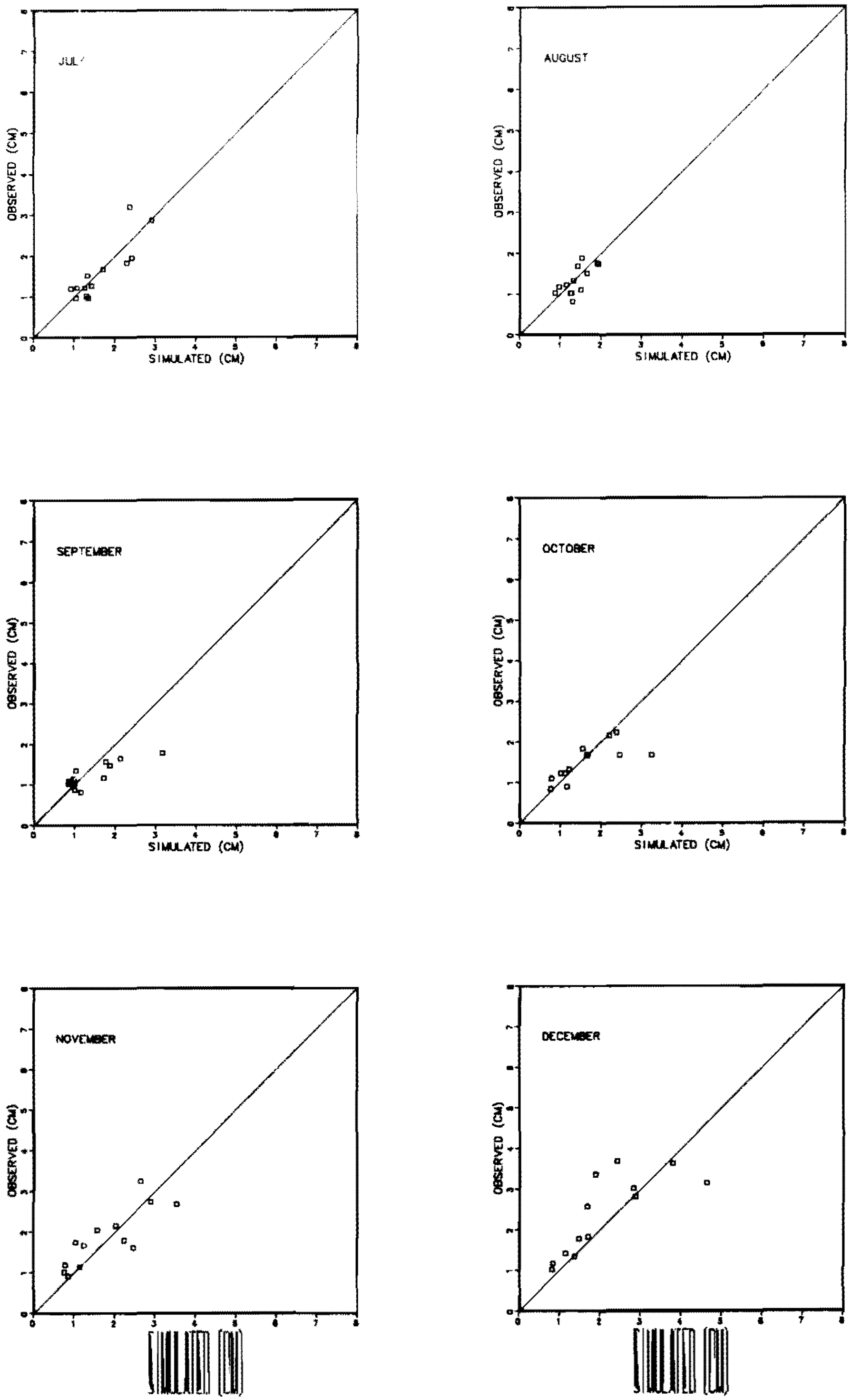

Figure 3. Comparison of Observed and Simulated Runoff for July Through December.

unusually large number of tornadoes. The undersimulation seems to be associated with gage undercatch caused by high winds. Large oversimulation of runoff occurred during 1964-66, a period of prolonged drought in the Great Lakes region, when more moisture was retained in the soil.

TABLE 1. Summary of Simulation Results Using Recorded Daily Data, 1961-73.

