REAPPRAISAL OF WATER SUPPLY RESOURCES IN DELAWARE RIVER BASIN USING SYNTHETIC HYDROLOGY[1]

Yu Shiao and John E. McSparran[2]

ABSTRACT. The 60's drought (1961-1966) which hit the Northeastern United States, had its center over the Delaware River Basin and caused water supply shortages to New York City, Philadelphia, and many other towns and industries in the Basin. Until this event occurred, the existing water supply sources and those planned for the future had been considered adequate, as they were designed for the worst drought of record (usually the 1930-31 drought). In view of this "change in hydrology," the Delaware River Basin Commission authorized a study (DRBC Resolution 67-4) to re-evaluate the adequacy of existing and planned water supply sources of the Delaware River Basin and its Service Area (New York City and northern New Jersey).

Synthetic hydrology is a tool which can be used to overcome many of the limitations of the traditional approach. By analyzing generated streamflow traces in this study, it has been determined that there is a definite relationship between the accumulated rainfall deficiency during the drought and the return periods associated with various durations of runoff in the drought. This indicated that generated traces can be used to standardize the hydrology over an area where the intensity of drought varied. This represented an important facet in the study, because it provided a means to equalize the effects of this drought over the study area, and gave the Delaware River Basin Commission more information so that it could better plan and manage its water resources equitably, not only for the people within the Basin, but for the New York City and northern New Jersey areas as well.

Synthetic hydrology was used to determine yield-probability relationships for 50-year periods, and storage-yield-frequency relationships for existing and planned water-supply reservoirs. It was also used to determine yield-probability relationships for reservoir systems within the Basin. In the study, it was determined that monthly streamflow traces and uniform draft rates could be used in yield analysis because of the magnitude of the reservoirs and because seasonal variations of draft rate are small in the study area.

Although it was found that with the streamflow generating models (first order Markov) in common use today, it is not possible to definitely determine the actual frequency of a very severe historic drought, it is possible to place a drought in perspective by using synthetic hydrology. The study showed that it is a useful tool in determining water availability over a basin and is useful in studying water management problems such as interbasin transfers, and reservoir systems operations. (KEY WORDS: drought; water supply; planning; synthetic hydrology; yield-probability; storage-yield frequency; reservoir operations; water management; Delaware River Basin)

INTRODUCTION

The Delaware River Basin (Figure 1) which includes parts of Delaware, New Jersey, New York and Pennsylvania has a total drainage area of 12,765 square miles, an average annual precipitation of 44 inches and an average annual runoff of 22 inches. It provides water to a

[1] Paper No. 71052 of the *Water Resources Bulletin* (Journal of the American Water Resources Association). Discussions are open until December 1, 1971.

[2] Respectively, formerly employed by the Pennsylvania Department of Forests and Waters, Water Resources Branch, recently took employment with Stone and Webster Engineer Corporation, Boston, Massachusetts; Assistant Chief, Water Resources Branch, Pennsylvania Department of Forests and Waters, Harrisburg, Pennsylvania.

service area which contains nearly 16 million people. The upper portion of the basin has been developed by New York City with three reservoirs–Pepacton, Cannonsville, and Neversink–having a combined total water supply storage of 270.8 B.G. and controlling a drainage area of 917 square miles. Two hydroelectric dams, Wallenpaupack and Rio which are located on tributaries above the index stream gage station, Montague, have a combined drainage area of 430 square miles and storage of 58.1 B.G. In the middle and lower portion of the basin below Montague seven significant multiple purpose reservoirs are either proposed or existing which will augment the flows for the ever growing needs for water quality and water supply on the Lehigh and Delaware Rivers. In addition there are canals and proposed pumping stations which will divert water from the Delaware.

