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USE OF LOW-FLOW TREND AND TRANSFER-FUNCTION MODELS TO DETERMINE RELATION OF LOW FLOWS TO REGIONAL URBANIZATION AND PRECIPITATION, RAHWAY RIVER BASIN, NEW JERSEY, 1940-91

Open File Report 99-257

Prepared in cooperation with the

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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By Thomas H. Barringer, Robert G. Reiser, and Curtis V. Price

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West Trenton, New Jersey
2000

science for a changing world

U.S. DEPARTMENT OF THE INTERIOR

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ERRATA SHEET

This errata pertains to the Open-File Report 99-257, “Use of low-flow trend and transfer-function models to determine relation of low flows to regional urbanization and precipitation, Rahway River Basin, New Jersey, 1940-91,” by Thomas H. Barringer, Robert G. Reiser, and Curtis V. Price.

Tha annual sewage flow referred to in figure 5 and throughout the document is that which is discharged from the Rahway Valley Sewage Authority, not from the City of Rahway. The sewage output data used in the statistical analysis were also for the Rahway Valley Sewage Authority facility.

USE OF LOW-FLOW TREND AND TRANSFER-FUNCTION MODELS TO DETERMINE RELATION OF LOW FLOWS TO REGIONAL URBANIZATION AND PRECIPITATION, RAHWAY RIVER BASIN, NEW JERSEY, 1940-91

By Thomas H. Barringer, Robert G. Reiser, and Curtis V. Price

ABSTRACT

The Rahway River Basin in northern New Jersey has become heavily urbanized. The importance of the Rahway River as a water-supply source for the region led to an investigation of trends in the river's low-flow characteristics over time and their relation to regional urbanization and precipitation. Since 1950, low flows at a stream-gaging station near Springfield, N.J., increasingly have tended to exceed those at a station at Rahway. Polynomial-trend models for three measures of low-flow difference between the two stations during 1940-91 show trends in all three measures, indicating that they have changed significantly in level during the study period. Transfer-function models indicate that differences in low flows between the two gaging stations are significantly related to measures of basin urbanization and regional precipitation. A rough water budget for the inter-gage part of the basin confirms these results.

INTRODUCTION

More than one-half of New Jersey's population depends on surface water as a source of water supply (U.S. Geological Survey, 1985). One important source of surface water in northern New Jersey is the Rahway River (fig. 1). Since the late 19th century, the Rahway River Basin has experienced extensive residential and industrial development. The population of Union County, in which much of the basin lies, was 305,200 in 1930, rose to 543,100 in 1970, then fell to 493,800 in 1990 (Frank Ferdetta, N.J. State Data Center, written commun., 1994).

Changes in the physical characteristics of a drainage basin can affect both stream base flow and overland runoff (Simmons and Reynolds, 1982). For example, urbanization leads to an increase in the amount of impervious surface, increasing overland runoff and evaporation and reducing recharge to the water table and ground-water flow compared to those under predevelopment conditions (Waananen, 1961; Spinello and Simmons, 1992). At the same time, increases in population and industrial activity that accompany urbanization can raise the demand for water, thus affecting surface- and ground-water withdrawals. Decreased recharge and increased ground-water pumpage can affect base flow and alter low-flow characteristics (Thomas and Schneider, 1970). Stream low flow also can be affected by the proportion of land cleared and its location in a drainage basin (Riggs, 1965).

An example of the effect of changes in drainage basins resulting from human activities on the flow characteristics of streams can be seen in the time-series plots of logarithms of annual 7-day mean low flows for the two streamflow-gaging stations on the Rahway River (fig. 2). The annual 7-day mean low flow at the upstream station (Springfield) was approximately the same as that at the downstream station (Rahway) until about 1950. Since then, low flow at Rahway has fallen increasingly farther below that at Springfield.

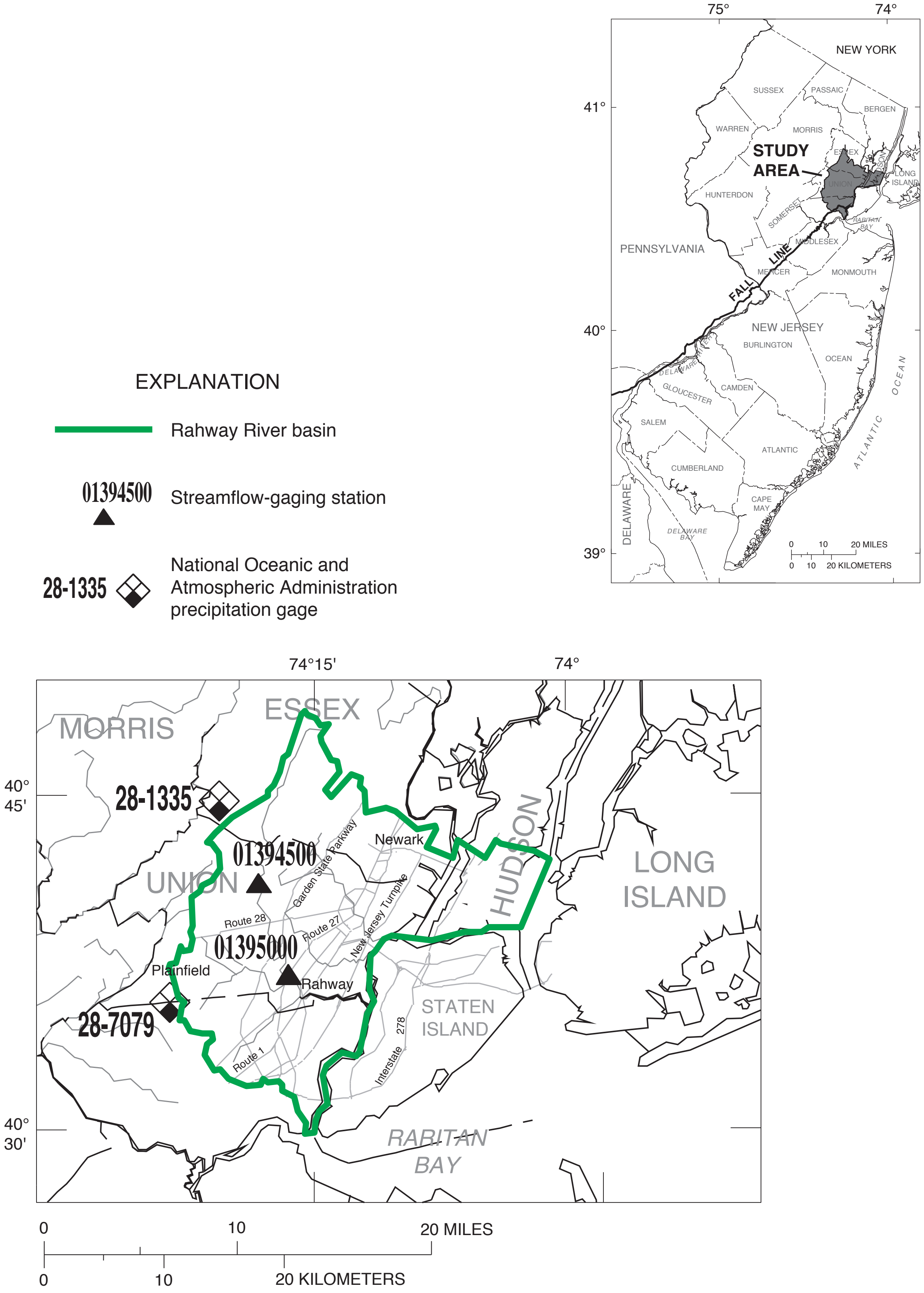

Figure 1. Location of study area and inset map showing location of U.S. Geological Survey streamflow-gaging stations, National Oceanic and Atmospheric Administration precipitation gages and major roads.

