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A HYDROLOGIC WATER RESOURCE SYSTEM MODELING TECHNIQUE

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ABSTRACT

The record Northeastern United States drought of the 1960's has necessitated a detailed reappraisal of water resource systems previously proposed in the affected areas. The ability to judge the competency of proposed engineering structures in the Delaware basin has been hampered by the diversity of projects, the political constraints on existing projects in the upper portion of the basin and the numerous alternative demands on available surface water. To facilitate analysis of the effects of the drought, a mathematical modeling technique has been developed to allow simulation of the hydrologic properties of the lower Delaware basin and proposed engineering structures. The technique and its application to the Delaware are discussed. The results of the reappraisal of project yields utilizing the model are presented and compared with pre-1960 yield estimates.

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THE DROUGHT AND THE DELAWARE

Perhaps the greatest surface water supply demand in the United States is generated in the populous northeast. The record drought in this section of the country which exceeded previous records began in August 1961 and persisted for a period of six years. Subnormal precipitation and deficient water supplies occurred over an area extending from Maine to Virginia and at times westward to Indiana. The most continuously dry weather occurred in northern New Jersey and southeastern New York. Within the Delaware River Basin there was an accumulated surface water deficiency equivalent to more than two and a half years of normal runoff.

Precipitation over the Delaware Basin was below normal for six consecutive years, from August 1961 through May 1967.[3] Historical records indicate that droughts of this length and severity in this part of the United States have a recurrence interval of about once in every 140 years.[4] Precipitation and stream flows for the drought fell below all minimums recorded in the previous 1930-31 basin-wide drought of record. A study of the drought of the 1960's for flows at Montague, New Jersey on the Delaware River indicates that the minimum 18- and 30-month flows have recurrence intervals of approximately 500 years and 400 years, respectively.[5]

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[3]Delaware River Basin Commission Resolution 67-3, dates 15 March 1967

[4]Palmer Drought Index

[5]Probability of Allowable Yields in the Delaware River Basin, by Clayton H. Hardison, USGS, Washington, D. C.

In comparison, the previous 1930 drought of record had recurrence intervals of 12.5 years and 15.5 years for the 18- and 30-month minimum flows.

Although the Delaware River Basin has a drainage area of approximately 13,000 square miles, its service area is much larger. The water service area of the basin includes about 25,000 square miles comprising 53 counties located in the states of Delaware, Pennsylvania, New Jersey, New York, and Connecticut. The water resources of the basin are fundamental to the economic and social well-being of some 25 million people who live within the water service area, most of whom live within the Wilmington-Phildelphia-New York City urban corridor.

Figure 1 shows the limits of the basin and its general water service area. An interconnected three-reservoir-system is a major water supply source for New York City in the upper portion of the basin in New York State. The downstream releases and out-of-basin diversions from the three reservoirs (Cannonsville, Pepacton, and Neversink) are regulated by Supreme Court Decree[6] which limits diversions to 800 m.g.d. and requires maintenance of minimum flows downstream at Montague, New Jersey (Milford, Pa.) to 1,750 cfs. These three reservoirs control 915 square miles of the total drainage area of 3480 square miles above Montague. A brief description of the system is presented below.

[6] 1954, Amended U. S. Supreme Court Decree, 347 US 995 (1954)

The proposed development of the water resources of the Delaware River Basin was embodied in a comprehensive study which culminated in a plan[7] for eight major federal and numerous smaller reservoirs, and the creation of a joint federal-state commission to administer basin water resources. The resulting Delaware River Basin Commission adopted the comprehensive plan as its own and subsequently evoked emergency powers[8] to control diversions during the record drought. With the conclusion of the drought it became evident that a reappraisal of the yield prospects of major reservoirs in the comprehensive plan would be required.[9]

NEW YORK CITY RESERVOIR SYSTEM

The New York City water supply system is comprised of three major reservoir sub-systems; the Croton, Catskill and the Delaware. The Delaware sub-system on the western and southern slopes of the Catskill Mountains is over 100 miles from New York City and uses Rondout Reservoir in the Hudson for intermediate storage by conduit connection. Rondout Reservoir is located on Rondout Creek, a tributary of the Hudson River, and has a capacity above minimum operating level of 153,250 acre feet, (50 billion gallons). Neversink, Pepacton and Cannonsville Reservoirs have capacities above minimum operating levels and watershed areas of 107,300 acre feet (35 billion gallons) and 93 square miles, 429,100 acre feet (140 billion gallons) and 375 square miles and 294,200 acre feet (96 billion gallons) and 45 square miles, respectively.

[7]House Document 522, 87th Congress - 2nd Session

[8]Delaware River Basin Compact

[9]"River Basin Management", An Interstate Approach by James F. Wright, No. 6058, Vol. 94, Journal of Hydraulics Division, ASCE, Aug. 1968

The Delaware Aqueduct can deliver water to New York City via Rondout at a maximum rate of about 890 million gallons per day. This 890 m.g.d. capacity compares with capacities of 590 m.g.d. from the Catskill Aqueduct, 290 m.g.d. from the Corton Aqueduct, and a Supreme Court Delaware Decree limiting rate of 800 m.g.d.

COMPREHENSIVE PLAN RESERVOIR SYSTEM

The comprehensive plan includes eight major reservoirs above Trenton, in addition to the three owned and operated by New York City. Of the eight reservoirs, two are already in operation, but have not been modified to include water supply storage, one is under construction and three are in preliminary design stages. The eight reservoirs are : Prompton, Tocks Island, Francis E. Walter, Beltzville, Aquashicola, Trexler, Hackettstown, and Tohickon. All of the reservoirs, except Prompton, are located below Montague, New Jersey. Figure 1 shows the location of the eight comprehensive plan and New York City reservoirs with respect to the Delaware River Basin above Trenton. Six projects are to be developed by the federal government with significant local cooperation, the Hackettstown and Tohickon projects to be developed by non-federal interests. Table 1 below gives pertinent details for each of the eight reservoirs.

RE-EVALUATION OF THE NEW YORK CITY DELAWARE SYSTEM YIELD

In the Amended Decree of the U. S. Supreme Court, dated 7 June 1954, New York City was authorized to divert water from its reservoirs in the Delaware River Basin, and was required to make compensatory releases to the Delaware River to maintain certain minimum rates of flow at the gaging station at Montague, New Jersey. Diversions equivalent to 800 m.g.d. were authorized by the decree with all three New York City reservoirs in full operation.

TABLE 1

PERTINENT DATA - COMPREHENSIVE PLAN RESERVOIRS

BASIN	PROJECT NAME	DRAINAGE AREA SQ.MI.	EXISTING PROJECT TO BE MODIFIED	NEW PROJECT	EXISTING PROJECT PURPOSES	FUTURE PURPOSES	TOTAL FUTURE STORAGE ACRE-FEET	FUTURE WATER SUPPLY STORAGE ACRE-FEET
Lackawaxen River	Prompton	60	X		Flood Control Minor Recreation	Water Supply, Flood Control, Recreation	51,700	28,000
Delaware River	Tocks Island	3827		X	---	Water Supply, Flood Control, Hydropower, Recreation	845,400	425,600
Leigh River	F. E. Walter	288	X		Flood Control, Recreation (Controlled Conservation Storage of 20,000 A-F)	Water Supply, Flood Control Recreation	180,000	70,000
Pohopoco Creek	Beltzville	96		(Under Construction)	---	Water Supply, Water Flood Control, Recreation	68,250	39,800
Aquashicola Creek	Aquashicola	66		X	---	Water Supply, Flood Control, Recreation	45,000	24,000
Jordan Creek	Trexler	52		X	---	Water Supply, Flood Control, Recreation	39,000	24,200
Musconetcong River	Hackettstown (Non-federal)	70		X	---	Water Supply, Recreation	23,000	22,000
Tohickson Creek	Tohickson (Non-federal)	75		X	---	Water Supply, Recreation	31,500	30,000

The decree specified that the compensatory releases were to be made from one or more of the reservoirs and was designed to maintain a minimum basic rate of flow at Montague of 1,750 cfs; in addition, excess quantities of water, depending upon New York City consumption, were to be released beginning 15 June each year and to be continued not later than the following 15 March.