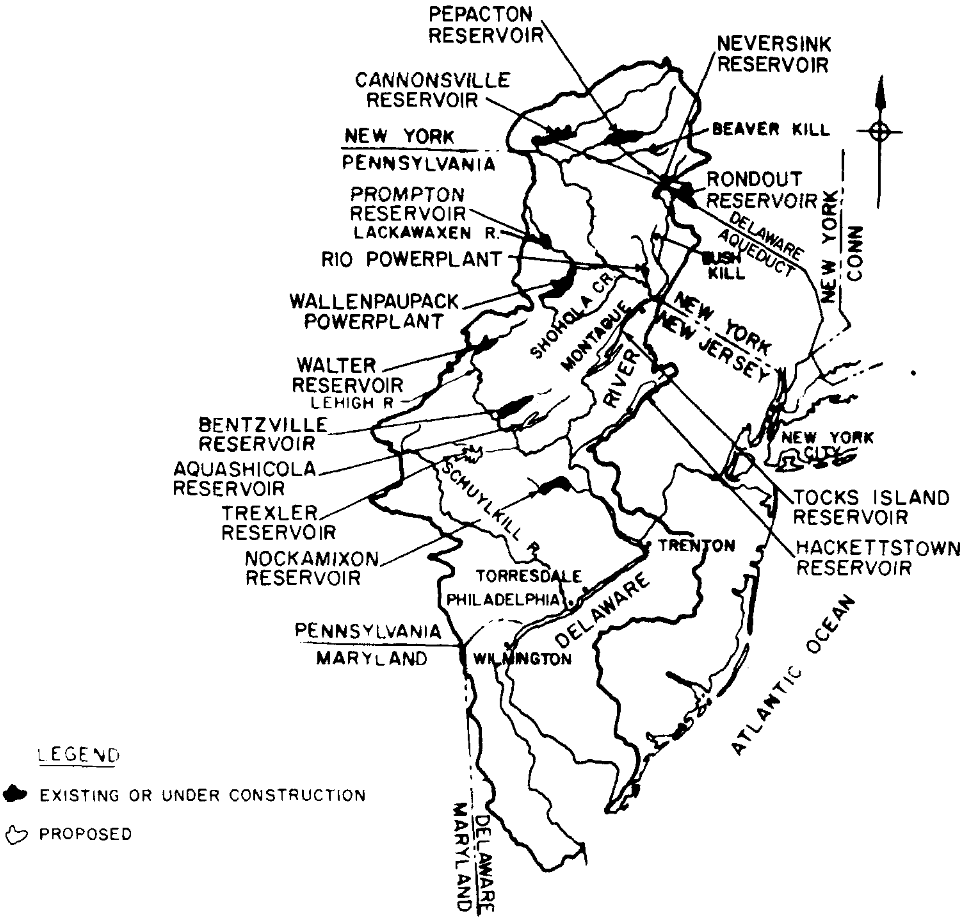


Figure 1. Delaware River Basin.

The 60's drought (1961-1966) which hit the Northeastern United States had its center over the Delaware River Basin and caused water supply shortages to New York City, Philadelphia and many other towns and industries in the basin. Until this event occurred, the existing water supply reservoirs and those planned for the future had been considered adequate, as they were designed for the worst drought of record (1930-1931).

The six-year drought accumulated a deficit of more than a full year's precipitation, reaching 70 inches and more in some areas, and included record breaking low runoff with accumulated deficits of over 40 inches below normal. As a result, the Delaware River Basin Commission (DRBC) had to declare an emergency and regulate the operation of the reservoirs in the Basin between July 8, 1965 and March 2, 1967, in order to equitably apportion the water for water supply.

Following the drought, the DRBC found it "necessary and desirable to provide for a study of the adequacy of existing and planned water supply sources and storage facilities available to the Delaware River Basin and its service area in view of changes in hydrology evidenced by drought experience" [1967]. On March 29, 1967, DRBC resolution 67-4 was adopted which directed the Commission Staff to make such a study in cooperation with the U.S. Army Corps of Engineers and other federal agencies, the States of the basin and the cities of New York and Philadelphia.