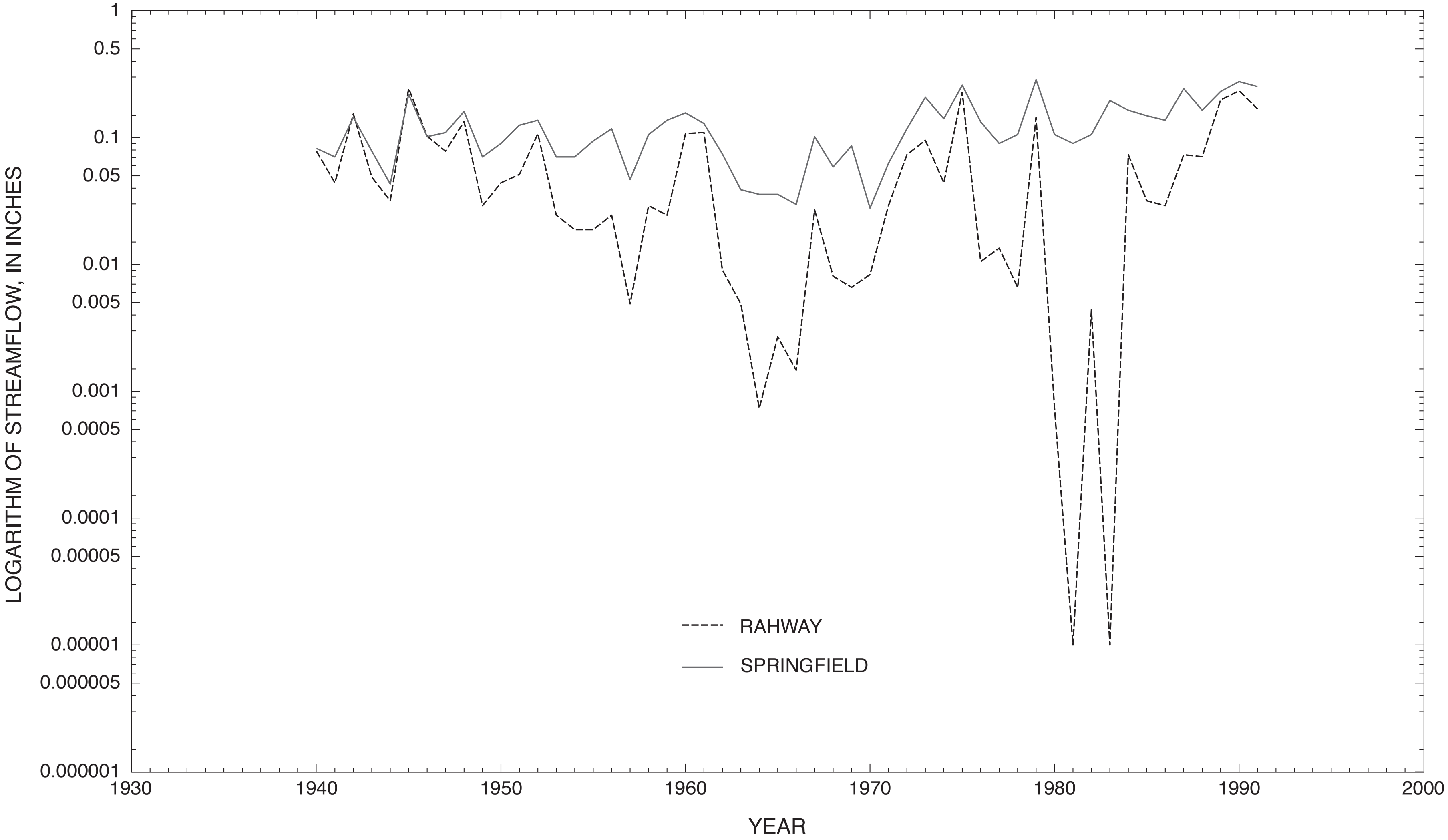

Figure 2. Area-normalized annual mean 7-day low flow, Rahway River at Rahway and Rahway River near Springfield, N.J.

The importance of the Rahway River as a source of public water supply led to an investigation of trends in low-flow characteristics and relations between those characteristics and possible causative factors. The two objectives of this study, conducted by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers and the New Jersey Department of Environmental Protection, were to (1) describe and characterize trends in low-flow characteristics at two selected streamflow- gaging stations in the study area during 1940-91, and (2) determine the effect of basin urbanization on selected low-flow characteristics of the Rahway River during that period. Trend and transfer-function models were used to gain a quantitative understanding of the effects of regional development and precipitation on surface-water flow in the Rahway River Basin during periods of low streamflow.

Purpose and Scope

This report presents trend-modeling results for three measures of low-flow difference in the Rahway River Basin: annual median base flow difference, annual mean 7-day low-flow difference, and difference in annual number of days below a State minimum passing flow. Three transfer-function models are described that relate those measures of low-flow difference to regional precipitation and to several measures of basin urbanization. In addition, a rough water budget for the part of the basin between the two gages is presented.

Description of Study Area

The Rahway River Basin covers an area of about 82.9 mi^2 (square miles) (214.7 km^2 (square kilometers)), 75 percent of which is gaged (fig. 1). Much of the river downstream from the streamflow-gaging station in the city of Rahway is subject to tidal fluctuation. All of the gaged part of the basin lies in the Piedmont Physiographic Province (Fenneman, 1946). The Rahway River Basin was glaciated during the last glacial advance (Anderson, 1968). Pleistocene terminal moraine forms the southwestern drainage divide, and glacial-drift deposits that range from 0 to about 200 ft (feet) (0 to about 60 m (meters)) in thickness cover most of the bedrock in the basin (Nemickas, 1974). Bedrock is composed predominantly of sedimentary rocks of the Passaic Formation except in a small area in the northwestern part of the basin that is underlain by the Orange Mountain Basalt, Feltville Formation, and the Preakness basalt. The chief source of ground and surface water in the study area is precipitation. Some precipitation runs directly into surface-water bodies as overland runoff, and some recharges the basin’s ground water by percolating into the surficial glacial deposits in interstream areas. The remaining precipitation--about half the total--is lost to evaporation. Ground water flows through pore spaces in the surficial deposits to enter fractures in the underlying bedrock. It discharges from the glacial drift and bedrock fractures as base flow to the region’s dendritic stream system and to lakes that have formed in depressions in the surficial deposits. As of 1974, approximately 26 percent of the 25.5-mi^2 (66.0-km^2) drainage area above the gaging station on the Rahway River near Springfield was estimated to be impervious cover (Stankowski, 1974; U.S. Geological Survey, 1974, 1986), compared with 24 percent of the 40.9-mi^2 (105.9-km^2) drainage area above the station on the Rahway River at Rahway. The streamflow-gaging station on the Rahway River near Springfield (01394500) is located at U.S. Route 22 and has a period of record of about 54 years (water years[1] 1939-92). The station on the Rahway River at Rahway (01395000) is located at St. Georges Avenue and has a continuous period of record of 71 years (water years 1922-92) (Bauersfeld and others, 1993). Precipitation data for a sufficiently long period of record are

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[1] A water year is the 12-month period beginning October 1 and ending September 30. It is designated by the calendar year in which it ends.

available from two stations: one near the northern end of the study area--Canoe Brook (28-1335)--and one near the southern end--Plainfield (28-7079) (fig. 1). The period of record for precipitation data from both stations was 62 years as of 1992 (1/1931-12/1992) (National Climatic Data Center, 1992).

Modeling Methods

Trend Models

Polynomial regression, with elapsed years since 1939 as the independent variable, was used to estimate trends in low-flow measures over time. Coefficient significance is denoted by asterisks attached to the coefficients. Three 2-tailed significance levels are reported: 0.05 (*), 0.01 (**), and 0.001 (***). Degrees of freedom (df) also are reported.

Transfer-Function Models

The relational models described below were used to examine the difference between corresponding low-flow values at the two stations (rather than the low-flow values themselves) as a function of population density, sewage output, Union County building permits and road mileage, water diversions at Rahway, and regional precipitation. The low-flow difference represents the sum of flows added and lost between the two stations. Transfer-function methods (Box and Jenkins, 1976) were used to estimate relations between low flow and these measures of basin urbanization. The models were fitted to data that, in some cases, were scaled to enhance numerical precision or to eliminate negative values. Where necessary, data were transformed to square roots or logarithms to stabilize variance. Models were estimated by using Autobox Plus (c), 2.0, software of AFS, Inc.[2], as described in AFS, Inc. (1984).

Selection and Description of Low-Flow Characteristics and Independent Variables

The availability of complete time series of sufficient length for analysis is an important consideration in selecting variables for inclusion in a time-series modeling study. Ideally, annual series for sewage input or output, ground- and surface-water diversions, population density, and precipitation would be available by township. This generally was not the case in the study area. For example, various parts of the study area are served by four different sewer authorities, all of which have service areas that extend beyond the drainage-basin divide. Commonly, two or more authorities serve a given township. As growth has occurred, records have been lost, aggregated, or archived remotely, making disaggregation difficult. Similarly, water utilities can have ground- and surface-water sources both inside and outside the basin. These utilities have grown by merger and by extension of their source and distribution systems to regions far outside the study area. To add to these complicating factors, one new municipality came into existence in the basin during the study period. Finally, although decennial population data are collected at the lot and block levels, disaggregation into within- and without-basin units is beyond the scope of this study. These problems can be addressed to some degree by assuming that the city of Rahway is representative of the part of the basin that lies between the two streamflow-gaging stations. This approach is desirable for several reasons. First, although most of the city lies downstream from the Rahway station, all city withdrawals of water (both ground and surface) are made upstream from the station, and all sewage discharges of the Rahway Valley Sewerage Authority are made downstream from it. Second, complete annual series exist for Rahway's sewage output and for ground- and surface-water diversions. Third, the unit for which population estimates are made is the city itself. Therefore, this approach was adopted.

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[2] The use of brand, trade, or firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Low-Flow Characteristics

Low-flow differences between the two stations were computed by subtracting the values of low flow at Springfield from the corresponding values of low flow at Rahway. The same order of subtraction was used for all three low-flow-difference measures investigated.

Annual Median Base-Flow Difference

Base flow was estimated by performing base-flow separation on hydrographs of streamflow during individual storms by using Sloto's (1990) HYSEP program, which is based on a modification of the method of Pettyjohn and Henning (1979). The variable-slope method (Chow and others, 1988) was used. Individual base flows were summed to obtain annual totals. Streamflow at the two streamflow-gaging stations was separated into base-flow and overland-runoff components. Monthly mean base flows were used to compute the annual median base flow, from which median base-flow differences were computed. (This statistic is actually a median of monthly means; however, to avoid the awkward "annual median of monthly mean base-flow differences," the abbreviated phrase has been used throughout the text.) The median was chosen rather than the mean in an effort to obtain a more robust estimate of the center of mass of the flow-difference distribution. The true median could not be computed because of the way in which streamflow unit values are recorded and because of difficulties in retrieving and reprocessing archived data.

Annual Mean 7-Day Low-Flow Difference

The annual mean 7-day low flow represents the lowest annual mean flow observed over 7 consecutive days during a given year.

Difference in Annual Number of Days Below Minimum Passing Flow

The State of New Jersey assesses an excess-diversion charge to all surface-water purveyors based on their diversions and the level of low flow in the stream. For the purpose of this assessment, a low-flow criterion of 125,000 gallons per square mile per day (1 cubic meter per square kilometer per day) is used. First minimum passing flows were computed for each station. Then the number of days per year when flow was below a station's minimum was counted, and the difference was computed.

Independent Variables

In addition to the independent variables that ultimately were included in the models, several other independent variables initially were considered. These include miles of electrical circuit strung in the study area, annual withdrawals from major public-supply and industrial wells, regional sewage output, major modifications to basin geometry (for example, construction of the Garden State Parkway), numbers of houses served by sewers, and numbers of power poles erected in the townships that make up the study area. These potential predictors of low-flow difference were not used for various reasons. The independent variables that were included in the estimated trend models are discussed below, and time-series plots for three of these variables are shown in figures 3-5.

