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14. ABSTRACT
Procedures of a comprehensive computer program that performed an elaborate hydrologic analysis of a system of reservoirs and assigned economic values to the output were described. The objective of the study was to lay a foundation for obtaining objective functions that expressed the socio-economic effects of a system, to provide intermediate hydrologic and economic data and a method of basin the actual design and operation of a hydrologic system on theoretical optimization techniques. The computer program described performed an elaborate and detailed sequential analysis of almost any configuration of water resource projects. System characteristics and requirements could be specified in any desired degree or detail with minimum effort. Output included detailed data on the month to month operation, as well as hydrologic and economic summaries useful for rapid evaluation of system performance.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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24 May 1968

ECONOMIC EVALUATION OF RESERVOIR SYSTEM ACCOMPLISHMENTS*

Leo R. Beard
Director, The Hydrologic Engineering Center
Corps of Engineers
Sacramento, California

INTRODUCTION

There has been considerable engineering and scientific literature on simulating water resource systems and mathematically optimizing the system design and operation. While a variety of simulation work has been done in planning and design studies, very little actual design has been based on theoretical optimization techniques. One of the reasons is that satisfactory objective functions that express the economic (or preferably the socio-economic) effects of the system in a single figure have not been developed. Work described herein is intended to lay a foundation for obtaining such a function and to provide intermediate hydrologic and economic data required for detailed study.

The increasing complexity of water resources developments and the importance of accurately evaluating system accomplishments require that a detailed sequential analysis of system operation over a long period of time be made. Differences in seasonal variations of runoff and evaporation, and in requirements for storage levels, power generation, and water supplies make the application of simplified storage-yield procedures

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impractical in the analysis of most reservoir systems, particularly where long-term carry-over is concerned.

The procedures described herein are incorporated in a comprehensive computer program that performs an elaborate hydrologic analysis of a system of reservoirs and assigns economic values to the outputs. The procedures include monthly analysis of system operations for all types of water supply and low-flow regulation, and for power generation. Flood control constraints are adhered to, but detailed analysis of flood regulation is not included.

HYDROLOGIC ANALYSIS

The hydrologic analysis for a water resource system such as that illustrated in Figure 1 requires that all of the inflows, requirements, and operating rules be specified, generally as described in the following paragraphs.

The computer program first establishes "local inflows" for all subareas above points of interest and below upstream reservoirs. These are computed as linear functions of specified inflows at relevant locations where such flows are available. In this manner, minimum preparation of data is required, and either highly detailed or very general runoff data can be supplied.

Operation controls include the storage and release capacity of each reservoir, power plant capacities, channel and diversion capacities, and delineation of reservoir operating levels. The operating levels can be specified differently for each month during the year, and differently in different years, if desired. They consist of the full reservoir level, bottom of the flood control space, the top of the buffer space, top of the minimum pool, and intermediate levels between the top of the buffer space and bottom of the flood control space. These intermediate levels are used to control the priority of release among the various reservoirs in the system.

To the extent possible, services that can be provided by more than one reservoir will be provided by that reservoir having storage in the highest range of these intermediate levels. Water is stored in the flood control space only when there is insufficient outlet capacity or channel capacity downstream to release that water. Whenever the buffer pool is not full, only priority requirements are satisfied from that reservoir. Typical specification of reservoir levels is illustrated in Figure 2, which provides that flood-control space in reservoirs 2, 3 and 5 be emptied first, then active storage in reservoir 1, then reservoir 2, then reservoir 3 and half of reservoir 6 simultaneously, then reservoir 5, and then reservoirs 4 and 6 simultaneously. Lastly, buffer storage in reservoirs 2 and 6 is released, but only for priority purposes. The reservoirs can be out of desired balance, of course, if large demands exist that can be satisfied by only certain reservoirs.

Two sets of flow requirements can be specified at each location, total requirements and priority requirements. Each of these can be either constant throughout the year, or different for each month during the year. It is also possible to change requirements at specified locations from year to year.

Requirements for diversion out of the system can be specified as a uniform rate or as a different rate for each month of the year. These can also be changed from year to year, if desired. Such diversions are automatically given priority over river requirements downstream. Diversions into the system can be specified in the same manner. When these constitute return flows, they can be specified as a ratio of some simultaneous diversion upstream.