Amended United States Supreme Court Decree of 1954

This decree [1954] which amends the 1931 decree specifies the allowable out-of-basin diversions by New York City from its reservoirs in the upper Delaware River and its tributaries and the terms and conditions from which the authority is granted. Briefly, with all three reservoirs in operation, the City may take a diversion to an average maximum of 800 million gallons per day (computed as a running average beginning on June 1 of each year) provided that required releases to the river to maintain a basic flow rate of 1750 cfs at index station Montague at all times and that excess release requirements are maintained during the seasonal period (June 15 to March 15). Excess releases are defined as a "quantity of water equal to 83 per cent of the amount by which the estimated consumption during such year is less than the City's estimate of the continuous safe yield during such year of all its sources obtainable without pumping." The City must release the excess quantity at rates designed to release the entire quantity in 120 days. The excess quantity shall not exceed 70 billion gallons and the City is not required to maintain a flow at Montague of a rate greater than the minimum basic rate plus the excess quantity divided by 120 days or a maximum of 2650 cfs.

DRBC 67-4 Study

The study, of necessity, investigated both supply and demand but only the analysis of the supply will be presented here. A comparison of yields was made for each existing or planned water supply reservoir based on the historic 30's records and the 60's records. This was done by the Rippl mass-diagram method. The three New York City reservoirs were analyzed as a system by the same procedure with certain modifications to allow for the release requirements. The other major concern of the study was the determination of the flow rate which could be sustained at Trenton, New Jersey. A flow rate of 3000 cfs is requied at Trenton to push back the salt water advance from the Delaware estuary below the mouth of the Schuylkill River. To find this yield it was necessary to simulate the entire basin above Trenton with a computer model which included the three New York City reservoirs and the 7 major multipurpose structures below Montague. A reservoir operating rule was used which took water from the reservoir(s) based on the percent of storage available and chance of refilling in the next 12-month period. By an iterative process, a yield was determined for the 60's drought.

However, as learned from the recent drought experience, the criteria of determining design yields based on the drought of record is not satisfactory because of the following reasons:

1. As soon as a more severe event occurs, the entire water supply picture of the basin must be re-evaluated.
2. The drought of record is not uniform over the area; so each source would be designed with a different probability of shortage. This is unfair from a water allocation standpoint as well as an economic standpoint to the water users.
3. It could result in either overdesign (too expensive) or underdesign (apt to have shortages) because the streamflow records are too short to place the drought in proper perspective. The degree of protection, or probability of risk, cannot be obtained from only a few sets of critical flows.
4. The same flow sequence will not occur in the near future.

Synthetic Hydrology

Synthetic hydrology or stochastic hydrology is a tool which can be used to overcome these limitations because many different sequences of flow as well as many droughts of various durations can be generated. With sufficient streamflow generation (1000 years is generally considered adequate) a fair representation of what might be expected in the future on a particular stream can be obtained. For the upper Delaware River Basin, it has been estimated in a study by Hardison [1968] that the drought of the 30's had a return period of 12.5 to 15.5 years, whereas the drought of the 60's had a return period of 400 to 500 years. In both droughts the severity varied considerably over the entire basin, and though the 60's drought had the more severe effects, there are portions of the lower basin where the 30's drought is still the worst drought of record. It is desirable to know the yields associated with reservoirs and other sources of supply under these historic droughts, but it is no basis for design of a dam since it has no relationship with the economic life of the structure [Thomas and Burden, 1963] and for reasons already stated it is not satisfactory for budgeting water equitably throughout a basin.

On this basis, it was decided to apply synthetic hydrology in this study. Numerous mathematical models have been developed to create probabilistic flow sequences which have the same characteristics as the historical streamflow records. The Hydrologic Engineering Center's multiple regression model [Beard, 1965] and the Harvard Water Resources' principal component model [Fiering, 1964] are perhaps the most widely known. Both models use the Markov chain to express the auto-regressive concept of natural flow events. The HEC model is used in this study.