Regional Precipitation

Precipitation, the primary source of water to the regional hydrologic system, was expected to affect regional flow patterns significantly. The average annual total precipitation recorded at the National Oceanic and Atmospheric Administration precipitation gages at Plainfield and Canoe Brook (fig. 3) was used as a precipitation measure.

Annual Ground- and Surface-Water Withdrawals

All ground- and surface-water withdrawals by the city of Rahway during the period of this study were made within the basin (fig. 4). The city's well field is adjacent to the river and just upstream from the gaging

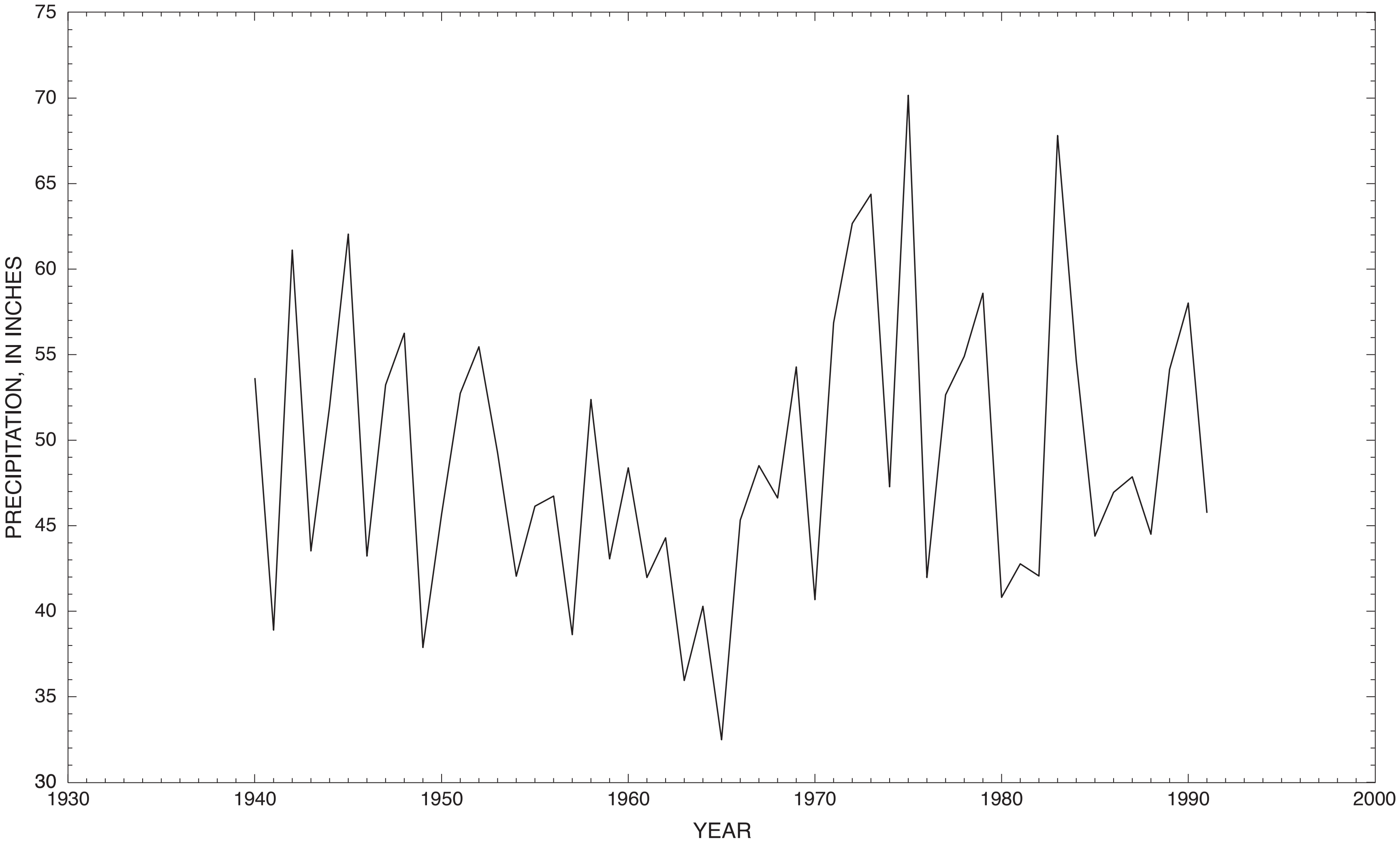

Figure 3. Averaged annual total precipitation, Canoe Brook and Plainfield, N.J.

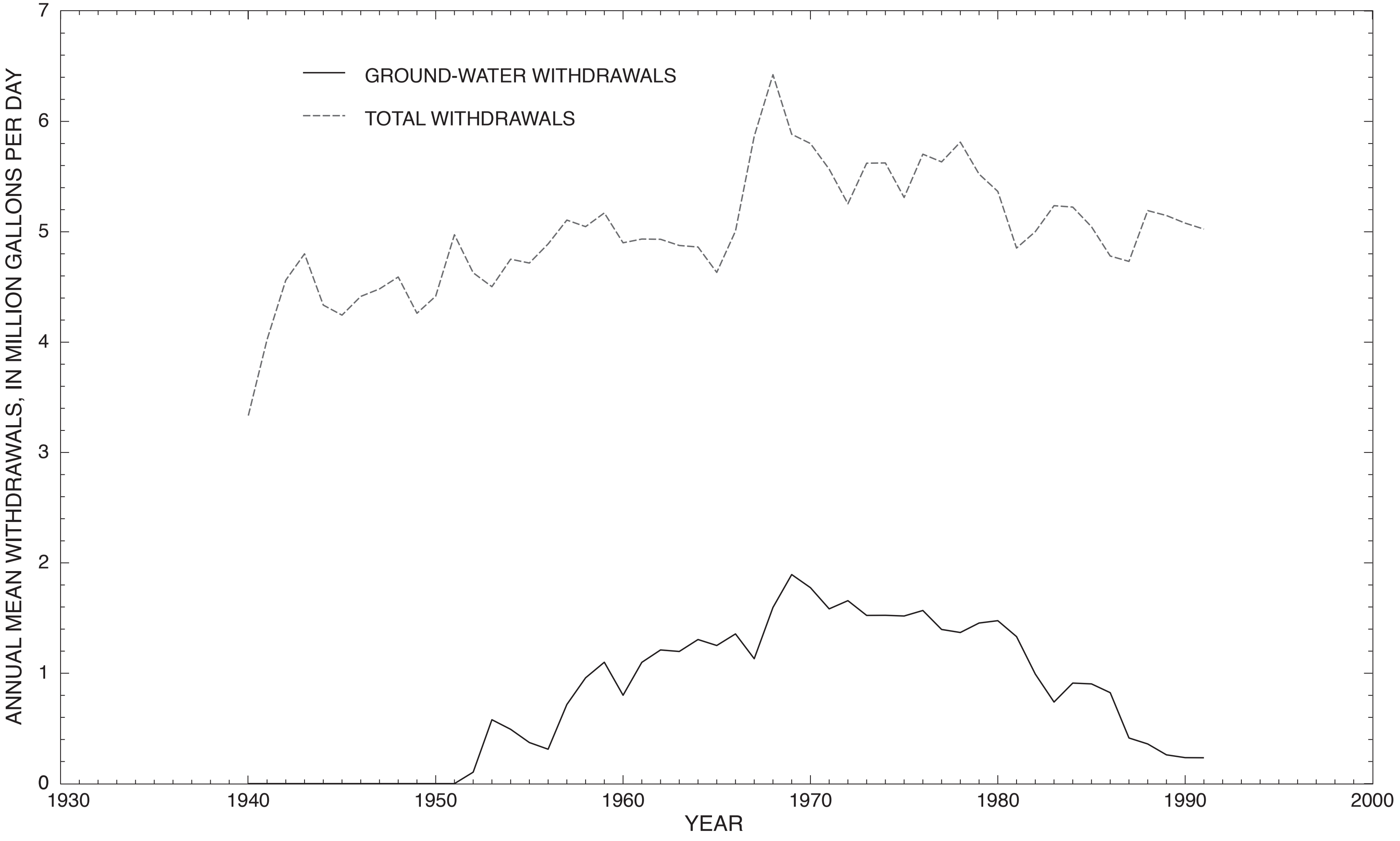

Figure 4. Annual total withdrawals and ground-water withdrawals, City of Rahway, N.J.

station. Withdrawal amounts (George Hulnik, Rahway Division of Water, written commun., 1993; New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, unpublished quarterly reports on file at the U.S. Geological Survey office in West Trenton, N.J.) are considered to be representative of basin-scale withdrawals. The amounts withdrawn by the city of Rahway obviously are not the only withdrawals made in the region between the two stations. As a result of the geographic scale of the basin, however, withdrawals by townships within the basin were assumed to be temporally correlated.

Annual Sewage Output

Annual sewage output from the city of Rahway (fig. 5) also was considered as an independent variable. The city's sewage utility does not serve a significant population beyond its own boundary. Rahway's sewage is discharged downstream from the gaged part of the basin. Data on annual discharges were obtained from the city (Andrew Doyle, Rahway Valley Sewerage Authority, written commun., 1993) and from Killiam Associates (David Klemm, Killiam Associates, written commun., 1993).

Population-Density Estimates

The census population of townships that lie wholly or partly within the basin (New Jersey Department of Labor, 1991) was assumed to be uniform within a given township. For townships that lie only partly within the basin, a geographic information system was used to determine the percentage of each township's area inside the basin. The result was then used as a weight to estimate each township's contribution to total basin population. The population for years between census years was interpolated linearly from the census estimates. The population for 1991 was extrapolated linearly from the 1990 estimate by using the 1980-90 trend. Populations within the basin and within Rahway were divided by basin area and city area, respectively, to obtain the density values.

