IMPACT OF IRRIGATION EFFICIENCY IMPROVEMENTS ON WATER AVAILABILITY IN THE SOUTH PLATTE RIVER BASIN

by

M.W. Bittinger
R.E. Danielson
N.A. Evans
W.E. Hart
H.J. Morel-Seytoux
M.M. Skinner

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COLORADO WATER RESOURCES RESEARCH INSTITUTE

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Environmental Resources Center
Colorado State University
Fort Collins, Colorado

Norman A. Evans, Director

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PERSONNEL

Leader: Norman A. Evans, Director
Colorado Water Resources Research Institute

Manager: Morton W. Bittinger, Vice Pres.
Resource Consultants, Inc.

Staff: (all CSU)
William E. Hart, Dept. of Agr. Engr.
Robert E. Danielson, Dept. of Agronomy
Morris M. Skinner, Dept. of Civil Engr.
Hubert Morel-Seytoux, Dept. of Civil Engr.
Charles J. Daly, Dept. of Civil Engr.
Tissa Illangasekare, Dept. of Civil Engr.
Abdallah Bazaraa, Dept. of Civil Engr.

Advisory Committee:

George Lamb, State Drought Coordinator
Charles Calhoun, U. S. Bureau of Reclamation
Ted Hurr, U. S. Geological Survey
David Carlson, Colo. Dept. of Agriculture
C. J. Kuiper, State Engineer
Frank Akers, Colorado Water Conservation Board
Bill McDonald, Colo. Dept. of Natural Resources
Earl Phipps, No. Colo. Water Cons. Dist.
Gary Friehauf, Lower So. Platte Water Cons. Dist.

Others: Many other individuals were interviewed and provided information important to this study. These individuals are listed in the report at the appropriate places.

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P R E F A C E

EFFICIENCY OF WATER USE--AN OVERVIEW

By Norman A. Evans

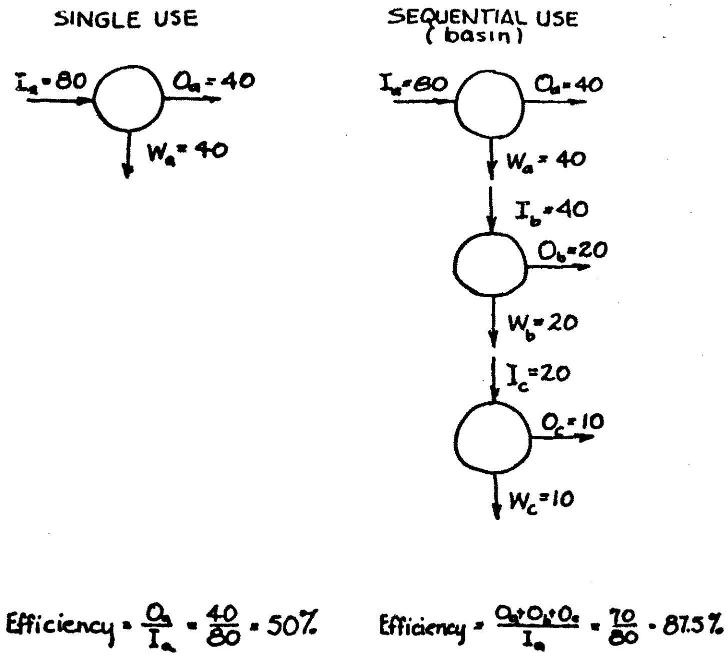
Water-use efficiency is used to describe how well the resource is conserved or utilized. Higher efficiencies in particular uses are assumed to have the effect of releasing unneeded resources for use by others. The purpose of this study is to examine that question as it applies to water in the South Platte River Basin.

Efficiency is evaluated by dividing the quantity of output from some given system by the quantity of input. A high efficiency implies that there is little waste involved in the system. In the case of water systems, if a high proportion of the water withdrawn from supply for a particular use is utilized in that use, the efficiency is said to be high. Although this concept is useful, its indiscriminate use can be deceiving.

For example, a high proportion of waste through deep percolation and surface runoff from an irrigated farm would result in a low irrigation water-use efficiency. This waste may be a real one to the individual farm, but the water is still contained within a larger hydrologic system of which the farm is merely a part. The water is not lost to the larger system; it is merely routed differently through the system. High seepage losses in conveyance or through deep percolation and surface runoff are not critical in terms of reducing the total water supply for a basin. It is true that its rerouting affects water distribution with time through the basin; this may be a benefit. There may be a loss of quality, however.

Extrapolation of efficiencies from a single user to regional or basin-wide efficiency would give misleading indications of new water supplies that could be available through adoption of efficiency measures. This is because one user's waste may be another user's supply.

The following diagram compares the efficiency concept applied to a single use for that of a larger system where several single uses are tied together in sequence, as is the case in a river basin. It is quite evident when the net output is compared to the net input for the basin, the calculated efficiency is quite different from that for an individual use by itself.



While aggregated systems are much more complex than indicated in the diagram, such sequential uses are the common pattern in western river basins. The South Platte Basin is often described as the most complex sequential or reuse system in the entire western region. The important point to recognize is that an efficiency measurement is associated with a very specific boundary. Its implications must be viewed likewise in terms of the same boundary. High efficiency may be very meaningful to the single user in terms of volumes of water to be handled(because of associated costs - treatment, delivery), while from the viewpoint of the entire basin it may be insignificant.

In discussing water uses, it should be emphasized that all uses are not consumptive. Legitimate and beneficial uses range from "contact" and "in-stream" uses (boating, swimming, fishing); to withdrawals which do not consume (hydro-power); to withdrawals which consume (irrigation, municipal, industrial). The efficiency criteria can not be applied with the same meaning to all these different uses.

Efficiency criteria as applied to water use has not incorporated quality considerations. Yet quality is a key element today in water management. Referring again to the diagram of single and sequential uses, if the first withdrawal contains water having 100 ppm of dissolved solids, and if the output is evapotranspiration through growing crops, the dissolved solids must be carried out of the first individual system by the water identified as "waste." Thus the concentration of dissolved solids in the supply to the second individual user will be 200 ppm unless salt accumulation is allowed in the first system. Each sequential user will receive a water supply of lesser quality compared to the preceding user. The quality factor is not normally reflected in efficiency terms, yet it has significant economic impacts.

In a limited sense the economic efficiency of a specific water use is reflected by the ratio of dollar output per unit of water input. In the case of irrigation, the yield of agricultural product per acre-foot of water withdrawn from supply would represent the economic efficiency relative to water use. In this connotation the most efficient use would be that which adds the greatest value to the general economy.

Institutional and legal circumstances have an important influence on how well a given water supply can be made to accommodate all legitimate uses. If these elements are flexible and up-to-date, they can facilitate improvement in efficiencies of water use. If not, they can be a serious deterrent to improvements even though technical and managerial options may be available.

IMPACT OF IRRIGATION EFFICIENCY CHANGES ON WATER AVAILABILITY IN THE SOUTH PLATTE RIVER BASIN

I. INTRODUCTION

As the competition for limited water supplies increases, interest in achieving higher efficiency of water use is a natural result. Thus it is natural that efficiency of irrigation water use is becoming specifically of interest in Colorado, because irrigated agriculture is the largest user of water in a rapidly growing, water-short, state.

The Colorado Department of Agriculture Commission recognized the need to obtain more information about potential water saving in irrigated agriculture by passing the following motion at its regular meeting held May 20, 1977:

> To seek available information regarding the efficiency of the present delivery system for irrigated agriculture, to determine those system improvements, technological advancements and changes in irrigating practices which could be applicable to the present system, to evaluate the water consumption efficiencies to be gained, and to recommend actions, federal programs, legislative initiatives, and education programs deemed appropriate as a result of this investigation.

The motion led to a study funded by the U. S. Bureau of Reclamation pursuant to the Emergency Drought Act of 1977. The Bureau of Reclamation made the funds available to the State Drought Coordinator, Office of the Governor, who in turn contracted with the Colorado Water Resources Research Institute (WRRI) to conduct the study.

Purpose and Objectives

As stated in the agreement between the Colorado WRRI and the State Drought Coordinator, the purpose of the study is to:

> . . . provide the State with information on hydrologic and economic impacts of applying efficiency criteria to the irrigation conveyance, distribution and application system of the South Platte River Basin.

Specific objectives of the study are:

1. To adapt and expand the current CSU computer model for conjunctive management of a surface-ground water supply to the assessment of hydrologic impacts of improved irrigation water-use efficiency in the South Platte River Basin, and

2. To operate the conjunctive model with a range of assumed "efficiency" improvements in delivery, distribution and application systems and in irrigation water management practices so as to evaluate the basin-wise hydrologic impacts and costs.

Method of Approach

Many complex interacting factors must be considered in order to properly evaluate the benefits of increasing efficiency in irrigation. The larger the area considered the more this statement is true. The loss of water from one field or farm is often a part of the water supply historically used on other farms. Likewise, all seepage losses from ditches and reservoirs are not necessarily losses to a river reach or a basin.

In order to adequately take into consideration even the major interactions in an area of any size it is necessary to be able to compute the effects of the many interactions in both space and time. This requires development of a mathematical model which must be solved on a large computer because of the mass of data and the complexity of the calculations. For this study, a mathematical approach developed by Dr. Morel-Seytoux was chosen to be used. This model approach is described in general in a later section of this report along with references to more detailed descriptions.

A specific study area and base time period were selected for use in the model. These choices, described in detail below, were made principally because of availability of data. No inference should be drawn that the efficiency of irrigation and irrigation systems in the study area is better or worse than any other portion of the South Platte River Basin.

II. IRRIGATION WATER-USE EFFICIENCY

Irrigation water-use efficiency can be discussed and defined from several standpoints. From the standpoint of an individual farmer, the efficiency of use once he has taken delivery of the water from the irrigation company canal (and/or a well) is the only part of the entire system over which he has some direct control. These on-farm efficiency considerations, field irrigation efficiency and farm irrigation efficiency, are discussed in following sections.

From the standpoint of the canal and reservoir companies, the efficiency with which the water they are entitled to can be diverted, conveyed and delivered to the farm headgates is of interest. This is discussed below under the heading "Canal and Reservoir System Efficiency."

From a broader standpoint, one needs to be also concerned about efficiencies of water use on a larger scale, such as for an entire river reach or river basin. These concepts are discussed below under the headings "River Reach Efficiency" and "River Basin Efficiency."

Water Use in Crop Production

Water from the soil is absorbed by the plant root system and a very high proportion of it is transferred through the plant to the leaf surfaces where it is evaporated and lost to the atmosphere as water vapor. This process is universally referred to as transpiration. Although most of the absorbed water is ultimately transpired, a small but very important amount is used in metabolism and growth by the plant. Plant growth is a result of many complex processes within the various tissues, and the rate of these processes, and thus the growth rate, is determined by genetic and environmental factors. One of the most important environmental factors is the internal water balance within the plant cells. This water balance is a result of the relative rates of water uptake by the root system and the loss of transpired water from the leaf surfaces. As soon as absorption from the soil lags only slightly behind transpiration, a water deficit in the plant occurs and a decrease in the quantity or quality of growth results.

Thus, the production of high yielding crops requires a continued supply of readily available moisture in the soil root zone so that, even when the evaporative demand is high, water deficits in the plant are minimum. The principle purpose of irrigation is to maintain the soil-moisture level at sufficiently high values to meet the plant uptake requirements for maximum transpiration.

In addition to transpiration of water through the plants, some water is consumed in crop production by direct evaporation from the soil surface. To some extent this evaporation reduces transpiration because the relative humidity of the air within the crop canopy is increased. Consequently it has become customary to refer to the consumptive water use by crops as the sum of evaporation from the soil and of transpiration from the leaves (evapotranspiration). Evapotranspiration (ET) is dependent almost exclusively on meteorological conditions throughout the crop growing season if soil moisture does not become a limiting factor to water uptake by the root system. When soil moisture is reduced to such a degree that root absorption cannot meet the ET demand, a plant water deficit develops, leaf stomates partially close, and transpiration is restricted to the rate of root absorption. Plant growth and subsequent yield of the crop is reduced somewhat proportionally to the degree of plant water stress.

The amount of water used in the production of a crop may be expressed in many ways. The water actually consumed is simply that evaporated into vapor (from plant stomata or the soil) or converted into plant tissue. However, it is usually more meaningful to include water having other fates, such as runoff from the field or deep percolation through the soil to points below the root zone. In irrigation water management it is usually of great concern to determine the efficiency with which the water supply is used in crop production.

In the following sections various aspects of irrigation-water efficiency are discussed.

Field Irrigation Efficiency

Field irrigation efficiency has been defined for this study as:

$$\text{Field irrig. eff.} = \frac{\text{Volume of crop evapotranspiration}}{\text{Volume of water delivered to field}}$$

Several factors which affect field irrigation efficiency are discussed in the following paragraphs. Some of these can be altered by management and others can not. Two specific types of losses which decrease the field efficiency and which may be altered by management are those of deep percolation below the root zone and surface runoff from the field.

Soil type

Perhaps the most influential factor affecting the field irrigation efficiency, and which is generally only slightly alterable by management, is the soil type. Two very important soil properities are involved.

Soil water-holding capacity. The ability of the soil to hold water available for plant uptake is determined by the texture and the soil depth. In general, sandy soils have low, loam soils high, and clay soils intermediate available water-holding capacities. Typical values expressed as inches of available water per foot of soil are given in Figure 1. When the soil has a low capacity for holding water, due either to texture or depth, there is a much greater potential for loss of water by deep percolation. The irrigation application requirement must necessarily be low, and the ability of the irrigator to apply the correct amount without excessive leaching is considerably more difficult regardless of the application method used. Essentially nothing can be done to alter the water-holding capacity of a soil.

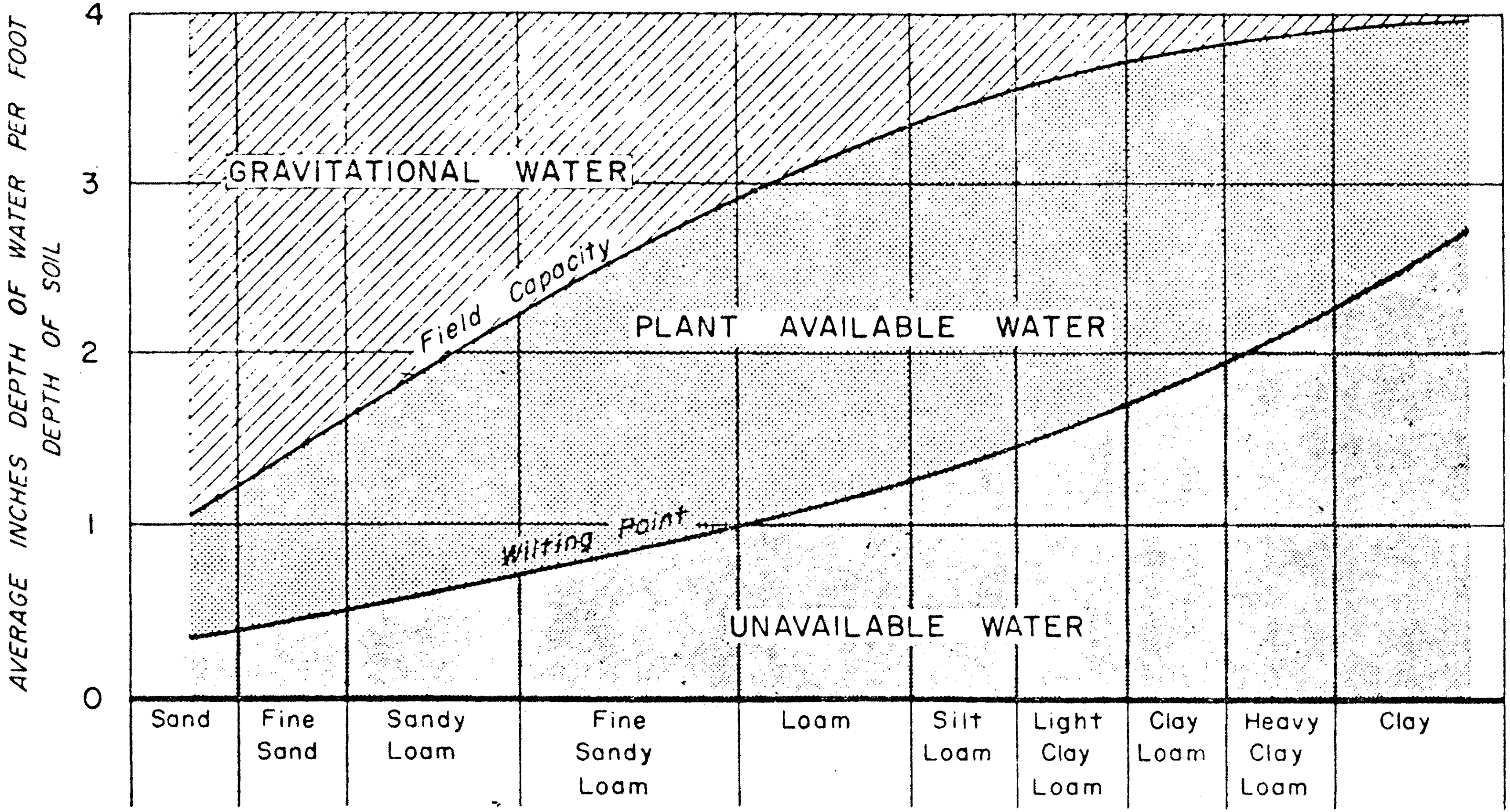


Figure I-1. --Typical water characteristics of different-textured soils.

