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Only through the use of electronic computers have hydrologic engineers been able to complete the fundamental hydrologic studies that serve as the foundation for most engineering and economic analyses of complex regional water resources developments. Studies recently completed or in progress include development of a regional flood control site screening plan, use of streamflow simulation for planning and operation of the Missouri River mainstem projects, development of an operation plan for the Arkansas-White-Red Rivers reservoir system, standard project flood estimates, flood frequency estimates, and several other projects.

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TP-17

HYDROLOGIC ENGINEERING TECHNIQUES FOR REGIONAL WATER RESOURCES PLANNING[1]

by

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INTRODUCTION

The demand for water for an increasing number of competitive and interacting uses, the necessity to evaluate as many alternative plans of development as possible, and the need for and emphasis upon regional analyses and development of water resources have caused an increase in complexity of water resources studies that threatens to completely overrun the technical capabilities available for performing the necessary analyses. Only through the use of electronic computers have hydrologic engineers been able to complete the fundamental hydrologic studies that serve as the foundation for most engineering and economic analyses of complex regional water resources developments.

Computer programs that incorporate many of the existing hydrologic engineering techniques have enabled the hydrologic engineer to provide quick answers to traditional problems at a relatively low cost. In the earliest comprehensive planning efforts, these answers were incorporated into the overall studies to the satisfaction of both the engineer and the planner.

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As the scope of the comprehensive study increased and as more beneficial uses of water began to be considered, it became apparent that computerization of existing techniques would not completely satisfy the emerging requirements. Not only were existing techniques inadequate for supplying answers to the relatively new problems - it was discovered that in many instances the answers produced by traditional techniques were not consistent with the scope and objectives of the comprehensive study. Consequently, money and time were being consumed in the production of answers which were not always really commensurate with the requirements for the overall study. Furthermore, in many instances where simplified techniques were used to produce results of limited utility, it was discovered that, because of legal and institutional constraints, the data and decisions resulting from preliminary analyses were carried through to the final project design. Therefore, the influence of an inappropriate simplified technique may prevail throughout the planning and design of a project. Thus, it became apparent that the real need was for new techniques - techniques developed with consideration being given to the ultimate applications of the results and which would employ the capabilities of the computer to go beyond techniques primarily oriented toward manual computation.

Several obstacles stand in the way of the development of new hydrologic techniques. First, there has sometimes been a notable communication failure between persons responsible for planning the overall study and persons responsible for conducting the hydrologic analyses. Differences in planning objectives are not always effectively communicated to the hydrologic engineer, and consequently there are too many instances where the hydrologic analyses are not completely responsive to the overall study needs. Expensive restudies are sometimes required and the overall study progress can be delayed until they are completed. On the other hand, the hydrologic engineer sometimes fails to clearly identify the problems associated with the analysis of basic hydrologic data. When this happens, the planner is unable to properly program the hydrologic analyses, and the usual result is that the time and funds allowed for hydrologic analyses are not adequate.

Another problem which can impede development of new techniques is the reluctance on the part of some engineers to deviate from the traditional techniques. The significance of this problem is decreasing rapidly as more engineers become familiar with the objectives and standards of comprehensive studies.

A third factor which may adversely affect the development of new techniques is the imposition of an aribtrary standard of accuracy or reliability upon the results produced by new techniques. Hydrologic engineers are concerned that the results of their analyses might be used to substantiate or justify water resources developments when the accuracy and limitations of these results are not thoroughly understood by the decision-makers. This concern is probably not unfounded; but the solution to this problem is to emphasize the development of explanations which clearly identify the significance and limitations of results from new procedures rather than to impose arbitrarily high standards of accuracy which might not be consistent with the intended use of the results.

DEVELOPMENT OF NEW TECHNIQUES

Success in developing new techniques or methods for hydrologic analyses for regional planning studies is dependent upon overcoming the above described obstacles. The developers of the methods must have a thorough understanding of the problem to be solved, the data available for use in the solution, the time and funds constraints which will be imposed upon the users, and the potential uses of the results. The engineers who will actually employ the techniques must, of course, understand the application of the technique, develop the required data, be able to explain how the method was used, and be capable of describing the accuracy or reliability of the results and the limitations on their use. The persons responsible for directing the comprehensive study must insure that the scope and objectives of the planning are fully understood, develop chronological schedules and fund allotments which are consistent with the required hydrologic analyses, acquire an understanding of the technique and the results in order to insure proper integration of the results into the overall effort, and develop a means of presenting the results of the studies in a way which minimizes the possibility of invalid use of the results without destroying the credibility of the work for its intended purposes.

The Hydrologic Engineering Center has participated in the development of new techniques for use in comprehensive planning studies through cooperative studies with other Corps of Engineers offices. Most of the new techniques developed to date have emphasized computational procedures designed specifically for use with electronic computers. Applications of the new techniques have ranged from framework-type planning studies to development of day-to-day operational criteria for water resource systems. Studies recently completed or in progress include: (1) development of a regional flood control site screening plan for the North Atlantic Region study, (2) use of streamflow simulation for planning and operation of the Missouri River mainstem projects, (3) development of an operation plan for the Arkansas-White-Red Rivers reservoir system, (4) standard project flood estimates and flood frequency estimates for use in the Colorado River Basin Framework study, and several other projects, some of which are described in more detail in the following paragraphs to illustrate the nature of the new techniques.

