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PREDICTING THE HYDROLOGIC EFFECTS OF LAND MODIFICATIONS

by

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SUMMARY:
The increased flood potential of an urbanized semiarid watershed, an example of land use changes, is demonstrated by a procedure that couples a stochastic rainfall model and a widely used runoff estimation method. Claimed advantages include rainfall variability considered directly and rainfall and watershed parameter estimates are readily obtained.

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INTRODUCTION

Protection and enhancement of the environment has become one of the key issues of the day. Section 102 of the National Environmental Policy Act of 1969 reflects this concern. According to White (1972),

> "...no other legislation inspires a more sober recognition of the risk and uncertainty attaching to current efforts to assess the effects of manipulating soil, minerals, water, air, vegetation, transport, and land use."

In an activity that will be affected by this legislation, Nolte (1972) states that a recent national survey of small watersheds indicates that there are more than one-half billion acres of land in the United States that have water management problems to the extent that either or both structural and land treatment measures are considered feasible. Man's efforts to increase the production of minerals, vegetation and water and to find a better place to live have also altered the environment to some extent. In this paper, of concern are the hydrologic effects, perhaps more readily discernible than others, but nonetheless elusive insofar as obtaining an accurate forecast of the results of man's activities.

The basic objective of this paper is to present a methodology that can predict the long-term hydrologic effects of land modifications on ungaged watersheds. As used here, to predict is used interchangeably with to forecast in the hydrologic sense. The essential components of the procedure are an event-based stochastic model of precipitation as input into a deterministic watershed model that transforms the inputs into such desired hydrologic variables as water yield, peak runoff rate and sediment yield.

EVALUATING WATERSHED CHANGES

Many of the changes affecting watersheds are difficult to detect with available field data. The problem may be further confounded by the nonstationarity of the inputs, the climatic variables, throughout the forecast period. Changes in inputs include those effected in rainfall, temperature and radiation brought about by cloud seeding, air pollution, urbanization and climatic change;

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These are in addition to the normal seasonal variation in hydrometeorologic inputs. An excellent overview of the problem of detecting nonstationarities in input functions is given by Changnon and Schickedanz (1971). They focus on the statistical evaluation of precipitation anomalies. If the detection of watershed changes is to be effective, then careful evaluation of changes in inputs is necessary; otherwise, nonstationary behavior of the input might be falsely assigned to the watershed.

Hydrologic effects that may be used for evaluating watershed modifications include probability distributions of extreme events such as floods, by the long-term build up of sediments in reservoirs or the related process of land erosion, or by a seasonal or annual distribution of runoff to indicate the effects on water yield from a drainage basin. In addition, the generation of a synthetic sequence of events would be useful for the design of structures to protect man, the selection of treatments to protect the watershed, and to determine the cumulative effects of man's activities while attempting to live in harmony with the environment.

Hydrologic variables that may be used for determining the above effects include volume of flow, peak flow rates and sediment production and other water quality factors. A problem may arise when attempting to evaluate the relative merits of more than one consequence of manipulating the land. The probability exists that a course of action may result in both beneficial and harmful changes. The question arises, what is the tradeoff between increased water yield and lower water quality, for example. That is a problem of the decision maker whereas the hydrologist or engineer is concerned with the forecasting problem itself. The next section will deal with hydrologic forecasting procedures.

HYDROLOGIC FORECASTING PROCEDURES

Predicting the effects of a proposed action which will modify the land implies that the hydrologic variables can be estimated under a variety of rainfall and watershed characteristics. Since most small to moderate sized watersheds are ungaged, this places an added constraint on a usable procedure. Procedures for estimating runoff from watersheds of all sizes can be classified as follows:

(1) Engineering design approaches
(2) Statistical approaches
(3) Regional analysis
(4) Simulation

Engineering design approaches

A comprehensive summary of various methods that incorporate hydrologic variables in the design of small drainage structures is reported by Chow (1962). Included in this group are such widely used procedures as the Talbot and rational methods and the more recently developed Bureau of Public Roads method (Potter, 1961).

For larger watersheds, records of past flow events are often used to develop unit hydrographs for various storm sizes and watershed conditions. Such procedures are almost impossible to use in a forecasting situation for ungaged watersheds.

