REGIONAL WATER EXCHANGE FOR DROUGHT ALLEVIATION

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FOREWORD

The two major drought control measures external to water users have been water flow regulation and water transfer from water surplus areas to water deficient and drought prone areas. Both approaches are under severe criticism at present. Surface water storage is being questioned because of the inundation of valuable lands, scenic areas, natural wonders and wildlife habitats. Underground storage is being over-used by excessive withdrawals. The transfer of surplus water from one area to another faces opposition on the grounds that it will be needed for local developments within the next generation or two. These two basic measures, therefore, are critically evaluated at present in many cases, in the light of related drought control and water shortage aspects, and under the particular economic, social and environmental conditions. Besides, economic sites for water storage are exhaustible with time, while the surplus water available for transfer steadily decreases as water development progresses in the areas having the surplus.

Evaluation of basic approaches to important water resources problems is necessary from time to time. Groups of specialists for water resources planning, design and operation build philosophies of attack and develop the corresponding technologies at a given time. When social conditions and goals change, both philosophies and resulting technologies for solving water resources problems may become obsolete. The inertia of the past is often so strong that special investigations are needed to discover discrepancies between the past and the present, or pending discrepancies between the present and the future. All this may be pertinent for classical approaches to drought control measures, namely with the long-term water regulation and the long-distance uni-directional water transfer.

It is most likely that future solutions of drought problems will require a set of well integrated measures rather than only one particular measure, as often practiced. It is also likely that the concept of solving drought problems "once and for all" by a one-sided measure will prove to be neither an economic nor a permanent solution. Drought control measures are either external or internal to water users, and both must be considered in finding an optimal set of measures.

The planning of various water resource projects most often does not readily take into account the control of droughts of severe proportions. Present or future water resources projects could increase the drought control if conditions are left for economic modifications or additions. Investigation of all technologic drought control measures may well help in the identification of those modifications and additions which will tend to minimize future severe drought consequences.

Many water resource planners often demonstrate the attitude that water is a cheap commodity which does not warrant or justify a large regional grid of interchange conveyance structures. This attitude may have been a feasible approach in the initial stages of water resource development, when the individual water resource systems were very far apart. However, with the development of large metropolitan areas, or even the megalopolis-type of regions (e.g. U.S. East Coast from Boston to Washington, D.C.), individual water resource systems have spread so much that they have approached each other. Besides, water becomes an expensive commodity, because of increased pressure on all the available water resources, and therefore interconnections and water exchanges may become a feasible alternative for drought control.

The transfer of water over large distances by shifting it from one area to another is worthy of investigation, as it is usually with shifting the electric power from surplus to deficit areas over the intermediate areas, and for a given time interval. A regional or national grid of water conveyance structures might be the ultimate goal for water resource use and development. This may be compared to other grids which cover any developed region, such as a grid of electric power transmission lines, or a grid of gas lines.

Many water resource systems, composed of storage capacities, conveyance structures, electricity generating or water pumping plants, water treatment plants, etc., are already highly developed. The major effort in the past has been in transferring water from areas of water surplus to areas of water deficit by considering the average water yield. Two water resource systems are rarely interconnected for the purpose of interchanging water in both directions. The economic feasibility of interconnecting adjacent water resource systems, for the purpose of drought control by conveyance structures under pressure for two-way flow, may be fulfilled in particular cases at present. It might be more useful in the future. A methodology for investigating the feasibility of interconnection of two or more adjacent water resources systems is needed.

This paper by Dr. Kuniyoshi Takeuchi mainly investigates the properties of water interchange between the water resources systems by using the bi-directional flow conveyance structures. It is part of a continuous effort of the graduate and research program in hydrology and water resources in the Department of Civil Engineering at Colorado State University, to investigate various aspects of droughts, particularly drought control measures. Dr. K. Takeuchi, in the capacity of the post-doctoral fellow and research associate at Colorado State University from May 1, 1971 through December 31, 1972 was associated with the research projects on droughts and on the application of stochastic processes in water resources, sponsored by the National Science Foundation. His research on water exchanges by interconnecting systems may be considered as a worthy attempt to develop a methodology of measuring the physical aspects, and then based on these results, the economic aspects of interconnecting water resources systems. Expectations are that both, the theoretical analysis and the practical testing of methods developed, will focus on the importance, potential and limitations of this third most important approach (besides water regulation and uni-directional water transfer) in the form of interconnection of water resources systems over large distances for drought control, as a measure to external water users who are subject to drought risks.

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ABSTRACT

The hydrologic, geographic, engineering, socio-economic and other feasibility conditions are investigated for the concept of regional water exchanges. As a drought alleviation alternative, it is determined that regional water exchanges, using a bi-directional pipe-line networks, have some advantages over the other drought alleviation measures, external to users. The exchange systems have the advantage of being free from inter-regional controversies commonly involved with the uni-directional water transfer. The partial substitution for the required storage capacity is important advantage of exchange systems. To measure the magnitude of this effect, α_n^*, the maximum reduction ratio of the sum of ranges, is introduced and its implication and practical use are demonstrated using the river basin systems of the Central West part of the United States as a case study.

CHAPTER 1

INTRODUCTION

1.1 Objective

The general objective of this study is to examine the physical and socio-economic feasibility of the regional water-exchange concept as an alternative to all other current alternatives in alleviating drought problems. Here, a regional water exchange is defined as the exchange of water between areas experiencing water surplus and areas experiencing water deficit by using the inter-regional water transmission networks made up of bi-directional conveyance structures under pressure.

The need for this study is based on the following recognitions:

(1) The regional water-exchange concept is relatively neglected by the water resources planners, and its practical implications have not been intensively investigated.

(2) The need for broadening the spectrum of alternatives for drought alleviation is quite prominent since some of the currently used alternatives, such as water storage and uni-directional water transfer, are subject to various socio-political and environmental criticisms.

(3) Since the water demand, socio-economic, political and other conditions change in an area with time, a concept, previously either neglected or found economically unacceptable, may become presently a feasible measure. Therefore, the acceptance of the apparent intuitive judgment that regional water exchange is too costly or too far remote from reality may not be a sound approach.

Despite the advancement of science and technology and their applications to both engineering and economics of water resources development, the threat of drought is still one of the major problems not only in water-shortage areas, but also in water rich areas, both in moderately developed and highly developed areas. The pace of advancement of science and technology, and especially the pace of their applications to actual problems, which requires large investments, is not sufficiently rapid in meeting the growing water needs. Even if the advancement of science and the investments are sufficient to keep up with the growing water demands, the susceptibility of water resource systems to droughts increases with the demand pressure on the available water.

In general, as water resources systems become more developed and a society relies more and more on the already developed water supply systems, the consequences of droughts increase in severity with time. As a society grows and becomes more productive, the society's willingness to pay to guard against the hazards of drought also increases, because it can afford to pay for the protection and cannot afford to suffer the drought losses of highly productive operations and activities.

In addition to changes in a society's internal conditions regarding the adoption of a particular drought alleviation measure, the external conditions governing the types of measures that the society may choose from,also change over the time. For instance, environmental issues and regional planning of development may make certain drought alleviation measures such as the construction of large storage reservoirs or uni-directional interstate transfer channels, less desirable.

Based on the fact that a greater effort is required to guard against the hazards of drought and the fact that the society's internal and external conditions, governing the choice of drought alleviation measures, change with time, this study examines the conditions under which the concept of regional water exchange may become feasible.

The three specific objectives of this paper are:

(1) To investigate the specific characteristics of the regional water-exchange concept, in terms of its hydrologic, engineering, economic and political implications.

(2) To examine the effectiveness of regional water exchange relative to other drought alleviation measures, such as uni-directional water transfer,water storage and drought insurance.

(3) To establish a measure for evaluating the effectiveness of regional water exchanges, which, by considering the hydrologic conditions of the regions involved, may be used to assess the desirability of a proposed regional water exchange.

1.2 Methodology and Procedures

The basic methodology adopted for the first specific objective is a comparative study of various drought alleviation alternatives. Not only their physical effectiveness upon a water-deficit situation, but also their engineering, socio-economic, political and other aspects are considered as a basis of comparison. By a comparative study, it is expected that some of the unique characteristics of the regional water-exchange concept will be better understood.

The methodology adopted to accomplish the second specific objective is a cost-effectiveness study. Instead of estimating the actual costs required for the accomplishment of a given objective, a set of conceptual cost-effectiveness contour maps for the major alternative measures are drawn with the abscissae being the regional variance and covariance of the differences between water supply and demand.

The methodology for the third specific objective involves the introduction of a new concept, the sum of ranges of multiple streamflows. This concept is an extention of range concept as defined for a single stream into the range of multiple streamflows. The range concept is chosen as a measure of the effectiveness of a regional water exchange since the most important and attractive advantage of a regional water exchange is its partial substitution for storage capacity, and also since the magnitude of this substitution effect can be quantitatively measured in terms of a change in the range. The practical use of this measure is demonstrated through a hypothetical case study in the Central West of the United States.

The following is a discussion of the stepwise procedure taken in this paper, with each step forming a chapter. In Chapter 2 drought is precisely defined in a manner that allows a drought to be objectively investigated. After a brief review of the literature on drought definitions, a set of definitions are selected which do not violate the widely accepted common sense connotations associated with drought. These definitions then serve as the basic tools for an objective discussion of drought problems.

In Chapter 3, various alternative measures of alleviating drought problems are critically examined in order to point out under what conditions these alternative measures are either feasible or infeasible of alleviating drought problems. This survey leads to the finding that some measures are more reliable than others. At this point, the more reliable, large-scale measures are selected for further comparison with the regional water-exchange measure. One of these major measures is a drought insurance program which is based on a statistical principle similar to that of the regional water exchange. In Chapter 4, the problems involved with a drought insurance program are investigated. This step is necessary not because of the similarity between the drought insurance programs and the regional water exchanges, but rather because drought insurance is complicated by a number of unique problems.

In Chapter 5, the regional water-exchange concept is examined in depth in terms of its geographical, hydrologic and engineering requirements, and sociopolitical implications. In Chapter 6, the cost-effectiveness analyses are applied to four of the major drought alleviation measures: uni-directional water transfer, water storage, drought insurance and regional water exchange. The conceptual cost-effectiveness contour maps are drawn to show the effectiveness of each of these measures under varying characteristics of regional water supply-demand imbalances.

As an effectiveness measure for a regional water exchange, a reduction ratio of the sum of ranges is selected and then defined in mathematical terms in Chapter 7. In order to maximize the effectiveness of a regional water-exchange system, the optimal control rule for the system is analytically determined in Chapter 8 under the assumption of unlimited capacity for each of the exchange pipelines or other conveyance structures under pressure.

In Chapter 9 the use of the efficiency measure selected in Chapter 7 is illustrated by giving a case study using the Central West of the United States as an example.

CHAPTER 2

DROUGHT DEFINITIONS

This chapter examines some of the major existing drought definitions and sets forth a set of consistent and refined definitions for drought and the drought related concepts. Although the application of these definitions is not the purpose of the latter chapters of this paper, the definitions will aid in the understanding of those chapters. The main purpose for developing the definitions is to form a concrete basis for future rigorous and objective discussions.

2.1 Review of Existing Drought Definitions

Drought definitions differ greatly according to one's interest. For meteorologists, the magnitude and duration associated with subnormal precipitation are of major concern. For agronomists, a drought does not occur until the soil moisture is reduced to a point where the conditions become detrimental to plants. Hydrologists, on the other hand, view drought as subnormal streamflows, lake surface elevations, ground water levels and the like. For people living in urban areas, a drought is indicated by reduced levels in storage reservoirs for water supply. Definitions discussed in this section are limited to those which are, to some extent, comprehensive in their scope.

Since a drought is often defined by some indicator of the severity associated with a water deficiency, the terms "drought definition" and "drought (or water shortage) indicator" are considered to be interchangeable.

Palmer (1965), on the basis of earlier work done by C.W. Thornthwaite (1948), proposed a drought indicator, based on soil moisture excess and deficit, which is often referred to as the Palmer Drought Index or simply the Palmer Index. This index measures the effect of abnormal precipitation on soil moisture, or in the author's own words, provides "meaningful measures of departure of the moisture aspect of the weather from normal" (Palmer, 1965: p.15). The first step in computing the value of this index for a particular area is to measure the potential moisture recharge to the soil and the potential evapotranspiration, runoff, and loss from the soil in that area at the time in question. The amount of precipitation necessary to maintain normal soil conditions is then computed, where the normal conditions are predetermined for the area and time on the basis of a hydrologic accounting of soil moisture by months over a long series of years. The resultant amount of necessary precipitation is called the "climatically appropriate precipitation for existing conditions," denoted by P . The discrepancy d of the actual precipitation from the precipitation P is an indication of whether there is an excess or deficit in the precipitation from that needed to maintain normal soil conditions. The last step in computing the Palmer Index is to convert this physical value d into a regional severity index z by multiplying it by a coefficient representing the regional resistance to drought. The coefficient is empirically determined according to the area's past drought history. The value z is then the Palmer Index. Depending on the negative matnitude of z , a meteorological drought may then be defined as mild, moderate, severe or extreme.

The approach taken by Palmer for defining drought has two important implications. One is that the imbalance between water supply and water demand is the key to defining droughts. The other is that the severity of a drought depends not only on the area's water deficit, but also the region's drought resistance characteristics. The first implication is also stressed in the following two definitions.

Yevjevich (1967) has proposed an objective approach for defining drought. Unlike Palmer, who considered only the soil moisture aspect, Yevjevich considers all hydrologic factors involved, such as effective precipitation (precipitation minus evaporation), surface runoff, and all sources of stored water. He then considers the crossing properties of the time sequences for water supply and water demand in terms of negative run sum and negative run length. By considering these properties, a drought can be measured for any hydrologic phenomena without resortingo to subjective judgments, provided that the water supply and water demand in sequences are measurable. It has, however, not been shown how the various water supply elements, such as groundwater, streamflow, precipitation, etc., can be computed into a single value representing water supply. The actual applications are thus far limited to time series involving streamflow with a constant seasonal truncation level. This is, nevertheless a realistic approach for measuring the severity of droughts for areas which depend mainly upon streamflow for their water supply.