In reappraising the safe yield for the Delaware System for the drought of the 1960's, both the office of the Delaware River Master and the New York City Department of Water Supply, Gas, and Electricity (now the Bureau of Water Resources) were requested to undertake separate studies. The studies by the two organizations were carried out as parallel but separate work and generally used the same methodology.

In the analysis the amount of water available was considered to include full reservoirs at the beginning of the period and the inflow which was actually received. For each reservoir the usable capacity was that allowable above the minimum operating level. The three reservoirs were analyzed in combination. The draft requirements were diversion to New York City for water supply, and releases to maintain specified flow rates of the Delaware River at Montague, New Jersey. Releases were made at "conservation" rates when a larger rate was not required to maintain the applicable minimum flow at Montague. Conservation rates were defined as minimum releases to maintain at all times a suitable streamflow below the reservoirs.

Several "design" or specified minimum flow rates at Montague were studied rather than different diversion rates for ease of computation. Various design rates ranging from 0 to 2,650 cfs were considered.

It was assumed that the three reservoirs would be operated as a unit so that, after considering inflow, the contents of the reservoirs would be maintained at equal per cent capacity. It was also assumed that the combined capacities of individual reservoir outflow facilities could accommodate all releases and this was found to hold true in all cases examined. Monthly flow data were used, except daily data were substituted for months of the critical period.

These data were used as basic upper basin inflow for study of drought effects downstream. The results of the individual studies by both the City of New York and the Delaware River Master were essentially the same and are summarized in table 2.

A comparison of N.Y.C. diversion rate for the drought of the 1930's and that of the 1960's, with a design rate of 1,750 cfs being maintained at Montague, shows a capability of 800 mgd for the 1930's versus 480 mgd for that of the 1960's.

TABLE 2[10]

RELATIONSHIP OF DIVERSIONS AND RELEASES - NEW YORK CITY RESERVOIRS - DROUGHT OF 1960's

DESIGN RATE AT MONTAGUE C.F.S.	DIVERSION RATE M.G.D. Del. River Master Analysis	New York City Analysis
1750 and 2650 1/	225	235.7
1750 and 2200 1/	354	---
1750 2/	482	482.3
1700 2/	502	---
1525 2/	576	579.1
1400 2/	---	622.1
1200 2/	680	683.3
1000 2/	---	734.6
950 2/	743	---
0 3/	821	822.5
0 4/	848	848.1

1/ 2650 and 2200 cfs are rates for excess release period only

2/ No Excess Releases

3/ Conservation Releases Only

4/ Excluding all Downstream Releases

10/ Results of New York City and Delaware River Master studies as presented in Delaware River Basin Commission Committee Report Chapter 2 Section 9

MODELING REQUIREMENTS

With the chronological limits of the drought defined and the reservoir system and upstream flow constraints delineated, four decisions were required before developing a mathematical simulation model for yield analysis. Each decision is discussed below.

a. Flow Records The use of streamflow records in simulation models requires that the averages for the time period employed (daily, weekly or monthly average flows) reasonably describe actual flow histograms. If large deviations from averages occur during the beginning and later periods of a drought, and the length of drought is short with respect to these deviations, a significant error in the estimate of yield or required storage may result.

The continuous yield available from a single reservoir is simply the sum of the storage and the accumulated inflow minus losses, such as evaporation, divided by the duration of drawdown. During the duration of drawdown it is further understood that the storage at any intermediate time can be no greater than the initial value. Conversely, at no time, except at the end of the drawdown period, can the storage be less than the minimum available if the yield is to be continuous. These relationships may be expressed mathematically as follows:

$$Y = \left(S_1 - S_2 + \sum_{T = T_1}^{t = T} (I_t - E_t)\right) / (T_2 - T_1) \; ; \qquad (1)$$

$$S_1 + \sum_{t = T_1}^{t = i} (I_t - E_t - O_t) \geq S_2 \; ; \qquad (2)$$

and

$$S_1 + \sum_{t = T_1}^{t = i} (I_t - E_t - O_t) \leq S_1 \quad ; \qquad (3)$$

where:

Y = average continuous yield,

S_1 = initial storage available,

S_2 = minimum storage available,

t = time period number,

T_1 = first time period number,

T_2 = last time period number,

I_t = inflow during time period t,

E_t = losses, including evaporation, during time period t,

O_t = outflow during time period t,

i = any time period between T_1 and T_2, inclusive.

The most accurate method of determining the error resulting from hydrologic modeling using longer period streamflow records would be to compare the results of two models, one using longer period flows such as monthly averages, and the other using shorter period records such as daily flows. Such a luxury was not available for this study. An estimate of the potential errors inherent in the use of monthly average streamflow records was assumed to be the magnitude of errors resulting from predicting local continuous yields on a monthly basis, and then using daily records to check the prediction. The assumption was further simplified by neglecting evaporation and variations in yield requirements (potential errors from these sources have been investigated previously[11/]).

11/ Techniques for Evaluation of Long-Term Droughts, by A. J. Fredrich, Presented at ASCE Water Resources Conferences, New Orleans, Feb. 1969.

Streamflow records selected for analysis were those required for simulation of daily reservoir system operation and are listed in table 3. The period of record utilized was from June 1960 through May 1967.

Storage at the end of any day in excess of the starting value was ignored. If in making the continuous yield release the hypothetical reservoir storage was negative, the release was limited to the inflow for the day and the average outflow available from the storage remaining at the beginning of the day. The flowing equations were then assumed to represent the magnitude of yield and storage errors in the use of average monthly and daily streamflows.

$$E_Y = \left(\frac{Y_m - Y_d}{Y_d}\right) 100 \qquad (4)$$

$$E_S = \left(\frac{S_m - S_d}{S_d}\right) 100 \qquad (5)$$

where:

E_Y = potential error, in per cent, in yield estimates using monthly in place of daily streamflow records,

Y_d = average yield using daily flows,

Y_m = average yield using monthly flows,

E_S = potential error, in per cent, in estimates of storage required to maintain Y_m,

S_m = storage required to maintain Y_m using monthly flows,

S_d = storage required to maintain Y_m using daily flows.

The errors were then plotted against the yield expressed as a percentage of the average annual flow. An enveloping function was drawn to represent the upper limit of each type of potential error. Figure 2 is a typical plot.

Table 3 summarizes the maximum potential yield and storage errors from enveloping functions for each streamflow record studied.

The relative order of magnitude of the potential yield error indicated in table 3, possible use of the model for simulating hydroelectric power facilities on a daily basis and the necessity for determining flow-durations for period other than calendar months, resulted in the use of daily flows in the simulation model.

b. Flow Requirements. Individual reservoir yields are generally based upon a demand at a single point. With a system of reservoirs, however, the demands at downstream points controlling more than one reservoir must be considered. For the Delaware, a single downstream control point at Trenton was selected as critical. The basic constraint on the entire system, therefore, was the determination of the maximum flow which could be maintained at Trenton throughout a recurrence of the drought. In addition, conservation requirements immediately below each project will require a minimum release at all times, and the possibility of out-of-basin diversions must be considered. Variability in demand with respect to time was not considered.

c. Reservoir Operation. Recreation, water supply and flood control requirements at each project will allow the use of operational rule curves, or time variable desirable conservation pool levels. The additional project at Tocks Island, hydropower, will allow the use of multiple rule curves. Accordingly, the model must take cognizance of individual reservoir operational constraints. Individual rule curves for each project, with two for Tocks Island, were, therefore, specified.