GENERALIZED STANDARD PROJECT RAINFLOOD COMPUTATIONS

In the course of comprehensive planning for flood control for the Santa Ana River and Orange County areas in southern California, it became necessary to make standard project flood estimates for a large number of locations. The standard project flood estimate represents flood discharges that may be expected from the most severe combination of meteorologic and hydrologic conditions that are considered reasonably characteristic of the geographical region involved, excluding extremely rare combinations. The practice prior to this study was to make a separate analysis of the standard project flood

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estimate for each location as the need arose. The estimates of representative loss rates and unit hydrographs were usually made independently from one location to another, although common data and techniques were usually used. Many of these procedures were not programmed for the computer, and much of the work was accomplished with desk calculators. The need for standard project flood estimates at a large number of locations suggested the probable advantage of generalized standard project rainflood criteria and associated generalized computer programs for an economical determination of the required quantities. Also, it was felt that the generalized criteria and computer programs could be made applicable to other southern California coastal areas.

The standard project general storm criteria were developed by determining the depths of rainfall for various durations and area sizes for the largest observed storms in the southern California area. It was recognized that orographic effects greatly influenced rainfall in this area. In order to account for this, general storm rainfall was expressed as a ratio to the 3-day-storm precipitation exceeded once in 10 years which can be determined easily for any location in the study area from isohyetal maps developed in an earlier study (reference 11). An envelope procedure applied to these ratios for all pertinent durations and area sizes was adopted as a primary basis for standard project general rainflood criteria.

The time distribution pattern for the standard project general storm is governed effectively by these depth-duration-area values. However, a reasonable sequence of short-interval values is required for flood computation. The sequence used for the generalized criteria is that observed near the center of the January 1943 storm and modified to conform to standard project storm amounts for all durations.

While considerable information on unit hydrographs and loss rates for the southern California area exists, it was decided for this generalized study to derive criteria that would be readily adaptable for computer use. Accordingly, new studies were made on 40 southern California areas where adequate storm rainfall and runoff data are available. These areas were considered to be generally typical of the different types of drainage basins located in the southern California area. Unit hydrographs and loss rates were derived for each of these areas by use of a unit hydrograph and loss rate optimization computer program (reference 1). The optimization technique employed is the "Univariate Method" described in reference 7.

The principal analysis for the determination of unit hydrograph coefficients was a correlation study which related time of concentration and the storage coefficient to drainage area, normal annual precipitation, stream length, stream slope, average elevation of the basin, average basin slope and median stream length. These characteristics were selected in part since the values were readily attainable and did not require a large amount of computation. All correlations performed indicated large residual errors due to the impossibility of expressing many relevant factors numerically. However, an effective relationship was developed, relating time of concentration to drainage area and median stream length. The studies indicated that use of an average value of the ratio of storage coefficient to time of concentration would be acceptable, and the average value developed in the reconstitution studies was adopted for use in the generalized criteria.

By plotting the data developed in the correlation study on a map of the southern California area, it was possible to identify somewhat the effect of various types of topographic areas. Three identifiable types of topography (mountain, foothill, and valley) were selected, and the relationship developed in the correlation analysis was modified to permit inclusion of numerical coefficients which would reflect topographic influences. In basins where significant channel improvement exists, the coefficients can be reduced in proportion to the decrease in total time of concentration effected by the channel improvement, as indicated by Manning's equation.

A two-parameter loss rate function was used to establish representative losses for the standard project storm. This function is described in detail in reference 8. The first parameter, which relates loss rates to rainfall intensity, was derived directly from the reconstitution studies. The second parameter, relating loss rates to type of soil and soil moisture, was effectively related to general soil types. A map, shown as plate 1, was constructed from a generalized soil map and the reconstitution studies to facilitate estimation of this parameter. An estimate of initial moisture conditions was also required and was developed from the reconstitution studies.

Other factors, such as snowmelt, local (cloudburst) storms, urbanization and future developments were considered, and have been included in the criteria where their effect is appreciable. A computer program was written to perform the computations necessary to develop standard project flood hydrographs from the criteria (reference 2). Determination of the required parameters from topographic maps and plates, such as plate 1, is accomplished manually and the computer program performs the rest of the necessary computations automatically. The program is written in such a way that any of the criteria can be suppressed by input options. This allows the user to override the generalized criteria if more detailed data are available at a particular location, and furthermore, any future, more detailed information that would alter the criteria can be readily incorporated without the necessity of rewriting the computer program. A complete description of the criteria derived for this study is contained in reference 12.

GENERALIZED WATER SUPPLY STUDIES

The recent drought in the Northeastern United States was the subject of a preliminary study involving the evaluation of both present and proposed future water supply reservoirs in that region. This study was one of a series undertaken as part of the Northeastern United States Water Supply Study. The objective of the study was to demonstrate the relative merit of integrating alternative proposals with existing water supply systems serving the northern New Jersey-New York City-Western Connecticut metropolitan area. For the purpose of this study, it was stipulated that no regard should be given to institutional constraints whether they were organizational, legal or economic. Also, no attempt was to be made to consider the effects that proposed structures might have on the utilization of the water resources for purposes other than water supply. However, minimum streamflow requirements that were required by law or derived for the purposes of this study to support water quality or existing supplies were maintained. Generally, in areas where statutory requirements did not prevail, a minimum streamflow requirement was selected. This study was intended only to demonstrate the physical possibilities of regionalized water supply.