Another important proposal made by Yevjevich (1972: p. 178) was to combine the relationship between two or more regions' drought situations. He suggested the use of the joint properties of the regions' run sums and run lengths as inter-regional drought indicators. Although, thus far, applied only to streamflow in two regions, its basic intention is to be expanded to include a more general situation.

As an indicator of the severity of a water shortage, Russell et al. (1970) proposed a ratio of the projected demand D minus V , the normal supply , minus emergency supply, to the projected demand D, i.e. the percentage shortage index $S = (D-V)\cdot 100/D$. Per capita demand for this method is projected using a regression function estimated by observations made during previous non-shortage years. Time, a weather index (Palmer Index), and industrial employment are considered as arguments for the regression function. Furthermore, the demand D and normal supply V are then divided by the system's safe yield level SY , which is determined from the most severe water shortage experienced in the region's recorded history. The resultant values are called "chosen level of system inadequacy" ($\alpha = D/SY$) and "percentage of the safe yield level normally available without emergency supply" ($\alpha^* = V/SY$). Using these relationships, the equation for the shortage index becomes $S = (\alpha-\alpha^*)\cdot 100/\alpha$, and may then be plotted against the system inadequacy level α . Obviously, as the system inadequacy becomes larger, more frequent and more severe shortages will be expected.

Russell's approach is the most general among the three mentioned in the sense that water supply and demand are measured not with respect to streamflow, water shortages, or soil moisture, but as regional totals. This approach may be considered to be the most practical approach when regional water supply and demand imbalances are of major concern. This is the situation found in this paper.

In summary, each individual has his own particular interest in a different aspect concerning droughts: Palmer chooses a soil moisture aspect; Yevjevich focuses on the crossing properties of hydrologic time series; and Russell considers the total regional water balance. However, there is one common concept behind each of these. That is, a drought should be considered as a function of the difference between water supply and demand. This implies that in an area where no water demand exists there cannot be a drought, no matter what the meteorological conditions are. In accordance with this concept, the next section intends to refine the definitions of various terms relating to drought such as water supply, demand, drought, and water shortage.

2.2 Basic Terminology

In the existing definitions of drought, the difference between water supply and water demand plays the key role. However, what is meant by the terms water supply and water demand is not very precise. The difference between drought and water shortage is also vague. The purpose of this section is to establish a consistent and precise terminology related to droughts, which will be followed in the next section by the definitions for the conditions of drought and water shortage.

(1) Water demand is that amount of water necessary for satisfying man's activities, which includes water not only for man's physical and economic needs, but also for the environmental, ecological and cultural needs which have benefits to man but not necessarily measured as tangible benefits.

(2) Established water demand in a region i at time t, denoted by $D_{est.}(i,t)$, is that water demand which is expected and relied upon by the people in the region at that time. Since this portion of the total water demand is expected and relied upon by the people, it is presumed, not only that there are facilities to utilize this quantity of water when it is available, but also, that there will be losses experienced if it is not supplied. However, even if the water-use system has the capacity to utilize additional water, it is not included in the established demand unless it is presently expected and relied upon. For instance, an owner of a garden in a semi-arid region may be ready to sprinkle a large quantity of water on the garden whenever the water is available. Since he knows through experience that the garden's water needs cannot as a rule be met always, he does not expect that sufficient amount of water to be available for the garden all the time. In this case, even though he suffers occasionally from withered plants, the losses are expected and as such are considered a portion of the operating cost of the garden. Therefore, the possible water use in a system is not necessarily the established water demand.

(3) Potential water demand in a region i at time t, denoted by $D_{pot.}(i,t)$, is that water demand in the region at that time which is not expected or relied upon, but in addition to the established water demand, would become a portion of the established water demand if additional water was available. By this definition, it is clear that once additional water becomes available, and is utilized, then that additional portion utilized is immediately a part of the established water demand. Thus, the established water demand is somewhat a function of the availability of water. Accordingly, the potential water demand is also a function of the availability of water. Using the same example stated above, once the water which was not expected or relied upon, becomes available for use in the garden, and the garden owner utilizes it and begins to rely upon it, then this portion of the potential water demand has been activated and transformed into an established water demand. Thus, the total potential water demand would be reduced and the total established water demand would be increased by this amount.

(4) Actual water use in a region i at time t, denoted by $U_{act.}(i,t)$, is that amount of water which is actually utilized in the region at that time. The actual water use, $U_{act.}(i,t)$, is not necessarily equal to the established water demand if the supply is not ample to meet the established water demand, otherwise it will equal the established water demand. Therefore, the following inequality always holds:

$$U_{act.}(i,t) \leq D_{est.}(i,t) \quad . \qquad (2.1)$$

(5) Water supply is that amount of water available for satisfying man's activities.

(6) Developed water supply in a region i at time t, denoted by $S_{dev.}(i,t)$, is that water supply which has already been developed and can be provided in the region at that time through the existing facilities with the existing water supply-system operational rules imposed. Since any amount of water exceeding the developed water supply will not be utilized, the following relationship always holds:

$$U_{act.}(i,t) \leq S_{dev.}(i,t) \quad .$$

(7) Potential water supply in i at time t, denoted by $S_{pot.}(i,t)$, is that water in the region at that time which is not yet developed or usable with existing facilities, but which can be utilized by further development of the water sources or by enlargement of the water acquisition and distribution facilities.

(8) Water supply-demand imbalance in a region i at time t, denoted by Imb.(i,t), is equal to the established water demand subtracted from the developed water supply in the region at that time; namely,

$$\text{Imb.}(i,t) = S_{dev.}(i,t) - D_{est.}(i,t) \qquad (2.3)$$

In case of Imb.(i,t) being negative, that is the established water demand exceeding the developed water supply. the imbalance is called water deficit and, conversely, in case of Imb.(i,t) being positive, that is, the established water demand being less than the developed water supply, the imbalance is called water surplus.

It must be noted that $D_{est.}(i,t)$, $S_{dev.}(i,t)$,

$D_{pot.}(i,t)$, $S_{pot.}(i,t)$, $U_{act.}(i,t)$ and $Imb.(i,t)$ are the realizations of random events, each of which occur according to its respective probability distribution. Such randomness is a consequence of many factors. For instance, the established water demand is a function of weather conditions, availability of water and many of the conditions associated with man's activities. The developed water supply is a function of precipitation, streamflow, groundwater, conditions involving water supply facilities, and the operational rules applied to the operation of the water supply system.

2.3 Definitions of Drought and Water Shortage

Using the terminology developed in the previous section, the concepts of drought and water storage are now rigorously defined.

A drought exists in a region i at time t if a water deficit exists in the region at that time; namely, the condition of drought existence is satisfied if

$$S_{dev.}(i,t) < D_{est.}(i,t) \quad . \tag{2.4}$$

Whenever the developed water supply is less than the established water demand, the developed water supply is always used completely, and therefore, the actual water use equals the developed water supply; namely,

$$U_{act.}(i,t) = S_{dev.}(i,t), \text{ if condition (2.4) holds.} \tag{2.5}$$

By this relation, condition (2.4) is equivalent to

$$U_{act.}(i,t) < D_{est.}(i,t) \quad . \tag{2.6}$$

The definition given above implies that, whenever the amount of water which has been expected and relied upon for use in any of man's activities cannot be met for some reason, a drought condition is established. This definition eliminates the role of subjective judgment as much as possible in determing drought situations. Subjectivity comes in, to a substantial extent, only in making the decision of whether people have expected and relied upon or have merely desired a certain quantity of water. This degree of subjectivity is considered inevitable regardless of what definition is chosen. However, since even a very minor water deficit is categorized as a drought, the common sense feeling that a drought is an extraordinary phenomenon seems to be violated. This definition takes the position in this matter that any water deficit is of an extraordinary nature as long as the deficit has not been expected by the users as a regular event. Therefore, the definition selected here does not, in fact, conflict with common sense.

A water shortage is defined as a situation in which a water surplus does not exist on the average and a potential water demand exists. The first condition implies that the developed water supply has been exhausted in meeting the established water demand on the average over some period of time. The concept of "on the average" is introduced to describe the situation in which surpluses may exist occasionally, but are typically very minor and cannot be utilized as a reliable source for meeting any established water demands. Therefore, some demands are forced to remain a part of the potential water demand. This averaging may be taken over any length of time, such as months, weeks or seasons. Let $x(\overline{i},s)$ be defined as the average (expected) value of the random variable $x(i,t)$ over time period s . Then, the average developed water supply and the average established water demand may be expressed as $\overline{S}_{dev.}(i,s)$ and $\overline{D}_{est.}(i,s)$, respectively. Using these terms, a water shorgage in the region i at time t is indicated by the following condition:

$$\overline{S}_{dev.}(i,s) - \overline{D}_{est.}(i,s) \simeq 0, \text{ and } D_{pot.}(i,t\varepsilon s) > 0 \ . \tag{2.7}$$

The essential difference between a drought and a water shortage is that during a drought the expected and relied upon water is not met, while during a water shortage the unexpected but desired water is not met. The following example may illustrate this difference more clearly. Suppose there is a city with the growing population and the industrial activities are being intensified. The people in the city may not be aware of the degree of water deficiency they should normally expect. Therefore, they may expect more water to be supplied than they can actually get. This means they will face a drought situation whenever there are unexpected water deficits. However, they will soon learn that such deficits are to be expected and they adjust themselves to the reality of the situation. In this period of adjustment, they will essentially be decreasing their established water demand as the discomfort and/or economic loss becomes partly expected and partly eliminated due to the adjustments the people are making. The previously unexpected water deficit thus becomes expected and may be correctly identified as a water shortage. Since the realization of the situation may not be simultaneous for all the various groups of people within the city, the city may have both a drought and water shortage at the same time.

Considering the shift of $D_{est.}(i,t)$ into $D_{pot.}(i,t)$ in the example, this phenomena may be expressed as follows for any region. The situation

$$\overline{D}_{est.}(i,s) > \overline{S}_{dev.}(i,s) \tag{2.8}$$

tends in time towards the situation

$$\overline{D}_{est.}(i,s) \simeq \overline{S}_{dev.}(i,s) \quad , \tag{2.9}$$

because of people becoming aware of the situation and making adjustments to it.

The concepts of drought problems and water shortage problems are defined in accordance with the previously defined concepts. Since a drought is defined in the sense that people suffer from an unexpected, and thus unprepared for, water deficit, they definitely face (drought) problems whenever a drought occurs. Similarly, in a water shortage situation, the potential demand, which is desired to be met but is not, creates suffering because of the unsatisfied situation, and people face (water shortage) problems as a result of this lack of satisfaction. Therefore, in this paper, droughts and drought problems are considered as equivalent, and accordingly water shortages and water shortage problems are also considered as equivalent.

CHAPTER 3

ALTERNATIVE MEASURES FOR DROUGHT ALLEVIATION

The purpose of this chapter is to provide a brief discussion of various drought countermeasures by considering the nature of each measure and its alleviating capability. Since many of the drought alleviation measures can be applied simultaneously for alleviating water shortage problems, all water resources techniques which relate to water supply and demand are considered.

In order to make the discussion systematic, a rough classification of alternatives is attempted. As classification criteria, several ways are possible. One of them is structural (engineering) measures versus nonstructural (non-engineering) measures. Another is nature control measures versus human adjustment measures. These classification criteria are especially meaningful for emphasizing the importance of non-structural and human adjustment measures as against structural and nature control measures. Since the usefulness of these criteria in terms of comprehensiveness, simplicity, and applicability to the classification of drought alleviation alternatives is limited, a classification criterion has been selected in this chapter from a systems point of view, namely, considering the entire water resources complexity as a system.

Water resource systems, as a whole, have multiple purposes and include various functions such as flood water courses, wilderness, scenic and recreation areas, energy generation, irrigation, domestic use, industrial use, navigation and so forth. Each function can then be treated as a subsystem; namely, as a combination of input activities, output activities and a functional body which carries out the purpose of the subsystem. However, instead of treating each function individually, all functions of the water resource system are considered as a single, consolidated body of water users. Then the system as a whole can be treated as a combination of input to users, output from users and the user system itself, which, in this case, is called a water-supply use system. The water-supply use system is composed of supply sources, storage reservoirs, distribution systems, users, water treatment facilities, recycling systems, return flows and output to other systems. Input is flow into the system from sources such as streamflow, groundwater reservoirs, lakes and output from other water-supply use systems. The user system includes distribution networks, qualitative as well as consumptive users, water treatment and reclamation facilities, sewerage systems, recyclying systems in the form of conduit, stream and groundwater flows which go either to oceans, rivers, and lakes, or to other systems.

The total water use system is a combination of many subsystems that are connected by input and output lines. Each subsystem may in turn be composed of smaller subsystems, connected with each other. If the total system is considered as a nationwide or subcontinental network, subsystems are designated, according to geographical considerations, river basins, urban areas, big industrial complexes and the like. The water-supply use system as discussed in this paper generally refers to a sybsystem of the total nationwide system.

Since each system is composed of input, output and the body of the system, they can be classified as external components and internal components. Therefore, the system can be controlled externally as well as internally, and accordingly, the alternatives for alleviating drought problems may also be classified as external adjustment and internal adjustment measures. The advantage of this criterion for classification is quite significant in the sense that the highly reliable countermeasures to drought problems are all external adjustments.

Major external adjustment measures include four basic alternatives: uni-directional transfer of water from other regions, development of water storage, inter-regional water exchange, and drought insurance. Weather modification and desalination are also classified as external adjustment measures, since they increase the input to the system. Except for the insurance program which is a nonstructural human adjustment measure, all others are structural measures.