TABLE 3

ESTIMATED CONTINUOUS YIELD AND STORAGE ERROR USING MONTHLY FLOWS

(June, 1960 through May, 1967 period)

Streamflow Station	Mean Annual Flow-cfs	Yield as Percentage of Mean Annual Flow	Storage dsf	Yield Error % Ey	Storage Error % Es
Delaware River @ Montague, N.J. (adjusted to reflect operation of NYC reservoirs) during the drought	6,408	19.6	20,270	4.9	35.5
Delaware River @ Montague, N.J. (historical)	6,408	25.3	165,340	6.2	12.3
Bushkill @ Shoemakers	238	19.7	2,740	7.6	14.8
Lehigh River @ Walter Dam	196	35.6	1,080	6.3	47.0
Inflow, Walters Dam	196 est.	43.5	1,970	7.9	38.5
Lehigh River @ Walnutport	1,940	13.7	5,480	5.8	32.3
Pohopoco Creek near Parryville	228	34.7	8,320	6.5	12.3
Aquashicola Creek near Palmenton	158	9.5	155	4.7	26.6
Jordon Creek @ Allentown	118	25.5	4,400	5.2	8.2
Jordon Creek near Schnecksville	92 est.	32.2	126	26.8	297.7
Lehigh River @ Bethelehem	2,294	49.8	105,200	4.7	10.4

TABLE 3

ESTIMATED CONTINUOUS YIELD AND STORAGE ERROR USING MONTHLY FLOWS

(Contd.)

Streamflow Station	Mean Annual Flow-cfs	Yield as percentage of Mean Annual Flow	Storage dsf	Yield Error % Ey	Storage Error % Es
Musconetcong River Hackettstown	121	25.2	1,660	4.2	13.2
Delaware River @ Belvidere	8,223	23.3	78,480	3.2	13.7
Delaware River @ Regilsville	11,260	24.8	83,400	2.4	9.7

System operation, and the resulting determination of individual project releases to meet downstream requirements, was based on allocation of the flow deficiency at the downstream control point. An index parameter was used which included consideration of a combination of storage remaining in the individual project below specified rule curves as a percentage of the total storage left in the system, and the ability of the individual reservoir to refill itself to maximum conservation pool level under an assumed minimum future inflow condition. By using such a combination, consideration is given to both existing and potential (future) conditions.

The actual future inflows could be used in a "hindsight" evaluation. Conversely, a prediction of future flows could be used which would take into account some estimate of minimum future inflows. It was desirable that the model not be of the hindsight type, i.e. that it embody only knowledge of what has occurred to form a basis for future reservoir operation. Accordingly, minimum historical sequential flows were used to project future storage levels in the allocation of releases.

The mathematical relationships used to determine the necessary individual project release for each day of simulated operation are as follows:

$$R_R = C_R + K_R + WS_R \tag{6}$$

$$K_R = (S_R - RC_R) - C_R \tag{7}$$

$$WS_R = IVOL\ (D_R) \tag{8}$$

and

$$D_R = \{(RC_R - S_R) / \sum_{R=1}^{N} (RC_R - S_R)\} \; (I - T_R/I) \qquad (9)$$

where:

R_R = average daily reservoir release in cfs,

C_R = required daily conservation release in cfs,

K_R = average daily flood control release in cfs,

WS_R = average daily supplemental release from reservoir R in cfs

S_R = projected storage in reservoir R, in dsf, at the end of the day with evaporation but no releases,

RC_R = rule curve storage in dsf,

C_R = average daily conservation release in cfs,

IVOL = total daily reservoir system release required at Trenton, in cfs,

D_R = release distribution factor for reservoir R,

T_R = time in months, to fill reservoir R from its present level to its rule curve assuming minimum future inflow,

I = arbitrary maximum reservoir filling period of 12 months.

d. Routing Requirements. The short time frame selected, one day, requires downstream routing of reservoir inflow holdouts and subsequent releases from their respective locations in the basin. Considering the time frame of one day, a simple travel time - volume algorithm was employed which allows the time of each reservoir's operation to be adjusted to the time at the downstream control point. That is, releases from reservoir R to meet downstream flow requirements would begin the number of travel time hours before the beginning of the day at the downstream control point and continue for a full day. Therefore, each day's release from each reservoir would be composed of any flood control release, miminum conservation release and the allocated and routed supplemental water supply demands on two different days.

With the method of determining reservoir releases established, it is then necessary to develop the algorithm for ascertaining the maximum flow which could be maintained at the downstream control point during the simulated drought. The method employed is simple interval halving. An initial estimate of the maintainable flow at the control point is assumed and the system operated until any of the reservoirs becomes empty, or until the period of simulation has been completed. If no reservoir was emptied, the maintainable flow is increased; conversely, if a reservoir(s) was emptied the maintainable flow has been assumed, a new value equal to half the previous estimate is furnished. If a previous lower estimate was made, a new value equal to the average of the present and previous lower values is computed. Conversely, if the maintainable flow is to be increased, and no higher previous estimate was made, a new maintainable flow equal to twice the present value is computed. If a larger value had been tested, the new value of the maintainable flow is computed as the average of the higher and present values. With a new estimate of the maintainable flow available, simulation is again begun and the process repeated until the difference between successive estimates is within a specified tolerance, or until a specified maximum number of iterations have been made.

THE MODEL

The reservoir system, the general method of analysis and its internal and external constraints are discussed above. With these in mind, the final requirements for the model are the determination of the locations of streamflow simulation in the model, the "design" features to be studied, and the statement of the logical methodology required for conversion to instructions necessary for computer processing. Figure 2 shows the locations of 15 gaging stations that were used as key flow points in the model. These stations were selected for use as either a means of determining inflow into a reservoir, or as a streamflow routing check point and for computing intervening area flows. Inflows into the reservoirs were computed by two methods. Where gaging station records were available in the same watershed, simple drainage area ratios were used to adjust such records to approximate inflow. Where such records were not available, correlation relationships with streamflow data elsewhere in the area were used.

The gaging stations employed, and their use, are listed below.

GAGING STATION USE

RESERVOIR INFLOWS

Project	Use	Gage Locations
1. Tocks Island	Inflow	- Delaware River @ Montague, N. J.
	Inflow	- Bushkill Creek @ Shoemakers, Pa.
2. F. E. Walters	Inflow	- determined from existing pool. Lehigh River @ White Haven, Pa.
3. Beltzville	Inflow	- Pohopoco Creek @ Parryville, Pa.
4. Aquashicola	Inflow	- Aquashicola Creek @ Palmerton, Pa.

GAGING STATION USE

RESERVOIR INFLOWS

(Contd.)

Project	Use	Gage Locations
5. Trexler	Inflow	- Jordan Creek near Allentown, Pa. (June 1961 - Sept 1966) Jordan Creek near Schnecksville, Pa. (Oct 1966 - May 1967)
6. Hackettstown	Inflow	- Musconetcong River @ Hackettstown
7. Tohickon	Inflow	- Tohickon Creek @ Pipersville

INTERMEDIATE CHECK POINTS-AND INTERVENING FLOW

Delaware River

Delaware River at Belivdere, N. J.
Delaware River at Riegelsville, N. J.
Delaware River at Trenton, N. J.

Lehigh River

Lehigh River at Walnutport, Pa.
Lehigh River at Bethlehem, Pa.

The "design" features required for simulation by the model are as follows:

a. Variable control of inflow to the largest reservoir in the system; i.e., control of inflows to Tocks Island Reservoir by the New York City Delaware River Reservoir System at various minimum or "design" levels;

b. Staging of projects in the system; i.e., the effects of various combinations of reservoirs in the system;

c. Variable individual project water supply storage capacities;

d. Variable diversions from reservoirs and/or downstream control points.

The statement of the methodology of the logical process of reservoir and control point simulation is shown in figures 4 and 5. Each descriptive block indicates a logical separable process or event. Lined arrows connecting the blocks illustrate the sequence of events within the model. The statement of this methodology allowed the direct development of the computer program employed for use in the Delaware Basin.

