EVALUATION OF URBAN WATER MANAGEMENT POLICIES IN THE DENVER METROPOLITAN AREA

by

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EVALUATION OF URBAN WATER MANAGEMENT POLICIES IN THE DENVER METROPOLITAN AREA

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by

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ABSTRACT

EVALUATION OF URBAN WATER MANAGEMENT POLICIES IN THE DENVER METROPOLITAN AREA

A management level urban water system model has been developed to answer basic questions relating to optimal management of water in the urban environment. The model which coordinates water supply, distribution, and wastewater treatment is applied to the water management problems of the Denver, Colorado metropolitan area. Denver presently supplements diversions from the South Platte River with interbasin transfers, agricultural water right transfers, and groundwater. Although plans are being made to increase the capacity of these sources, increasingly stringent standards on wastewater effluents are enhancing the feasibility of reuse. In order to facilitate the implementation of optimal policies such as reuse, various institutional constraints must be evaluated. Certain of these including the legal interpretation of water rights, public opinions, management consolidation, and water quality control philosophies are explored.

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KEYWORDS - institutional constraints, interbasin transfer, mathematical models, optimization, urbanization, wastewater treatment, water distribution systems, water quality, water resources, water reuse, water treatment.

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SECTION I

INTRODUCTION

Purpose

Institutional arrangements for allocating and managing water resources are well established in the policy making political structures of the United States. In the semi-arid western states, the complexity of such factors assume added significance due to the scarcity of water supplies. As various water demands continue to increase, it is necessary to reevaluate these institutional arrangements in order to initiate changes which promote more effective utilization. As a first step in such investigations, optimal water management strategies need to be determined. Then, the specific institutional parameters restricting the implementation of optimal policies, as well as the costs of such constraints, can be identified.

Among the administrative formulas requiring periodic assessment are those coordinating water management in rapidly urbanizing river basins. In such areas, the growth of metropolitan demands comes in sharp conflict with adjacent agricultural, recreational, and industrial interests. As a means of investigating the institutional requirements for optimizing water management strategies in arid urban areas, the Denver metropolitan area has been selected for studying the effects of institutional constraints upon optimal water management strategies. Such constraints include those presently operating such as water rights, those expected to fluctuate such as public attitudes, and those to be imposed such as water quality standards on urban effluents.

The purpose of this research effort is to evaluate this array of institutional influences from a macro point of view "by initially determining the functional dependence of optimal water management strategies on parametric decisions imposed upon the urban system." From this analysis, a comparison can be made between the optimal policies previously derived and those permissible under the existing and expected institutional conditions. The respective costs of institutional constraints can thus be determined and various alternative measures suggested which would permit more effective water management programs.

Scope

In order to disseminate the results of this study to the specific interests of the readers, four reports have been generated. The first of these entitled "Mathematical Modeling of Water Management Strategies in Urbanizing River Basins," serves as the basis of the next three, one of which is this report. In the modeling report, the mathematical background and assumptions used to optimize water management policies in the Denver area were developed. This model was then applied to the Denver conditions, with the results being presented and discussed herein. Understanding the scope of the model will aid the reader in placing the results of this report in clearer perspective.

Water management in an arid urban area consists of several institutional levels and many divisions within each level. Any attempt to "optimize" water management must account for the relationships involved between levels and within divisions at each level. These "relationship" constraints determine the course of the overall water management program of an area.

To illustrate, consider a typical river basin in the western United States. Since the first uses of water were made in the basin, additional demands emerged, one of which may be an urban area. The deteriorating water quality in this country's streams prompted the Federal Government to require that the states submit water quality standards on all interstate streams for approval by the Federal Government, and then the states were required to abide by these standards (U.S. Environmental Protection Agency, 1972). While it is often difficult to abide by the standards, the requirement of at least setting the appropriate standards has been met by most basin authorities. By placing water quality constraints throughout the basin in this manner, the search among water management alternatives became somewhat of a local problem in which local decision makers investigate ways to feasibly meet their individual water demands and at the same time subscribe to the water quality standards in the stream.

To the student of operations research, the procedure of setting guidelines for pollution abatement, and then allowing each individual water user to amend his plans to conform with these constraints, is quite analogous to a technique called multilevel optimization. This optimizing method is based on a decomposition of the large scale system into independent subsystems. The procedure involves the introduction of what are called coordinator variables, or pseudo-variables, which tie together the different levels in the system decomposition. Thus, what may seem to be an inefficient process of "reacting" may in reality be a systematic approach.

If indeed the argument that the evolving mode of evaluating water use is a multilevel one, then the technical input from researchers should probably be modified. For example, in the development of system and subsystem models, the emphasis should be directed toward the smaller limited purpose model usable by decision makers and less emphasis need be placed on the large and comprehensive model. It is upon this premise that the scale and scope of the model has been developed. Specifically, it was the intention of this study to develop an optimizing model for the broad decision processes in arid urban areas. It is the purpose and scope of this report to substantiate the effectiveness of the proposed tool by applying the model to the Denver, Colorado area. However, the purpose is not to point out any inefficiencies of this city's planning, but rather to delineate the institutional constraints which limit the changes necessary to improve the water utilization in the Denver metropolitan area.

A model of the quantity and quality aspects of an urban water network would incorporate three basic components. These are the water sources (including recycled water), the internal water uses, and the waste water treatment facilities. When these parts are integrated, a model such as the one illustrated schematically in Figure 1 can be derived. Each of the basic segments of the model is in reality comprised of a complex set of physical, economic, social, and political subsystems. However, the detail in which a general urban level model can examine these basic components cannot include a thorough examination and analysis of each respective subsystem without becoming completely entangled in their complexities. Therefore, each of the general parts of the system are examined in somewhat macroscopic detail, with future research or technological development being relied upon to improve the models' interpretation of the behavior of these subsystems.

Qualifications

This report is intended to serve part of the need for evaluating the institutional restrictions imposed on

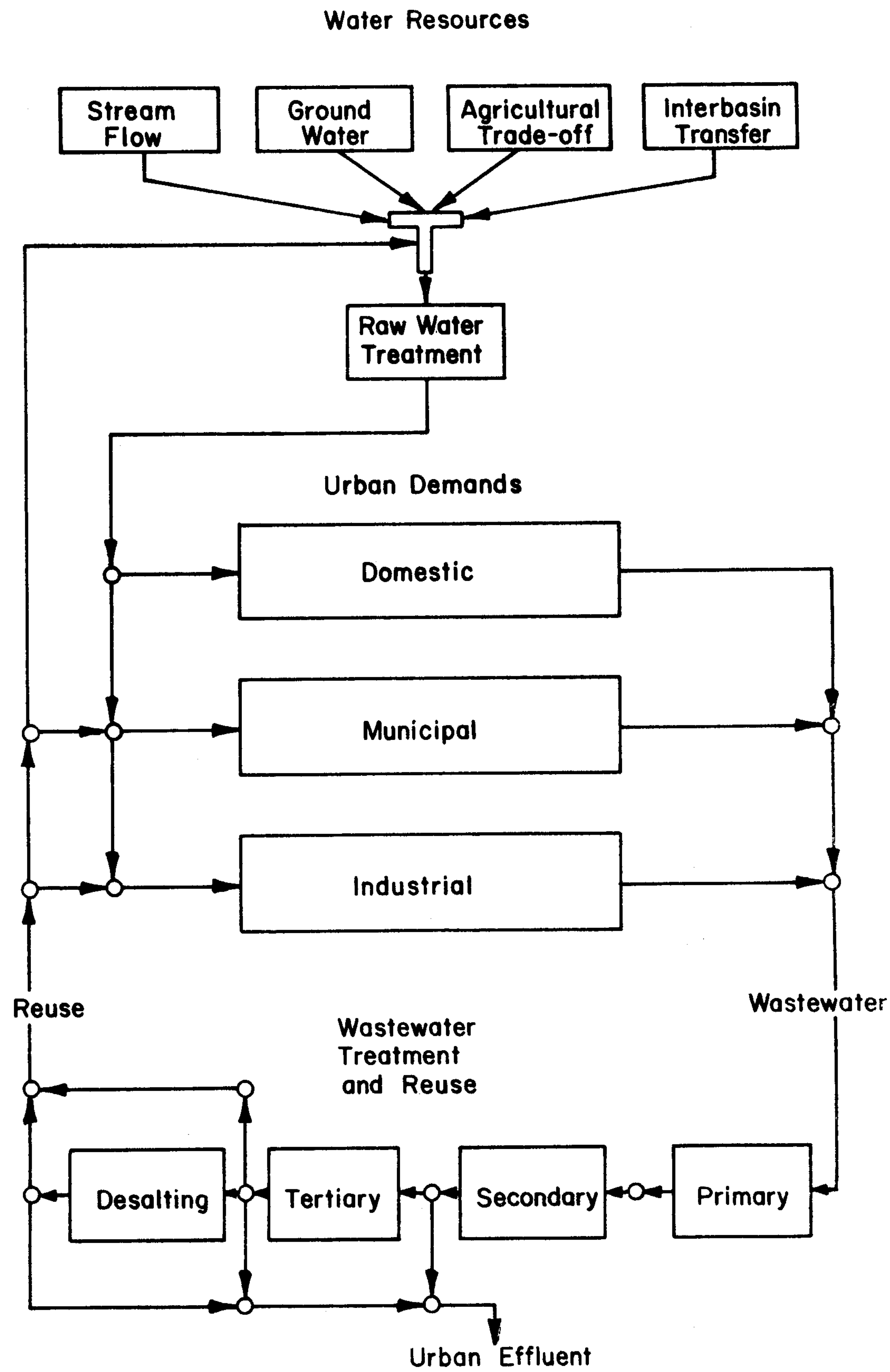

Figure 1. Urban water system model.

more effective water management practices in urban locations such as Denver, Colorado. The approach being followed is primarily a technical one because of the background of the authors. Consequently, it is worthwhile to suggest three qualifications of this work. First, this study has been made from an external viewpoint, even though it was directed at the urban water resource planner's level. The authors therefore have little "in-house" experience from which a more realistic concept of the day-to-day compromises and half-measures required to operate the Denver system could be evaluated. Secondly, the engineering expertise of the authors tends to make the method of analysis more pragmatic than similar studies performed by researchers in other disciplines. And finally, the tone of this report is not intended to imply criticisms of personalities or operations in the Denver area. It is, however, submitted to illustrate the nature of institutional weaknesses in the existing management system, from an external viewpoint not available within the decision structure. Hopefully, this study can serve as a guide to developing water management strategies in Denver, as well as other cities of similar characteristics, that are both efficient and effective.

SECTION II

WATER MANAGEMENT IN THE DENVER AREA

Introduction

A study of water management in an arid urban area has ramifications which extend beyond the metropolitan boundaries. Denver, Colorado, is a good example of a local water problem of state-wide concern. Water supplies for the city are obtained from sources in both the headwaters of the South Platte River Basin, and the headwaters of the Colorado River Basin. Although water management in the recent past dealt mainly with supply and development, the present and future emphasis can be expected to include water quality control and regional water use efficiency.

Denver evolved from a stopping place for Indians, fur trappers, traders, and explorers prior to 1858 to an expansive metropolitan area containing over half of the state's population in 1973. The catalyst for the founding of Denver was the "Pikes Peak or bust!" gold rush of 1859 stemming from Green Russell's discovery of gold at the confluence of Cherry Creek and the South Platte River in 1858 (Schierbrock, 1960). The initial settlements of Placer Camp and Montana gave way to Auraria and St. Charles, then Auraria and Denver, and finally Denver, the capital of the Colorado Territory and later the State of Colorado. Because St. Charles was actually in the western reaches of the Kansas Territory when the name change occurred, the name selection was made in recognition of the current governor of the territory, James W. Denver. From these early beginnings to the present, Denver's life-blood has been the commerce supported by its water resources.

It is interesting and important to view an area's present conditions in light of the historical events leading to the current status. Much of the social influence responsible for an area's operation can be traced to those times when significant decisions were made and the populace concurred. The structure for administrating an area can often be linked to the regulatory system which evolved as a result of correcting the periodic difficulties experienced in a region. In addition, future events are often best evaluated on the basis of past experience.

This section is presented to describe the conditions in the Denver area, especially with regards to water resources and their associated water quality characteristics.

Regional Characteristics

Location

The Denver area is located at the eastern base of the Rocky Mountains in the state of Colorado. To the east are the flat high plains and broad rolling prairies, while the regions to the west are mainly mountainous with arid or desert-like valleys. These topographical characteristics have a profound influence on both water quantity and quality. Because the general air flow is west to east, Colorado's water resources are found more abundantly on the western upslope regions than on the eastern side of the mountains. Conversely, most of the state's population is centered along the eastern base. Consequently, water management in Colorado is largely a problem of adjusting the spatial distribution of water resources to satisfy the needs of the people.

Due to its high elevation, Colorado contains the headwaters of four major river basins; (1) Colorado, (2) Rio Grande, (3) Arkansas, and (4) Missouri, as shown in Figure 2. Since these river systems transport water from the state into adjoining states, Colorado has first use of its water resources, a condition which is very advantageous to the water users from a water quality standpoint.

The South Platte River, which passes through Denver as shown in Figure 3, begins in the front ranges of the Rocky Mountains and flows in a northeast direction for approximately 442 miles until its confluence with the North Platte River in Nebraska. Demands for the annual flows generally exceed the available supplies thereby necessitating careful management of the resource.

Climate

The climatalogic conditions in the South Platte River Basin are primarily a function of elevation, which

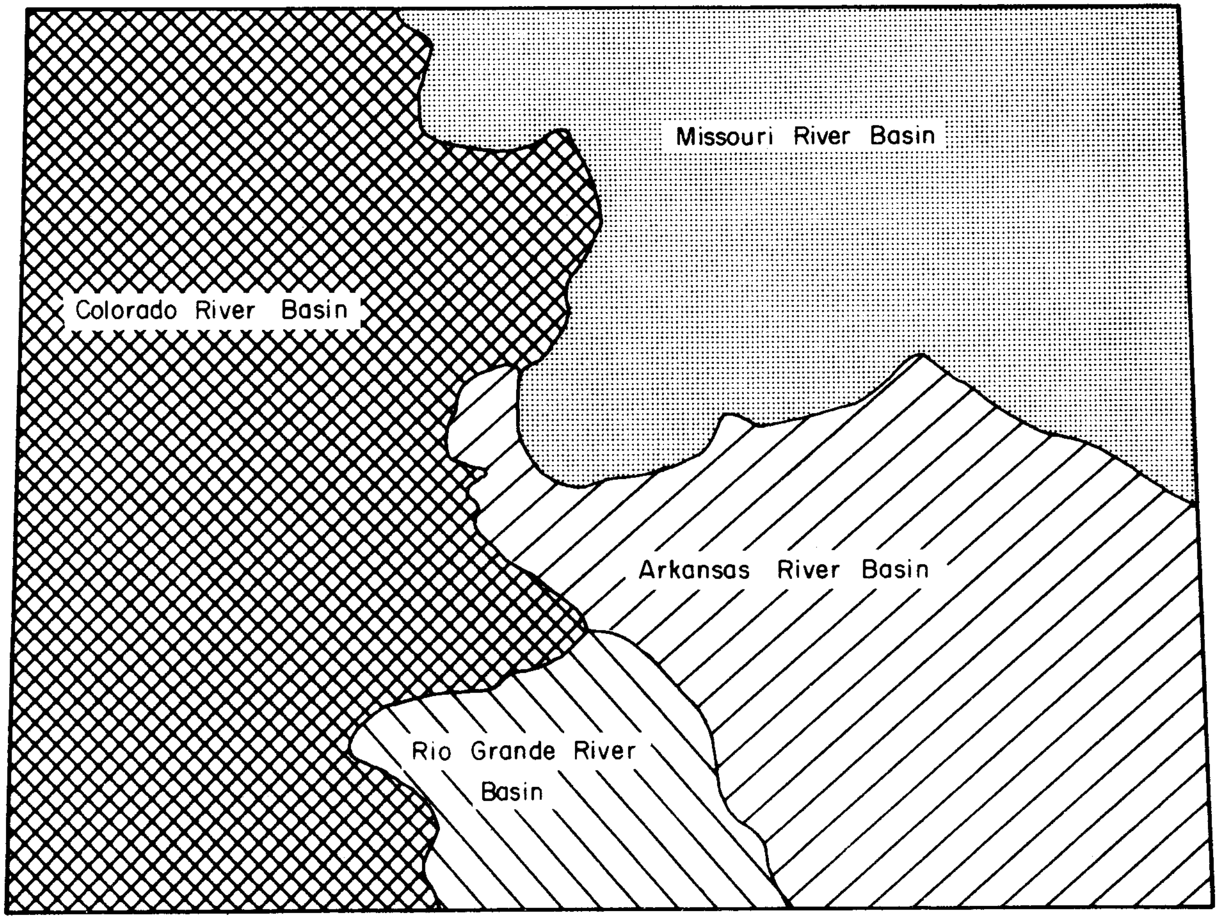

Figure 2. Colorado's major river systems.

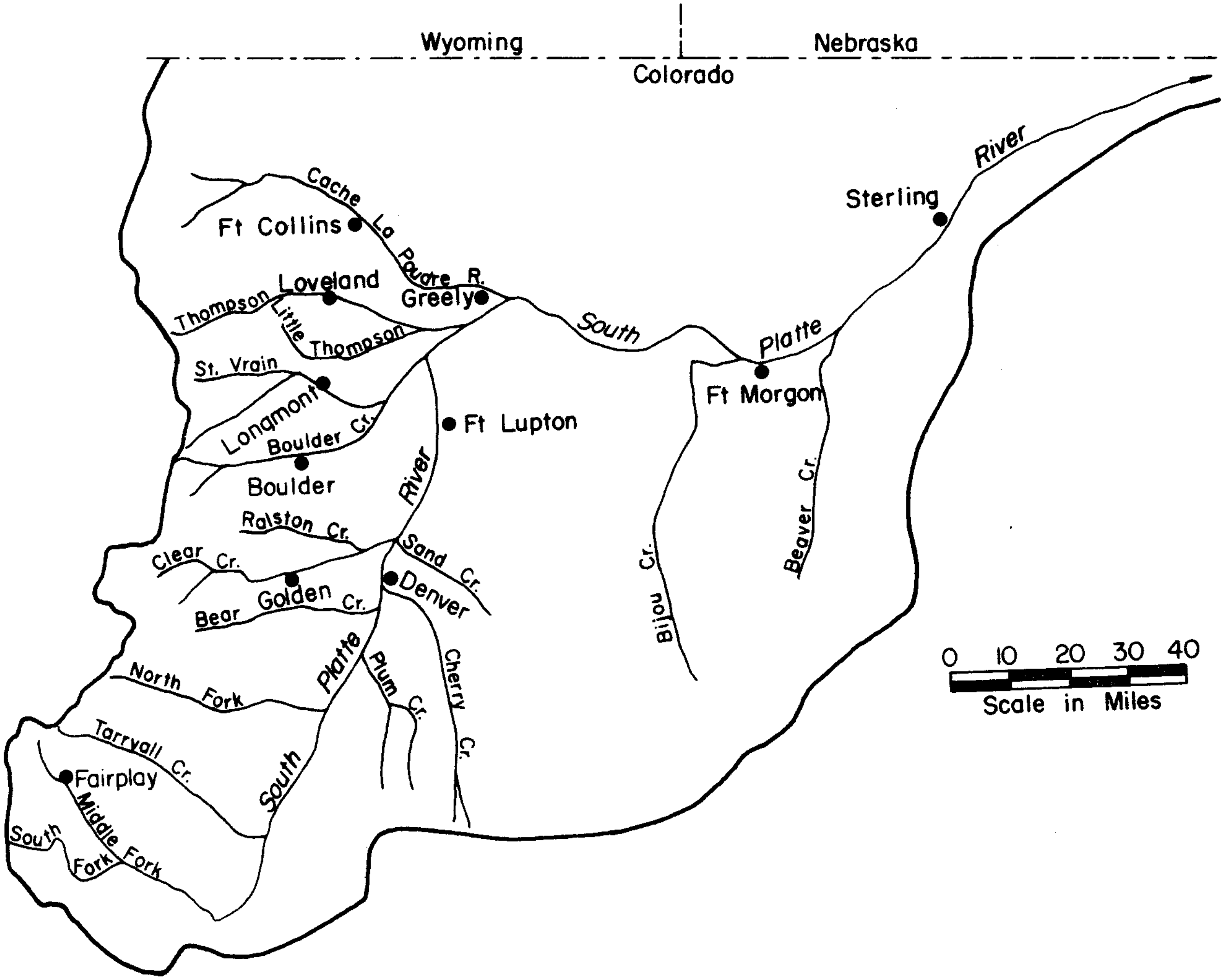

Figure 3. The South Platte River Basin in Colorado.

ranges from 3,500 feet above sea level in the eastern portion of the basin, to 5,280 feet at Denver, to 14,000 feet in the upper reaches of the watershed. The foothills due west of Denver experience elevational differences of 5,000 feet to 8,000 feet and provide the climatological transistion between the dry, warmer plains and the wetter, colder mountains. The climate in the Denver area, although marked by wide seasonal variations, is characterized by low relative humidity, 12-14 inches of rainfall, and moderate temperatures in both summer and winter.

Population

The population of Colorado showed an increase of 25.8% between the census of 1960 and 1970, resulting in a current total of about 2.3 million people. Of this total, approximately 74% live in the foothills area between Fort Collins and Pueblo. The Denver metropolitan area accounts for more than one-half of the state's population as illustrated by the historical and projected population trends shown in Figure 4. Much of these increases are due to the net influx of people into Colorado.

Economy

Colorado's economy has historically been based on its natural resources like mining, agriculture, and recreation. However, the rapid expansion of the states's urban centers lured a large number of diverse industries and supporting activities into the area. Consequently, the present

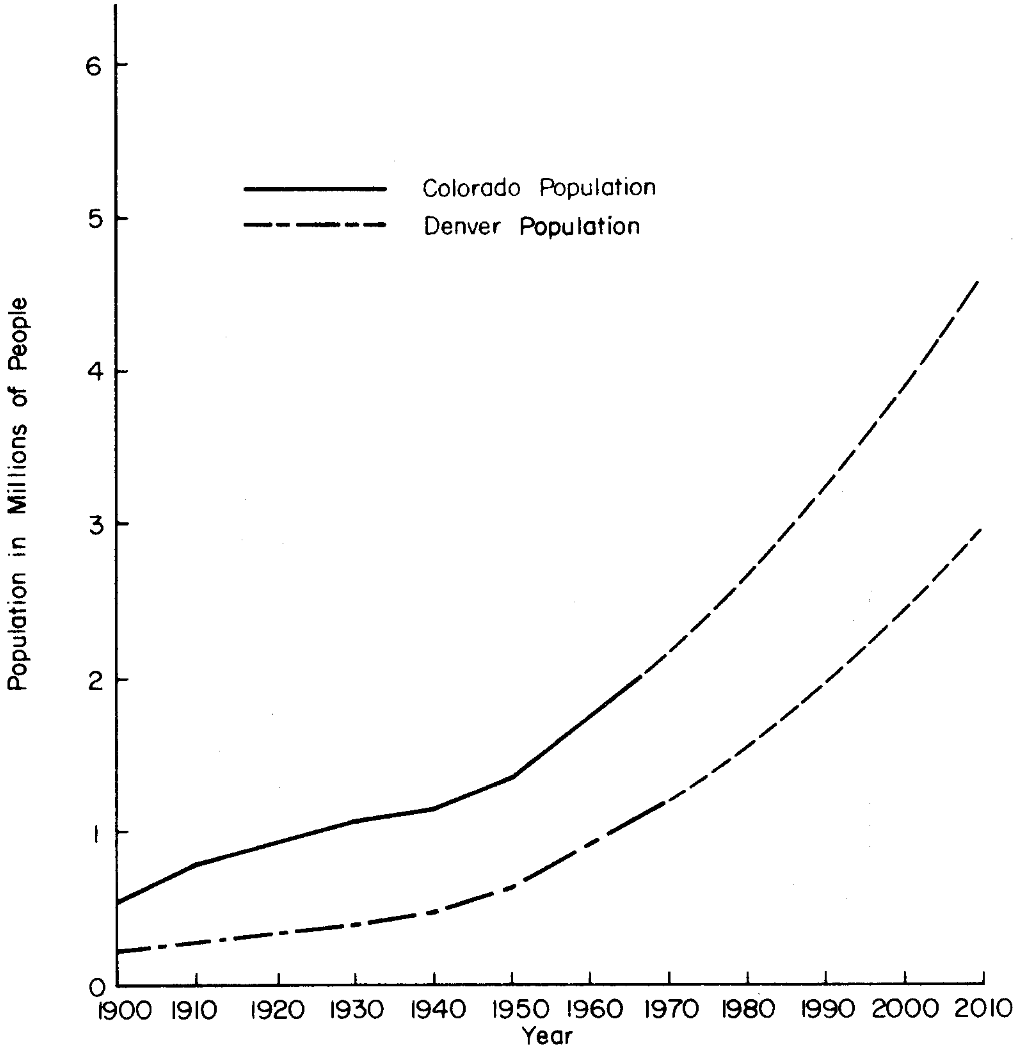

Figure 4. Population trends in the Denver, Colorado, area.

economic conditions of Colorado appear to be a well balanced mixture of economic enterprises.

Surrounding the Denver area in the South Platte River Basin, irrigated agriculture constitutes the largest water use. Of the approximately 69% of the basin comprising the agricultural industry, nearly all of it is fertile enough to support profitable alfalfa, small grains, corn, and sugar beet production. In addition, this vigorous agriculture supports related industries including livestock feeding, meat packing, sugar beet processing, milk production, and canneries.

Historical Water Development and Management

At the time the United States acquired the South Platte River Basin as a part of the famous Louisiana Purchase, four principal overland routes had been established into the Denver area. These trails were along the South Platte, Arkansas, Smoky Hill, and Republican Rivers (Schierbrock, 1960). It was along the South Platte route that the Stephen H. Long expedition of 1819-1820 made an exploratory trip into the area. The journals from this exploration were the first written description of the countryside and received wide readership in the east. However, the report of Major Long was negative in nature, stressing the forbidding nature of the plains to the east and the rugged mountains to the west. Among the conclusions drawn was the inability of the area to support more than a sparce population, nomadic in nature, since the area was unfit for cultivation. Like so many others at the early stages of exploration, Long attempted to access the capability of the land upon the eastern concept of agriculture and, consequently, made an erroneous judgement.

Early water use in the Denver area was agricultural, as would be expected. Residents diverted water from rivers and wells to supplement the croplands with water in the semi-arid environment. In 1859, James McBrown staked a claim on the lower reaches of Bear Creek and with the enactment of Colorado Water Laws, this right became the first priority in the South Platte Basin (Denver Water Department, 1969).

With the practices of constructing ditches to connect and irrigate the lands bordering the stream systems, it became necessary to formulate or devise a legal structure for distributing and administering the water resources. In 1861, the Colorado Territorial Legislature passed a bill which allowed individuals with off-stream land to secure a right-of-way for water crossing adjacent lands and use the water for a beneficial use on these lands. This attitude was a radical departure from the riparian rights doctrine inherited by the eastern areas of the United States from English Common Law. This principle, which eventually became the prior appropriation doctrine, was again alluded to when the territorial Supreme Court decided the case of Unker vs. Nichol in 1872 (Crawford, 1957). In 1876, when the state framed its constitution, the principle of prior appropriation philosophy was included as the state's law. This doctrine states simply that the appropriator who was the first to apply water to a beneficial use also acquires the first right to that water.

Because most of the early appropriations were for agricultural use, the water available for urban areas were largely based on junior rights. However, as the urban areas grew, the water formally used for irrigation was converted for municipal uses by a transfer of the water rights from one use to another. Such transfers is the manner in which most domestic supplies have developed (Denver Water Department, 1969). Although other projects had been conceived, the first successful attempt to bring domestic water to the residents was made by the Denver City Water Company in 1872.

By the early 1900's, all the dependable flow of the South Platte River and its tributaries had been appropriated for use, principally as supplemental irrigation water. Although the application of water to the farm lands had greatly stabilized the base flow, flood flows were common and could not be utilized. Due partly to these flood losses, and the junior nature of Denver water rights, the Denver Union Water Company, organized in 1894, built Cheesman Dam and reservoir in 1905 to collect these surplus flows.