This model considers the dependence of streamflow with its own previous streamflow as well as the streamflow at other stations in the basin. In addition to correlation to previous month's streamflows at some stations, correlation to the present month's streamflows at other stations is also considered. The form of the generating equation is as follows:

$$K_{ij} = \sum_{a=1}^{j-1} \beta_{aj} K_{ia} + \sum_{a=j}^{N} \beta_{aj} K_{i-1,a} + \sqrt{1 - R_j^2}\; Z_{ij} \tag{1}$$

in which i = subscript denoting the i^{th} month of the generation

j = subscript denoting the j^{th} station in the generation

K_{ij} = the standard deviate of the monthly flow for month i at station j

β_{aj} = the beta coefficient, i.e., the regression coefficient of the normalized standard deviates

R_j^2 = multiple determination coefficient

Z_{ij} = a random number with zero mean and unit variance
N = total number of stations for which streamflows are generated.

The model uses the mean, standard deviation, skew coefficient, and first order cross and serial correlation coefficients. All of these statistical parameters are estimated from historical records. The frequency distribution of the generated variables, K, is assumed to be Pearson Type III.

By personal experience, three factors were found to have a significant effect on the characteristics of the generated records: (1) the serial and cross correlation coefficients of the records; (2) the length and relative length of the historic streamflow records; and (3) the order of the stations within the group being considered. In other words, the selection of stations to be included in a group for simulation must be done with care or the generated records may have undesirable characteristics which one could not accept with confidence as being representative of possible future flows events and sequences. To overcome these weaknesses, the following set of procedures were devised to determine homogeneous stations to be included in a group:

1. The historic record of each station should be 10 years or greater.
2. The cross correlation coefficients between historical records should be as high as possible (preferably greater than 0.9).
3. Correlograms of the stations which qualified under the first two tests are then compared. If the correlograms appear similar, then the stations are grouped; otherwise, the station(s) with the dissimilar correlogram(s) is dropped.
4. The record of this group of stations are then arranged in descending order according to the length of each record for simulation.

These tests are easily performed and are based on considerations of hydrology and geology of the watersheds involved. The assumption is that if the cross correlation coefficients between the records are high then they are under similar meteorologic and hydrologic influences. Likewise, if the correlograms of the station records are similar then the geologic characteristics of the watersheds exhibit comparable responses as it affects the base flow of the stream. Figure 2 illustrates the correlograms for 4 stations in the Lehigh River Basin which had similar records based on the first two tests. However, on the basis of the correlograms, gages 4525 and 4515 had to be separated from gages 4520 and 4530. The results obtained by using these procedures has been very encouraging. One of the characteristics of the model is that the statistics are preserved. Consequently, the average flows will always be the same as the historic records, but the low and high flows may be greatly different and this is the key indicator of how good the generated record is. Since the low flows are lower bounded, they are not as sensitive an indicator as the high flows. However, a comparison of the low flow frequency curves of the generated record with those of the historic record can be enlightening. Although the curves do not have to be the same, they should be in the same range, especially for the more frequent events.

Of concern in using synthetic streamflow records was the question of whether generated records could "standardize" the drought effects over an entire basin area. Some insight was gained on this question by generating 1,000 years of record for several stations within the basin and developing a 54-month runoff frequency curve for each and determining the "return period" for the 54-month historic flow. A comparison of these "return periods" with the estimated rainfall deficiency for the period 1962 to 1966 for several watersheds are presented in Table 1. These results indicate that where the drought was more severe, as given by the amount of rainfall deficiency below the average, the frequency of occurrence was much less.

It is impossible to state whether the "return periods" are realistic, but confidence is gained by the fact that where the drought was most severe, the generated output indicates the same.