The net change in evaporation from the reservoir area between conditions with and without the reservoir is specified as a uniform seasonal pattern for all reservoirs. A coefficient by which this pattern is multiplied is specified for each reservoir. The evaporation is applied by the computer to the average area of the reservoir for each period. Since the average stage of the reservoir for any period is not known until the entire system requirements are searched, accurate computation of evaporation requires two system searches for each period, the first to establish average reservoir stages very closely, and the second to compute evaporation accurately.

Hydroelectric power requirements at each power plant are specified by months as total requirement in thousand kilowatt-hours or as a plant factor. Water required to generate that power and the power generated by the water actually released are computed either from the reservoir head and plant efficiency or from a table of power generation versus head for each reservoir. It is also possible to specify an over-all system requirement that exceeds the specified requirements at the individual projects. The excess system requirement is allocated to the various plants in such a way as to most nearly maintain the desired balance of storage within the system. Power computations for each project require two passes through the system during each period, the first to establish average heads for the period, and the second to compute required power releases accurately. System power computation requires three passes through the system each period, the first to determine the amount of excess requirement, if any, and the projects to which the surplus should be allocated, the second to establish average heads at each plant, and the third to compute required releases accurately.

There is also a provision in the program to provide contingency allowances for the fact that the system cannot be operated perfectly. This is done by multiplying the unregulated tributary inflow to any control point by a contingency factor, and considering that such amount does not contribute to the requirement at that location.

Computation of system operation for each period is accomplished by searching the system from upstream to downstream, determining at each control point the total requirements and the reservoirs from which those requirements will be satisfied. Recognizing all of the various controls at each upstream location and the commitments that were set at upstream locations and which must be adhered to, it is apparent that this computation is extremely elaborate. For a system of any size, it is only practical on the fastest and largest computers. A portion of the output for a small sub-system of Figure 1 is shown on Table I.

DETAILED ECONOMIC ANALYSIS

The detailed economic analysis incorporated in this program consists simply of a bookkeeping routine. The output at each control point, which might consist of a rate of river flow, reservoir storage, power generation, or diversion quantity, is assigned an economic function, which can differ from month to month. The function is expressed as a table of the hydrologic quantity versus the economic value in dollars, which is interpolated linearly by the program.

As in the case of hydrologic input, the economic input requirement is designed for maximum convenience. As many as eight output functions can be used. These might represent such items as power, recreation, fish requirements, navigation, quality control, and diversion for irrigation, municipal or industrial uses. An indicator is specified for each economic function and each control point, which determines whether or not that function is to be evaluated for that control point. An example of economic functions is illustrated in Figure 3.

In the case of economic values associated with river flows, the difference in economic value of such flows with and without upstream projects is of interest. Consequently, at these locations the hydrologic output on tape will include preproject (unregulated) flows at each location for each month. Both the project and preproject flows at these locations are evaluated economically in order to assess the gain (or loss) due to the projects.

At each location and for each month and economic function, the computer will determine the economic value for each item by interpolation, the corresponding economic value of preproject flows, if appropriate, the maximum economic value attainable with any hydrologic quantity, and the difference between this maximum value and the actual value obtained (remaining benefits). These quantities are summarized for the entire period of the operation study as illustrated in Table II.

The contribution of any particular project to over-all benefits of the system can best be assessed by performing a separate operation study without that project. However, there is often a desire to allocate benefits in some reasonable manner to the projects which created those benefits. For this reason, there is an allocation routine included, which assigns benefits (difference between project and preproject economic values) computed for flows at each location to upstream reservoirs. These benefits are simply allocated in direct proportion to the change in storage at the various upstream reservoirs. When the change in storage at a particular reservoir is opposite in sign to the net change at all upstream reservoirs, an economic contribution of zero is assigned to that particular reservoir. Benefits allocated on this basis are illustrated on Table II.

SHORTAGE INDEX

The above procedure is based on the assumption that benefits or losses occurring during one period are independent of events in preceding periods. In many cases, this assumption is not valid, and the actual interrelationship of benefits is extremely complicated. The recognition of this situation and of the fact that a planning study does not ordinarily reflect the exact quantities that would occur in actual operation, a shortage index useful in planning studies has been suggested.(1) This index consists of the sum of the squares of annual shortages, each expressed as a ratio to the annual requirement, for a 100-year base period.