For each day of simulation, the following process is followed:

a. compute the differences between anticipated and regulated flows at Montague and route the resulting holdouts (differences) to downstream control points without reservoir regulation;

b. determine all reservoir inflows and route differences between inflows and observed flows to downstream control points;

c. make mandatory conservation, power and flood control releases from all reservoirs, adjust reservoir storages and route inflow-outflow holdouts to downstream control points;

d. if the resulting flow at Trenton is less than the estimated minimum maintainable flow (TGOAL), allocate the difference, or supplement, among the upstream reservoirs, route the allocated releases and adjust storages.

e. if any reservoir in the system is drawn below its stipulated minimum operating level, or if the simulation period is over, compute a new estimated maintainable flow, and start simulation again.

f. if no reservoir is empty, or if the simulation period is not over, compute reservoir and flow statistics, advance calendar one day and repeat process.

The relative size of the model and its algorithm required the availability of a large-scale computer system. A Control Data Corporation CDC-6600 computer system at New York University and an IBM 360, model 65, at the University of Pennsylvania were employed.

The results of the use of the model in determining project yields and downstream maintainable flows by simulating the 1960's drought in the Delaware Basin, and a comparison with similar data previously developed for the second most severe 1930's drought, are presented in the following section.

CAPABILITY OF MAJOR RESERVOIR PROJECTS IN THE COMPREHENSIVE PLAN

Figures 1 and 2 show the location of the eight reservoirs in the comprehensive plan, the location of upstream reservoirs, and intermediate stream gaging stations which were simulated in the model to determine the effects of the recent (1961-67) drought. Table 1 lists the pertinent statistics for each reservoir in the comprehensive plan and indicates its present state of development. Water use studies made prior to the recent drought indicated that the 1930-32 period was the driest of record and yields based on this period, using monthly flow, are presented in table 5 for reference. The operation of the three New York City Delaware Basin reservoirs during the 1960-1967 period was not in accordance with the 1955 Amended Supreme Court Decree. Cannonsville was completed during the period and was not sufficiently filled to require meeting a 1750 cfs goal at

TABLE 4

RESERVOIR-STREAMFLOW STATION TRAVEL TIMES

Location	to	Location	Estimated Travel Times (Hrs.)
Tocks Island Reservoir		Belvidere	9
Belvidere		Riegelsville	6
Hackettstown Reservoir		Riegelsville	8.5
Walter Reservoir		Walnutport	20
Beltzville Reservoir		Walnutport	10
Aquashicola Reservoir		Walnutport	4
Walnutport		Bethlehem	16
Trexler Reservoir		Bethlehem	18
Bethlehem		Riegelsville	12
Tohickon Reservoir		Trenton	11
Riegelsville		Trenton	14

TABLE 5

COMPARISON OF CONSTANT PROJECT YIELDS[1]

Project	1930's Drought[2] Yield Estimate cfs	1960's Drought[3] Yield Estimate cfs
New York City Reservoirs	1240	747[4]
Prompton	66	68
Tocks Island	2777	2835
Walter	268	288
Beltzville	105	88
Aquashicola	78	76
Trexler	68	40
Hackettstown	85	57
Tohickon	54	41

[1] assumes 1750 design rate @ Montague

[2] using monthly pre-1960 flows

[3] using daily flows

[4] no excess releases

Montague. Furthermore, the depletion of the system required the implementation of emergency operations under control of the Delaware River Basin Commission. Because of the obviously limited amount of water available during the period, it was decided that flow would be simulated at Montague for several selected "design rates" varying from 950 to 2650 cfs. The reconstitution of Montague flows under a fully usable three-reservoir New York City Delaware System was accomplished by the New York City Department of Water Resources, Bureau of Water Supply, and checked by comparable computations made by the Delaware River Master. Data furnished for the lower basin model consisted of information from which the reconstituted Montague flows (June 1, 1961 to May 31, 1967) could be easily computed for any desired "design rate", or minimum flow.

Because of the location and relative size and effective contribution of Prompton Reservoir and Lake Wallenpaupak (a Lackawaxen Basin recreation-power reservoir) with respect to the other reservoirs in the system, it was concluded that simulation of these projects would not be required. Studies made for modification of Prompton Reservoir to include permanent water supply storage have been accomplished[12] and include the evaluation of the "1960's" drought through 1966. It was concluded, therefore, that the relatively small yield of 68 cfs from this project could be more easily added separately to the Tocks Island yield.

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[12] U.S. Army Engineer District, Philadelphis, Prompton Reservoir, Hydraulics and Hydrology Design Memorandum No. 10, dated Oct. 1966.

The specific numerical information desired from the model simulation of the 1960's drought consists of the following:

a. The maximum flow which could be maintained at Trenton for different minimum flow rates at Montague between 1000 and 2650 cfs with only Tocks Island Reservoir in operation;

b. The maximum flow which could be maintained at Trenton for different minimum flow rates at Montague between 1000 and 2650 cfs with Tocks Island and Beltzville Reservoirs in operation;

c. The maximum flow which could be maintained at Trenton for different minimum flow rates at Montague between 1000 and 2650 cfs with Tocks Island, Beltzville, Aquashicola, Walter, Trexler, Hackettstown, Tohickon and Prompton Reservoirs;

d. The average individual yield available from Tocks Island, Beltzville, Aquashicola, Walter, Trexler, Hackettstown, Tohickon and Prompton Reservoirs;

e. The additional potential yield available from use of Tocks Island storage between elevations 328 and 356 which is presently being considered as a minimum power pool;

f. The effects of out-of-basin diversion under the following two alternatives:

(1) 300 m.g.d. constant daily withdrawal from the Delaware River at Frenchtown, N. J.

(2) 150 m.g.d. constant daily withdrawal from Tocks Island Reservoir and 150 m.g.d. constant daily withdrawal from the Delaware River at Frenchtown, N. J.

Travel times between reservoirs and key stream gaging stations were based on data presented in the basin report referred to previously. Data available from gaging stations along the Lehigh River and the lower Delaware for actual releases from Walter Reservoir were used to check applicable travel times. The results indicated that the basin report values, presented in table 4 are quite variable within a probable range of at least ± 25 per cent. Table 6 lists maximum maintainable flow which could have been anticipated at Trenton, and the average yield from each project, during the 1960's drought as a function of the "design rate" at Montague, reservoir staging, individual project water supply storage and extra-basin diversion rates.

Comparison of project yield estimates for a Montague "design rate" of 1750 cfs with estimates using the 1930's drought is made in table 5. It is noted that only a general comparison can be made because of the two time frames used to make each estimate. The 1930's drought yield estimates were based on monthly flow records and are not considered as accurate as the estimate for the more recent period using daily flows. The table does, however, illustrate the relative severity of the 1960's drought in the upper and lower portions of the basin.

Figure 6 is an illustration of the relationship between the minimum flows maintainable at Trenton as a function of the Montague "design rate." Different curves are provided for the various reservoir staging assumptions. Table 6 summarizes the results of the entire analysis.

TABLE 6

Condition Code*	Minimum Montague Flow (DSF)	MINIMUM STORAGE ATTAINED IN EACH RESERVOIR Tocks Island** (DSF)	F.E. Walter (DSF)	Beltzville (DSF)	Aquashicola (DSF)	Trexler (DSF)	Hackettstown (DSF)	Tohickon (DSF)	Date of Maximum Drawdown
A	1000	48494	279	1404					26/12/64
B	1000	48756	234						26/12/64
C	1000	9527	-85						26/12/64
D	1000	48586	55	752					26/12/64
E	1000	48797	188	972					26/12/64
F	1000	55562 (1)	6935 (1)	4457 (1)	2557 (1)	1919 (2)	503 (3)	2281 (2)	(1) 26/12/64 (2) 25/12/65 (3) 11/02/66
A	1400	48582	440	1808					26/12/64
B	1400	48681	232						26/12/64
C	1400	9839	153						26/12/64
D	1400	48903	159	828					26/12/64
E	1400	48621	105	875					26/12/64
F	1400	56954 (1)	7455 (1)	4780 (1)	2757 (1)	1911 (2)	507 (3)	2293 (2)	(1) 26/12/64 (2) 25/12/65 (3) 11/02/66
A	1750	48573	432	1708					26/12/64
B	1750	48622	138						26/12/64
C	1750	10073	262						26/12/64
D	1750	48591	24	729					26/12/64
E	1750	48776	156	913					26/12/64
F	1750	60907 (1)	8059 (2)	5016 (3)	2964 (2)	1940 (3)	496(4)	2366 (3)	(1) 27/12/64 (2) 26/12/64 (3) 25/12/65 (4) 11/02/66
A	2650	48435 (1)	509 (2)	3008 (3)					
B	2650	48697 (4)	484 (5)						
C	2650	9676 (2)	535 (3)						
D	2650	48774	82	734					26/12/64
E	2650	48611 (6)	123 (1)	815 (1)					
F	2650	56940 (2)	8623 (1)	5401 (1)	3177 (1)	2098 (7)	507 (6)	2516 (6)	(1) 26/12/64 (2) 12/02/66 (3) 28/09/64 (4) 07/02/65 (5) 24/11/64 (6) 11/02/66 (7) 25/12/65