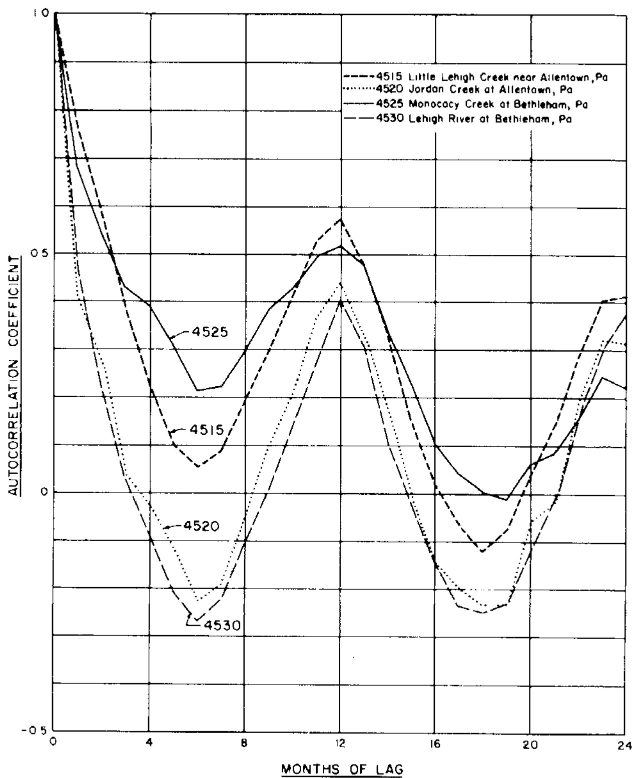


Figure 2. Comparison of correlograms.

TABLE 1. Comparison of Drought Return Periods with Accumulated Rainfall Deficiences

Station	Drainage Area, Sq.mi.	Return period of 54 months historic low flows	Estimated Accumulated Rainfall deficiency (1962-66) in inches
4,395	117	3,200	62
4,478	290	340	65
4,500	109	1,700	58
4,505	76.7	1,360	52
4,520	75.8	270	45
4,595	97.4	200	45
4,720	1147	180	45
4,810	247	100	39

Basin Simulation

In order to determine the adequacy of the planned system of reservoirs in the Basin to maintain a target flow of 3,000 cfs at Trenton, a simulation model was developed by the Philadelphia District, Corps of Engineers. Originally, the model was designed to use daily historic flow records, but to accommodate synthetic records it was changed to use monthly data. The reservoirs included in the model are listed in Table 2 and illustrated in Figure 1.

TABLE 2.

Reservoir	Location	Drainage Area, sq.mi.	Storage Allocated for Water Supply, M.G.
Tocks Island	Delaware	3,627	133,500
F. E. Walter	Lehigh River	289	22,800
Beltzville	Pohopoco Cr.	96.3	13,000
Aquashicola	Aquashicola Cr.	66	7,800
Trexler	Jordan Cr.	51.8	7,900
Nockamixon	Tohickon Cr.	78	9,800
Hackettstown	Musconetcong River	70	7,200

The model [Corps of Engineers, 1969] computes the flow at Trenton based on uncontrolled runoff and conservation releases from the reservoirs and determines the supplemental flow that is required to meet the target discharge. That supplement is then allocated among the seven reservoirs based on the available long-term storage left in each reservoir and the projection that the reservoir would be replenished in the following twelve months, using the minimum sequential inflow of record.

With regard to the New York City reservoirs, the model used as input actual historic flows or a minimum flow of 1750 cfs at Montague. Because only the period of drought was analyzed, it was not necessary to consider an operation model for the NYC reservoirs. However, for synthetic records, an operating model had to be devised. The operating model adopted is illustrated in Figure 3A. Conceptually it considers the three reservoirs lumped into one with three inflows entering it and releases, diversions and spills as outflows. Rules for operating this reservoir were developed based on storage levels for each month of the year to meet certain release and diversion rates during average streamflow conditions and during the 1960's drought conditions.

In Figure 3C, two schematic operation models are shown which have been selected for use in this study. The minimum safe, M.S., storage levels shown in the tables correspond to the number of billions of gallons of water required at the first of the month for the system to be in a safe condition. Releases and maximum diversions can both be made. These figures are based on average flow conditions. The emergency storage levels were determined from average monthly drought conditions in the period June, 1961 to May, 1967. The releases and the diversions above and below this level are as indicated in the two models. Below the emergency storage levels, for each 10 billion gallons the diversions and releases are reduced as indicated. An intermediate storage level was found necessary to serve as a buffering level between the safe and emergency levels, so that if a drought condition began, measures could begin quickly enough to prevent or minimize the emergency condition.