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(1) L. R. Beard, Estimating Long-Term Storage Requirements and Firm Yield of Rivers, XIII General Assembly of IUGG, Berkeley, 1963.

Such a function, when used as an index of economic value, simply assumes that the economic loss associated with a shortage is a function of the square of the total shortage for a year and that the actual operation will be such as to minimize the effects of that shortage through forecasting and spreading the shortage over several months. Although the actual economic function might be more closely related to some other power of the shortage, a quadratic function can usually represent the actual function very closely, given the proper coefficient. Big advantages of adhering to the quadratic function are that the shortage index can be multiplied by a constant to convert the value of shortages to dollars in one simple operation and that the index can be computed independently of the actual economic values. A typical shortage relationship is shown in figure 4. Losses shown are reasonable for agricultural areas. Those for municipal supplies would be far greater.

If a coefficient is assigned to the shortage index at each location and for each function, the shortage indexes that are printed out at the end of the hydrologic computation can be multiplied by these coefficients to establish easily and fairly accurately the economic loss due to the shortages. If this is done, then the basic detailed economic analysis described in the preceding section could ignore shortages by assigning the same value to an inadequate flow as to an adequate flow, thus excluding any penalty for shortages in that computation. The penalty for shortages could then be assigned on the basis of the shortage index, which appears to be a more reasonable function for this purpose. Furthermore, if there is negligible economic value of surpluses, then the detailed economic computation can be dispensed with, and the shortage index used to subtract a loss quantity from the total value of the firm yields required.

CONCLUSION

The computer program described performs an elaborate and detailed sequential analysis of almost any configuration of water resource projects. System characteristics and requirements can be specified in any desired degree of detail with minimum effort. Output includes detailed data on the month-to-month operation, as well as hydrologic and economic summaries useful for rapid evaluation of system performance.

The procedures for evaluating the economic accomplishments of a water resource system provide a unique expression of benefits and yet provide a detailed break-down of the benefits attributable to the various purposes and to the various projects and to the locations where they occur. Their computation requires a minimum of preparation and is very inexpensive, once that all of the pertinent project features and economic functions have been determined. Benefits can readily be recomputed for changes in any of the project components or economic functions, and are therefore highly useful for cost allocation purposes and for selection of optimum system configuration.

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The work described herein was conducted in The Hydrologic Engineering Center of the Corps of Engineers. Initial support of the project and many useful suggestions have been obtained from Mr. Harry Schwarz, Chief of the North Atlantic Regional Study Group, New York. The economic features of the program were developed in cooperation with Mr. Ken McElroy of the Baltimore District, Corps of Engineers.

TABLE I - EXAMPLE OF HYDROLOGIC PRINT-OUT

```
 ALL FLOWS IN CFS, STORAGES AND EVAP IN AC-FT AND POWER IN THOUSAND KWH

   1  RESERVOIR A                              SERVED BY    1
                                          SERVING      1   2   4

 YR 1935      AVG       JAN       FEB       MAR       APR       MAY       JUN       JUL
 LOC FLW      862      1330      1852       980      1776      1424       942       414
 UNREG        862      1330      1852       980      1776      1424       942       414
 INFLOW       862      1330      1852       980      1776      1424       942       414

 EOP STR              156000    185973    197741    268709    321202    350600    338000
 EOP EL              1448.85   1466.59   1472.73   1506.72   1528.83   1541.15   1535.87
 EVAPO       5148         0         0         0       600       631       990      1275
 REQ PWR    52560      4464      4032      4464      4320      4464      4320      4464
 REQ PWR   150378      4464      4032      4464      4320      4464      4320      4464
 POWER     150378     16066     14775     10431      7936      8845      6989     10130
 SHORTGE        0         0         0         0         0         0         0         0
 CASE                   103       202       202       202       202       103       103
 LEVEL                 6.00      4.21      3.98      4.90      5.62      6.00      6.00

 CSV REL      794       370      1312       789       573       560       267       598
 RIV FLW      923      1330      1312       789       573       560       431       598
 DES FLW        0         0         0         0         0         0         0         0
 SHORTGE        0         0         0         0         0         0         0         0

   2  RESERVOIR B                              SERVED BY    1   2
                                          SERVING      2   4

 YR 1935      AVG       JAN       FEB       MAR       APR       MAY       JUN       JUL
 LOC FLW     1353      2290      2258      1620      3054      2276      1618       666
 UNREG       2215      3620      4110      2600      4830      3700      2560      1080
 INFLOW      2276      3620      3570      2409      3627      2836      2049      1264

 EOP STR              118800    194078    222331    333863    413551    443100    420000
 EOP EL               825.00    867.07    864.15    897.87    918.18    925.71    919.82
 EVAPO       9094         0         0         0      1098      1140      1753      2230
 REQ PWR   210240     17856     16128     17856     17280     17856     17280     17856
 REQ PWR   261271     17856     16128     17856     17280     17856     17280     17856
 POWER     261271     26270     16128     17856     17280     17856     18437     20128
 SHORTGE     1263         0         0         0         0         0         0         0
 CASE                   203       202       202       202       202       203       203
 LEVEL                 6.00      4.21      3.98      4.90      5.65      6.00      6.00

 CSV REL     1807      2461      2215      1949      1734      1522      1428      1423
 RIV FLW     2280      3620      2215      1949      1734      1522      1523      1604
 DES FLW        0         0         0         0         0         0         0         0
 SHORTGE        0         0         0         0         0         0         0         0
```