TABLE 6 (Cont'd)

Condition Code*	DEPENDABLE YIELF OF EACH RESERVOIR Tocks Island *** (DSF)	F.E. Walter *** (DSF)	Beltzville *** (DSF)	Aquashicola *** (DSF)	Trexler *** (DSF)	Hackettstown *** (DSF)	Tohickon *** (DSF)	Maximum Maintainable Trenton flow (DSF)
A	2197 (G)		88 (I)					3302
B	2197 (G)							3199
C	2431 (H)							3423
D	2197 (G)		88 (I)	76 (G)	40 (J)	57 (K)	41 (L)	3226***
E	1965 (G)		88 (I)	76 (G)	40 (J)	57 (K)	41 (L)	3226***
F	2197 (G)	288 (G)	88 (I)	76 (G)	40 (J)	57 (K)	41 (L)	3598
A	2522 (M)		88 (O)					3612
B	2522 (M)							3510
C	2624 (M)							3736
D	2522 (M)		88 (O)	76 (N)	40 (P)	57 (Q)	41 (R)	3541***
E	2290 (M)		88 (O)	76 (N)	40 (P)	57 (Q)	41 (R)	3541***
F	2522 (M)	288 (N)	88 (O)	76 (N)	40 (P)	57 (Q)	41 (R)	3905
A	2835 (S)		88 (V)					3935
B	2835 (S)							3832
C	3041 (T)							4057
D	2835 (S)		88 (V)	76 (W)	40 (X)	57 (Y)	41 (Z)	3859***
E	2603 (S)		88 (V)	76 (W)	40 (X)	57 (Y)	41 (Z)	3859***
F	2835 (S)	288 (U)	88 (V)	76 (W)	40 (X)	57 (Y)	41 (Z)	4197
A	3555 (TT)		88 (VV)					4754
B	3555 (TT)							4672
C	3552 (UU)							4778
D	3555 (TT)		88 (VV)	76 (WW)	40 (XX)	57 (YY)	41 (ZZ)	4638***
E	3323 (TT)		88 (VV)	76 (WW)	40 (XX)	57 (YY)	41 (ZZ)	4638***
F	3555 (TT)	288 (M)	88 (VV)	76 (WW)	40 (XX)	57 (YY)	41 (ZZ)	5006

TABLE 6 (Cont'd)

NOTES

*Condition Code

A - Tocks Island Reservoir and Beltzville Reservoir in Operation
B - Tocks Island Reservoir with Long Term Inactive Storage of 48,500 DSF
C - Tocks Island Reservoir with Long Term Inactive Storage of 9,600 DSF
D - All Reservoirs in Operation, except F.E. Walter as authorized, with 465 DSF Diversion from Frenchtown, N.J.
E - All Reservoirs in Operation, except F.E. Walter as authorized, with 232 DSF Diversion from Tocks Island Reservoir and 232 DSF Diversion From Frenchtown, N.J.
F - All Reservoirs in Operation with No Diversions

** Variable Rule Curve Used
*** Adjusted for Remaining Available Storage in Reservoir System, Represents the Individual Average Project Yields which could be expected
**** Includes Diversion from Lake Hopatcong, N.J.

RESERVOIR INFORMATION

	Inactive Long Term Storage (DSF)	Active Long Term Storage (DSF)	Minimum Releases (DSF)
Tocks Island	48550 1/	263,100 3/	1500 5/
F.E. Walter	100 2/	1,008 4/	50 6/
Beltzville	699	20,084	35
Aquashicola	500	12,000	15
Trexler	514	12,383	5
Hackettstown	500	11,000 7/	32
Tohickon	750	15,000	5

1/ 9600 DSF for Condition C
2/ 1008 DSF for Condition F
3/ Variable Rule Curve Used
4/ 36050 DSF for Condition F
5/ 1900 DSF for Montague Flow of 1400; 2250 DSF for Montague Flow of 1750; 3150 DSF for Montague Flow of 2650
6/ 100 DSF for Condition F
7/ State of New Jersey uses 19,000 DSF

NO. OF DAYS TO REACH MAXIMUM DRAWDOWN

G - 185 Days	N - 184 Days	U - 188 Days	UU - 613 Days
H - 177 Days	O - 551 Days	V - 551 Days	VV - 544 Days
I - 552 Days	P - 542 Days	W - 184 Days	WW - 185 Days
J - 544 Days	Q - 592 Days	X - 548 Days	XX - 549 Days
K - 595 Days	R - 574 Days	Y - 598 Days	YY - 597 Days
L - 577 Days	S - 192 Days	Z - 579 Days	ZZ - 610 Days
M - 186 Days	T - 191 Days	TT - 260 Days	

CONCLUSIONS

The development of the mathematical model of the lower Delaware River Basin including eight water resources projects has allowed a more accurate determination of the effects of the recent record drought on future water supply developments. The use of a simulation model employing daily flow data is considered necessary in this basin because of the relatively short length of drought. Aside from the potential errors in pre-1960 yield estimates due to use of monthly instead of daily flow records, inspection of table 5 indicates the 1960's drought was substantially more severe than any previously recorded in the eastern and northern portions of the basin. In the western parts of the basin, however, the drought of the 1930's is still the most severe of record.

The method of allocating releases among upstream reservoirs could be improved if a "hindsight" model were employed by using actual future flow records during the simulation.

Finally, the assumption of a constant maintainable flow requirement at Trenton and the use of upstream reservoirs for this purpose appears fictitious. The purchase and use of storage in these projects for water supply will negate their direct use for downstream flow augmentation. Furthermore, it has been concluded elsewhere that the use of a constant instead of a variable demand for determination of project yields may lead to serious errors. Therefore, additional refinement appears warranted for each use of individual project conservation storage.