The primary water supply reservoirs presently serving this area are located in the Catskill and Delaware River Basins. However, these studies also investigated potential reservoirs on the Hudson, Raritan, Passaic, Hackensack, Housatonic and Connecticut Rivers. Some of the alternatives investigated included operational changes in utility management, large conventional storage reservoirs, pumped-storage reservoirs, interbasin transfers, flood skimming, and interconnection of utilities by large aqueducts.

The method of analysis selected was to simulate, on the computer, those reservoirs which would be operated as a system. Accordingly, simulation models were developed for 20 separate reservoir systems, and for several separate models within each system so that various alternatives could be investigated. In all, about 40 sets of operating conditions were investigated.

A generalized computer program which performs a multipurpose, multi-reservoir monthly routing of practically any reservoir system is available in The Hydrologic Engineering Center (reference 3). The method used in the program is to meet all necessary requirements to the system and to maintain a specified balance of storage in all reservoirs insofar as possible. This is accomplished by a balancing routine which determines releases from each

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reservoir based on specified levels each month. During operation, each level in all reservoirs operating for a given downstream control point, is evacuated before going to the next lower level. The physical characteristics of each reservoir (storage, area, outlet capacity, etc.)are described to the computer along with flow requirements and diversions in the system. Provisions are included for changes of basin development or operation plan at the ends of any designated years. Plate 2 shows a typical schematic diagram of one simulation model developed for this study.

Estimates of elevation-area-storage data and outlet capacity for potential reservoir sites were made by inspection of available topographic maps and by deriving generalized outlet capacity relationships from existing reservoirs in the region.

Unregulated flows into and between reservoirs were estimated from recorded flows in the system. In some cases, recorded flows had to be extended and missing flows estimated so all stations would have a common period of 1923 through 1967. For several areas, data on the effects of regulation to natural streamflows were available, and recorded flows were adjusted accordingly. However, for some areas, detailed information was not accessible in the time alloted for this study, and adjustments had to be made from general information of regulation in the basin. Average monthly net evaporation rates were estimated based on available records in the region.

Initial estimates of yield were made for potential reservoir sites using recorded monthly flows at nearby stream gages. These records were analyzed for a large number of locations by means of a computer program which computes the independent low-flow events for as many as twenty durations simultaneously and determines the probability of each event (reference 10). By examining these data, initial estimates of yield could be determined for potential reservoir sites, knowing only the contributing drainage area. Typical patterns of the monthly variation of the average demand within a year were selected, based on records of past use in the area. By successive trials with the simulation models, the initial estimates of average yield were adjusted until no shortages or unused storage occurred in the system. The yields determined by the operation of these systems were based strictly on the period of historical hydrologic records; however, operations were made to determine the relative severity of the two major droughts of record. It was found that the 1960's drought was more severe over the entire study area than the 1930's drought. Yields computed from the 1960's drought were 15 to 50 percent lower than yields for corresponding locations during the 1930's drought. No statistical analysis was made to determine the frequency of these droughts.

In this study, the emphasis was on development of the simulation models and on obtaining preliminary estimates of yield throughout the various systems. In developing the models, however, maximum consideration was given to flexibility which will permit use of the models in more detailed studies. Since these models are actually input data to a generalized computer program, they can be modified with very little effort. For instance, if more detailed information becomes available on one of the potential reservoirs, it would require that only 10 cards of the input data be changed before the entire model could be reanalyzed.

SCREENING STUDY FOR LOW FLOW REGULATION

At the request of the Work Group on Hydrologic Analyses and Projections - Missouri Basin Interagency Committee, a study was initiated to evaluate more than 700 potential reservoir sites with respect to storage requirements for low-flow augmentation. The situation was typical in that there were many alternatives to be evaluated, but there were limitations on both time and funds and there was a scarcity of physical and hydrologic data. As a basic requirement, the screening procedure was required to produce results which are consistent with respect to the screening objective; that is, no assumption which would substantially alter the ranking of alternatives could be tolerated. A second requirement was that the magnitude of the result, in this case the estimated storage requirement, is required to be of sufficient accuracy to permit its use in more detailed analyses of the surviving alternatives.

The procedure adopted consisted of performing monthly sequential reservoir routing studies by computer for each location to determine the storage required to supply the given demands under specified shortage tolerances. These routings incorporated all available hydrologic, physical, and climatologic data into the screening procedure. The influence of evaporation, seasonal variations in demands and streamflow, sediment reserve storage

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requirements, and intervening flow between damsites and demand points were all accounted for in the selected method.

Initially, the Missouri River Basin was divided into sub-areas of similar climatological and physiographic characteristics. Generalized reservoir area-capacity relationships were developed for each sub-area. Analyses of climatologic and hydrologic data for each sub-area provided seasonal patterns and annual indices of runoff and evaporation for computation of net evaporation. Existing sediment data for each subarea were related to soil types and runoff to develop generalized sediment deposition quantities for use in estimating sediment reserve storage requirements.

All available streamflow data were statistically analyzed using a computer program entitled, "Monthly Streamflow Simulation" (reference 5). Statistical characteristics of the available data were used with a multiple correlation analysis to estimate missing flow events. Geometric mean annual runoff and drainage area ratios were used as indices in estimating streamflow data for potential sites where no gaging station existed.