Union County Road Mileage

As a region becomes urbanized, the number of miles of road tends to increase. The construction of housing developments, the addition of secondary routes in response to increased traffic, and the construction of expressways to relieve traffic congestion are all examples of this phenomenon. Annual road-mileage estimates (J.E. Martakis, Union County Department of Operational Services, oral commun., 1994), therefore, were considered as a potential independent variable in the models.

Union County Building Permits

The number of building permits issued annually by Union County also can be expected to respond to the urbanization process. New dwellings are constructed and existing ones are expanded or modified to accommodate the increasing population. These data were provided by the New Jersey Department of Labor (Frank Fazetta, N.J. Department of Labor, written commun., 1994).

TRENDS IN LOW-FLOW DIFFERENCE AND CORRELATIONS WITH URBANIZATION AND PRECIPITATION

Trends in Low-Flow Difference

All three base-flow-difference variables showed quadratic trends. The models for annual median base-flow difference (BASDF) and annual mean 7-day low-flow difference (LO7DF) are linear; that for the difference in annual number of days below minimum passing flow (BLODF) is log-linear.

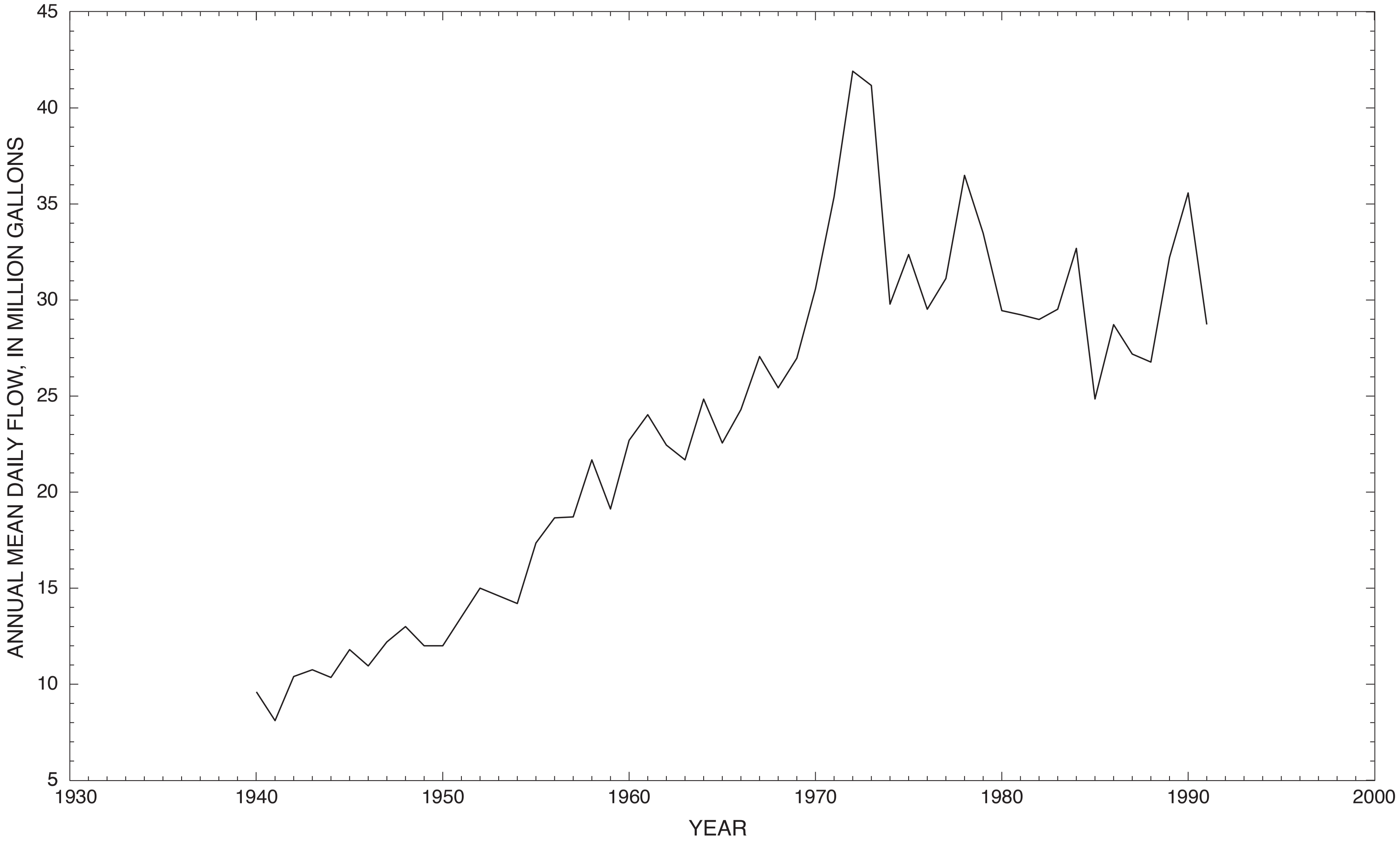

Figure 5. Annual total sewage output, City of Rahway, N.J.

Annual Median Base-Flow Difference

The trend for BASDF is expressed in equation 1. The numbers that appear below the model coefficients are the t-ratios of the respective coefficients. A t-ratio is the ratio of a coefficient to its standard error. Asterisks denote their significance, as described in the section on modeling methods.

$$\begin{array}{llll} \mathrm{BASDF} = 1.818 & -\ 0.1152\,t & +\ 0.0018\,t^2 & (1) \\ & -4.71\ (***) & 4.12(***) & \end{array}$$

$$R^2 = 0.34 \qquad df = 50.$$

In these models, the time variable, t, should not be confused with the t-ratio statistics. R^2 values and t-ratios reported for the trend regressions are only guidelines as a result of the presence of serial correlation in the time series being modeled. The estimated trend model shows a quadratic trend (fig. 6), with a minimum occurring about 1970. The first-order trend is negative.

Annual Mean 7-Day Low-Flow Difference

The trend in LO7DF (fig. 7), like that in BASDF, is quadratic, but the minimum occurs about 4 years later. As for BASDF, the first-order trend is negative. The estimated trend model is given by equation 2:

$$\begin{array}{llll} \mathrm{LO7DF} = 1.909 & -\ 0.1979\,t & +\ 0.0029\,t^2 & (2) \\ & -3.47\ (***) & 2.74(**) & \end{array}$$

$$R^2 = 0.27 \qquad df = 50.$$

Difference in Annual Number of Days Below Minimum Passing Flow

Equation 3 is the estimated trend model for difference in number of days below minimum passing flow (BLODF) (fig. 8). (Sixteen was added to the raw data to permit the log transformation.)

$$\begin{array}{llll} \mathrm{Log}\ (\mathrm{BLODF} + 16) = 0.7605 & +\ 0.0435\,t & -\ 0.0005\,t^2 & (3) \\ & 3.64\ (**) & -2.28\ (*) & \end{array}$$

$$R^2 = 0.44 \qquad df = 49.$$

Figure 8 shows a quadratic trend in the log of the dependent variable that first rises, then falls, with a maximum in the early 1980's. This contrast in trend direction with the two previous models is discussed farther on.

Transfer-Function Models

Transfer-function models were used to estimate relations between each of the three measures of low-flow difference and the measures of urbanization and precipitation. Model coefficients are given as rational fractions of polynomials in backward-difference operators (B's) in which moving-average effects form the numerator and autoregressive effects form the denominator. Backward-difference operators are shift operators that increase a variable's lag:

$$B^1(x_t) = x_{t-1},\ B^2(x_t) = x_{t-2},\ \ldots,\ B^k(x_t) = x_{t-k}.$$

The terms in lags of A that appear at the ends of the models represent the noise model. The numbers below the coefficients are their t-ratios. As before, asterisks refer to significance levels. R^2 values and degrees of freedom (df) also are given.

Annual Median Base-Flow Difference

The estimated trend model, given by equation 4, contains three independent variables: annual sewage output (SEWER), total annual ground- and surface-water withdrawals (TWD), and averaged annual precipitation at Plainfield and Canoe Brook (PPT). Plots of the observed and estimated time-series model are shown in figure 9.

$$\begin{array}{lllll} \mathrm{BASDF}_t = 2.49 + \{3.32 & [1 - B]\ \ln(\mathrm{SEWER}_t)\}/ & [1 - 0.443B] & & \\ \quad 5.80\ (***) & & 2.62\ (**) & & \\ + [20.5 & -\ 13.5B & +\ 12.1B^2]\ [\mathrm{TWD}_t^{-1} - 0.202] & & \\ \quad 3.62\ (***) & 2.16\ (*) & 2.80\ (**) & & (4) \\ + [-5.38 & -\ 8.96B]\ [\mathrm{PPT}_t^{-0.5} - 0.456] & + [1 + 0.556B]\ A_t & & \\ \quad -3.08\ (**) & 5.47\ (***) & 4.00\ (***) & & \end{array}$$