Soil intake rate. The water intake rate of the soil influences, to a great extent, water losses from the field due to both runoff and deep percolation. If the intake rate is excessively low, it is difficult to irrigate without "tail water" running off the lower end of the field. The time that water must cover the soil in order to apply the required amount to recharge the root zone is increased by low intake rates, and, unless very special precautions are taken, this cannot be accomplished without runoff using surface irrigation methods. If the intake rate is excessively fast, it is difficult to uniformly recharge the soil moisture from one end of the field to the other without excessive application, and resultant leaching, at the upper end of the field. The use of sprinkler irrigation is usually the best procedure for preventing low field irrigation efficiencies when intake rates are very high. Intake rates are influenced to a great extent by surface soil texture but also by other factors influencing soil structure, compaction, aggregate dispersion and soil cracking. Management practices can be used to control, within limits, the intake rate of soils, but it is impossible to prevent some change in this property throughout the irrigation season as well as between years when different crops are grown and different tillage practices are required.

Surface contour and slope

Deep percolation and field runoff of irrigation water are both influenced by land topography. If the land is nearly level, as may be the case on alluvial soils near the river, it is difficult, with the small water-flow rates usually available in the lower South Platte Valley, to apply sufficiently large streams in furrows or border strips to cover the "set" before excessive penetration takes place at the head ditch end of the field. On the other hand, if the slope is steep, runoff at the lower end is essentially impossible to avoid before adequate water has been applied. Non-uniform slopes and land with high spots or swales make attainment of high field efficiencies difficult unless sprinkler or trickle irrigation is used or the land is reformed for efficient surface irrigation. This latter approach can be quite beneficial.

Type of crop

The influence of type of crop on field irrigation efficiency is chiefly one of dictating the method of irrigation water application. Row crops, such as corn, sugar beets, beans, sorghum, etc., are irrigated by the furrow method. Close-growing crops, such as pasture, alfalfa and small grains, are flood irrigated. Any crop may be sprinkler irrigated providing the sprinkler system used conforms satisfactorily to the height of the crop.

The type of crop also influences the frequency of irrigation and the depth of water required at each application. Alfalfa, a perennial crop that can establish a very deep root system, is ordinarily irrigated less frequently. Potatoes must have a relatively wet soil during the entire growing season if good quality tubers are to be produced, and thus they require frequent, light applications. (Light applications are often associated with low field irrigation efficiencies.) Corn develops a deep root system capable of removing water from the lower subsoil depths. It can thus, although to a lesser extent than alfalfa, utilize large, infrequent irrigations. Field beans, on the other hand, have a comparatively shallow root zone and require small depths of water applied at frequent intervals. Although field efficiencies may not be greatly affected when proper precautions are taken, depth of application is a real consideration.

Method of irrigation

Three general methods of irrigation are employed in the production of crops in Colorado: furrow, flood and sprinkler. Each of these are used with variations depending upon crop type, land slope and the personal desires of the farmer. Characteristically, sprinkler applications are associated with the highest field irrigation efficiencies, and flood methods with the lowest. However, in most cases, the attention and care exercised by the irrigator can cause far greater variation in irrigation efficiency than will that of the method employed.

When the land surface slope is variable, with high spots and steep slopes, a wild flooding application is frequently used. Large deliveries are usually required to force the water to the higher elevations and field runoff commonly results. With proper design and location of field ditches the tail water may be picked up and redistributed to maintain relatively good efficiency. When fields are of moderate and uniform slope in one direction, the border dike method of flood irrigation can be utilized to provide very high field efficiencies. Again, however, the result is largely governed by how well the irrigator controls the stream size, by the width and length of the border strips and by the time of set.

Application efficiency when using furrow irrigation may also vary appreciably. If the furrows are directed down steep slopes it is difficult to prevent field runoff. Contour furrows, running in general across slope, greatly increase the potential for uniform application of the desired water depth. Close attention to water control and proper field layout are essential.

Sprinkler irrigation provides the best method for water control and uniform application, especially on lands of variable topography and soil characteristics. Caution is required, however, to prevent application rates in excess of soil intake rates. If this occurs, runoff results and attained efficiencies may be considerably below attainable efficiencies. Thus, the sprinkler systems which are common to Eastern Colorado (i.e., center-pivot systems), with their inherent high application rates, are limited to the coarser textured soils which have high infiltration rates.

Whatever method of irrigation water application is employed, certain precautions and design techniques may be used to improve efficiency. Proper farm ditch locations, field design, stream size and cut-back techniques can be specified by trained irrigation technicians. Collection of runoff water into ditches for subsequent redistribution or into tail-water reuse pits, where it can be pumped back to the upper end of the field or directed to another field, is becoming increasingly popular with concerned irrigators.

Limits to field irrigation efficiency

It is important to recognize that the upper limit of irrigation application efficiency, even under the most ideal field conditions, is limited by the natural variability found in soil conditions. Soil intake rates vary from one place to another so it is impossible to apply the desired amount at one location without applying more than is needed at another location. Some drainage below the root zone necessarily results. Under furrow irrigation, tractor or implement wheels compact some furrows resulting in greatly decreased intake rates. It is practically impossible to have the intake time the same at all points along the length of the field. Thus, it cannot be expected that irrigation efficiencies should be above 70 to 75 percent if the entire irrigation requirement is met.

Soil salinity control under irrigated agriculture is an important management factor. The only satisfactory control measure is to periodically leach the soil salts below the crop root zone by the application of excessive irrigation water. By the above definition this decreases the field irrigation efficiency, but it is a necessary requirement for obtaining profitable yields.

Under many geological conditions in irrigated areas the "loss" of water to deep percolation is not a total loss. The ground water may flow to streams where it is again available for public use, or it may be pumped for reuse at the surface. In fact, the storage of ground water resulting from over-irrigation, and its rate of controlled release for reuse, may be an important factor in water management of an irrigated basin.

Farm Irrigation System Efficiency

Farm irrigation system efficiency includes in its definition the losses in the delivery system from the farm turnout on the canal system to the irrigated fields. All other components are the same as for field irrigation efficiency. Thus,

$$\text{Farm irrigation system efficiency} = \frac{\text{Volume of crop evapotranspiration}}{\text{Volume of water delivered to farm turnout}}$$

The losses along the farm conveyance system are of several kinds, but perhaps the greatest is seepage from ditches. Although seepage can be reduced by lining or surface treatment, it is not usually done because of high initial costs of lining material and the labor for installation.

Another loss, that of overtopping (spillage), can occur if ditch banks are not properly maintained. These losses can cause bank erosion and eventual bank failure with an associated loss. The problem is exacerbated if weeds are allowed to grow in the ditch, thus causing higher resistance to flow resulting in an increased flow for a constant depth for a given discharge.

Weeds outside the ditch cause an additional loss--that due to phreatophytic water use. Their removal of seepage water can increase the hydraulic gradient between the canal and the surrounding soil and thus increase seepage losses. They also prevent seep water from reaching the ground water for later pumping or return to the river.

Because one turnout may serve more than one field, additional losses may occur if there are leaks at farm gates. A neighbor may receive leakage water, or the farmer may have some of his water delivered where it is not needed or can not be used effectively.

A most important factor is the timing of water delivery to the farm. If sprinklers are used, economics dictate a relatively constant delivery rate during the irrigation season. If surface irrigation is used, it is necessary to have high flow rates, but unless the farm is quite large, only periodic deliveries are needed or can be used. If surface deliveries occur when water is not needed, such as after a substantial rain or during periods of low crop demand, that water which is not used by the system is wasted whether by diversion down a drain gulch or through application and subsequent deep seepage or runoff. Thus, it behooves the farmer to select cropping patterns with requirements which will in some way match his expected water delivery schedule.

The above comments pertain principally to farms and fields irrigated with surface water from mutual canal and reservoir systems. Some of the factors causing reduced efficiencies are overcome on farms and fields irrigated from wells because of shorter delivery canals and the capability of applying water on demand according to crop needs.

Canal and Reservoir System Efficiency

Canal and reservoir system efficiency can be defined as the percentage of water diverted from the river that is delivered to farm headgates or turnouts on the system. The principal factors that influence canal and reservoir system efficiency are (1) evaporation, (2) transpiration, (3) seepage and (4) operational losses.

Evaporation

Evaporation is defined as the process by which water is changed from the liquid into the gaseous state through the transfer of heat energy. At every free water surface, whether in a reservoir or a canal, there is a continuous interchange of water molecules across the free water surface. When the net sum of the interchange of the water molecules represents a loss from the water, there is evaporation. The evaporation rate is expressed in depth of water measured as liquid water removed from the free water surface per unit of time. The average annual evaporation rate from open water surfaces for the Balzac-to-Julesburg reach has been estimated to be about 50 inches per year.

Evaporation rates from free water surfaces have been established for specific areas using a "standard" circular pan, which is installed on the ground as a land pan or in the water as a floating pan. The U. S. Weather Bureau Class A pan is 4 feet in diameter and 10 inches deep. Theoretical approaches to the prediction of evaporation from free water surfaces involve equations representing mass transfer processes and energy transfer. Evaporation rate has been directly related to air and water temperature and wind speed.

Evaporation from open water surfaces is extremely high in the warmer regions of the United States. Values on the order of 90 inches per year and 80 inches per year have been recorded for southern California and southwestern Texas, respectively. A great deal of research has been conducted during the past several years on different methods for retarding evaporation from free water surfaces. Some reduction in evaporation has been accomplished by using thin films of chemicals spread over the water surface. Evaporation retardant processes are fairly expensive and are not being used extensively at this time. Operation of the water conveyance and storage systems, however, can be operated with the concept in mind that large, relatively shallow open water areas are susceptible to relatively large evaporation losses, particularly during the warmer seasons.

Transpiration

Transpiration is defined as the process whereby the water absorbed by the root system of plants is discharged to the atmosphere as a vapor from the plant leaves and other surfaces. Most of the water absorbed through the roots is discharged from the plants in this process. Only about one percent of the absorbed moisture is retained in the plant tissue. The annual transpiration rate for a given vegetative type is expressed in depth of water for the given area of a specific vegetative cover. The transpiration rate varies directly with the density of plant growth, the amount of sunshine, plant vigor and available moisture supply. Transpiration is essentially nonexistent below 40 degrees Fahrenheit.

Where there is sufficient soil moisture, growth and transpiration are determined mainly by temperature. Trees and other vegetation along canals and around reservoirs are generally blessed with adequate soil moisture during the growing season. The water used by plants in the transpiration process may be supplied directly from open bodies of water in reservoirs or canals (in the case of aquatic plants) or from water that has seeped from these facilities. The latter use can increase the seepage rate by increasing the hydraulic gradient.

Seepage

Seepage is defined as the slow movement, or percolation, of water through the pore structure and interstices of the soil around the wetted perimeter of a canal or reservoir. The seepage rate may be expressed as a flow volume per unit of time, and/or as a percentage of the flow rate occurring at a particular canal cross section. The rate of seepage from unlined canals and reservoirs is affected chiefly by the depth of water, permeability of the confining soil and the location of the ground-water table. Low seepage rates are generally associated with soils having fine particle size such as clay, loams and silts. Higher seepage rates occur in sands, gravels and decomposed granite. An estimated 2 million acre-feet of irrigation water is lost through seepage processes in Colorado each year. Seepage from canals and reservoirs not only reduces the availability of water to the operating company, but also (1) adds to the salt buildup in the soil profile and ground-water reservoirs, (2) sustains high-water-table areas and encourages the growth of phreatophytic vegetation and (3) reduces the area of land for agricultural use. On the other hand, seepage may be beneficial in that it recharges the underlying ground-water reservoir.

Depending on the cost and effort analyses of lining a specific canal or reservoir, various materials may be incorporated. Linings currently utilized in Colorado include (1) bentonite (or clay); (2) compacted earth; (3) both reinforced and unreinforced concrete; (4) asphalt, rubber and plastic membranes; and (5) chemical treatments.

Operational losses

Operational losses are defined as that water loss resulting from the manner in which the reservoir and/or canal system is operated. This loss includes overflow or breakage of canal banks, waste at the end of the main canal or lateral system, leakage past gates and other control structures, and direct dumpage back to the river system. In order to supply the most downstream lateral along a given canal, some overflow at the downstream end is often required. Direct dump back to the river system may be necessary during periods of unusually high precipitation or unanticipated canceling of a headgate diversion. In some instances such operational losses may be required to flush out excessive sediment loads or to satisfy downstream calls on the river.

It should be mentioned that seepage losses and operational losses which tend to reduce the efficiency of one canal and reservoir system may contribute to the water supply and thereby bolster the efficiency of one or more lower canal systems.

River Reach Efficiency

As discussed above, water losses from irrigated fields include water which percolates below the crop root zone and water which runs off the surface. Also, some of the "losses" in conveyance are made up of water which seeps downward, and upon occasion there are also operational spills into natural waterways.

In the cases of deep percolation and seepage, the water becomes part of the ground-water system. Fortunately, in many areas of the South Platte, the irrigated areas overlie permeable alluvium which serves as a natural drainage facility. Water in the alluvium, mostly put there from the irrigation activities, slowly moves back to the river to become available for diversion again (either by wells or by downstream ditches). This "return flow" is an important factor in the efficiency of water use in a reach or an entire basin.

The over-land flow of tail water from irrigated fields, as well as operational spills from ditches, also flow back towards the river. In the case of these surface flows, however, the water is often intercepted and used again by other irrigators either directly or through a lower canal system. This reuse is also an important factor in the overall water-use efficiency of a river reach or an entire basin.

Factors which influence reach efficiency include:

(1) The losses to nonbeneficial evaporation and transpiration which deplete both the ground-water and the surface-water return flow between the irrigation facilities and the river. Losses from the ground-water system occur in areas where the water table is near the land surface, resulting in direct evaporation as well as providing water for non-crop vegetation. The most severe area of high water table generally occurs in the immediate vicinity of the river. Typically, such an area supports a growth of phreatophytic vegetation capable of drawing water directly from the ground-water system.