Transfer of water from other regions increases the total availability of water whenever the source regions have surplus water. But, once a drought hits the source regions, no countermeasure may then be undertaken by using the water transfer system. Therefore, for the purpose of drought alleviation, a transfer does not serve during the occurrence of a drought, but rather reduces the probability of the occurrence of droughts. The larger the percentage of water available in source regions, the smaller is the probability of failure in meeting the established demand. However, since fluctuations of a natural phenomenon are practically unbounded, there always remains a given probability of drought occurrence. This is the major physical limitation of water transfer measures.

Two methods can be used in water transfer that can add to drought alleviation after a drought has started. One is to design a transfer line with a reserve idle capacity during normal operations and to utilize it when a drought occurs. Such a transfer line with reserve capacity and in the extreme case transfer lines which are used only when a drought occurs are very expensive. An emergency construction of transfer lines could serve after a drought has begun. However, by the time it has been constructed the severe drought situation may no longer exist. Even if it can be completed in time, the users may tend to rely on this extra capacity as a normal developed water supply. Then it will no longer serve as an emergency measure for the next drought. The other method by which the uni-directional water transfer can help after a drought has started is to construct a transfer line in such a way that it passes water to two or more regions so that the amount of water to be transferred to each region may be adjusted according to the respective magnitudes of water demand-supply imbalances. Then, even when the total transferable water is insufficient, the inter-regional demand-supply imbalances can be considerably smoothed so that the losses could be minimized. This essentially approaches the function of inter-regional water exchange as distinguished from the pure water transfer.

Development of water storages has some similar characteristics as uni-directional water transfer. As a larger storage capacity is developed, more of the streamflow can be prevented from flowing downstream without use by smoothing the fluctuations over the time, and consequently, the probability of drought occurrence becomes smaller. However, once a drought occurs after exhausting the stored water, there is no longer any capability for alleviating the drought situation. The emergency use of recreational lakes in city parks may be effective in some cases, but the available water is usually limited. Groundwater is also considered to be a type of water storage, although it takes a longer time for recharge than do the normal surface storage capacities. Development of groundwater increases the availability of water within the following limitations. One is to maintain an overall balance between the pumping rate and the recharge rate, natural plus artificial, over a long period of time. Other limitations may be necessary to prevent the land areas from sinking and a reduction of available water in adjacent surface streams or other groundwater aquifers. Besides, the pumping rate is limited by the capacity of the pumping facility. Within these limitations, additional groundwater can be utilized during a drought by pumping water at a higher rate or by installing new wells. However, it cannot be a reliable drought alleviation measure in most areas, since aquifer sources generally have very high correlation with surface water and therefore, at the time of a severe drought the groundwater levels may be reduced to low levels.

Weather modification and desalination cannot be considered yet as reliable drought alleviation measures. Even when desalination is economically feasible for municipal and industrial uses, or exceptionally for irrigation, it is unlikely to be justifiable as a drought alleviation measure, since desalination plants would require a large idle capacity for emergency use during droughts.

The other two external measures, regional water exchange and insurance, are considered to be the major countermeasures for drought problems. Their definitions are fully discussed in the subsequent text of this paper. Briefly, regional water exchange is made by conduit network under pressure, which connect two or more distant water resources systems and, as a result, smooth the economic consequences of droughts by pooling premiums collected from spatially distributed insurance customers. Obviously, these two measures do not create any new source of water. Their planning is based on the stochastic nature of water supply-demand relations not only over the time but also across the regions. Furthermore, drought insurance serves only when a drought occurs while the regional water exchange serves both in normal times and during droughts. These characteristics of drought insurance and regional water exchange are very distinct from characteristics of other measures and should be underlined.

For internal adjustment measures, one approach is to increase the water available either by a reduction of losses or by reuse. Evaporation control in reservoirs, rice paddies, and other bodies of surface water would contribute, although such techniques are still in experimental stages and have physical and economical limitations. As a more readily applicable measure, the leakage suppression in canals and distribution lines can be used. Such reduction could be significant in groundwater levels and return flows may not be insignificant. These methods are only the supplemental countermeasures against drought and cannot be relied upon heavily.

Reclamation and recycling of water can increase the efficiency of water use a great deal. Consequently, in order to maintain the same level of man's activities, a smaller water supply capacity is required. This implies that, for a given water-supply capacity, the probability of a drought occurrence is decreased by the introduction of reclamation and recycling techniques. However, they are not particularly useful after a drought has begun, unless an emergency introduction of reuse facilities can be considered, or unless an emergency idle capacity for further reclamation and recycling is built into the system.

Voluntary or imposed restrictions on water use are known to be quite effective for a temporary reduction of municipal and industrial usage. Partial prohibition of car washing, lawn sprinkling, use of swimming pools, or even flush toilet use, has been exercised in many cities. Part-time water supply is another restrictive measure. As a long-term policy, imposing metered water usage or imposing a price increase, can be helpful in reducing water demand and use. Although short-term restrictions are quite effective for solving some drought problems in municipal and industrial areas, with losses due to restrictions relatively small, because of the high flexibility of users in adjusting their way of using water, restrictions cannot be a general solution to drought problems. The magnitude of saving is limited and the duration that the users are able to stand them is also limited.

The other type of internal adjustment measures is to increase the efficiency of water use, namely to get a higher yield using the same amount of water. A transfer of water rights from less productive sectors to more productive sectors is one of these measures. Transfer from agricultural use to municipal and industrial use is widely discussed and is already exercised in some urbanized and industrialized regions. Once a water right is transferred to a highly productive sector, the productive sector expands its production scale as a consequence, relying on the new source of water, then, the economy as a whole becomes more vulnerable to droughts. Therefore, this approach cannot be considered as a drought alleviation measure. However, if water rights are set to be flexible, so that when droughts occur the more productive sectors can get more water than less productive sectors according to some economic loss criteria, such a measure can contribute to alleviating drought problems. This may be an extremely difficult approach. Another possibility is to select a process giving the same yield with a lower rate of water consumption. Examples include the development of drought resistant crops, development of steam and atomic power for replacing hydroelectric power, and industrial adjustments. Instead of producing water consumptive goods such as textile, steel, heavy chemical goods, the approach is to concentrate on less water consumptive industries such as printing, mechanical or electrical goods. This principle is to some extent already exercised as a result of agronomical research and rational economic choices. However, again they do not serve as significant measures for drought alleviations once a drought has started in the sense of negative imbalances in the water supply-water demand relation, because the demand has been already minimized as much as feasible.

Based on these findings, it was of interest to investigate the nature of two drought alleviation measures, drought insurance and regional water exchange. They are considered as the only major measures that can function once a drought has been initiated. The next two chapters analyze these two measures in detail.

CHAPTER 4

DROUGHT INSURANCE

4.1 Definitions and Feasibility Criteria

Any economic unit which relies on a positive difference of income over outcome, faces some risks of one sort or another. Such risk-taking could be a source of profits. As long as the risk is small enough for each unit to adjust by itself, it is simply a problem of internal management. However, once the economic risk becomes substantial and the resulting losses may jeopardize the maintenance of the activity, some kind of countermeasure is necessary. Insurance is an economic measure aimed against this risk based on the statistical characteristics of involved random variables, namely the larger their sample size, the smaller the variance of the sample mean. Here, the difference between the income and cost for each economic unit is considered as a random variable. Obviously, if random variables are not independent, then the principal basis for the insurance becomes complicated and the insurance may fail. In terms of drought problems, if the occurrence of drought problems is highly correlated over the regions, the fundamental condition of independence for the insurance makes the insurance implementation a very difficult problem. However, if regional occurrences are well scattered as if they were independent random events over the space, the average profit over the total area may not be very different from one year to the next. Thus, the economic losses in some regions will be offset by surplus gains in other regions. If droughts, resulting in economically adverse consequences, occur only over a very limited area every year, the amount of contribution to be shifted from the surplus areas to the deficit areas may be quite small. Every economic unit could then afford to insure against the possibility of a drought. Unfortunately, drought phenomenon is a space phenomenon, because of high space correlation among the drought producing factors.

Another possibility in applying this principle is based on the random independent occurrence of droughts over the time rather than over the space. One economic unit may experience occasional income losses due to drought. However, if by that time it has accumulated the surpluses necessary to carry it through the crisis, economic activity can again continue. Although such smoothing of losses over time is quite impractical, if an economic unit has to manage by itself, a combination of time and space smoothing will lead to a better feasibility of insurance. This is the basis of the currently existing insurance programs.

Economic feasibility for practicing an insurance program depends not only on statistical dispersion of drought occurrences over space and time, but also on another important criterion, namely the relative superiority of an insurance program in comparison with the alternative measures of drought alleviation. This can be called the external condition. This condition can be stated in the following manner. The cost required to operate the insurance program must be less than that of any alternative measure offering the same level of protection or assurance against drought-induced financial losses. This condition must be interpreted so that, as other less expensive alternatives become exhausted, and as the marginal cost of acquiring further protection increases, the insurance approach tends to become feasible.

Besides this external condition, the insurance program must be operated on a sound internal basis. That is, the total cost, which is a sum of the total indemnities to be paid plus the operating costs, must be less than the sum of the following: premiums paid, interest from investing the accumulated reserves, and any other financial support. If some years do not experience any serious drought losses, the surplus accumulated from premiums can then be reserved for compensation during future drought loss years. This capital reserve is essential for smoothing out the imbalances over the years.

The use of insurance programs to insure against drought damages has a history of more than thirty years in the United States, although confined principally to crop drought losses in the agricultural sector. The next task is to review this experience briefly and point out to difficulties involved in order to evaluate how practical this alternative is as a measure of drought alleviation. The possibility of applying this policy to non-agricultural sectors is of special interest in this study.

4.2 Experience with Drought Insurance Program

The earliest attempt (and failure) of weather-peril insurance in the United States was recorded in 1899 by a private company offering coverage in North Dakota and Minnesota. A few other attempts soon followed with the unexpected result of prompt discontinuation. The main reason for failures was large crop damages as a result of droughts. After the severe drought experienced in the early 1930's, the federal government assumed responsibility of an all-risk crop-insurance program in 1938 by authorizing the Federal Crop Insurance Corporation (FCIC). This program has been successfully operating since that date.

Other than the FCIC, there have been private insurance services since 1880 for crop insurance designed only to cover hail and wind. FCIC is the only insurance in the United States that covers crop damages caused by droughts. It must be noted, however, that FCIC is not designed only for drought damages, but also for other damages due to unavoidable causes such as flood, hail, wind, frost, winterkill, hurricanes, tornadoes, insect infection, plant disease and others, as may be determined by the Board of FCIC.

Although the total amount of insurance protection is increasing every year (Bailey and Jones, 1970:pp.26-27), the Federal Crop Insurance Corporation is facing many fundamental problems. These have some bearing on the desirability of an insurance program as an alternative measure for the drought damage alleviation.

The following major difficulties are experienced by FCIC:

(1) It is difficult to distinguish losses caused by natural hazards from those caused by idle or poor farming operation. As a result, the insurance operation is vulnerable because of undistinguishable and sometimes dishonest claims.

(2) It is difficult to establish a fair protection level for everyone. Usually, the average yield for

the county is used as a standard protection level. Many of the better farmers naturally complain of this arbitrary standard. As a result, the better farmers think they pay too much and in return get less than they deserve.

(3) For the experienced farmer, it is somewhat predictable whether a drought is coming or not. They, therefore, buy the insurance only when they think they will be hit. Those guesses are at times so accurate that the corporation cannot maintain a sound insurance business based on ordinary statistics. Experience of this sort and the loss of a considerable amount of reserves have been reported in Colorado recently (Sitler, 1972). To solve this problem, the FCIC Colorado branches decided that the crop insurance must be sold at least fifteen months before the harvest season for that crop. Presently, this policy is not universal in the United States.

(4) If a farmer is successful, he often can save his surplus income in good years to offset the unpredictable deficits in bad years without relying on help from an insurance program. In this manner, he can avoid the unfavorable imbalances between the premiums he would have paid and the indemnities he would have received.

(5) It is difficult to establish areas having a homogeneous risk concerning crop production or to specify the length of actuarial periods for the different crops in different areas would pay their premiums on a fair basis with others. According to Delvo (1969), during the period of 1948 through 1967, Montana and North Dakota made the largest contributions to the national reserve, while Colorado and Minnesota have experienced the largest losses. By crop, the wheat and tobacco insurance program have contributed the most, while the cotton program has drawn the largest indemnities for losses.

There are quite a number of drought control measures for protecting crop production, which tend to make the insurance approach less attractive. One measure is the fallow land rotation technique. In the United States, it is accepted as a rule of thumb that any crop lands receiving less than 14 inches of precipitation a year should be cultivated under this method in order to conserve enough soil moisture for crops to survive. On lands with 14 to 26 inches of precipitation a year the exercise of this technique is optional. Where the precipitation is more than 26 inches, it is unnecessary (Kasle, 1972). The fallow land technique is to plant crops only on one-half of the land each year and to leave the other half fallow or unplanted. These planted lands and fallow lands are alternated every year. By doing this, the lands left fallow can accumulate soil moisture beneath the surface even during a relatively dry year, because there are no significant plants which would otherwise remove the water from the deep layers and bring it up to the surface and by transpiration on into the air. Minor weeds cannot survive once the top three to four inches of the surface layer becomes completely dry. Therefore, they are not a problem on the fallow lands. With this method the chances are quite high that the water accumulated in deeper layers will be enough to support grain crops until harvest the following year, even if it is quite dry during the growing season. This method is encouraged in the United States in connection with the government agricultural price support policy, which was designed primarily to reduce the over-production. Even in the East, where this technique is unnecessary, farmers use fallow land rotation practices and alternate plantings.

Another protection measure taken by farmers is to scatter their lands among different geographical areas. One portion of land is located several miles from another portion so that the weather characteristics and irrigation systems are different for the two portions of lands. This method is particularly effective against hail storm damages, because most hail storms have paths less than one mile wide. Against droughts, the effect of this strategy must be considered small for the individual land owner. In the case of large crop production companies, they may be able to scatter their land ownership over hundreds of miles and thus derive some relief.