The application of the synthetic unit hydrograph to ungaged watersheds is perhaps the most common procedure in the design of water control structures. In the previously mentioned national survey of small watersheds that have water management problems (Nolte, 1972), the average size of the watershed was 125 square miles. The design of structures for preventing floodwater, erosion and sediment damage on many of these watersheds will probably be based on procedures adopted by the Soil Conservation Service (SCS) and the Bureau of Land Management (BLM). These two agencies, who manage a large percentage of the federal lands, utilize a synthetic unit hydrograph procedure developed by the SCS (Soil Conservation Service, 1972). The method relates runoff to rainfall using a combination hydrologic soil group and land treatment class parameter called a runoff curve number. Information for estimating this watershed parameter has been compiled by the SCS for many areas of the United States. A synthetic triangular hydrograph is obtained from storm runoff, a rainfall parameter related to the storm's duration and intensity, and a time lag parameter based on the basin's physical characteristics.

Statistical approaches

Various statistical techniques have been considered in an effort to overcome a lack of reliability of currently used methods. These include stepwise multiple regression, principle component analysis, factor analysis and synthetic hydrology. A brief discussion on these approaches is presented by Bock et al. (1972). In general, these methods are handicapped by an insufficient understanding of the hydrologic phenomena and a lack of verification of the prediction equations using data other than was used in the development of these equations.

Regional analysis

The analysis of hydrologic data from relatively homogeneous areas to obtain general relationships between various hydrologic factors for the region encompassing the areas may be referred to as regional analysis. An example of this procedure is regional frequency analysis developed for large areas by the U. S. Geological Survey (Dalrymple, 1951). The shortage of small watershed data restricts the use of this type of analysis.

Simulation

An approach that appears to hold the greatest potential for producing a continuous hydrograph synthesis from inputs of precipitation, evaporation and watershed data is through the use of computer simulation programs. Two such procedures that have had some use are the Stanford Watershed Model (Crawford and Linsley, 1966) and modified versions and the SSARR program developed by the U. S. Army Engineer Division North Pacific (U. S. Army Corps of Engineers, 1972). The SSARR program is intended to be used on large watersheds such as the Columbia River basin and its major tributaries while the Stanford Watershed Model seems to be more applicable to the size of watersheds under discussion.

The Stanford Watershed Model and its modifications consists of a number of mathematical functions to simulate the various phases of the hydrologic cycle. A continuous hydrograph for gaged watersheds is synthesized under specific input and initial conditions. Thus, until some form of regional analysis is developed to estimate parameters for homogeneous soil-cover-rainfall regimes, its use will be restricted to gaged watersheds.

PROPOSED PROCEDURE

Forecasting the long-term hydrologic effects of land modifications on ungaged watersheds by the proposed methodology is based on a probabilistic rainfall model and a means for converting runoff-producing rainfall into the desired hydrologic variables.

Relating rainfall to runoff

The SCS method was chosen to relate rainfall to such hydrologic variables as storm runoff volumes and peak runoff rates not only because of its widespread use but also because of its simplicity in serving as an example in illustrating the proposed procedure. The two basic equations of this method are as follows:

$$V = \frac{(R - A)^2}{(R - A) + S} \qquad R > A \tag{1}$$

where

V = storm runoff volume
R = rainfall
A = initial abstractions
S = potential infiltration term related to runoff curve number (CN)

$$Q_p = \frac{484\ AV}{0.5D + 0.6T_c} \tag{2}$$

where

Q_p = peak runoff rate
A = watershed basin area
D = duration of excess rainfall
T_c = time of concentration

Only the first relationship, equation 1, will be used in developing the proposed procedure. Peak runoff rates are related to runoff volumes as suggested by equation 2 and sediment yield may be assumed to be caused by a runoff event (Woolhiser and Todorovic, 1971). Thus, while only one hydrologic variable of interest, runoff volume, will be presented in the development, predicting the effects of watershed changes on peak runoff rates and sediment yield can be handled in a like manner.