Period	R	Sy, cm	RMS Error, cm	Mean Error, cm	Max Error, cm	Mean Observed Runoff, cm	Mean Simulated Runoff, cm
January	0.96	1.28	0.49	–0.03	0.91	2.34	2.31
February	0.95	1.05	0.62	0.36	1.19	2.36	2.72
March	0.74	1.12	0.79	–0.31	1.78	3.75	3.45
April	0.55	1.15	0.94	–0.18	2.16	3.82	3.64
May	0.89	0.67	0.55	0.28	1.07	2.86	3.15
June	0.81	0.77	0.48	0.09	1.09	2.01	2.10
July	0.87	0.71	0.34	0.03	0.84	1.61	1.64
August	0.70	0.35	0.26	0.06	0.48	1.32	1.39
September	0.78	0.36	0.46	0.14	1.40	1.29	1.43
October	0.74	0.44	0.51	0.14	1.57	1.50	1.64
November	0.83	0.72	0.49	–0.06	0.84	1.85	1.79
December	0.78	0.98	0.74	–0.26	1.47	2.37	2.11
All Months	0.88	1.17	0.59	0.02	2.16	2.26	2.28
January-March	0.93	2.71	1.08	0.02	1.68	8.45	8.47
April-June	0.71	2.15	1.64	0.19	3.12	8.70	8.89
July-September	0.79	1.16	0.74	0.23	1.88	4.22	4.45
October-December	0.77	1.91	1.53	–0.19	3.89	5.72	5.53
Annual	0.84	6.83	3.62	0.26	8.71	27.09	27.35

The summer and fall months show marked improvement in the runoff simulation. Sporadic deviation of data points are associated with periods of severe weather. The largest errors occur during the drought period, with substantial oversimulation during 1964-66. September and October are the only months for which the RMS errors exceed the standard deviation (128 and 116 percent, respectively) and the maximum errors exceeded the mean monthly runoff. Because of low seasonal runoff values during these months, the large oversimulation obtained for a single year (1965) had a great effect on monthly statistics. Conditions in December are similar to those in March and the early winter deterioration of runoff simulation is attributed to intermittent rain and snow.

The overall results of monthly runoff simulation are summarized in a graph showing the relationship between observed and simulated values for all months (Figure 4). The correlation coefficient for the relationship is relatively high (0.88) and the RMS error indicates a 50 percent improvement of the simulation over the standard deviation. The graph shows good distribution of points about the 45° line, indicating a well calibrated model for the entire 12-month period. There appears to be no bias in the calibration, with the possible exception of a slight tendency to undersimulate at high flows.