In 1918, the Denver Board of Water Commissioners assumed control of Denver's water supply system which had as its major source of water the surface water of the South Platte River. Around this time, however, it became evident that within planning horizons the water rights for the South Platte's water would soon be completely utilized. As a result, planning for alternative supplies such as inter-basin diversions was begun.

Development of the South Platte River as a source of water supply for the Denver area essentially ended in 1932 with the completion of the Eleven Mile Canyon. Up until this time, Denver had either built or purchased Marston Lake, Cheesman Reservoir, and Antero Reservoir, the major reservoirs on the South Platte system. Raw water is stored in these reservoirs and then brought down the South Platte to Denver's raw water treatment system through a series of regulatory reservoirs.

With this maximum development of the South Platte water, Denver was in a good position to justify the diversion of water from the western slope. The early planning performed by Denver proved very valuable in obtaining western slope water rights needed for diversion projects to be successful. The first trans-mountain diversions to serve as additional supplies to Denver's water supply system came with the completion of the Fraser system in 1936. This water flows through the six-mile-long Moffat Water Tunnel after being collected from the Fraser River and its tributaries on the western slope. Development of this water tunnel was tied in very closely with the development of the Moffat railroad tunnel. In fact, Moffat Tunnel is the pioneer bore of the railroad tunnel.

In 1955, the Board of Water Commissioners acquired the Williams Fork Collection System and the three-mile-long A. P. Gumlick Tunnel (formerly Jones Pass Tunnel). This system had been constructed in the 1930's by a grant from the Public Works Administration to the Denver Public Works Department. The Williams Fork system was connected to the Fraser system in 1958 through construction of the Vasquez Tunnel. Consequently, water from the Williams Fork system now goes to the eastern slope via the Gumlick Tunnel, but rather than go down Clear Creek to Denver, the water travels back to the western slope via the Vasquez Tunnel and enters the Moffat Tunnel. This is accomplished so that water from the Williams Fork system can be stored, along with the Fraser system water, in Ralston Reservoir constructed in 1937 and Gross Reservoir completed in 1955. Prior to completion of the Blue River diversion project, the Fraser-Williams Fork system supplied almost 50 percent of Denver's municipal water supply (Board of Water Commissioners, 1971).

The largest diversion project to be completed by the Board of Water Commissioners is the Blue River Diversion System. Initial work on this system can be traced back to studies performed in the early 1920's, but was delayed until about 1955 by legal entanglements. With the passage of a $75 million bond issue in 1955, and a supplement of $40 million in 1959, construction was begun in earnest. The key part of the system, the Harold D. Roberts Tunnel, was completed in 1962, is 23.3 miles long and has a dog-leg to the south. Its western portal is located at Dillon Reservoir, elevation 8,844 feet, while the eastern portal is at Grant, Colorado, on the North Fork of the South Platte River, 174 feet lower than the west portal.

The major storage facility in this system, Dillon Reservoir, was completed in 1963 with an effective storage capacity of 254,000 acre feet.

The Denver Board of Water Commissioners in continuing to plan for future demands, submitted a $200 million bond issue to the people of Denver. But, in refusal of past support, they turned down the bond in 1972, which would have permitted the development of the Eagle-Piney Collection System. This system would have added an additional 100,000 acre-feet of water to the Denver municipal water system. Through an intricate system of tunnels, canals and reservoirs, it would have transported Eagle-Piney water to Dillon Reservoir for transmission to Denver via the Roberts Tunnel (Board of Water Commissioners, 1971).

The diversion of water from the western slope to the eastern, has not been accomplished without a lengthy and costly battle over water rights. There have been, and continue to be, controversies of water rights and it is doubtful that any type of agreement will end the controversy indefinitely.

Present Conditions

Although Denver is located in the rain shadow of the eastern slopes of the Rocky Mountains, investment of time, money, and technology have been successful in redistributing water resources to supply local demands. Those responsible for acquiring, treating, and delivering water supplies must insure a dependable supply even in long periods of drought. To date, the Denver area water planners have been relatively successful in accomplishing this objective by comprehensive and long range analysis of needs and trends. In the recent past, the growth and merger of the city of Denver and the communities in the surrounding counties prompted study on a metropolitan basis. Consequently, this study will also include these dimensions to the extent that the Denver water and wastewater facilities connect with the others.

Periodically, it is interesting to examine existing conditions in order to better evaluate the needs for future decisions. These existing conditions are also well defined and readily available so the effects of future decisions can be extrapolated from existing information.

Available Water Supplies

From the two major sources, the South Platte and Colorado River Basins, Denver has currently a usable water supply of about 310,000 acre-feet annually. The distribution of this supply is composed of about 61,000 acre-feet from the Moffat System, 168,000 acre-feet from the Blue System, and 81,000 acre-feet from the South Platte rights (Hobbs, 1971).

The availability of the flows which serve these systems is not continuously congruent with the demand distribution, so storage and distribution reservoirs have been constructed and maintained for adjusting local hydrology to the pattern of the needs. In the South Platte system, the storage capacity of Lake Cheesman, Eleven Mile, Antero, and a portion of Soda Lakes reservoirs amounts to over 193,000 acre-feet. This along with the 43,000 acre-foot Gross Reservoir in the Moffat System and 254,000 acre-feet in Dillon Reservoir of the Blue System provide Denver with a storage capacity of about 490,000 acre-feet (Board of Water Commissioners, 1972). In order to adequately supply the wide variations in monthly and daily demands, operation reservoirs serving the system have been implemented to yield a capacity of over 30,000 acre-feet. These reservoirs include Platte Canyon, Long Lakes, Ralston, and Marston Lake. In order to pictorially view these reservoirs, Figure 5 has been included.

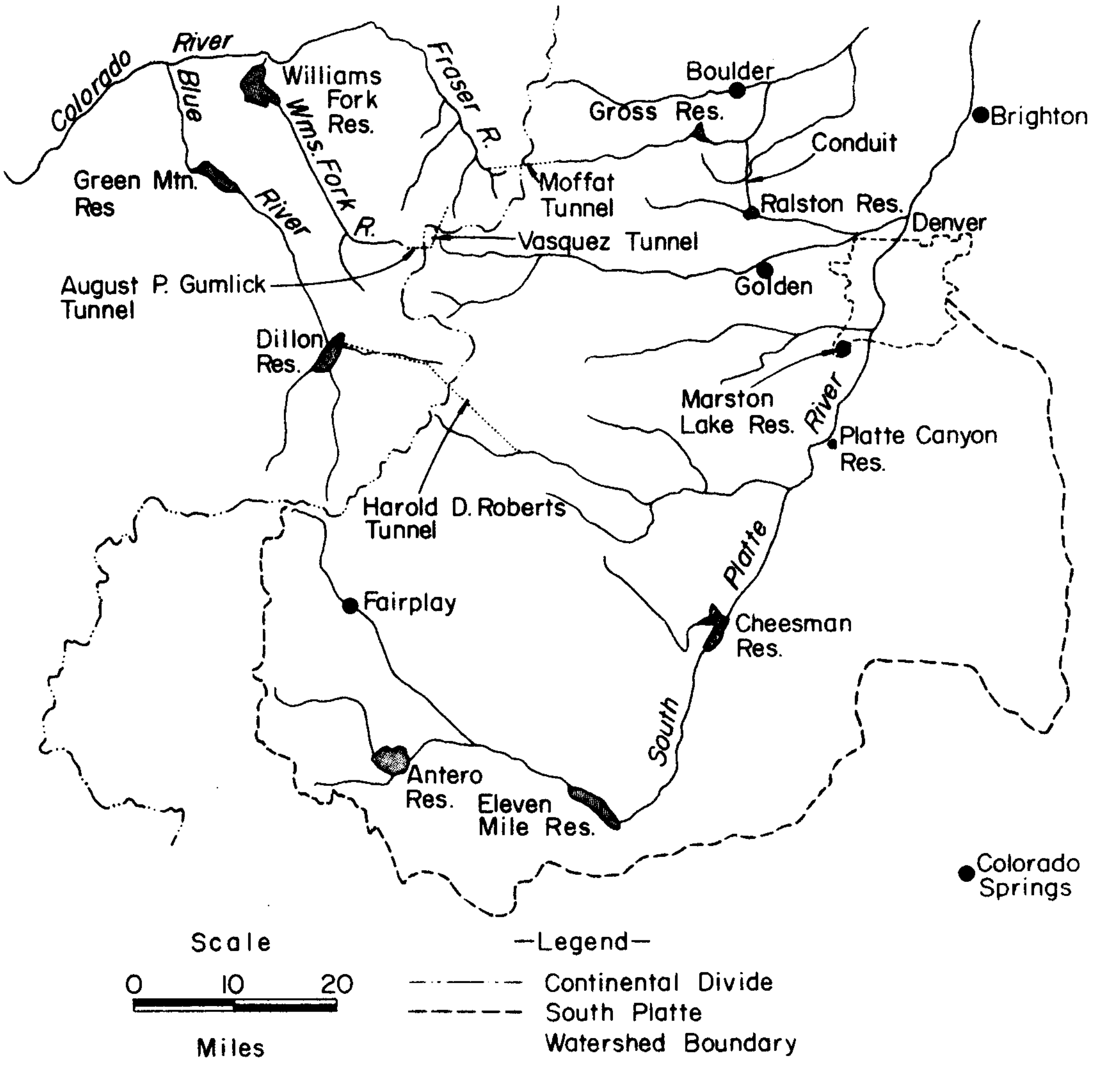

Figure 5. Denver's water system storage and operating reservoirs (Board of Water Commissioners, 1972).

The water quality of the flows supplied to Denver users is far below the upper limits placed on domestic, municipal, and industrial waters. A continual monitoring program is undertaken by the Board of Water Commissioners, U.S. Geological Survey, and Colorado Public Health Department as required by the purposes of these organizations. Although all important water quality parameters are checked, of interest in this study are the BOD and TDS concentrations. The Board of Water Commissioners (1971) lists water quality characteristics of the South Platte supplies. TDS levels in these flows average about 150 mg/l, but have reached highs as much as 300 mg/l. Iorns, Hembree and Oakland (1965), in an exhaustive study of Upper Colorado River Basin water resources, show TDS levels in the upper reaches of the watershed to be about 100 mg/l. This figure is also verified by Denver Water Department analyses. BOD concentrations in the total water supply is insignificant, indicating as well that color, turbidity, and fecal coliforms are minimal.

Raw water treatment is an absolute necessity even though the water supplies are of high quality. The first treatment facility, the Kassler Plant, was built in 1890 to process water from the South Platte River with underground filtration galleries. Then in 1906, the plant was enlarged to its present capacity of 50 mgd and converted to the slow sand filtration process. Then in 1925, the North Side Marston Treatment Plant was constructed which added an additional 100 mgd to the existing system. Along with this duo-media rapid sand filtration plant, a 60 mgd addition was added in 1961 and another 100 mgd addition in 1967 was added to treat western slope water. The remaining treatment plant, the Moffat Water Treatment Plant was completed in 1937 to treat Moffat Tunnel imports. This treatment plant, which originally had a capacity of 80 mgd, was expanded in 1957 to 150 mgd. Together, these raw water treatment plants give Denver a 460 mgd capacity (Board of Water Commissioners, 1972). The location of these water treatment plants is shown in Figure 6.

Demands

To characterize the demands of a large municipal area such as Denver, several factors should be examined. For example, the time varying aspects of the demands are important planning and design parameters. In addition, the distinctive nature of the demands presented in the previous chapter suggest that water quality requirements and consumptive use characteristics are variables needing evaluation in order to make a more effective use of the water.

The Board of Water Commissioners (1971) present monthly water demands based on both a ten-year average and for the 1971 year. These data have been included in Figure 7. It is interesting to note the large increases during the peak use months of the summer, which indicate the use of water for irrigation of lawns, trees, and shrubs. If

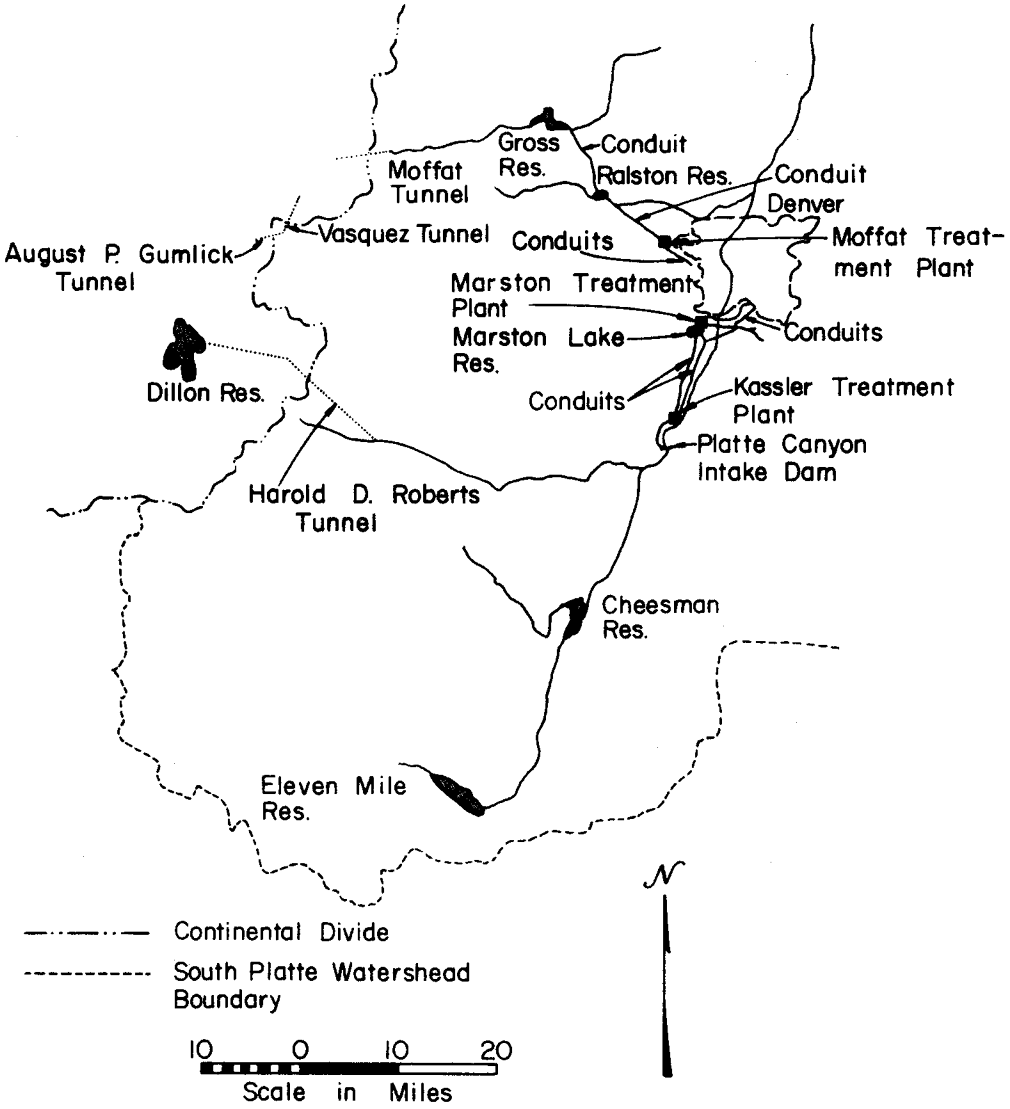

Figure 6. Existing raw water treatment facilities for the Denver supply network (Denver Water Department, 1969).

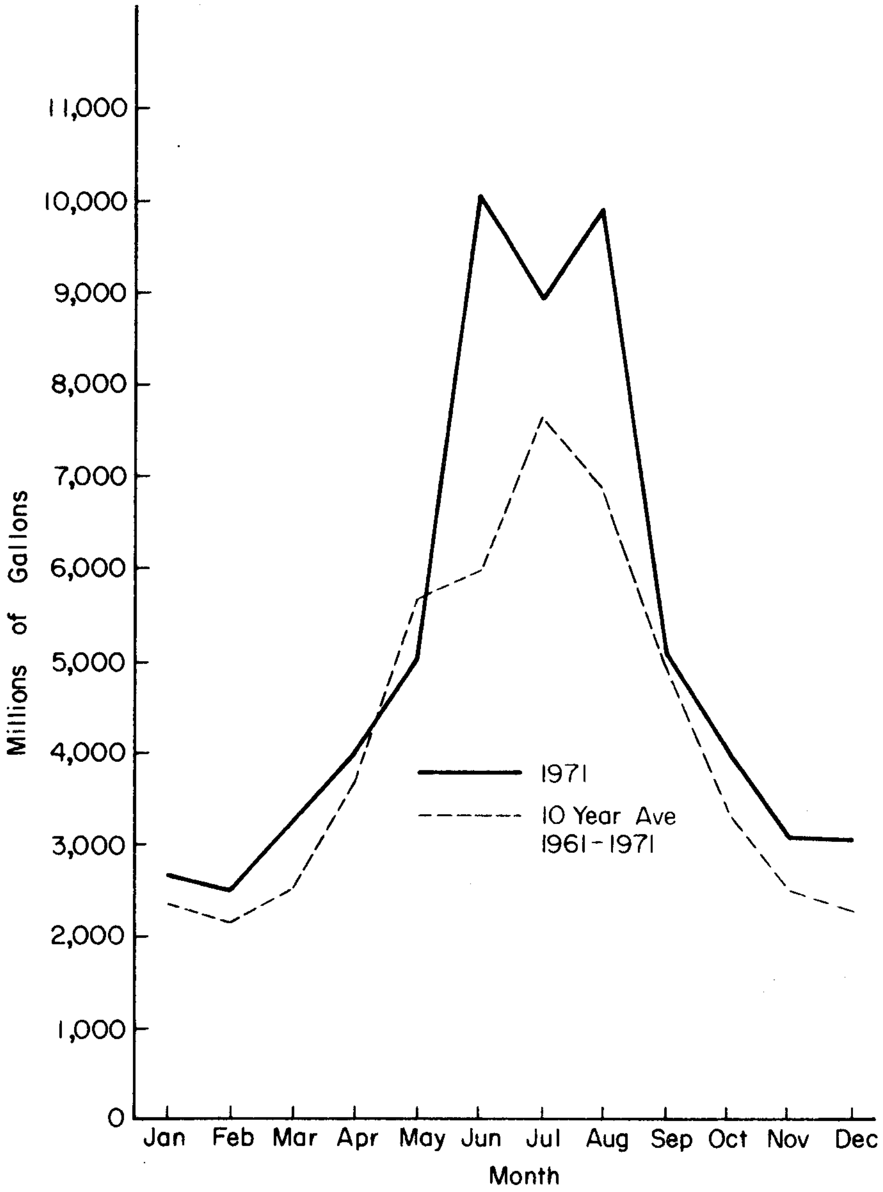

Figure 7. Monthly distribution of Denver water demands (Board of Water Commissioners, 1971).

the maximum day is divided by the average daily demands, the excess capacity factors for design of raw water treatment can be determined. This ratio during the 1970 water year was approximately 2.6. According to the Denver Water Board (1969), nearly 40% of the urban water supply was used for the municipal type demand, which verifies the cause of peaking in the hot summer months.

Although the actual per capita water use in the Denver area is close to 60 gallons per day, the total consumption divided by the population shows a steadily increasing rate. During 1971 it was on the order of 200 gpd. The reasons for these high consumption rates are explained by Denver water planners as increased industrial activity, expanding area, and a more affluent population.

Wastewater Collection and Treatment

The collection and treatment of wastewater in the Denver metropolitan area is presently unable to achieve the level of water quality control set forth by state and federal regulatory agencies (U.S. Environmental Protection Agency, 1972). The present system, shown in Figure 8, consists of fifteen major treatment systems serving more than 800,000 people and numerous industrial enterprises. Of this system, nearly 85% is served by the combined facilities of the North Denver Wastewater Treatment Plant (primary only), and the Metropolitan Denver Sewage Disposal

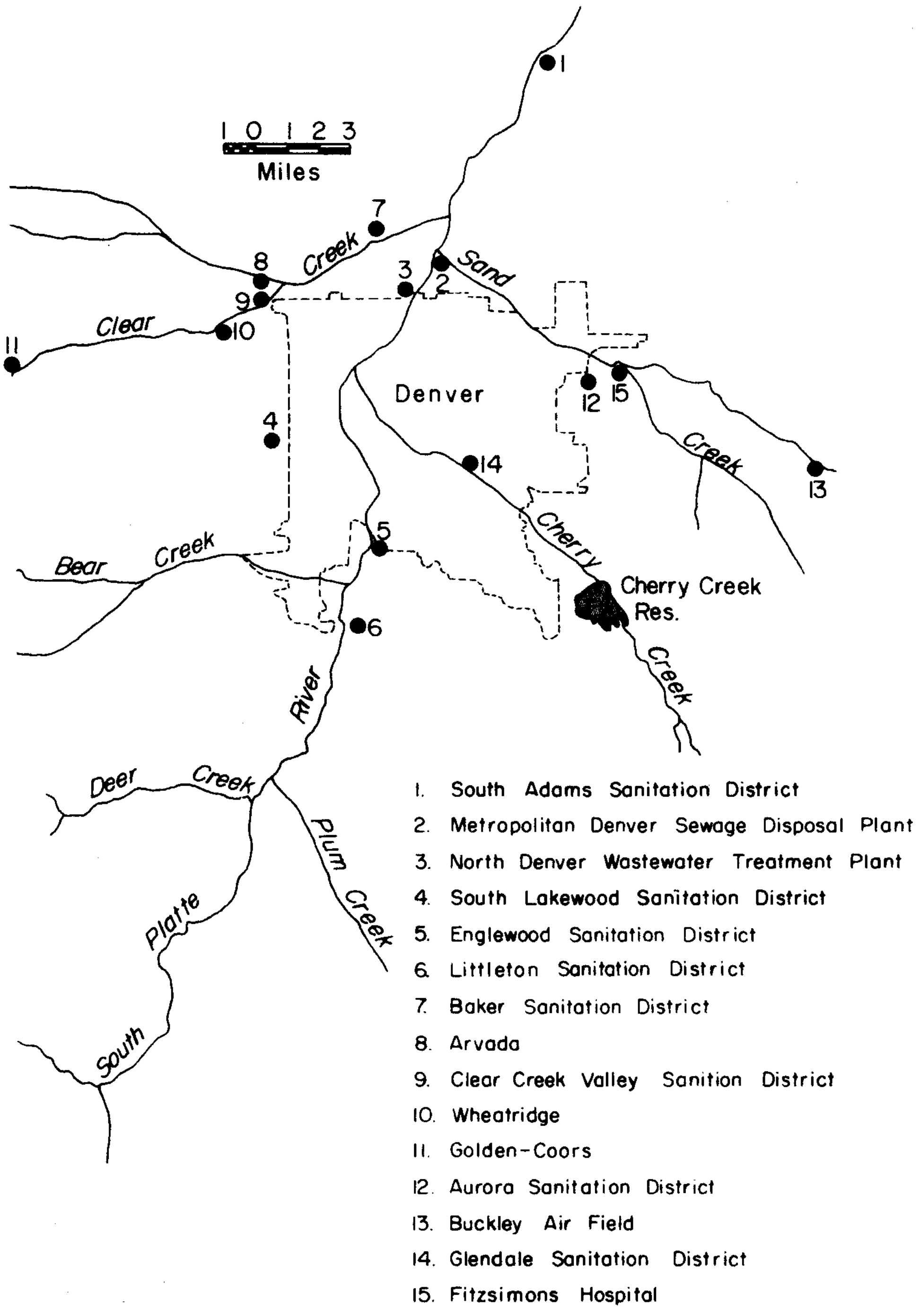

Figure 8. Municipal wastewater treatment facilities in the Denver area (U.S. Environmental Protection Agency, 1972).

District Plant #1. Consequently, the description presented herein can be limited to the flows at these two locations.

Prior to the completion of the metro plant, the majority of the flows were subjected to only primary treatment. As a result, the South Platte River in the Denver area was severely polluted and steps to alleviate this condition were investigated. During three study periods extending from August of 1964 to October of 1965, this reach of the river system was extensively examined by the South Platte River Basin Project of the Federal Water Pollution Control Administration (U.S. Environmental Protection Agency, 1972). The results indicated that the quality deterioration occurring through the city area in terms of dissolved oxygen ranged from 6-10 mg/l at the 19th Street station to 1-3 mg/l at York Street, to 0.2-4 mg/l at the vicinity of 88th Avenue. BOD concentrations increased from 10-20 mg/l at the 19th Street sampling point to 45-170 mg/l at the downstream locations. In addition, the density of fecal coliform bacteria was extremely high, exceeding one million organisms/100 ml at both York Street and 88th Avenue (Federal Water Pollution Control Administration, 1966).

As a result of these studies, recommendations were made to state and local authorities. The Colorado Water Pollution Control Commission in compliance with Public Law 84-660, Federal Water Pollution Control Act, submitted stream standards and classified the flows in the South Platte River accordingly.

During the August-December period of 1971, the personnel of the Environmental Protection Agency conducted additional water quality investigations in the South Platte River Basin (U.S. Environmental Protection Agency, 1972). These studies not only included the stream surveys as in the previous studies, but also an in-plant survey of the Metropolitan Denver Sewage Disposal District Plant #1, the North Denver Wastewater Treatment Plant, and nine of the satellite plants shown in Figure 8. The purpose of this follow-up investigation was primarily to evaluate the success of the abatement efforts to that date. Some of the important conclusions reached included:

(1) The North Denver Treatment Plant had BOD removal efficiencies ranging from minus 11 percent to 58 percent, but according to plant records, average between 22 and 36 percent. Because the sewage collection system is also a storm water drainage network, high flows of raw sewage are occasionally spilled directly into the river. In addition, the periods of poor removal efficiencies cause difficulties such as overloading in the secondary treatment facilities of the metro plant.

(2) The metro plant, overloaded both hydraulically and organically with peak flows exceeding the design capacity by 60 mgd and the organic loading by 10 percent. Four of the twelve aeration bases are being used for sludge digestion.

(3) Adequate treatment was not being provided by the metro plant for BOD, resulting in an average discharge of about 30,200 lb/day. Including the removal of the North Denver facility, BOD removals for the metro plant ranged from 63 percent to 96 percent on a daily average and were below the state requirement of 80 percent BOD removal 20 percent of the time.

Improvements are continually underway to reduce the contaminants contained in the effluents from this urban area. From the first sanitation district, called the 16th Street Sanitation District in 1882, to the metro concept of the 1970's, wastewater treatment has been among the goals of the Denver area. Current conditions have been defined by Henningson, Durham, and Richardson (1970), and reviewed by Alexander Potter Associates (1970). Data collected by these investigators, as well as reports on plant loadings by the U.S. Environmental Protection Agency (1972) and the Metropolitan Sewage Disposal District #1, are summarized in Table 1 to indicate the presently encountered wastewater conditions in the Denver area.

Table 1. Wastewater characteristics of the Denver metropolitan area.

	Influent	Effluent
North Denver Wastewater Treatment Plant		
Average Daily Flows, mgd	85	-
Peak Daily Flows, mgd	153	-
Average Daily BOD, mg/l	270	180
Average Daily Suspended Solids, mg/l	260	150
Average Daily TDS, mg/l	-	-
Metropolitan Sewage Disposal District #1		
Primary Treatment		
Average Daily Flows, mgd	22	-
Peak Daily Flows, mgd	41	-
Average Daily BOD, mg/l	460	350
Average Daily Suspended Solids, mg/l	420	160
Average Daily TDS, mg/l	-	-
Metropolitan Sewage Disposal District #1		
Secondary Treatment		
Average Daily Flows, mgd	107	-
Peak Daily Flows, mgd	190	-
Average Daily BOD, mg/l	214	31
Average Daily Suspended Solids, mg/l	152	56
Average Daily TDS, mg/l	739	739

Future Developments

Although the future is completely unknown, it is nevertheless necessary to plan the future delivery of goods and services in order to insure their availability. Since many variables influence the outcome of future events, the planning process is forced to rely on extensions of past experience. Such a basis for prediction has been repeatedly demonstrated as ineffective in dynamic societies, but no better alternative is currently available.