The purpose of the model is to determine what the inflows will be to Tocks Island reservoir under any flow condition. Inflows to Tocks Island are composed of uncontrolled natural runoff, releases from the NYC reservoirs, release from the two hydroelectric dams and spills from the NYC dams. In the basin simulation model uncontrolled natural runoff is generated, as are the inflows to the NYC reservoirs. In order to determine the release requirement from the NYC reservoirs to satisfy the 1750 cfs Montague objective, the curve in Figure 3B was devised from historic records. This model is relatively simple, and briefly it assumes that New York City will take as much water as possible without jeopardizing its reservoirs' ability to meet the basic release requirements.

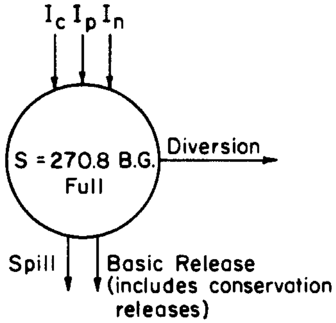
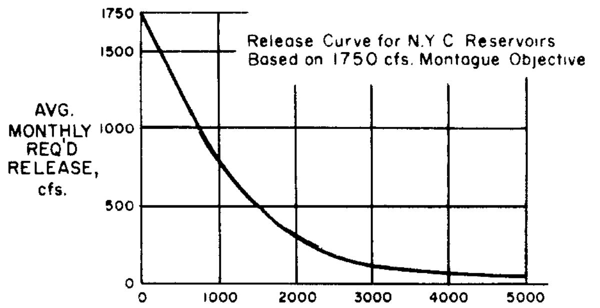


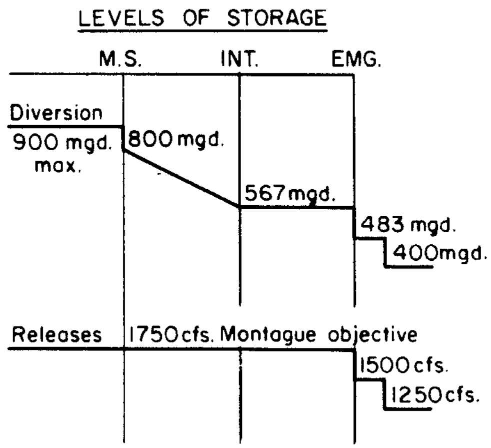
Figure 3A. Conceptual Model of NYC Reservoirs.



AVG. MONTHLY UNCONTROLLED DISCHARGE AT MONTAGUE, cfs.

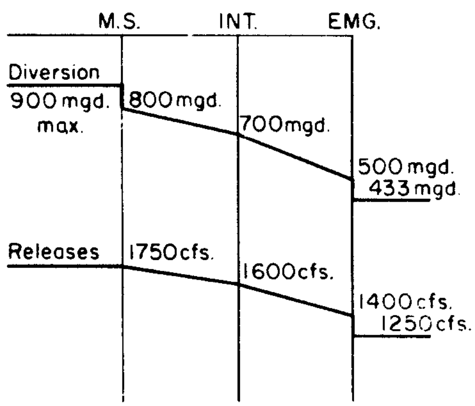
Figure 3B

FIRST DAY OF MONTH	M. S.	INT.	EMG.
6	240	200	165
7	230	190	155
8	195	155	120
9	165	125	90
10	135	95	60
11	105	65	30
12	95	55	20
1	105	65	30
2	120	80	45
3	150	110	75
4	190	150	115
5	220	180	145



MODEL A

FIRST DAY OF MONTH	M. S.	INT.	EMG.
6	240	200	165
7	230	190	155
8	195	155	120
9	165	125	90
10	135	95	60
11	105	65	30
12	95	55	20
1	105	65	30
2	120	80	45
3	150	110	75
4	190	150	115
5	220	180	145



MODEL B

Figure 3C. Schematic Operational Models of NYC Reservoirs.