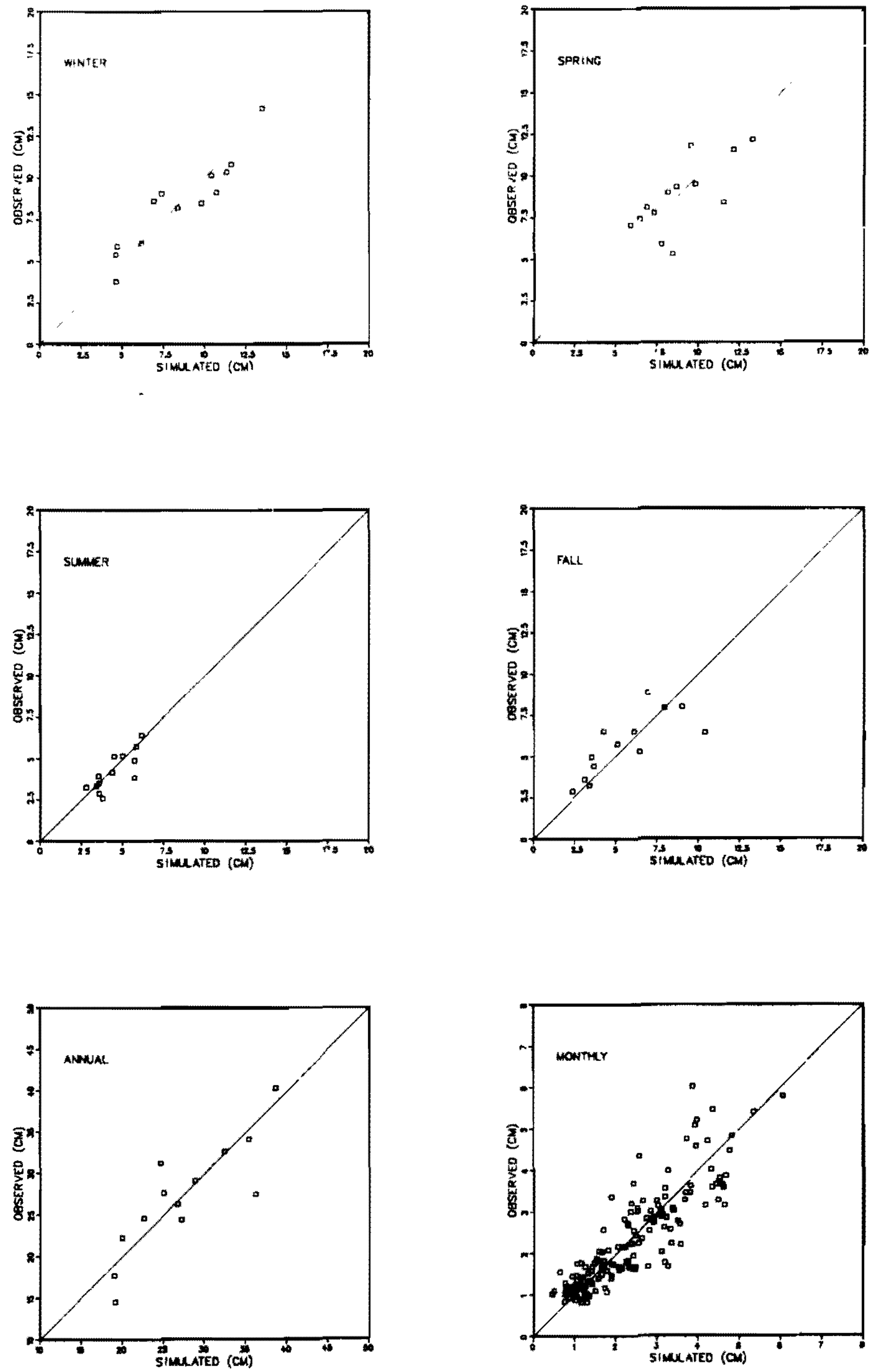

Figure 4. Comparison of Observed and Simulated Runoff for all Months, Four Seasonal, and Annual Values.

Other graphs in Figure 4 show the cumulative effect of monthly runoff simulation on seasonal and annual periods. The monthly values were combined for three consecutive calendar months to indicate seasonal results corresponding roughly to winter, spring, summer, and fall. These in turn were combined for the annual results. Because of continuous simulation for a given moisture input, larger monthly errors are generally compensated for within the season, except for severe weather periods. During those times, the moisture input is incorrectly measured, producing errors without subsequent compensation.

The cumulative distribution of the observed, simulated, and long-term mean (1950-75) runoff for the entire 13-year period is shown in a mass diagram on Figure 5. The runoff trend corresponds to lake level fluctuations on Lake Michigan. The simulated runoff agrees well with the observed values through 1965. During 1966, which corresponds to the end of the drought period, simulated runoff is considerably higher. This oversimulation is reduced somewhat during 1967, which produced many tornadoes in the spring, after which the two graphs are nearly parallel until 1973. Despite these deviations, runoff simulation is much superior to climatology (long-term mean runoff) for hindcasting purposes or determination of runoff on a near-real time basis, when streamflow records are not available.