Urban water planners are faced with a dangerous task. Because of the institutional constraints, the time between project conception and water delivery may be as much as 30-50 years for many large projects. In such cases, the designs must be based on 50 year demand projections which are difficult if not impossible to formulate. In addition, the question of whether it is more desirable to emphasize current needs rather than future conditions nearly always arises. A good example is the political and economic philosophy regarding interest or discount rates in project feasibility evaluations. Consequently, the urban water planner is charged with meeting a demand at the end of the planning horizon, at minimum cost (political, social, economic), subject to the restrictions of an immense administrative structure. Some of the expected conditions in the Denver area are discussed below.

The most commonly used tool in projecting the aggregate demand is the per capita consumption. Since the principal variable in the demand function is population, total demands can be shown to be related to the population. The metropolitan area population can be delineated as shown in Figure 9. Based on historical data, per capita consumption can be projected as illustrated in Figure 10.

Another important consideration in facility planning is the hourly, daily, and monthly demand characteristic. System storage allows treatment plant capacities to be designed on maximum day requirements. The nature of the Denver demands are shown in Figure 11. It is interesting to note the widening gap between maximum day and average day demands. This condition places particular emphasis on careful planning since the construction costs for these treatment facilities are high.

Water Supplies

The future water supplies for the region will be supplied from the present sources. Better storage management and gradual acquisition of in-basin water rights will expand the South Platte supply from the 80,000 - 90,000 acre-feet presently to 110,000 acre-feet in 1990 and 121,000 acre-feet in 2010. Of course, these figures are based on the safe annual yield concept which tends to be conservative (Denver Water Department, 1969).

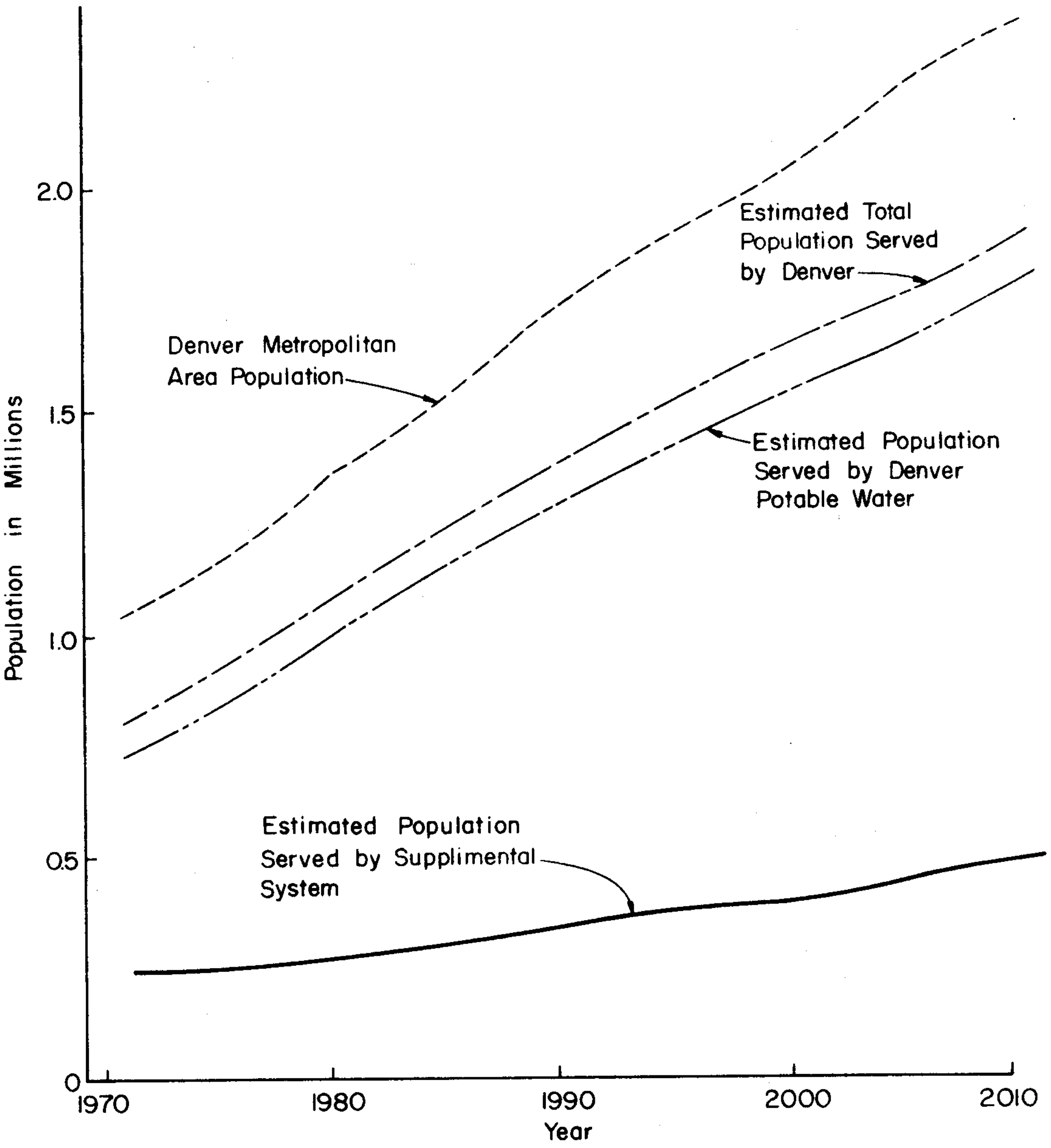

Figure 9. Denver metropolitan area population trends (Board of Water Commissioners, 1972).

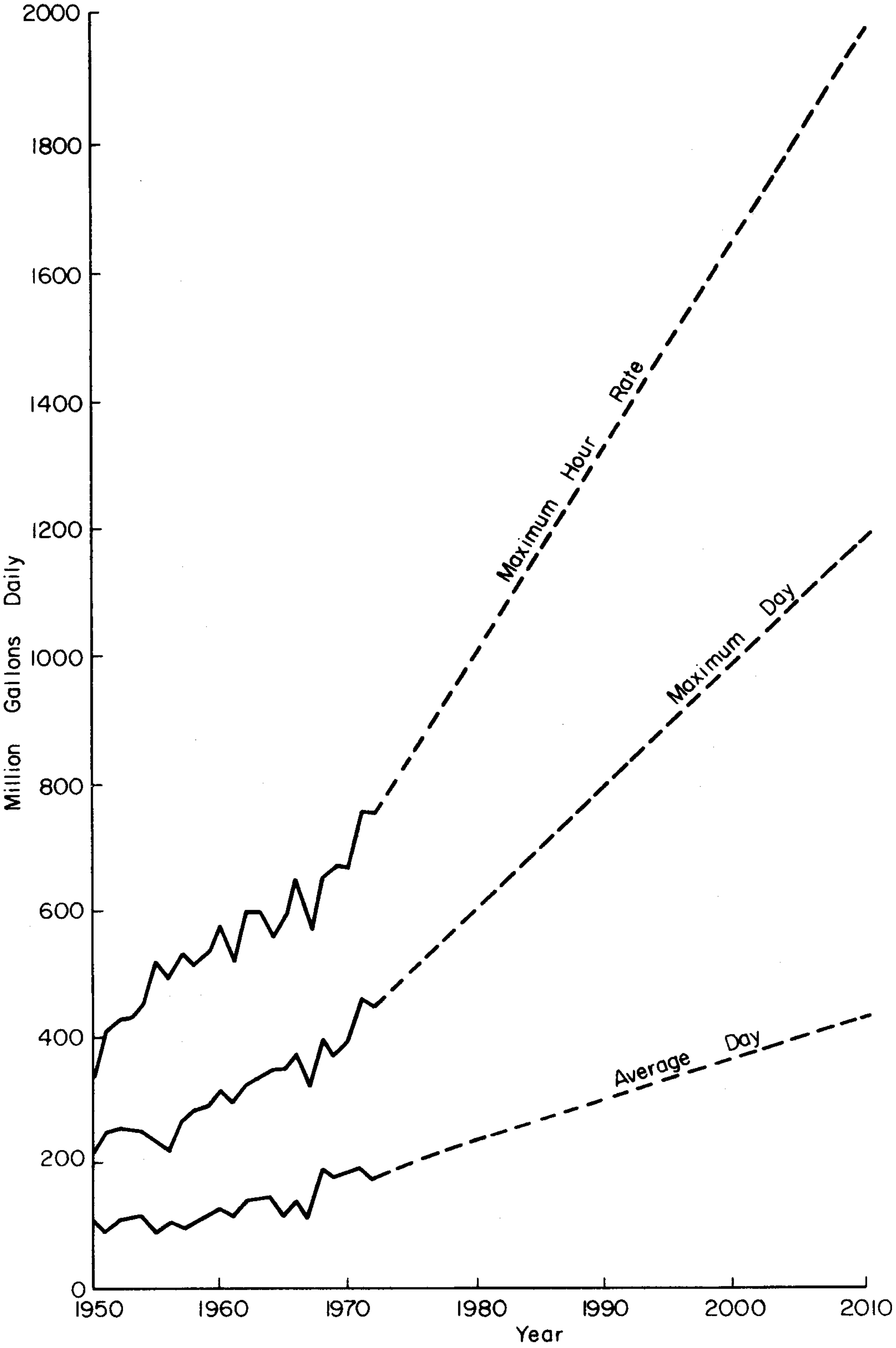

Figure 10. Historical and projected per capita water consumption in Denver (Board of Water Commissioners, 1972).

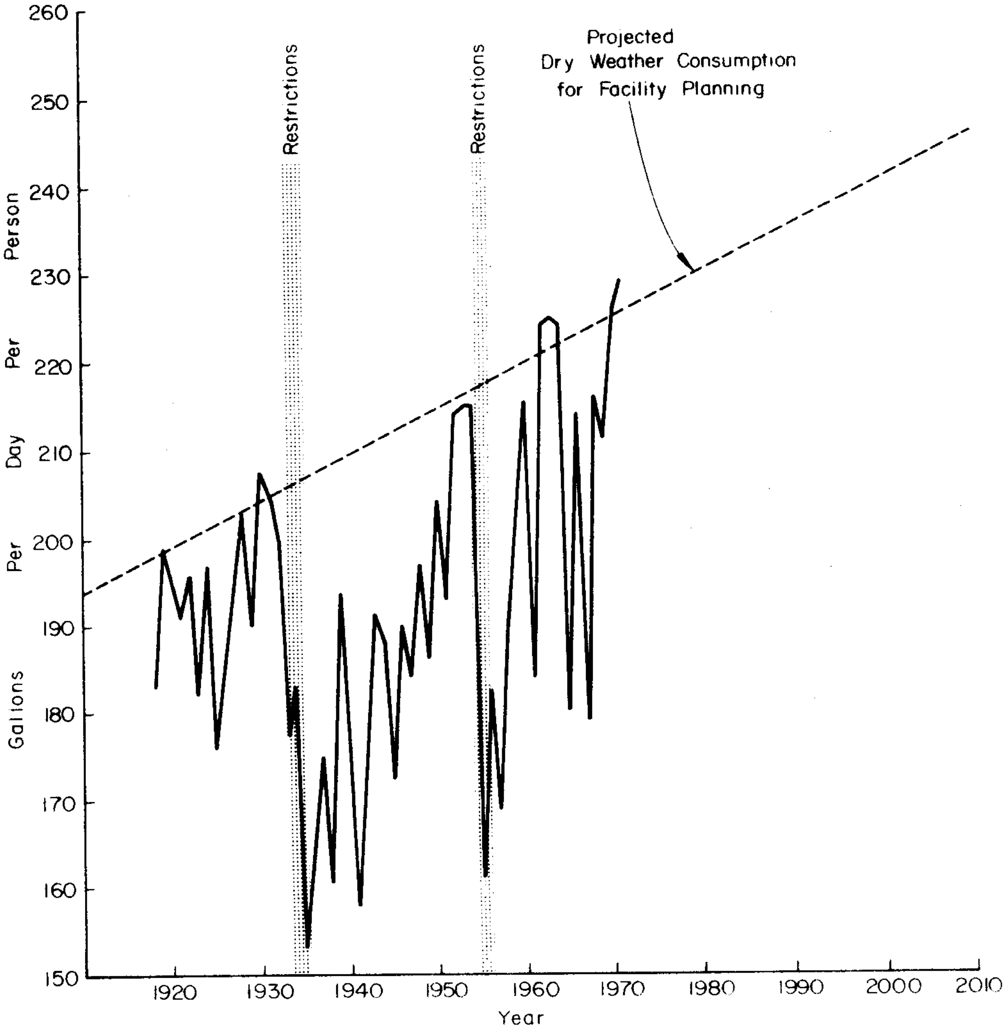

Figure 11. Denver's treated water demand characteristics, historical and future (Board of Water Commissioners, 1972).

The Moffat system is expected to be increased from present capacity of 70,000 acre-feet to 122,000 acre-feet in 1990 and 136,000 acre-feet in 2010. However, these expansions, along with the doubling of the Blue network, will require large capital outlays for new construction. Supply costs in present-worth form are listed at $750 per acre-foot (Denver Water Department, 1969).

Water Quality Management

There seems to be little doubt that more stringent water quality controls will be required in the immediate future. Recent Federal legislation has adopted the tentative philosophy of zero pollutant discharge, but the ability of regulatory agencies to accomplish such comprehensive controls remains to be seen. State pollution control agencies are also formulating schedules for increasingly rigid effluent standards.

Except for agricultural return flows, water quality management has been primarily concerned with organic pollutants. However, the most serious water contaminant may very well be the concentrations of dissolved solids, or salinity. All water uses in which water is consumptively used concentrate these salts, but some uses such as agriculture and urban uses add additional salts to the system. As a result, TDS standards may be expected to be imposed in the near future as well.

SECTION III

INSTITUTIONAL ARRANGEMENTS FOR WATER MANAGEMENT IN THE DENVER AREA

Introduction

Institutions are significant factors affecting water use in the Denver area. An institution may be defined as "well established social structures within which men do collectively the things which seem right and proper, in regard to some fundamental interest in life" (Renne, 1947). The fundamental interest here is water management and its related institutions. These institutions include such diverse topics as government programs, water rights, commodity markets, water districts, and traditional farming methods. These institutions are the product of political acts, customs, court decisions, common law, tradition, and other social phenomena. The institutions are complex and they tend to be lasting and inflexible. However, since they are created by man, they can be altered to meet changing needs (Trock, 1972).

In order to be able to effect a change in the institutions, they must be understood as to their nature and influence. The mechanisms by which they control and direct resources, water resources in this case, must be delineated so that change can be made. In order to know the type and direction this change should take, it is necessary that the effects of various institutional arrangements be quantified. Only after quantification can the consequences of various changes be known to the decision maker and he must have this information if he is to make rational decisions.

Historical Development

Over the years, water quantity and quality institutions have evolved separately. However, with increased use of water resources, optimization of management will dictate a unified management program. For purposes of a historical review, however, it will be best to discuss quantity and quality institutions separately.

Water Quantity Institutions

Water quantity management institutions beyond the point of diversion can be divided into two general categories: (1) those organized for irrigation water quantity management, and (2) those organized for domestic and municipal water quantity management. Each system is based upon the water right, which is the primary allocation tool under the prior appropriation doctrine. The concepts and rules of this doctrine dictate how water in the western United States is allocated and distributed. Before discussing the two categories of institutions, the basis of these institutions--the water right and its allocation procedure--must be completely understood.

Water Rights. The prior appropriation doctrine was developed during the mid-1800's as a solution to then current conflicts arising among those competing for available stream flows. Over the years, few changes have occurred in the substantive or procedural aspects of the law, resulting in the application of a 19th century legal arrangement to 20th century problems. The added problem of water quality not being included in the appropriation doctrine further complicates attempts to establish water quality management strategies (Radosevich, 1972).

Under Colorado law this doctrine states: (1) water in its natural course is the property of the public, and is not subject to private ownership; (2) a vested right to use the water may be acquired by appropriation and application to beneficial use; (3) the first person in time to use the water is first in right; and (4) beneficial use is the basis, the measure, and the limit of the right (Colorado Water Pollution Control Commission, 1967).

There are certain preferences in use of water under Prior Appropriation as stated in the Colorado Constitution. It states in Section 6, Article XVI, that:

> The right to divert the unappropriated waters of any natural stream to beneficial use shall never be denied. Priority of appropriation shall give the better right as between those using the water for the same purpose; but when the waters of any natural stream are not sufficient for the service of all those desiring the use of the same, those using the water for domestic purposes shall have the preference over those claiming for any other purpose and those using the water for agricultural purposes shall have preference over those using the same for manufacturing purposes.

From the above, it can be seen that an individual does not actually own the water, but he has the right to take from the source of supply, sufficient water to meet his daily needs. "Sufficient" depends upon the limit of his decree.

In Colorado, the system employed to direct public waters to private beneficial use evolves through district court issuance of decrees which give the authority to private persons to develop property rights in water. This involves a hopeful water user bringing a private suit in the appropriate district court in which he requests the privilege of using waters of a given stream in a specific amount, in a specific use, and at a specific time. The petitioner is to furnish evidence that there is unappropriated water available and that it will be put to beneficial use. The petition is advertised in the state, so that protesting parties may be heard in the district court. Water transfers (change use of water or when a potential new user requires a change in point of diversion) are handled by the same process (Hartman and Seastone, 1970).

The district court is to determine: (1) whether unappropriated water exists; (2) if the petitioner will put the water to beneficial use; and (3) if a water transfer is involved, if the change in point of diversion will be a detriment to established water rights. Once a decree is granted by the court, it is administered by a county water commissioner. He insures that the water is delivered according to the court decrees (Hartman and Seastone, 1970). For a more detailed discussion of water rights, see the Denver Law Journal (1970). The Journal discusses the acquisition, exercise, legal control, legal extent, protection, administration, and adjudication of a water right in a very readable manner.

Water Right Regulating Institutions. Around the water right concept, an institutional (administrative) hierarchy has been established to supervise the management of appropriated water.

In Colorado, water quantity regulation at the point of diversion is handled by a system of state, regional, and local organizations. At the local level, the governor appoints a water commissioner (from several recommended by the boards of county commissioners involved), who physically allocates water according to district court decrees. The jurisdiction of the water commissioner is designated a water district of which there are currently 80 in Colorado. (These "districts" are not to be confused with water supply districts.) The water districts follow drainage basin lines and the water commissioners are vested with the powers of constables (Cox, 1967).

At the regional or river basin level, Colorado is divided into seven water divisions, each of which contains a number of water districts. The division jurisdictions follow the major river drainage basins in the state. A division engineer, appointed by the governor, is administratively responsible for executing the laws of the state in his region.

At the state level, the state engineer is responsible for administering the appropriated water rights of Colorado. He is appointed by the governor and has supervisory control over the division engineers.

Beyond the point of diversion, another institutional situation exists. As noted earlier, there are two broad categories of institutions existing at this point: (1) those organized primarily for irrigation purposes and (2) those organized primarily for domestic and municipal water supply. The main purpose of these institutions is to distribute water among the individual water right holders (Denver Law Journal, 1970). In the initial development of water in Colorado, water deliveries were the concern of the individual water right owner. However, as the demand for water increased, these individuals banded together to form ditch, canal, or irrigation companies (Primarily distributing water for irrigation purposes) or water supply districts (primarily distributing water for domestic or municipal purposes).

The water conservancy district came on the scene in Colorado during the severe drought in the 1930's. Its main purpose is to serve as a public agency through which individual and corporate water users could contract to repay the federal government for large water projects which increased the water supply of an area. Transmountain diversions have a high initial cost which preclude ditch companies or small water supply districts from sponsoring the project, thus the need for federal assistance. The Northern Colorado Water Conservancy District, whose purpose is to allocate water from the Bureau of Reclamation's Colorado-Big Thompson project, is a good example (Hartman and Seastone, 1970). Project water is then allocated to the ditch companies and water supply districts. In Colorado, Water User Associations have a combination of these responsibilities; they deliver water as a ditch company or a water supply district, but they also have the power to contract with the federal government to secure water.

To encourage water development and utilization by irrigation and municipal organizations formed under U.S. or Colorado laws, Colorado established the Water Conservation Board as an agency of the state. Its main purpose is one of assistance in development of water rather than in the actual distribution to individual water users. Beyond the Water Conservation Board, there are interstate compacts and international agreements, to which the Board has input, which determine the amount of water allocated to Colorado.

Since this report deals primarily with urban water systems, these will not be detailed. Since water is a scarce resource in the West, the description of an urban area's potential water supply cannot overlook the water currently used for irrigation purposes. The institutions for delivery of irrigation water may greatly influence the institutions for delivery of domestic or municipal water.

Water Supply Institutional Types Pertinent to Denver Area. There are several statutes which authorize the formation of water supply districts in Colorado for purposes of domestic or municipal use. These are briefly detailed below.

1. Domestic Waterworks Act of 1905: This act allows cities over 10,000 population to form domestic waterworks districts (CRS, 1963, Chapter 89, Article 7).
2. Domestic Waterworks Act of 1913: This legislation permits the formation of domestic waterworks districts in unincorporated areas (CRS, 1963, Chapter 89, Article 1).
3. The 1939-49 Water and Sanitation District Act: This legislation authorizes the formation of water supply districts, sanitation districts, or a combination of the two (CRS, 1963, Chapter 89, Article 5).
4. Metropolitan Districts Act of 1947: This permits the formation of districts to do one of several functions - water supply, sanitation, fire protection, street improvement, police protection, etc. (CRS, 1963, Chapter 89, Article 3).
5. Metropolitan Water District Act of 1955: This act permits two or more municipalities to form a

metropolitan water district (CRS, 1963, Chapter 89, Article 12).

6. <u>Moffat Tunnel Improvement District</u>: An Act to set up a special district for the purpose of providing transportation and a tunnel (to carry water) through the Continental Divide (Cox, 1967 and CRS, 1963, Chapter 89, Article 1).

The 1939-49 Water and Sanitation Act is used most often in establishing a water supply district. All the above Acts have specific ways and means of organizing and operating the established district. The different laws tend to compound the complexity of the governmental framework established to supply water. In 1969, the Denver metro area contained 23 agencies supplying water and nearly 200 participating in the distribution of water (Denver Regional Council of Governments, 1969). Not all of these agencies are of the type of districts described above.

In Colorado, the responsibility of supplying water to most incorporated areas rests with the municipality. Many of these municipalities supply water beyond their boundaries, thus the large number of distribution agencies as compared to supply agencies in the Denver area.

The powers of a municipality with respect to water in Colorado varies with the type of city involved. There are three categories: (1) general law cities and towns, (2) home rule cities, and (3) cities over 200,000 in population. Legislatively, general law municipalities are given the authority to purchase and operate canals as a means of supplying water to its inhabitants upon an affirmative vote of the taxpaying electorate. They may also purchase water rights, but this does not require a vote of the people. Water rights may also be obtained by condemnation. As with irrigation, municipalities are required to put the appropriated water to a beneficial use (Cox, 1967).

In addition to purchasing or erecting a waterworks, upon a favorable vote of the people, general law towns and cities may grant a franchise to a private company to supply water to all or part of the city or town. This does not preclude the city or town from erecting its own system or condemning the private company for public purposes at a later date. These municipalities may also supply water to customers outside the corporate limits of the municipal corporation under such conditions as the city or town may enact by ordinance (Cox, 1967).

Home rule cities authority over water supply depends upon the particular powers granted by their charter. In general, the powers of the home rule city are similar to those of the general law cities and towns except for one major difference: home-rule municipalities can purchase or erect waterworks without an affirmative vote of the taxpaying electorate. The charter itself determines many of the specific powers of the home-rule city (Cox, 1967).

For cities over 200,000 population, Colorado law excludes the requirement that water must be put to a beneficial use before an appropriation is perfected. This provision permits the City and County of Denver (the only city in Colorado over 200,000 population) to store water for future use. This provision is designed to allow Denver to obtain water for its projected growth (Cox, 1967). For a more detailed discussion of city classification and definition, see Bernard (1970) and Banks (1971).

As noted earlier, water service has been extended beyond corporate boundaries. This is done many times as a means of insuring annexation of these unincorporated areas to the municipality supplying the water. Until the <u>Municipal Annexation Law of 1965</u>, the use of water service to induce annexation was carried on in a extra-legal manner. In addition to municipalities supplying water beyond their boundaries, it is also possible for water supply districts to supply water to a town or small city. This permits a very complex set of water supply arrangements to form over the years, and, apparently, the state presently has little control over the situation according to the following quote from Cox (1967).

> . . . the Colorado Public Utilities Commission, or any other state regulatory body has no jurisdiction over the operation of municipally owned utilities, insofar as they provide service within their corporate limits. However, a dichotomy exists between municipally owned electric utilities and municipally owned water utilities, insofar as they provide service outside their corporate limits. The Public Utilities Commission has jurisdiction concerning

> the extraterritorial operation of municipally owned electric utilities, but not with respect to the operation of municipally owned water utilities.
>
> Colorado law thus extends a wide range of powers and a great deal of independence to municipalities in connection with the operation of water supply systems. In addition to providing an essential governmental service, a municipally owned water utility can produce considerable revenue for the city, and it may be used to complement the municipality's annexation policy.

Municipal Acquisition of Water Rights for Water Supply. There are basically four means by which the above described municipal water supply institutions can obtain water to meet increasing urban water needs: (1) Filing for a water right on unappropriated water in the river basin of the municipality; (2) Transferring appropriated water to municipal use in the river basin of the municipality; (3) Filing for and/or transferring water rights to the municipality in a river basin other than that of the municipality's location (interbasin transfer of water); and (4) Recycling water which has already been used by the municipality. Groundwater wells are not considered as a means of increasing municipal water supply in the Denver area because of the volumes required and potential pollution. Currently, the Denver area has a safe annual yield of 429,000 acre-feet, of which only 7,000 comes from wells, and it has been noted that "groundwater is not anticipated to be a major additional source of water" (Denver Regional Council of Governments, 1969).

The main purpose for filing a water right is to notify affected parties of an intended appropriation. This permits the adjudication of any problems that may arise with respect to effects upon other water rights. Once a date of priority has been established, the water right must be developed and the water put to beneficial use before the appropriation is perfected. If this is not done with due diligence, the water right is forfeited.

The transfer of water use can occur in both location of use and character of use as long as the transfer does not injure the vested rights of senior and junior water users. The burden of proof that no injury will occur rests with the person making the change. The recognized rule in this regard is that a junior right water user is entitled to have the conditions continued and maintained that existed on the stream when he obtained his right. The court decides whether a change is to be allowed (Cox, 1967). There is a large amount of uncertainty involved when a transfer is considered by the courts. The problem stems from court attempts to quantify water rights. This problem is pointed out very well by Hartman and Seastone (1970) in the following quote.

> Consider the impact of this uncertainty, for purposes of illustration, upon municipal agencies whose function is to project water supplies and requirements into the future. The obvious case in point in Colorado is the city of Denver. With more than 600,000 water users and with projected users in excess of one million before the end of the century, Denver has had to plan for a large expansion of its water supply. Looking back at its

> unpredictable and uneven success in being allowed to change points of diversion along the South Platte River, its historical water source, Denver has long since decided to seek water elsewhere and under different procedures. In the nine transfer cases brought by Denver from 1925 to 1934, to transfer 396.80 second-feet of water, only 77.39 second-feet were transferred, more than half of it in a single case. Denver has not only turned to transfers of water from the western slope of the continental divide but has also followed a policy of buying irrigation water without using the water directly.
>
> A further examination of transfer decrees, as recorded in the State Engineer's office, reveals that only 33 municipal transfer cases, other than those for Denver, have been successfully completed. These 33 cases involved the transfer of approximately 122 second-feet from agriculture to municipal use. Of these transfers only nine have occurred since 1930.
>
> In short, the process of water transfer in Colorado makes no provision for continuing survey and adjudication processes which attempt to provide information on the current allocative patterns of water use. In place of a continuing, state-supported hydrographic survey, Colorado employs an ad hoc, case-by-case court procedure for determining current water use patterns. The result is continuing uncertainty and confusion in the use and development of water resources.