One of the most important aspects of this study was the necessity for establishment of a shortage indicator that would give an accurate representation of the comparative shortages at various locations and yet be amenable to some type of mathematical evaluation. It was believed that shortage frequency which is often employed as an indicator would not be suitable for this study because available methods of estimating drought frequency do not permit consideration of the sequence of flow events within the drought and are, therefore, not compatible with the reservoir routing techniques that were to be employed in the study.

It appeared that some indicator which would account for both frequency and magnitude would be more desirable than one which accounted for frequency alone. An indicator of this type, if properly computed, could embody all of the pertinent information relative to shortages except for information concerning their time distribution. Another important property of this type of indicator is the likelihood that there would be a recognizable relationship between the indicator and storage requirements. The indicator adopted was the shortage index originally proposed by Leo R. Beard (reference 6). This index possessed all of the necessary properties and a definite relationship was found to exist between shortage index and storage requirements.

The sequential routings were performed with a modified version of a computer program entitled, "Reservoir Yield" (reference 4). The primary modification consisted of an optimization routine which enables the computer to analyze the results of a routing, make a new estimate of storage required, and make new routings until a pre-specified target shortage index is achieved. As shown on plates 3 and 4, the relationship between storage and shortage index is very irregular as one might expect since it is dependent upon seasonal variations in streamflow, evaporation, and demand. The optimization routine was required to be relatively efficient because each trial requires a complete month-by-month routing of the 40-year study period.

Plate 5 shows the progress of the optimization routine in determining the required storage at Galt, Missouri, for a target demand of 15.5 cfs.

The estimated storage requirement and the resulting shortage index are underlined for each trial and the trials are separated by dashed lines. The curve showing storage vs. shortage index for this location is included as plate 4. On this plate the small numbers near the circled points denote the optimization trial number and thus one can readily trace the progress of the optimization routine. The unnumbered points were computed after the study was completed in order to better define the curve for illustrative purposes.

Upon determination of the storage requirement, the program prints out a detailed monthly routing for the 40-year study period. This routing shows, for each month of each year, the inflow, end-of-month storage, evaporation, demand, release, and shortage. This can be used to determine when the shortages occurred and the magnitude of each shortage. It can also be used as a guide in estimating changes in operating criteria to minimize shortages in future analyses.

The study was completed in less than 5 months and at a cost of about $5 per site evaluated. The above data include both the development and application of the procedure, but do not include the cost of gathering the data and processing it for use with the computer. A more detailed description of the technique is contained in reference 9.

CONCLUSIONS

From the foregoing, it may be concluded that there are many potential areas of application for new hydrologic engineering techniques for use in regional water resources planning. The versatility and utility of new techniques are enhanced considerably by using computational algorithms that take full advantage of the power of the electronic computer. Consequently, it appears that the maximum value from new techniques can be achieved by emphasizing the development of new technical procedures rather than by computerizing existing techniques.

On the basis of the experience acquired to date, it appears that a new technique will be most beneficial when it is designed to (1) produce results which are consistent with the scope, objectives and requirements of the overall planning study, (2) use all pertinent available physical, hydrologic, and climatologic data which will significantly affect the results without requiring data that is not available and cannot be developed within reasonable time and budget constraints, (3) take advantage of the capabilities of the computer and related data storage, retrieval, and processing systems, and (4) produce results which, insofar as possible, form a firm basis for future, more detailed planning and design studies instead of being limited in usefulness to the study at hand.

ACKNOWLEDGMENT

The studies described herein have been accomplished through the cooperative efforts of engineers in several Corps of Engineers District and Division offices and through the efforts of fellow staff members of The Hydrologic Engineering Center. It is impossible to identify each of the persons who have made significant contributions to the studies, but the importance of their contributions must be acknowledged. Likewise, the principles of generalized computer programs and regional analyses described in this paper are the products of the efforts of the entire staff of the Hydrologic Engineering Center, particularly Mr. Leo R. Beard, the director.

The opinions expressed herein are those of the authors and do not necessarily reflect the official policies and procedures of the Corps of Engineers.

REFERENCES

1. Beard, Leo R., "Unit Hydrograph and Loss Rate Optimization", Computer Program Description, HEC Program 23-11, 1966.

2. Beard, Leo R., "Unit Graph and Hydrograph Computation, Southern California Coastal Stream", Computer Program Description, HEC Program 23-59, 1967.

3. Beard, Leo R., "Reservoir System Analysis-Conservation", Computer Program Description, HEC Program 23-53, 1968.

4. Beard, Leo R., "Reservoir Yield", Computer Program Description, HEC Program 23-45, 1965.

5. Beard, Leo R., "Monthly Streamflow Simulation", Computer Program Description, HEC Program 23-67, 1967.

6. Beard, Leo R., "Estimating Long-Term Storage Requirements and Firm Yield of Rivers", General Assembly of Berkeley of International Union of Geodesy and Geophysics, 1964, Surface Waters, pp. 151-166.

7. Beard, Leo R., "Optimization Techniques for Hydrologic Engineering", Water Resources Research, Vol. 3, No. 3, Third Quarter 1967, pp. 809-815, American Geophysical Union.