TABLE I - EXAMPLE OF HYDROLOGIC PRINT-OUT
(Continued)

```
  3  RESERVOIR C                                    SERVED BY    3
                                                SERVING      3   4
                                                LOCAL DIVERSIONS    3

 YR 1935    AVG        JAN       FEB       MAR       APR       MAY       JUN       JUL
 LOC FLW     418       935      1020       615       870       475       492        75
 UNREG       418       935      1020       615       870       475       492        75
 INFLOW      418       935      1020       615       870       475       492        75
 REQ DIV   127.9        0.        0.        0.      16.0     149.0     317.0     508.0
 DIVERSN   127.9        0.        0.        0.      16.0     149.0     317.0     508.0
 SHORTGE     0.         0.        0.        0.        0.        0.        0.        0.

 EOP STR              10000     58000     84000    109000    117500    117500     86271
 EOP EL              728.00    789.47    809.37    824.80    830.00    830.00    810.88



 EVAPO      3551          0         0         0       526       519       761       883
 CASE                   303       303       303       303       303       303       301
 LEVEL                 1.00      6.00      6.00      6.00      6.00      6.00      5.31

 CSV REL      61         61        61        61        61        61        61        61
 RIV FLW     285        935       156       192       425       179       162        61
 DES FLW      61         61        61        61        61        61        61        61
 SHORTGE       0          0         0         0         0         0         0         0

   4  CONFLUENCE                                    SERVED BY    1    2    3
                                                LOCAL DIVERSIONS    3    4

 YR 1935    AVG        JAN       FEB       MAR       APR       MAY       JUN       JUL
 LOC FLW    -403       562     -1450       419     -1252     -1235      -482      -386
 UNREG      2230      5117      3680      3634      4448      2940      2570       769
 INFLOW     2034      5117       921      2560       892       317       886       770
 REQ DIV   -32.0        0.        0.        0.      -4.0     -37.2     -79.2    -127.0
 DIVERSN   -32.0        0.        0.        0.      -4.0     -37.2     -79.2    -127.0
 SHORTGE     0.         0.        0.        0.        0.        0.        0.        0.
 RIV FLW    2066      5117       921      2560       896       354       966       897
 DES FLW     142       100       100       100       150       200       200       200
 SHORTGE       0         0         0         0         0         0         0         0
 MIN FLW     100       100       100       100       100       100       100       100
 SHORTGE       0         0         0         0         0         0         0         0
```