Transmountain water diversions (inter-basin transfers), when it is possible to obtain the water rights, have proved most successful in augmenting the water supply of the Denver area in recent years. The right to divert water from one basin to another has been established in the Colorado courts; however, it is doubtful that any transmountain diversion will take place without considerable protests by people in the basin losing the water. These protests occur due to the fact that a very scarce resource is being allocated. More specifically, Denver and other cities along the eastern edge of the Rockies believe that their use of water for municipal purposes should have precedence over the use of water for agricultural purposes on the western slope. However, western slope interests feel that when the energy resources are developed in their area, they will need the water for municipal and industrial purposes. By losing the water now, development is precluded. The eastern slope says the water is needed now on their side of the mountains and they should not be denied its use (Cox, 1967).

The major tool which is utilized as a means of preventing the loss of water by western slope interests is the water right and particularly the priority of the rights on Colorado River water. An excellent example of the controversy and its complexity can be seen by reviewing the Green Mountain Reservoir problem. Cox (1967) presents an excellent review of the legal battles and maneuvering associated with this particular problem.

Recycling of wastewater to meet a growing water demand in the Denver area has received increased interest in the past few years. The technology of wastewater renovation for recycling is relatively new and has not been used to develop water for actual potable consumption in this country. Systems which would completely renovate wastewater for recycling purposes are available, but they do not appear to be economically competitive with conventional sources and treatment. There is currently much work in the area of wastewater renovation and within a few years, recycling may prove to be economically competitive. Koening (1972) illustrates this point very clearly for the San Antonio area for the year 2000.

Public acceptance and appropriated water rights on the wastewater are two additional problems that must be faced when recycling is considered. Bruvold (1972) has studied the problem of public attitudes and found that the preceived water supply situation affects attitude. Where water is scarce there is more acceptance. This indicates that water reuse may not be implemented as a potable water supply until a critical situation forces its acceptance.

Denver has just recently received a favorable court opinion on its use of 50% of its transmountain diversion for recycling purposes. In-basin wastewater from Denver which is returned to the South Platte River, is needed to satisfy existing water rights and is therefore not available for recycling.

Water Quality Institutions

The institutions established to deal with water pollution in Colorado have evolved from many sources. As is the case with many states, health considerations were the first major concern. This resulted in the formation of sanitation districts and municipal sewage systems. As time passed, the treatment facilities of these districts and municipal systems and industrial systems stretched the streams assimilative capacity and indicated the need for comprehensive water quality management institutions. It is the larger (federal and state) institutions that have the largest impact, and which will now be reviewed. These institutions are concerned with navigation, odors, fish and wildlife, oil pollution and aesthetics, as well as health.

Federal Activities. For a long period of time, the Federal Government has been the initiating legal backbone to environmental protection and water pollution control in the United States. Through a long and complex involvement with environmental problems of various forms, the congressional, executive and judiciary branches of government have evolved an increasingly ubiquitous system of legislation and institutions.

The Federal action has resulted in a series of Acts that began in 1899. For the sake of comparison, the intent and policy of water pollution legislation through 1972 is listed below.

River and Harbor Act of 1899 - Established the unlawfulness of discharging any refuse matter into any navigable water in the United States.

Oil Pollution Act of 1924 - Protects navigation from obstruction and injury by preventing the discharge of oil into the coastal navigable waters of the United States.

Water Pollution Control Act of 1948 - Establishes the policy of the Congress to preserve states' rights and prevent pollution of water bodies primarily for health protection. Also established the format of the enforcement conference procedure.

Water Pollution Control Act Extension of 1952 and Water Pollution Control Act Amendments of 1956 - Extends and reiterates Congress' stand on protecting states' rights with financial aid for reserach again primarily directed toward health hazards.

Federal Water Pollution Control Act of 1961 - Broadens the scope of water pollution control to include projects for water storage, suggesting a trend to the "multi-purpose" philosophy. Also, opens the door for cooperative Federal-State investigations.

The Oil Pollution Act of 1961 and Amendments to the Oil Pollution Act of 1961 - Extends the oil pollution policy to international waters.

Federal Water Pollution Control Act of 1965 - Dissolves the states' autonomy in dealing with pollution problems and establishes a national policy for pollution abatement within the states for aesthetic and health reasons. Requires state adoption of water quality criteria and plans of implementation and enforcement subject to Federal approval.

The Clean Waters Restoration Act of 1966 - Extends and improves the 1965 Act and also lifts the ceiling on grants for water pollution control projects.

The Environmental Policy Act of 1969 - Initiated machinery for dealing with a number of environmental questions, including water pollution. Required Federal agencies to make detailed environmental impact statements on all projects. Established the Council on Environmental Quality to act in an advisory capacity to the President on formation of national environmental policy.

Water Quality Improvement Act of 1970 - Title I and Environmental Quality Act of 1970 - Title II -- Title I prescribes in considerable detail a management scheme for oil and mine acid waste pollution. Title II created a supporting staff and funding for a new Office of Environmental Quality.

Federal Water Pollution Control Act Amendemnts of 1972 - Establishes the legal basis for a permit system and appropriates large sums of money for wastewater treatment plant construction.

The most significant Acts are those of 1948 and 1956 which established the enforcement conference procedure, the Act of 1965 which created a national water quality control policy, and the 1972 Act which establishes effluent controls as opposed to in-stream control. The 1972 Act is currently being implemented and it is difficult to evaluate its effect upon water quality management; therefore, it will not be discussed in detail.

Public Law 80-845, the 1948 Act, gave authority for water pollution control activities to the Public Health Service. The Surgeon General was authorized to develop a comprehensive program for eliminating or reducing pollution of interstate waters. The expressed purpose of abating pollution is to reduce health hazards connected with impure water.

Provisions were made for the establishment of a Water Pollution Advisory Board to guide the institutional implementation of the law. Provisions for pollution abatement action initiation at the Federal level had to have the consent of the state or interstate agencies involved, but apparently this procedure was not used until after 1956. In the Act, the Surgeon General was directed to encourage cooperation in and between states to adopt comprehensive programs for abatement of water pollution. The Federal function was to provide technical services at the request of states. For more details on the 1948 Act, refer to Nichols (1972).

Ineffectiveness of the 1948 Act was recognized in 1956 by the House Appropriations Committee who refused new funding to the Public Health Service for enforcement. A significant revision of the procedure for Federal participation in pollution problems was included in the 1956 Amendments. A statement was included as in 1948 to preserve states' rights. As with the 1948 Act, once a problem was identified the polluter was notified of the recommended remedial action to abate, but instead of waiting for compliance, the Surgeon General was directed to "call promptly a conference of the State water pollution control agencies and interstate agencies . . ." of the states affected by the pollution. Following the conference, the Surgeon General was to prepare a summary of the conference discussion, including a statement of the occurrence of pollution, the adequacy of measures taken toward abatement, and the nature of delays encountered in abating the pollution. The 1956 Act did not remove the requisite for state permission before court action. The conference, however, could be recommended at any time (Water Pollution Control Act Amendments of 1956, PL84-660).

The next major legislation at the Federal level is the Federal Water Pollution Control Act of 1965. First, water pollution control was placed under the jurisdiction of a new agency within HEW; the Federal Water Pollution Control Administration (FWPCA). Second, Federal policy was changed from careful protection of states' rights to using Federal legislation to force the states into considering, establishing, and implementing water pollution abatement plans, a point of great significance as evidenced by subsequent Colorado legislation. Previous water pollution acts were authorized only to encourage "cooperation among states" and "assist states in prevention and control."

The 1965 Act required the Governor of the state to file a letter of intent within one year after October 2, 1965, to adopt on or before June 30, 1967, water quality criteria to be applicable to interstate waters or portions thereof within the state and a plan for implementation and enforcement of those water quality criteria adopted. Upon approval of the Secretary of HEW, the criteria and plan then became the state's water quality standards. If the state did not develop these standards and submit the plan of implementation, the Secretary could then do so. Not only was the intent of the Act to prevent and control pollution as before, but also to enhance or actually improve water quality. This is the so-called "non-degradation" clause.

Contained in the 1965 Act were several significant points. Most significant of all perhaps is the fact that Congress required stream standards and not effluent standards. Each poses formidable technical and political problems for adoption, implementation, and enforcement (Nichols, Skogerboe, and Ward, 1972). The fact is, however, stream standards were required which in turn shaped the structure of water pollution control agencies in the states, as will be seen in Colorado.

The final major legislative action at the Federal level are the 1972 Amendments. As noted earlier, these are currently being implemented. As an indication of the impact this law may have, its opening statement is as follows: "It is the national goal that the discharge of pollutants into the navigable waters be eliminated by 1985."

The Act appropriates large sums of money for waste treatment plant construction. It also sets timetables for the establishment of water quality standards, performance standards and the issuance of discharge permits. The discharge permit program and regulatory functions are the states' responsibility.

Colorado Activities. Colorado has, for a long period of time, dealt with problems relating to water pollution primarily as a result of concern over health (see Colorado Department of Health, 1969, for a general history). Colorado law in the process delegated powers and jurisdiction to a number of entities concerned with water pollution control.

These laws, powers, and jurisdictions are reviewed in detail by Nichols (1972). Until 1965, Colorado had not been extremely active in water quality management except for the enforcement conference called in 1963 to look at water pollution problems in the South Platte River. A quote from the State Health Department (no date) explains the situation before 1966.

> Until recent years, both state and Federal water pollution control laws were weak, confused and ineffective. States have had water pollution control laws for years, but neither found it economically feasible to prosecute offending industries, nor politically expedient to crack down on polluting municipalities. Cities have applied political pressure against attempts by the states to force abatement.
>
> The authority for water pollution control in Colorado prior to 1966 was vested in several

> state agencies. The Colorado Department of Health had the authority for standards regarding discharges of human wastes. The State Department of Game, Fish and Parks enforced control of pollution causing damage to fish, spawning areas and aquatic life. The Oil and Gas Commission had the power to control pollution to waters resulting from oil and gas production. The laws gave pollution control powers to other state agencies and municipalities over special sources and areas. Water pollution control in Colorado, like that in many other states, suffered from divided authority and hard-to-enforce laws.

The rising crisis of polluted water in the 1950's and 1960's, especially within the South Platte Basin, showed that the State's ability to deal with pollution problems was weak. Population and industry were growing rapidly within the Basin and particularly in the Denver metropolitan region. The problems of waste disposal were becoming increasingly severe.

On July 18, 1963, Governor John Love of Colorado requested that an enforcement conference be called. The stated purpose of the study was to locate the sources of pollution having an adverse effect upon water quality; determine the physical, chemical and biological responses of the river to pollution; evaluate the previously located sources of pollution with respect to conditions in the river; compute the waste load reductions necessary to obtain desired water quality; and recommend water quality control measures needed to effect the desired waste load reduction.

Following the 1963 conference, a two and one-half year study was undertaken on the water pollution problems of the South Platte River Basin. The second session of the conference, on April 27 and 28, 1966, was called to consider the results of the investigations. A series of reports revealed the nature of water pollution in the Basin with great emphasis placed on problems of the Denver metropolitan area. The results of the study bore out Governor Love's concern for calling the conference in 1963.

Overall, the data for the Denver metropolitan area showed poor quality sewage treatment. Plants were frequently operating at capacity or were overloaded. Treatment was generally inefficient and provided low removal of BOD and TDS concentrations. High tonnages of these wastes were being dumped into receiving streams daily.

The interim period between the South Platte Conferences saw the Federal 1965 Water Quality Act come into existance. Colorado adopted legislation to comply with Federal law on March 1, 1966, just prior to the convening of the Second Conference in April. Because of the South Platte Conferences, Colorado had the strong advantage of an outstanding, detailed inventory and report of water quality conditions in the South Platte River, which were utilized primarily for establishing abatement schedules for polluters in the South Platte River Basin.

As was mentioned above, Colorado adopted legislation March 1, 1966, according to the Federal requirement for a plan of implementation and enforcement by the state. Within the new Colorado legislation was contained the establishment of the administrative body, the Water Pollution Control Commission. The first meeting of the Commission was held in conjunction with the April session of the Conference. In light of this fact, the conferees agreed to meet on November 10, 1966, to allow the new commission sufficient time to study and evaluate the Federal report, and develop a program for implementation of remedial measures and a time schedule in compliance with Federal requirements (Federal Water Pollution Control Administration [FWPCA], 1966).

The technical report presented to the conferees by the FWPCA's South Platte River Basin Project contained both general and specific recommendations for pollution abatement action, including appropriate time schedules for all major waste sources in the Denver metropolitan area, as well as for feedlot operations and the sugar beet industry throughout the basin (FWPCA, 1966).

Colorado's 1966 Act provides for basically two main aspects of the state's water pollution control organization. These are the Water Pollution Control Commission and the Division of Administration. The Commission has eleven members - four members represent state government agencies and seven are state citizens appointed by the Governor. The Commission is designated as the state water pollution control agency for Colorado for all purposes of the Federal Water Pollution Control Act as amended. The

Commission, therefore, not only has duties assigned to it by state law, but it is also required to carry out directives of the Federal law. Federal directives have included the establishment of stream criteria, development of an implementation plan to enforce criteria, initiation of a planning effort, and currently, the consideration of a permit system.

The Commission is required to hold quarterly meetings, but in actual practice it meets once-a-month. During these one-day meetings, the Commission discharges its duties and provides supervision and guidance to the Division of Administration. A point of clarification is needed here to distinguish between the Division of Administration (DOA) and the Water Pollution Control Division (WPCD).

The relation of WPCD to the DOA is not made clear in the law. Article 66-28 dealing with water pollution control makes no specifications of a particular Division under the DOA; therefore, it must be assumed from actual practice that the WPCD is the agent of the DOA in charge of water pollution control affairs.

While the activities and duties of the Commission are fairly clear in the law, the structure and functional duties assigned to the Division of Administration (Water Pollution Control Division) are, to a large extent, left to the Commission's desires and the existing nature of the Department of Health where the Division is housed.

As a result of the law, the Commission's supervision, and the Department of Health's nature, an organizational structure and functional assignments have been developed. These assignments and the structure serve to guide the Division in its everyday activities (Nichols, Skogerboe, and Ward, 1972).

The Division of Administration is shown to be responsible to the Water Pollution Control Commission, which in turn is basically appointed by the Governor. The Division of Administration is a division of the Colorado Department of Health and therefore, the administrative services of the department handle the budgetary and personnel activities of the Division. Budget requests to the Legislature are a part of the Department of Health's requests and once obtained, the funds are channeled through the Department's money management personnel. The Division, as a part of the Health Department, is also under the same personnel management scheme as the Department. The same job classifications and pay scales that apply to the Department also apply to the Division.

Beyond the organization of Colorado's water pollution control efforts are the actual activities required to satisfy the objectives of the law. In general terms, the Commission establishes policy and supervises the total water pollution control effort, while the WPCD primarily administers the overall effort. The WPCD administers loans and grants, while the Commission accepts and supervises. The WPCD is to develop comprehensive water pollution control programs, and the Commission is to adopt the program. The Commission has the authority to adopt water quality standards, and the WPCD is to administer the standards. This carries on for other activities.

Once Colorado had established (in conformance with Federal laws) its legislative and administrative base for water pollution control, it had to satisfy the additional Federal requirement of establishing stream criteria and a plan of enforcement. This constituted the first major administrative undertaking by the Water Pollution Control Commission.

The establishment of water quality criteria and a plan of implementation had to be accomplished by June 30, 1967, in order to meet the Congressional deadline. For clarity, streams and water bodies were divided into two groups and assigned classifications according to their use and condition. Group I described standards basic to all waters of Colorado. Group II established specific chemical criteria for the following uses:

1. Public Water Supply
2. Recreation Waters
    a. Fish and Wildlife
    b. Body Contact Sports
3. Industrial Water Supply
4. Agricultural Water Supply

These criteria are the basis upon which abatement schedules were then formulated. Abatement dates were set by the Department of Public Health by letters of request to known polluters. If no response was received, a second letter was mailed to request a proposed abatement schedule from the polluter. As a final step, the Health Department assigned an abatement date.

In an effort to trace violators of the standards, 70 surveillance stations were established throughout the state.

On June 12, 1967, the Commission arrived at specific classifications for the streams and tributaries in every basin throughout Colorado. The Commission attempted to provide for multiple use, and in general classified the South Platte as follows.

1. Public water supply and cold water fishery from its source to Waterton;
2. Public water supply and warm water fisheries to Englewood's Union Avenue treatment plant; and
3. Industrial and agricultural use from there to Nebraska State Line.

For purposes of further discussion of the results of administrative activities needed to satisfy legislative goals, the list of objectives developed by Ward (1971) will be used. He suggested that the objectives of a state water pollution control agency could be broken down into seven categories. These are planning, research, and aid programs, which can be associated with preventing water pollution; technical assistance, regulation, and legal enforcement, which can be grouped under abatement; and the seventh objective is data collection and dissemination, which is basically a support activity to the first six.

Colorado has no research effort and is just beginning a major emphasis upon planning. Aid programs have been pursued by the WPCD in a quite successful manner. Technical assistance is a description of work that the agency does with respect to the installation and inspection of sewage treatment facilities, site approvals, training of sewage treatment plant operators and the technical recommendations associated with eliminating stream standard violations. Regulation and legal enforcement are tied together in that, if through regulation stream standards cannot be maintained, then legal enforcement must be utilized.

Regulation or "enforcement" of stream standards in Colorado involves the following process. When the WPCD or a county health department finds a violation of stream standards, the first step is to endeavor to eliminate the alleged violations by "conference, conciliation, and persuasion." At this point, the WPCD utilizes much of the available technical assistance. If this tactic fails within a reasonable amount of time, a cease and desist order is issued by the Commission stating the problem and the time by which the problem must be corrected. If the violator so chooses, he may request a hearing on the order and the order is then stayed until the hearing is held. The results of the hearing can be either to withdraw the order or to uphold the order. If the order is upheld, the violator will then enter district court if he continues to violate stream standards, as the Commission will cause the district court to issue an injunction or restraining order against the violator. After a cease and desist order has been upheld and is not subject to a stay pending judicial review, the violator is subject to a fine of $2500 per day of continued violation.

Effects of Institutions on Future Water Management Decisions

The previous discussion has described the water quantity and quality institutions. The effects of the institutions must be quantified if rational decisions are to be made with regards to possible modifications which would help to achieve optimum utilization of water in an arid urban situation. The purpose of this discussion is to identify where institutional problems may exist. The problems will be quantified in a following section of the report.

Water Rights

Several problems associated with water rights have been alluded to previously. One of these is the problem of water right transfers and the attendant uncertainty that exists in Colorado. Hartman and Seastone (1970) list three dimensions of this uncertainty:

1. The inherent difficulties posed by the physical interrelatedness among water users;
2. The absense of continuing hydrographic survey and adjudication processes and the consequent lack of knowledge about the actual extent of consumptive use of water in a specified use; and
3. Lack of engineering data prepared by a professionally competent public agency during the course of transfer suits.

Much of the problem stems from the initial establishment of the water rights themselves. Radosevich (1972) notes that the administrative and adjudicative mechanism was in its infancy when confronted with the task of determining and awarding water rights to applicants. Adequate means of accurately measuring diversions did not exist or were not used in these early appropriations. As a result, the tabulation of water rights eventually far exceeded the actual stream flows. As this was occurring, appropriators were receiving valid water rights which may later be exercised to their full capacity if beneficial use could be shown. This difference between quantity decreed and available supply makes it extremely difficult, if not impossible, to effectively manage water at the state level. Also, it makes the water right transfer process complicated and very difficult to utilize as a means of achieving better water management. Grigg (1972) discusses the problem of water transfers as a legal constraint on water development in an arid urban area.

Another major water management problem with respect to water rights arises from the nature of the right itself. There is a fear of loss through abandonment or forfeiture if the right is not exercised. As a result, appropriators divert as much of their allotment as possible to protect their right. This results in an overapplication of water and a subsequent reduction in quantity flows. Another similar aspect of the water right is the need to secure it against claims that changes in practice result in changes in beneficial use. This tends to bind the exercise of the right to particular practices (Radosevich, 1972).

Water quality has never been an element of a water right under the appropriation system. This is due to the initial reason for formation of the appropriation system - to allocate a scarce resource. Thus, the water right specifies a quantity of water to be used within a given priority. Some cases have decided that an appropriator has a right to a usable quality of water, but these were primarily early decisions and their holdings are subject to question under revised and amended water codes (Radosevich, 1972).

Moving from the state level to the total picture of water quantity and quality management in the West, the water right problem becomes even larger. There are interstate compacts, judicial decisions, congressional allocations, and international agreements which further complicate the picture since many of these agreements have neglected water quality. Thus, the states are not sure of their obligations with respect to water rights on interstate streams.

In conclusion, the problems associated with water rights with respect to municipal acquisition, stem from a high degree of rigidity that has developed in the law of water rights. The rigidity, in turn, stems from physical externalities which pose complexities for a legal solution (Hartman and Seastone, 1970). The acquisition of data and information on the effects of water right transfers poses a technical and economic barrier to many municipalities who are trying to obtain additional municipal water supplies through acquisition of water rights.

Public Attitudes

Public attitudes are an important factor that must be considered by a municipality in its acquisition of water. This is especially true in the reuse of water as a means of augmenting supply and the environmental impact of further acquisition.

Reuse of reclaimed water can take many forms. Bruvold (1972) classified reuse possibilities into five categories: (1) Food production, (2) Recreation, (3) Domestic use,

(4) Commercial use, and (5) General use. For his study, he was able to make the following conclusion.

> . . . it cannot be stated that the public will not accept reclaimed water for domestic use but will accept it for commercial use. Public opinion on the matter is more complex than might first be conjectured. While certain uses in each of the five categories of use studied are likely to be acceptable to the public, certain uses in each category are likely unacceptable. New use of reclaimed water designed to foster public acceptance might well start with the "ladder" position of lowest opposition and then move upward step by step as desirable and as reclamation technology improves. Following this line of thought, domestic use should start with water for lawn irrigation. These are, of course, problems of dual water systems and health protection that must be dealt with. However, public opinion in California apparently will not yet tolerate direct reuse and further cost-benefit analysis might well justify reuse for domestic irrigation, especially in new housing developments. Similar recommendations for beginning uses of reclaimed water can be made for the four other usage categories . . .

In evaluating the effects of public attitudes on optimal water management policies, several factors, as noted in the above quote, must be considered. One is the dual delivery systems that would be required. More will be said on this later. Another is the health aspects and the economics required to overcome the hazard. Evaluation of these factors may be easy for a specific project, but when an evaluation of reuse is made for the entire Denver area, for example, the lack of data creates a problem. It is difficult to estimate the costs of a second delivery system since it is difficult to know where the reclaimed water would be used and in what manner. For this reason, an evaluation of reuse for Denver must necessarily utilize ball-park estimates.

The other area where public attitudes are playing an increasing role, especially for Denver, is in the acquisition of additional surface water supplies. The best example of this increased interest is the defeat of a $200 million bond issue by Denver voters in July, 1972. The bond issue was to finance a program to: (1) increase water treatment capacity in Denver by 64%, (2) increase raw water supply by 38%, and (3) increase transmission systems by 50%. Also to be funded was the initial development and construction of a water recycling plant. The layout expenditure for completion of the Eagle-Piney water collection system near Vail, Colorado was roughly $100 million. It was also this expenditure that drew the most criticism from environmental and ecological groups. The main reasons given against the Eagle-Piney project was: (1) previous diversions dried up streams; and (2) further diversion presents a threat to recreation and economic development on the western slope of Colorado. The bond issue lost by a small margin (53.6% against).

Public attitudes are becoming more important to the successful implementation of means of augmenting municipal water supplies. Public attitude, therefore, has an effect upon optimal water management. Again, however, quantifying this effect is difficult, but it must be done if rational decisions are to be made.

Water Distribution System Structures

As noted above, the form of the water distribution system can effect water supply policies and vice versa. A single water distribution system, which exists today, encourages the acquisition of new water sources, while if a dual system were installed, the use of reclaimed water would be encouraged. Public acceptance and economics currently play a large role in the policy decision with respect to a dual versus single system. The public attitude was discussed above.

The economics of reuse is rapidly ceasing to be a factor due to the increased cost of acquiring new water supply sources and the high levels of treatment being demanded. Koening (1972) performed a study of the economics of reuse in the San Antonio, Texas, area. From this study, he made the following conclusions.

> The cost of supplying the projected San Antonio water supply and waste treatment at the quality and cost levels of 1969 and at the quantity levels estimated for the year 2000 by the conventional means of importation and sewage treatment and discharge according to the current Texas Water Plan would be within 10% of the cost of not discharging any wastes but treating all sewage by advanced waste treatment and reusing the product water. The 10% difference is well within the estimating error which means that the complete reuse cost is comparable with the conventional importation and discharge cost.

This illustrates the need to seriously consider reuse and its attendent water delivery systems. If they are not considered, the optimal water management scheme may not be reached, thus resulting in a higher cost of water management. Grigg (1972) points this out for the Denver area.

Water Management Administration

The traditional separation of water quantity management from water quality management costs money in terms of lost efficiency. The use of small fragmented management agencies also costs money. Continued use of existing management institutions may prevent the optimal use of available water supplies. This is especially true in the area of reuse of reclaimed water.

The use of many management institutions to deal with the many aspects of a scarce resource results in each institution optimizing its own operations and returns and caring less what happens to the others. The problem is compounded with water management when the return flow of one agency or institution becomes the source for another. The disposal problem of one institution is the supply problem of another. As higher treatment requirements are placed into effect, the differientation between quality at the inflow and quality at the outflow is reduced. This presents an area, like the Denver area, with some interesting possibilities with respect to water management.

The Colorado legislature passed the Colorado Service Authority Act of 1972 as a means of coping with afore mentioned problems. The law provides for the establishment of a service authority, often referred to as Regional

Service authority, which would constitute a new form of government designed especially to provide a number of specified services on a regional basis (Denver Regional Council of Governments, 1972).

This act provides the mechanism by which water quantity and quality could be managed on a regional basis and it also permits the consolidation of the many smaller single purpose districts. Once formed, no smaller districts could be formed within its boundaries to provide the same services it is authorized to provide. Voter approval is required to establish the regional service authority.

At the state level in Colorado, water quantity management is in the State Engineer's Office under the Department of Natural Resources and water quality management is in the Water Pollution Control Division of the Department of Health.

Water Quality Standards

The impact of rising water quality standards on optimal water management has been alluded to several times earlier. When the federal law states that there will be no pollutant discharged to navigable water by 1985, the effects or ramifications can be enormous on the water management program (Grigg, 1972). These effects will have an impact on optimal water management policies.

Both in-stream water quality standards and effluent standards greatly affect the water management decisions. Low standards tend to discourage the use of sophisticated waste treatment techniques, encourages the acquisition of more fresh water supplies, and precludes the consideration of a reuse system. High standards tend to encourage the use of advanced waste treatment and causes the water manager to look at his effluent as a potential source. A large amount of money has been invested in the water as it leaves the waste treatment plant and to simply dump it into a stream for disposal seems wasteful.

Thus, the impact of stream or effluent standards must be quantified. What is the added cost of recycling reclaimed water if the treatment requirements almost make the water potable? How does this cost compare to the acquisition of water on the western slope in Denver's case? Answering these questions will not be simple due to a lack of good data on the quality of water and the costs involved.

SECTION IV

ANALYSIS OF URBAN WATER MANAGEMENT STRATEGIES

Introduction

In the metropolitan setting, water management includes accounting of the supply, measuring the demand, and allocating efficiently according to political reality and economic ability (Flack, 1971). Accomplishing these objectives requires the continual improvement of the methods used to manage water under conditions of competition and scarcity.

This section presents the analysis obtained from the urban water management model which hopefully extends the knowledge concerning such water management policies. The results are divided into an examination of the essential system characteristics, evaluation of important institutional structures, and the future strategies suggested by expected conditions in the urban area. Although these conclusions apply only to Denver, it is hoped that they have been derived in a general enough manner to apply broadly to other arid urban areas as well.

Characteristics of Urban Water Management Policies

The alternative water supplies for the area of Denver can be reasonably limited to interbasin transfers, stream flows, and reuse. Groundwater is generally omitted because of the unconfined nature of the stream-aquifer system and the consequent contamination of the groundwater supplies. The transfer of in-basin agricultural water rights is also an important water source, but is difficult to examine directly in the model. Consequently, it is necessary to evaluate the potential for this source indirectly in order to test its feasibility by varying the permissible levels of reuse. Since the system depletes approximately 50% of the inflows, allowing reuse of more than 50% of the interbasin transfers actually implies the reuse of some in-basin flows, which thus gives some indication of the costs or price of agricultural water right acquisition.