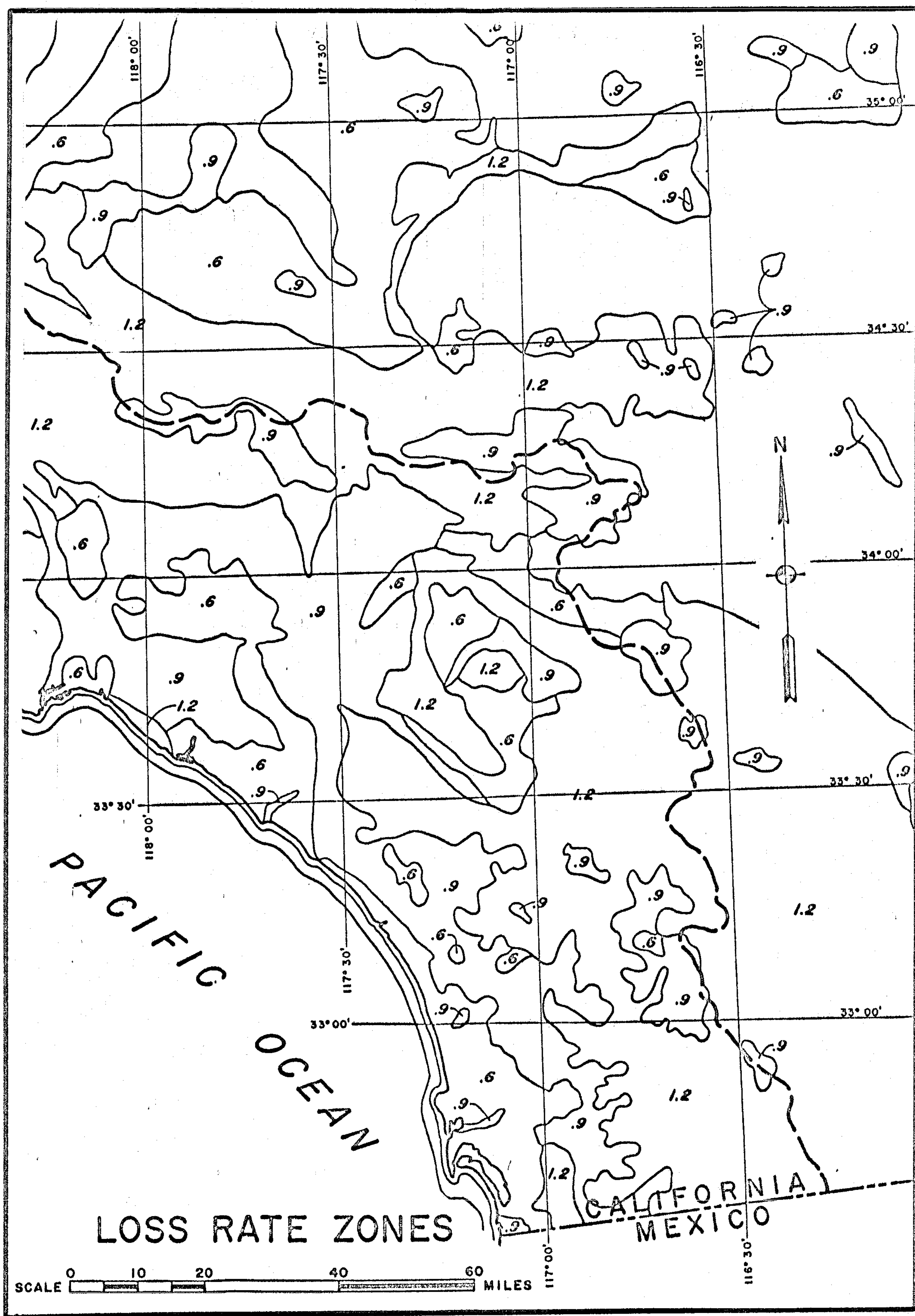
8. Beard, Leo R., "Hypothetical Flood Computation for a Stream System", International Association of Scientific Hydrology Symposium, December, 1968, pp. 258-267.

9. Fredrich, Augustine J., "A Pilot Study of Storage Requirements for Low-Flow Augmentation", 49th Annual Meeting of American Geophysical Union, April 1968.

10. Sharp, Warren L., "Partial Duration-Independent Low-Flow Events", Computer Program Description, HEC Program 23-47, 1966.

11. U. S. Corps of Engineers, "Ten-Year Precipitation in California and Oregon Coastal Basin", Technical Bulletin No. 4, U. S. Army Engineer District, Sacramento, 1957.

12. U. S. Corps of Engineers, "Generalized Standard Project Rainflood Criteria for Southern California Coastal STreams", U. S. Army Engineer District, Sacramento, 1967.