PROPOSED USE OF SYNTHETIC HYDROLOGY

Unforeseen delays in programming the model, collecting of basic data, and effecting coordination among the many involved interests of the study have prevented us from presenting any results of this effort at this time. However, many possibilities exist for using synthetic hydrology in this study and they will be presented here. It should be mentioned that the purpose of the Committee's study is to provide proposals for Commission consideration and action on revision or amendment of the Comprehensive Plan, and for policies and projects, as may be deemed necessary and desirable.

With the basin simulation model, monthly flows at Trenton can be determined for as many years as desired. It is proposed that these simulated flows be broken into various "design periods" such as 100, 50, 25, and 10 year lengths. Then each of these shorter records could be analyzed to determine the low flow for each. The low flows could be ordered and a low flow-probability curve [Quirk *et al.*, 1968] could be developed for each design period. This would provide yields for the basin above Trenton for whatever operating conditions that would be considered. A parallel study which would offer additional information would be the determination of a shortage index [Hydrologic Engineering Center, 1967] associated with different flows at Trenton. A shortage index is defined as the sum of squares of the monthly fractional shortages incurred during a drought, reported on a 100-year basis. The assumption is made that economic losses are proportional to the square of the shortages, thus the shortage index is an indicator of the economic consequences of the drought.

The yield-probability curve and the yield-shortage index relationship could likewise be determined for each of the major reservoirs in the basin, as well as subsystems of reservoirs (i.e., reservoirs above Bethlehem).

The yield-probability curves could also be used to determine yield frequency curves in the range below the 100-year return period. Because the generating model uses a Pearson Type III distribution of standard deviates, it would be unrealistic to project yields for return periods greater than 100 years. An example of yield-probability curves is given in Figure 4. If a decision maker had such a curve, he could make a choice of yield for a project based on the degree of risk he was willing to take that the project would have shortages during the design period. However, unless the decision maker were a statistician or mathematician, he would be faced with an equally tough choice as to what is a proper criteria. Perhaps all he wants to know is what will be the design yield for the project that will have a shortage on the average of once every 50 years. The 50-year curve gives the percent chance that the project with a certain yield will have a shortage in the next 50 years. Using the binomial distribution equation with the probability of occurrence equal to 0.02 and the probability of nonoccurrence equal to 0.98 there would be a 0.364 probability that a 50-year event would not happen in the next 50 years. In other words, there would be a probability of 0.636 that there would be one or more shortages in that interval. Therefore, the 63.6% probability level would intercept a 50-year yield on the 50-year curve. It may be argued that the binomial distribution assumes independent events and that droughts, particularly long ones, are not independent on an annual basis. Assuming that annual events are independent, the equation for the probability of no events in the design period, n, is

$$P_o = (1 - \frac{1}{n})^n . \tag{2}$$

For droughts of duration, D, a maximum number of independent events in the design period, n, would be n/D. Therefore, substituting these independent events into equation (2) which had n independent events would give

$$P_o = (1 - \frac{D}{n})^{n/D} \tag{3}$$

If n were equal to 50 years and D equal to 5 years, then P_o would equal 0.348, which compares quite favorably to 0.364. In other words, equation 2 and equation 3 are approximately the same and one can determine a project yield for a given return period by this procedure.