$$R^2 = 0.79 \qquad df = 41.$$

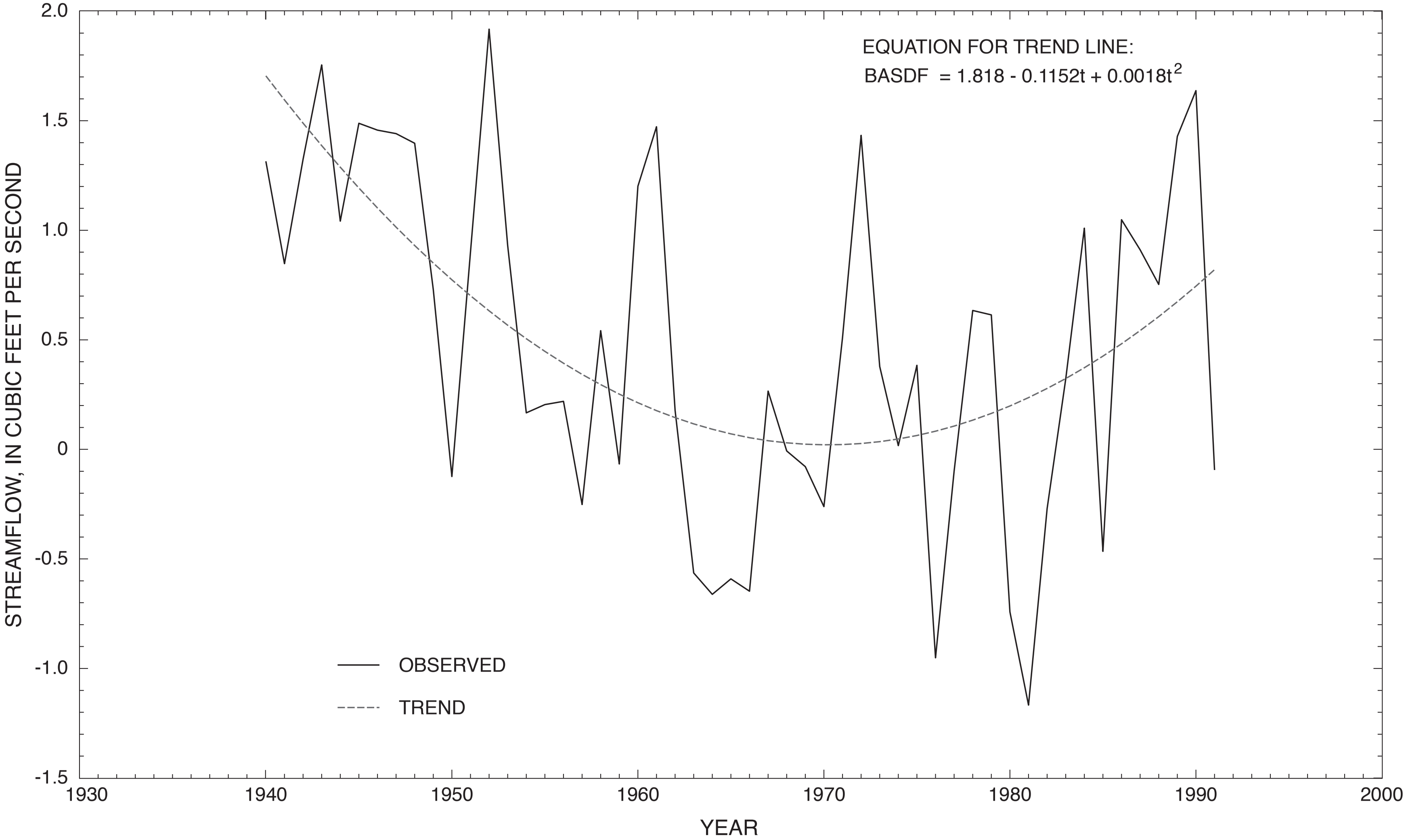

Figure 6. Observed annual median base-flow difference and trend, Rahway River at Rahway minus Rahway River near Springfield, N.J.

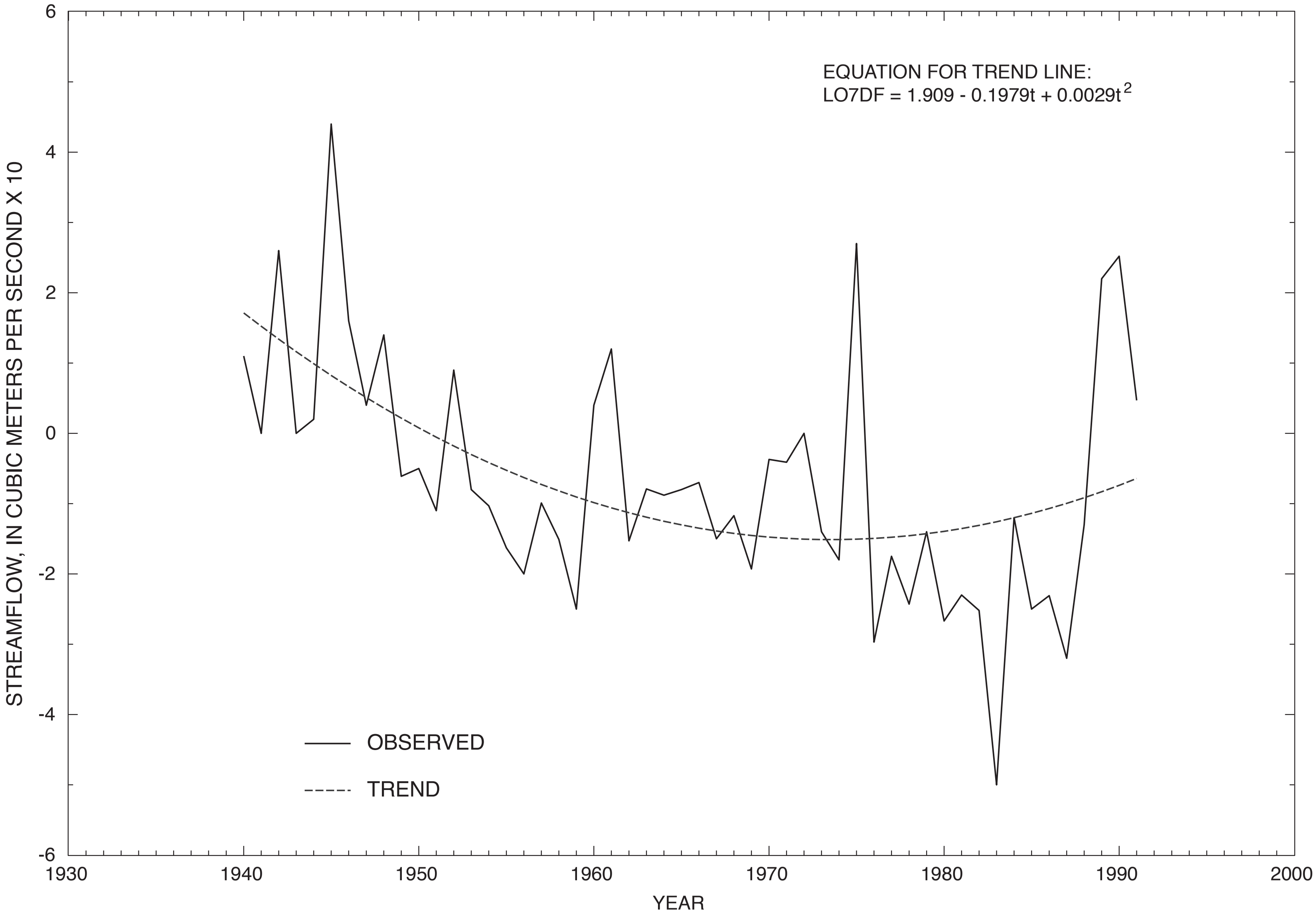

Figure 7. Observed annual mean 7-day low-flow difference and trend, Rahway River at Rahway and Rahway River near Springfield, N.J.

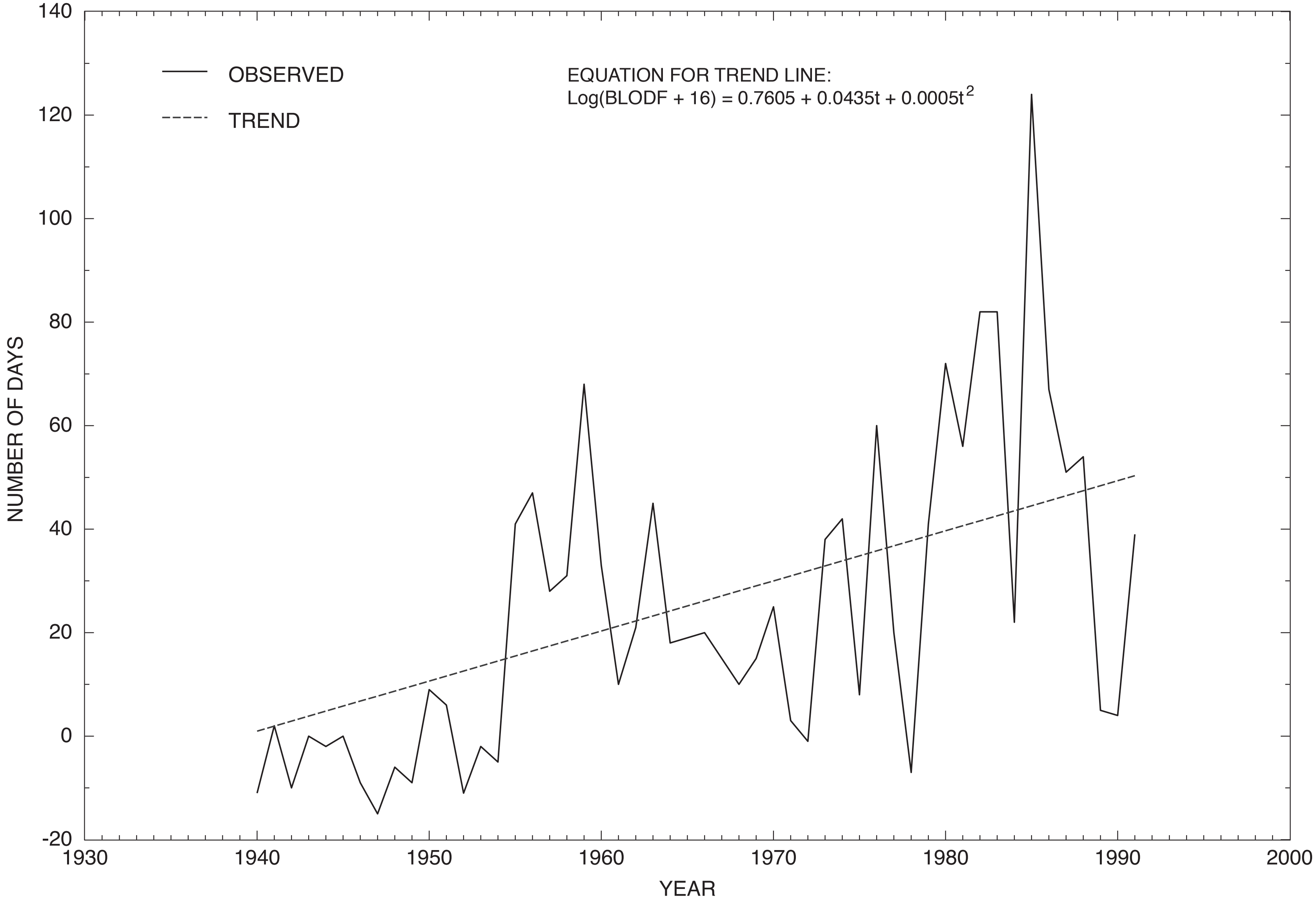

Figure 8. Observed difference in annual number of days below minimum passing flow and trend, Rahway River at Rahway minus Rahway River near Springfield, N.J.