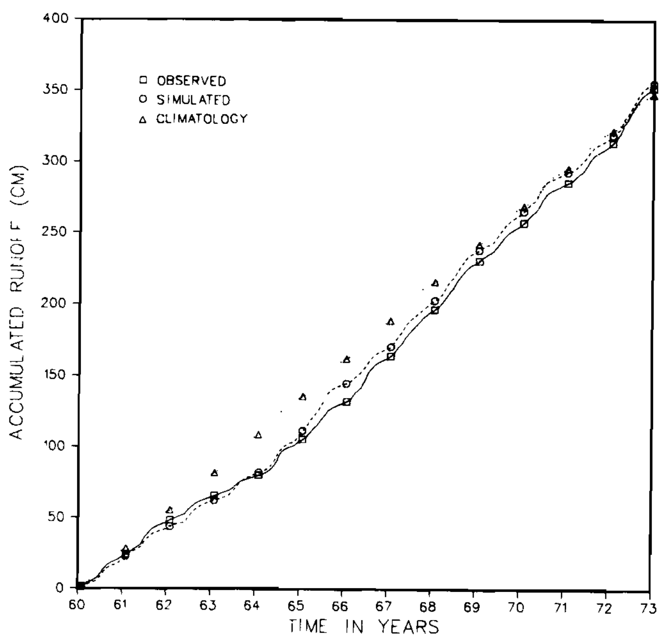

Figure 5. Mass Diagram for Observed, Simulated, and Long-Term Mean Runoff (climatology).

Another potential application of runoff simulation is in the development of monthly runoff forecasts. The feasibility of runoff forecasts was tested over two successive six-month periods (October-March and April-September), by using average monthly precipitation and temperature data. For the purpose of initiating runoff forecasts for both periods, soil moisture conditions for the preceding months (September and March) were adjusted to obtain correct starting runoff. Both periods represent approximately equal runoff volumes, but because of the weakness of the snow ablation model results were generally better for the April-September period.

Comparison of the six-month runoff forecasts with climatology for three selected years representing low, median, and high runoff years is shown in Figure 6. For the high runoff year (1973) the simulated forecast came out very well and is much superior to climatology. During the median runoff year (1961), the simulated forecast also shows some improvement over climatology, which may not be significant for this limited test since for the average conditions climatology represents an ideal forecasting method and is probably unsurpassable in the long run. For the low runoff year (1964), the simulated forecast is again much better than climatology. All three forecasts exhibit some deterioration in accuracy, starting as early as the second month. However, results for the high and low runoff years still indicate approximately 90 and 50 percent improvement over climatology, respectively, at the end of six months. These results are encouraging and will be examined on a much more comprehensive scale in the next phase of the study.

In the actual implementation of monthly runoff simulation, the entire drainage basin of a lake would have to be considered. It is anticipated that two to three equivalent basins might be needed for each of the Great Lakes, chosen with such general guidelines as similarities in climate, geology, topography, drainage pattern, and location. A correlation of recorded monthly runoff from the study area and from the entire Lake Michigan basin was made by using several regression formulas. Results are listed in Table 2. Although correlation for some months is strong, the overall results are too varied to be of practical use. Consequently, the 35 percent of the total area included on the lee side of the lake cannot be used to estimate runoff from the entire lake basin.

TABLE 2. Relationship Between Observed Runoff for Southeast Lake Michigan and for the Total Drainage Basin, 1961-73.

Month	Correlation Coefficient	Type of Regression
January	0.96	Linear
February	0.93	Power
March	0.79	Power
April	0.73	Power
May	0.26	Linear
June	0.93	Linear
July	0.92	Linear
August	0.78	Linear
September	0.41	Linear
October	0.78	Linear
November	0.76	Power
December	0.87	Power