As water supplies become pressed to satisfy the needs, sources with poorer quality must be utilized. This is especially applicable in the case of recycled water, which becomes less expensive as its TDS levels are increased. As an indication of the effects of placing a priority on the quality of the flows within the urban distribution system, three distribution philosophies are explored:

(1) Alternative 1. Public attitudes, legal restrictions, or the physical structure of the distribution system, may require that wastewater be only recycled through existing raw water facilities. In this situation, where recycling directly to municipal and industrial demands is not possible, the reused flows are blended with the other

sources. As noted in previous sections, a limit on TDS in this case will be set at the highest level currently encountered, so that domestic supplies remain undegraded.

(2) Alternative 2a. Recycling individually to municipal and industrial demands may be permissible, but only if water quality levels are maintained at their current values. This policy may be inefficient from the standpoint of supplying individual demands with permissible water quality characteristics, but adds flexibility to the system.

(3) Alternative 2b. Probably the most economical long range distribution strategy for arid urban areas is to supply each need with water at the tolerable limits of TDS for each use. This practice allows the best water to be used for the most sensitive use and the poorest for the least sensitive. To accomplish this investigation, the TDS levels allowable for municipal uses is set at 800 mg/l while that for industrial is set at 500 mg/l. This alternative will serve as the basis for comparison between various combinations of alternatives.

Intuitively, if a more degraded water is supplied to the urban demands, the effluent quality will also reflect the change. Consequently, if recycling is employed, the

TDS levels in the area's effluent will increase. Since downstream water rights demand maintenance of quality as well as quantity, the effects of reuse are important considerations. An assumption has been made that these TDS effects are proportional to the changes in TDS supplied to the demands. In a limited search, little information on the Denver area was available to answer this question and the simplified approach appears necessary.

In this section, a thorough analysis of conditions as they existed in the early 1970's will be made to develop the basic characteristics of the model.

Optimal Policy Spaces

When the institutional limitations on the model are temporarily ignored, optimal water management policies depend exclusively on the relative feasibility of the recycled water. This characteristic results from the assumption of linear cost functions representing the interbasin transfers and in-basin stream flow diversions. Since the average costs for recycled water depend on effluent BOD and TDS goals, the optimal water management decisions can therefore be expressed in terms of these variables. In this manner, water quality considerations are linked to the problems of water supply and distribution and thus an integration of both aspects of water management in an urban area is accomplished. When the decision for each point corresponding to a specified value of effluent BOD and TDS standard is evaluated, the policy space is defined and can be presented graphically. The term "policy space," whether optimal or not, is thus a representation of decisions which are shown as functions of important system parameters.

The optimal policy space for the first distribution scheme, Alternative 1, is shown in Figure 12. Under the assumptions of this alternative, the quantities of water diverted from each of the sources depends upon their supply costs. Since the in-basin stream flows are relatively inexpensive to deliver, all decisions would incorporate stream flows in their available quantities. As a result, the optimal strategies deal principally with the trade-off between interbasin transfers and recycled wastewater. The three areas delineated in Figure 12 represent: (1) zero reuse, (2) reuse limited by TDS concentrations, and (3) reuse limited by the constraint on the allowable percentage of interbasin transfers which are available for recycling.

In the space occupied by a zero reuse strategy most present day conditions are encountered, thereby indicating wastewater costs are yet higher than the costs of the other two sources. The "all or nothing" type strategies resulting from the linearity of these costs are demonstrated in the plot as illustrated by the sharp step-like nature of the boundaries between respective areas. A relatively large percentage of the plot represented by the zero reuse

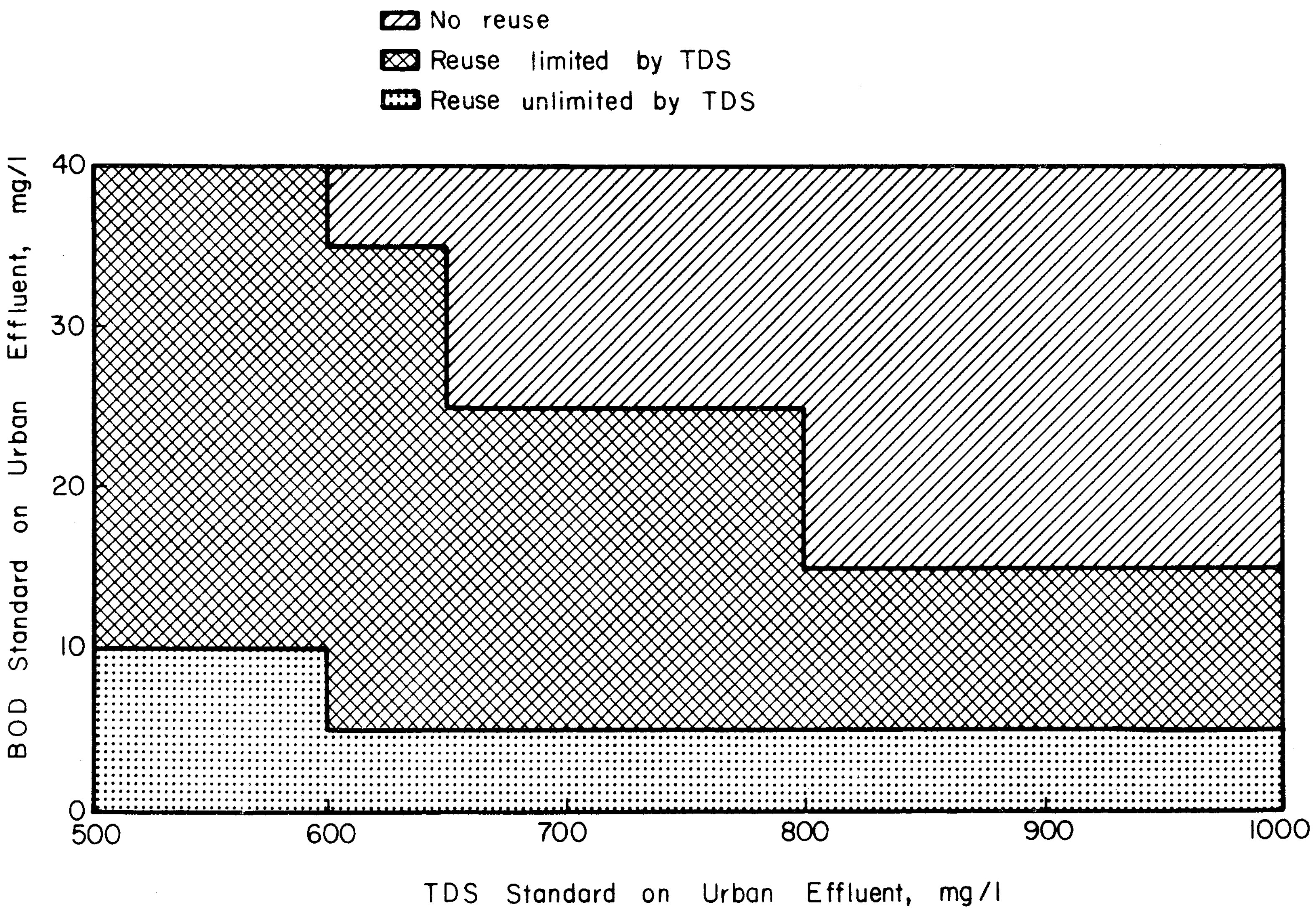

Figure 12. Optimal water management policy space for Alternative 1.

sector in this system of management supports many of the current plans being implemented in the Denver area.

The transistional area in Figure 12, representing conditions where the quantities of reuse used are dependent upon the quality of the flows, is applicable to situations of water quality management which are expected in the near future. The limitation on reuse in this sector of the plot results from the costs of reused water with low TDS concentrations not being competitive with the other sources. However, at the higher TDS concentrations, where the costs are competitive, the water quality constraint in the model protecting the quality for the domestic demands is activated and only a portion of the permissible reuse is utilized.

The final sector of the optimal policy space shown for Alternative 1 in Figure 12 is the condition when water quality standards on the urban outflow are sufficiently rigid to insure feasible recycling at any TDS level in the expected range. Recalling that reuse costs are the unit differences between the total costs without reuse and the total costs with a specified level of reuse, this sector illustrates the decrease in reuse costs as effluent quality levels are restricted.

The optimal strategies discussed for Alternative 1 were also generated for Alternatives 2a and 2b. It is probably worth noting, however, that unlike Alternative 1, these two remaining alternatives compare the feasibility of water sources at the point of demand delivery. In

Alternative 1, the sources were evaluated on the basis of supply cost, but in Alternatives 2a and 2b, the interbasin transfers and in-basin stream flows are increased in price by the costs of raw water treatment.

The optimal policy space for Alternative 2a, shown in Figure 13, illustrates the increased use of recycled water even when present quality criteria are met. The blending of recycled water directly with diversions from the other sources is sufficient to expand the region of unlimited reuse to include most of the space. There is a significant reduction in the transitional zone between Figure 12 and 13. The importance of being aware of this occurrance is that the optimal decisions are essentially ones of whether to reuse or not.

The distribution of the sectors in the policy space of Figure 13 suggest that if it is possible to recycle wastewater directly to municipal and industrial demands, plans should be rapidly made to do so because the boundaries of this area are very near present conditions. In this figure, the quality parameter most affecting the decision is the BOD standard on the urban effluent. This characteristic is markedly different from the results shown in Figure 12, which are about balanced between TDS and BOD effects. Because increased BOD removal efficiencies are expected sooner than requirements for TDS removals, the need for immediate planning is apparent.

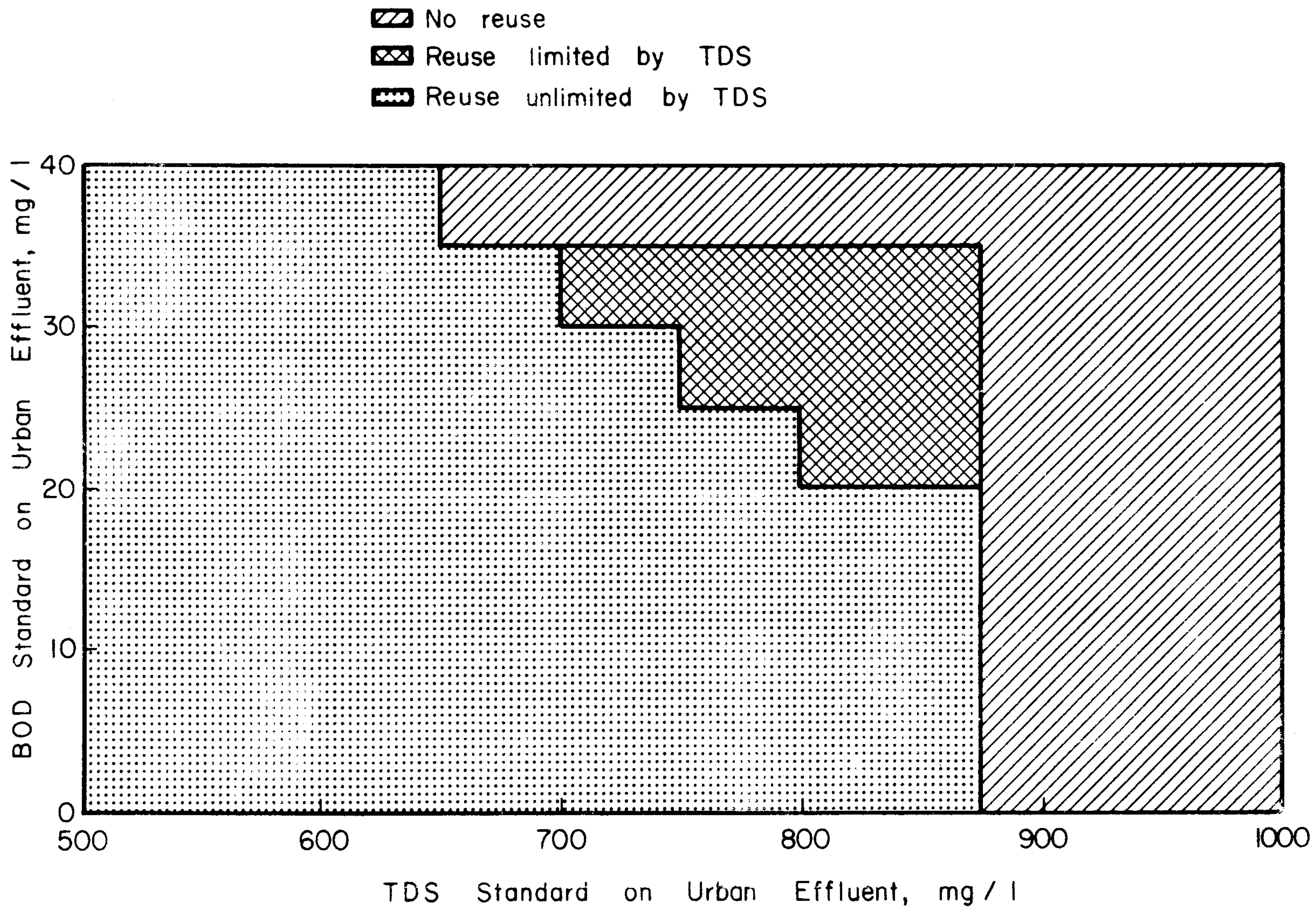

Figure 13. Optimal water management policy space for Alternative 2a.

The majority of the policy space occupied by the unlimited reuse sector suggests the need for separate distribution systems to serve both domestic as well as the municipal and industrial demands. The feasibility of constructing such dual systems as part of new developments, or as part of system rehabilitation, will be left to the water planner, but the costs of the alternatives will be shown later.

The final alternative, recycling to individual urban demands based on relaxed water quality goals (Alternative 2b), is shown in Figure 14. Again, the limits of the distribution system should be expanded to a dual system. Because of the zoning in most cities, a separate system for industrial reuse may not be too difficult to achieve.

The examination of the preceding policy space charts illustrated the feasibility for recycling wastewater in the metropolitan environment. The expected requirements for more refined wastewater treatment before releasing these flows to downstream users is obviously in favor of the recycling concept.

Water Supply Costs

In addition to supply and treatment costs, the expenditures and investments necessary to supply a city with the water resources it needs included distribution networks, storage and pumping facilities, and metering and control structures. In the analysis presented herein, these

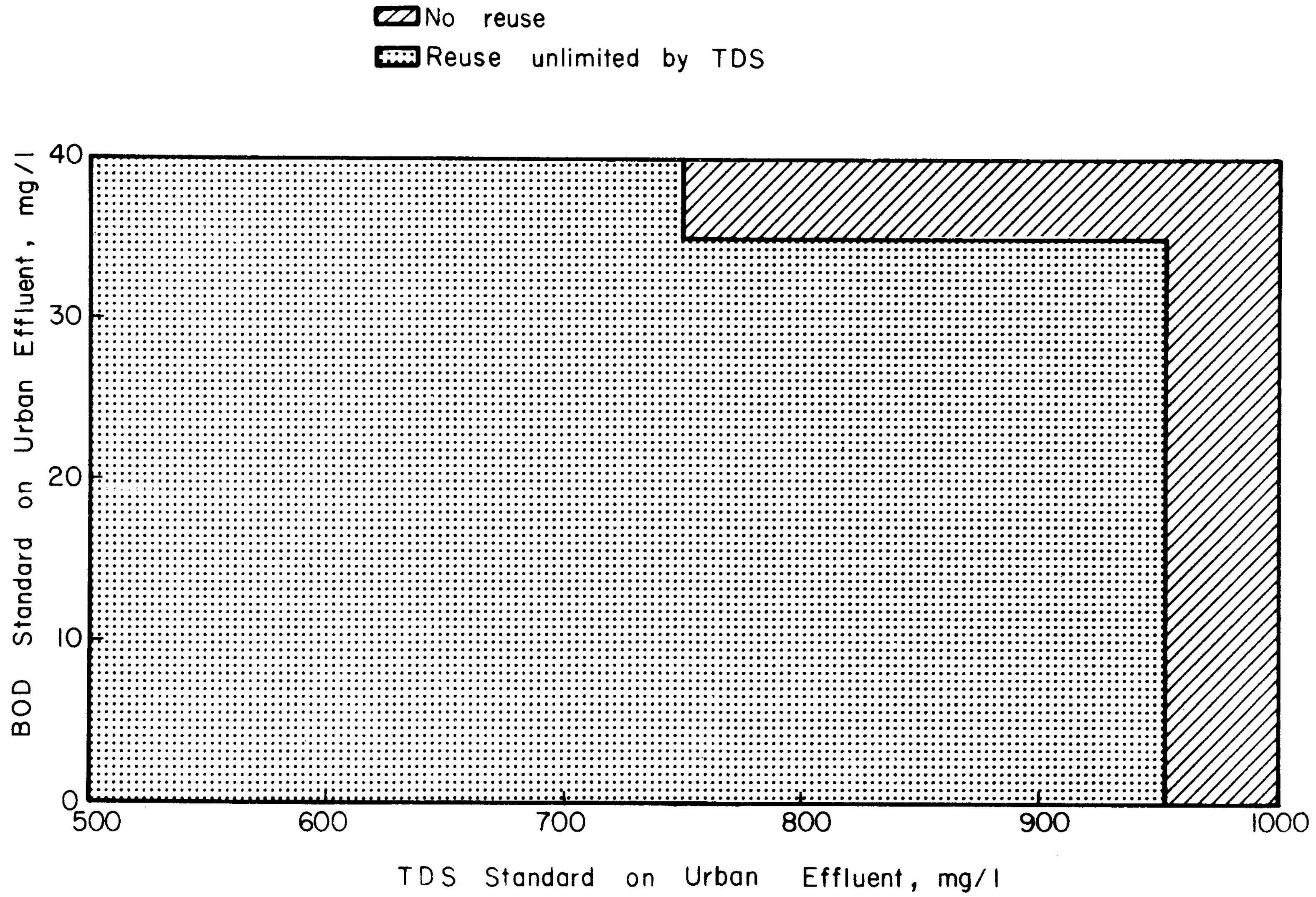

Figure 14. Optimal water management policy space for Alternative 2b.

additional costs have been omitted because of their occurrence in all planning alternatives. A comparison of model data with annual reports for the Denver area indicate the model analysis accounts for approximately 70-75% of the total annual expenditures.

The urban water system model was designed to accept mixing or blending of water supplies at each individual urban demand. Furthermore, the same structure in the wastewater treatment and reclamation model discussed previously was implemented. The effect of this blending ability is to render these cost functions unpredictable in shape unless one or two of the model parameters are completely dominating. From the previous section, it was shown that three basic policies were involved in evaluating optimal water management strategies. In each segment of the policy space, the combinations of reuse quality and blending ratio may be numerous. Consequently, if a cost function traversed several of these decision policies, its form may well be irregular.

The effects of effluent standards on urban water management decisions have been demonstrated to be relatively important. As a consequence of this and in order to provide a consistant presentation, the relationships in this and following sections will be plotted against effluent quality standards. Because of the irregular nature of the cost functions to be presented in this section, which illustrate many facets of the models operation, it is helpful to detail the causes for these irregular functions. In addition, several of the analyses in the following sections exhibit the unexpected geometries shown in this section. So, rather than repeatedly explain such irregularities, care will be taken here to note the reasons for the behavior of the model results.

The annual water supply costs have been plotted in terms of 1970 dollars in Figures 15 and 16 for Alternatives 2a and 2b. In addition to the curves for the various BOD standards, points are also plotted for the case in which 100% of the interbasin transfers are recycled. The relevance of the differences between the cost functions for the two magnitudes of recycling (50% and 100%) will be shown in a later section.

There are three primary characteristics of the urban water system model shown in Figures 15 and 16. The first can be demonstrated by examining the curve representing an effluent BOD constraint of 35 mg/l (CBO = 35 mg/l). In Figure 15, for example, the points between an effluent TDS standard of 500 mg/l and 700 mg/l define a monotonically increasing curve with decreasing marginal costs. Referring once again to Figure 13, the optimal policy space for this alternative, it can be seen that the decisions in this range of the curve lay in and along the unlimited reuse sector. Under this policy then, the only varying model parameters are the effluent TDS constraints and thus the desalting plant, as well as the prepatory tertiary

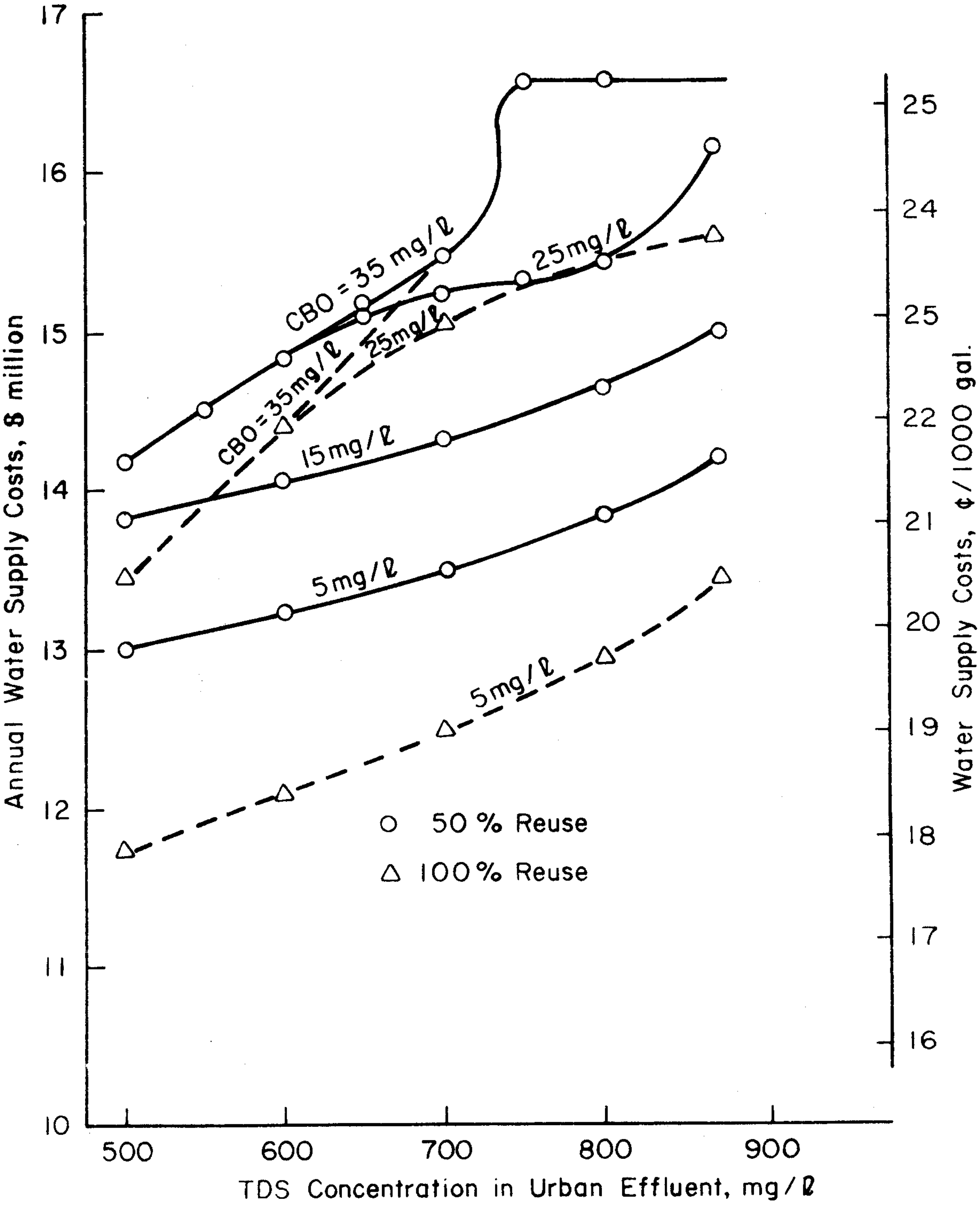

Figure 15. Annual water supply costs for distribution Alternative 2a.

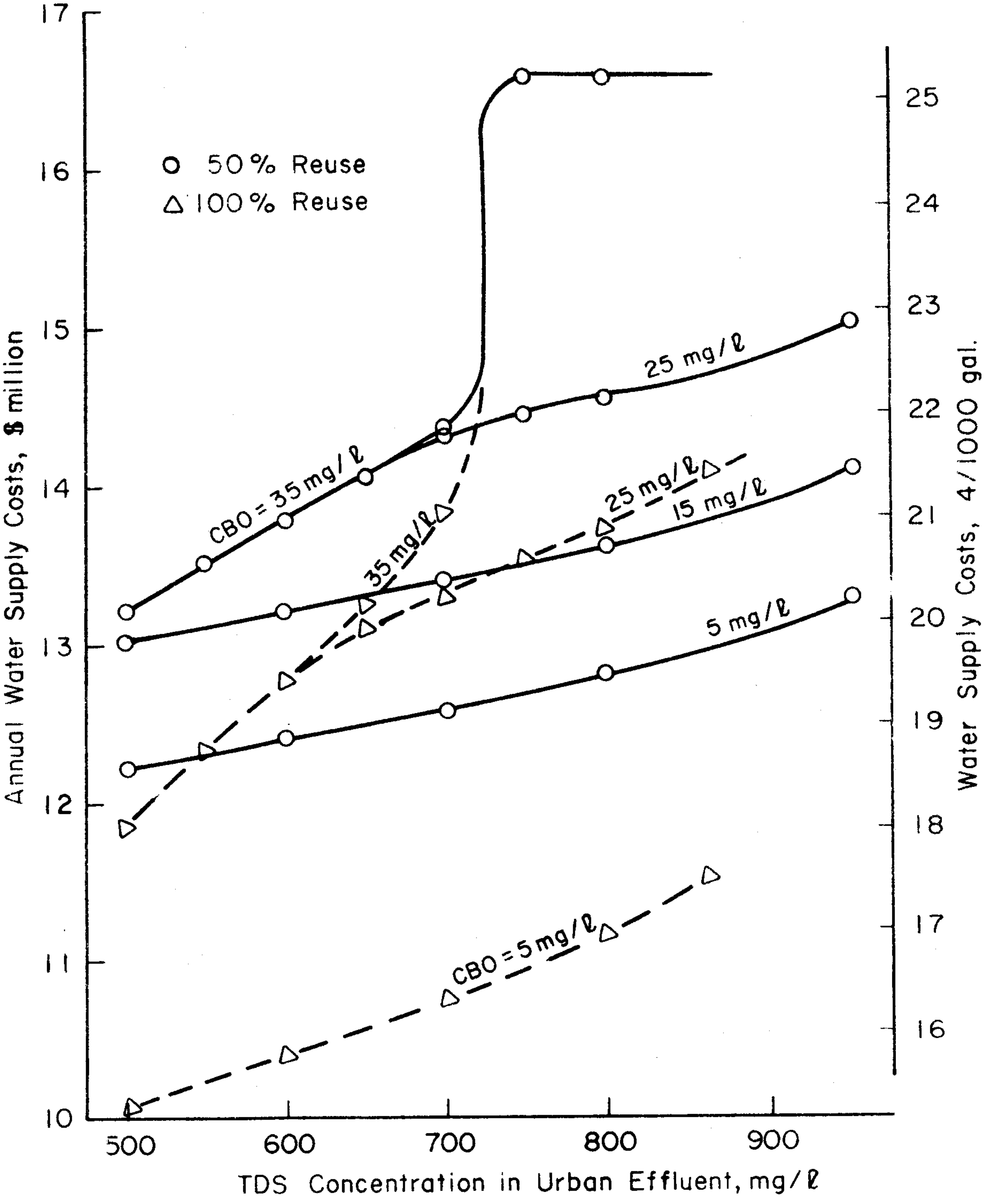

Figure 16. Annual water supply costs for distribution Alternative 2b.

treatment capacity. The cost functions depicted in Figure 15, therefore, not only illustrate the decreasing marginal cost characteristics of the wastewater treatment facilities, but also a reduction in the relative price advantage of the reused flows. At the interval between 700 and 750 mg/l on the abscissa, the strategy passes rapidly through first the limited reuse sector into the zero reuse sector. This transition is not clearly indicated in Figure 13 because the CBO = 35 mg/l points mark the boundary between the two sectors of the plot. The upward transition curve in Figure 15 at about 720-730 mg/l ends in a vertical segment which then is joined by a horizontal line to another curving transition. The linearities of the cost functions in the model create this geometry in the region, the "all or nothing" decisions, but should probably be a more uniform transition when better cost information can be utilized.