TABLE II - EXAMPLE OF BENEFITS PRINT-OUT

```
                    AVERAGE ANNUAL BENEFITS IN THOUSAND DOLLARS

                              NET BENEFITS GAINED (UNALLOCATED)
                                       FUNCTION
 STA      SUM        1        2        3        4        5        6
  1       301        0        0      136      164        0        0
  2       159        0        0      171      -12        0        0
  3       381        0      -15       52        0      344        0
  4        68       68        0        0        0        0        0

 SM       910       68      -15      360      152      344        0

                              NET BENEFITS GAINED (ALLOCATED)
                                       FUNCTION
 STA      SUM        1        2        3        4        5        6
  1       354       52        1      136      164        0        0
  2       237       76        2      171      -12        0        0
  3       369      -15      -12       52        0      344        0
  4       -51      -46       -5        0        0        0        0

 SM       910       68      -15      360      152      344        0

                                   GROSS BENEFITS
                                       FUNCTION
 STA      SUM        1        2        3        4        5        6
  1       301        0        0      136      164        0        0
  2       159        0        0      171      -12        0        0
  3       535        0      138       52        0      344        0
  4       779      299      480        0        0        0        0

 SM      1773      299      618      360      152      344        0

                              POTENTIAL GROSS BENEFITS
                                       FUNCTION
 STA      SUM        1        2        3        4        5        6
  1       538        0        0      250      288        0        0
  2      1502        0        0      350     1152        0        0
  3       769        0      240      150        0      379        0
  4      1080      600      480        0        0        0        0

 SM      3889      600      720      750     1440      379        0

                                  REMAING BENEFITS
                                       FUNCTION
 STA      SUM        1        2        3        4        5        6
  1       237        0        0      114      124        0        0
  2      1343        0        0      179     1164        0        0
  3       234        0      102       98        0       35        0
  4       301      301        0        0        0        0        0

 SM      2116      301      102      390     1288       35        0
```