Basic probability distributions

In an earlier paper, Duckstein et al. (1972) presented a probabilistic rainfall model and demonstrated how the rainfall events could be transformed into runoff events. The procedure requires obtaining two probability distributions, one for the number of events per season and the other for the magnitude of the event.

A runoff event was defined as one in which the storm rainfall R exceeded the initial abstractions A. Both rainfall and runoff events were found to follow a Poisson distribution (Fogel et al., 1971; Kisiel et al., 1971).

Thus, the probability mass function (pmf) of the number of runoff events per season M is defined as

$$f_M(m) = e^{-k} \frac{k^m}{m!} \qquad m = o, 1, \cdots \tag{3}$$

where k is the mean number of events in which R exceeded A. The parameter k is readily obtained from rainfall records.

The second distribution for which information is needed pertains to the magnitude of the event such as the depth of rainfall. For the random variable R, an exponential probability density function (pdf) is assumed to be representative such that

$$f_R(r) = ue^{-ur} \qquad r > o \tag{4}$$

To obtain the distribution of storm runoff, it is first necessary to define a new random variable, effective rainfall, R_e where

$$R_e = R - A \tag{5}$$

The pdf of the runoff volume V can then be obtained by transforming R_e by means of a rainfall-runoff relationship such as the SCS procedure (Duckstein, et al., 1972). This study showed that the cumulative distribution function (cdf) of effective rainfall is

$$F_{R_e}(r) = 1 - e^{-u(r + A)} \tag{6}$$

The mean and variance of the above distribution are

$$E(R_e) = e^{-uA/u} \tag{7}$$

and

$$\mathrm{var}(R_e) = \frac{2e^{-uA} - e^{-2uA}}{u^2}$$

Similar to the rainfall parameter k, the parameter u can be estimated from rainfall records and the above relationships. Finally, using the SCS method (equation 1), the transformation of random variables R_e to V (Benjamin and Cornell, 1970) results in the cdf

$$F_V(v) = 1 - \exp\{- \frac{u}{2} [v + 2A + (v^2 + 4Sv)^{\frac{1}{2}}]\} \tag{9}$$

The stage is now set to evaluate the hydrologic effects of land modifications in terms of the expected return period for a given flood, the seasonal water yield, possible droughts, the long-term sediment yield, etc.

Maximum distribution of storm runoff

To obtain the return period for a given flow volume, the maximum distribution function is required. With the assumption that M and V are independent, Duckstein et al. (1972) have shown that the maximum distribution function $\phi_V(v)$ is

$$\phi_V(v) = e^{-k[1 - F_V(v)]} \tag{10}$$

The return period for V is readily calculated from

$$T_r(V) = [1 - \phi_V(v)]^{-1} \tag{11}$$

Fig. 1 illustrates the sensitivity of the return period of V to the two rainfall parameters k and u. In Fig. 2, the model is compared to annual maximum series of rainfall and runoff each fitted to a Gumbel or extreme value distribution. A 75-year record of a Tucson, Arizona station was used for the rainfall series while a 15-year history of an experimental watershed, located in the vicinity of Tucson, was used for the runoff series (Fogel, 1969). In both cases, the model exhibited a similar mean but a greater variance than the annual maximum time series. Since the slopes of the two series differ, the distribution functions of rainfall and runoff also differ. This is to be expected as the transformation of rainfall to runoff is non-linear (equation 1). It is implied in the SCS procedure, however, that the two distributions are the same.

Referring to equation 2, the return period for peak flow rates can also be obtained. If the duration of excess rainfall D is assumed to be a constant, the pdf for peak flow rates Q_p should be similar to that for V differing only by a scale factor. A more realistic interpretation is to consider D another random variable for which data can be extracted from readily available sources. Thus, peak flow is seen to be a function of what Eagleson (1970) calls the two principal parameters defining storm size, total storm depth and total storm duration. Eagleson suggests a two-parameter gamma function for fitting the conditional pdf of storm depth for each class interval of storm duration.