ACKNOWLEDGEMENTS

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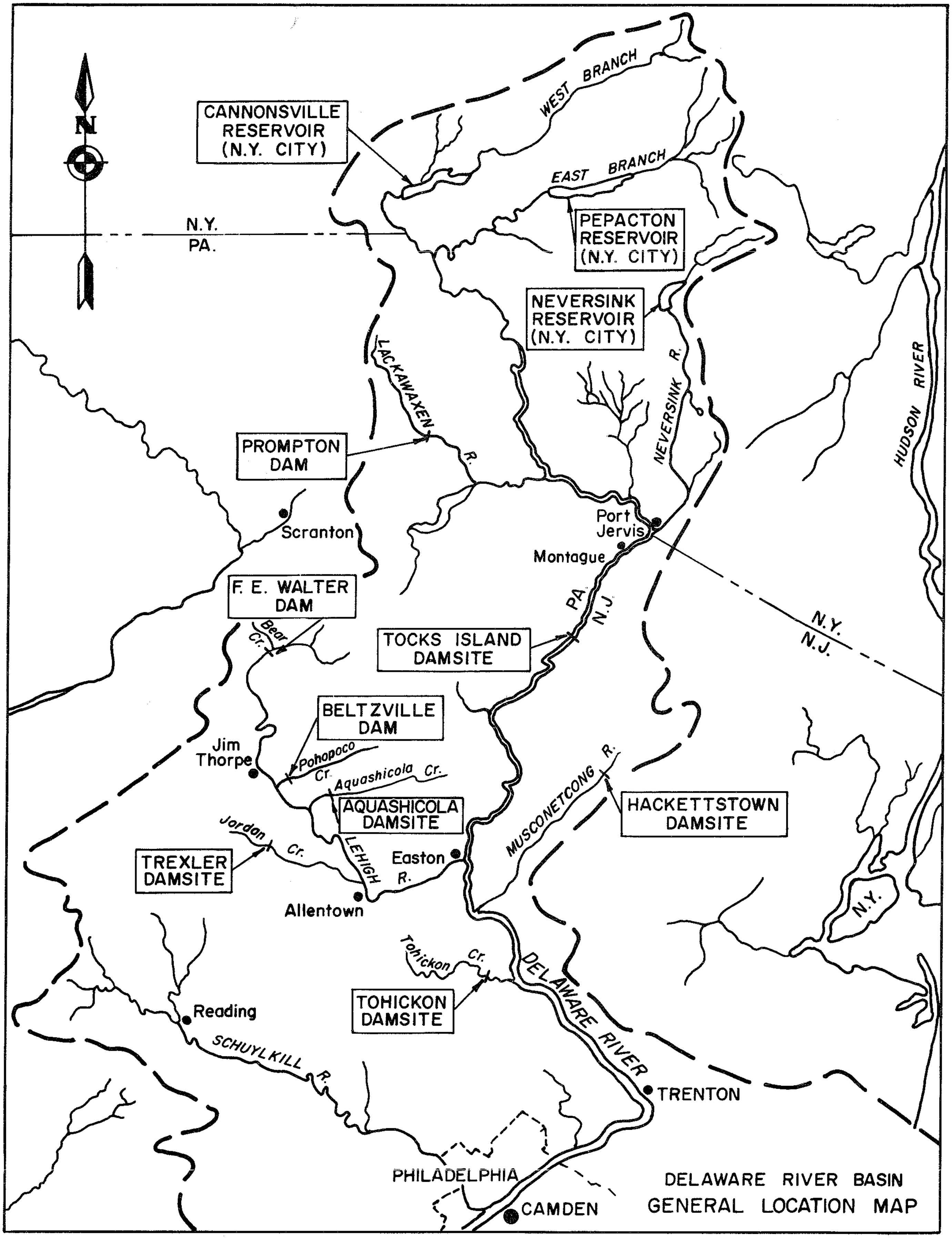
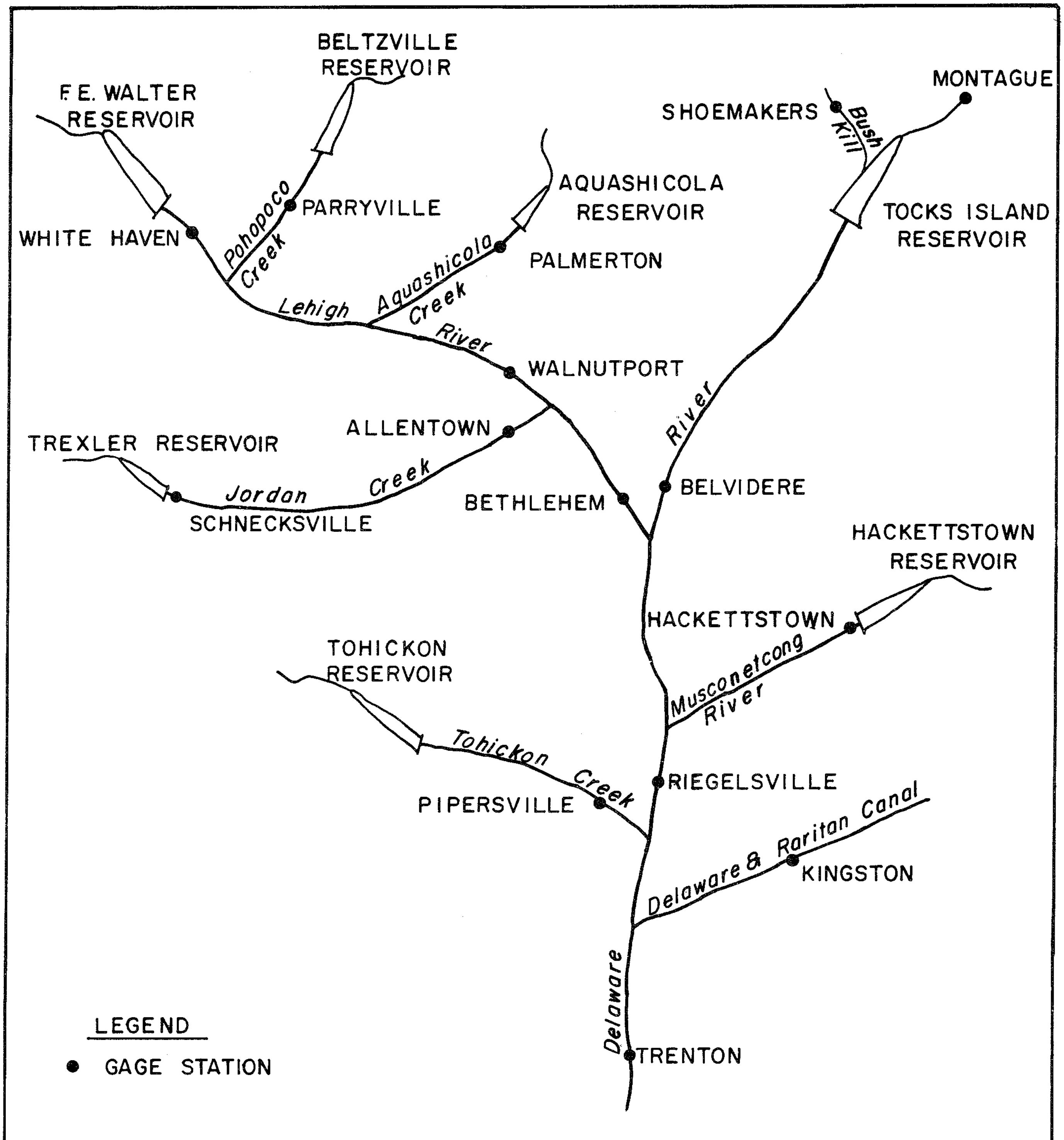
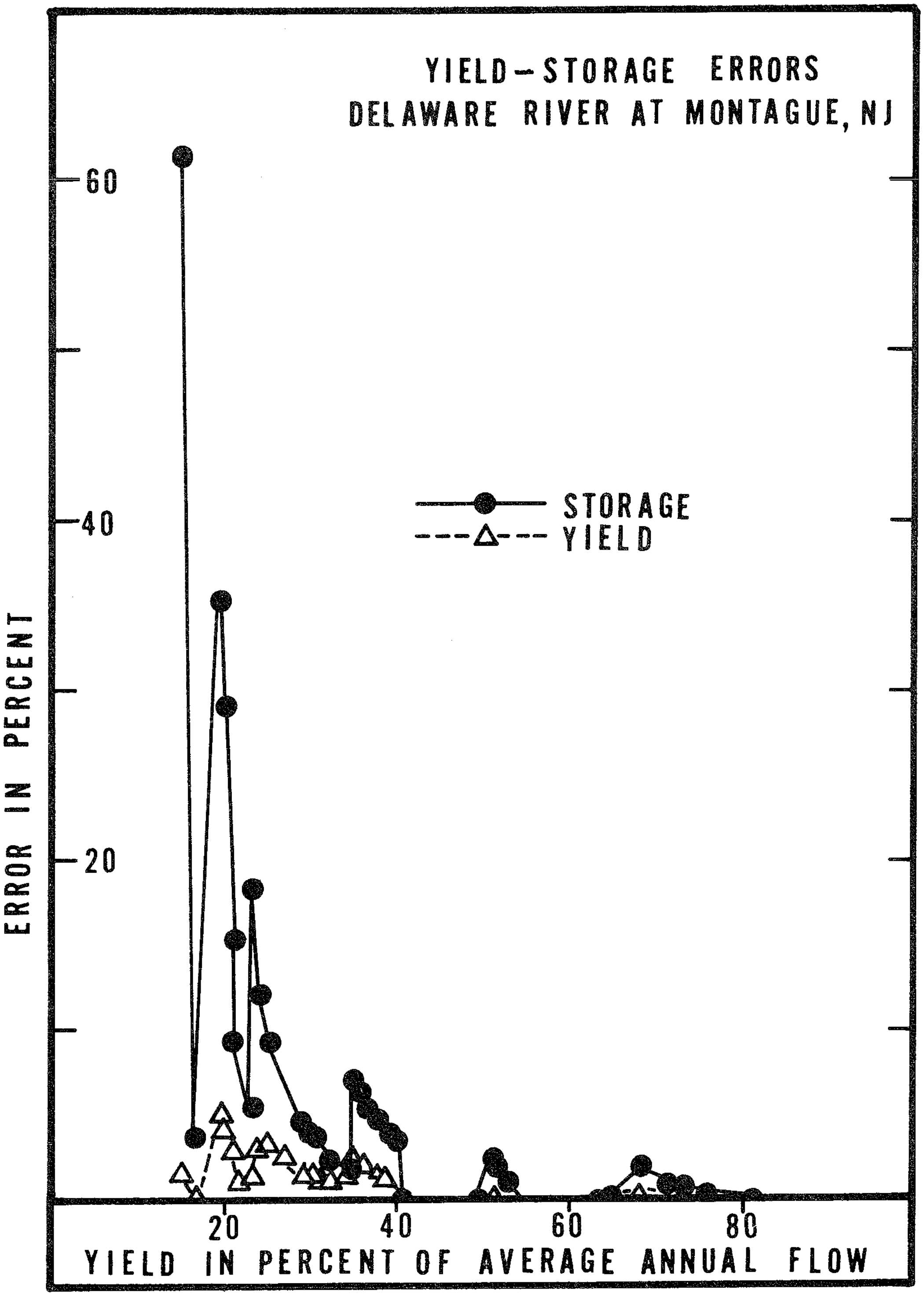