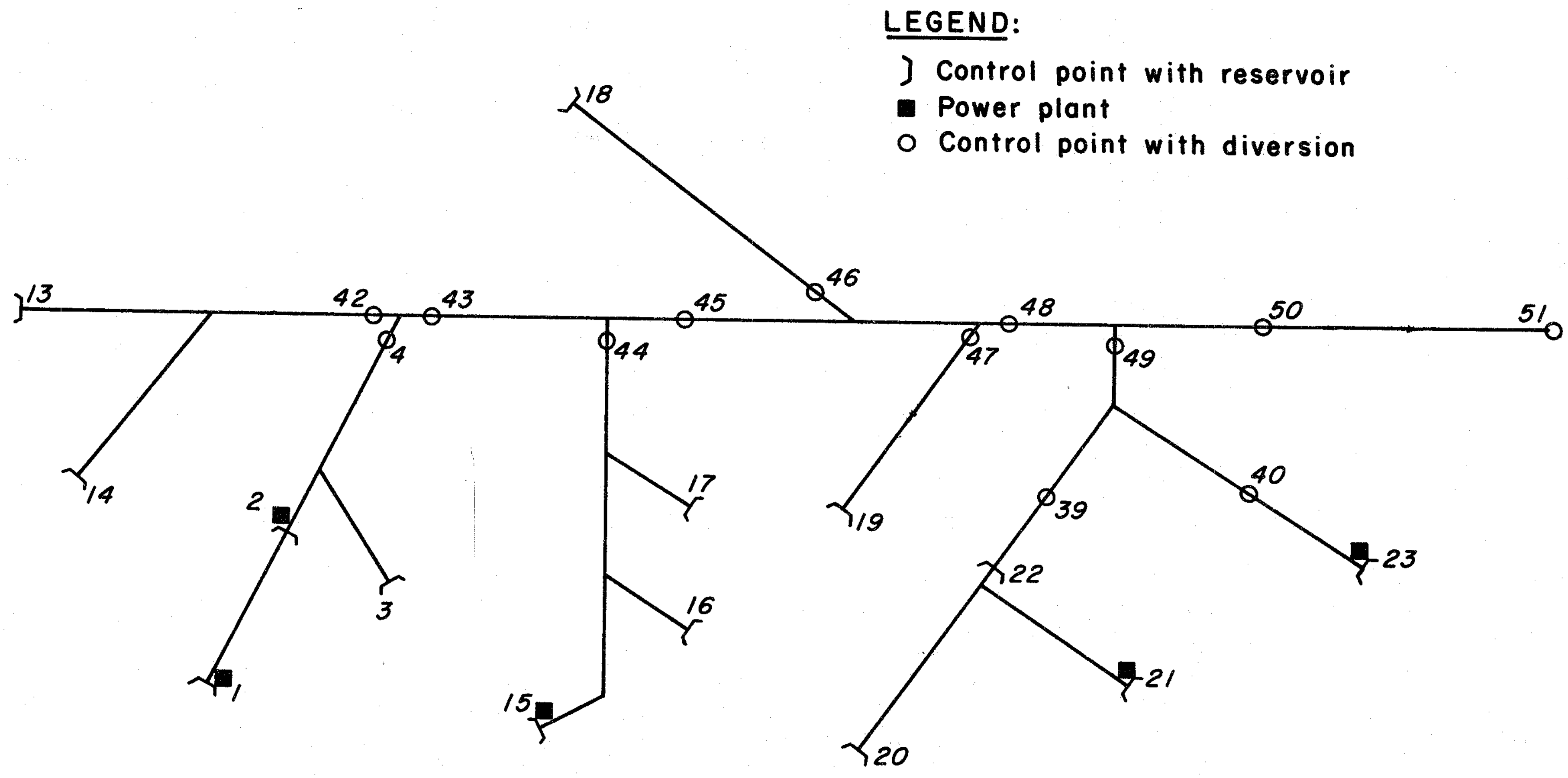

Figure I

WATER RESOURCES SYSTEM
SCHEMATIC DIAGRAM

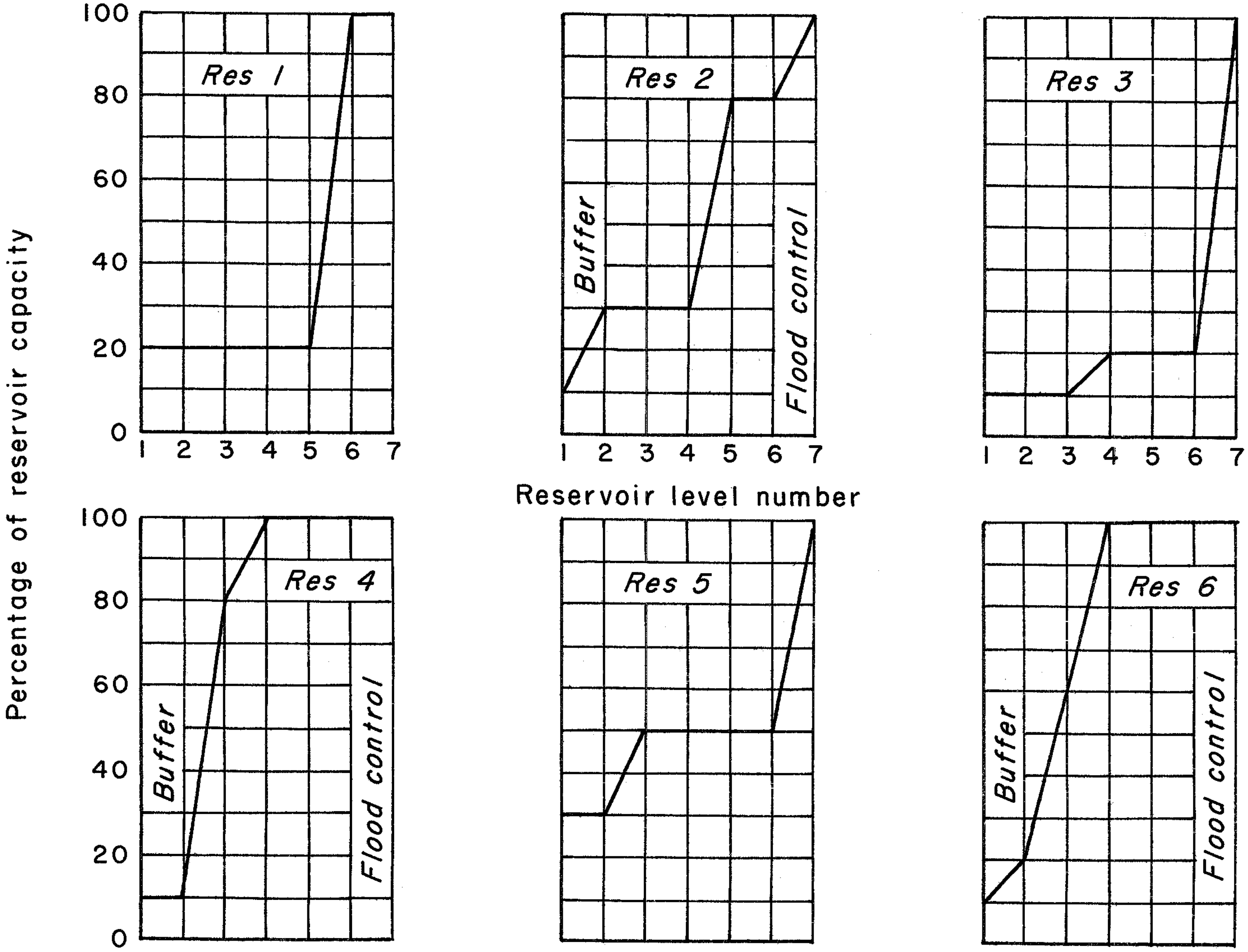