Total seasonal water yield

Assume that W, the total water yield of a basin during a season, is the sum of independent, identically distributed random storm runoff variables V in M runoff events (itself random and independent of V), then

$$W = V_1 + V_2 \cdots + V_M \tag{12}$$

Benjamin and Cornell (1970) have shown that the mean and variance of the distribution for W is

$$E(W) = E(M)\ E(V) \tag{13}$$

and

$$\text{var}(W) = \text{var}(M)\ [E(V)]^2 + E(M)\ \text{var}(V) \tag{14}$$

The pdf of W is obtained by successive differentiations of its generating function $G_W(w)$ and requires the use of the transformation

$$G_W(w) = F_M\ [G_V(w)] \tag{15}$$

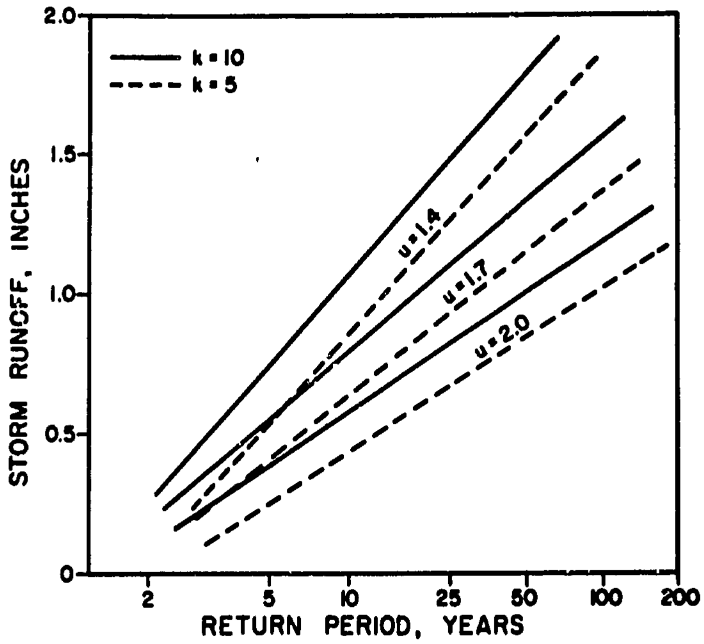

Fig. 1. Effect of rainfall parameters on the return period of a given runoff event.

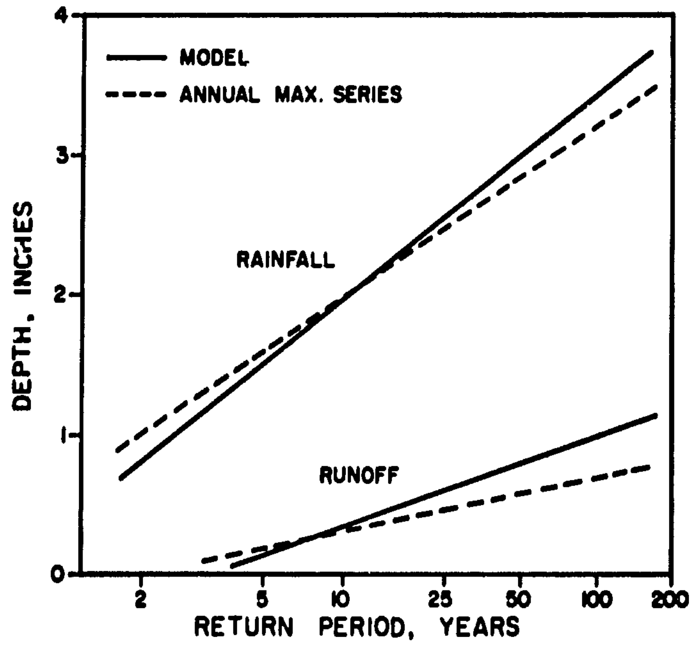

Fig. 2. Comparison of model with annual maximum series of rainfall and runoff.

where $G_V(w)$ is the generating function of V obtained from equation 9 (Feller, 1957).

In many instances, the mean and variance of a distribution (equations 13 and 14) are sufficient information on which to base a decision concerning a proposed project (James and Lee, 1970). Since the number of runoff events M is a Poisson variate, the mean and variance are equal and, as previously mentioned can be obtained from rainfall records. The mean and variance (first and second moments) of the distribution for V can be obtained from the relationship

$$E[V^n] = \int_{-\infty}^{\infty} v^n f_V(v)dv \qquad (16)$$

where $E[V^n]$ is the n^{th} moment of V and $f_V(v)$ is the pdf obtained by differentiating the cdf of V (equation 9).