LOSS RATE ZONES
SCALE
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10
20
40
60
MILES
PACIFIC OCEAN
CALIFORNIA
MEXICO
N
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117° 30'
117° 00'
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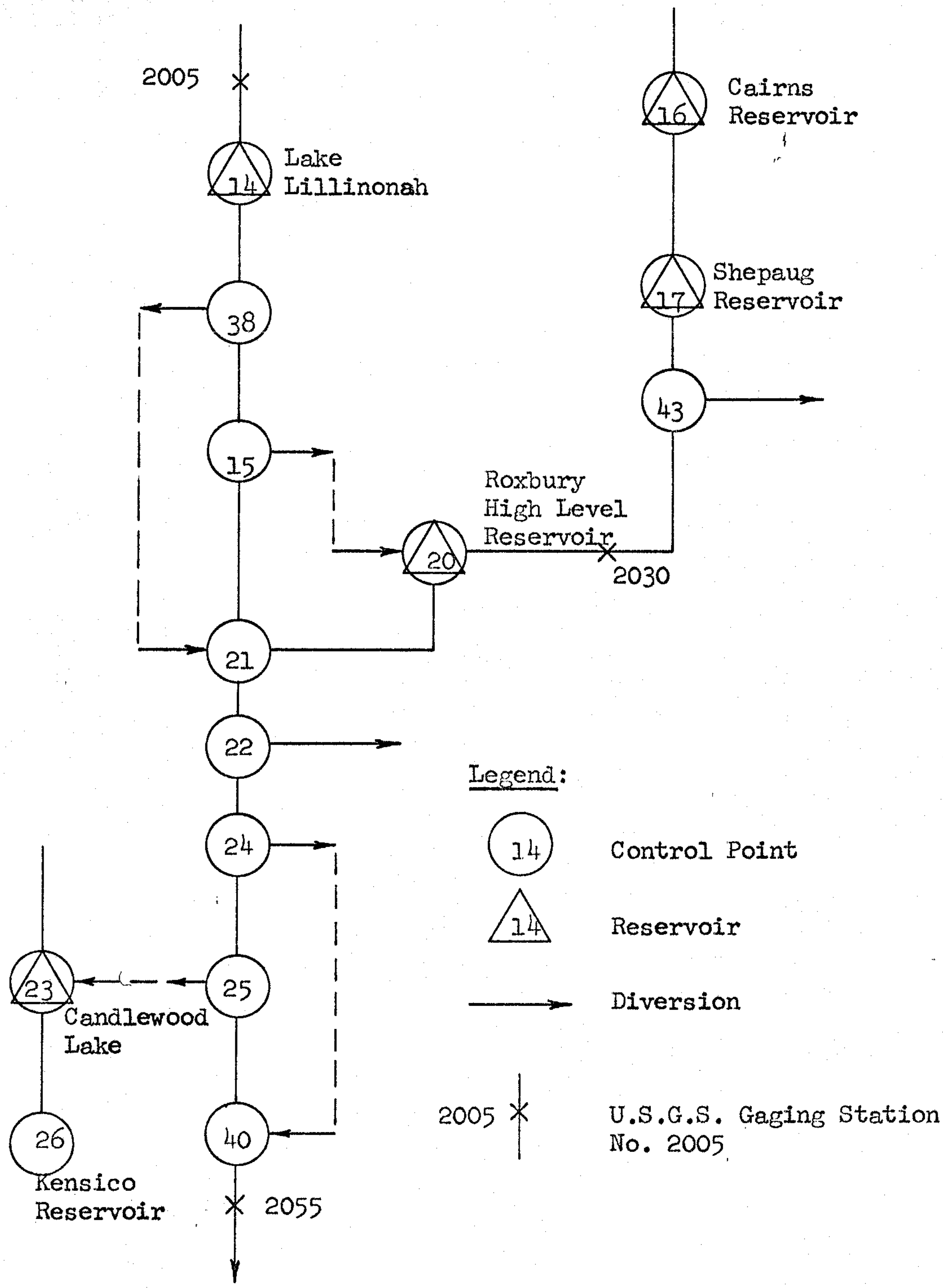
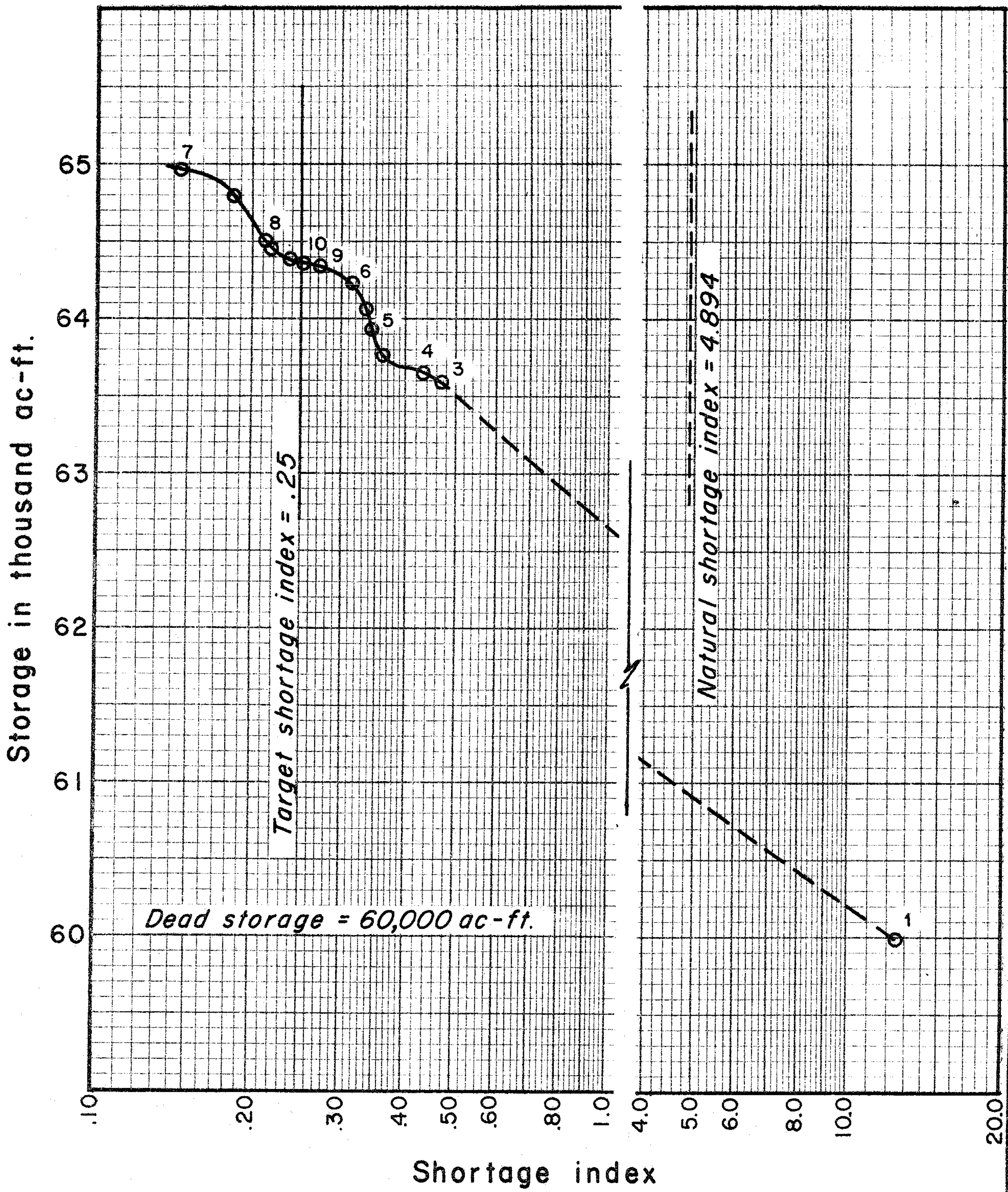
35° 00'
34° 30'
34° 00'
33° 30'
33° 00'
.6
.9
1.2