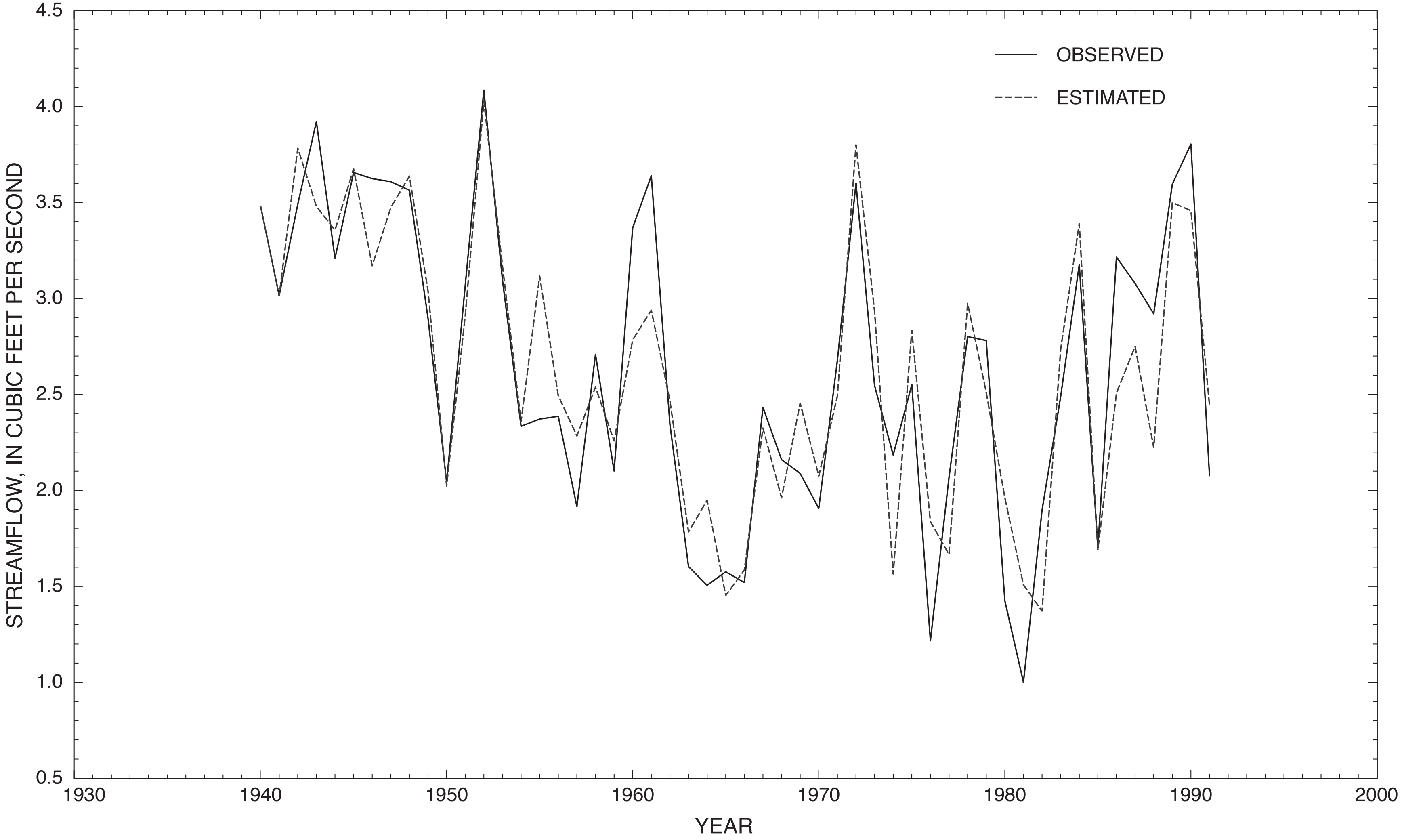

Figure 9. Observed and estimated annual median base-flow difference, Rahway River at Rahway minus Rahway River near Springfield, N.J.

The effects of these three independent variables on BASDF are interpreted as follows. First, SEWER is directly related to BASDF, but their correlation is negative. Therefore, increased sewage output acts to decrease base flow at Rahway relative to that near Springfield. Next, although BASDF is positively correlated with a function of TWD, TWD appears as an inverse in that function so that an increase in TWD has the same effect on BASDF as does an increase in SEWER--a decrease in base flow at Rahway relative to that near Springfield. The third independent variable, PPT, also appears as an inverse, but all of the coefficients in the PPT function are negative, indicating that the effect of PPT on BASDF is the opposite of the effect of the other two independent variables--that is, an increase in PPT causes base flow at Rahway to increase relative to that near Springfield. Causally, these relations are appropriate. SEWER and TWD both act to remove water from the system and transport it out of the gaged area, thus lowering base flow at Rahway relative to that near Springfield. In contrast, PPT is a source of water to the system and acts to replace the loss due to SEWER and TWD. It acts to raise base flow at Rahway relative to that near Springfield. Variation due to variables not included in the model and random noise can affect the observed series. Variation due to nonrandom exogenous effects is included in a noise component. In addition to variation accounted for by the noise model, random variation effects are present and represent the remaining 19 percent of the total variance of the observed median base-flow difference between the two stations. These effects are unpatterned variation that is not associated with the endogenous variables (independent variables) or exogenous variables (noise component).

Annual Mean 7-Day Low-Flow Difference

As for BASDF, the best-fit model for LO7DF, equation 5, is a three-variable model with independent variables that are functions of sewage output, total withdrawals, and averaged total precipitation. The directions in which the effects represented by the independent variables act upon LO7DF also are the same as in the model for BASDF. Plots of the observed and estimated flow series are shown in figure 10.

$$
\begin{aligned}
\mathrm{LO7DF}_t &= 5.38 + \underset{-2.56\,(^{**})}{3.11\,[1-B]}\ \ln(\mathrm{SEWER}_t) + \underset{5.35\,(^{***})}{49.1}[\mathrm{TWD}_t^{-1} - 0.202] \\
&+ [\underset{-3.01\,(^{**})}{-12.7} - \underset{-2.01\,(^{*})}{7.53B}]\,[\mathrm{PPT}_t^{-0.5} - 0.456] \\
&+ [1 - \underset{-2.56\,(^{**})}{0.410}B^6]\,[1 - \underset{-3.79\,(^{***})}{0.605}B^8]\,A_t \;/\; [1 - \underset{-2.51\,(^{**})}{0.359}B] \qquad (5) \\
&\qquad R^2 = 0.60 \qquad df = 42.
\end{aligned}
$$

Difference in Annual Number of Days Below Minimum Passing Flow

The best-fit model (equation 6) for the difference in number of days below minimum passing flow between the two stations (BLODF) is a function of two independent variables--SEWER and total ground-water withdrawals (GWD). BLODF is directly related to SEWER at lags 0 and 1, and to GWD at lags 0, 1, 2, and 3. The correlation of both SEWER and GWD with BLODF is negative as a result of model-coefficient signs; consequently, as sewage output and ground-water withdrawals increase, the difference between the number of days that streamflow at Rahway is below minimum passing flow and the number of days that streamflow near Springfield is below minimum passing flow will increase. Like SEWER and TWD in the first two transfer-function models (equations 4 and 5), sewage output and ground-water withdrawals act to remove water from the gaged area, in this case causing the number of days below minimum passing flow at the Rahway station to increase relative to those at the station near Springfield. A time-series plot of observed and estimated difference in number of days below minimum passing flow is shown in figure 11.