Synthetic set of runoff events

With the pmf of M and the pdf of W known, it is now possible to generate a succession of yearly combination of runoff events through Monte Carlo simulation. Duckstein et al. (1972) have demonstrated this procedure for rainfall events which can also be utilized for runoff events.

A synthetic set of events so obtained is another means for evaluating the hydrologic effects of the modifications in land use. By obtaining a time series of events, potential floods and their damages can be estimated for as long a time as is desired. Average annual damages for the watershed can then be determined in making an economic evaluation of the proposed project. It would appear that this is a more reliable approach than extrapolating from one or two flood events. The procedure has the added capability for obtaining a time series of available moisture in the soil from simultaneous sets of rainfall and runoff. Then, with the use of production functions, the effects of the modifications on vegetative production can be studied.

DISCUSSION AND CONCLUSIONS

The proposed methodology for evaluating the effects of land modifications has several limitations, one of which is that the rainfall models have been validated only for a few local areas (Fogel et al., 1971; Duckstein et al., 1972; Duckstein et al., 1973). The areas, however, are sufficiently widespread (Tucson, Chicago, and New Orleans) to justify an attempt at regionalization. On the other hand, the rainfall model can consider the effects of elevation (Duckstein et al., 1973) and can utilize the distribution function for mean areal rainfall rather than point rainfall (Duckstein et al., 1972). A possible limitation for some areas is that an event-based approach for converting summer rainfall events into runoff events is used with no consideration of base flow. The effect of antecedent soil moisture or precipitation is not directly considered by the procedure. This, however, can be overcome by using a synthesized set of runoff events and adjusting the runoff curve number to reflect antecedent moisture conditions.

The procedure used to transform rainfall into runoff is the SCS method. The authors recognize the limitations of this procedure in that parameters are combined and lumped to the extent that forecast reliability is threatened. However, unlike most other methods, a means is available for estimating watershed parameters for most of the United States. While the procedure requires judgement on part of the user, the important characteristics are readily identified in a quantitative manner.

As with any method, local data can be used to firm up parameter estimation. In an effort to determine the hydrologic effects of urbanization of a desert shrub watershed, three urban watersheds were installed within the city of Tucson, Arizona (Kao et al., 1973). Results were to be compared with an essentially pristine experimental watershed of comparable size. Results of a regression analysis shown in Table 1, indicate that the use of runoff curve

Table 1. Runoff potential of experimental semiarid watersheds utilizing the Soil Conservation Service runoff curve number as an index (after Kao et al., 1973).

PARAMETER	WATERSHED			
	RR	HS	ARC	ATT
Area, sq. mi	1.9	0.9	3.5	0.5
% impervious area	40	29	22	0
Curve number	89.7	87.4	85.9	72.7
Explained variance	95.6	76.3	84.3	76.2

numbers in the SCS method can explain at least 75 percent of the variance in predicting runoff from rainfall for all four watersheds. What is of additional importance is that the results are consistent with watersheds of greater impervious areas having the greater runoff potential. Figure 3 illustrates the use of the proposed procedure to determine the increased flood potential brought about by urbanization. For example, an urban watershed with a 40 percent impervious area will yield approximately three times the volume of water as a desert shrub watershed.

While Fig. 3 is based on data to estimate rainfall and watershed parameters, Fig. 4 shows the use of the method to estimate the effects of a range improvement program in southern Arizona where only rainfall data are available. Using BLM procedures (Bureau of Land Management, 1966) runoff curve numbers are selected for an area of herbaceous vegetation that will undergo a grass reseeding program. The condition, either fair or good, is an indication of the grazing practices allowed on the rangeland. While only the effects of the program on runoff volume is shown, the use of a synthetic set of rainfalls can be used to estimate the probability of success of the range reseeding. The pdf of seasonal water yield or a simulation of runoff events might be used to estimate the size and number of stock tanks needed to supply water to the range. Since the effect of grass reseeding is to reduce runoff, it is possible that this result may be so successful that the use of surface