PLATE 1



Housatonic River Basin - Alternative No. 1

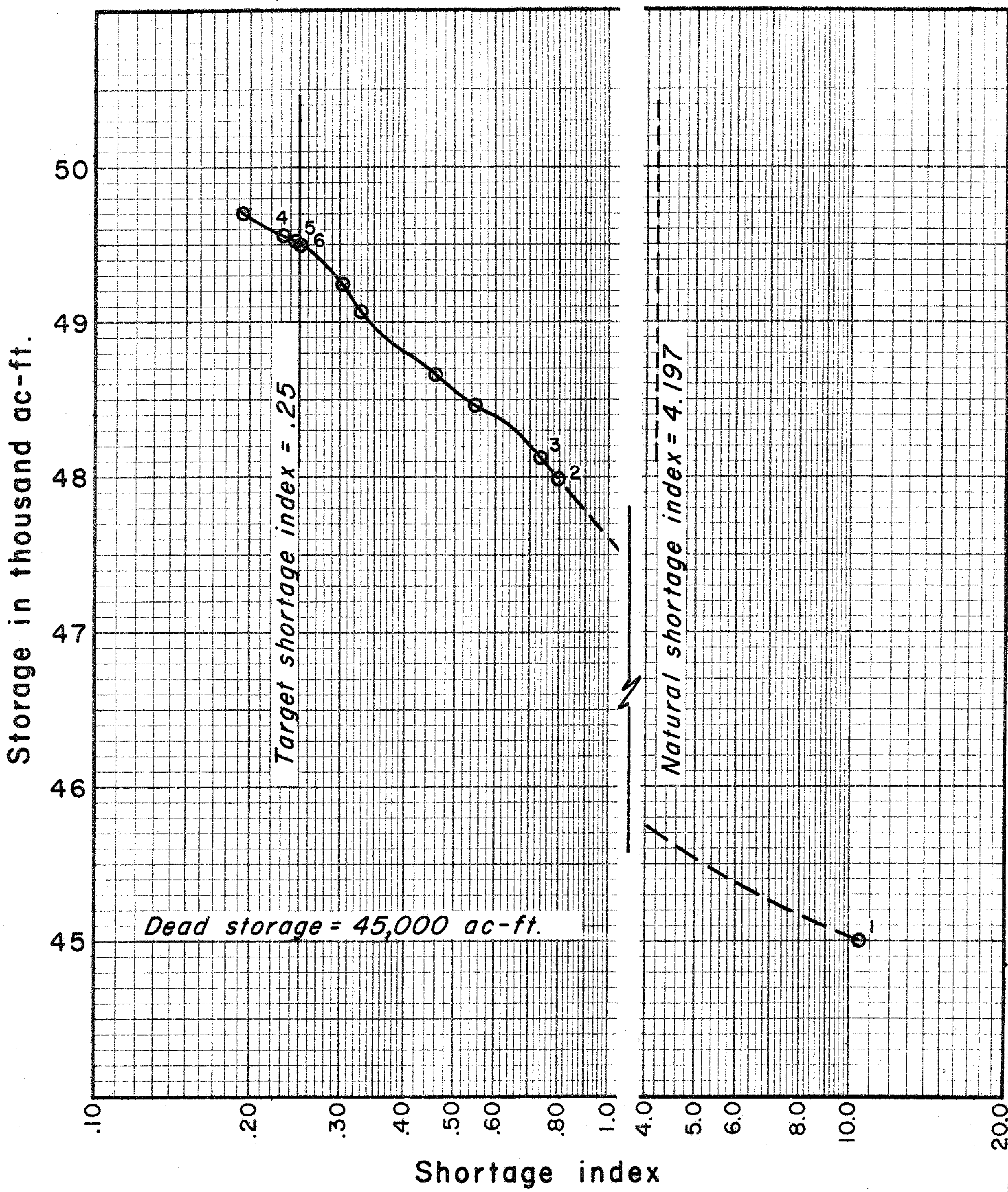
Typical Schematic Diagram of One of the Simulation Models



BETHANY - STA. NO. 10

STORAGE VS SHORTAGE INDEX

TARGET Q = 4.99 c.f.s.