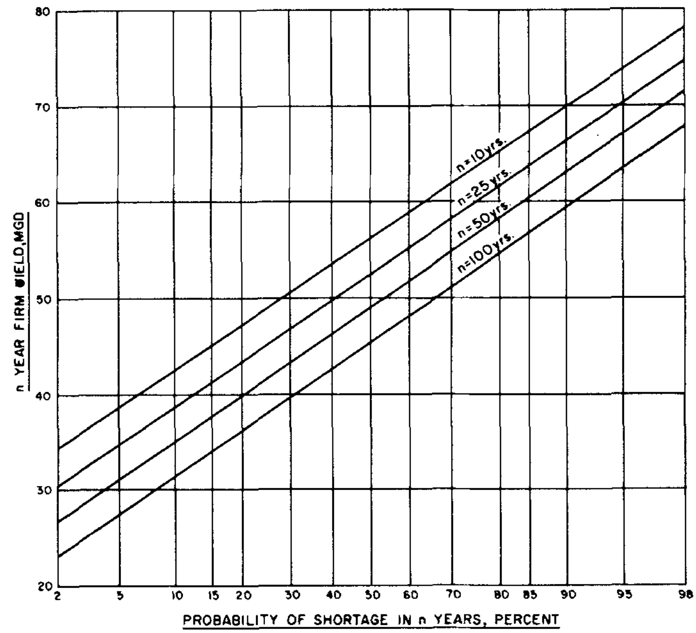


Figure 4. Frequency distribution of n year firm yields.

In Figure 4, there are 4 yield probability curves based on 100, 50, 25 and 10 years design periods. By solving equation 2 for each value of n the probabilities of no shortages in the design periods are 0.366, 0.364, 0.359, and 0.348 respectively. Therefore, by entering the respective curves at the point where there is a probability of at least one shortage (i.e., 0.634, 0.636, 0.641 and 0.652) a curve of yield versus return period can be plotted.

CONCLUSIONS

Synthetic hydrology is a valuable tool for a water availability study such as the one being conducted by the Delaware River Basin Commission. The generation of streamflow records for gages over an entire river basin standardizes the hydrology, by creating enough low flow events to put historic droughts in proper perspective. Synthetic hydrology can be combined with reservoir systems simulation to determine total system yields as well as the consequences of various operating procedures. The parallel use of the shortage index method with the yield-probability relationship for various design periods on synthetic hydrology gives the decision maker a basis for establishing a uniform design criteria for water supply projects.

ACKNOWLEDGEMENTS

The advise, assistance and cooperation extended by the members of the Coordinating Committee for the Reappraisal of Water Supply Resources of Delaware River Basin and Service Area has been most helpful in this effort. Mr. Robert Goodell, Chairman of the Committee, effected excellent coordination throughout the study. Mr. Leo Beard and his staff at the Hydrologic Engineering Center supplied us with the streamflow simulation program and offered helpful advice and assistance. Appreciation is extended to the various members of the Department of Forests and Waters staff who have assisted and supported this effort, particularly Secretary Maurice K. Goddard, who was instrumental in making synthetic hydrology part of the Committee Study.

REFERENCES

Beard, L. R. 1965. Use of interrelated records to simulate streamflow. Proc. A.S.C.E. 91(HY5):13-22.

Delaware River Basin Commission. 1967. DRBC Resolution 67-4 relating to a reappraisal of the long-term water supply resources available to the Delaware River Basin and its service areas. Adopted: March 29, 1967.

Fiering, M. B. 1964. Multivariate technique for synthetic hydrology. Proc. A.S.C.E. 90(HY5):43-60.

Hardison, C. H. 1968. Probability of allowable yield in the Delaware River Basin. U.S. Geological Survey, Washington, D.C.

Hydrologic Engineering Center, U.S. Army Corps of Engineers. 1967. Reservoir-storage-yield procedures, methods systemization manual.

Quirk, T. P., J. P. Lawler and F. E. Matusky. 1968. Surface water supply capabilities of northern New Jersey river basin. Northeastern United States Water Supply Study, North Atlantic Division, U.S. Army Corps of Engineers, Chapter IV.

The Supreme Court of the United States. 1954. Amended Decree of the Supreme Court of the United States regarding Delaware River Diversion, order June 7, 1954.

Thomas, H. A., Jr. and R. P. Burden. 1963. Statistical analysis of the reservoir-storage-yield relation. Chapter I in Operations Research in Water Quality Management, Harvard University.

U.S. Army Corps of Engineers, Philadelphia District. 1969. Draft report of the coordinating committee for the reappraisal of the water supply resources of the Delaware River Basin and service area. Chapter IV.