(2) The opportunities for re-diversion of the return-flow water (and therefore an increase in reach efficiency) depends somewhat upon relative locations of water rights in the reach. For instance, if a senior water right for a large amount of water is located at the upper end of a particular reach, the downstream appropriators in the reach have an opportunity to redivert return flow generated by the senior right, even though their priorities are inferior. On the other hand, if, in a particular reach, the large senior right is located at the lower end of the reach, the water-use efficiency could be quite low. During times of shortages the upstream junior rights would be required to curtail diversions so as to allow water to flow to the senior right.

(3) Conveyance losses in the stream itself during low-flow conditions can be significant. A broad streambed and a low flow results in a large amount of surface area exposed to evaporation.

(4) Timing of return flows coming back into the stream is of importance, especially for direct-flow rights. If most of the return flow generated from irrigation in June does not get back to the stream during the irrigation season, it is not available to downstream direct-flow rights. If the reach under study does not have facilities to store the return flow accumulating during the nonirrigation season, that water is lost to the reach.

River Basin Efficiency

As the size of the area under consideration increases, so does the opportunity for reuse of water. This is particularly true in a basin such as the South Platte where the principal source of water is in the upper reaches and the major uses occur in the lower reaches. The efficiency of irrigation water use in the South Platte Basin as a whole is considerably higher than the average field or farm irrigation efficiency (or even the efficiencies within individual reaches) because of return flow and reuse.

As discussed above for a river reach, the distribution of water-right priorities can also have an influence on the overall basin water-use efficiency. For example, if most of the senior water rights are located at the lower end of the basin, these rights would be able to call out the upstream junior rights during periods of shortage. Under such a distribution of rights, it would be important that the water use under those senior rights be efficient such that the amount of call is no greater than necessary and the return flow from the seniors' use is held to a minimum.

On the other hand, if the most senior rights tend to be located in the upper reaches of the water-use area, the downstream junior rights have an opportunity to make reuse of the return flow and accomplish a high overall basin efficiency.

Assuming that in any basin water uses can be separated into "beneficial" and "nonbeneficial," the only opportunities for improving river basin water-use efficiency lie in <u>increasing</u> beneficial uses by <u>decreasing</u> nonbeneficial uses and/or by managing water diversions for direct use and storage (including groundwater storage) in the basin which will <u>decrease</u> the outflow at the lower end of the basin.

III. APPLICATION TO LOWER SOUTH PLATTE RIVER

For purposes of this study, a reach approximately 90 miles long at the lower end of the South Platte River in Colorado was chosen to be modeled. The reach is essentially that formerly known as Water District 64.

General Description of Reach

The study reach begins a few miles upstream from the gaging station at Balzac and ends at the Colorado-Nebraska State line (Julesburg gaging station). The reach contains about 120,000 acres of irrigated lands served by 30 ditch systems and 3 major reservoirs. In addition, there are about 750 irrigation wells, some of which serve the same land and are supplemental to the ditch-water supplies. An estimated 25,000 additional acres are irrigated from ground water only.

Stream-aquifer system

The water supply for the study reach comes from an hydraulically connected surface-water and ground-water system--generally referred to simply as a stream-aquifer system. The principal aquifer involved is the alluvium of the South Platte River from which most of the 750 irrigation wells withdraw their supplies. The alluvium varies from 2-1/2 to 7-1/2 miles in width, averaging about 4.3 miles. The saturated thickness exceeds 100 feet under about 76,000 acres between the North Sterling Canal headgate and the State line. The alluvium contains an estimated 3.5 million acre-feet of ground water under about 388 square miles.

The principal source of recharge to the alluvial aquifer is the deep percolation of irrigation water from canals, reservoirs and irrigated fields overlying the aquifer. In addition, other investigators have estimated that approximately 75,000 acre-feet of water a year flows into this reach of the South Platte alluvium from the High Plains ground-water system south of the river (Waltz and Sunada, 1972).

The water added to the ground-water system in the study reach is generally sufficient to maintain a water-table level higher than the streambed level, thus creating ground-water flow toward the stream and causing a gaining or effluent stream condition. During dry periods when the draft upon the ground water is high (from both wells and phreatophyte growth) this situation is probably reversed in portions of the reach, causing a losing or influent stream condition.

Selection of study period

A 15-year study period for the model analysis was chosen to begin January 1947 and run through December 1961. This time period was chosen principally for two reasons:

(1) Data for the study period, such as estimates of amount of ground water pumped under each ditch system, were previously assembled by the U. S. Bureau of Reclamation studies made in connection with the Narrows Reservoir project.

(2) The time period includes the major drought period of 1954 through 1956.

Water budget

The annual irrigation water supply for the study reach is highly dependent upon the return-flow phenomena discussed earlier. Except for the heavy mountain snowmelt runoff times in May and June, and the occasional flood runoff due to summer thunderstorms, the water used in the study reach is return flow from irrigation activities upstream. This is not only true for the direct-flow rights but also for the storage rights in that the stream flow during the fall, winter, and early spring months is essentially all derived from irrigation return flow.

Tables 1 and 2 show the estimated average water budget for the stream and the stream-aquifer system for the 15-year study period of 1947 through 1961. The importance of ground-water return flow and deep percolation of irrigation water can be seen in these budgets.

Table III-1

Average Annual Stream Water Budget for Study Area, 1947-61, Inclusive

Inflows		1000's of acre-feet
Streamflow[1/]		399.6
Prewitt Reservoir releases to stream[2/]		10.4
Tributary inflow[2/]		14.5
Ground-water return flow[3/]		225.2
	Total	649.7
Outflows		
Streamflow[4/]		314.5
Canal diversions[2/]		332.4
Net evaporation from stream[5/]		2.8
	Total	649.7

1/ Measured streamflow at Balzac gaging station plus diversions by North Sterling, Prewitt, Johnson & Edwards, and Tetsel canals.

2/ From U. S. Bureau of Reclamation (1965).

3/ Calculated as remainder in balance equation.

4/ Measured streamflow at Julesburg gaging station.

5/ Estimated (1100 acres @ 2.5 ac-ft/ac).

Table III-2

Average Annual Combined Stream-Aquifer System Water Budget for Study Area, 1947-61, Inclusive

Inflows		1000's of acre-feet
Streamflow		399.6 1/
Ground-water flow in South Platte alluvium at North Sterling headgate		13.4 2/
Ground-water inflow from High Plains		75.0 3/
Deep percolation of irrigation water and precipitation to aquifer		221.0 4/
Tributary inflow (surface)		14.5 5/
Reservoir releases to stream		10.4 5/
	Total	733.9
Outflows		
Streamflow		314.5 6/
Ground-water flow in South Platte alluvium at Julesburg		8.0 2/
Canal diversions		322.4 5/
Ground water pumped		22.8 5/
Phreatophyte and other ET from high water table areas		53.4 7/
Net evaporation from stream		2.8 8/
	Total	733.9

1/ Measured streamflow at Balzac gaging station plus diversions by North Sterling, Prewitt, Johnson & Edwards, and Tetsel canals.

2/ Calculated from data presented by Hurr et al. (1972).

3/ From Waltz and Sunada (1972).

4/ Calculated as remainder in balance equation assuming no change in storage.

5/ From U. S. Bureau of Reclamation (1965).

6/ Measured streamflow at Julesburg gaging station.

7/ Estimated (20,000 acres @ 2.67 ac-ft/ac).

8/ Estimated (1,100 acres @ 2.5 ac-ft/ac).

Irrigation water requirement

The amount of irrigation water required for optimum crop growth and production depends upon many factors including type of crop, stage of crop growth and climatic factors. Several methods are available for estimating irrigation water requirements. The method used in this study is commonly referred to as the Modified Blaney-Criddle Method as published by the USDA Soil Conservation Service (1967). This method is based upon correlations of field research on crop-water use with temperature, length of day, stage of crop growth and effective precipitation. Using these data and the coefficients recommended by the Soil Conservation Service, calculations of irrigation water requirements for each major crop grown in the study reach were made by weeks over the 15-year study period.

Colorado agricultural statistics for Logan and Sedgwick counties were used to estimate the percentage of each crop grown during each year of the 1947 through 1961 study period. These percentages were then used along with the Modified Blaney-Criddle analysis to estimate the total irrigation water requirements in the reach on a weekly basis. It should be emphasized that these figures represent an optimum or desirable amount of water each week and do not necessarily represent the amount of water actually received. A summary of the calculated annual irrigation water requirements per acre, using the appropriate crop mix for each year and measured climatological data at Fort Morgan, Sterling and Julesburg, is presented in Table 3.

Table III-3

Calculated Annual Irrigation Water Requirement per Irrigated Acre of Study Reach

Year		Ac-ft/ac
1947		1.46
1948		1.59
1949		1.58
1950		1.64
1951		1.30
1952		1.83
1953		1.69
1954		1.86
1955		1.64
1956		1.53
1957		1.49
1958		1.45
1959		1.76
1960		1.86
1961		1.34
	Ave.	1.53

Water rights

Water rights in the study reach carry appropriation dates beginning with May 1, 1872, and extending to nearly the present time. Except for times of flood on the South Platte River, only the earliest of these water rights are in priority. The amount and distribution of direct-flow rights diverted between the Balzac and Julesburg gages which have appropriation dates senior to 1897 are given in Table 4. This table is arranged with the point-of-diversion locations in order from upstream to downstream along the top and priorities arranged from senior to junior along the left side; therefore, the resulting display of amounts of the rights provides a picture or graph of rights by location and priorities. It is readily apparent from the table that the most senior rights tend to be at the upper end of the reach, and the most junior rights at the lower end. As discussed earlier, such an arrangement is conducive to good reach efficiency in that the junior rights are able to take advantage of the return flows from the upstream senior diversions. For instance, the Liddle Ditch has very junior rights of 10 and 12 cubic feet per second, but is often able to divert all or most of this amount even when many of the upstream senior

TABLE III-4

Distribution of Direct-Flow Water Rights on South Platte River, Water District 64

Canals: / Approx. Dates (1900's)	South Platte (175.4 miles)1/	Farmers Pawnee (180.0 miles)	Davis Bros. (180.8 miles)	Schneider (183.6 miles)	Springdale (188.9 miles)	Batton (190.9 miles)	Sterling No. 1 (191.9 miles)	Sterling No. 2 (195.3 miles)	Henderson & Smith (196.5 miles)	Lowline (196.8 miles)	Bravo (201.4 miles)	Farmers (Peoples) (202.5 miles)	Iliff & Platte V. (205.5 miles)	Lone Tree (208.9 miles)	Powell (213.0 miles)
5/01/72	22.50														
4/10/73				11.00 2/											
7/15/73							113.90								
9/17/73		14.40													
4/10/74			2.00 2/												
7/15/75			6.90	18.10											
2/15/76	7.50														
10/20/80			6.07	15.93											
11/30/80									12.50						
6/22/82		126.00													
10/14/82										39.90					
4/21/83	20.00														
10/01/83													150.00		
6/07/84								50.00							
7/19/86					62.50										
5/01/90	37.50														
12/01/90			3.00												
9/14/92															
2/21/93											40.00				
8/03/94															
9/17/94														10.00	
9/20/94			20.00												
2/19/95															40.00
4/28/95															
5/04/95															
7/11/95												16.00			
7/15/95														82.00	
4/01/96	50.00														
5/03/97															
10/22/90 3/															
10/21/93 3/															
3/01/95 3/															
6/16/97															
Total (cfs)	137.50	140.40	37.97	65.03	62.50	—	113.90	50.00	12.50	39.90	40.00	16.00	150.00	92.00	40.00
Accum. Total (cfs)	137.50	277.90	315.87	360.90	423.40	423.40	537.30	587.30	599.80	639.70	679.70	695.70	845.70	937.70	977.70

Canals: / Approx. Dates (1900's)	Harmony No. 2 (216.4 miles)	Ramsey (216.4 miles)	Chambers (218.4 miles)	Harmony No. 1 (220.2 miles)	Harmony No. 3 (220.4 miles)	Tamarack (224.6 miles)	Settlers (228.3 miles)	Long Island (230.5 miles)	Hemminghouse (231.2 miles)	Peterson (240.4 miles)	South Reservation (246.0 miles)	Liddle (248.2 miles)	Carlson (249.6 miles)	Colo.-Nebr. Compact Julesburg gage (257.6 miles)	Total (cfs)	Accumulated Total (cfs)
5/01/72															22.50	22.50
4/10/73															11.00	33.50
7/15/73															113.90	147.40
9/17/73															14.40	161.80
4/10/74															2.00	163.80
7/15/75															25.00	188.80
2/15/76															7.50	196.30
10/20/80															22.00	218.30
11/30/80															12.50	230.80
6/22/82															126.00	356.80
10/14/82															39.90	396.70
4/21/83															20.00	416.70
10/01/83															150.00	566.70
6/07/84															50.00	615.70
7/19/86															62.50	679.20
5/01/90															37.50	716.70
12/01/90															3.00	719.70
9/14/92											25.00				25.00	744.70
2/21/93															40.00	784.70
8/03/94		12.00													12.00	796.70
9/17/94															10.00	806.70
9/20/94															20.00	826.70
2/19/95															40.00	866.70
4/28/95				252.00											252.00	1118.70
5/04/95			30.00												30.00	1148.70
7/11/95															16.00	1164.70
7/15/95															82.00	1246.70
4/01/96															50.00	1296.70
5/03/97	50.00														50.00	1346.70
10/22/90 3/												12.00			12.00	1358.70
10/21/93 3/												10.00			10.00	1368.70
3/01/95 3/										184.00					184.00	1552.70
6/16/97														120.00	120.00	1672.70
Total (cfs)	50.00	12.00	30.00	252.00	--	—	—	—	—	184.00	25.00	22.00	—	120.00		
Accum. Total (cfs)	1027.70	1039.70	1069.70	1321.70	1321.70	1321.70	1321.70	1321.70	1321.70	1505.70	1530.70	1552.70	1552.70	1672.70		

1/ Figured from the South Platte River gaging station at Littleton, Colo.
2/ Meadow rights, limited to use from April 10 to July 10.
3/ Rights administered in order shown because of later adjudications.

rights do not have sufficient water physically available. Even though there are 1347 cubic feet per second of senior water rights upstream from the Liddle Ditch, because of the return-flow phenomena that ditch may be able to divert even when at times only 100 cubic feet per second is flowing by the Balzac gage.

The most junior appropriation date shown on Table 4 (June 14, 1897) has specific importance because of the compact between Colorado and Nebraska on the South Platte River. According to terms of the compact, if during the period between April 1 and October 15 of each year the flow at the Julesburg gage falls below 120 cubic feet per second, the compact puts a "call" on rights which are junior to that date within the Balzac to Julesburg reach in Colorado. As can be seen from the table, some 1550 cubic feet per second of direct-flow rights in this reach are senior to the compact date; so, in general, the rights junior to the compact are usually out of priority when the streamflow at Julesburg drops below 120 cubic feet per second. About six ditches in the lower 30 miles of this reach are the principal ones influenced by the compact terms.

Existing Efficiencies

Field and farm irrigation efficiencies

The field irrigation efficiencies and farm system irrigation efficiencies are most accurately determined for an area by actual field measurements. In an attempt to find what data were available and what efficiencies might be expected for the area, the following people were contacted.

(1) Mr. Floyd Brown, Colorado State University, retired. Mr. Brown was Extension Irrigation Specialist and worked for many years in the study area.

(2) Mr. Brice Boesch, Soil Conservation Service. Mr. Boesch is Irrigation Engineer for the study area and works out of the Denver office. He has had extensive experience on the Welton-Mohawk project (Arizona) on studies which are related to irrigation efficiencies and irrigation efficiency improvement.