GALT - STA. NO. 31

STORAGE VS SHORTAGE INDEX

TARGET Q = 15.50 c.f.s.

PILOT STUDY FOR MRD LOW FLOW ANALYSIS
GRAND RIVER BASIN - NOVEMBER, 1967

GALT STA NO 31
NO. OF YRS = 40 OPT RUN NO 1 TOTAL STORAGE = 48000 DEAD STORAGE = 45000 TARGET FLOW = 15.50
SHORTAGE INDEX IS 4.197 UNDER NATURAL CONDITIONS

GRAND AVERAGE

PER	CFS INFLOW	END OF MONTH STORAGE IN AC-FT MIN	BUFFER	ACTUAL	MAX	AC-FT EVAP	CFS TO PIPELINE REQ	ACTUAL	SHRTG	RELEASE TO RIVER IN CFS REQ	ACTUAL	SHRTG	MAX	CASE	RES QUAL
YR	138	43220			45000	1399	0	0	0	7.78	136.15	1.79	999999		

SHORTAGE INDEX, PIPELINE 0. OUTLET 10.636 DOWNSTREAM 0. POWER 0.

SHORTAGE INDEX IS 10.636 WITH NO ACTIVE STORAGE

GALT STA NO 31
NO. OF YRS = 40 OPT RUN NO 2 TOTAL STORAGE = 48000 DEAD STORAGE = 45000 TARGET FLOW = 15.50

GRAND AVERAGE

PER	CFS INFLOW	END OF MONTH STORAGE IN AC-FT MIN	BUFFER	ACTUAL	MAX	AC-FT EVAP	CFS TO PIPELINE REQ	ACTUAL	SHRTG	RELEASE TO RIVER IN CFS REQ	ACTUAL	SHRTG	MAX	CASE	RES QUAL
YR	138	44135			48000	1459	0	0	0	7.78	136.01	.27	999999		

SHORTAGE INDEX, PIPELINE 0. OUTLET .794 DOWNSTREAM 0. POWER 0.

GALT STA NO 31
NO. OF YRS = 40 OPT RUN NO 3 TOTAL STORAGE = 48170 DEAD STORAGE = 45000 TARGET FLOW = 15.50

GRAND AVERAGE

PER	CFS INFLOW	END OF MONTH STORAGE IN AC-FT MIN	BUFFER	ACTUAL	MAX	AC-FT EVAP	CFS TO PIPELINE REQ	ACTUAL	SHRTG	RELEASE TO RIVER IN CFS REQ	ACTUAL	SHRTG	MAX	CASE	RES QUAL
YR	138	44135			48170	1463	0	0	0	7.78	136.00	.23	999999		

SHORTAGE INDEX, PIPELINE 0. OUTLET .735 DOWNSTREAM 0. POWER 0.

GALT STA NO 31
NO. OF YRS = 40 OPT RUN NO 4 TOTAL STORAGE = 49570 DEAD STORAGE = 45000 TARGET FLOW = 15.50

GRAND AVERAGE

PER	CFS INFLOW	END OF MONTH STORAGE IN AC-FT MIN	BUFFER	ACTUAL	MAX	AC-FT EVAP	CFS TO PIPELINE REQ	ACTUAL	SHRTG	RELEASE TO RIVER IN CFS REQ	ACTUAL	SHRTG	MAX	CASE	RES QUAL
YR	138	44540			49570	1497	0	0	0	7.78	135.95	.09	999999		

SHORTAGE INDEX, PIPELINE 0. OUTLET .231 DOWNSTREAM 0. POWER 0.

GALT STA NO 31
NO. OF YRS = 40 OPT RUN NO 5 TOTAL STORAGE = 49520 DEAD STORAGE = 45000 TARGET FLOW = 15.50

GRAND AVERAGE

PER	CFS INFLOW	END OF MONTH STORAGE IN AC-FT MIN	BUFFER	ACTUAL	MAX	AC-FT EVAP	CFS TO PIPELINE REQ	ACTUAL	SHRTG	RELEASE TO RIVER IN CFS REQ	ACTUAL	SHRTG	MAX	CASE	RES QUAL
YR	138	44540			49520	1496	0	0	0	7.78	135.96	.09	999999		

SHORTAGE INDEX, PIPELINE 0. OUTLET .246 DOWNSTREAM 0. POWER 0.

GALT STA NO 31
NO. OF YRS = 40 OPT RUN NO 6 TOTAL STORAGE = 49510 DEAD STORAGE = 45000 TARGET FLOW = 15.50

GRAND AVERAGE

PER	CFS INFLOW	END OF MONTH STORAGE IN AC-FT MIN	BUFFER	ACTUAL	MAX	AC-FT EVAP	CFS TO PIPELINE REQ	ACTUAL	SHRTG	RELEASE TO RIVER IN CFS REQ	ACTUAL	SHRTG	MAX	CASE	RES QUAL
YR	138	44540			49510	1496	0	0	0	7.78	135.96	.10	999999		

SHORTAGE INDEX, PIPELINE 0. OUTLET .250 DOWNSTREAM 0. POWER 0.

Technical Paper Series

TP-1 Use of Interrelated Records to Simulate Streamflow
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