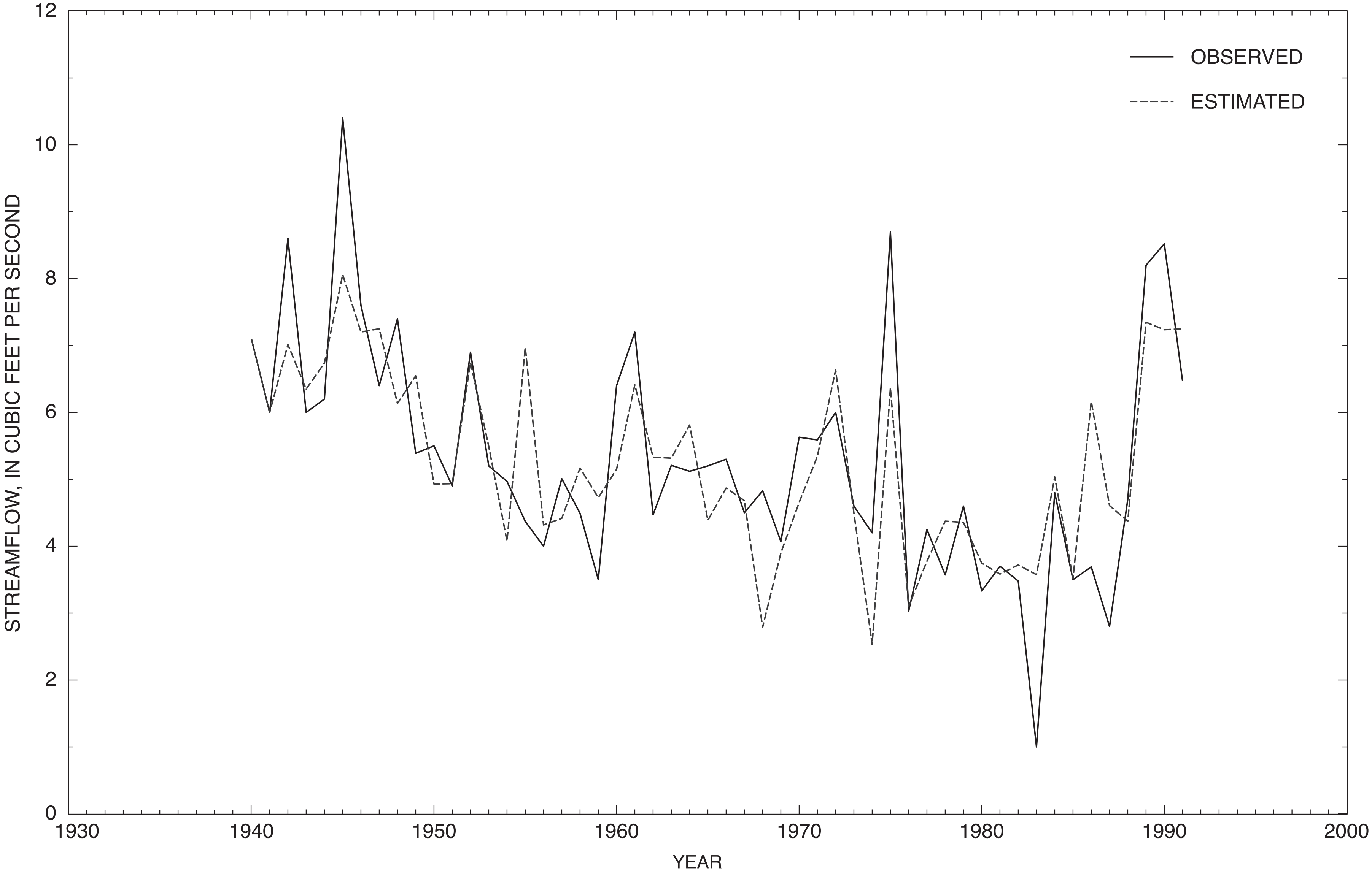

Figure 10. Observed and estimated annual mean 7-day low-flow difference, Rahway River at Rahway minus Rahway River near Springfield, N.J.

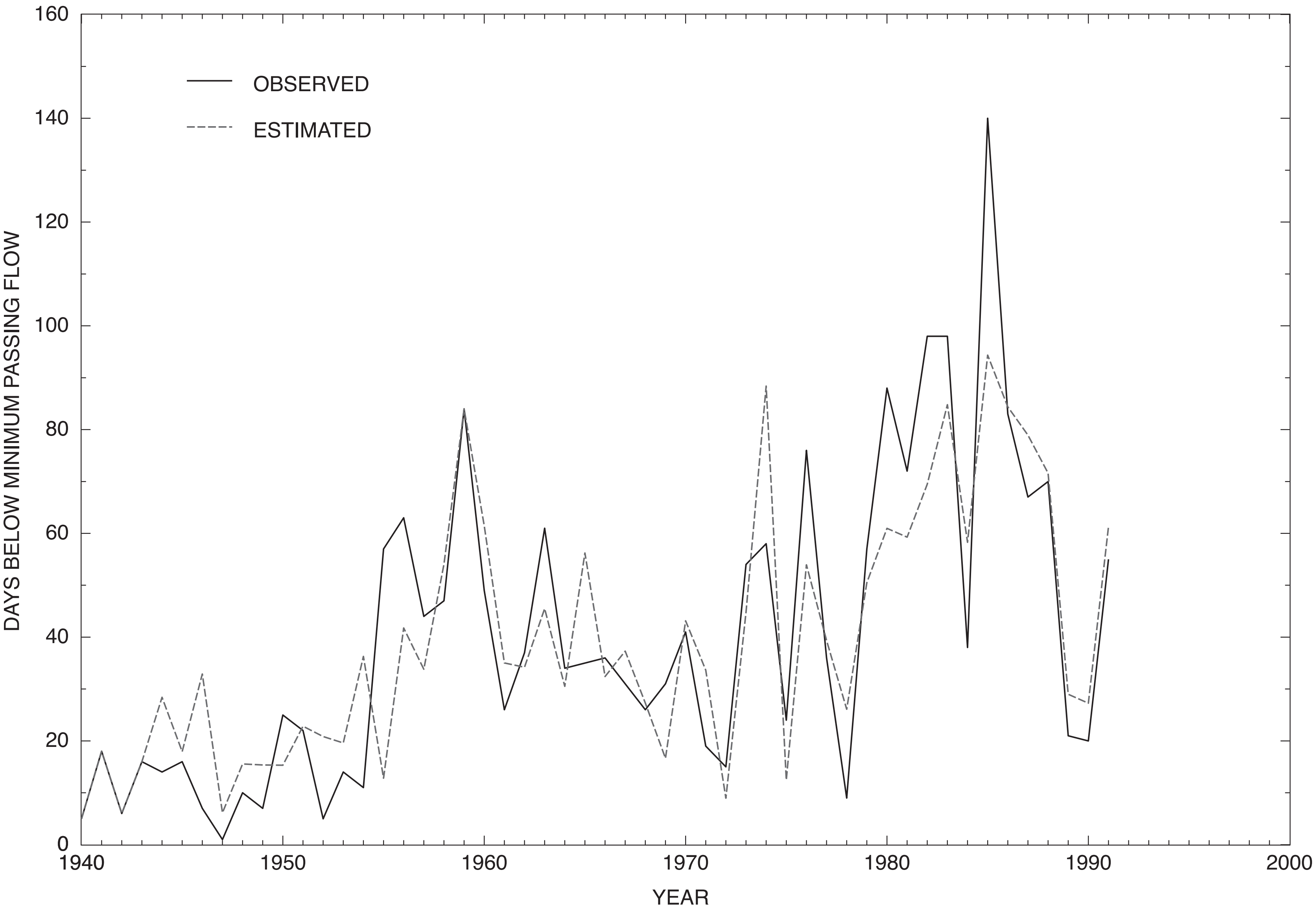

Figure 11. Observed and estimated difference in number of days below minimum passing flow, Rahway River at Rahway minus Rahway River near Springfield, N.J.

$$
\begin{aligned}
BLODF_t &= 42.3 - \underset{-7.07\ (***)}{3.98}\ [1\text{-}B]\ SEWER_t \\
&\quad + [\underset{-2.33(*)}{-23.3} + \underset{2.48(**)}{23.9}B^2]\ [1\text{-}B]\ GWD_t \qquad\qquad (6) \\
&\quad + [1 + \underset{3.59\ (***)}{0.494}B^3]\ A_t/\ [1 - \underset{4.97\ (***)}{0.622}B] \\
&\qquad R^2 = 0.70 \qquad\qquad df = 42.
\end{aligned}
$$

Other models

In the process of seeking best-fit models for the three measures of base-flow difference that were considered, more than 100 alternatives were evaluated. These models did not fit as well as those reported above for several reasons. Some of the models failed to converge as a result of numerical instability in the computations. In other cases, models that could be estimated successfully failed to satisfy stationary or invertibility conditions required by the mathematical assumptions upon which these models are based. A third, more obvious, reason is that significance levels of the model coefficients or goodness-of-fit R^2 values were lower than for the models ultimately selected. The options selected to perform estimation also can affect the result. Transfer-function models can be estimated either by the standard method of Box and Jenkins (1976) or by the common-filter method of Liu and Hanssens (1982). These methods generally produce similar, but not identical, results.

In addition to numerical and mathematical reasons for the unsuitability of the alternative models, the assumptions upon which the models rest can vary in degree of correctness. For example, the assumption of uniform population density requires the disaggregation of population data. Some independent variables that appear to be alternative measures of the same effect (for example, Union County road mileage and basin population density) have differences in dynamics to which time-series models are sensitive. As the basin was developed, values of both of these variables increased. When population decreased after 1970, however, the infrastructure, such as roads, that had increased with population inflow did not decrease with population outflow. Thus, correlation of these measures with a low-flow-difference measure can be strong during one phase of the development process but weak during another, resulting in a predictor that is mediocre overall.

COMPARISON OF TRENDS IN LOW-FLOW DIFFERENCES

All three low-flow measures show quadratic trends; those of untransformed BASDF and LO7DF fall, then rise, whereas that of the log of BLODF first rises, then falls. Although trend directions differ between the first two models and the third, trend effect is the same for all three models; that is, increasing differences in the first two flow measures lead to larger negative numbers, but increasing differences in the number of days below minimum passing flow lead to larger positive numbers. Thus, all three low-flow difference measures show similar trend effects. The extrema of the trends occur in 1970 (BASDF), about 1973 (LO7DF), and about 1983 (log BLODF). The shapes of the trend lines and the locations of their extrema probably are associated with the regional drought that ended in the mid-1960's as well as with population density, which increased in the basin until about 1970 and since has decreased to earlier levels. This pattern of increase followed by decrease also is observed in sewage output and in ground-water withdrawals by the city of Rahway--variables that are significant in explaining low-flow difference in the transfer-function models discussed below. Differences in the dynamics among the three measures, the presence of statistical noise in the data, and the shortness of the series are possible explanations for the loglinear trend of BLODF and the varying locations of the minima and maxima of the three trend relations.