N
CANNONSVILLE RESERVOIR (N.Y. CITY)
WEST BRANCH
EAST BRANCH
PEPACTON RESERVOIR (N.Y. CITY)
N.Y.
PA.
NEVERSINK RESERVOIR (N.Y. CITY)
LACKAWAXEN R.
NEVERSINK R.
HUDSON RIVER
PROMPTON DAM
Scranton
Port Jervis
Montague
F. E. WALTER DAM
Bear Cr.
PA.
N.J.
N.Y.
N.J.
TOCKS ISLAND DAMSITE
BELTZVILLE DAM
Jim Thorpe
Pohopoco Cr.
Aquashicola Cr.
AQUASHICOLA DAMSITE
MUSCONETCONG R.
HACKETTSTOWN DAMSITE
Jordan Cr.
TREXLER DAMSITE
LEHIGH R.
Easton
Allentown
N.Y.
Tohickon Cr.
TOHICKON DAMSITE
DELAWARE RIVER
Reading
SCHUYLKILL R.
TRENTON
PHILADELPHIA
CAMDEN
DELAWARE RIVER BASIN
GENERAL LOCATION MAP

FIGURE 1



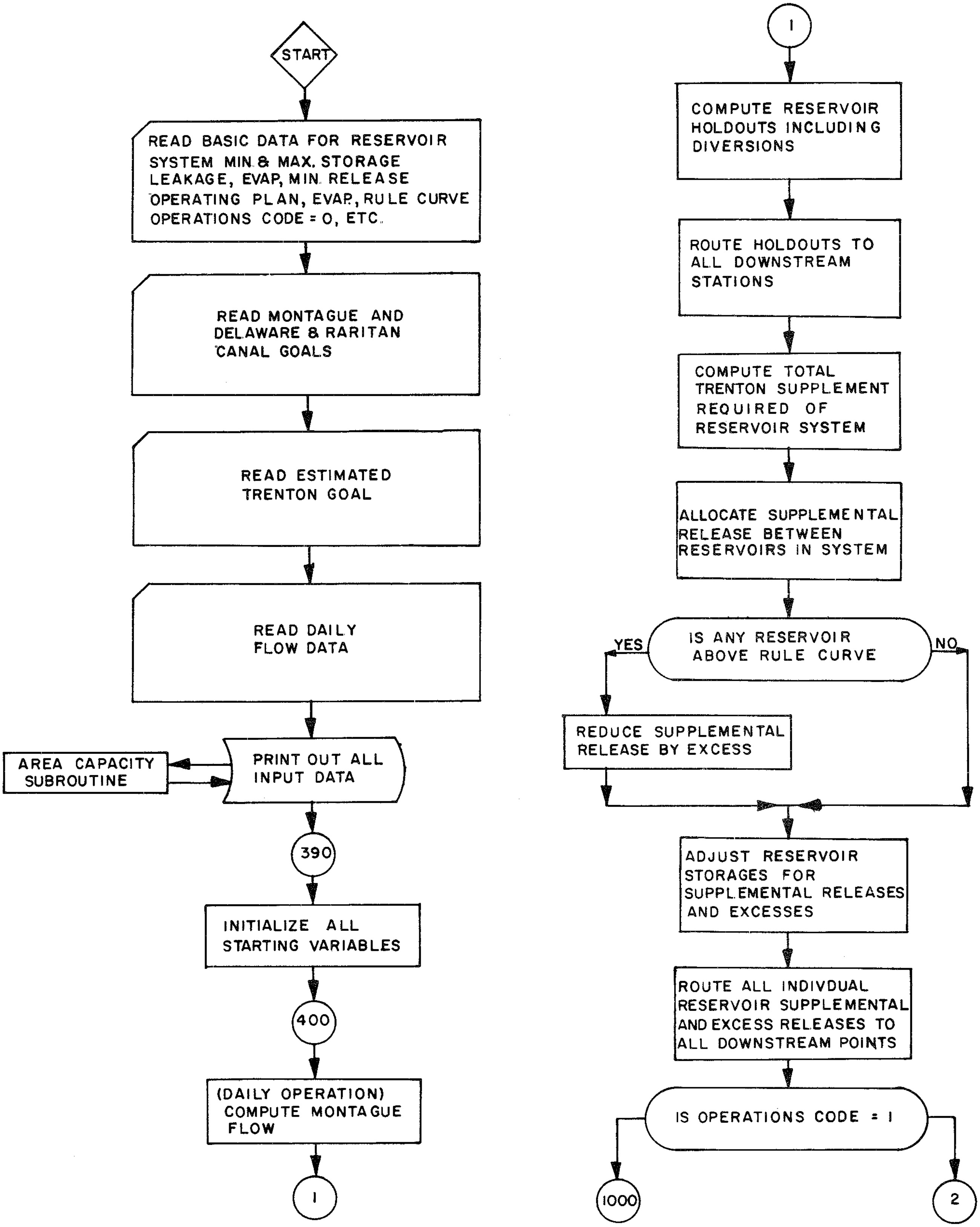
SCHEMATIC DIAGRAM
DELAWARE RIVER BASIN RESERVOIR SYSTEMS OPERATION

FIGURE 2



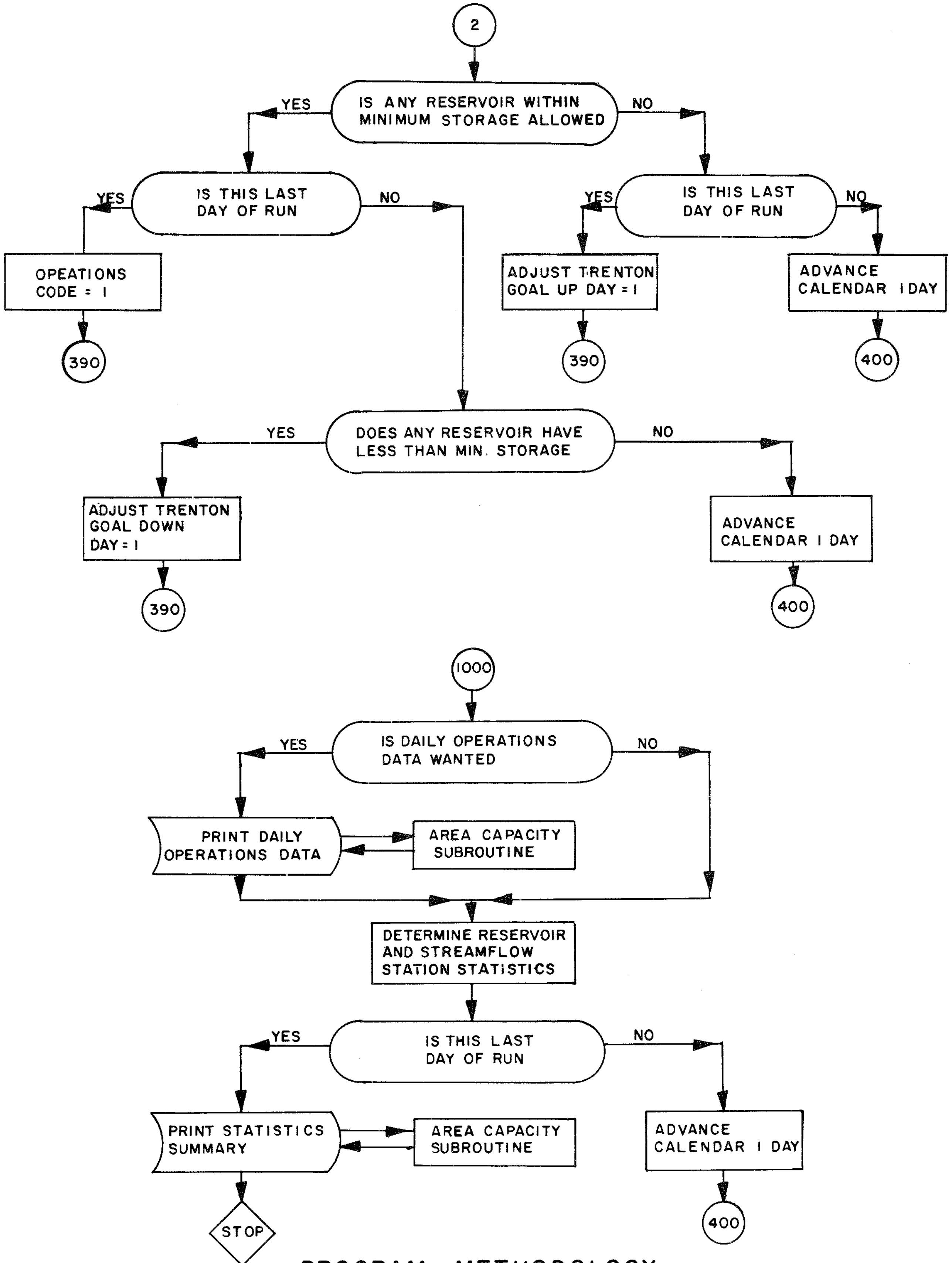
YIELD-STORAGE ERRORS