(3) Mr. Don Brosz, Agricultural Technology Company. Mr. Brosz heads up the farm management services offered by this company out of their McCook, Nebraska, office. These services include recommendations for irrigation amount and timing.

(4) Mr. Rich Drew, Toups Corporation, Loveland. Mr. Drew, Project Engineer, is working on a related drought program, Conjunctive Surface Water/Ground Water Management Plan for Drought Relief in the South Platte River Basin.

(5) Dr. Dale Heermann, Agricultural Research Service, Fort Collins. Dr. Heermann has been working for several years on the management of center-pivot irrigation systems.

(6) Mr. Earl Hess, Soil Conservation Service, Denver. Mr. Hess is using the SCS Irrigation Methods Analysis (IRMA) computer program, the analysis and design of irrigation systems in the study area and other areas of Colorado.

(7) Mr. Keith Keppler, Toups Corporation, Loveland. Mr. Keppler has been working on a water management study near Loveland and has obtained field data on efficiencies.

(8) Dr. Eugene Maxwell, Colorado State University. Dr. Maxwell, Associate Professor of Earth Resources, has used satellite data in studies of the use of center-pivot irrigation systems in the study area.

(9) Mr. Charles Mitchell, Soil Conservation Service, retired. Mr. Mitchell was irrigation engineer for the South Platte River valley and had many years of field experience with irrigation.

(10) Mr. Earl Phipps, Northern Colorado Water Conservancy District. Mr. Phipps, Director, is familiar with the ditch systems in the study area.

(11) Mr. Elwin Ross, Soil Conservation Service, Greeley. Mr. Ross is Area Engineer for the study area.

(12) Mr. LeRoy Salazar, Colorado State University. Mr. Salazar is a master's candidate in the Department of Agricultural and Chemical Engineering. He directed a comprehensive study on farm irrigation efficiencies which was conducted on a farm near Lucerne (north of Greeley) during the summer of 1977.

(13) Mr. Walter Trimmer, University of Nebraska, Scottsbluff. Mr. Trimmer is District Extension Irrigation Engineer and is largely responsible for the irrigation scheduling portion of the AGNET system which is available to Nebraska farmers.

In the course of interviews with the above, it was recommended that we also interview Kenneth Ververs (SCS, Loveland), William Kipper (SCS, Julesburg) and Joseph Krib (SCS, Sterling). However, it was not possible to coordinate our schedules and theirs, so these interviews did not take place.

The interviewers arrived at several conclusions as a result of these interviews. It is clear that there is no definitive literature on irrigation efficiencies in the study area. Many investigations have been made in the past, and as a result of these some general trends are known. A few recent studies were completed which included measurements of runoff as well as deep seepage (through soil-moisture sampling). These were limited in scope, however, and give only isolated data points. However, as a result of these conversations, the following conclusions were reached by the writers.[1/]

(1) The range of field irrigation efficiencies for the study area varied from an average low of 20 to 40 percent to an average high of 75 to 80 percent (surface irrigation).

(2) Field efficiencies will be higher when water availability is low (i.e., ratio of requirement to delivery is high).

(3) Field efficiencies will be affected by soils, topography and irrigation application depth in a manner which is generally known (see efficiency calculations below).

(4) Farm ditch losses may vary greatly depending upon length, soil and frequency of use.

(5) Field irrigation efficiencies for center-pivot systems in the study area can range from an average low of 63 percent to an average high of 83 percent, depending upon the level of management used (i.e., irrigation scheduling).

[1/] The conclusions drawn are those of the writers, based upon their interpretation of interviewee remarks. They are not necessarily the conclusions of the interviewees.

Establishing field input conditions. Soil associations were transferred to the computer model grid system from soil survey maps of Sedgwick and Logan counties (USDA, 1969; USDA, 1977). The soil series making up these associations were determined and evaluated as to texture and slope. Each grid point associated with an irrigation area (i.e., ditch) was identified by the appropriate soil association. The number of grid points of each soil association was tabulated for each irrigation area. The Soil Conservation Service intake family (USDA, 1974) was determined for each soil association, based upon its surface texture, using Figure 2. These intake families are the water intake rate of the soil in inches per hour at extended times. The soil series information gave information on land slopes. The average soil association properties for the study reach are summarized in Table 5.

Table III-5

Soil Association Average Properties
Lower Platte River Valley Irrigated Land, Colorado

Soil association	Plant available water (in.)	Slope (%)	Surface texture	Intake family (in./hr.)	Field irrig. eff.
2 L	8.4	1 - 3	loam	0.9	0.45
3 L	11.6	0 - 1	si. c. loam	0.6	0.55
4 L	5.3	5 +	l. sand	2.0	0.45
5 L	5.7	5 +	l. sand	2.0	0.45
7 L	5.4	5 +	f. s. loam	1.5	0.45
9 L	5.7	3 - 5	loam	0.9	0.45
11 L	10.7	5 +	loam	0.9	0.30
14 L	11.7	5 +	loam	0.9	0.30
2 S	11.0	1 - 3	loam	0.9	0.45
3 S	8.4	1 - 3	loam	0.9	0.45
4 S	4.4	5 +	f. sand	3.4	0.30
5 S	6.0	5 +	gravelly sa loam	2.0	0.45

Determination of initial values of farm irrigation system efficiencies. As indicated earlier, there is no information on farm irrigation system efficiencies which relate this parameter to slope, requirement and intake. However, it is recognized that the parameter is indeed dependent upon these

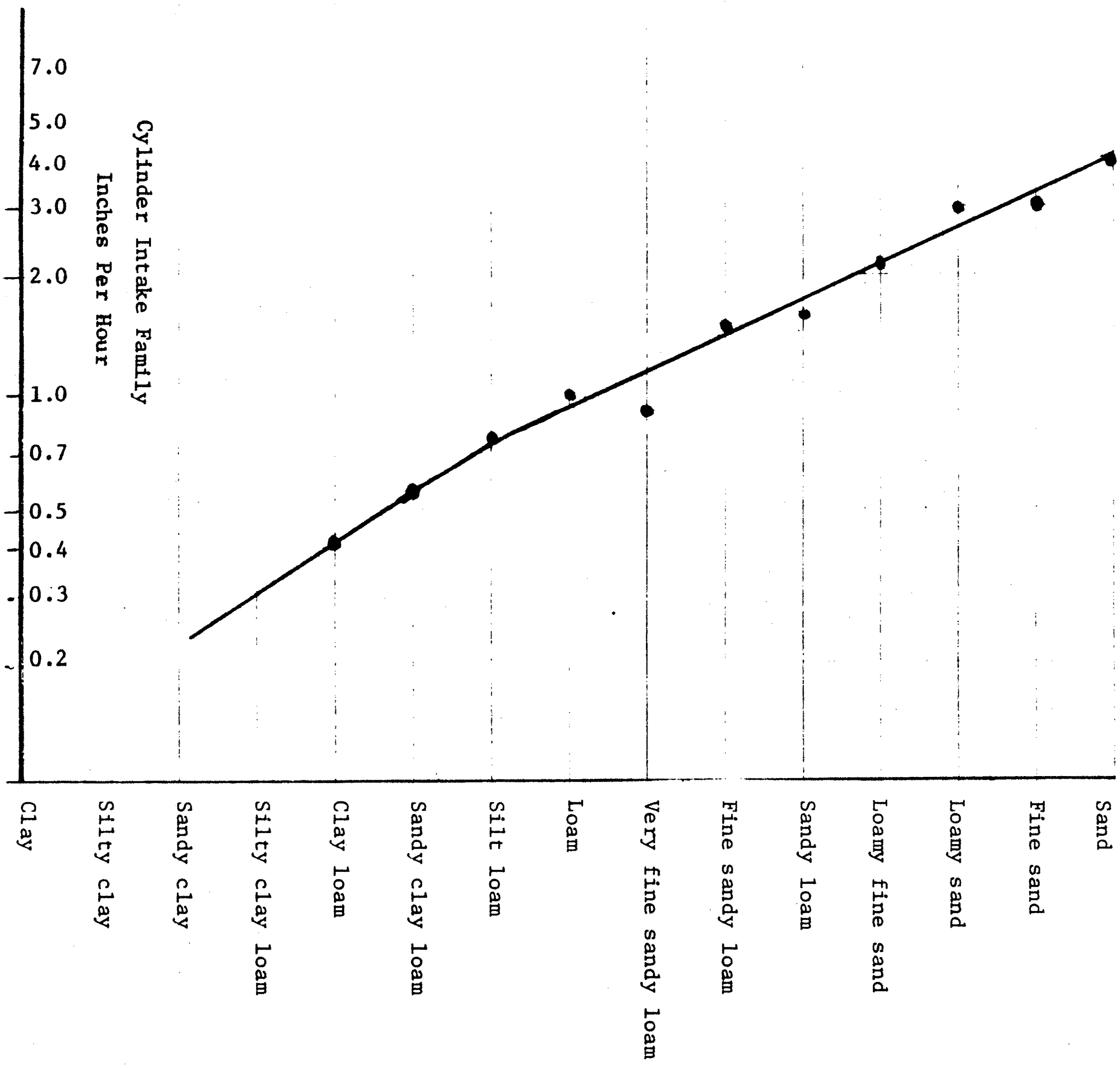


Figure III-2 Soil intake rates for various surface soil textures. (Adopted from Soil Conservation Service Engineering Handbook, USDA, 1974.)

factors. In order to arrive at a rational method of determining efficiency variations, the SCS recommendations for attainable field irrigation efficiencies under border irrigation were used as a base point (USDA, 1974). Recognizing that farmers do not reach attainable efficiencies, and that there are conveyance losses from the irrigation company canal to the farm, the SCS values were reduced by a constant value, 0.1. The SCS does not recommend irrigation for some combinations of slope, requirement and intake, and therefore give no values of field irrigation efficiency. These places in the table were filled with a value of 0.3, which is 0.1 lower than any value in the original table. In order to reduce the size of the table, and because the slope values determined from the soil association information were on a coarser scale than in the SCS original table, efficiencies were averaged over some ranges of slopes. The resulting table is given as Table 6.

Table 6 was used as follows. From the tabulation for each irrigation area, the expected value of farm irrigation system efficiency was determined and a composite efficiency was found as a weighted average. These base values are given in Table 7.

Adjustment for Water Supply. Essentially, all water delivered by the ditch company in excess of that which is necessary to meet the requirement is wasted through deep seepage or runoff (unless it is required for leaching in salinity control). This, in effect, decreases the efficiency. On the other hand, as water becomes in short supply, irrigation efficiencies increase because the farmer will take more care to use his water wisely. However, even with the most restricted water supply it is probable that there are some losses. Therefore, the following algorithm was developed as the basis for relating level of water supply to efficiency in order to estimate current farm irrigation efficiencies.

Table III-6

Expected

Farm Irrigation System Efficiencies, E_{is}

Related to Slope, Irrigation Requirement and Intake Rate[1/]

S Slope (ft./ft.)	D_u, Req't (in.)	Intake Family, I 0.3	0.5	1.0	1.5	2.0	3.0	4.0
0 to 0.01	0 to 1.5	.45	.50	.55	.55	.55	.55	.55
	>1.5 to 2.5	.45	.50	.55	.55	.55	.60	.60
	>2.5 to 3.5	.40	.55	.60	.60	.60	.60	.60
	>3.5 to 4.5	.30	.55	.60	.60	.60	.60	.60
	>4.5 to 5.5	.30	.55	.60	.60	.60	.30	.30
>0.01 to 0.03	0 to 1.5	.30	.30	.45	.50	.50	.50	.30
	>1.5 to 2.5	.30	.30	.45	.50	.50	.55	.50
	>2.5 to 3.5	.30	.30	.45	.55	.55	.55	.50
	>3.5 to 4.5	.30	.30	.40	.55	.55	.55	.50
	>4.5 to 5.5	.30	.30	.30	.55	.55	.30	.30
>0.03 to 0.05	0 to 1.5	.30	.30	.45	.50	.50	.50	.30
	>1.5 to 2.5	.30	.30	.45	.50	.50	.55	.50
	>2.5 to 3.5	.30	.30	.45	.55	.55	.55	.50
	>3.5 to 4.5	.30	.30	.40	.55	.55	.55	.50
	>4.5 to 5.5	.30	.30	.30	.55	.55	.30	.50
>0.05	0 to 1.5	.30	.30	.30	.40	.30	.30	.30
	>1.5 to 2.5	.30	.30	.30	.40	.45	.30	.30
	>2.5 to 3.5	.30	.30	.30	.45	.45	.30	.30
	>3.5 to 4.5	.30	.30	.30	.40	.45	.30	.30
	>4.5 to 5.5	.30	.30	.30	.30	.30	.30	.30

1/ Adapted from USDA (1974), by reducing each "attainable" efficiency value by 0.10 and filling blank spaces with 0.30.

Table III-7

Base Values of Farm Irrigation System Efficiency, E_{is}, in Study Area

Irrig. Area No.[1/]	No. of model grid points	Mean E_{is}	Irrig. Area No.	No. of model grid points	Mean E_{is}
2	12	0.45	21	11	0.46
3	1	0.45	22	4	0.50
4	90	0.31	23	1	0.55
5	3	0.45	24	3	0.45
7	6	0.45	25	17	0.42
8	11	0.45	26	3	0.45
9	21	0.45	27	3	0.45
10	3	0.45	28	16	0.46
11	5	0.45	29	2	0.45
12	6	0.45	30	5	0.45
13	3	0.45	31	24	0.43
14	19	0.44	32	3	0.45
15	3	0.45	33	2	0.45
16	1	0.45	34	2	0.45
17	4	0.45	36	7	0.43
18	8	0.45	37	1	0.45
19	1	0.45	38	32	0.45
20	13	0.47	39	19	0.45

[1/] Identified in computer model.

First, select an appropriate base farm irrigation system efficiency, E_{is}, from Table 7 which is to be adjusted in accord with level of supply. Then calculate:

$$R = \frac{D_u}{D_d}$$

where D_u is the requirement at the time of irrigation and D_d is the amount of water delivered. The units of requirement and water delivered are depth or volume per unit area. Three levels of supply are considered.

Case I $E_{is} \geq R$; $D_d > D_u$

This implies that an excess of water over that required for good irrigation is available. All in excess is lost. Therefore,

$$D_\ell = D_d - D_u$$

where D_ℓ is the water lost, in the same units as D_d and D_u.

Case II $E_{is} < R$; $D_d > D_u$

This implies that there is not sufficient water to meet the requirement, although there could be enough if the irrigation efficiency were increased. Make an adjustment to the base efficiency by calculating a new value of field irrigation system efficiency.

$$E_{is} = E_{is} + 0.2 \, [D_u/E_{is}) - D_d]/[(D_u/E_{is}) - D_u]$$

where E_{is}' is the adjusted value of E_{is}. The losses are calculated as follows:

$$D_\ell = (1 - E_{is}') \, D_d$$

It is to be noted that the above calculation limits the value of E_{is}' to a maximum of $E_{is} + 0.2$.

Case III $E_{is} < R$; $D_d \leq D_u$

Water has become even more limiting. The maximum possible value of irrigation efficiency is used, and this is the base value plus 0.2 Thus,

$$D_\ell = (0.8 - E_{is})D_d$$

Farm irrigation efficiencies used in this study were selected by determining the level of supply for each model grid point and making the foregoing adjustment to the base efficiency for that point.

Allocation of lost water to runoff and deep seepage. No attempt was made to determine whether lost water ran off or whether it went into deep seepage. On the flatter lands it is probable that most lost water goes into seepage or is evaporated. This is because if it is reused by the farmer, it probably goes into a borrow pit, and only those fields on the edge of an irrigated area would have runoff into another area. On the steeper lands this may not be the case. There is some evidence in the study area that water passes on down the hillside and is collected in the next lower irrigation canal. The amount of direct reuse of this type is a refinement that should be worked into the model as soon as the quantities can be better identified.