RELATIONS OF LOW-FLOW-DIFFERENCE CHARACTERISTICS TO URBANIZATION AND PRECIPITATION

The similarities among models reveal more about the low-flow dynamics of the stream than does their detailed structure. In the first two models (BASF and LO7DF), the same three independent variables are present, although at different lags. Also, when coefficient signs and inverse/direct considerations are taken into account, the direction of effects is the same in both. Sewage output and total withdrawals are effects resulting from human activities. The third variable is regional precipitation. As discussed above, effects resulting from human activities tend to increase low-flow differences between the two stations, whereas precipitation acts to reduce them. The model for BLODF is a two-variable model in which only independent variables that represent human activities are present. As in the first two models, SEWER is present; in contrast, GWD also is present. This difference seems less important when it is recalled that TWD was significant in the first two models. Again, when signs are taken into account, the directions of effects are consistent among the three models. The fact that all three low-flow models contain independent variables that represent human activities, the effects of which act in a consistent direction, is convergent evidence that streamflow in the region served by the two streamflow-gaging stations is affected by urban development of the intensity found there. Moreover, the divergence in low flows that began around 1949 indicates that the threshold at which development affects this system is about the level observed then. As in an earlier qualitative study of two north-central New Jersey watersheds (Barringer and others, 1994), precipitation also appears to be a determinant of surface-water low flow. The importance of precipitation to the system is established by the presence of the PPT variable in two of the three models. Its absence from the third model may result from a difference in the dynamics of BLODF or from the numerics of estimating trends with this type of model with data series of minimal acceptable length.

A gross water budget for the part of the drainage basin that lies upstream from the gaging station at Rahway but downstream from the station near Springfield would show two inputs (flow from above Springfield and precipitation) and four outputs (flow out of the basin at Rahway, sewage diversions, total ground- and surface-water withdrawals, and evapotranspiration (ET)). If ET is ignored, the ratio of sewage and total withdrawals to precipitation would provide an indication of the relative effects of these variables on flow. Such a budget was constructed by first reducing total withdrawal amounts by 75 gallons (0.28 m^3) per day per capita to avoid double-counting when combining sewage and total withdrawals, converting all inputs and outputs to acre-feet per year, and computing the ratios of TWD, SEWER, and their sum to PPT. Because ET was assumed to be zero, estimates of the percentage of precipitation falling in the basin that is diverted by the city of Rahway are conservative. The input/output percentages for the budget are listed in table 1. The ratio of TWD + SEWER to PPT reached more than 92 percent by 1963. In 17 of 29 years from then through 1991, diversions by Rahway have exceeded 90 percent of basin precipitation. In seven of those years, diversions have exceeded 100 percent of basin precipitation. Diversions for the rest of the basin population outside the city of Rahway are not included in this estimate; those withdrawals must be statistically significant at some level, however. Because of basin scale, withdrawals by other communities upstream from Rahway are assumed to be positively correlated with those of Rahway.

Sewage is always the larger of the two types of diversions (TWD and SEWER). It exceeds total withdrawals by a factor of from 2 to about 8. In one year, sewage alone accounted for more than 102 percent of basin precipitation. The water budget and transfer-function models both show the importance of

Table 1. Percentage ratios of total withdrawals (TWD), sewage diversions (SEWER), and their sum to total precipitation (PPT) and ratio of sewage output to total withdrawals

[Withdrawal and diversion data are for Rahway, N.J. Precipitation data are for the part of the drainage basin of the Rahway River above the gage at Rahway and below the streamflow-gaging station near Springfield, N.J.]

Year	TWD / PPT	SEWER / PPT	TWD & SEWER / PPT	SEWER / TWD
1940	5.15	24.42	29.57	2.88
1941	9.41	28.41	37.82	2.01
1942	7.13	23.22	30.35	2.28
1943	10.66	33.69	44.36	2.24
1944	7.64	27.18	34.82	2.39
1945	6.14	25.95	32.08	2.78
1946	9.25	34.56	43.81	2.48
1947	7.61	31.27	38.88	2.72
1948	7.40	31.53	38.93	2.83
1949	9.70	43.22	52.92	2.82
1950	8.42	35.85	44.27	2.72
1951	8.61	34.92	43.53	2.71
1952	7.22	36.90	44.12	3.24
1953	7.65	40.44	48.08	3.24
1954	9.61	46.07	55.69	2.99
1955	8.52	51.30	59.82	3.68
1956	8.77	54.48	63.25	3.82
1957	11.21	66.08	77.28	3.66
1958	7.99	56.47	64.45	4.30
1959	9.95	60.58	70.53	3.70
1960	7.96	64.01	71.97	4.63
1961	9.25	78.11	87.37	4.87
1962	8.73	69.16	77.88	4.55
1963	10.50	82.28	92.78	4.45
1964	9.29	84.11	93.40	5.11
1965	10.50	94.73	105.24	4.87
1966	8.62	73.14	81.76	4.85
1967	10.44	76.10	86.55	4.61
1968	12.47	74.42	86.89	3.96
1969	9.33	67.79	77.11	4.58
1970	12.13	102.56	114.69	5.27
1971	8.16	84.89	93.05	6.36
1972	6.76	91.26	98.02	7.98
1973	7.40	87.25	94.65	7.32
1974	10.13	85.96	96.10	5.30
1975	6.26	62.95	69.20	6.09
1976	11.79	95.96	107.75	5.18
1977	9.26	80.64	89.91	5.52
1978	9.37	90.68	100.06	6.28
1979	8.15	77.96	86.11	6.06
1980	11.24	98.45	109.69	5.49
1981	9.12	93.27	102.39	6.03
1982	9.79	94.04	103.83	5.80
1983	6.57	59.39	65.96	5.64
1984	8.14	81.59	89.74	6.26
1985	9.51	76.38	85.88	4.93
1986	8.25	83.46	91.71	6.01
1987	7.99	77.51	85.49	5.75
1988	10.03	82.07	92.10	5.16
1989	8.16	81.19	89.35	6.26
1990	7.47	83.67	91.14	7.01
1991	9.35	85.68	95.03	5.72

diversions and precipitation to low flows in the Rahway River Basin.

SUMMARY AND CONCLUSIONS

Sewage discharges and water diversions in the Rahway River Basin, New Jersey, have significantly affected base flows in the region. In some years, diversion amounts have exceeded estimated basin precipitation. These exceedences are made up either by reducing ground-water levels (thereby reducing stream base flow) or by importing water from outside the basin. The effect of these diversions on base flow first was observed when diversion levels reached about 40 percent of basin precipitation input in the late 1940's. As diversion amounts continued to increase, the effect on base flow increased commensurately. Since 1963, when annual diversions first exceeded 92 percent of basin precipitation, diversions have exceeded 90 percent in 17 of the 29 years through 1991.

The two objectives of the study described in this paper were to (1) describe and characterize trends in low-flow characteristics at two streamflow-gaging stations in the study area during 1940-91, and (2) determine the effect of basin urbanization on selected low-flow characteristics of the Rahway River during that period. The first of these objectives was addressed with trend models, and the second with transfer-function models and a gross water budget. These show that the difference in low flows between the two gaging stations increased, then decreased, during the study period, as did the logarithm of the difference in the number of days below minimum passing flow. The trends in annual median base-flow difference (BASDF) and annual mean 7-day low-flow difference (LO7DF) reversed in the early 1970's, probably as a result of the end of the 1960's drought and the concurrent reversal in the direction of population change in the basin from a net increase to a net decrease. The logarithm of the difference in the number of days below minimum passing flow (BLODF) shows a similar pattern of effect, but with the minimum occurring later. In the transfer-function models, two of the three measures of base flow (BASDF and LO7DF) were significantly related to both the urbanization-related variables (TWD and SEWER) and regional precipitation (PPT). The third variable (BLODF) was exclusively related to variables associated with development (GWD and SEWER). The differences in low flows between the two streamflow-gaging stations clearly were affected by urbanization (as measured by population-related diversions) that occurred during the study period. Before 1950, differences in low-flow measures between the gaging stations near Springfield and at Rahway did not appear to be significant. After 1950, however, net outflows from the basin (that is, sewage, surface-water withdrawals, and outflow at the Rahway gage) became greater than net inflows (that is, precipitation and inflow at the Springfield gage) on a per-square-mile basis, resulting in reduced low flow. The threshold at which development affects low streamflows in the Rahway River Basin, therefore, is inferred to have been crossed when development reached the levels of the late 1940's. Most importantly, diversions significantly affect flows in the study area. Indeed, sewage diversions were observed to exceed total basin precipitation in one year, and combined withdrawals and sewage exceeded basin precipitation in several years from the 1960's on. Impervious surface can add to diversion effects by reducing ground-water recharge and, hence, base flow. In this study, however, road mileage in Union County--a surrogate for development and itself a measure of impervious surface--was not significant in any of the models. This also is true of new dwellings in Union County as represented by building permits. Thus, an impervious-surface effect in the basin could not be explicitly identified and, therefore, the effect of the interaction between impervious surface and diversions on low flows could not be determined. The failure of estimators of impervious-surface area to prove significant does not mean that such an effect is not present. Larger areas of impervious surface or better estimators of impervious surface than those used in this study could result in a significant relation. In this basin, base-flow differences between the two gaging stations began to appear in the late 1940's, when total withdrawals plus sewage reached about 40 percent of basin precipitation. If the assumption of positive correlation of diversions is correct, and given that evapotranspiration was omitted from the analysis, the actual percentage is probably somewhat greater. Convergent evidence provided by the transfer-function models and the water-budget analysis clearly identifies the importance of diversions in determining base flow in the Rahway River Basin. Although an effect of impervious surfaces on base flow was not found in this study, it is likely to become significant in the future. The results reported here are conditioned on basin geohydrology, spatial and temporal patterns of urbanization, and local precipitation patterns. Direct transferability of results is therefore likely to be imperfect. The methodology, in contrast, can be used wherever data are adequate to support its application.

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