DELAWARE RIVER AT MONTAGUE, NJ
60
40
20
ERROR IN PERCENT
STORAGE
YIELD
20
40
60
80
YIELD IN PERCENT OF AVERAGE ANNUAL FLOW

FIGURE 3



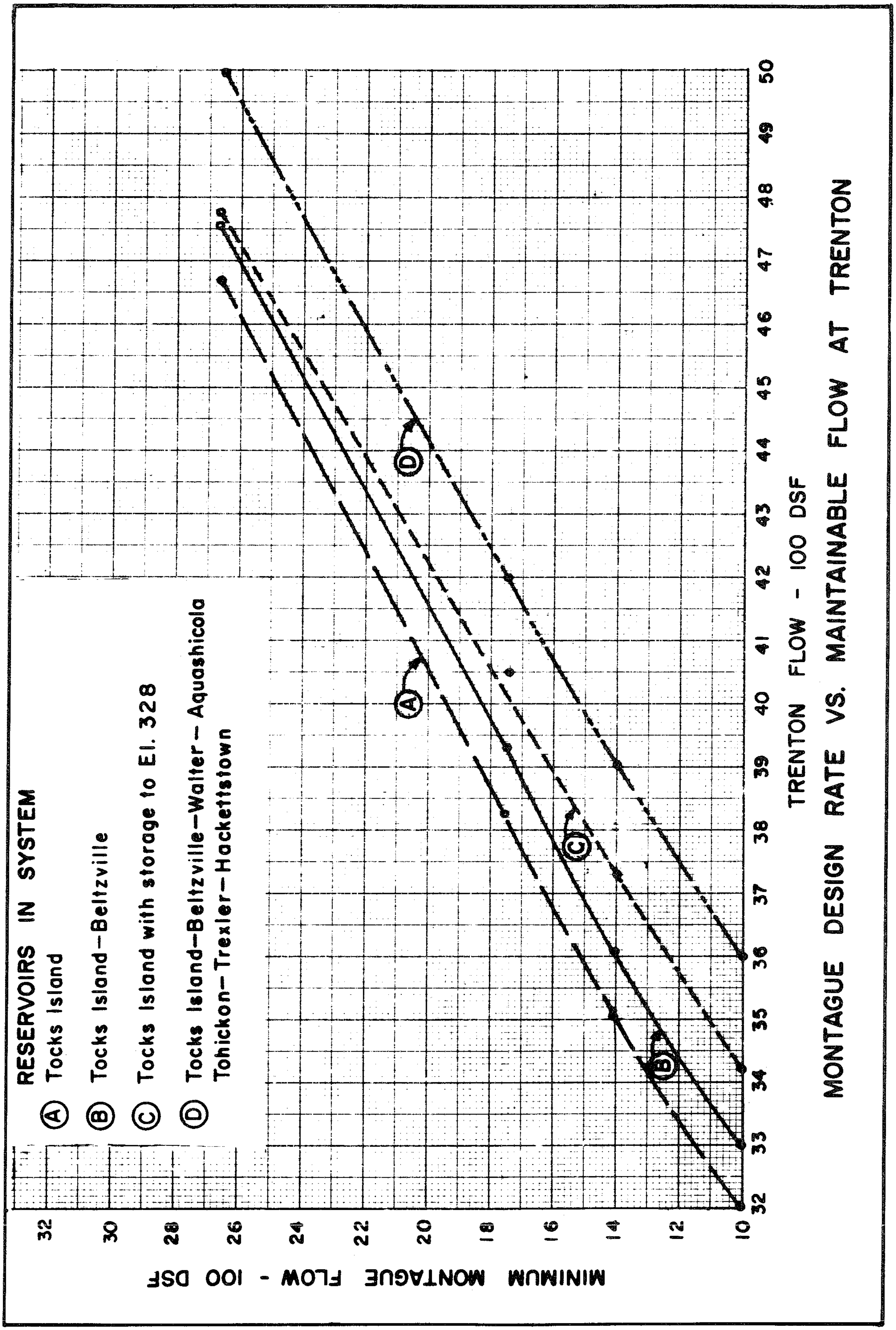
PROGRAM METHODOLOGY

FIGURE 4



PROGRAM METHODOLOGY

FIGURE 5



RESERVOIRS IN SYSTEM
(A) Tocks Island
(B) Tocks Island—Beltzville
(C) Tocks Island with storage to El. 328
(D) Tocks Island—Beltzville—Walter—Aquashicola
Tohickon—Trexler—Hackettstown
MINIMUM MONTAGUE FLOW - 100 DSF
10
12
14
16
18
20
22
24
26
28
30
32
TRENTON FLOW - 100 DSF
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
A
B
C
D
MONTAGUE DESIGN RATE VS. MAINTAINABLE FLOW AT TRENTON

FIGURE 6

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TP-108 Role of Small Computers in Two-Dimensional Flow Modeling
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