In irrigated farm lands, the farmers can observe the storage levels of the irrigation supply sources such as reservoirs, ponds and aquifers, and can tell whether or not a drought situation may be coming in the near future. Knowing the potential for occurrence of a drought many months ahead, they can then take various control measures to avoid some effects of the drought. One farmer may choose not to grow crops in order to save the operating cost. Another farmer may plant less water demanding crops, which while less profitable are nearly guaranteed even during a drought. Furthermore, even when a drought occurs, farmers can shift water from one user to another through irrigation ditches by treating the water as a commercial commodity. A farmer who is growing a less profitable crop would then sell his water to a farmer who is growing a more profitable crop and then share in the profits. In general, the crops that are most affected by droughts are those that normally do not receive supplemental water through irrigation. Therefore, the only way to offset the drought risk for these crops is an insurance program. In fact, drought insurance is not sold for crops on irrigated lands (Anderson, 1972).

Based on the experiences of the FCIC, the feasibility of applying the insurance program exclusively for drought problems may be predicted. There are a number of reasons that tend to prevent such a policy from being operational. One problem may be the difficulty in discriminating the drought damages from the damages due to causes other than drought such as wind, insects and poor farming operations. Secondly, drought can be an important factor in serious crop damage only in about fifteen or twenty of the western and mid-western states. Also, once a large continental drought hits the United States, most of these western states would experience the full effects and as a result the indemnities to be paid would easily be tremendous. In other words, a drought insurance operation would not be able to rely on a small variance for the mean risk. This is a violation of the fundamental principle of the insurance concept. The result is that the necessary capital reserve for the sound operation of the insurance policy would be very high, with the farmer's willingness to pay such large premiums questionable.

If substantial governmental support for building reserves is available, a considerable portion of the financial problem will disappear. In fact, such support is not unlikely when one considers the production control program that is in effect for major overproduction crops in the United States (Wilcox and Cochrane, 1958: Chapt. 31). The justification for appropriating the tremendous capital needed for a drought insurance reserve would, however, be unrealistic since there is no advantage of a single cause insurance over all-risk insurance.

The rationale of applying drought insurance to non-agricultural industries and domestic uses may be even less plausible than that for crops. First of all, a large portion of the water necessary for man's activities cannot be substituted by any form of economic measures. For instance, a man who is suffering from water shortage does not need money for washing dishes, clothes and cars or for sprinkling lawns, but needs water itself. A considerable portion of industrial water demand is of the same nature. The application of an insurance program to such a water demand should not be even considered. For those cases for which an economic trade off can be established, there still remain many reasons for not implementing an insurance program. One reason is the fact that the real water demand in municipalities and industries is unestimatable due to its flexibility. In domestic use, for instance, even a thirty to fifty percent reduction of water supply may not cause any significant losses or damages to users except for some discomforts. Even in industry, the normal production level can be maintained with reduced level of water usage simply by increasing the efficiency of its usage.

Furthermore, municipalities and industries are in a similar situation to that of irrigated farms. The water supply systems for municipalities and industries are usually relying upon various water storage facilities such as reservoirs, ponds and aquifers. By observing the storage levels of these supply sources, the prediction of a potential drought situation is feasible many months in advance. Then the people and industries involved are able to take various measures to prevent the occurrence of large economic losses due to the drought. It is unreasonable to assume that anybody would maintain normal activities knowing that a drought situation was impending or in progress.

Any conceivable orthodox insurance concept seems incapable of covering drought losses incurred by the industrial sector. A water shortage which is extraordinary in magnitude and duration brings about a grave regional economic depression, which must by nature be cured by financial aid on the national basis rather than by indemnities accumulated from premiums paid by the beneficiaries.

A similar program on droughts, the Common-Wealth Drought Bond in Australia, is worth mentioning. (Glan, 1970). In 1969, the Australian Government issued their first series of drought bonds to those who derive the bulk of their income from grazing sheep and cattle in arid areas as a means of setting aside funds as a provision against drought, fire and flood. Since in Australia the agriculture is concerned with raising of livestock, an insufficient yield of feed as a result of a drought is a serious matter. It should be noted that the protection is provided not only against droughts. The essential difference of a bond program from an insurance program is that while the bondholders can receive no more than they paid plus interest when they have losses, they can redeem the bond at face value at maturity even if they have not incurred any loss. On the other hand, while the insurance holders can receive far more in the event of loss than they had paid, they cannot get the premiums refunded if they did not have any loss. The attractiveness of the bonds is that when the holders had losses before maturity, they may receive the full face value of bonds which otherwise would be paid only at maturity. Since the drought bond policy has very limited experience thus far, a fair assessment of that policy is not yet feasible.

CHAPTER 5

REGIONAL WATER-EXCHANGE SYSTEMS

5.1 Definition of Regional Water-Exchange Systems

A regional water-exchange system is a network made up of bi-directional water transmission lines interconnecting two or more regions or river basins so as to smooth spatially, as well as over time, the water supply-water demand imbalances by exchanging water among the regions.

The bi-directional water transmission lines must be closed, pressurized conduits, such as pipelines, tunnels and siphons. In order to transmit water against gravity, pumping stations may also be necessary. These structural components are different from those of uni-directional water transfer lines, which are primarily some type of free surface flow, mainly as canals or channels.

Using a network of bi-directional water transmission, an exchange system can smooth spatially the separate water supply-water demand imbalances by shifting water from areas of surplus, or less severe negative imbalances, regions of deficit or more severe negative imbalances. In different seasons or years, these surplus and deficit areas tend to vary spatially. Therefore, transmission lines must be bi-directional. In the long run, the regional give-and-take of water may or may not be equal, but each region will get its share of benefits in time of need.

As an example of smoothing temporal imbalances, consider two regions which are receiving water from their own streamflows and are interconnected by a water-exchange network of pipelines which enable each region to utilize the available water from the other region. Suppose that the water supply-water demand imbalance for the two regions taken together is positive (i.e., a surplus exists). Then, if one region's system has no remaining storage capacity and the other still has available storage capacity, then it is desirable to transfer water into the region where storage capacity exists for use when future negative imbalance may occur. If both systems can store, it is desirable to only use water in the region whose expected future inflow is higher, and store water in the region whose expected future flow is lower. Such operations will lead to a minimization of unused (waste) output from the total system. Obviously, since both the available capacity of reservoirs in two river basins and the future inflows from their basins will fluctuate, the water transmission lines must be bi-directional.

In other activities, such as power transmission networks, gas networks or telephone networks, exactly the same idea has been already implemented. In power networks, electricity is transmitted whenever it is needed, even over thousands of miles. A similar situation is with the gas transmission. In telephone networks, not only do the origins and destinations change, but the lines to be used also change in such a way that if the most direct lines are busy, another route is selected as the most efficient combination of available lines. The same type of optimal path may be also applied to regional water-exchange systems.

Although the insurance approach deals with the economic consequences, while the water-exchange systems deal with the physical water supply-water demand imbalances, the fundamental principle used is the same. Namely, the regional water-exchange concept relies on the statistical sampling properties of variables, namely as the sample size increases the variance of the mean decreases. Again, as in the insurance approach, the randomness of variables is essential. In terms of drought problems, this would mean that if the water supply-water demand imbalances are independent or nearly uncorrelated over space and time, the mean seasonal or annual imbalances over a large area will not vary a great deal, even though the imbalances of the individual portions of the area would vary a great deal over the same period of time. Therefore, by being able to exchange water spatially and as a consequence, temporally, the imbalances can be smoothed. This fundamental principle will hold less and less, the more correlated are imbalances over the space.

5.2 Feasibility Conditions

Based on the outlined principle, concrete feasibility conditions can be derived. The major factors affecting the water supply-water demand imbalances are the size of the geographical area to be covered by networks and the type of networks to be constructed.

Since the distribution over the area of water supply-water demand imbalances is a result of both supply and demand fluctuations, it is satisfactory if either of them satisfy the principle. The water supply may have low spatial correlations if the distances among regions or river basins are sufficiently large, and depending primarily on the regional characteristics of soils, plants, topography, geological and climatic conditions. For instance, if one region relies on snow melt in the spring as the major water supply source, and the other relies on seasonal rainfall which occurs in the summer or fall, the exchange of water from the former area to the latter in the spring, and conversely in the summer or fall, would be desirable. Even in case of insignificant seasonal imbalances in water supply over the space, the stochastic components of water supply of these two areas, if they are sufficiently apart, may have a low correlation, with the same exchange effect to be produced.

Similar spatial distribution imbalances can also exist on the demand side. The demand patterns often vary spatially. For instance, seasonal demand patterns are different in industrial and agricultural areas. Different crops have different growing seasons and different patterns of water need. Temperature and precipitation fluctuations similarly create differences but in a more stochastic manner.

An important implication is that the patterns of users' water demand can be deliberately differentiated over the time, and the water exchange instituted could smooth the imbalances among the users. Such differentiation is quite feasible in agricultural sectors. Some regions may concentrate on the early-season crops, others on the mid-season crops, and still others on the late-season crops. Such crop variations may be encouraged by economic reasons such as a greater profit for the growers by producing an even supply of produce over a longer period.

The size of the area to be covered by the network should not be judged only in geographical sense. The principle is most likely to be met if areas are sufficiently distant, since climatic conditions over long distances are less correlated. However, the size of a suitable total area for water exchanges should not necessarily be very large. The basic condition can be met even in a small geographical area if the water supply-water demand imbalances are sufficiently dispersed over that area. For example, a single urban area may meet this criterion. In a large urbanized area such as New York or Tokyo, the municipal water supplies rely on three, four or more river basins, with different degrees of reservoir regulations, and a distribution network interconnecting these urban areas. The concept of multiple basin water exchanges may not be fulfilled if interconnecting transport facilities of water-supply system within these urban areas are inadequate. If a river basin experiences a water deficit, the portion of the urban area which relies on that basin will suffer from the deficit, while areas relying on the other river basins may have a sufficient or even a surplus water supply. Even if all subsystems within these urban areas are interconnected through a distribution network, it does not necessarily guarantee a major water exchange between subsystems. The total water supply system, covering a large metropolitan area, when it relies on multiple water supplies, may for all practical purposes be a mere composition of independent water supply subsystems. The water deficit problems in urban large metropolitan areas may not be the result of the deficit in the total water available but a matter of internal distribution. Greenberg and et al. (1971) made a test study in the New York metropolitan area revealing its inadequate distribution network. In the Tokyo metropolitan area, the construction of facilities is underway to make the two major supply sources, the Tama and Tone Rivers, a joint supply source in order to attain a higher efficiency for the total water system (Tokyo Metropolitan Water Supply Bureau, 1972).

Basically three forms of network patterns for water exchanges are feasible. One is to interconnect the water systems by means of their input structures. For instance, the interconnection of two reservoirs or two streamflow sources belong to this category. Another type is the interconnection through an already existing distribution system. Any urban water-supply distribution system relying on two or more water supply sources is of this second type. Examples of New York and Tokyo belong to this type of exchange networks,requiring relatively modest engineering works to accomplish exchanges in comparison with the first type of exchanges. The third type is a combination of these two types,namely to connect both the separate water systems by major pipelines and the already existing internal distribution systems. For instance, a megalopolis, such as the east coast of the United States, could be connected by this type of networks. In general, the second type of exchanges should be the most economical.

5.3 Political and Social Implications

Likely, the most important social implication of regional water exchange is their effect on the total capacity of large reservoirs. By constructing the water-exchange network over two or more regions, a part of the reservoirs' function in smoothing the temporal water-supply fluctuations has been taken over. In other words, the reservoirs no longer are the only drought control measure. Therefore, their capacities may be reduced. This reduction can be substantial since the space normally reserved for drought control may be tremendous. This substitution effect is important both for the existing and planned reservoirs. The increasing socio-political resistance to building of large reservoirs is a new factor in water resources and control. This resistance develops not only from the land owners and people living in the areas to be innundated, but also from people to be affected in one way or another. Therefore, if the function of a large reservoir can be substituted, at least partly, by less controversial measures, the socio-political benefit may be larger and more important than the tangible economic benefit. Moreover, the need for such substitutions rapidly grows, as the best reservoir construction sites become exhausted and the people become more aware of consequences and reluctant to accept them by the construction of very large reservoirs. In some regions that substitution may become indispensable.

Furthermore, a water exchange system can also substitute for large scale water transfer lines to the extent that the transfer lines no longer must be a means for drought problem alleviation. This factor may result in the elimination of the construction of large reserved idle capacities for some large scale transfer lines.

Uni-directional water transfer is very controversial. It is not only an issue because of the future regional water development of the water producing area, regardless that the economic activities in this area may be much less advanced than in the area to which water will be transferred. Environmental and political issues of ecology, regional sovereignty and many other non-economic factors are involved. By regional water-exchange systems, the uni-directional transfer conflicts may often be eliminated, since both regions should be beneficiaries, with the total available water increased without a sacrifice by either region.

The regional water-exchanges may be necessary regardless of the use of large reservoirs and/or uni-directional transfers for drought control. The water resources systems may develop to the point that only the water-exchange can improve the internal efficiency of water utilization over the regions. Without the water exchanges the expensive components of water resource systems, such as reservoirs and uni-directional transfer lines, could not be fully utilized. This full utilization of available water supplies will become economically more and more important as the water resources system are more and more developed and the pressure on the available water resources intensifies.

CHAPTER 6

COST EFFECTIVENESS ANALYSIS

The topics of interest are the conditions under which the regional water-exchange system becomes competitive as compared with the alternatives. Although there have been no actual cost estimations of any kind, it is conceivable that large capital investment would be required for the construction of water-exchange networks of subcontinental size. The regions to which this concept may be applied are not only large areas, with scattered water resource systems and without the interconnecting lines, but also the large urban areas with distribution networks close one to another, or in two or more nearby areas of any size with local distribution systems easily to be interconnected.

In general, any measure can be considered as feasible only in comparison with the alternatives. Therefore, the relative advantage of one alternative over the others may be more important than the individual cost estimates. For instance, a unit increment of storage capacity becomes less efficient as the temporal variability of imbalances increases. On the other hand, a high variability of imbalances over space and time is essential to the water-exchange measure of drought control. This seems to suggest that when the variability of water supply-water demand imbalances attains a certain value, the marginal efficiency of two measures may be equal.