Canal and reservoir system efficiencies. Most of the canal systems and one of the three reservoirs in the study reach overlie the South Platte alluvium. Seepage losses from these result in an immediate recharge to the aquifer. This has been effectively shown by the monitoring of ground-water levels in the vicinity of the Sand Hill lateral of the South Platte Ditch in a demonstration recharge project (Colorado Division of Water Resources, 1977). However, portions of the North Sterling Reservoir Inlet Canal, the North Sterling Reservoir itself, and nearly all of the outlet canal overlie other geologic formations (Pierre shale, White River group and the Ogallala formation). Also, portions of the Julesburg Reservoir inlet canal, the Julesburg Reservoir itself and all of the Highline Canal overlie the White River group and/or the Ogallala formation. These formations, in general, have lower permeabilities than does the alluvium.

Very little published information on canal and reservoir losses or system efficiencies in the study reach are available. Therefore, canal and reservoir company personnel were interviewed to obtain information on their systems. Those interviewed were:

Paris Accomasso - - - - Davis Bros. & Schneider Ditches
Charles Barttlett - - - South Platte Ditch
Bud Bonesteel - - - - - Julesburg Irrig. District, including Harmony No. 1, Settlers and Peterson Ditches
Don Demers- - - - - - - Ramsey Ditch

Tom DeSoto- - - - - - - Peoples (Farmers) Ditch
Tom Frame - - - - - - - Red Lion Supply Ditch
Marvin Gardner- - - - - Tamarack Ditch
John Held - - - - - - - Bravo Ditch
William Huey- - - - - - Iliff and Platte Valley Ditch
Alfred Leckler- - - - - Springdale Ditch
Don Liddle- - - - - - - Liddle Ditch
David Littler - - - - - Pawnee Ditch
Bob Littler - - - - - - Water Commissioner
George Meyerholz- - - - Sterling No. 1 Canal
Alex Michel - - - - - - North Sterling System
Hub Reichelt- - - - - - Carlson Ditch
Scalva Bros.- - - - - - Henderson & Smith Ditch
Albert Workman- - - - - Lowline Ditch

The following paragraphs summarize information about the individual ditch and reservoir companies in the study reach obtained from those interviewed plus other sources.

North Sterling Irrigation System. The North Sterling Reservoir inlet canal diverts from the South Platte River at a point 3 miles upstream from the Balzac gaging station. The system lies north of the river and consists of the inlet canal of about 56 miles in length, the North Sterling Reservoir (also known as the Point of Rocks Reservoir) and an outlet canal of also about 56 miles in length. The outlet canal delivers water to over 40,000 acres of irrigated land, much of which is served from several privately owned and operated laterals. The North Sterling outlet canal is the highest canal on the north side of the study reach, paralleling the river at a distance of 6 to 7 miles. The average annual diversion by the North Sterling inlet canal during the 15-year study period was 92,400 acre-feet, varying from a low of 50,200 acre-feet in 1956 to a high of 165,300 acre-feet in 1957 (USBR, 1965). Releases from the North Sterling Reservoir during the same period average 67,100 acre-feet (USBR, 1965). On the surface, these figures indicate an average efficiency of water delivery to the outlet of the North Sterling Reservoir compared to the river diversions of about 73 percent. However, another factor which needs to be considered in this calculation is the difference in the amount of water stored in the North Sterling Reservoir between the beginning of the period and the end. Records indicate that 32,700 acre-feet more water was in the reservoir on January 1, 1962, as compared to January 1, 1947. Cranking an average annual change in storage of +2200 acre feet into an efficiency calculation indicates 75%

efficiency between the point of diversion and the point of release from the reservoir.

Current-meter measurements in the inlet canal were made in October 1971 when 508.5 cfs were being diverted. These measurements showed a loss of 85.9 cfs in the first 17 miles (16.9%) and 131.9 cfs (26.0%) in the total length (Toren, 1971). This estimate is further supported by the fact that over 75 irrigation wells below the north Sterling inlet canal derive their supplies from that canal's seepage losses. Net evaporation losses from the North Sterling Reservoir itself probably average about 5,000 acre-feet per year. It is believed that the amount of seepage from the reservoir itself is rather small compared to the other losses in the system. Seepage losses from the outlet canal are estimated to be 25 to 30 percent of that amount released from the reservoir. Therefore, the average delivery efficiency to farm turnouts and the several laterals of the system is somewhat under 50 percent.

Tetsel Ditch.[1/] The Tetsel Ditch diverts from the river 2.2 miles upstream from the Balzac gaging station and serves about 1,000 acres of irrigated land on the north side of the river. All of the irrigated land is close to the river and is immediately below the North Sterling inlet canal. During the 15-year study period the Tetsel Ditch diverted an average of 5,100 acre-feet per year. The lowest annual diversion was 2,600 acre-feet in 1947 and the largest was 6,400 acre-feet in 1956 and 1961. No Tetsel Ditch Company officials were interviewed, but based on similar small systems close to the river the efficiency of delivery is estimated to be about 75 percent. Most of the loss involved would be to seepage.

Johnson and Edwards Ditch. The Johnson and Edwards Ditch diverts from the river using the Prewitt Reservoir inlet canal. It serves approximately 1,700 acres of irrigated land on the south side of the river. The average annual diversion by the Johnson and Edwards system during the 15-year study period was 3,200 acre-feet. The lowest annual diversion was 2,100 acre-feet in 1959 and the highest was 5,200 acre-feet in 1952. The estimated delivery efficiency for the Johnson and Edwards Ditch is 75 percent.

[1/] No attempt has been made in this report to differentiate between "canals" and "ditches", but terminology common in each system has been used where known.

Prewitt Reservoir. The inlet canal to the Prewitt Reservoir diverts from the river 2.1 miles upstream from the Balzac gaging station. Releases from the reservoir come back into the river about 5.8 miles downstream from the gage. The Prewitt Reservoir has an available storage capacity of 28,960 acre-feet which is divided into 31,000 rights. The rights are held as follows:

1. Logan Irrigation District--17,000 rights
   (includes the South Platte, Pawnee, Davis Bros., Schneider and Springdale ditches)
2. Iliff Irrigation District--8,000 rights
   (includes the Bravo, Farmers, Iliff and Platte Valley, Lone Tree, Powell, Harmony No. 2, Ramsey and Harmony No. 1 ditches)
3. Morgan-Prewitt Reservoir Company--6,000 rights
   (Some of these rights are used by exchange upstream, but most are held by individuals under nearby downstream ditches such as the South Platte, Pawnee, Davis Bros., Springdale and Sterling No. 2.)

During the 15-year study period, an average of 41,000 acre-feet of water was diverted from the river to storage and an average of 10,400 acre-feet was released back to the river (USBR, 1965). Storage records show that there was 1,950 acre-feet more storage in January 1, 1962, than on January 1, 1947. Therefore the average river-diversion to reservoir-release efficiency was about 26 percent. The water released to the river suffers losses in transit to the receiving ditch (as much as 40 river miles downstream) and in the receiving ditch before delivery to farm headgates.

A large portion of the loss in the Prewitt Reservoir system is by seepage from the reservoir. Officials report that the seepage rate from the reservoir when it is full is 130 acre-feet per day. This water becomes available for diversion by ditches and wells downstream, although there is a significant loss to evapotranspiration from a high water table and phreatophytes supported by the seepage between the reservoir and the river.

South Platte Ditch. The South Platte Ditch diverts from the river 1.6 miles downstream from the Balzac gaging station and serves about 4,900 acres of irrigated land on the south side of the river. The average annual diversion during the 1947 to 1961 study period was 10,400 acre-feet, ranging from a minimum of 7,700 acre-feet in 1959 to a maximum of 13,400 acre-feet in 1948. The ditch diverted nearly the average amount during the drought year of 1977 indicating the stability of a senior water right. It is estimated that the delivery efficiency of the South Platte Ditch is about 67 percent. Most of the loss is due to seepage.

Farmers Pawnee Ditch. The Farmers Pawnee Ditch diverts from the river 6.2 miles downstream from the Balzac gaging station and serves about 10,600 acres of irrigated land on the north side of the river. A detailed study of this ditch system in 1969 (Bittinger & Associates, 1969) showed a high percentage of the Farmers Pawnee Company stockholders also had irrigation wells as a supplemental source of water. In addition, slightly over 900 acres within the ditch service area were being irrigated from ground water only.

The average annual diversion of river water by the Farmers Pawnee Ditch during the 1947 through 1961 study period was 26,200 acre-feet. The lowest annual diversion was 19,100 acre-feet in 1960 and the greatest was 37,000 acre-feet in 1948. It is estimated that the system delivers about 65 percent of the amount diverted. Most of the loss is due to seepage from the ditch.

Davis Bros. Ditch. The Davis Bros. Ditch is a relatively short ditch which diverts from the river 7.0 miles downstream from the Balzac gaging station. It serves about 2,000 acres of irrigated land within 1.5 miles of the river. The average annual diversion by the Davis Bros. Ditch during the 1947 through 1961 study period was 3,900 acre-feet, ranging from a minimum of 2,700 acre-feet in 1955 to a maximum of 5,400 acre-feet in 1948. It is estimated that the Davis Bros. Ditch delivers at least 75 percent of the water diverted to farm turnouts.

Schneider Ditch. The Schneider Ditch diverts from the river 11.8 miles downstream from the Balzac gaging station and serves about 2,400 acres of irrigated land on the south side of the river. The average annual diversion by the Schneider Ditch during the 15-year study period was 8,600 acre-feet. The smallest annual diversion was 5,600 acre-feet in 1957 and the largest was 11,200 acre-feet in 1950. The Schneider Ditch diverted about 1,000 acre-feet more river water during the drought year of 1977 than the 15-year average given above. A large proportion of the Schneider Ditch service area is also served by irrigation wells. The Schneider Ditch divides into two branches, north and south. It is estimated that the north branch (nearest the river) loses only 5 to 10 percent of the water carried, whereas the south branch loses about 30 percent.

Springdale Ditch. The Springdale Ditch diverts from the river 15.1 miles downstream from the Balzac gaging station, and serves about 4,000 acres of irrigated land on the north side of the river. The average annual diversion by the Springdale Ditch during the 15-year study period was 5,800 acre-feet, ranging from a minimum of 1,900 acre-feet in 1959 to a maximum of 9,000 acre-feet in 1948. The Springdale Ditch is a "slow" ditch with heavy losses, especially in the lower one half. The delivery efficiency is probably about 55 to 60 percent because of large seepage losses. Many wells in the service area of the Springdale Ditch undoubtedly benefit from this seepage.

Sterling No. 1 Ditch. The Sterling No. 1 Ditch diverts from the river 18.1 miles downstream from the Balzac gage and serves about 10,000 acres of irrigated land on the north side of the river. The average annual diversion by the Sterling No. 1 Ditch during the 15-year study period was 24,900 acre-feet. The lowest annual diversion amount was 16,300 acre-feet in 1957 and the largest was 32,700 acre-feet in 1954. The ditch diverted only 14,700 acre-feet of river water during the drought year of 1977, but received about 4,000 acre-feet of water from wells into the ditch by the Ground Water Appropriators of the South Platte (GASP) as replacement of surface-water depletions caused by ground-water pumping. The delivery efficiency of the Sterling No. 1 Ditch is estimated to be about 70 percent, with especially high seepage losses occurring from the ditch northwest of Sterling. Although the Sterling No. 1 Ditch service area overlies areas of significant saturated thickness of the alluvium, stockholders of the company have only a few irrigation wells--principally because of the senior surface-water rights.

Sterling No. 2 Ditch. The Sterling No. 2 Ditch diverts from the river 21.5 miles downstream from the Balzac gaging station and irrigates 1,000 to 1,200 acres on the north side of the river, all of which is within a mile of the river. The average annual diversion of river water by the Sterling

No. 2 Ditch during the 15-year study period was 1,800 acre-feet, ranging from a minimum of 300 acre-feet in 1959 to a maximum of 3,700 acre-feet in 1950. The high variability of diversions reflects the difficulty experienced by a relatively junior water right diverting immediately downstream from a senior water right. It is understood that as of 1977, all of the irrigated area under the Sterling No. 2 Ditch is being served by wells as alternate points of diversion. The efficiency of delivery during the 15-year study period is estimated to be 75 percent.

Henderson and Smith Ditch. The Henderson and Smith Ditch is a small ditch system on the south side of the river diverting from a point 22.7 miles downstream from the Balzac gaging station. Estimates of the area irrigated from this ditch vary widely between different sources, but it appears that about 900 acres is correct. The average annual diversion of river water during the 15-year study period by the Henderson and Smith Ditch was 2,100 acre-feet. The lowest annual diversion was 1,100 acre-feet in 1947 and the largest was 3,000 acre-feet in both 1954 and 1956. This reflects a favorable seniority and position on the river in order to record maximum diversions in dry years. The ditch diverted 2,558 acre-feet of river water in 1977. It is estimated that the delivery efficiency of the Henderson and Smith Ditch is about 75 percent.

Lowline Ditch. The Lowline Ditch diverts from the river 23.0 miles downstream from the Balzac gaging station and serves a little over 2,000 acres of irrigated land on the north side of the river. The average annual diversion of river water during the 15-year study period was 6,900 acre-feet. The lowest annual diversion amount was 4,300 acre-feet in 1957 and the largest was 9,900 acre-feet in 1950. The delivery efficiency of the Lowline Ditch is estimated to be about 80 percent of the water diverted.

Bravo Ditch. The Bravo Ditch diverts from the river 27.6 miles downstream from the Balzac gaging station and serves an area estimated by different sources as being as low as 1,200 and as high as 3,300 acres. During the 15-year study period, the Bravo Ditch diverted an average of 6,300 acre-feet and a minimum of 4,400 acre-feet (1954). With these diversions, it would appear that an irrigated area of about 3,000 acres may be correct. It is estimated that the delivery efficiency of the Bravo Ditch is about 70 percent.

Farmers (Peoples) Ditch. The Farmers Ditch diverts from the river 28.7 miles downstream from the Balzac gaging station and serves a small acreage (probably less than 400 acres) on the south side of the river within a short distance of the river. The average annual diversion of river water during the 15-year study period was 1,800 acre-feet. The lowest annual diversion was 600 acre-feet in 1959 and the largest was 2,900 acre-feet in 1951. The first 1/2 mile of the 5.3-mile ditch loses considerable water, but the remaining portion is not large. The overall efficiency of delivery by the Farmers Ditch is estimated to be about 80 percent.

Iliff and Platte Valley Canal. The Iliff and Platte Valley Canal diverts from the river 31.7 miles downstream from the Balzac gaging station and serves about 10,000 acres of irrigated land on the north side of the river. The ditch follows the north edge of the alluvium for a distance of about 35 miles. Because of its position, it picks up runoff and seepage from land above irrigated from the North Sterling Reservoir Outlet Canal and its laterals. During the 15-year study period the Iliff and Platte Valley Canal diverted an average of 18,500 acre-feet ranging from a minimum of 14,000 acre-feet in 1958 to a maximum of 23,000 acre-feet in 1948. The Iliff and Platte Valley Ditch seepage losses are quite variable along its length, but an overall delivery efficiency of about 80 percent is estimated for the system.

Lone Tree Ditch. The Lone Tree Ditch diverts from the river 35.1 miles downstream from the Balzac gaging station and serves approximately 1,000 acres of irrigated area on the south side of the river, all within a mile of the river. The average annual diversion by the Lone Tree Ditch during the 15-year study period was 3,800 acre-feet. The lowest annual diversion was 1,100 acre-feet in 1959 and the greatest was 6,500 acre-feet in 1954. It is estimated that the delivery efficiency of the Lone Tree Ditch is about 75 percent.