Figure 2

ILLUSTRATIVE PRIORITY OF RESERVOIR USE

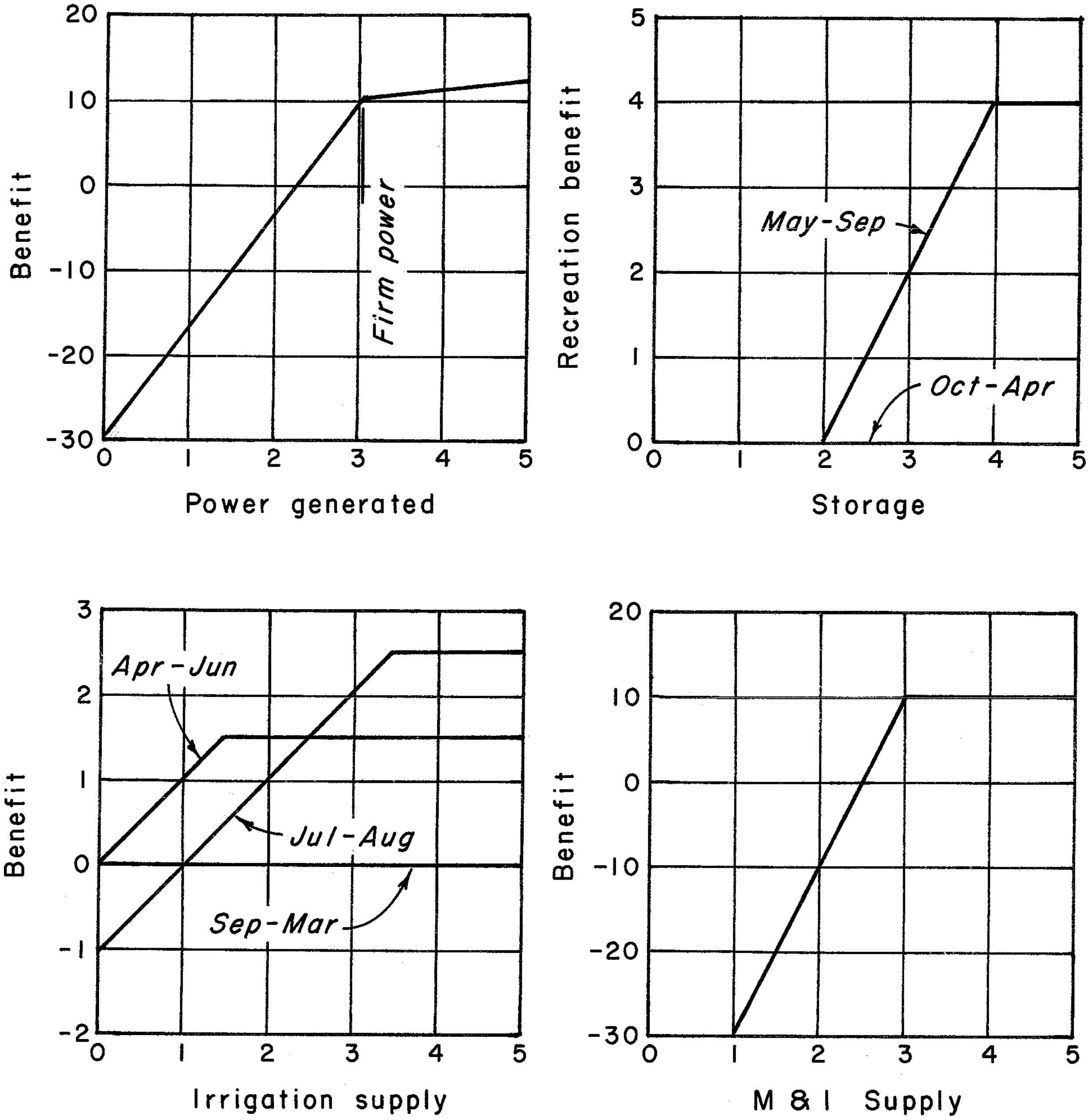

Figure 3

TYPICAL SIMPLIFIED BENEFIT FUNCTIONS