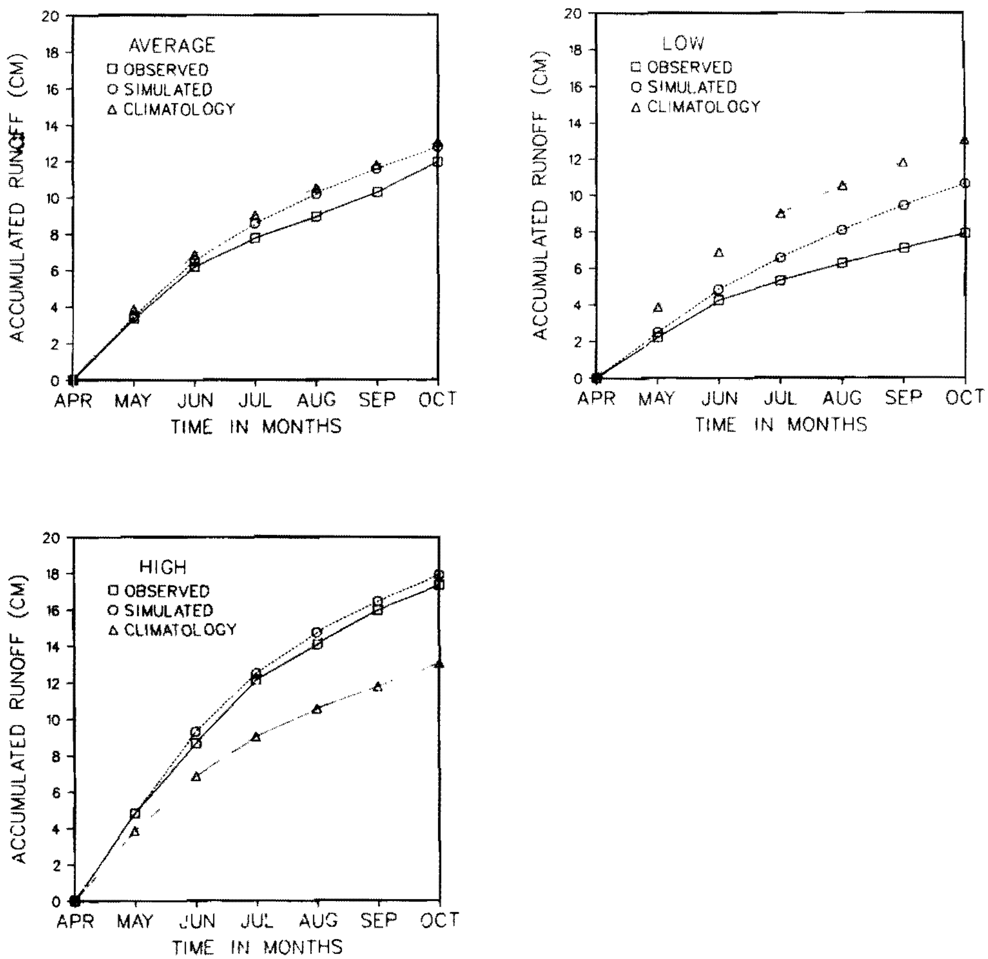

Figure 6. Six-Month Runoff Forecasts for High, Average, and Low Runoff Years.

SUMMARY AND CONCLUSIONS

The feasibility of simulating monthly runoff from a large area with multiple watersheds was evaluated with the SSARR conceptual watershed model, which requires daily precipitation and temperature data, along with average daily indexes for the evapotranspiration and soil moisture conditions. Because of the potential applicability of such simulation to runoff forecasting, runoff forecasts with average monthly precipitation and temperature data were also tested. The evaluation was conducted on the southeastern Lake Michigan basin, comprising an area of 41,320 km^2 (15,950 mi^2), over a 13 water-year period (October 1960 through September 1973). This period includes both the low (1964) and the high (1973) lake levels and covers a complete long-term runoff cycle.

Results of the study indicate that volumetric simulation of monthly runoff from multiple watersheds with an equivalent basin is feasible. Evaluation of simulation results and observed runoff volumes for monthly, seasonal, and annual periods produced reasonably strong correlations with an overall monthly correlation coefficient of 0.88, and showed significant improvement of the simulation over the use of mean runoff values, with the RMS errors substantially below the standard deviation. The mean errors were generally small, indicating good distribution of data points with respect to perfect simulation. The simulated runoff was much better than climatology for hindcasting purposes and for estimating runoff on a near real time basis, when observed streamflow data are normally not available. Snowmelt, especially during intermittent snow and rain periods, is the weakest part of the model.

A limited test of monthly runoff forecast feasibility, conducted for periods of six consecutive months, showed encouraging results. For the high and low runoff years, the six-month runoff forecasts were much superior to climatology in reproducing observed runoff volumes. For a median runoff year, representing average conditions, the results were similar and climatology is ideally suited for such conditions.

LITERATURE CITED

Derecki, J. A. and A. J. Potok, 1978. Evaluation of Runoff Simulation for Southeast Michigan with SSARR Watershed Model. U. S. Army Corps of Engineers, North Central Division, Hydrometeorological Data System for the Great Lakes, Appendix D, Chicago, Illinois.

Larson, L. W. and E. L. Peck, 1974. Accuracy of Precipitation Measurements for Hydrologic Modeling. Water Resources Research 10(4):857-863.

U. S. Army Corps of Engineers, North Pacific Division, 1972. Program Description and Users Manual for SSARR Model, Streamflow Synthesis and Reservoir Regulation (Revised 1975). Portland, Oregon.