Powell Ditch. The Powell Ditch diverts from the river 39.2 miles downstream from the Balzac gaging station and irrigates about 2,200 acres on the north side of the river. The average annual diversion of river water during the 15-year study period was 4,400 acre-feet. The lowest annual diversion was 1,800 acre-feet in 1948 and the largest was 6,300 acre-feet in 1954 and 1956. Officials estimate the seepage losses from Powell Ditch as being only about 10 percent of the amount diverted.

Ramsey Ditch. The Ramsey Ditch diverts from the river 42.6 miles downstream from the Balzac gaging station and 41.2 miles upstream from the Julesburg gaging station. It serves a small irrigated area on the north side of the river within 1/2 mile of the river. The average diversion during the 15-year study period was 1,100 acre-feet ranging from 200 acre-feet in 1952 to 2,300 acre-feet in 1955. The delivery efficiency of the Ramsey Ditch is estimated to be about 75 percent.

Harmony No. 2 Ditch. The Harmony No. 2 Ditch diverted, at one time, from the river at the same point as the Ramsey Ditch. In recent years the diversion has not been maintained. Apparently the ditch received sufficient runoff and seepage from lands above it irrigated from the North Sterling Reservoir Outlet Canal in order to supply its irrigated acreage in combination with irrigation wells.

Harmony No. 1 Ditch. The Harmony No. 1 Ditch diverts from the river 46.4 miles downstream from the Balzac gaging station. It carries both direct-flow water for irrigation of about 14,000 acres under the Harmony No. 1 and storage water for the Julesburg Reservoir. The average annual diversion for the 15-year study period was 25,500 acre-feet ranging from a low of 10,900 acre-feet in 1959 to a high of 39,400 acre-feet in 1957. The major losses in the Harmony No. 1 Canal are in the first few miles which traverse the alluvium. It is estimated that the delivery efficiency is about 75 percent.

Julesburg Reservoir and Highline Ditch. Water diverted to storage in the Julesburg Reservoir through the Harmony No. 1 Ditch during the 15-year study period averaged 14,600 acre-feet. The lowest diversion during the period was 4,200 acre-feet in 1956 and the largest was 24,000 acre-feet in 1955. Approximately 9,000 acres are irrigated from the Julesburg Reservoir through the Highline Canal. Besides the seepage losses in the inlet canal seepage and evaporation losses occur from the reservoir and from the Highline Canal. It is estimated that the overall efficiency of the system is in the neighborhood of 50 percent.

Settlers Ditch. The Settlers Ditch diverts from the river 54.5 miles downstream from the Balzac gage and serves about 4,000 acres of irrigated land on the north side of the river extending about 30 miles to near the State line. The average diversion of river water by the Settlers Ditch in the 15-year study period was 1,800 acre-feet. The lowest diversion was 0 acre-feet in 1956 and the highest was 5,100 acre-feet in 1958. The Settlers Ditch picks up water both directly and indirectly from the Julesburg Reservoir and the Highline Ditch. Many irrigation wells in the service area supplement the ditch water. The estimated efficiency of the Settlers Ditch delivery system is 75 percent.

Peterson Ditch. The Peterson Ditch diverts from the river 66.6 miles downstream from the Balzac gaging station (17.2 miles upstream from the Julesburg gaging station) and irrigates 9,000 to 10,000 acres of land on the north side of the river extending to the State line. The Peterson Ditch diverted an average of 8,700 acre-feet per year during the 15-year study period. The lowest diversion was 3,900 acre-feet in 1954 and the highest was 15,500 acre-feet in 1947. The estimated delivery efficiency of the Peterson Ditch is 70 percent. Many irrigation wells are in use between the Peterson Ditch and the river.

South Reservation Ditch. The South Reservation Ditch diverts from the river 11.6 miles upstream from the Julesburg gage and irrigates about 1,600 acres on the south side of the river, all within 1/2 mile of the river. During the 15-year study period, the South Reservation Ditch diverted an average of 3,700 acre-feet per year. The lowest annual diversion was 1,700 acre-feet in 1948 and the highest was 5,600 acre-feet in 1952. Ditch personnel estimate that only 5 percent of the water diverted is lost to seepage.

Liddle Ditch. The Liddle Ditch diverts 9.4 miles upstream of the Julesburg gaging station and serves about 1,350 acres of irrigated land on the north side of the river. The average diversion during the 15-year study period by the Liddle Ditch was 2,300 acre-feet, ranging from a low of 1,100 acre-feet in 1949 to a high of 3,300 acre-feet in 1959. The delivery efficiency of the Liddle Ditch is estimated to be about 75 percent.

Carlson Ditch. The Carlson Ditch is the last ditch diverting in Colorado, its diversion point being 8 miles upstream from the Julesburg gaging station. The Carlson Ditch irrigates about 2,000 acres on the south side of the river. The average diversion during the 15-year study period was 1,600 acre-feet per year. The lowest diversion was 0 acre-feet in 1960 and the highest was 3,000 acre-feet in 1954. The estimated delivery efficiency of the Carlson Ditch is 75 percent.

River reach efficiency

For the study reach, the outflow items of the stream-aquifer budget in Table 2 which have the greatest potential for reduction in order to increase beneficial consumptive use and thus increase river reach efficiency are (1) the stream outflow at Julesburg, and (2) phreatophyte consumptive use.

Except for the May and June snowmelt-runoff period, most of the water passing the Julesburg station is composed of irrigation return flow. About 127,500 acre-feet of the 314,500 acre-feet average annual outflow at Julesburg during the 15-year period occurred during the 5-1/2 months when the Colorado-Nebraska Compact was not in effect. The last opportunity for diversion to storage during the non-compact season in Colorado is by the Julesburg Reservoir. The point of diversion for the Julesburg Reservoir (headgate of the Harmony No. 1 Canal) is 37 miles upstream from the Julesburg gage. Therefore, any return flow to the stream within this 37-mile subreach during the non-irrigation season is physically unavailable even if legally available. Return flows reaching the river above the Julesburg Reservoir inlet is also often lost because the Julesburg Reservoir has no difficulty in filling during most years.

Studies by the U. S. Bureau of Reclamation indicate that operation of the proposed Narrows Reservoir would reduce the average annual flow at Julesburg by about 75,000 acre-feet. The effect of the reservoir would be to reduce the flow during the spring runoff period and provde more water to the study reach during the late summer and early fall months. It is likely that the return flow accruing in the reach during the winter months will be increased somewhat by operation of the Narrows Reservoir.

Additional surface reservoir sites, on stream or off stream, are essentially nonexistent in the study reach and therefore do not provide a viable solution to reducing the stream outflow lost to Colorado during the winter months. However, the groundwater reservoir offers the possibility for storage of outflow in excess of compact requirements. It may be possible to manage conjunctively the ground and surface waters during the irrigating season so as to minimize the amount of return flow reaching the river in the winter months. It may also be possible to draw more heavily on groundwater to meet crop irrigation requirements in below-average runoff years and then recharge groundwater heavily during wetter years.

The second item, phreatophyte consumptive use, is a sizable loss of water (53,400 acre feet) particularly when one realizes that it has an impact on the availability of water at the very times the crop irrigation requirements are highest. The reduction in streamflow during a hot July or August day by the evapotranspiration losses from high water table and phreatophyte areas probably exceeds 200 cfs. Control of the water table and phreatophytic growth is admittedly quite controversial and it is beyond the scope of this study to get into that aspect of the efficiency picture.

The flow at Julesburg during the period April 1 to October 15 is subject to the Colorado-Nebraska Compact. As mentioned earlier, the compact functions as a call on the river during this 6-1/2 month period whenever the flow at Julesburg is less than 120 cfs. Table 8 shows the number of days per week during the 15-year study period that the Julesburg flow was less than 120 cfs. It can be seen that the Compact "call" was on over 90 percent of the time during the dry years of 1954 and 1956. Obviously, it is years like 1954 and 1956 that additional ground-water use in the study reach would be desirable--but could further reduce the flow at Julesburg.

Table III-8

Days per Week South Platte River Flow at Julesburg was Below 120 cfs 1947 through 1961

Week No.	Week Beginning	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	Total	Percent
14	Apr 2	0	0	0	0	7	0	0	0	4	7	0	0	0	0	0	18	17
15	9	0	0	0	0	3	0	0	3	3	7	0	0	0	0	0	16	15
16	16	0	0	0	0	0	0	0	7	7	7	0	0	0	0	0	21	20
17	23	5	3	2	6	0	0	0	7	7	7	3	0	0	0	0	40	38
18	30	7	0	4	6	0	0	0	4	7	7	7	0	0	0	7	49	47
19	May 7	7	0	1	4	5	0	0	7	7	7	2	0	0	0	7	47	45
20	14	7	5	0	7	6	0	1	7	3	7	0	0	0	0	1	44	42
21	21	1	7	0	7	0	0	7	7	5	7	0	0	0	0	0	41	39
22	28	0	1	0	7	0	0	7	7	0	7	0	0	0	0	0	29	28
23	Jun 4	0	1	0	7	4	0	6	7	4	7	0	0	0	0	0	36	34
24	11	0	6	0	7	0	0	7	7	0	7	0	0	6	0	0	40	38
25	18	0	0	0	7	0	5	7	7	0	6	0	0	7	0	0	39	37
26	25	0	0	0	7	0	7	6	7	3	7	0	0	7	4	0	48	46
27	Jul 2	0	0	0	7	0	7	6	7	7	7	0	0	7	7	2	57	54
28	9	0	3	0	7	2	7	7	7	7	7	4	0	7	7	1	66	63
29	16	0	1	0	7	7	7	7	7	7	7	4	1	7	7	7	76	72
30	23	0	4	4	4	7	7	7	7	7	7	0	0	7	7	5	73	70
31	30	0	7	7	7	7	7	7	7	7	7	0	5	7	7	0	82	78
32	Aug 6	7	7	7	0	0	7	6	7	7	7	2	7	7	7	4	82	78
33	13	7	7	5	3	0	7	6	7	7	7	7	7	7	7	7	91	87
34	20	7	7	2	7	7	7	7	7	7	7	7	7	7	7	7	100	95
35	27	7	7	3	7	6	7	7	7	7	7	3	7	7	7	7	96	91
36	Sep 3	7	7	0	7	0	7	7	7	7	7	7	7	7	7	6	90	86
37	10	3	7	0	7	0	7	7	7	7	7	7	7	7	7	0	80	76
38	17	0	7	0	0	0	7	7	7	7	7	1	2	7	7	1	60	57
39	24	0	7	0	0	0	7	7	7	7	7	0	5	7	7	0	61	58
40	Oct 1	1	7	0	0	0	7	7	7	7	7	0	0	1	7	0	51	48
41	8	2	3	0	0	0	2	7	7	7	7	0	0	0	7	0	42	40
	Total	68	104	35	128	61	112	143	182	155	195	54	55	112	109	62	1575	
	%	34.7	53.1	17.8	65.3	31.1	57.1	72.9	92.8	79.1	99.5	27.6	28.1	57.1	55.6	31.6	53.6	

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IV. ESTIMATED COSTS OF EFFICIENCY IMPROVEMENTS

Farm Irrigation Efficiency Improvement Costs

The United States Bureau of Reclamation (USDI, 1970) reported detailed studies of field irrigation efficiencies of projects in the McCook, Nebraska, and Torrington, Wyoming, areas. They studied existing efficiencies, which were measured on 7 farms (31 fields), over a 5-year period. From these data they concluded that there are three levels of attainable efficiencies.

(1) Existing system, improved management, no additional labor

On-farm irrigation efficiency can be increased by scheduling irrigations according to monitored plant needs, rather than from a predetermined schedule or advice from neighbors. Such scheduling can be carried out by the farmer using resistance blocks and/or tensiometers, frequent sampling with an Oakfield probe, or by keeping a detailed day-to-day moisture budget using climatic data. The farmer would have to know the approximate water-holding capacity of his soil and the approximate infiltration rates to carry out this exercise.

Although the cited reference claims that favorable results can be obtained with a minimum effort on the part of the farmer, it is probable that he will use management services to attain this level of control if such services are available. In eastern Colorado they are offered by at least one company, at a rate of $4.50 to $5.50 per acre per year, depending on farm size. This is a total management service and includes advice on weed and pest control, planting dates, fertilization, etc. It is probable that the irrigation scheduling cost is no more than half the quoted cost for the entire package, or about $2.50 to $3.00 per acre per year.

The level of improved on-farm irrigation efficiencies to be expected were reported by the Bureau (USDI, 1970). They concluded that on-farm efficiencies could be raised from a 44 percent average without improved management to a 62 percent average with improved management. These values may be compared with an estimate made in this study of 41 percent for the study area without improved management. Whittlesey (1977) used a value of 44 percent for the South Platte River Valley.

(2) Existing system, improved management, additional labor

The second level of efficiency is attainable by additional improvements in water management, which include such practices as cut-back flows in row crops. These practices require additional labor. Farm irrigation efficiency can be raised from 41 percent to 68 percent by this approach.

(3) Improved system, improved management, additional labor

No estimated attainable efficiencies are given by the Bureau (USDI, 1970) for this level of improvement. However, it is expected to include a complete tailwater reuse system with a concrete-lined pond, a pipe conveyance system, and gated pipe for delivery to furrows. Alternatively, (1) an automatic surface irrigation system with an underground conveyance system and vertical risers to gated pipe, in conjunction with a reuse system and irrigation scheduling, or (2) sprinkler systems could be used.

The writer's experience indicates that in reality most farms in the study area obtain improved performance by going to a reuse system or center-pivot irrigation. The reuse system usually consists of an unlined pond, plus a pump and pipeline to the upper end of the field. As the result of conversations with the experts mentioned in an earlier portion of this report, it was concluded that center pivots operated without the benefit of irrigation scheduling would average about 63 percent field irrigation efficiency. Those operated with an irrigation scheduling program--one that determines the time and amount of water to apply based upon monitoring crop use--would have a field irrigation efficiency of about 83 percent.

For the purposes of the cost estimate it is assumed that the 75 percent farm irrigation system efficiency could be met in the study area if half the area in surface irrigation was provided with reuse systems, and if half was converted to center-pivot irrigation. The costs for these conversions can be estimated as follows from data in the literature.

Sheffield (1977) has given detailed costs for center-pivot irrigated cornfields. Extracting costs for the center-pivot system itself, the irrigation pump and gearhead, a diesel engine, other minor fixed costs, taxes and insurance, the annualized cost is $53.29 per acre. To this must be added a fuel cost at $6.06 per acre, and maintenance at $4.05 per acre. There should be a reduction in labor. Sheffield (1977) indicates that irrigation labor for center pivots is about $1.20 per acre (labor charged at $3.50 per hour). If center-pivot replaces a gated pipe system, Eisenhauer and Fischbach (1977) estimate labor charges for gated pipe systems at $4.13 per acre (at $4.00 per hour). Syphon systems, which are popular in the study area, take more labor but at a lower hourly labor cost. It is therefore probable that the labor saving would be about $4.13 minus $1.20, or $2.93 per acre. Thus, the total increased cost for center-pivot irrigation is about $60.47 per acre per year.

The yearly increased cost for a reuse system may be relatively small. Eisenhauer and Fischbach (1977) state that the annual fixed costs for a gated pipe system with a reuse system is $26.98. The increased fixed costs for reuse are only $1.71 per acre per year. Fuel and oil costs were estimated to decrease by $0.78 and $0.15 per acre per year, and maintenance costs were estimated to be increased by $0.15 per acre per year. Labor was assumed to be unchanged. Thus, the net increase in cost for reuse would be $0.93 per acre per year.

The estimated increased annual cost for obtaining a farm irrigation system efficiency of 75 percent is (under the assumption of half the area in center pivots and half the area in surface irrigation with reuse systems) the arithmetic mean of the two figures ($60.47 and $0.93) or $30.70 per acre per year.