The second aspect of the model shown in Figures 15 and 16 is demonstrated in the 25 mg/l curves, which initially coincide with the 35 mg/l line. This equivalence for a segment of the curves rests with the fact that in this region, the mixing in the effluents necessary to achieve the reduced TDS levels causes the actual effluent BOD concentrations to be below the constraint. Examination of the computer printouts revealed that the concentration of TDS in the reuse was the same for both BOD limits. Consequently, in both of these instances the tertiary and desalting capacities were the same, thereby causing the water supply costs to also be the same. After this initial segment of coincidence, the 25 mg/l curves separate and maintain a function exhibiting the decreasing marginal costs of the treatment facilities. In this situation, however, a mix is achieved in the effluent which satisfies both quality constraints. And finally, the last segment of the curve turns upward, which reflects the change in reuse policies described in the previous paragraph.

Finally, for the BOD levels of 15 and 5 mg/l, the curves show no effect of either policy changes or wastewater treatment configurations. When this stability is reached, the relationships can be summarized for the various alternatives at selected levels of permissible reuse, as shown in Figure 17, in order to visually compare differences.

Another view of the water supply cost curves is presented in Figure 18 where the effluent TDS levels have been fixed at two levels, namely 550 and 750 mg/l. The two upper plots represent the distribution Alternative 2a in which the reuse to municipal and industrial demands are restricted by a 300 mg/l TDS constraint, while the two lower figures represent Alternative 2b, in which municipal flows are limited by a 800 mg/l constraint and industrial flows by a 500 mg/l restriction. The range of effluent BOD standards is plotted along the ordinate and the annual water supply costs along the abscissa.

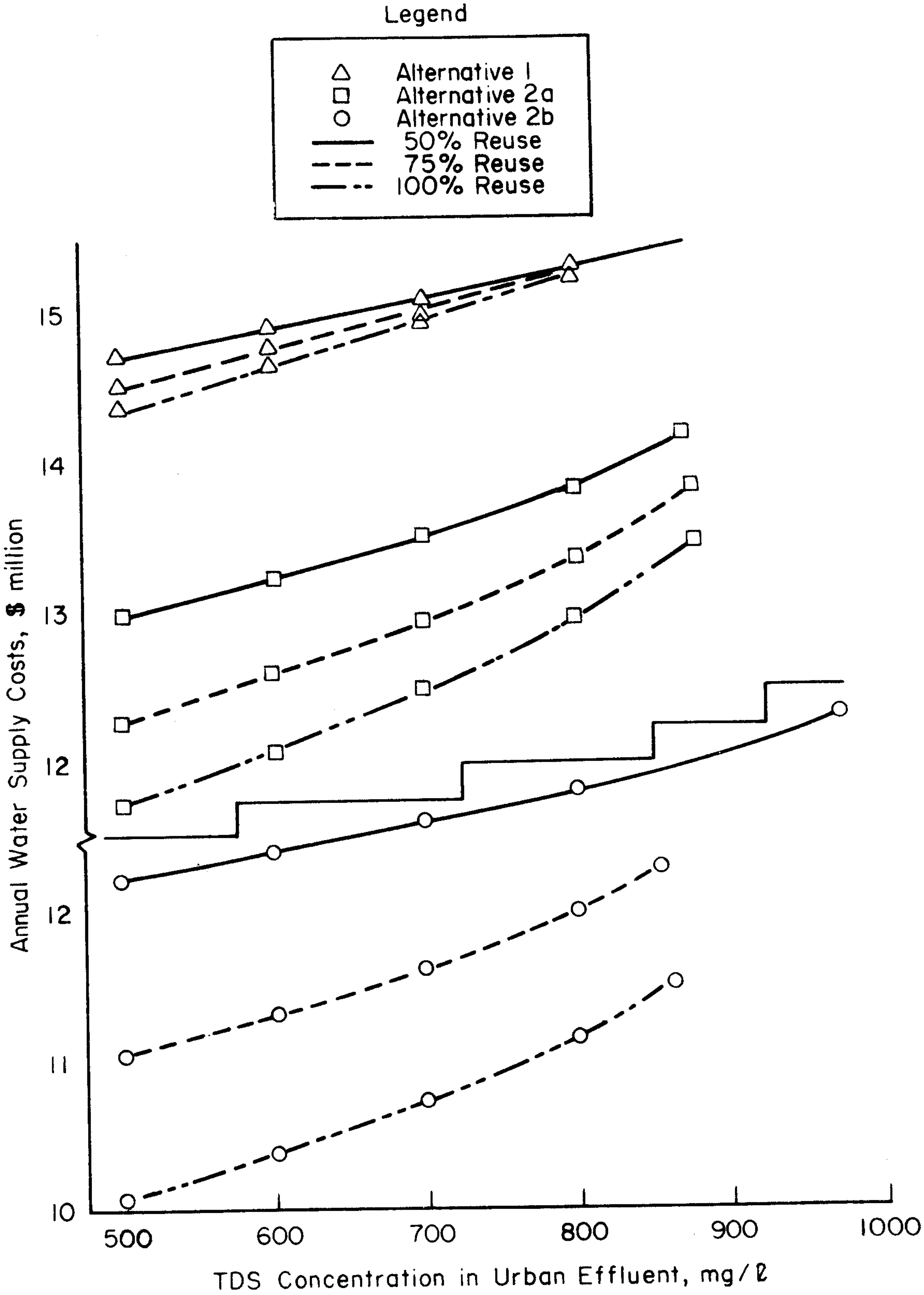

Figure 17. Annual water supply costs for the three distribution alternatives when the effluent BOD standard is fixed at 5 mg/l.

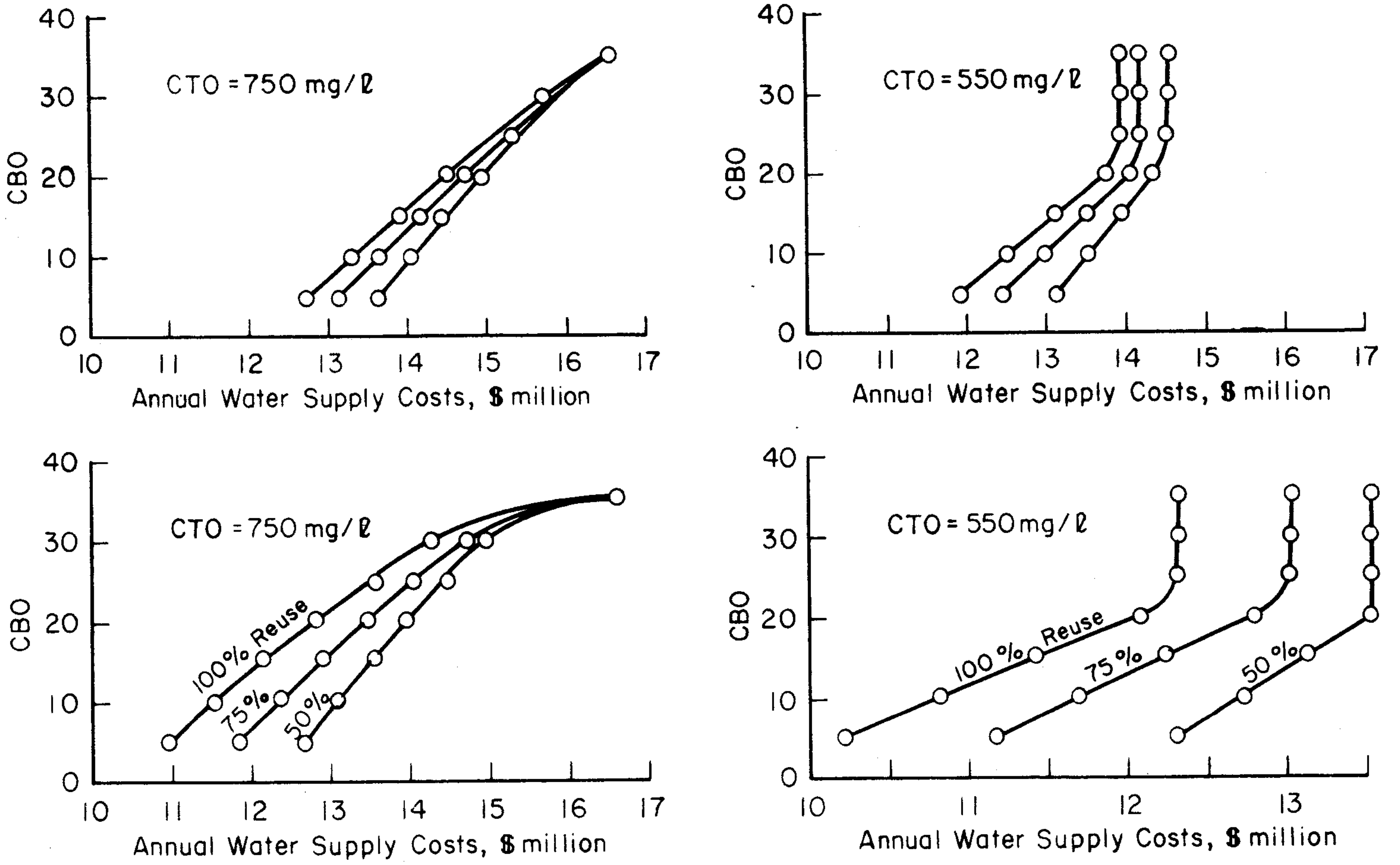

Figure 18. Annual water supply costs for distribution Alternatives 2a (upper curves) and 2b (lower curves) as functions of effluent BOD standards.

Drastically different relationships are shown in Figure 18 for the 750 mg/l and the 550 mg/l TDS levels. Again, the blending of flows in both the water supply and the wastewater treatment models is responsible. At a TDS standard of 750 mg/l on the urban effluent, the curves are smooth unimodal functions culminating at the single value noted previously as the zero reuse sector of the policy space. Considering first the 750 mg/l plots, the desalting plant capacity is fixed and thus the increase in the effluent BOD restrictions reduces only the capacity of the tertiary plant. If this is the case, it may be tempting to question why the costs do not actually decrease rather than increase. It is necessary to remember that as urban effluent water quality standards are relaxed, the costs of reused water increase resulting in less flows being reused. Thus, as recycled water becomes less competitive with the other water sources, the savings are also reduced. Eventually, no wastewater is reused and the optimal policy is at current conditions, as on the upper points of Figure 18.

In the curves representing the effluent TDS standard of 550 mg/l, the cost functions are independent of effluent BOD limits until about 20-25 mg/l, then the cost functions are similar to those for the 750 mg/l condition. The explanation for the occurrence of curves of this shape is the same as for the equivalent sectors in Figures 15 and 16, i.e., the desalting requirements are exclusively dictating the capacities of the systems. Until the BOD limits reach the 20-25 mg/l range, the TDS requirements dictate that more water must be subjected to tertiary treatment in order for desalting to be accomplished than is necessary to meet the BOD constraints. Consequently, no blending is possible and the curves are unaffected by BOD changes. When the BOD limits are lower than 20-25 mg/l, blending is possible and both TDS and BOD constraints are tightened.

Total System Costs

Up to this point, the emphasis has centered on optimizing the urban water supply costs. Since recycling wastewater is one alternative source of water, the operation of the water supply and distribution model is dependent upon the corresponding operations of the wastewater treatment and reclamation model. The primary conclusion which has been substantiated is that as water quality standards on urban effluents become more stringent, the feasibility of adding enough capacity to the treatment elements and recycling some of the wastewater flow is enhanced. In the previous analysis, the savings to the supply agencies are shown to be substantial when recycling is implemented under optimum strategies. The question that may very well be asked is, "Why not impose extremely rigid water quality controls on ones' effluent in order to more cheaply supply the urban demands?" The answer lies in the observation that although the unit costs of reused water are shown to decrease, the total expenditure necessary to achieve more refined pollutant removal is increase increased.

In order to evaluate the effects of different water and wastewater management schemes, the total annual system costs were computed. As an illustration of these costs, the total annual system costs were plotted for Alternative 2a. This plot, shown in Figure 19, again indicates instability of the decision at the higher levels of effluent quality. For effluent BOD standards, CBO, of 25 and 35 mg/l, the decisions being made are whether or not to use any recycled wastewater, where the upper curves represent decisions as to the magnitude of the reuse and its associated quality. Included in Figure 19 are 75% and 100% reuse of interbasin transfers for the CBO values of 5 and 35 mg/l. The relative differences at 35 mg/l are small in comparison with the 5 mg/l differences, which is of interest in evaluating the value of agricultural water rights to the urban user as will be noted later.

From Figure 19, it is apparent that the savings to the water supply system by recycling wastewater are more than compensated for by the increased treatment costs when viewing the system as a whole. As these water quality goals are strengthened, the initial cost increases will be significant. For example, the total annual cost change will be from about \$24.3 million at CBO = 35 mg/l, to \$26.1 million

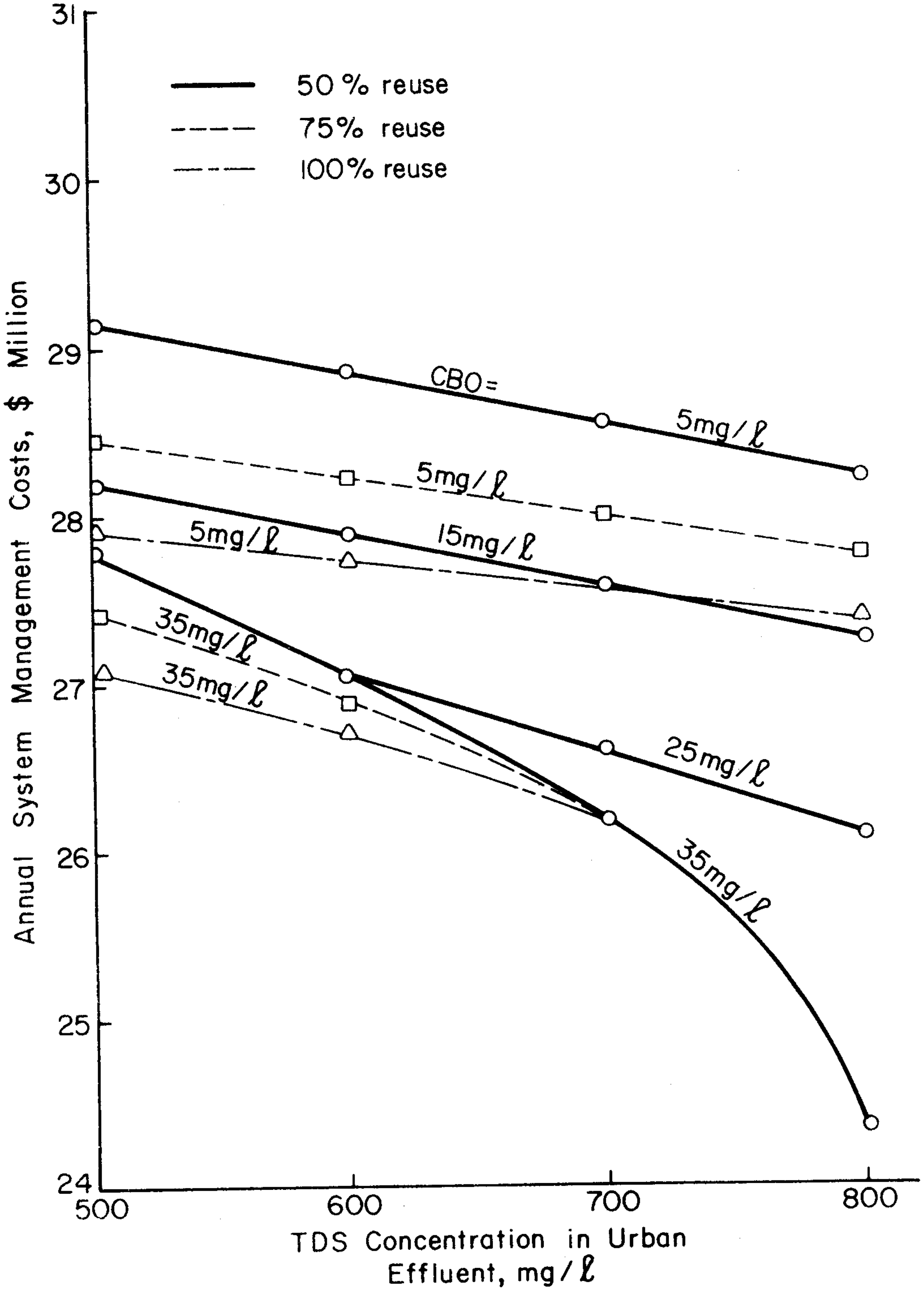

Figure 19. Annual system costs for distribution Alternative 2a.

at 25 mg/l, \$27.7 million at 15 mg/l, and \$28.2 million at 5 mg/l for an effluent TDS level of 800 mg/l. This is about a 15% increase which can be expected in the near future. If TDS standards as well as the BOD limits are enforced, the total cost increases will be approximately \$5.0 million annually or about a 20% increase.

Another important characteristic of the total cost function is illustrated in Figure 20. When the effluent BOD standard is fixed at 15 mg/l and the effluent TDS levels are allowed to range over the values for each of the three distribution alternatives, the effects of different levels of permissible reuse are shown to vary widely. For Alternative 2b the difference in total annual costs amounts to about 1.8 - 2.0 million dollars between the 50% and 100% reuse levels. Whereas the difference is only about \$0.5 - 1.0 million annually in the case of Alternative 2a, and almost no difference in the relationships for Alternative 1.

Effects of Reuse on Water Quality

It would seem justifiable to state that if an increase in the concentration of TDS occurred in Denver's raw water supplies, the TDS concentration in the wastewater would in some manner reflect such an increase. To precisely predict the effect of water quality fluctuations on effluent quality characteristics would necessitate detailed examination of the water use sectors in the metropolitan area.

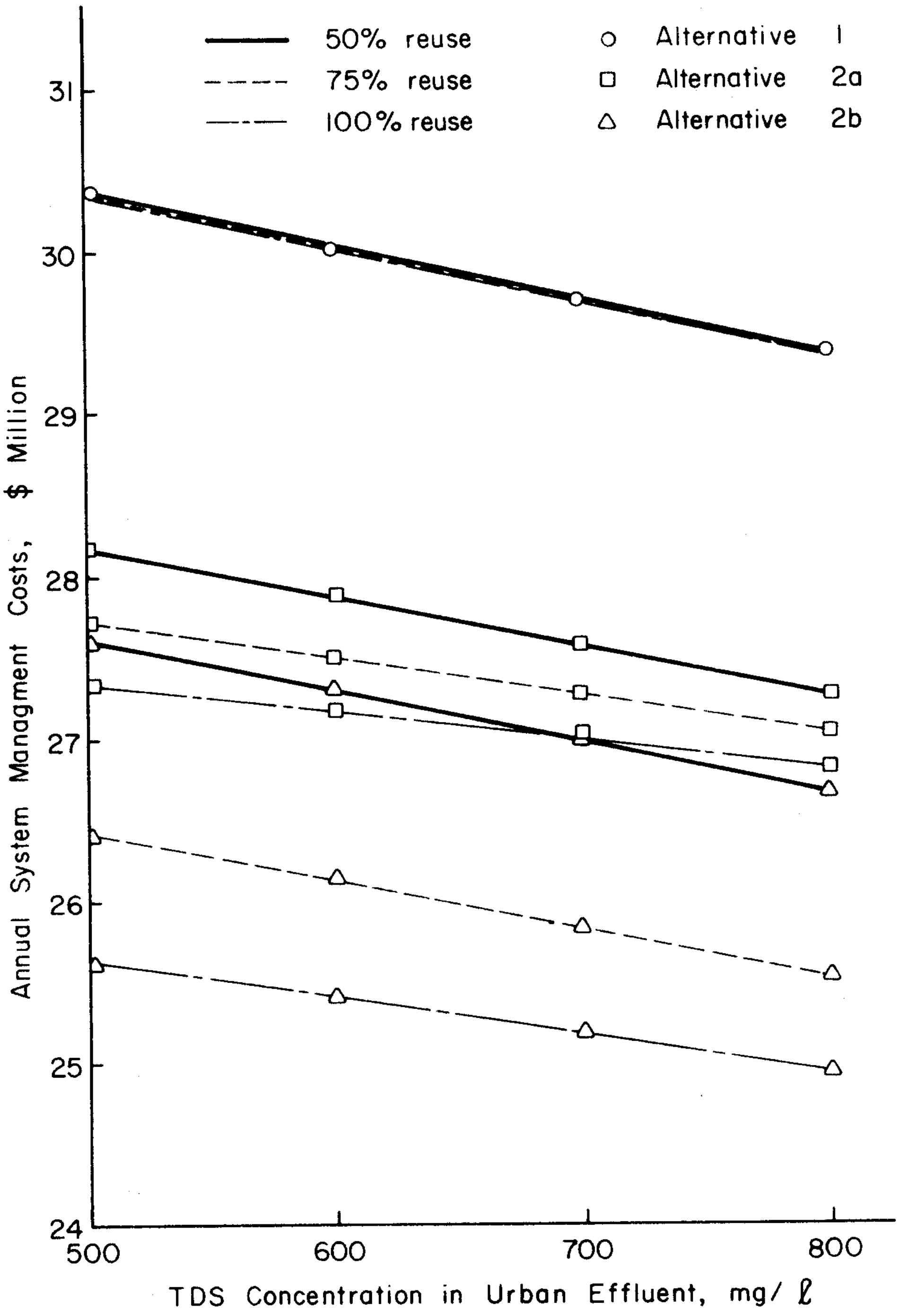

Figure 20. Annual system costs for the various distribution alternatives at an effluent BOD level of 15 mg/l.

Furthermore, the numerous sizes and composition of American cities would dictate that initial investigations would be primarily applicable only to the locale of the study. Since no such analysis has been made in the Denver area from which applications could be made in this analysis, it was assumed that influent quality changes would be reflected proportionately in the effluent. Some biasing was introduced in the assumption that only a small fraction of the flows supplied to municipal demands returns to the sewage collection system.

A simple water and salt balance on an urban area conclusively demonstrates that a "pickup" occurs in the system. Banks, et al (1971) suggests such a pickup amounts to an average increase in TDS concentrations, above the consumption concentrating effects, of about 300-400 mg/l for one cycle of use. In the Denver area, these pickup effects are on the order of 500-600 mg/l, but where such salt loads are acquired have not been delineated sufficienty to justify a more sophisticated analysis here.

The effects of recycling on TDS levels in wastewaters from the Denver metropolitan area is an important consideration. For the situation where recycling is accomplished through the existing raw water facilities, the exhibited water quality effects are governed by the constraints on domestic TDS levels. The results of this analysis indicates that the TDS concentration in the effluent flows could be expected to increase by about 200 mg/l when reuse is introduced. This increase is the largest encountered in the analysis and is due primarily to the fact that water of poorer quality cannot be directed to demands with high consumption ratios.

For the case of Alternative 2a, the TDS increases amounted to 70 mg/l. In this situation, most of the recycled water was diverted to the municipal demand where the return flow percentage is quite small and the effects on the wastewater were minimal. In addition, the maintenance of the domestic quality constraint (300 mg/l) limited the level of TDS in the recycled water to about 600 mg/l which further diminished the effects in the return flows.

Finally, the situation where recycling is accomplished according to Alternative 2b results in concentration increases of about 150 mg/l. The water quality constraints on both municipal and domestic demands became tight as the reuse quality approached 950 mg/l, indicating also that desalting was not necessary for the flows. This may be noted as the cost difference between the two latter recycling alternatives.

Because of the water quality constraints being tight in nearly all conditions of reuse, future policies and variable levels of reuse do not affect these results. Recycling does indeed affect downstream water quality and needs to be further evaluated.

Evaluation of Water Management Institutions

Water management institutions comprise the vast and complicated array of legal, social, political, and economic structures invented to accomplish equitable allocation of water resources. As the foundation of management practices, these factors require periodic and detailed scrutiny in order for proper modifications to be made which reflect the evolving requirements for efficient water utilization. Unfortunately, little or no modification in the administrative apparatus has been successfully completed until problems approach crisis proportions.

The nature of institutional restrictions have quite often been evaluated too late. Consequently, a useful analysis which could be performed by integrating urban water supply with its counterpart, wastewater treatment systems, in such a manner as to optimize the complete system is to examine the institutional restrictions violated by such a derived policy. This investigation yields two important results:

(1) Those constraints most affecting the implementation of optimal strategies are identified; and

(2) The cost or value of the restriction is determined.

As a result of identifying institutional constraints in this manner, the decision maker and the public are provided with information that can be used to rationally select or recommend changes which would achieve more efficient water management in the urban setting.

In this section, several of the more important institutional questions have been selected for analysis. First, in order to assess the effects of increasingly stringent requirements for wastewater treatment capabilities, the costs of these future plans in the Denver metropolitan area are evaluated. Secondly, the power of the public to direct water management policies through approval or disapproval of funding is evaluated and various non-optimal decisions are compared. Third, the value of agricultural water rights are determined so the feasibility of considering this water source for future supplies can be determined. Fourth, the costs associated with maintenance of downstream TDS levels are calculated to quantify the often overlooked aspect of water rights upon water quality. And finally, a discussion of institutional consolidation is presented to stress the need for regional planning and service coordination.

Costs of Water Quality Controls

The impact of the Denver metropolitan area on the quality of flows in the lower reaches of the South Platte River basin would be over-whelming if measures were not taken to alleviate the burden on the stream flows. With the expanding needs for recreation and the like, it will be necessary for wastewater treatment to become more and more efficient. As a means of demonstrating the added costs derived from these policies, the difference between present costs and costs associated with various levels of pollution abatement were computed and plotted in Figure 21. Included in this illustration are the costs of those added treatment requirements when no coordination is attempted between water supply and wastewater treatment agencies. With no attempt to optimize the total system, the added costs (occurring mainly in wastewater treatment facilities) are substantial. From Figure 21, it can be observed that the effect of varying TDS levels is much more significant at the higher levels of BOD. For example, the slope of the 35 mg/l line in both cases is more negative than for the 5 or 15 mg/l lines. For the case where no optimization occurs, the lines (with the exception of the 35 mg/l line) level out above 800 mg/l. This characteristic has been assumed since the TDS levels in Denver's effluents do not normally exceed 800 mg/l. Consequently, the higher permissible TDS levels actually represent a loosening of any TDS constraints and is not reflected in the system costs. The radical departure of the 35 mg/l line is due again to the common policy among either alternative. Therefore, the added costs at present conditions are equal to zero as would be expected.