For a complete discussion, the marginal efficiency and variability must be more precisely defined. Let the marginal efficiency be defined as the marginal cost effectiveness $\partial E/\partial c$, with E the effectiveness, measured in terms of the level of accomplishment towards a given objective, and c the cost necessary to obtain that accomplishment level. Obviously $\partial E/\partial c$ is a nonlinear function of the level of accomplishment because of scale economy. In drought problems, the objective may be the total protection from drought hazards and the level of accomplishment may be a protection level such as a drought hazard frequency of less than once in 10 years, 20 years, 40 years and so forth, on the average. Let the variability be defined as a two-dimensional vector with components made up of the time variance changes on the interval $[0,\infty)$, and the spatial correlation on the interval $[-1,1]$. If n is the number of regional water systems involved, there are n variances of and $n(n-1)/2$ pairs of spatial correlation coefficients between systems imbalances. Instead of treating each of them individually, let a variance and a spatial correlation coefficient be constructed in such a way that these two values represent both the regional characteristics and the original n and $n(n-1)/2$ values, respectively. It is admitted that finding a reasonable function for the mapping $E^n \to E^1$ and $E^{n(n-1)/2} \to E^1$ is an extremely difficult task. At this moment, such a transformation is considered as merely a matter of convenience in order to avoid a complex multi-dimensional discussion. The real economic analysis must be done under the exact dimensions. Using these conceptual values, the characteristic relations between $\partial E/\partial c$ and other regional properties can be established. All figures shown in this chapter are based on the same protection level to enable the comparison between the various drought control measures.

Figure 1 shows the relation between the effectiveness of water storage and transfer drought control measures and the variance of water supply-water demand imbalances. If the variance of imbalances is zero, obviously no storage effect exists since its function is the smoothing of the time variations in water supply so as to meet the demand patterns. As the variance increases, the storage can play more and more its role. However, once the variance becomes greater than a certain value, the effectiveness as measured by the marginal cost effectiveness gradually decreases because the range of the partial sums of the streamflows increases as their variance becomes large, and a large reservoir capacity is necessary. For the infinite variance the effectiveness is almost zero, that is a great cost for a given protection level. The effectiveness of unidirectional transfer is highest when the variance is smallest, since the quantity per unit time of water transfer required never changes when the variance is zero. Needless to say, the transfer measure is only feasible when the negative imbalances exist in water receiving areas and the positive imbalances exist in water providing areas. The highest ordinate value depends upon the difference between the negative and positive imbalances in the two areas. The effectiveness of water transfer measure decreases as the variance increases, because the amount to be transferred changes over the time and an idle capacity is necessary to insure the given level of protection. At the infinite variance, the efficiency is nearly zero as in the case of water storage measure. For these two measures, the spatial correlation does not have any affect, since no inter-regional connections are assumed to exist.

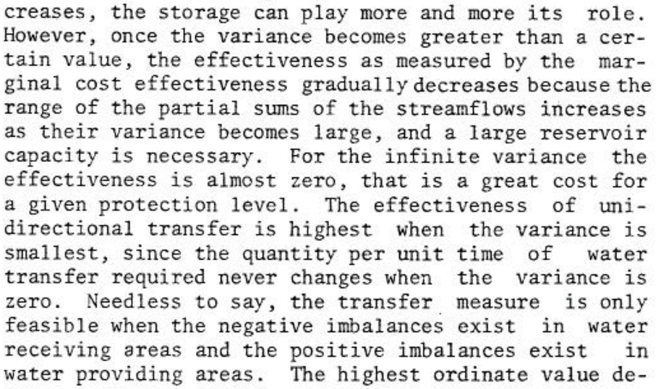

Fig. 1. Effectiveness of water storage and water transfer versus the variance of regional water supply-water demand imbalances.

Figure 2 shows the conceptual relation between the effectiveness of a water-exchange measure for a given level of protection and the variance and spatial correlation coefficient. Here both the variance and the spatial correlation coefficient of the supply-demand imbalances are the controlling factors. For the zero variance, the correlation is undefined. Figure 2 illustrates the concept that for the variance extremely small, the water-exchange system will function merely as transfer lines, since each region will have a nearly constant rate of imbalance. The effectiveness may then be positive with a very small magnitude only if one region has a positive imbalance and another has a

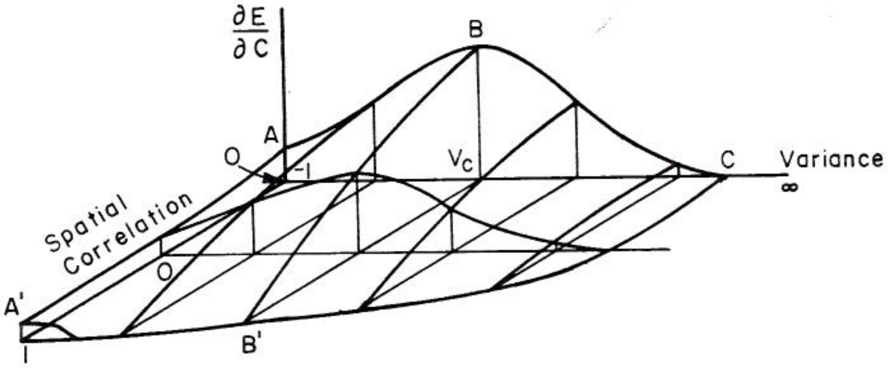

Fig. 2. Effectiveness of regional water-exchange systems versus the variance and the spatial correlation coefficient of regional water supply-water demand imbalances.

negative imbalance, as illustrated by the line AA'. In this case the spatial correlation between these two regional imbalances does not make a great deal of difference, although a small or negative correlation is advantageous.

As the variance increases, the effectiveness also increases since exchanges become feasible, as illustrated by the line AB. However, exchanges are practical only when the spatial correlation is relatively small and when the spatial correlation is negative, the effectiveness is highest. The hyperplane AA'B'B illustrates this point.

As the variance passes some critical value, V_c, the effectiveness decreases because a larger variance implies a larger capacity requirement for a given level of protection. The line BC illustrates this point. This relationship is the same for both the storage and transfer measures of drought control.

A similar relationship for the insurance policy is shown in Fig. 3. For a small variance, the insurance policy generally is not feasible since each region has nearly the same economic consequence every year, that is, some areas constantly have losses and some constantly have profits. However, in some cases, even if all areas are in the situation of neither gains nor losses every year, the insurance policy could be helpful in smoothing out the minor losses. If the spatial correlation is high, the smoothing must be made over the year, but if it is low, the smoothing applies both spatially and over the time, and will be more effective. These relationships are shown by the hyperplane AA'B'B. As the variance increases, the effectiveness of insurance increases, particularly if the spatial correlation is low. If the spatial correlation is close to unity, indemnities to be paid in time of drought are enormous even for a relatively small variance. As the variance passes some critical value, V_c, the effectiveness decreases because indemnities to be paid become large. The insurance policy is feasible, however, when the spatial correlation coefficient is near minus unity so that the smoothing can be made entirely within the year. Unfortunately, this can not be expected from the supply side but can be expected from the demand side of imbalances. If the spatial correlation coefficient is large, the year by year fluctuations in indemnities to be paid soon become so large that huge capital reserves are required. This in turn makes the policy either unattractive or infeasible. These relationships are shown by the hyperplane on the right-hand side of the line CC'.

Given these characteristic contour maps, Figs. 1 through 3, the choice of the best alternative can be made simply by superposing these maps. The best alternative can be made simply by superimposing these maps. The best alternative is selected depending on the regional characteristics of the variance and the spatial correlation coefficients of supply-demand imbalances. However, such a simple procedure is only feasible after all the coordinates are used as a consistent dimension, which in reality is extremely difficult. For instance, since the insurance program deals with the economic consequences of the water supply-water demand imbalances, such consequences must be a direct function of water imbalances in order to obtain the same dimensional coordinates. For the moment these maps are considered as purely conceptual, cost-effectiveness contour maps.

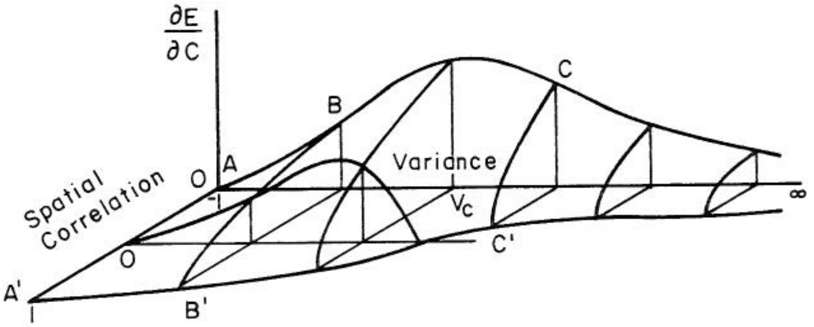

Fig. 3. Effectiveness of insurance program versus variance and spatial correlation of economic consequences due to regional water supply-demand imbalances.

CHAPTER 7

MEASURES OF EFFECTIVENESS

7.1 Introductory Remarks

Among the various merits of regional water exchange systems discussed in Section 4.3, their substitution for carry-over storages, at least partially, seems to be the most attractive approach, among other reasons also because of current increasing resistance to construction of large storage reservoirs. Chapters 7, 8 and 9 of this paper are intended to develop an objective measure for quantitatively evaluating the magnitude of the storage capacity saving. As discussed in Section 7.3, the selected measure involves a time-consuming optimization process; therefore, only a simplified case will be demonstrated.

7.2 Selection of Measure of Effectiveness

As a basic measure of storage capacity needed for any reservoir case, a concept of range was indirectly introduced by Rippl (1883) in the development of his mass-curve diagram. Its mathematical and statistical properties have been investigated in depth by mathematicians and engineers. However, the theory of range developed up to now, as it concerns its usefulness in the design of reservoir size requires a full development of the stream, that is, in the long run, the mean regulated outflow is equal to the mean inflow. For partial development of a stream, the use of range theory as applied to design of storage capacities is yet to be developed. Nevertheless, when used as a measure for reduced reservoir storage capacity, the range is excellent, because the regional water exchanges produce a direct reduction of the range. For a smaller regional range, a smaller total storage capacity in the region required for the same yield. If the total utilization of the streamflow is considered, the reduction of range is exactly equal to the amount of the potential reduction in storage capacity in the total, interconnected stream system. If only its partial utilization is considered, the reduction of range is still an indicator of storage saving, if the reduction of range is expressed in ratio to the original range. As an example, if twenty percent of the required storage capacity is saved by interconnection in case of total utilization of streamflow, nearly that same percentage of saving may be expected in case of partial utilization.

Let U_n^o be the range of streamflows without a regional exchange system and U_n the range of all streamflows within a regional exchange system, where n is the sample size for which the ranges are computed.

The range reduction ratio for the available sample is then defined as

$$\alpha_n = 1 - \frac{U_n}{U_n^o} .$$

For U_n small this reduction ratio approaches unity, namely, the water exchange system decreases the range significantly. Obviously, the reduction in range depends on the method of operation of an exchange system. When the range is minimized by some operational or optimization approach, the exchange system is said to be optimally operated, and that rule or approach is then called the optimal operation policy. The resultant maximum reduction ratio is denoted by α_n^*. In order to utilize this reduction of range as a measure of effectiveness, the range for multiple streamflows must be defined. In this paper, it is defined as the algebraic sum of ranges for all the individual streamflows interconnected by the exchange system.

In case of expected values $E(U_n)$ and $E(U_n^o)$ are known or estimated from data, the reduction ratio is defined as

$$\alpha_n = 1 - \frac{E(U_n)}{E(U_n^o)}$$

This approach is subject to an obvious criticism. That is, even if the sum of ranges for the interconnected systems is minimized, it does not necessarily minimize the total cost of construction of reservoirs on all of the individual streams. The reduction in storage at some streams may have a higher economic value than on other streams. Therefore, if the sole purpose of substituting a water exchange system for a large reservoir is to reduce the construction cost, the effectiveness of the regional water resource exchange system should not be measured simply by minimizing the simple sum of ranges. According to this reasoning, other efficiency measures might be formulated, based on economic considerations, rather than only on hydrologic considerations. Nevertheless, the reduction of a sum of ranges is a direct analytical expression for the effect of substitution. This maximum reduction is the simplest way of expressing the potential savings in storage capacity, and should be useful in preliminary, feasibility analysis of regional water exchanges. The maximum reduction ratio α_n^* in the sum of ranges is selected in this paper as a measure of effectiveness for regional water exchanges. The determination of α_n^* is an optimization problem. If the exchange lines are unlimited in capacity, the problem becomes an unconstrained maximization problem; otherwise, it is a constrained maximization problem. The major concern of Chapter 8 is the method of determining the maximum reduction ratio α_n^* under the assumption of unlimited capacity of exchange lines.

7.3 Mathematical Formulation Measure of Effectiveness

In this section, the effectiveness measure, α_n^*, will be rigorously formulated in mathematical terms, and at the same time mathematical notations will be developed for the use in further discussions.