Using the foregoing information, the cost of raising the average farm irrigation efficiency in the study reach to 60 percent by irrigation could be as little as $3 or $4 per acre per year--or a total of $375,000 to $500,000 on 125,000 acres. This can only be done, of course, with the full cooperation of the farm operators in adopting and following improved management techniques. The cost of increasing efficiencies on up to an average of 75 percent (one of the efficiency scenarios used in this study) requires more capital investment and operating costs. This could amoount to a total annual cost for the study reach of $3.75 to $4.5 million.

Canal Efficiency Improvement Costs

Estimated costs for lining selected canals and ditches are given in Table 9. Ditches or canals having an estimated seepage loss in excess of 25 percent were considered for lining. For each of the 10 canals or ditches, wetted perimeter measurements were made at selected locations along the reach of each system. These data were used to establish an existing wetted area. Cross-sectional width and depth and slope of the various reaches were also established.

In the cost estimate, five different lining processes were considered: (1) bentonite; (2) 12 inches of compacted earth; (3) .010 inch PVC with 12 inches of compacted earth cover; and (5) 3-1/2 inch thick unreinforced concrete. Costs per square foot for each of these treatments (including material and installation costs) were established from experience, interviews with suppliers, cost data supplied by the U. S. Bureau of Reclamation, Denver Federal Center, and construction cost trends. The unit costs for each of the five processes are enumerated in Table 9.

The bentonite lining is the least expensive of the five, but it would be expected to require more annual maintenance and supplemental replenishment. An application rate of 5 pounds/square foot applied by the wash-in method was considered. This method application requires very little preliminary work and a minimum of expense and time to install. With the wash-in method, only a near-surface seal would be achieved and should not be used where velocities are excessive or where considerable bed material transport is anticipated. It is recommended that only three of the ten ditches be considered for this treatment process--Springdale, Bravo, and Peterson.

The compacted earth, the PVC, and the catalytic blown asphalt treatments would require that the cross section be shaped on a 2:1 side slope with a variable base width. A small amount of bentonite could be add-mixed with the compacted earth process in order to insure a more impermeable boundary. The ten mill PVC and the 1/4-inch thick catalytic blown asphalt should be covered with 12 inches of compacted earth.

Table IV-9

Estimated Costs for Lining Selected Canals and Ditches

Ditch or Canal	Length (Miles)	Existing Wetted Area (Sq Ft)	Bentonite	Compacted Earth (12 in. thick)[1]	.010" PVC (12 in. Compacted Cover)	Catalytic Blown Asphalt (¼ in. thick) (12 in. Compacted Cover)	Unreinforced Concrete (3½ in. thick)[2]
			$0.10/ft^2	$ 0.22/ft^2	$ 0.33/ft^2	$ 0.39/ft^2	$ 1.16/ft^2
South Platte	11.3	750,000	--*	$ 148,500	$ 222,750	$ 263,250	$ 652,500
Pawnee	28.0	3,400,000	--*	673,200	1,009,800	1,193,400	2,958,000
Schneider (South only)	3.6	230,000	--*	45,540	68,310	80,730	200,100
Springdale	16.1	1,600,000	160,000	316,800	475,200	561,600	1,392,000
Sterling #1	26.5	2,900,000	--*	574,200	861,300	1,017,900	2,523,000
Bravo	7.4	510,000	51,000	100,980	151,470	179,010	443,700
Iliff and Platte Valley	15.0	1,900,000	--*	376,200	564,300	666,900	1,653,000
Harmony #2	7.9	750,000	--*	148,500	222,750	263,250	652,500
Highline	16.2	1,900,000	--*	376,200	564,300	666,900	1,653,000
Peterson	17.2	1,600,000	160,000	316,800	475,200	561,600	1,392,000

* Wash in bentonite method not recommended.

(1) Wetted area reduced by 10% to account for smoother canal boundary (Mannings' "n" = 0.022).

(2) Wetted area reduced by 25% to account for smoother canal boundary (Mannings' "n" = 0.014).

The 3-1/2 inch thick unreinforced concrete section would be a trapezoidal cross section having side slopes of 1-1/2:1.

The costs enumerated in Table 9 are current estimates and would be expected to change with time. These costs do not reflect the additional work that may be required for hydraulic structures such as turnouts, drop structures, and gates and valves.

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V. COMPUTER MODEL ANALYSIS

General Description of Model

The answers to the many and varied questions which naturally come to mind regarding a system's behavior under different physical or managerial circumstances are very difficult to secure for a complex water use system such as the South Platte basin, particularly if the answers are to be quantitative at the *operational* level. A computer program was written to represent (*simulate*) in great detail the physical and operational characteristics of the prototype system. The resulting developed program (*model*) simulates a reach of the South Platte from a point slightly upstream of the Balzac U.S.G.S. stream gaging station to a point slightly downstream from the Julesburg gate at the Colorado Nebraska state line. The length of the simulated river is approximately 90 miles which, for modeling purposes, is subdivided into a total of 93 sub-reaches. Figure 1 (in the pocket at back of report) displays the grid system superimposed on the study area. The behavior of the aquifer (e.g., water table elevation) can be predicted at more than 1,000 gridpoints, but for purposes of this study water table elevations are calculated only in cells which the river crosses where the information is needed to calculate return flows. These return flows are directly proportional to the difference in mean cell aquifer level and river stage.

Pumping from wells located in the same cell of one square-mile size is assumed to be distributed uniformly over the entire cell. Loosely speaking, the pumping is assumed to be concentrated at a single point at the center of the cell. This point is referred to as a *grid* point. The square with the grid point at its center is sometimes referred to as the square of influence of the grid point.

The computer model specifically developed for the study consists of several components. On a tape are stored the influence coefficients of aquifer drawdowns at one grid point due to pumping at another grid point, for sets of discrete time values (e.g., one week, two weeks, three weeks, etc.). The amount of information gathered on this tape is enormous, since the system consists of 1057 grid points and behavior of the system is simulated at *weekly* intervals for a period of 10 years. However, with various techniques and simplifications it was possible to considerably reduce the amount of information on the tape. The procedure by which the influence coefficients (*discrete kernels*) are generated has been discussed in the literature (Morel-Seytoux and Daly, 1975; Illangasekare and Morel-Seytoux, 1977). (For the interested reader a summary of the mathematical basis for the concept and the generation of the *discrete kernels* is presented in Appendix A.) The discrete kernels on the tape are read in the computer whenever aquifer water-table levels are needed in the calculations.

On a second tape is stored all the known historical information about the system, such as: (1) weekly diversions from the South Platte at each of the 13 major diversions (as estimated by a Bureau of Reclamation study for the period 1947-1961); (2) weekly streamflows at the two gages of Balzac and Julesburg as recorded by the U.S. Geological Survey; (3) weekly effective precipitation; and (4) crop irrigation water requirements.

The main program performs the same sequence of calculations for every week and calls the tapes for information as necessary. Schematically the steps in the calculation are as follows:

1. Given the river inflow into the system the *legal* water availability is determined at each diversion point. This legal water availability is calculated as the upstream river inflow plus the aquifer return flows upstream of the diversion point minus the sum of all diversions of higher seniority, regardless of location. The calculations are performed starting with the diversion of highest seniority down to the one with lowest priority. Note that the *physical* water availability at a diversion point *exceeds* the legal water availability by the downstream diversions of more senior rights.

2. Given the just calculated legal and physical water availabilities, a decision is made as to the actual amount of water to be diverted for the week from each diversion point. The decision is reached from an *a priori* specified set of rules. This set of rules constitutes a *water allocation* strategy. For example, a *purely historical* water allocation strategy consists of reaching precisely the decision that was made by the river commissioner historically on that date. A *purely legal*

strategy consists of diverting exactly the full water right (no more, no less) of the irrigation ditch company if legally available at the diversion point.

3. Given the diversion amount decided upon by the water allocation strategy, availability on the farm served by the ditch is calculated. It is the diversion amount reduced by canal seepage losses. This water availability (expressed by then as a depth) on the farm is compared to the irrigation water requirement (also expressed as a depth) which is determined from the effective precipitation, crop evapotranspiration and farm irrigation efficiency.

If the calculated irrigation water requirement exceeds the surface water availability on the farm, pumping from the aquifer to supplement the surface water supply is considered. Again a predetermined set of rules is used to calculate the amount of pumping. For example, under a *purely historical* strategy the known historical volume would be pumped from the ground whether or not in fact it was needed by the crops. Under a *purely unconstrained* strategy, pumping would be limited only by the pumping capacity up to irrigation requirement.

4. Given the just determined seepage losses, pumping volumes and irrigation applications on the land, aquifer recharge rates and net withdrawal rates from the aquifer are calculated for every cell of the model.

5. Given the just calculated net withdrawal rates from the aquifer in every cell, water table elevations in every reach cell (i.e., a cell crossed by the river) are calculated. Given the river flows in every reach cell, namely upstream inflow into the reach plus return flow into the reach less diversion (if any) in that reach, river stages (elevations) are calculated from a stage-discharge curve. Based on the difference in elevation between the water table and the stream surface, return flows in each river cell are calculated. These return flows are used for the sequence of calculations to be performed for the following week.

6. Various outputs of interest are saved on tape or printed out for later analysis. For example, predicted stream outflow from the system and percentage degree of satisfaction of irrigation water requirement for the various irrigated areas are calculated. The cycle of calculation is repeated for the next week until the complete selected time horizon has been covered. By changing system efficiency (canal losses, farm

irrigation efficiencies, etc.) and water allocation strategies, one can evaluate the influence of such changes on streamflow, satisfaction of irrigation water requirements, etc.

Description of Model Runs

Runs of the mathematical model of the Lower South Platte river reach described above were made in several series. The first series used historical data in order to calibrate the model with the hydrologic situation which existed in the 1952 through 1961 period as closely as possible. Series II through V runs were designed to evaluate the sensitivity of the river reach efficiency to efficiency improvements in various components of the irrigation systems. The following sections describe the runs in more detail.

Series I run--historical data

The purpose of the Series I run was to duplicate the historical return flow situation in the study area as closely as possible for the study period of 1952 through 1961. It was particularly of interest to duplicate the situation during times of inadequate water supply to meet the irrigation needs, such as the 1954 through 1956 drought period.

The actual measured weekly volume of streamflow at Balzac was used in all Series I runs as well as the later series runs. The volumes of water diverted by ditches and estimates of ground water pumped under each ditch system by months during the study period were obtained from the USBR Farm Water Utilization Study (1965). The estimates of canal seepage losses and reservoir losses described earlier as developed by Dr. Skinner were used, as were the estimates of deep percolation from on-farm irrigation activities developed by Dr. Danielson and Dr. Hart. Weekly estimates of irrigation requirements by crops during the study period were used as discussed earlier.

The principal calculation of interest in the Series I runs was the estimated weekly flow at Julesburg. The estimated or calculated values were compared with actual measured values in the 1947 through 1961 study period. Minor adjustments were made and a final Series I run was conducted which was used as the comparison run for the later series.

Series II run--varying canal losses

The purpose of the Series II run was to evaluate the sensitivity of water use efficiency in the reach to changes in canal seepage losses. The input data used for the Series II run was the same as the final Series I run with the exception of changes assumed in canal losses with corresponding adjustments in ditch diversion explained below.

In this run, canal seepage was assumed to be zero in selected canals: The North Sterling Outlet Canal, the South Platte Ditch, the Sterling No. 1 Ditch, the Harmony No. 1 Ditch and the Highline Canal. These are principally canal systems with relatively senior rights and large diversion. In the Series II run, diversions by these canals were reduced so that the deliveries to the farm headgates remained the same as in the Series I runs. Water saved by such diversions was made available to any downstream canals (according to priority) which were then receiving less than the irrigation water requirement delivery at the farm headgates adjusted for on-farm efficiencies.

Series III run--varying on-farm efficiencies

The purpose of the Series III run was to evaluate the sensitivity of irrigation water use efficiency in the reach to changes in on-farm efficiencies. The input data for Series III run were the same as for the final Series I run with the exception of changes in on-farm efficiencies with corresponding adjustments in ditch diversions.

In this run it was assumed that all on-farm efficiencies which historically were estimated to be lower than 75 percent were raised to the 75 percent level. Ditch diversions were adjusted so that the crop received the same soil-moisture situation as in the Series I or historical run. Any reduction in diversions resulting from this assumption was allocated to downstream canals in accordance with the priority if said canals were receiving less than the estimated irrigation water requirement for that time period adjusted for on-farm efficiencies. As was done in the Series II runs also, the historical pumping was assumed to have taken place. The unfilled irrigation requirement adjusted for on-farm efficiency was used to determine the amount of canal water required to be delivered at the farm headgate.

Series IV run--varying groundwater pumping

The purpose of the Series IV run was to evaluate the sensitivity of irrigation water use efficiency in the reach to changes in use of groundwater. The input data for the Series IV run was the same as the final Series I run with the exception of the amount of groundwater pumped. In the Series IV run, it was assumed that sufficient groundwater was pumped under each canal system to meet the irrigation water requirements not satisfied by historical diversions. Under this assumption the groundwater reservoir was being used as a supplemental supply, pulled upon heaviest during drought years and replaced during years of good surface water supplies.

Series V run--combinations of Series II, III and IV runs

The purpose of the Series V run was to evaluate the change in irrigation water use efficiency in the reach attributable to the combination of improvements in canal seepage, on-farm efficiency and groundwater pumping as assumed in the Series II, III and IV runs.

Summary of Results

As described in Chapter III, five model runs were made. In the first run (Series I or *Reference* run) the system was the historical system as it existed during 1952 through 1961. The diverted and pumped volumes are the historical ones. The calculated outflow at Julesburg was compared with the measured historical flow of the Julesburg gaging station for model calibration. A full discussion of the calibration process is presented in Appendix B.

In the second run (Series II or Lined Canals Run) some of the canals were lined with the result that along these canals seepage losses were zero. The canals that were assumed lined are: North Sterling Outlet Canal, South Platte Ditch, Sterling No. 1 Ditch, Harmony No. 1 Ditch and Highline Canal. The results are also shown for comparison on Figures 2, 3 and 4. The water allocation strategy in this case consisted of allowing for the diversion of the minimum of the four quantities: water need, water right, legal water availability and historical diversion. Pumping is limited to its historical (1952-61) value.

In the third run (Series III or 75% Farm Irrigation Efficiency Run) it is assumed that, by whatever means, the farm efficiency has been uniformly improved over the entire system from a historical value of 40-50% depending on areas to a value of 75%. The water allocation strategy for diverted surface water and for pumped aquifer water is the same as for Series II.

In the fourth run (Series IV or Increased Groundwater Pumping) the system is the historical system (no lining, no improved farm efficiency, etc.) but the water allocation strategy for pumped water is more liberal. The surface water allocation strategy is the same as in Series II and III. However, pumping is allowed in excess of historical value but not to exceed the pumping capacity (as estimated from well records in 1973) and just enough to meet the crop water need not satisfied by the available surface water at the farm. Results are graphically displayed on Figures 2, 3 and 4.

In the fifth run (Series V or Combination Run) the same canals that were lined in Series II are lined, the farm efficiency has improved to the value of 75% as in Series II, and the water allocation strategy for surface and groundwaters is the same as in Series IV. Results are shown on Figures 2, 3 and 4.

Interpretation of Results

Merit of Series II Strategy (Lining of Canals)

The impact of this management strategy on the outflows is negligible for the entire duration of the simulation period (1952-1961). It cannot be seen graphically on Figure 2. The reduction in outflow was at most of the order of 5 cfs. The conclusion to be drawn is that lining of the canals (as assumed in this run) would not result in significantly more water being consumptively used in the study reach. Although the lining may improve the delivery efficiency of each system where it is applied, it does not make more water available for the reach - there is merely a relocation of water use and groundwater recharge.