The savings resulting from the optimization can now be seen. If the differences between corresponding curves in Figure 21 are evaluated, as had been done in Figure 22,

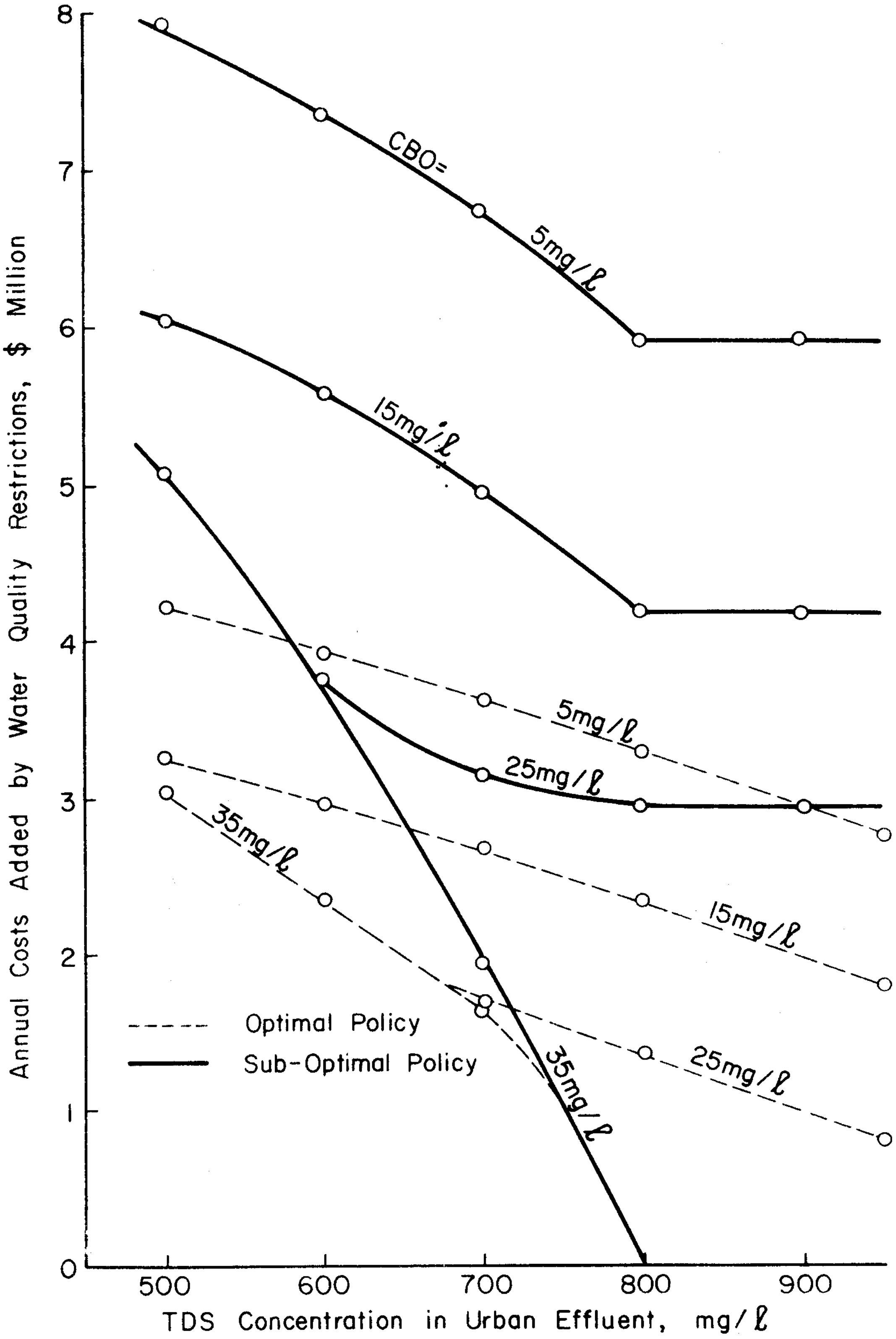

Figure 21. Annual system costs added by more rigid effluent quality standards under Alternative 2b.

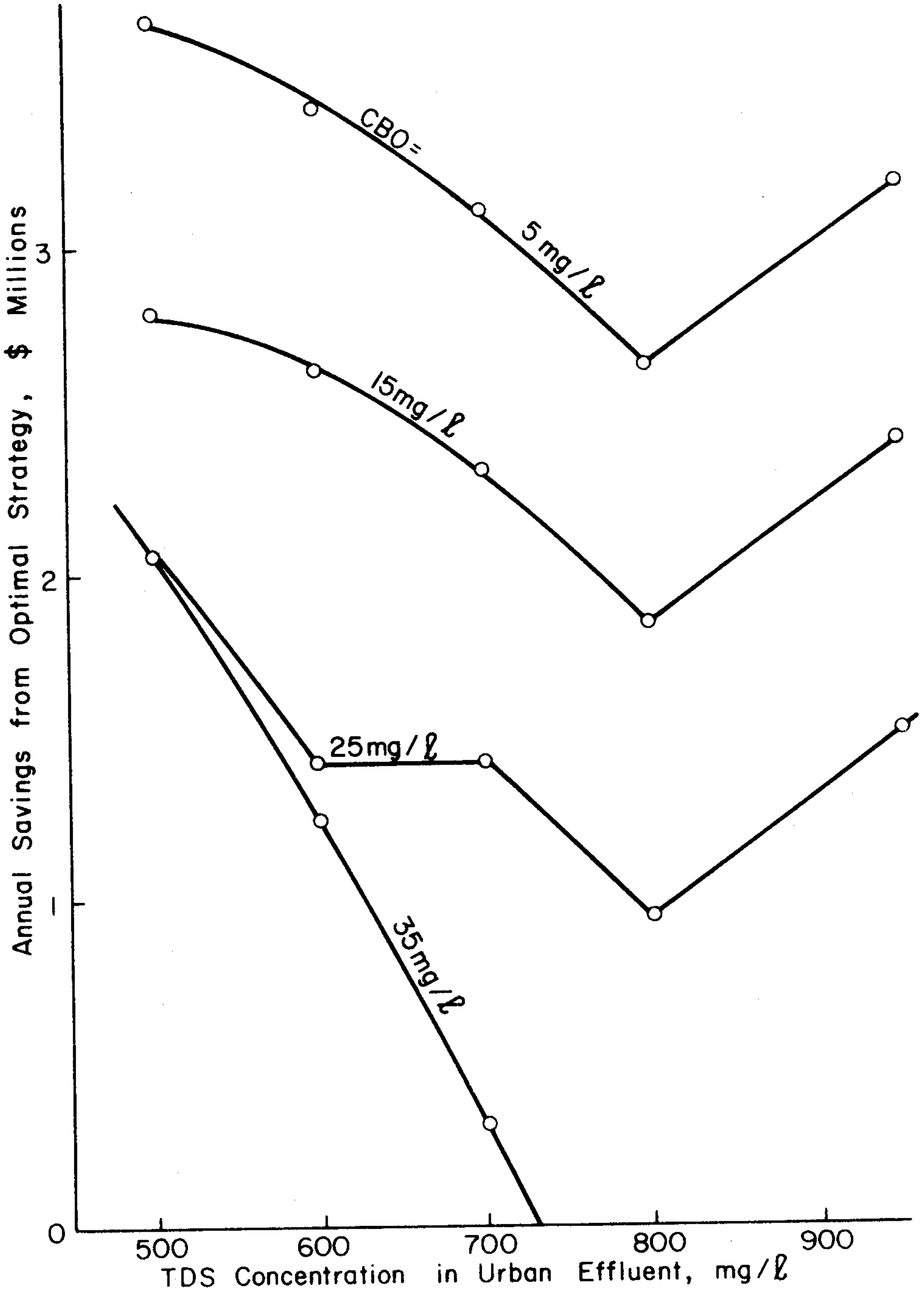

Figure 22. Annual system savings by optimal management policies as effluent quality standards are raised under Alternative 2b.

it is apparent that the need to implement optimal policies for urban water management is paramount. At an effluent BOD standard of 5 mg/l, for example, and no limit on effluent TDS, the system savings amounts to more than 3 million dollars per year, or about 5-10% of the annual system costs.

Even in a metropolitan area as large as Denver with large expenditures for water management, the costs of ignoring system coordination are significant. As water quality goals become more stringent (tighten), as they will in the near future, optimizing urban water management strategies will become more necessary.

Costs of Public Decisions and Attitudes

Public attitudes towards water management alternatives are undoubtedly the most important factor in future actions. In this regard, public attitudes are in reality an institutional force which, by controlling the funding for various projects, exercises the final decisions regarding feasibility. One of the strengths in this system of government is the decisions are made on the preference of the voters based on conclusions drawn from assimilated information. However, the source and intensity of information is critical to the voters choice.

Another problem is that some decisions can be made which are really detrimental in nature because of the lack of information available to the public. For example, decisions can be based on cultural connotations, like the thoughts of drinking sewer water. In order to quantify some of the effects of public disapproval of optimal policies, the model data was analyzed in the same fashion previously described. The results of several of these analysis follows.

From most of the previous analysis, the optimal water management strategies have stressed recycling as being extremely important because it promotes optimal coordination of urban water supply and urban wastewater policies. A comparison was made between the water supply costs as they currently exist and those under the strategy of recycling to municipal and industrial demands suggested by Alternative 2b. The results, shown in Figure 23, point out the high costs of not employing the optimal strategy. The curve representing 35 mg/l BOD shows the transition between the present and the optimal policies and indicates little difference between alternatives under present restrictions. At the lower concentrations of BOD in the urban effluent, the cost became substantial. For example, at a BOD level of 25 mg/l, the cost difference ranges between 2-3 million dollars annually. Comparison with the total water delivery system costs presented by the Board of Water Commissioners (1971) show this is about a 10% savings. If a comparison is made on the basis of water supply and treatment, omitting distribution system costs and the like which are common to the alternatives, this difference is approximately

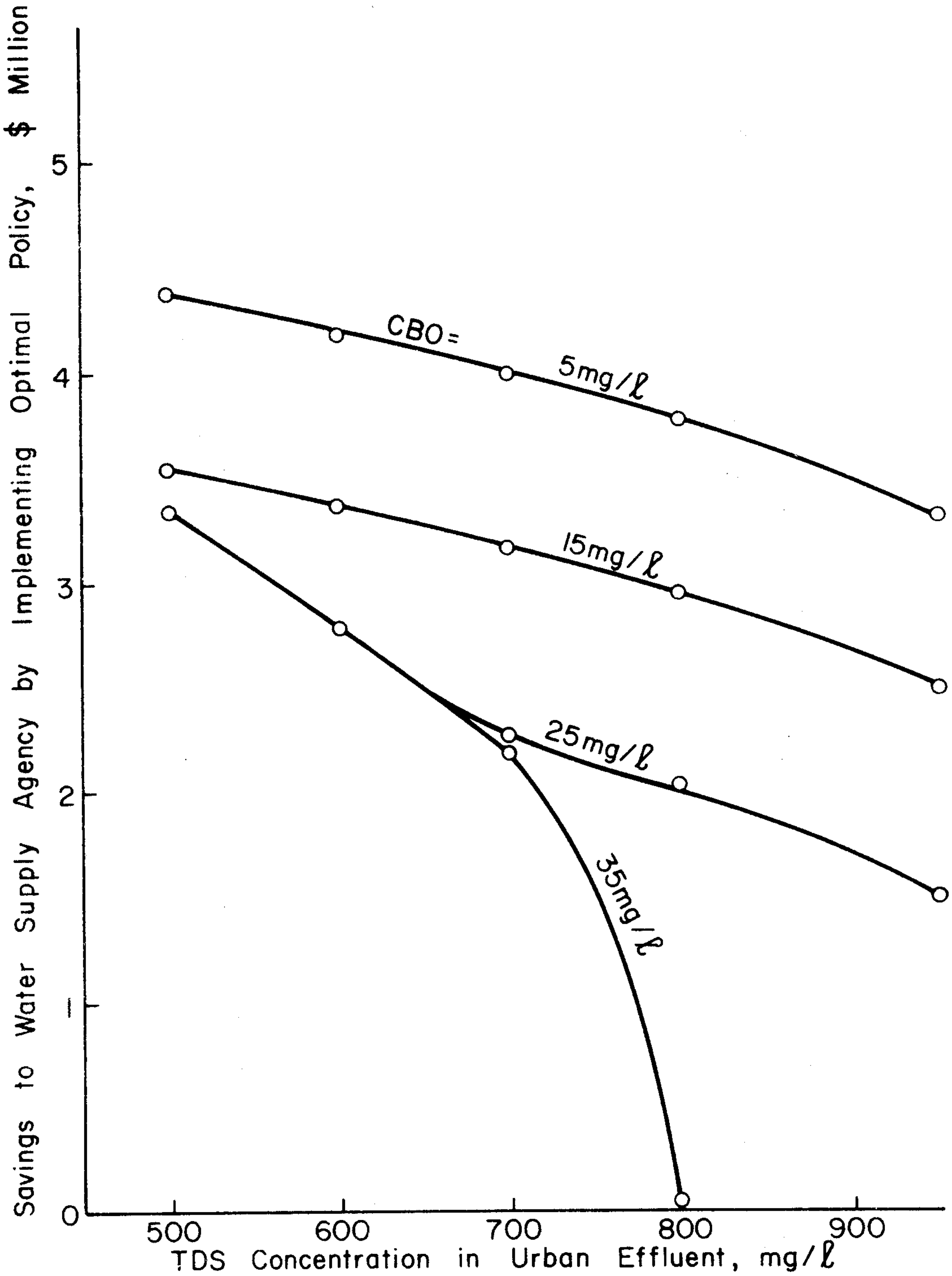

Figure 23. Savings to water supply agency by implementing Alternative 2b.

15%. If the 5 mg/l curve is examined, a policy which can be expected quite soon, the differences amount to approximately 20% of the total annual water delivery system costs.

These costs can also be presented in terms of the expected savings in ¢/1000 gal, as shown in Figure 24, in order to present these results in typical urban water assessments. In 1971, the Board of Water Commissioners (1971) listed an aggregate water supply cost of about 22.6 million dollars for the 62 billion gallons consumed. This fugure thus represents a unit cost of about 36¢/1000 gal. Examination of Figure 24 reveals the savings in water rates is thus about 5-10% of the price listed above, but 15-20% of the actual supply and treatment costs. It should be noted, however, that since the recycled flows are being diverted to the municipal and industrial user exclusively, the price changes are much more likely to be reflected in these sectors. Consequently, the cost figures were derived for these sectors and the differences again calculated and presented in Figure 25. When computed in this manner, the savings are substantial, amounting to as much as 20%.

Before concluding this particular analysis it may be worthwhile to point out two more savings that can be achieved in an urban area. The analysis thus far has dealt with the policy of recycling under relaxed TDS constraints indicated by Alternative 2b. A similar analysis

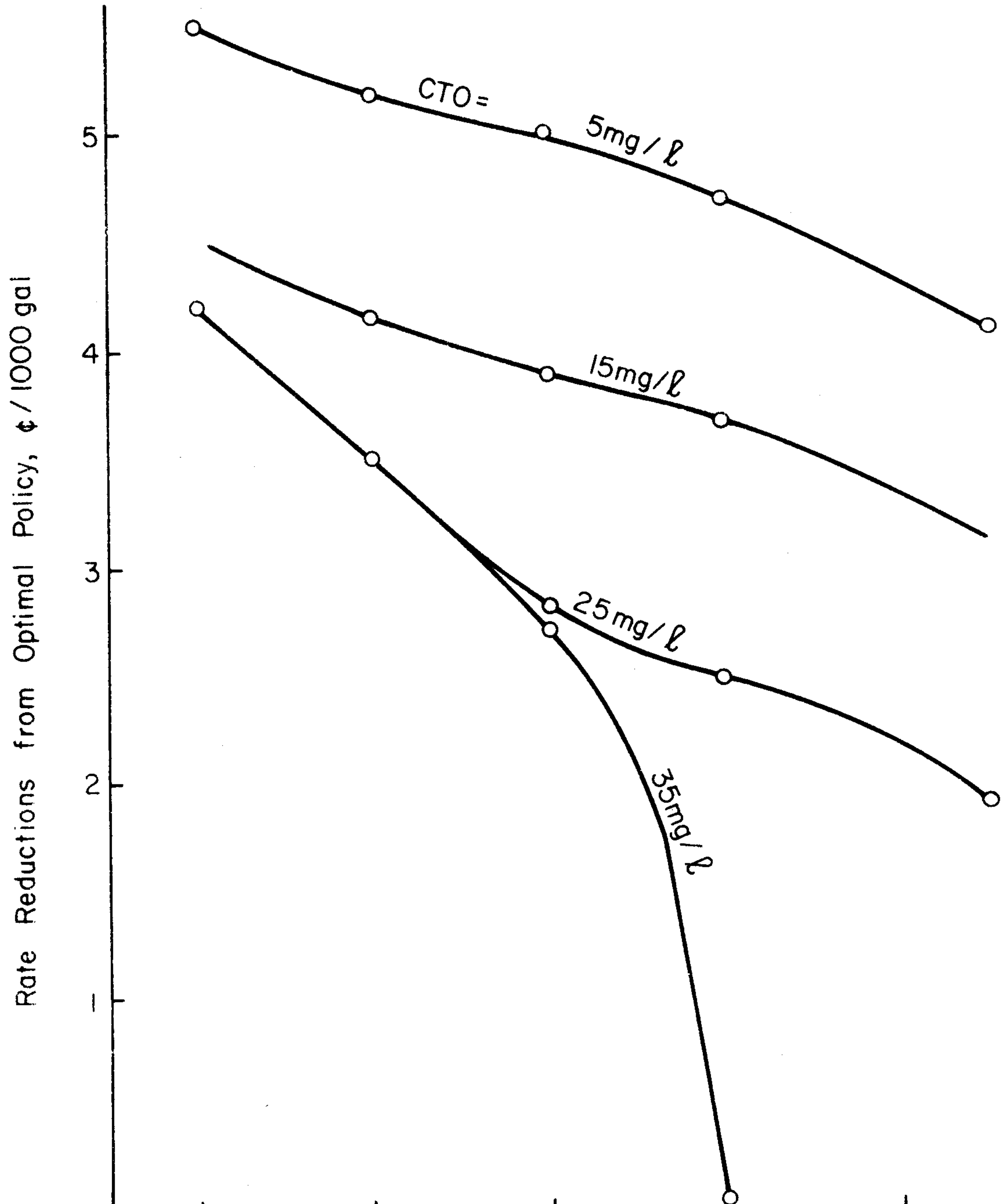

Figure 24. Possible rate reductions to urban water users by implementing Alternative 2b.

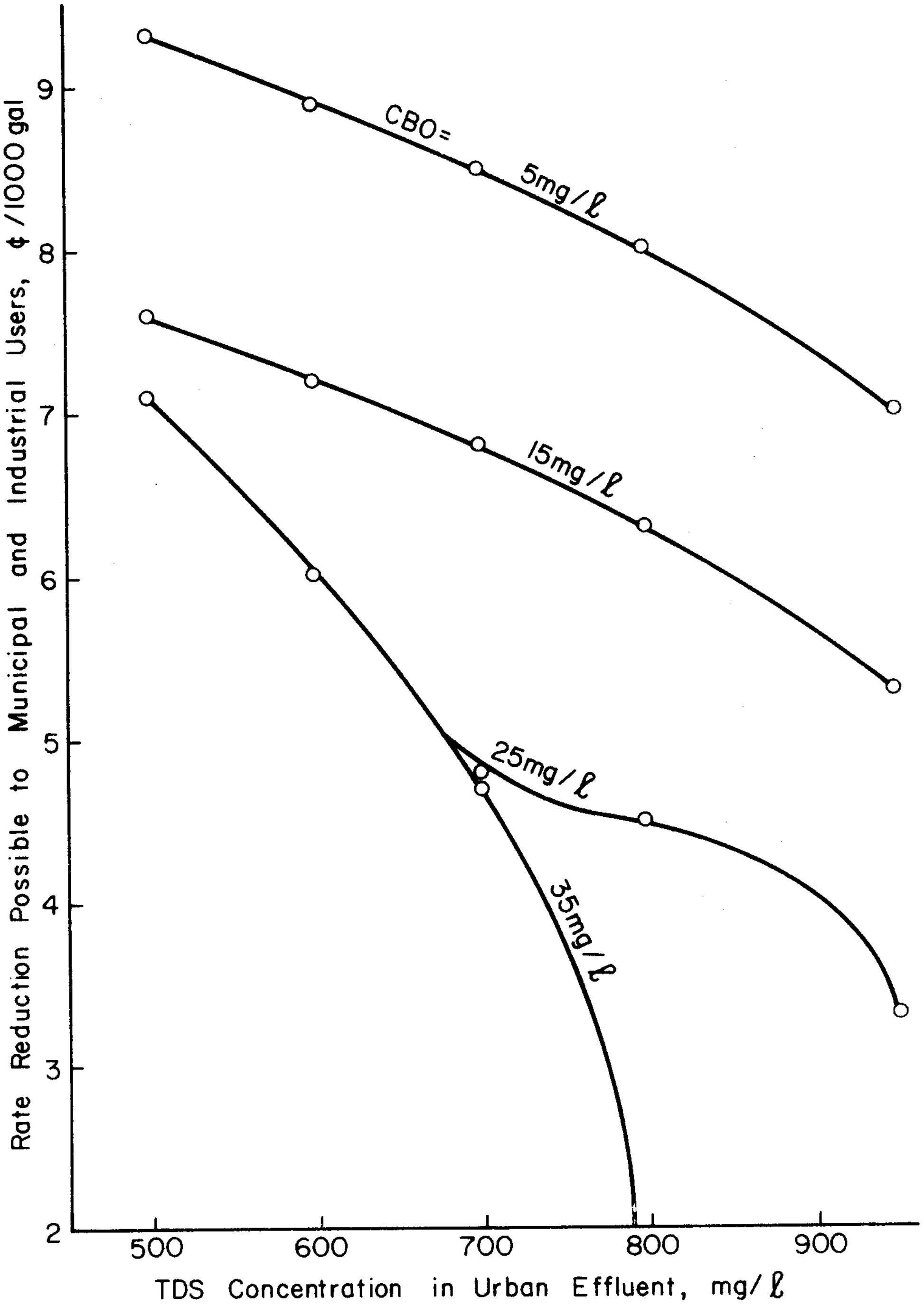

Figure 25. Possible rate reduction to municipal and industrial water users by implementing optimal strategies.

can be made for the costs associated with the other two alternatives, 1 and 2a.

First, a comparison of rates between the Alternative 2a policy and Alternative 2b is shown in Figure 26. At first glance, the array of curve shapes in this plot are confusing. However, keeping in mind that these curves reflect differences between curves with widely varying slopes the question may be somewhat alleviated. The significance of this plot is that it indicates the costs associated with the public attitudes regarding quality of recycled water, rather than recycling itself.

In the second example, the cost difference to water supply agencies between the Alternative 2b policy and the optimal Alternative 1 policy is presented in Figure 27. These curves are very significant to the water planner in an urban area (Denver, specifically) because they actually represent the value of the dual distributative capacity to the distribution system. For example, consider the condition where effluent BOD and TDS limits are set at 25 mg/l and 800 mg/l, respectively. From Figure 27, a savings of more than 2 million dollars could be realized if the dual systems should be installed in new developments and in the rehabilitation of existing networks. The extent and annual outlay for such construction is not indicated herein and is left to individual planners.

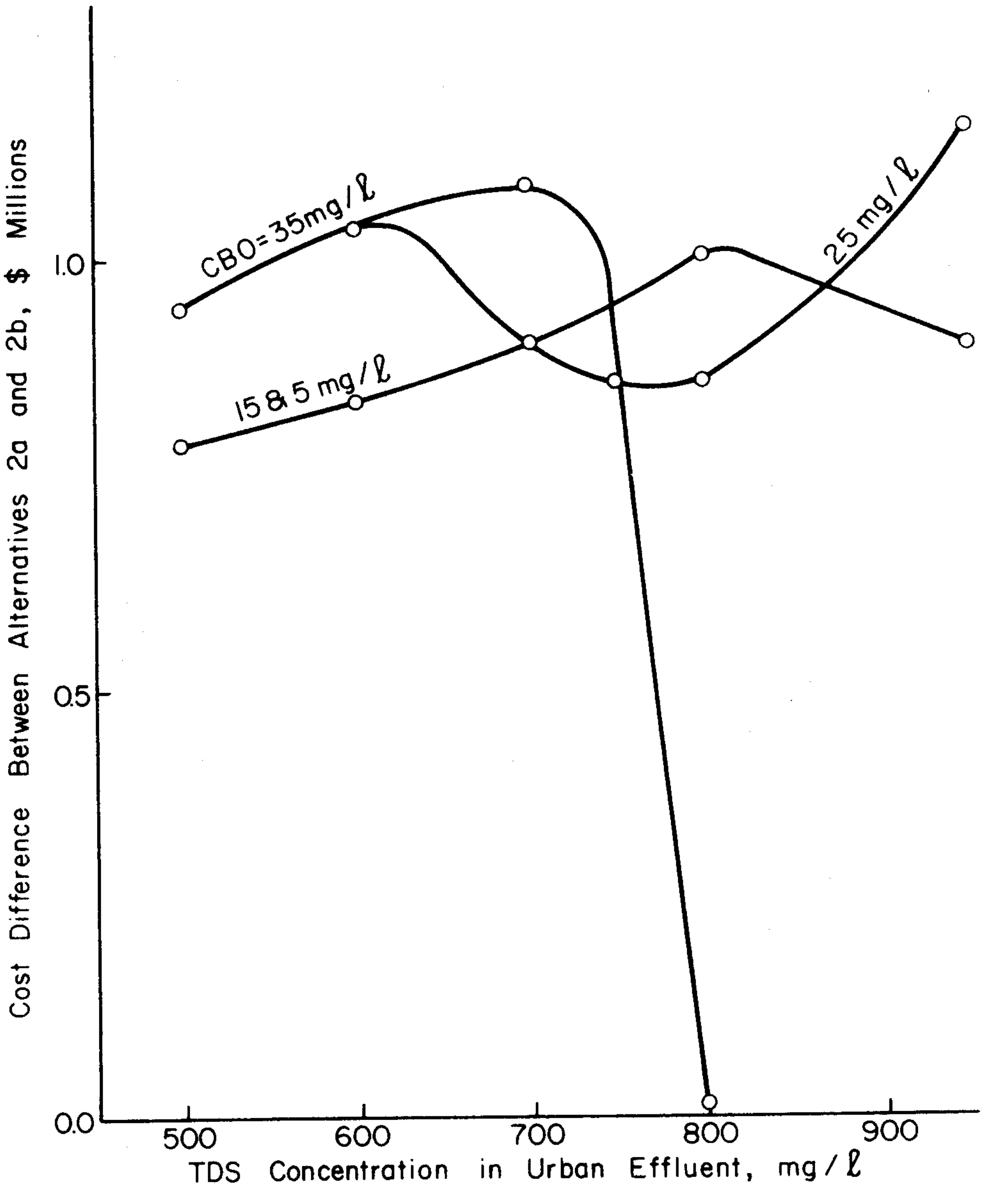

Figure 26. Cost difference between distribution Alternatives 2a and 2b.

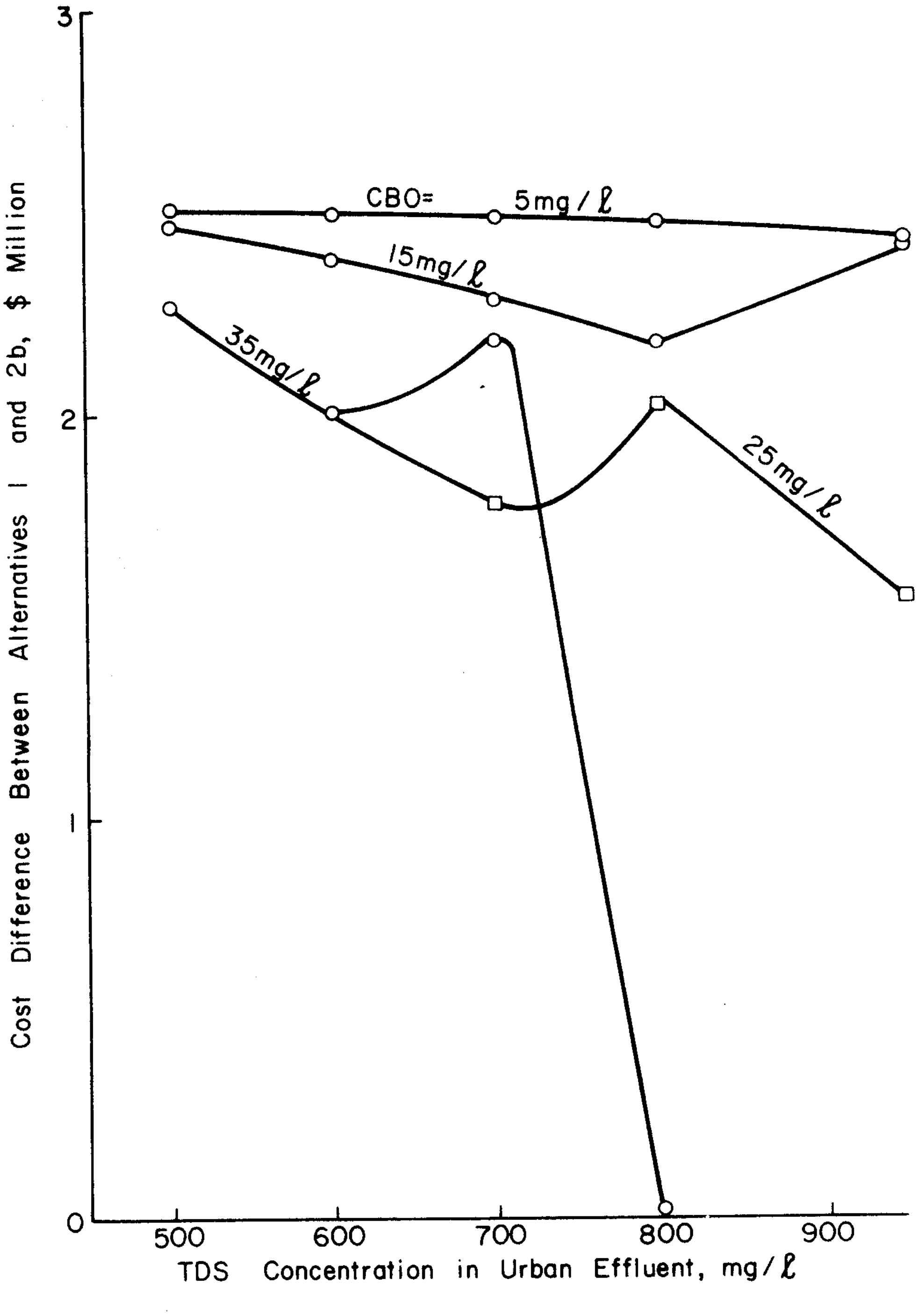

Figure 27. Cost differences between distirubtion Alternatives 1 and 2b.