Let M be the number of streams in a system to be connected by a water exchange network. The streamflow x_i at time t is denoted by $x_{i,t}$, where i is an integer 1 through M, and t is an integer 1,2,3, ...,n. Its mean is denoted by $\overline{x}_i$ as the estimate of $E(x_i)$. Suppose each stream is interconnected with its adjacent stream by a water exchange line with a capacity $\overline{r}_{i,j}$, and the amount of water shifted from stream i to stream j at time t is $r_{i,j,t}$, then obviously,

$$0 \leq r_{i,j,t} \leq \bar{r}_{i,j}, \quad \text{for all } i, j, \text{ and } t \quad . \qquad (7.1)$$

with i,j symbol representing the flow in the direction j to i. After exchanges are made, the total water in the stream i at time t equals $y_{i,t}$, with the streamflow exchanges made with $(i-1)$-th and $(i+1)$-th streams, or $j=i-1$ and $j=i+1$,

$$y_{i,t} = x_{i,t} - [(r_{i,i+1,t} - r_{i+1,i,t}) + (r_{i,i-1,t} - r_{i-1,i,t})] \qquad (7.2)$$

and

$$r_{i,j,t} = 0 \quad \text{for } i \text{ or } j < 1, \quad \text{or } i \text{ or } j > M \; . \qquad (7.3)$$

Equation (7.2) is the mass balance equation for individual streams, assuming that the river i exchanges water only with the two adjacent rivers. Since a streamflow cannot be negative,

$$y_{i,t} \geq 0 \quad \text{for all } i \text{ and } t \quad . \qquad (7.4)$$

The deviation $\Delta_{i,t}$ of actual streamflow $y_{i,t}$ from the mean discharge $\bar{x}_i$ of the stream is

$$\Delta_{i,t} = y_{i,t} - \bar{x}_i \quad \text{for all } i \text{ and } t \; , \qquad (7.5)$$

with $\bar{x}_i$ the mean of the sample of size n.

Figure 4 illustrates the relations among x, r, y and $\bar{x}$. It should be noted that if connections are among the regions rather than among the streams, connections between all combinations of adjacent regions must be included as shown in Fig. 5. In this case, the range makes sense when based on deviation of the water supply input to a region from its regional demand. However, since the regional water supply is dependent on the water use of adjacent regions such a concept may be applicable only with some general assumptions.

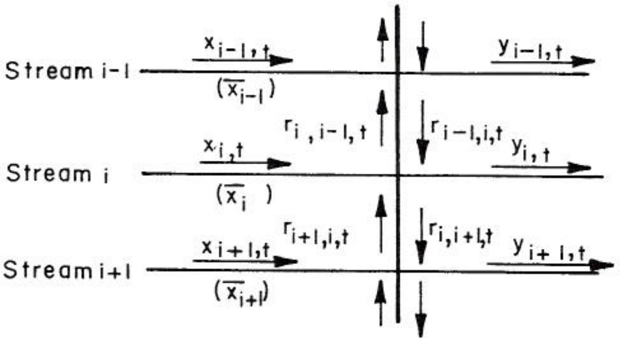

Fig. 4. Interconnections between adjacent streams.

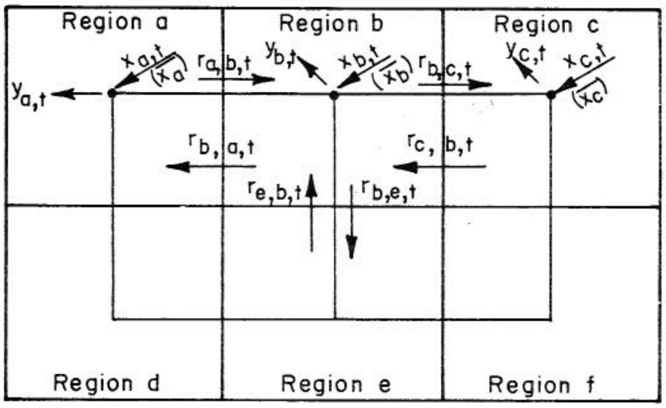

Fig. 5. Interconnections among adjacent regions.

The total sum of input-demand deviations in the system, denoted by Δ_t, must be equal to the difference between inflows to the system at time t and the mean inflows to the system, namely,

$$\sum_{i=1}^{M} \Delta_{i,t} = \sum_{i=1}^{M} x_{i,t} - \sum_{i=1}^{M} \bar{x}_i = \Delta_t \quad , \qquad (7.6)$$

as a mass balance equation for the system.

Let $S_{i,n}$ denote the partial sum of deviations for the stream i from time 1 through n,

$$S_{i,n} = \sum_{\tau=1}^{n} \Delta_{i,\tau} = S_{i,n-1} + \Delta_{i,n} \quad , \qquad (7.7)$$

where

$$S_{i,o} = 0 \quad \text{for all } i \quad . \qquad (7.8)$$

Let $S^-_{i,t}$ and $S^+_{i,t}$ be the minimum and the maximum values attained by the partial sum between time 0 through time t, that is

$$S^-_{i,t} = \min\{0, S_{i,1}, \ldots, S_{i,t}\} \qquad (7.9)$$

$$S^+_{i,t} = \max\{0, S_{i,1}, \ldots, S_{i,t}\} \quad . \qquad (7.10)$$

The initial values $S^-_{i,o}$ and $S^+_{i,o}$ are then equal to zero, i.e.,

$$S^-_{i,o} = 0 \quad \text{and} \quad S^+_{i,o} = 0 \quad \text{for all } i \quad . \qquad (7.11)$$

The range of partial sums is defined as the difference between the maximum partial sum and the minimum partial sum. Thus, the range of partial sums of the stream i for the first t time intervals is

$$R_{i,t} = S^+_{i,t} - S^-_{i,t} \quad , \qquad (7.12)$$

with

$$R_{i,o} = 0 \quad \text{for all } i \quad . \qquad (7.13)$$

The sum of the ranges for the total system during the n time intervals (the sample size) is denoted by

$$U_n = \sum_{i=1}^{M} R_{i,n} \quad . \tag{7.14}$$

When no water exchange exists, or

$$r_{i,j,t} = 0 \quad \text{for all} \quad i, j \quad \text{and} \quad t \quad , \tag{7.15}$$

the resultant sum of ranges is called the original sum of ranges and is denoted by U_n^o . Finally, the afore mentioned range reduction ratio due to water exchanges, α_n , is defined as

$$\alpha_n = 1 - \frac{U_n}{U_n^o} \quad . \tag{7.16}$$

In case that the water exchange system is operated so as to minimize the sum of ranges, the resultant sum of ranges and the reduction ratio are indicated by U_n^* and α_n^* , where

$$U_n^* = \min U_n \quad \text{with respect to} \quad \Delta_{i,t} \quad \text{for all} \quad t\epsilon[1,n] \tag{7.17}$$

and

$$\alpha_n^* = 1 - \frac{U_n^*}{U_n^o} \quad . \tag{7.18}$$

Furthermore, as an estimator of α_n^* , β_n^* is defined as

$$\beta_n^* = 1 - \frac{E(U_n^*)}{E(U_n^o)} \quad , \tag{7.19}$$

which is not necessarily equivalent to $E(\alpha_n^*)$, unless U_n^* and U_n^o are independent quantities.

CHAPTER 8

MAXIMUM REDUCTION RATIO OF SUM OF RANGES

8.1 Mathematical Formulation of Minimization Problem

Since U_n^o does not depend upon the water exchanges $\Delta_{i,t}$, it follows, from the definition of Eq. 7.18, that the maximization of α_n^* with respect to $\Delta_{i,t}$ under a given sequence of streamflows $x_{i,t}$ is equivalent to the minimization of U_n.

The deviation $\Delta_{i,t}$ of the actual downstream flow $y_{i,t}$ from the mean $\overline{x}_i$ is a fuction of the water exchanges $r_{i,j,t}$ as defined previously. Then the partial sum of the deviations, $S_{i,n}$, the maximum partial sum $S_{i,n}^+$, the minimum partial sum $S_{i,n}^-$, and consequently the range $R_{i,n}$ and the sum of ranges U_n are all functions of water exchanges. In a minimization problem of U_n, the water exchanges are the only control variables.

A complete mathematical expression of this problem can be given in the form of an ordinary control problem.

The objective function is:

$$\min U_n, \text{ or equivalently, } \min \sum_{i=1}^{M} R_{i,n} \text{ with respect to } r_{i,j,t}\,,\ i,j = 1,2,\ldots,M \text{ and } t = 1,2,\ldots,n \quad (8.1)$$

The constraint set is composed of three classes. The first class is a constraint on the control variables; namely the inequality (7.1). The second class is a constraint on the phase space; that is, the streamflow cannot be negative, namely, the inequality (7.4). The third class of constraints is a state equation system which is composed of the mass balance equations and the basic definitions of deviations, partial sums and ranges; namely, the equalities (7.2), (7.3) and (7.5) through (7.13).

The direct solution of this multi-stage optimization problem is very difficult, mainly because of the definition of the range. The range is a nonlinear function because it is defined as the difference between the maximum and the minimum of a series of partial sums. A dynamic program can be formulated by treating the partial sums as state variables. In this case, the sum of ranges U_n is a function of M partial sums. Since the final states are not given for this problem, the forward recursive formulation is desirable.

Let $U_n^*(S_{1,n}, S_{2,n},\ldots,S_{M,n})$ be the minimum of the sum of ranges having an ending state $(S_{1,n}, S_{2,n}, S_{M,n})$. Then, the following functional equation holds

$$U_n^*(S_{1,n}, S_{2,n},\ldots, S_{M,n}) =$$

$$\min\{U_{n-1}^*(S_{1,n-1},\ldots, S_{M,n-1}) +$$

$$+\Delta U_n(r_{1,2,n}, r_{2,1,n},\ldots, r_{M-1,M,n}, r_{M,M-1,n})\}$$

where
$$\Delta U_n = U_n - U_{n-1} \quad . \qquad (8.2)$$

Although this dynamic programming approach is simple in theory, the computational task involved is tremendous as M and n become large and the desired level of accuracy becomes high. If only a rough evaluation of the effectiveness of a regional water exchange system is the main purpose in calculating U_n^*, such a computational effort would be wasteful. In the next section, a simplified case with some specific assumptions is solved.

8.2 Minimum Sum of Ranges Assuming Unlimited Water Exchange Capacities.

If the constraint given by inequality (7.1) is released assuming that the capacities of the water exchange lines are unlimited, constraint (7.1) is then simplified into

$$r_{i,j,t} \geq 0 \quad \text{for all } i,j \text{ and } t \quad . \qquad (8.3)$$

Such an assumption is obviously unrealistic and, accordingly, the resultant measure of effectiveness has a very limited usefulness. However, it must be stressed that this assumption leads to an absolute minimum for U_n^* which, regardless of measures undertaken cannot be reduced further. Therefore, the reduction ratio, which is an indicator of the potential reduction in the sum of ranges which can be brought about by the introduction of regional water exchanges.

Before giving a solution to this problem, the constraint set is reformulated by changing the control variable from $r_{i,j,t}$ to $\Delta_{i,t}$, which results in a considerable simplification of the problem.

From definition (7.5), the phase space constraint of Eq. 7.4 becomes

$$\Delta_{i,t} \geq -\overline{x}_i \quad \text{for all } i \text{ and } t \quad . \qquad (8.4)$$

Since

$$\{(r_{i,i+1,t} - r_{i+1,i,t}) + (r_{i,i-1,t} - r_{i-1,i,t})\} \qquad (8.5)$$

can take on any value while satisfying the constraint of Eq. 8.3, any other constraint which includes this expression as a term is, in reality, no longer a constraint and may be eliminated. As a result, with the assumption of unlimited water exchange capacities, constraints (7.1) through (7.5) can be replaced as an inequality, designated by (8.4). The constraint set now becomes the phase space constraint (8.4), the mass balance equation (7.6) and definitions (7.7) through (7.13), as Eq. 8.5.

Another addition is the introduction of the notation ΔR_t and $\Delta R_{i,t}$, denoting an increment in the sum of ranges and an increment in the range of the stream i during the interval t, respectively. Accordingly,

$$\Delta R_t = R_t - R_{t-1} \tag{8.6}$$

and

$$\Delta R_{i,t} = R_{i,t} - R_{i,t-1} \quad . \tag{8.7}$$

Obviously,

$$\Delta R_t = \sum_{i=1}^{M} \Delta R_{i,t} \tag{8.8}$$

and

$$R_n = \sum_{t=1}^{n} \Delta R_t \quad . \tag{8.9}$$

Regarding the position of $S_{i,t-1}$ in the interval $[S^-_{i,t-1}, S^+_{i,t-1}]$, let the non-negative values at time t-1, $P_{i,t-1}$, $Q_{i,t-1}$, P_{t-1} and Q_{t-1} be defined respectively as

$$P_{i,t-1} = S^+_{i,t-1} - S_{i,t-1} \quad , \tag{8.10}$$

$$Q_{i,t-1} = S_{i,t-1} - S^-_{i,t-1} \quad , \tag{8.11}$$

$$P_{t-1} = \sum_{i=1}^{M} P_{i,t-1} \quad , \tag{8.12}$$

and

$$Q_{t-1} = \sum_{i=1}^{M} Q_{i,t-1} \ . \tag{8.13}$$

Finally let the sign $\{\ \cdot\ \}^+$ be defined as

$$\{\ z\ \}^+ = \begin{cases} z & \text{for } z \geq 0 \\ 0 & \text{otherwise ,} \end{cases} \tag{8.14}$$

then it can be easily proven that

$$\{z_1\}^+ + \{z_2\}^+ + \dots + \{z_n\}^+ \geq \{z_1 + z_2 \dots + z_n\} \tag{8.15}$$

where equality holds if and only if

$$z_1 \geq 0 \quad \text{for all} \quad i\varepsilon[1,n] \tag{8.16}$$

or

$$z_i \leq 0 \quad \text{for all} \quad i\varepsilon[1,n] \quad . \tag{8.17}$$

Using these notations and parameters, an important theorem and its corollary can now be proven for the case of unlimited water-exchange capacities.

Theorem 1

The sum of ranges of streamflows, interconnected by water exchange networks having unlimited capacities, is a minimum at any n if and only if the deviations of streamflows from their means are controlled by exchanging water so as to satisfy the following conditions at every $t\varepsilon[1,n]$:

$$\Delta_{i,t} \geq -\bar{x}_i \quad \text{for all i,} \tag{8.18}$$

and either

$$\Delta_{i,t} \geq S^+_{i,t-1} - S_{i,t-1} \quad \text{for all i,} \tag{8.19}$$

or

$$\Delta_{i,t} \leq S^-_{i,t-1} - S_{i,t-1} \quad \text{for all i,} \tag{8.20}$$

or

$$S^-_{i,t-1} - S_{i,t-1} \leq \Delta_{i,t} \leq S^+_{i,t-1} - S_{i,t-1} \quad \text{for all i .} \tag{8.21}$$

Proof to Theorem 1

Proof to this theorem takes two steps. The first step is to prove that ΔR_t is a minimum when the above conditions are satisfied at time t . The second step is to prove that if ΔR_t is kept minimum in each individual time period, their sum R_n is then automatically minimized.