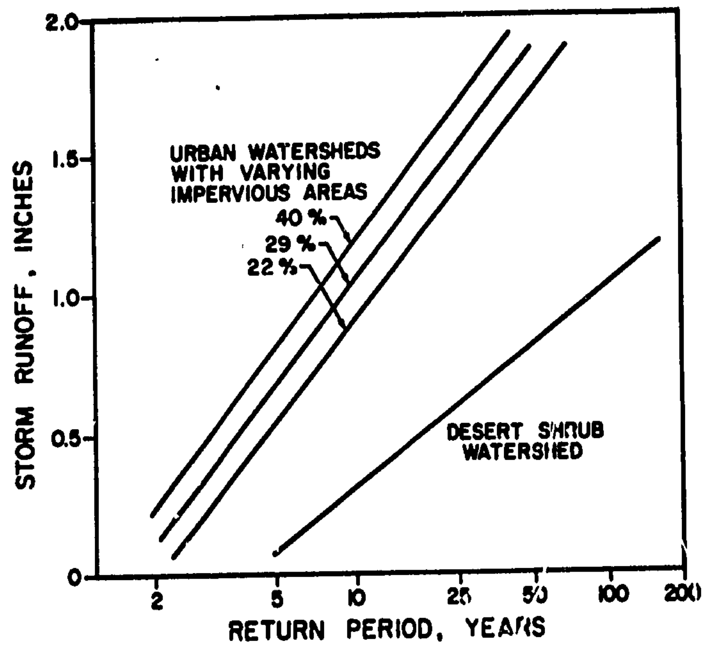

Fig. 3. Effect of urbanization of a semiarid area on the return period of storm runoff.

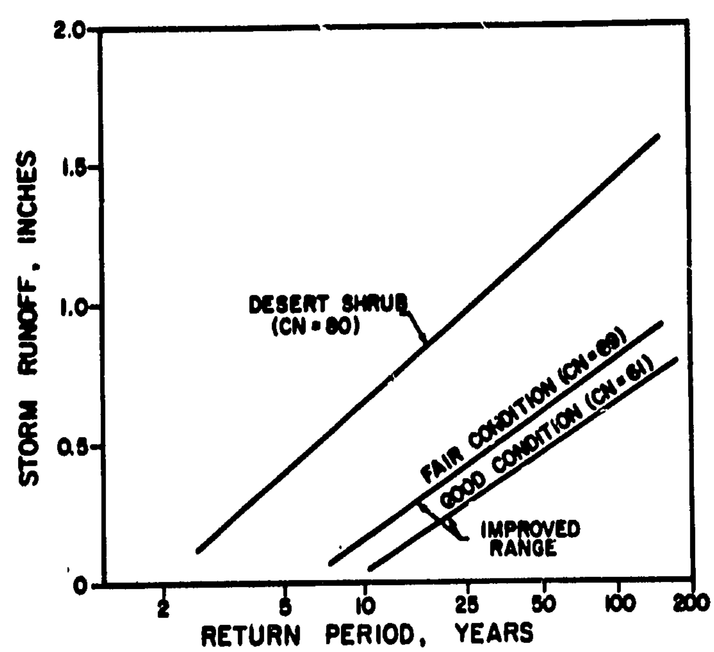

Fig. 4. Estimating the change in the frequency distribution of runoff as a result of a proposed grass reseeding program.

water is negated. The proposed procedure can estimate this possibility prior to implementing the range program.

On a larger scale, the proposed procedure can be used to determine the effect of a watershed treatment on the optimum size of a floodwater retarding structure for watersheds on the order of magnitude of 100 square miles in size. In the past, the 100-year flood was used by the SCS in determining the size of such water control structures whose cost can run into the millions of dollars. Currently the concept of maximum probable precipitation for a given class (size) of structure is used to overcome the uncertainties in flood frequency estimation. With the pdf of runoff (equation 9), the optimum size of a project can be determined from a range of benefits due to flood prevention and a range of costs of structures determined or estimated for floods of varying frequencies. Fig. 5 illustrates this procedure as presented by James and Lee (1971). The effect of a land treatment program on the optimum size of structure can be readily assessed by the proposed procedure.