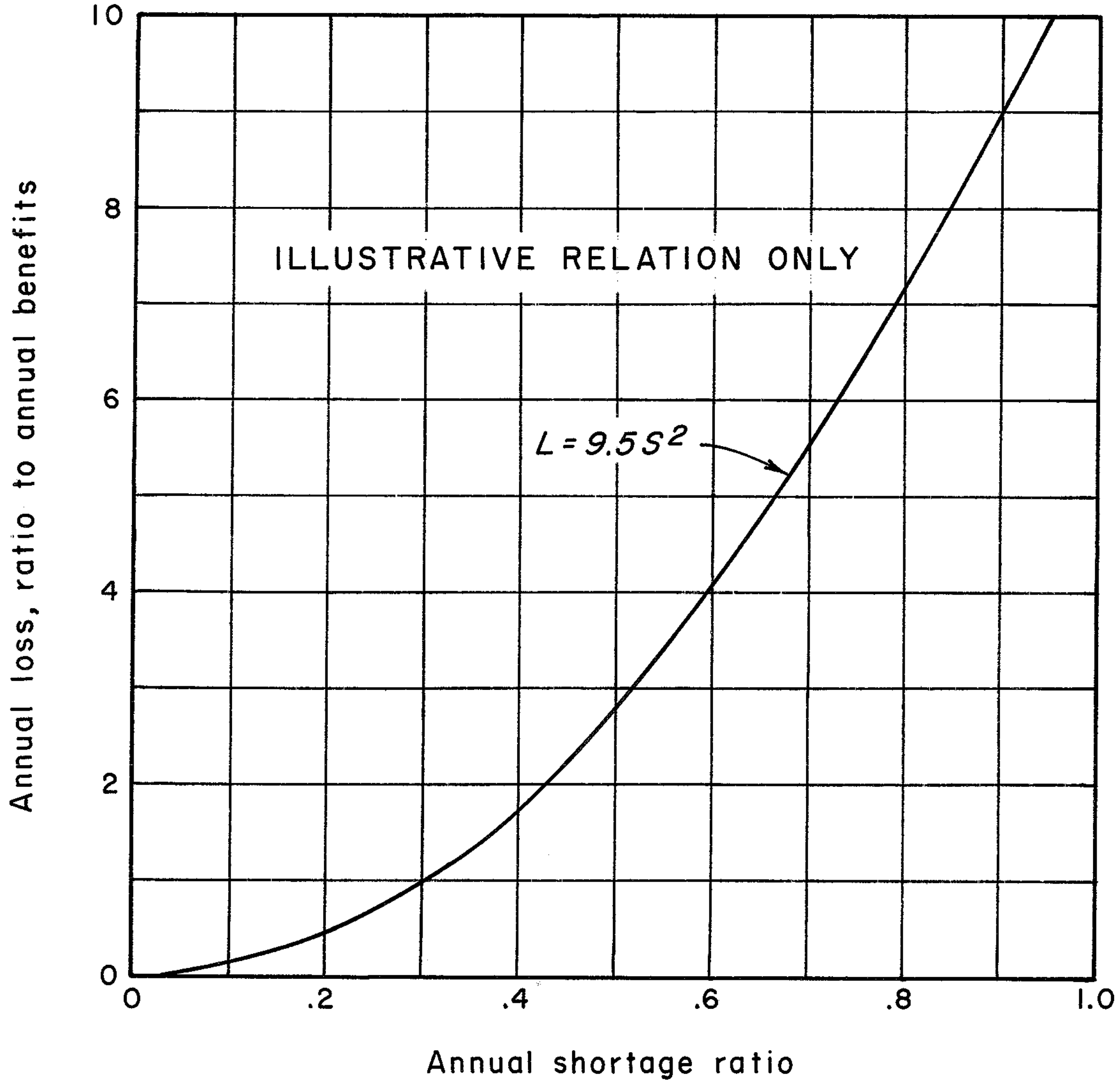

Figure 4

ILLUSTRATIVE SHORTAGE LOSS RELATION

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