Valuing Agricultural Water to Urban Users

One of the most interesting results obtainable from the modeling of urban water management decisions concerns the value that agricultural transfers have in the respective metropolitan uses. In Figures 15, 16, 17, 19, and 20 of the preceding sections, the optimal management policies at different levels of reuse were plotted, and it was clear that significant savings could be realized. However, reuse levels higher than 50% of the imported transbasin diversions would constitute a reuse of other in-basin water rights. Consequently, by varying the level of reuse allowable, it was possible to indirectly evaluate the effect of violating current water rights. Then, by comparing system costs at various levels of reuse, the costs of the right constraint could be determined. In addition, the difference between system costs for the reuse levels also indicate the value of additional inbasin stream flows to the urban user.

In order to demonstrate these results, the value of agricultural water rights to the Denver water user were computed and then plotted in Figure 28. The upper set of curves represent the value of this water to the total urban system when effluent BOD standards are at an anticipated level of about 15 mg/l. There are some apparent contradictions in these curves. First, the value of additional agricultural water decreases as the TDS restrictions on the effluent are relaxed. In fact, if the

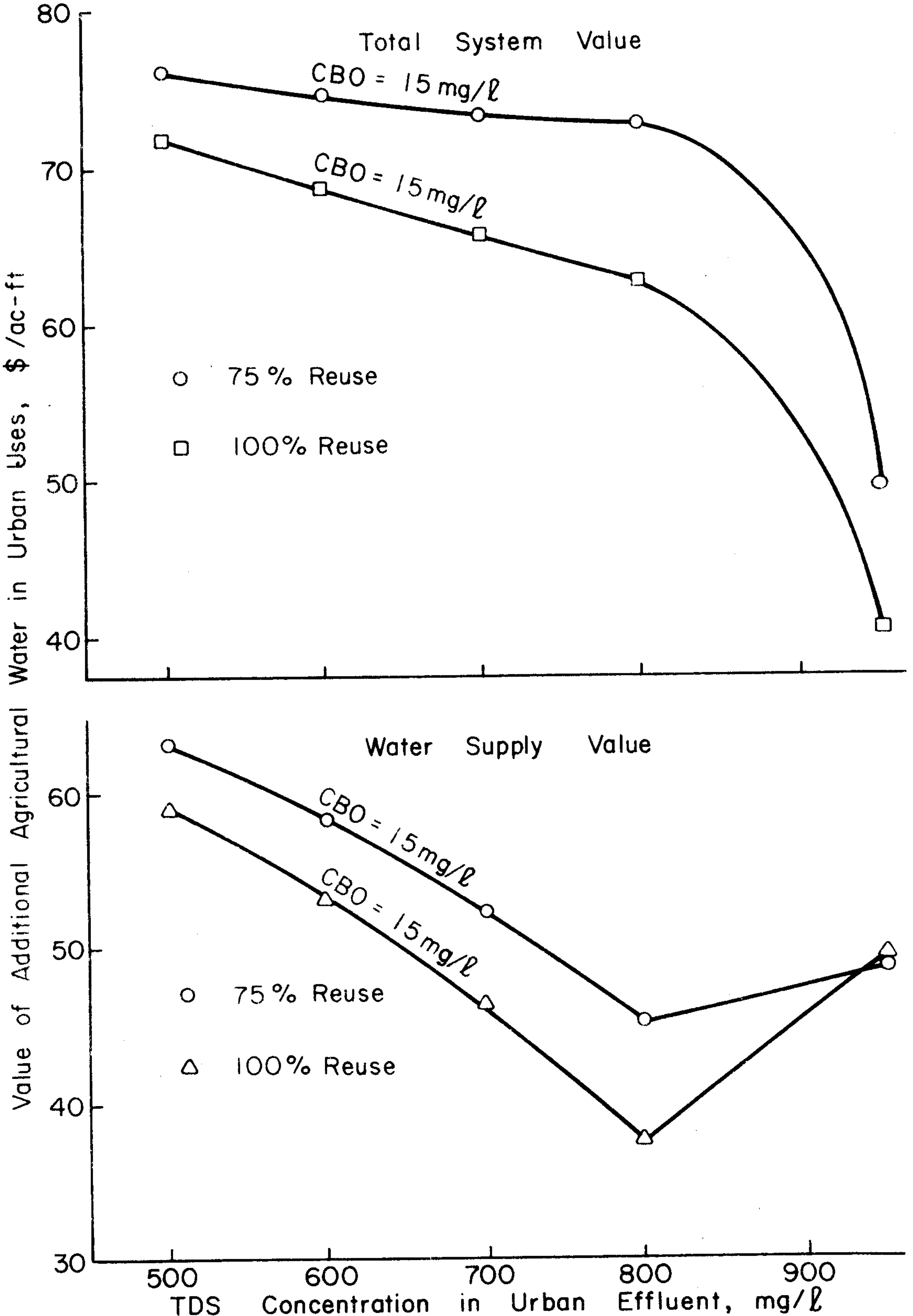

Figure 28. Value of agricultural water right transfers to the metropolitan water user.

constraints are completely relaxed, the value decreases markedly. Keeping in mind that these data were determined from the cost savings derived from allowing higher levels of reuse, the decline in values indicate the decreasing competitiveness of reuse with existing in-stream rights. Thus, as the TDS restrictions are relaxed, the costs of recycling wastewater increase and the overall savings gained from additional reuse are reduced. Another point of interest in these curves is that the 100% reuse level has actually a lower unit value than the 75% reuse alternative, even though an examination of Figures 15 to 20 would point out that the total savings were greater at the 100% reuse level. The curves in Figure 28 illustrate that agricultural transfers have characteristics of diminishing returns.

In the lower curves of Figure 28, the value of the agricultural transfers are shown in terms of the water supply system. The surprising point resulting from these plots is the fact that the supply value is significantly lower than the value to the total urban water system. From Figure 20 and 21 it was noticable that the total savings within the system were greater in the supply portion of the model than in the total system framework. This characteristic is thus another indication of the need to coordinate all aspects of urban water management.

Evaluating the Quality Aspects of Water Rights

Historically, there has been so much concern in the developing river basins of the west for preserving the quantitative aspects of water rights that the qualitative aspects may have been overlooked until the pollution problem reached crisis proportions. For example, the Colorado River Basin has been the scene of quantity conflicts since the early years of the century, but the quality aspects have only recently been under examination. Now, the quality aspects of water utilization may have become the more important consideration.

As new developments occur, or changes in the pattern of use are experienced, effects will undoubtedly be reflected in wastewater salinity levels. In an earlier section, the effects of reuse on effluent TDS levels in the Denver area were shown to vary between 50-250 mg/l, depending on the various parameters characterizing the system. Even with the deficient methods for detecting such changes, it is likely that recycling policies will be constrained by limitations such as those insisting that downstream quality not be deteriorated beyond historical levels. If this is the situation, desalination or mixing with interbasin transfers must be incorporated within the management strategies. The model was operated in a manner which would yield results illustrating the costs of these institutional constraints. When these costs were evaluated, it was noted that although they did not vary between the various strategies, the results were opposite with respect to water supply costs and total system costs. From the water supply viewpoint, an annual savings actually resulted by maintaining current TDS levels downstream amounting to about 0.5 million dollars annually over the range of effluent BOD concentrations. In the case of the total system, however, the data indicate that restricting TDS in this manner actually cost almost an additional 0.5 million dollars annually.

Organizational Consolidation

In much of the analysis presented thus far, the emphasis has generally centered around the optimization of both water supply and wastewater disposal operations. It has been tacitly assumed that a linkage between the two sectors could be arranged. However, the present institutional structure demands independently operated systems, which would possibly be inefficient in the future. Governmental management in the Denver area has already attempted to solve problems of this nature when several wastewater treatment systems were consolidated into the Denver Metropolitan Sewage Disposal Distract. A similar consolidation is necessary between the water supply and wastewater handling sectors as well. As with many of the institutional constraints evaluated thus far, such changes may be difficult to achieve but if not successfully attempted, the water users of Denver can expect significant costs for future water resources.

There are three primary areas where consolidation of management and operation responsibilities need to be accomplished in order to implement the strategies in this model. The first is the objective of water supply. Although Denver is by far the largest water supplier (almost 80%), it is necessary to test the feasibility of incorporating all agencies into a single unit. In this manner, the local discrepancies in water supply can be uniformally corrected to give more equitable service throughout the metropolitan area. The model described and used in this work has not included the capability for pricing the effects of this institutional structure although it may be of interest.

The second area for consolidation is in the area of sewage treatment facilities. The Denver area has already accomplished a great deal in this regard with the Regional Service Authority Act of 1972 which allowed the combination of several sewerage agencies into the Denver Metropolitan Sewage Disposal District. The costs associated with not operating in this manner do not only include the facility economics of scale, but also the costs of numerous operational and testing functions. To the extent additional consolidation is possible, it appears to be feasible. As water quality control requirements become more important, centralized treatment is advantageous from both a monitoring, as well as operational viewpoint.

The final consolidation consideration, that of joining water supply and wastewater treatment and disposal function, is of particular importance in the urban water model. Dependence between the two systems is shown as the quantities of water recycled. The costs of the reused water were based on consolidated treatment facilities and would thus be increased by the effects of the scale economics in these structures if the water supply agencies operated their own reclamation plants. The institutional costs of not performing system consolidating thus lies in these scale effects. The cost difference between tertiary and desalting plants in the model and those for separate systems for a typical situation in Denver would be about 0.5 - 1.0 million dollars annually. Thus, multipurpose treatment systems represent savings of 5 - 10% of the total annual water supply costs.

Projecting Present Analyses to Future Policies

Since the events expected to occur in the future cannot be assessed in a reliable fashion, the approach taken in this writing is to exhaustively examine current management decisions and exogeneous constraints on the behavior of optimal policies. Then, by means of extending this investigation towards future conditions, the foundations for rational decisions can be laid as they become necessary.

Optimal Policy Spaces

An analysis of decision points identified in the modeling revealed that the future policy spaces are almost identical with current ones. Thus, Figures 12, 13, and 14 are fair representations of optimal management schemes in the years to come. This may be initially surprising until it is recalled that the only changes made in the model inputs were demand increases. Since these were also proportionately the same, the optimal policy spaces could be expected to be the same. With homogeneous policy spaces, the shape of cost curves could also be expected to remain similar. An examination of the results in this regard substantiated this hypothesis.

Future Costs

As a means of expanding current conditions and costs to a future date, the ratio of present costs and the results of a future analysis was determined. Beginning first with the water supply costs as functions of time, the ratios for various times were computed for Alternative 2b with a fixed TDS level of 800 mg/l. The results of these calculations are shown in Figure 29. The variance reflected for different levels of water quality in previous plots is almost absent here. One interesting point can be made, however. Notice that the supply ratio decreases slightly with BOD concentrations. This characteristic follows the analysis of total water supply

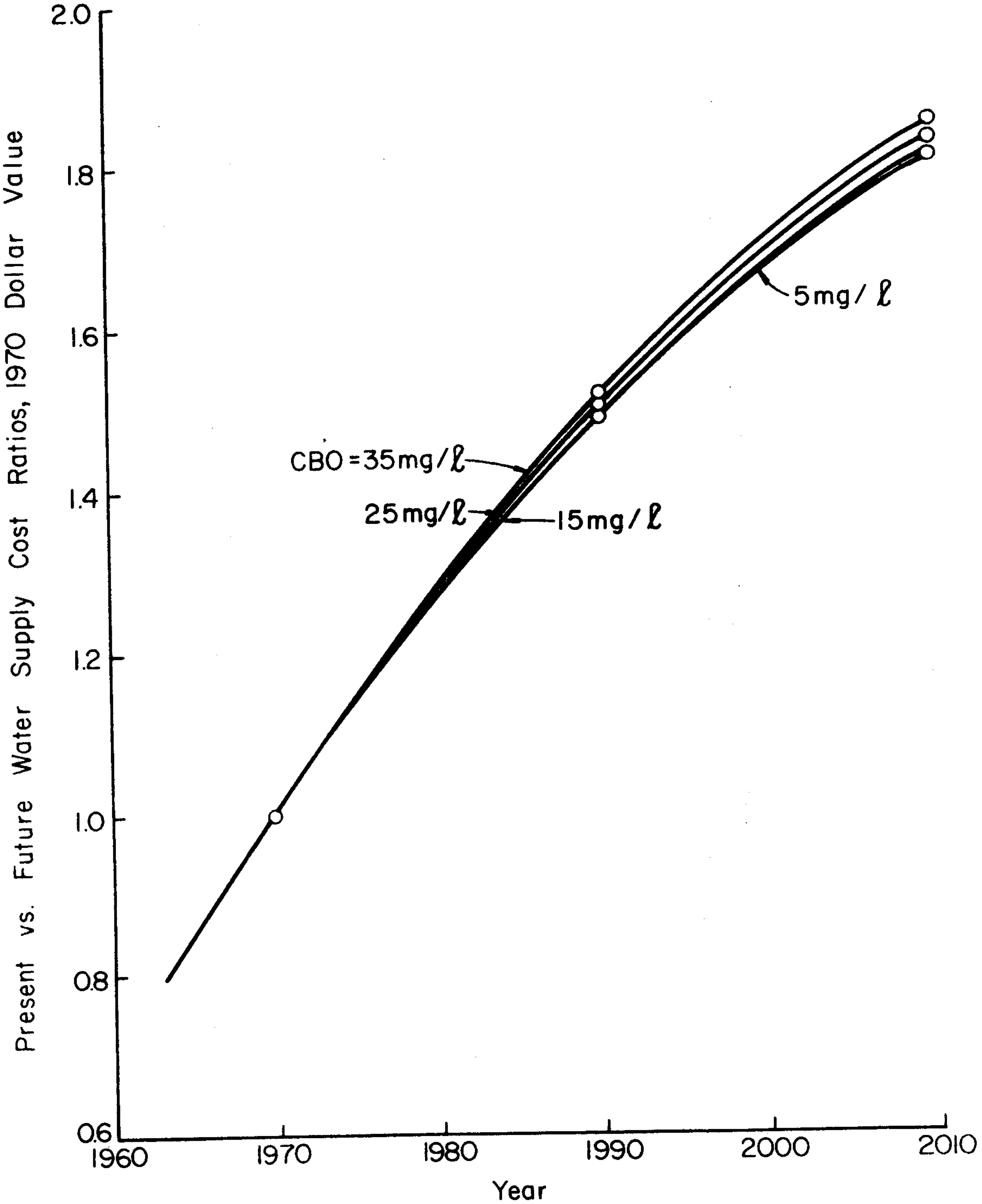

Figure 29. Ratios of present water supply costs to those expected in the future for Alternative 2b at a fixed effluent TDS level of 800 mg/l.

costs, which substantially decreased when more restrictive water quality controls were imposed upon the effluent.

This analysis was repeated for wastewater reclamation and treatment costs for Alternative 2b, which is presented in Figure 30. The condition is again similar to the change in total costs of wastewater treatment as a function of water quality produced. Almost no variation was found when ratios were computed for total system costs. As a result, the curves presented here can be used as an index to expected costs in the future. All data analyzed were in terms of 1970 dollar values and do not account for inflationary trends. These curves demonstrate the economies of scale associated with constructing the facilities to accomplish optimal water management strategies.

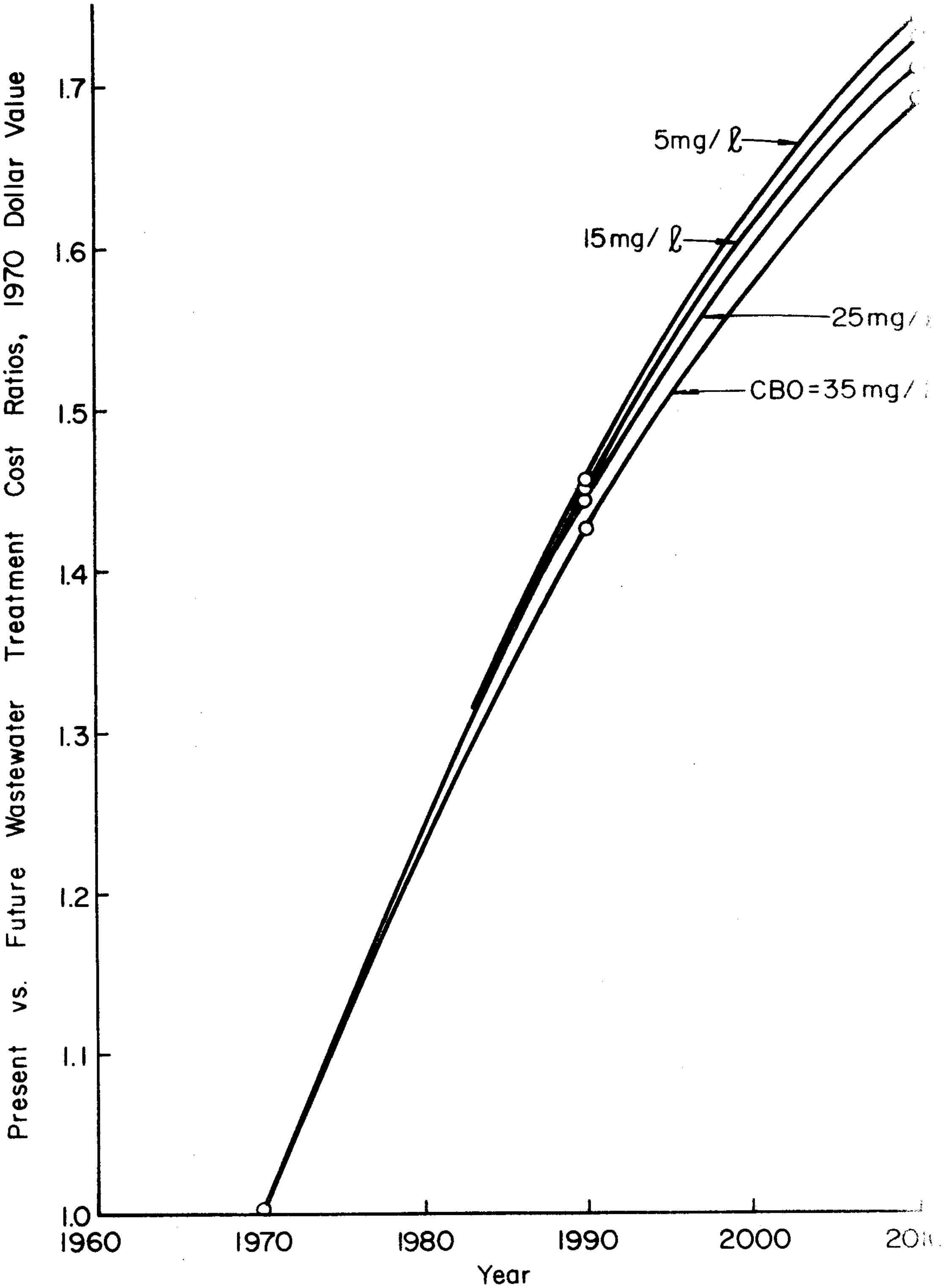

Figure 30. Present versus future wastewater treatment cost ratios for Alternative 2b at a fixed effluent TDS standard of 800 mg/l.

SECTION V

SUMMARY AND CONCLUSIONS

Introduction

An analysis of water management strategies has been undertaken for conditions encountered in the Denver, Colorado area. The purpose of the study was to test the utility of a urban water system model which integrates the management level characteristics of water supply, distribution, and wastewater treatment. From this analysis, alternative strategies for meeting the requirements of future conditions were tested and then the effects of various institutional constraints were determined. In this final section, a summary of the results and major conclusions drawn from this work are presented.

Summary

The urban water system is basically three interrelated subsystems: (1) the sources of water supply; (2) the individual urban demands; and (3) the collection and treatment of wastewater.

Current sources of water for Denver come from interbasin transfers and direct diversions from the South Platte River. In the future, however, the alternative of recycling the unused portions of the interbasin transfers and acquisition of agricultural water rights deserve careful attention. Linear costs amounting to 1¢/1000 gal for South Platte supplies and 10¢/1000 gal for the interbasin transfers out of the Colorado River basin were determined from planning reports and other similar studies. Then, these costs were compared with the costs of recycled water to determine the optimal combination of supplies which meet the urban demands.

In order to test the strategies involved with distributing water to the urban demands, three distribution alternatives were defined. First, Alternative 1 represented the case in which recycling would take place through existing raw water treatment facilities. Second, recycling to individual municipal and industrial demands was allowed, but restricted to an aggregate TDS concentration of 300 mg/l, the value for the domestic supplies. This scheme was termed Alternative 2a. And finally, Alternative 2b was outlined in which recycling was allowed directly to the municipal and industrial demands but at the relaxed TDS standards of 800 mg/l and 500 mg/l, respectively. These three alternatives were delineated to evaluate the effects of public attitudes and the costs of modifying the distribution system to allow for efficient allocation of water within the urban area.

The most important aspect of this modeling effort is the coordination of the wastewater treatment system with the water supply and distribution system through the vehicle of reuse. Various water quality standards were shown to substantially affect the costs of the recycled flows, and thus to significantly influence the broad water management strategies.

Optimal water management strategies were generated for a wide range of model inputs for each distribution alternative. From these results, three primary policies evolved which were compared to determine both the characteristics of the system and the effects of institutional factors involved with its operation. Initially, the costs associated with reclaiming and recycling wastewater were prohibitive and this supply alternative was not used. However, as the water quality standards on the urban effluents became more stringent, the economies of scale in the wastewater treatment facilities reduced the unit costs of the recycled water until it was feasible to use poor quality recycling. As the effluent standards forced implementation of more refined methods for pollutant removal, the costs of recycling eventually became feasible at any quality in the range of values examined, and it therefore became a part of the water supply and distribution policy.

Total system costs, as well as water supply costs, were determined for each distribution alternative over a range of effluent quality standards. These costs were then compared to determine the effects of various constraints and modes of operation. Since these results were generated for present conditions, the procedures were repeated for expected 1990 and 2010 conditions, and presented as multipliers of present costs to illustrate the effects of the model parameters in the future.

Conclusions

The major conclusions drawn from this work can be organized into three topics. First, the characteristics of optimal water management in Denver can be examined to better understand the basic nature of the strategies. Second, the array of institutional factors involved in administering water resources in the urban setting indicate the policies which can be implemented. And third, the conditions which can be expected in the future suggest the direction which should be taken to achieve effective water management.

System Characteristics

Because of the linear cost assumptions for both stream flows and interbasin transfers, the strategies in the urban water system model as it is applied to Denver are primarily ones indicating the trade-off between recycling and importations. The factors which affect the economic feasibility of reuse (effluent water quality standards) therefore act as prime variables in the integrated urban system. The annual water supply costs indicate that as BOD and TDS constraints on the urban effluents are reduced to 5 mg/l and 500 mg/l respectively, the implementation of recycling in Alternatives 2a and 2b will annually save the users between \$3 and \$5 million, a savings of about 10-20%. This savings, amounting to about 4-6 ¢/1000 gal, is somewhat misleading, however, as the total system costs (water supply plus wastewater treatment) actually increase by \$4 - \$5 million annually. Consequently, as water quality standards are imposed to force wastewater treatment to remove more and more of the pollutants, the money which must be spent will be substantial. It may be of interest to note that if coordination of water supply and wastewater treatment is not facilitated, the total system costs can be expected to increase about \$7 million annually.

There are certain characteristics of the urban water system which must be considered as part of any policy towards recycling. For example, if reuse is introduced as a source of water, it will be characterized by TDS concentrations more than twice the same levels in interbasin transfers or streamflows. The net result will be that overall water quality to the urban demands will be deteriorated to the permissible limits. These effects are certainly to be reflected in the outflows from the urban area. An assumption was made that these effects would be proportional, and the results indicated that TDS concentrations could be expected to increase in the outflows between 50 and 250 mg/l for Alternatives 2b and 1, respectively. However, the nature of these increases was not examined and may be of interest in further studies, since downstream interests would resist degradation in their water supplies.

Evaluation of Institutional Factors

The complex economic, legal, political, and social structures formulated to accomplish equitable allocation of water resources need periodic evaluation to insure that improvements are being made which result in more effective water use.

Public attitudes towards water management alternatives are undoubtedly the most important factors affecting future policies and must therefore be evaluated. Occassionally, public decisions are made which are detrimental to themselves under long range considerations. As a result, it is important that these decisions be made with full knowledge of the alternatives. One of the principal decisions to be made concerns the question of recycling. If the system conditions change to the point where recycling is indicated, the savings realized by recycling will be substantial as noted previously. However, the methods employed to accomplish recycling are also of importance. For example, if recycling in accordance with Alternative 1 rather than Alternative 2b is selected, it will cost about $2 million more annually. In addition, if Alternative 2a is allowed, additional annual costs of $1 million will be incurred. As a result, it is advantageous for recycling to be facilitated in the manner suggested by Alternative 2b.

These effects amount to about 5-10% of total water system costs in most cases, but have far more important implications.

Water is becoming a scarce resource not only because the supply is diminished through increased depletions, but also because the quality is being degraded to the extent that the more sensitive uses are unable to use these flows. A need therefore exists to consider setting priorities based on the sensitivity of various water uses to water quality. In the urban environment, this can be accomplished by supplying industrial and municipal demands with poorer quality water, while using the best water for domestic uses. Such a policy will reduce rates if implemented, especially to the municipal and industrial users, which may realize as much as a 5-10 ¢/1000 gal reduction.

Another institutional factor considered was the value of agricultural water to the urban user. Transfers have not been widely attempted to date, but may be necessary in the future. By allowing higher levels of reuse than are currently permissible, an indication of this value is gained. The results of this study indicate that this water is worth about 60-70 $/ac-ft to the urban system, but only 40-50 $/ac-ft to the water supply agencies. This source of water exhibits decreasing marginal value with scale, so large transfers are not desirable. It should be noted however, that these values do not suggest unlimited transfer from agricultural to urban use, but rather the price the urban user can pay to acquire such rights.

Finally, the costs of constructing and then operating and maintaining the facilities inherent in urban water systems are very substantial expenditures in the budgets of metropolitan areas. These systems generally exhibit some economy of scale, which suggests that water management be consolidated to the extent possible. In addition, close coordination should be made between the individual sectors of the system to realize the benefits of recycling.

Future Policies

Although the events of the future remain unknown, plans must nevertheless be formulated to insure the ability of the urban system to satisfy its water demands. Denver has rapidly expanded in recent years and this growth is expected to continue in the future. As a result, the question of future water supply and sewerage are important.

Federal water pollution control policies are certain to require greater pollutant removal efficiencies in the future, so recycling must be considered as the prime water source for the future. Results of this study were projected into expected conditions for the years 1990 and 2010 and suggest little change in the strategies outlined for the immediate future. However, new advances in technology and the probability of population control in metropolitan areas cannot be included in such predictions. Thus, a need exists to repeatedly review the situation.

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