In summary, by comparing the "before" and "after" predicted hydrologic outputs from a coupled stochastic rainfall model and a deterministic method for estimating runoff, a procedure for comparing the hydrologic effects of land use changes on ungaged watersheds has been demonstrated. The procedure is limited primarily by the method of relating rainfall and runoff. However, local data can be used to estimate watershed parameters and thus remove some of the variablilty of the procedure. While the rainfall model has been validated for only a few areas, the authors feel that this type of model will reduce additional uncertainties in the current practice of implying that rainfall and runoff have similar frequency distributions. Another advantage of the proposed procedure is the flexibility of the previously developed rainfall model. Elevation effects can be taken into account, the distribution function of mean areal rainfall can be utilized, the pdf of runoff can be obtained and used in economic evaluations and finally the procedure can generate simultaneous synthetic sets of rainfall, runoff and soil moisture for more detailed hydrologic investigations.

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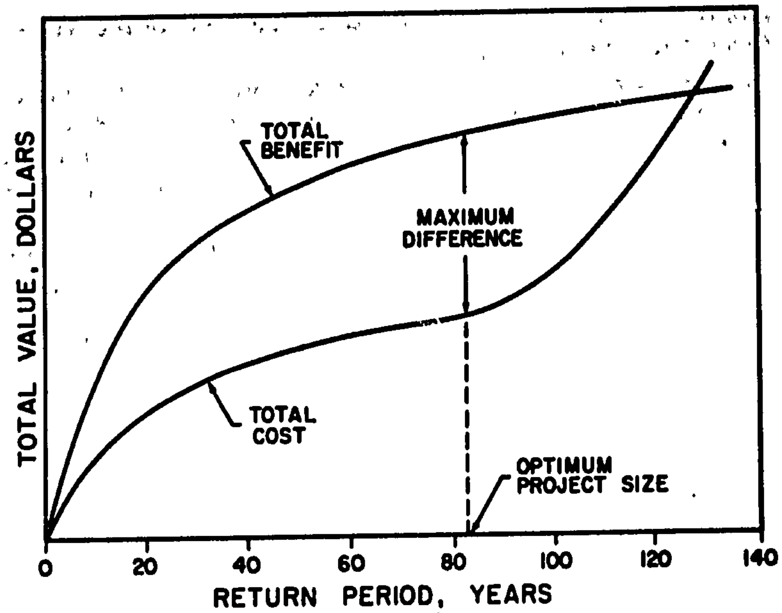
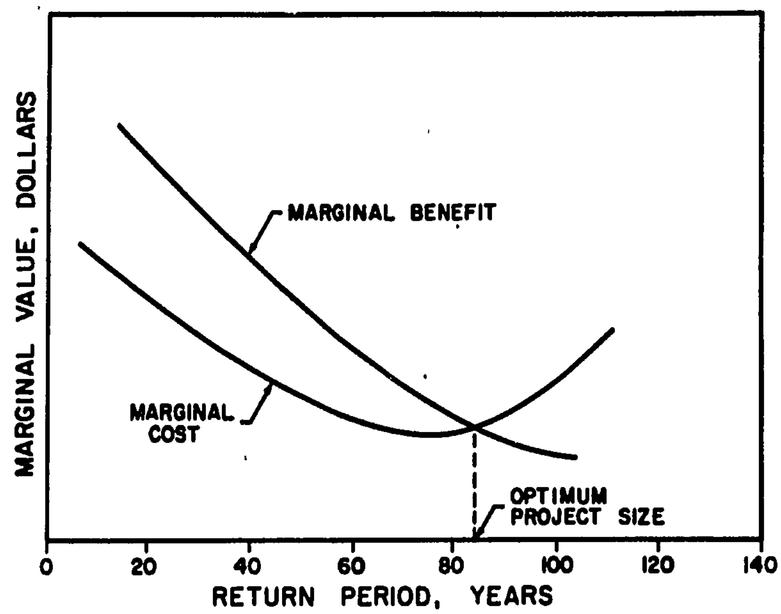


(a) Total value curves



(b) Marginal value curves

Fig. 5. Representative benefit-cost curves for determining the optimum size of a flood control project (after James and Lee, 1971).

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