Proof to the first step. From definitions (8.7), (8.8), (7.7) through (7.12) and (8.10) through (8.13), ΔR_t can be rewritten as

$$\Delta R_t = \sum_{i=1}^{M} \{(S^+_{i,t} - S^-_{i,t}) - (S^+_{i,t-1} - S^-_{i,t-1})\} \tag{8.22}$$

$$= \sum_{i=1}^{M} [\{\max(S^+_{i,t-1}, S_{i,t}) - S^+_{i,t-1}\} + \{S^-_{i,t-1} - \min(S^-_{i,t-1}, S_{i,t})\}] \tag{8.23}$$

$$= \sum_{i=1}^{M} [\{S_{i,t} - S^+_{i,t-1}\}^+ + \{S^-_{i,t-1} - S_{i,t}\}^+] \tag{8.24}$$

$$= \sum_{i=1}^{M} [\{\Delta_{i,t} - P_{i,t-1}\}^+ + \{(-\Delta_{i,t}) - Q_{i,t-1}\}^+] \ . \tag{8.25}$$

Using the inequality formula (8.15),

$$\Delta R_t \geq \{\sum_{i=1}^{M} (\Delta_{i,t} - P_{i,t-1})\}^+ + \{\sum_{i=1}^{M} [(-\Delta_{i,t}) - Q_{i,t-1}]\}^+ \tag{8.26}$$

$$= \{\Delta_t - P_{t-1}\}^+ + \{(-\Delta_t) - Q_{t-1}\}^+ \ , \tag{8.27}$$

where equality holds if and only if $\Delta_{i,t}$'s satisfy one of the following conditions

$$\Delta_{i,t} - P_{i,t-1} \geq 0 \text{ and } (-\Delta_{i,t}) - Q_{i,t-1} \geq 0 \text{ for all i,} \tag{8.28}$$

$$\Delta_{i,t} - P_{i,t-1} \geq 0 \text{ and } (-\Delta_{i,t}) - Q_{i,t-1} \leq 0 \text{ for all } i,$$

or

$$\Delta_{i,t} - P_{i,t-1} \leq 0 \text{ and } (-\Delta_{i,t}) - Q_{i,t-1} \geq 0 \text{ for all } i, \tag{8.29}$$

or

$$\Delta_{i,t} - P_{i,t-1} \leq 0 \text{ and } (-\Delta_{i,t}) - Q_{i,t-1} \leq 0 \text{ for all } i. \tag{8.30}$$

(8.31)

By the rearrangement of (8.28) through (8.31), the equality condition for (8.26) becomes:

$$\Delta_{i,t} \geq P_{i,t-1} \quad \text{for all } i , \tag{8.32}$$

$$\Delta_{i,t} \leq -Q_{i,t-1} \quad \text{for all } i , \tag{8.33}$$

or

$$-Q_{i,t-1} \leq \Delta_{i,t} \leq P_{i,t-1} \quad \text{for all } i , \tag{8.34}$$

which is identical to conditions (8.19) through (8.21).

Recall now the constraint (8.4) imposed on $\Delta_{i,t}$ for non-negativity of streamflows, that is,

$$\Delta_{i,t} \geq -\bar{x}_i \quad \text{for all } i \text{ and } t .$$

Let this condition at time t be the condition (8.35), i.e.,

$$\Delta_{i,t} \geq -\bar{x}_i \quad \text{for all } i . \tag{8.35}$$

Then for the equality of (8.26) to hold it is necessary that $(\Delta_{i,t},\ i=1,\ \ldots,\ M)$ should belong to the intersection of (8.35) and (8.32), or (8.35) and (8.33, or (8.35) and (8.34); in other form the necessary condition is

$$(\Delta_{i,t},\ i=1,\ \ldots,\ M)\varepsilon\Omega_t , \tag{8.36}$$

where

$$\Omega_t = (8.35) \bigcap ((8.32) \bigcup (8.33) \bigcup (8.34)) . \tag{8.37}$$

It is unknown, however, whether $\Delta_{i,\tau}$ could belong to Ω_τ for all $\tau\varepsilon[1,t]$ regardless of streamflow $x_{i,\tau}$, and accordingly the sufficiency should be examined. For this purpose it will be shown that at least one rule exists that determines a sequence of $\Delta_{i,\tau}$ so as to always belong to Ω_τ regardless of $x_{i,\tau}$.

Consider a rule of determining $\Delta_{i,\tau}$ such that

$$\Delta_{i,\tau} = \frac{\bar{x}_i}{\sum_{i=1}^{M} \bar{x}_i} \Delta_\tau \quad \text{for all } i \text{ and } \tau , \tag{8.38}$$

then it can be easily shown that

$$P_{i,\tau} = \frac{\bar{x}_i}{\sum_{i=1}^{M} \bar{x}_i} P_\tau , \tag{8.39}$$

and

$$Q_{i,\tau} = \frac{\bar{x}_i}{\sum_{i=1}^{M} \bar{x}_i} Q_\tau . \tag{8.40}$$

From definition (7.6),

$$\Delta_{i,\tau} = \frac{\bar{x}_i}{\sum_{i=1}^{M} \bar{x}_i} \left(\sum_{i=1}^{M} x_{i,\tau} - \sum_{i=1}^{M} \bar{x}_i \right)$$

$$= \bar{x}_i \sum_{i=1}^{M} \frac{x_{i,\tau}}{\bar{x}_i} - \bar{x}_i \geq -\bar{x}_i . \tag{8.41}$$

Thus constraint (8.35) is always satisfied. If $\Delta_\tau \geq P_{\tau-1}$, then from (8.39) and (8.40)

$$\Delta_{i,\tau} \geq \frac{\bar{x}_i}{\sum_{i=1}^{M} \bar{x}_i} P_{\tau-1} = P_{i,\tau-1} \quad \text{for all } i . \tag{8.42}$$

If $\Delta_\tau \leq -Q_{\tau-1}$, then similarly

$$\Delta_{i,\tau} \leq \frac{\bar{x}_i}{\sum_{i=1}^{M} \bar{x}_i} (-Q_{\tau-1}) = -Q_{i,\tau-1} \quad \text{for all } i . \tag{8.43}$$

Finally if $-Q_{\tau-1} \leq \Delta_\tau \leq P_{\tau-1}$, then

$$-Q_{i,\tau-1} \leq \Delta_{i,\tau} \leq P_{i,\tau-1} \quad \text{for all } i . \tag{8.44}$$

Thus the rule to determine $\Delta_{i,\tau}$, formula (8.38), allows for a sequence of $\Delta_{i,\tau}$ to always belong to the intersection Ω_τ regardless of $x_{i,\tau}$ for all $\tau\varepsilon[1,t]$.

Consequently condition (8.37) is necessary and sufficient to make ΔR_t minimized at any t. This completes the proof to the first step.

Proof to the second step. When the minimum ΔR_t is greater than zero, either (8.32) or (8.33) holds. By adding $S_{i,t-1}$ to both sides of those inequalities, they become

$$S_{i,t} \geq S^{+}_{i,t-1} \quad \text{for all } i , \tag{8.45}$$

and

$$S_{i,t} \leq S^{-}_{i,t-1} \quad \text{for all } i , \tag{8.46}$$

respectively. It implies that whenever ΔR_t becomes greater than zero, all the partial sums of deviations of streamflows, $S_{i,t}$, from the mean are on or outside of either the lower edge $S^-_{i,t-1}$ or the upper edge $S^+_{i,t-1}$ of their respective previous range, $R_{i,t-1}$. In other words, whenever a partial sum is beyond the previous range, all other partial sums are also on or beyond their previous ranges. It follows, therefore, that when ΔR_t is greater than zero, the previous decisions governing the sequences of partial sums, namely, how the sequences of partial sums have reached limits, do not influence the decisions concerning future sequences of partial sums, that is, those after time t. Hence, if ΔR_t is minimum for all $t \varepsilon [1,n]$, the sum R_n is automatically minimized for all n.

This completes the proof of Theorem 1.

Corollary to Theorem 1

The sum of ranges for streamflows, interconnected by water exchange networks having unlimited capacities, is a minimum at any time if the streams are considered to be consolidated into a single stream with the inflow equal to the sum of inflows.

Proof to Corollary. Since there is no capacity limit in the size of water exchanges, streams can be considered as fully connected, namely as a single consolidated stream. Once all streamflows are consolidated into a single stream, there exists only one deviation Δ_t. From relation (7.6), $\Delta_t \geq -\sum_{i=1}^{M} \bar{x}_i$. Hence condition (8.18) holds. By consolidation of streamflows there exist only one cumulative sum of deviations S_t, and accordingly exists one S^+_t and S^-_t at every t. Therefore S_t, i.e., $(S_{t-1}+\Delta_t)$ belongs either to the interval $[-\infty, S^-_{t-1}]$ or to $[S^-_{t-1}, S^+_{t-1}]$ or $[S^+_{t-1}, \infty]$ at every t. This satisfies the condition given by Theorem 1.

8.3 The Minimum Sum of Ranges in Independent Normal Streamflows

Using the corollary to Theorem 1, the minimum sum of ranges can be calculated very easily for the case of unlimited water exchange capacities. As for as the theoretical sum of ranges is concerned, however, very little can be said, except in those cases where the streamflows have an independent identical normal distribution. Although such conditions are generally unrealistic, a brief inspection of such cases will point out some of the basic properties of the sum of ranges.

The expected value of range for a given period n of an independent normal random variable with distribution $N(0,\sigma_i^2)$, is given by Anis and Lloyd (1953) as

$$E(R_{i,n}) = \sqrt{\frac{2}{\pi}}\, \sigma_i \sum_{t=1}^{n} t^{-1/2} . \qquad (8.47)$$

In the case of M streamflows, each having an independent normal distribution and if there is no water exchange among the rivers, the expected value of sum of ranges is simply a sum of all individual expected ranges; namely,

$$E(U_n^o) = \sqrt{\frac{2}{\pi}} \sum_{i=1}^{M} \sigma_i \sum_{t=1}^{n} t^{-1/2} . \qquad (8.48)$$

However, if the M streams are interconnected by an unlimited water exchange network, they can be considered as a single consolidated stream. Therefore, for the minimum sum of ranges of a single consolidated streamflow, the previous formula becomes

$$E(U_n^*) = \sqrt{\frac{2}{\pi}} \sqrt{\sum_{i=1}^{M} \sigma_i^2 + 2 \sum_{j=2}^{M} \sum_{\ell=1}^{j-1} \rho_{j\ell}\, \sigma_j\, \sigma_\ell}\, \sum_{t=1}^{n} t^{-1/2} . \qquad (8.49)$$

where $\rho_{j\ell}$ is a lag zero cross correlation between stream j and stream ℓ. The values given by Eq. (8.49) are equal to those given by Eq. (8.48) only if $\rho_{j\ell}$ equals unity for all values of j and ℓ. Otherwise, $E(U_n^*)$ is alsays smaller than $E(U_n^o)$.

If β_n^* defined by (7.19) is used as an estimator of α_n^*,

$$\beta_n^* = 1 - \sqrt{\sum_{i=1}^{M} \sigma_i^2 + 2 \sum_{j=2}^{M} \sum_{\ell=1}^{j-1} \rho_{j\ell}\sigma_j\sigma_\ell} \Big/ \sum_{i=1}^{M} \sigma_i , \qquad (8.50)$$

which implies that the maximum reduction ratio is on an average a constant independent of time period n.

From expression (8.50), it is clear that the reduction in sum of ranges is dependent upon the cross correlation among the streamflows. If they are highly correlated, no substantial reduction is attainable, while in the case of low cross correlation, and especially when some negative correlations are present, the sum of ranges can be substantially reduced. This is simply the mathematical expression for intuitively obvious facts regarding the effectiveness of exchange methods.

CHAPTER 9

CASE STUDY IN THE CENTRAL WEST OF THE UNITED STATES

The case study presented in this chapter uses historical data of streamflows for obtaining the maximum reduction in the sum of ranges with an unlimited water exchange network. The following are the results of this study and analyses of its practical implication.

9.1 Case Study Area

The six rivers listed in Table 1 were selected for interconnection. The exchange lines were determined by both intuitive judgment based on the geography and by the availability of historical runoff data, as shown in Fig. 6.

Table 1. Rivers and Stations in Case Study Area

Rivers	Stations of Interconnection	Sources of Data
Missouri River	Pierre, S.D.	Water Supply Paper No. 1309, 1729
North Platte River	Oskosh, Nebr.	Water Supply Paper No. 1310, 1730
South Platte River	Julesburg, Colo.	Water Supply Paper No. 1310, 1730
Arkansas River	La Junta, Colo.	Water Supply Paper No. 1311, 1731
Rio Grande River	Embudo, N.M.	Water Supply Paper No. 1312, 1732
Colorado River	Lees Ferry, Ariz.	Colorado State University collection

Note: 1. Monthly streamflow data from October 1932 through September 1960 have been obtained.

2. Monthly data for the Missouri River at Pierre, S.D., influenced by reservoir regulation, have been corrected by considering monthly changes in storage volumes in upstream reservoirs, the Fort Peck Reservoir in Montana, the Garrison Reservoir in North Dakota, and the Oahe Reservoir in South Dakota, (data obtained from Water Supply Paper No. 1309 and 1729).

9.2 Computational Results

Following the procedure given by Corollary to Theorem 1, α_n^*'s are calculated for four cases -- Case 1: monthly flows, six rivers; Case 2: monthly flows, four rivers. In case of four rivers, they are those of Table 1 excluding the Missouri and Colorado Rivers. The reason for omitting these two rivers in Cases 2 and 4 is that their mean discharges and standard deviations are much higher than for the rest (see Table 3), so that the water exchanges would be determined for all practical purposes only by these two dominant rivers. The calculated values for α_n^* are listed in Table 2.

9.3 Interpretation of Results

It is difficult to draw a definite conclusion about the exchanges from the available historical data alone. The time series of α_n^* does not appear to be either stationary or to have an asymptotic trend in any of the cases. If the streamflows are serially independent and normally distributed, the value of maximum reduction ratio for the sum of ranges must be a time invariant as the expression (8.48) implies. It is difficult, however, to tell from results in Table 3 whether α_n^* is independent of n . Such a test may be possible through the simulation of equally likely synthesized streamflows.

For the time being, lacking a better information on this aspect, the discussion is based on the intuitive assumption that the last α_n^*'s , namely, α_{348}^*'s and α_{29}^*'s , are more reliable than any of the others. The findings are listed below, followed by comments.

(1) Reduction ratios are larger for the four-river case than for the six-river case, although the absolute values of the expected ranges are higher in the six-river case.

(2) Annual series show a larger effectiveness of water exchanges than monthly series, with about a 20 percent difference in the reduction ratios.

(3) At best, less than a 20 percent reduction in the sum of ranges can be expected with the postulated operation at the water exchange network.

Finding (1) suggests that the Colorado and Missouri Rivers may be separated from the North and South Platte, the Arkansas and the Rio Grande Rivers interconnection project. This may be explained by a relatively high cross correlation between these two dominant rivers as compared with the correlations among the four other rivers. The cross correlation matrices are shown in Table 3.

Finding (2) can be attributed to the positive difference between the serial correlation coefficients of monthly flows and than those of the annual flows. It also implies that it is more beneficial to construct storage reservoirs for within-the-year regulation than to construct water exchange networks for the partial regulation of within-the-year fluctuations. This implication is also valid from another point of view. Since flood control cannot be taken care of by water exchange networks, storage reservoirs are necessary for controlling flood discharges.

Finding (3) may well be the most important of this case study. The question is whether or not 20 percent reduction in sum of ranges is significant. This is a socio-economic question which cannot be answered by using the hydrologic factors alone. It should not be overlooked that, even if water exchange networks have not yet been constructed, considerable amounts of water from two or more basins are used in a complimentary manner. For instance, the irrigation area between the North and South Platte Rivers receives water from the stream which has more water. Therefore, a step towards the reduction of the sum of ranges may be practiced already without an exchange network. This fact can be taken into account by using the reduction ratio α_n^* minus that due to the already existing water exchanges. Even a 20 percent reduction in the sum of ranges may represent large benefits compared with the measure of constructing the most economical reservoir sites, because of socio-economic, political, ecological, and/or geophysical constraints in building reservoirs. Such situations may exist in many areas, especially for those in which a number of reservoirs has already been constructed and additional increments of the total storage capacities are under consideration.

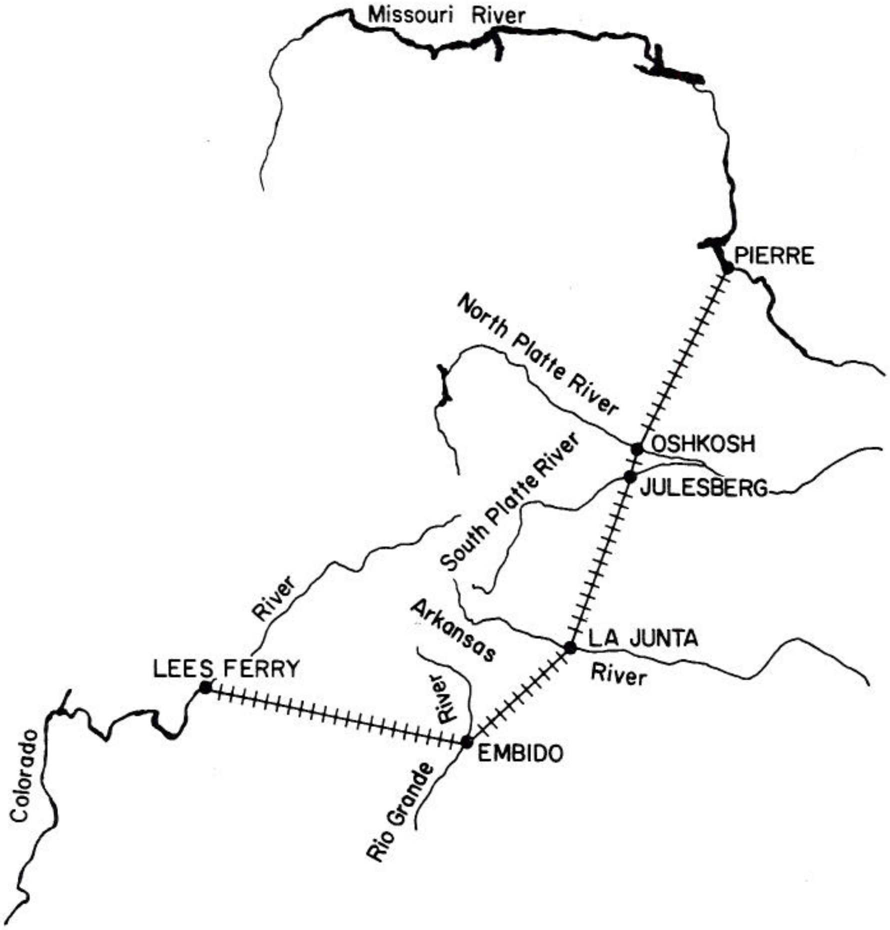

Fig. 6. Schematic sketch of water exchange network system in the study area

Table 2. Maximum Reduction Ratios (α_n^*)

n	Case 1 Monthly Six Rivers	Case 2 Monthly Four Rivers	n	Six Rivers	Case 4 Annual Four Rivers
1	2.3%	43.7%			
10	2.5%	46.9%	1	10.7%	76.8%
20	6.0%	68.9%	2	29.9%	79.0%
30	8.4%	71.4%	3	6.3%	62.0%
40	4.6%	52.7%	4	4.3%	53.8%
50	5.0%	47.3%	5	4.0%	35.0%
60	4.9%	45.2%	6	5.2%	39.7%
70	6.0%	42.8%	7	7.7%	42.5%
80	7.5%	43.9%	8	8.7%	42.5%
90	7.6%	44.9%	9	1.7%	23.7%
100	7.6%	44.9%	10	10.9%	41.8%
110	4.0%	28.8%	11	14.1%	38.8%
120	2.7%	35.3%	12	14.1%	38.7%
130	8.9%	34.4%	13	14.4%	32.9%
140	8.9%	32.1%	14	14.5%	30.1%
150	8.9%	31.8%	15	14.5%	30.1%
160	9.2%	28.4%	16	14.7%	25.5%
170	9.3%	28.1%	17	15.2%	12.9%
180	9.3%	28.1%	18	11.9%	10.8%
190	9.5%	22.8%	19	9.9%	11.5%
200	9.7%	15.8%	20	12.2%	14.2%
210	11.1%	10.6%	21	7.2%	17.9%
220	9.2%	8.2%	22	9.6%	17.9%
230	7.5%	8.5%	23	10.0%	19.0%
240	9.8%	10.2%	24	10.0%	19.0%
250	4.4%	14.6%	25	10.0%	19.0%
260	5.4%	16.1%	26	10.0%	19.0%
270	7.9%	16.1%	27	10.0%	19.0%
280	8.1%	16.1%	28	10.0%	19.0%
290	8.1%	16.1%	29	10.0%	19.0%
300	8.1%	16.1%			
310	8.1%	16.1%			
320	8.1%	16.1%			
330	8.1%	16.1%			
340	8.1%	16.1%			
348	8.1%	16.1%			

Note: Four rivers are those of Table 1 except the Missouri and Colorado Rivers.

Table 3. Standard Deviations and Cross Correlation for the Six Rivers in the Study Area

(a) Monthly standard deviations and cross correlation

	Mo.	N.P.	S.P.	Ark.	Rio.	Colo.
Missouri	17.1					
North Platte	.083	.579				
South Platte	.161	.499	.766			
Arkansas	.304	.232	.606	.531		
Rio Grande	.297	.215	.513	.530	1.10	
Colorado	.511	.087	.394	.535	.799	18.5

(b) Annual standard deviations and cross correlation

	Mo.	N.P.	S.P.	Ark.	Rio.	Colo.
Missouri	76.0					
North Platte	.656	3.38				
South Platte	.264	.438	3.78			
Arkansas	.109	.344	.749	2.85		
Rio Grande	.087	.227	.505	.574	5.44	
Colorado	.336	.371	.481	.519	.785	59.5

Notes: 1. Diagonal elements, underlined, are standard deviations given in 10^3 cfs.

2. Off-diagonal elements are cross correlation coefficients.

SUMMARY

1. A drought is defined as conditions of a water resources system which are expected and relied upon by users, fails to be met. A water shortage is defined as conditions of those systems in which the potential water demand, which is neither expected nor relied upon but is desired for man's activities, is not satisfied after the developed water supply is exhausted. These definitions are based and elaborated upon the basic philosophy which is common to all current drought definitions.

2. For the alleviation of droughts, there are four major external adjustment measures which are applicable to water supply-water use systems: uni-directional water transfer, water storage, water exchange and drought insurance. The latter two measures are capable of dealing with drought problems once the drought has begun, while the first two can only reduce the probability of drought occurrences and cannot help once a drought has started beyond the existing capacities of these measures.

3. The Federal Crop Insurance Corporation is the only institution in the United States which offers a crop insurance against drought hazards. Based on its experience,it is unlikely that a drought insurance program can be expanded to cover anything other than crops on unirrigated lands. A drought insurance for industries and/or municipalities is concluded to be realistic.

4. A regional water exchange system, by using the bi-directional water transmission under pressure, can alleviate drought situations by smoothing the regional water surpluses and deficits. Such water transmission networks may be established without huge economic investments in large urban areas or megalopolicies. By smoothing water supply-water demand imbalances over the space, the need for additional water storage capacities may be reduced significantly. By this partial substitution for water storage, the ever-increasing resistance against the construction of large reservoirs could be met together with the increased potential for drought control. Besides, since the exchange system can be beneficial to all the interconnected regions, the interregional disputes commonly involved in uni-directional water transfer can also be avoided or minimized.

5. In a cost-effectiveness analysis of various drought control measures, the regional variances and covariances of the water supply-water demand imbalances play a key role. A regional water-exchange system tends to be more advantageous than the other alternatives for drought control when the spatial correlations between the imbalances are relatively low.

6. As a measure of effectiveness for the regional water-exchange systems, the concept of the sum of expected ranges is introduced. The amount of substitution for storage capacity can be directly measured by the reduction in the sum of expected ranges. The maximum substitution in the interconnected regions is measured by α_n^* , the maximum reduction ratio of the sum of ranges.

7. In order to maximize the substitution effect, the water-exchange system should be optimally operated. This optimization problem is solved partially by introducing the assumption of unlimited capacities in the water-exchange lines.

8. The analytical solution for the optimization problem, developed in this paper, is applied using the 29 years of historical data, and a hypothetical regional water-exchange system which interconnects the six major streams: the Missouri, North Platte,South Platte, Arkansas, Rio Grande, and Colorado rivers. The result is that the sum of expected ranges can be reduced about 20 percent for this interconnected system.

REFERENCES

Anderson, Raymond L., Economic Research Service, USDA, Colorado State University, Fort Collins, Colorado, personal communication, fall 1972.

Anis, A.A. and E.H. Lloyd, On the Range of Partial Sums of a Finite Number of Independent Normal Variables, Biometrika, Vol. 40, 1953.

Bailey, Warren R. and Lawrence A. Jones, Economic Consideration in Crop Insurance, ERS-447, Economic Research Service, USDA, Washington D.C., August, 1970.

Delvo, Herman W., Reserve Accumulated by the Federal Crop Insurance Corporation from 1948 through 1967: Analysis by Region, State, and Crop, Department of Agriculture Report No. 52, University of Nebraska, Lincoln, Nebraska, August 1969.

Glan, T.E., The Commonwealth Drought Bond, The Australian Journal of Agricultural Economy, Vol. 2, December 1970.

Greenberg, M.R., G.W. Carey, L. Zobler and R.M. Hordon, A Geographical Systems Analysis of the Water Supply Networks of the New York Metropolitan Region, The Geographical Review, Vol. 61, No. 3, June 1971.

Kasal, James M., Economic Research Service, USDA, Colorado State University, Fort Collins, Colorado, personal communication, fall 1972.

Palmer, Wayne C., Meteorological Drought, U.S. Weather Bureau Research Paper No. 45, U.S. Department of Commerce, Washington D.C., February 1965.

Rippl, W., The Capacity of Storage Reservoirs for Water Supply, Proceedings Institute of Civil Engineers, Vol. 71, 1883.

Russell, Clifford S., David G. Arey and Robert W. Kates, Drought and Water Supply: Implications of the Massachusetts Experience for Municipal Planning, (Baltimore: Johns Hopkins Press, 1970).

Sitler, Harry G., Economic Research Service, USDA, Colorado State University, Fort Collins, Colorado, personal communication, fall 1972.

Thornthwaite, C.W., An Approach Toward a Rational Classification of Climate, Geographical Review, Vol. 38, 1948.

Tokyo Metropolitan Water Supply Bureau, Meeting the Metropolitan Water Needs, (in Japanese) City of Tokyo, July 1972.

Wilcox, Walter W. and Willard W. Cochrane, Economics of American Agriculture (New York: Prentice-Hall, 1951)

Yevjevich, Vujica, An Objective Approach to Definitions and Investigations of Continental Droughts, Hydrology Paper No. 23, Colorado State University, August 1967.

Yevjevich, Vujica, Stochastic Processes in Hydrology (Fort Collins: Water Resources Publications, 1972), p. 178.

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