It is possible that the lining as assumed (of major senior-priority canal systems) would have some beneficial effect upstream from the study reach. This would occur at times one or more of the senior-priority canals would otherwise be causing a call to be placed against upstream junior priorities if it were not for the water saved by the canal lining.

Lining of the canals as assumed improved the satisfaction of irrigation water requirements by, at most, an absolute 10% [1/] (see Figure 3). Naturally during the periods of particularly severe shortage (e.g., 9-12th week of 1952 irrigation season or 4-7th week of 1954 season) lining of canals does not provide much absolute relief to the acute water shortage. For instance, the water saved by lining the Sterling No. 1 canals is used entirely by this senior water right and no relief is felt at all by the junior downstream Settlers Ditch area (Figure 4).

Merit of Series III Strategy (75% Farm Irrigation Efficiency)

This management strategy reduces the downstream outflows noticeably late in the irrigation season (see Figure 2, 1955 and 1970 irrigation season) and also after the irrigation season. As opposed to the Series II (lining of canals) result, there is now a clear reduction in system outflow. This is evident, e.g., in the pattern of outflow following the 1953 or the 1960 irrigation season. It is noteworthy that the relative position of the Series I line (Reference Run) and of the Series III line does not change much from year to year and that the magnitude of the effect is about the same in 1960 as it was in 1953. One is tempted to say that a new stream-aquifer equilibrium position has been found as a result of the new strategy and that the new equilibrium is reached within a couple of years. Essentially, then, the reduction in system outflow is equal to the increased consumptive use of water on the farms.

The improvement in irrigation water requirement satisfaction is clear on Figures 3 and 4, e.g., for the 1953 irrigation season. However, when water is really scarce, e.g., as for weeks 9-12 in 1952 or 4-7 in 1954, the strategy does not help much. Little water used efficiently is still little water. Surprisingly, in late 1955 and 1956, after a net improvement in satisfaction of irrigation need early in the season, worse results are

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[1/] For instance, if the historical percentage of satisfaction were 60% for a particular time period the canal lining as assumed improved it to no more than 70%.

obtained as compared to Series I and II. This effect occurred only in 1955 and 1956. It may be due to a significant reduction in streamflow, thus water availability for diversion, caused by the very low aquifer recharge occurring early in the season. Generally a clear improvement is realized, but not when it is needed most. Improved farm efficiency is not therefore, an effective remedy under a severe surface water drought condition as experienced in 1952, 1954, 1955 and 1957.

Merit of Series IV Strategy (Increased Groundwater Pumping)

Under this strategy the system outflow is further reduced because much more water is available on the farm *even* when surface water supply is very scarce. Irrigation water requirements are more fully met, resulting in a decrease of system outflow. Note that the steady application, starting in 1952, of this pumping strategy leads promptly to a new

equilibrium between the stream and the aquifer, apparently in a couple of years. The relative pattern of the outflows is very much the same in 1960 as it was in 1953. In other words, the strategy does not result in a continued mining of the aquifer but rather in a new equilibrium. To save computer costs, at some point in the duration of the study it was considered to make runs only for a few years. Now with hindsight it is fortunate that a 10-year horizon was chosen because the fears of a continuous decline in aquifer storage with time as a result of increased ground water pumping appear unfounded. This is a very significant result with important management implications.

With this strategy, satisfaction of irrigation water requirement is drastically improved as compared to the previous strategies (see Figures 3 and 4) even during periods of severe surface water drought (e.g., weeks 4-7 of 1954 season, 5-7 of 1955 season, etc.). Lining of canals and increased farm efficiency are only relative remedies. With these strategies the extra amount of available water is proportional to the amount available. If it is small, the water saving is also small. A strategy of increased pumping making better use of the ground water reservoir is an absolute remedy. Except for pump capacity limitations, water is made available as needed.

Merit of Series V Strategy (Combination Run)

Under this combination strategy downstream flows are further reduced and irrigation satisfaction is increased. With this strategy 100% irrigation satisfaction is achieved practically every year for the irrigation season. Notice that the same result could have been achieved with increased pumping capacity alone. Where pumping capacity is limiting (see weeks 5-7 of 1955 season) improved (75%) farm efficiency brings the system to perfect performance. With more pumped water available the same result could be achieved.

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VI. SUMMARY AND CONCLUSIONS

1. Irrigation water use efficiency can be viewed from a number of different standpoints. The individual farmer is primarily concerned about how efficiently he can use water on his farm. Officials of canal and reservoir companies are principally concerned about delivering a high percentage of the amount of water diverted from the river to the farm turnouts. On a larger scale, the efficiency of water use within a river reach or river basin is important. This study was directed at evaluating the effects of improved farm and canal system efficiencies upon river reach water use efficiency.

2. Existing farm irrigation efficiencies in the study area were evaluated by the study team using technical guidelines of the Soil Conservation Service together with opinions of professionals experienced in the area. The estimated farm irrigation efficiency ranges from 31 percent to 50 percent with an average of 41 percent.

3. Estimates of existing canal and reservoir system efficiencies were obtained from canal and reservoir company personnel and other individuals knowledgeable in the study area. The delivery efficiencies of the systems vary considerably, but most are in the 60-80 percent range. One system delivers less than 30 percent of the water it diverts from the river, but most of the losses from the system are recovered by downstream ditches and wells.

4. Costs of improving farm and canal system efficiencies were estimated. The cost of raising the average farm irrigation water use efficiency from 41 percent to 62 percent by improved water management (scheduling) may be only a few dollars per acre per year. The cost of further increasing the average farm efficiency to 75 percent would be on the order of $30 per acre per year because significant capital investments and operation costs would be required.

5. The computer model analysis in which major senior-priority ditches were assumed to be lined showed little gain in the overall efficiency of water use in the study reach (lower 90 miles of the South Platte River in Colorado). Although the satisfaction of irrigation need on individual ditch systems that were lined was improved, no additional water was made available to other appropriators.

6. The computer model analysis in which the average farm irrigation efficiency in the study reach was raised to 75% resulted in slightly improved river reach efficiency. However, during times of water shortage the reach efficiency was improved very little. Obviously, the improvement of farm irrigation efficiency can help an individual farmer use limited water, but a large-scale program of farm irrigation efficiency improvement would not make significantly more water available to a reach or river basin at those times of the season or in dry years when additional water is most needed.

7. The computer model analysis in which additional groundwater pumping was allowed to supplement surface water supplies showed the greatest increase in overall water use efficiency in the river reach of any of the changes from historic conditions that were tested. The improvement is due principally to the fact that water can be made available when and where it is needed through conjunctive use of the groundwater reservoir. In effect, water is saved for additional beneficial uses in the reach. Improvements in ditch conveyance and farm irrigation efficiencies do not accomplish the same result. An important finding from this analysis is that under increased pumping a new equilibrium was rapidly (2 years) established in groundwater level and return flow. This means that increased pumping on a sustained basis is possible.

VII. FUTURE STUDIES

The improvement in efficiency of water use in a river basin or reach has many physical, legal, economic, social and institutional ramifications. The study reported herein only addresses a portion of the physical aspects and should be considered only the beginning of studies necessary for a basis of making major water management decisions. Brief descriptions of further studies needed follow:

1. Optimal use of the groundwater reservoir in conjunction with surface water supplies to meet specific goals should be determined. The study reported herein shows the potential for increasing overall water use efficiency in the study reach, but does not necessarily assume the most optimum combination of conjunctive uses for various water availability situations.

2. Model studies should be extended to upstream reaches of the South Platte River in order to evaluate the total effect of water use efficiency and management changes in the basin. The influence of such changes can reach upstream because of changes in calls by senior appropriators.

3. The potential of increased control of surface water flows by on-stream storage reservoirs in conjunction with planned groundwater storage and use should be explored. Such studies could evaluate proposed reservoirs, such as Narrows, for capturing flood flows and releasing same for planned groundwater storage. Substitution of groundwater storage for surface storage could also be evaluated.

4. The increased consumptive use of water and increased water use efficiency in a reach or river basin can also have negative aspects, such as the increase in salinity that may result. Also, consideration should be given to interstate compact obligations.

5. Many legal and institutional problems need to be solved in implementing a conjunctive use plan. For instance, flexibility in water withdrawals from surface and groundwater sources (still in harmony with water right ownership) will be necessary to implement improvements in utilization of the annual combined supply which are found to be possible by this model study. This model did not differentiate areas served only by surface sources. To accomplish the satisfaction of

irrigation water requirement calculated in the model, transfers of water under each ditch system would be required such that at times all or most of the surface water would supply lands where wells cannot be obtained. Similarly, during times of surplus surface water those lands overlying the alluvial aquifer should take additional ditch water for purposeful recharge. The techniques and authorities for accomplishing and financing these kinds of transfers need to be worked out, with the roles of the ditch and reservoir companies, the Conservancy District and the Colorado Division of Water Resources defined. Legislative action may be required.

APPENDIX A

MATHEMATICAL BASIS FOR THE STREAM-AQUIFER INTERACTION MODEL

Background

Isolated aquifer

At the heart of the mathematical modeling of the physical (hydrologic) interaction of an alluvial water-table aquifer with a hydraulically connected stream is the Boussinesq equation, namely:

$$\phi \frac{\partial s}{\partial t} - \frac{\partial}{\partial x} (T \frac{\partial s}{\partial x}) - \frac{\partial}{\partial y} (T \frac{\partial s}{\partial y}) = \sum_{p=1}^{P} q_p \qquad (1)$$

where ϕ is the effective porosity (specific yield), s is drawdown at the point of horizontal coordinates x and y and at time t, T is the transmissivity of the aquifer at point of coordinate x and y, q_p is the net pumping (withdrawal) rate per unit area at well (withdrawal) point p and P is the total number of well (withdrawal) points.

For an aquifer which is not mined and relatively deep, the transmissivity can be considered to be constant. Then Eq. (1) is a linear equation and it is known then that the solution of Eq. (1) for drawdown at a point w for week n is of the form:

$$s_w(n) = \sum_{p=1}^{P} \sum_{\nu=1}^{n} \delta_{wp} (n-\nu+1) \; Q_p(\nu) \qquad (2)$$

where $\delta_{wp}(\ )$ is the discrete kernel function (influence function) of drawdown at point w due to pumping at point p and $Q_p(\nu)$ is the net withdrawal volume from the well p. The coefficients $\delta_{wp}(\ )$ are calculated for a given system by a numerical solution of a finite-difference approximation to the Boussinesq Eq. (1). These procedures are discussed in detail in various publications (Morel-Seytoux and Daly, 1975; Morel-Seytoux et al., 1975). Figure A-1 displays a typical grid system superimposed on the area of interest with one well at the center. Figure 6 shows the discrete kernel function of drawdown 350 m (about 1000 feet) away from the center well due to pumping at the center well. As an example let us assume that the well pumped water volumes during 10 weeks according to the schedule shown in Table 1.

TABLE 1

Week	1	2	3	4	5	6	7	8	9	10
Volume (million m^3)	0.2	0	0	0.1	0	0	0.2	0	0.1	0
$\delta(\ )$ m/million m^3	3.6	3.3	2.6	2.0	1.5	1.3	1.1	1.0	0.9	0.8
Drawdown (m)	0.72	0.66	0.52	0.76	0.66	0.52	1.14	1.01	1.19	1.00

The values of δ (in m/million m^3) in Table 1 were read from Figure A-2 From Eq. (2) one can calculate drawdown 350 m away from the well at the end of one week, two weeks, three weeks, etc., namely:

$$s(1) = \delta(1)\ Q(1) = 3.6 \times 0.2 = 0.72 \text{ m}$$

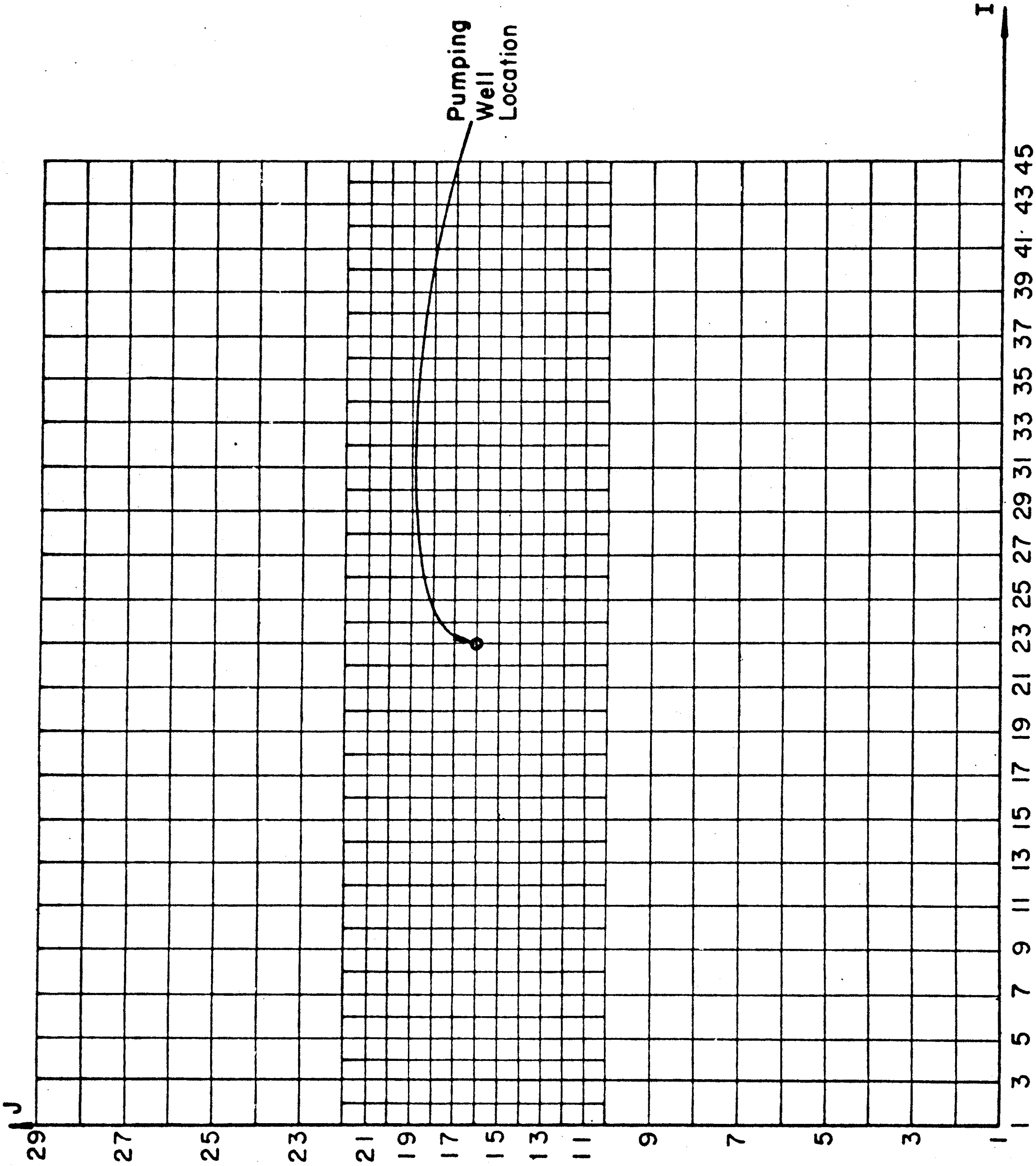
$$s(2) = \delta(2)\ Q(1) + \delta(1)\ Q(2) = 3.3 \times 0.2 = 0.66 \text{ m}$$

Note that during week 2 the water table recovers at point w. Proceeding similarly for the other weeks:

$$s(3) = \delta(3)Q(1) + \delta(2)Q(2) + \delta(1)Q(3) = 2.6 \times 0.2 = 0.52 \text{ m}$$

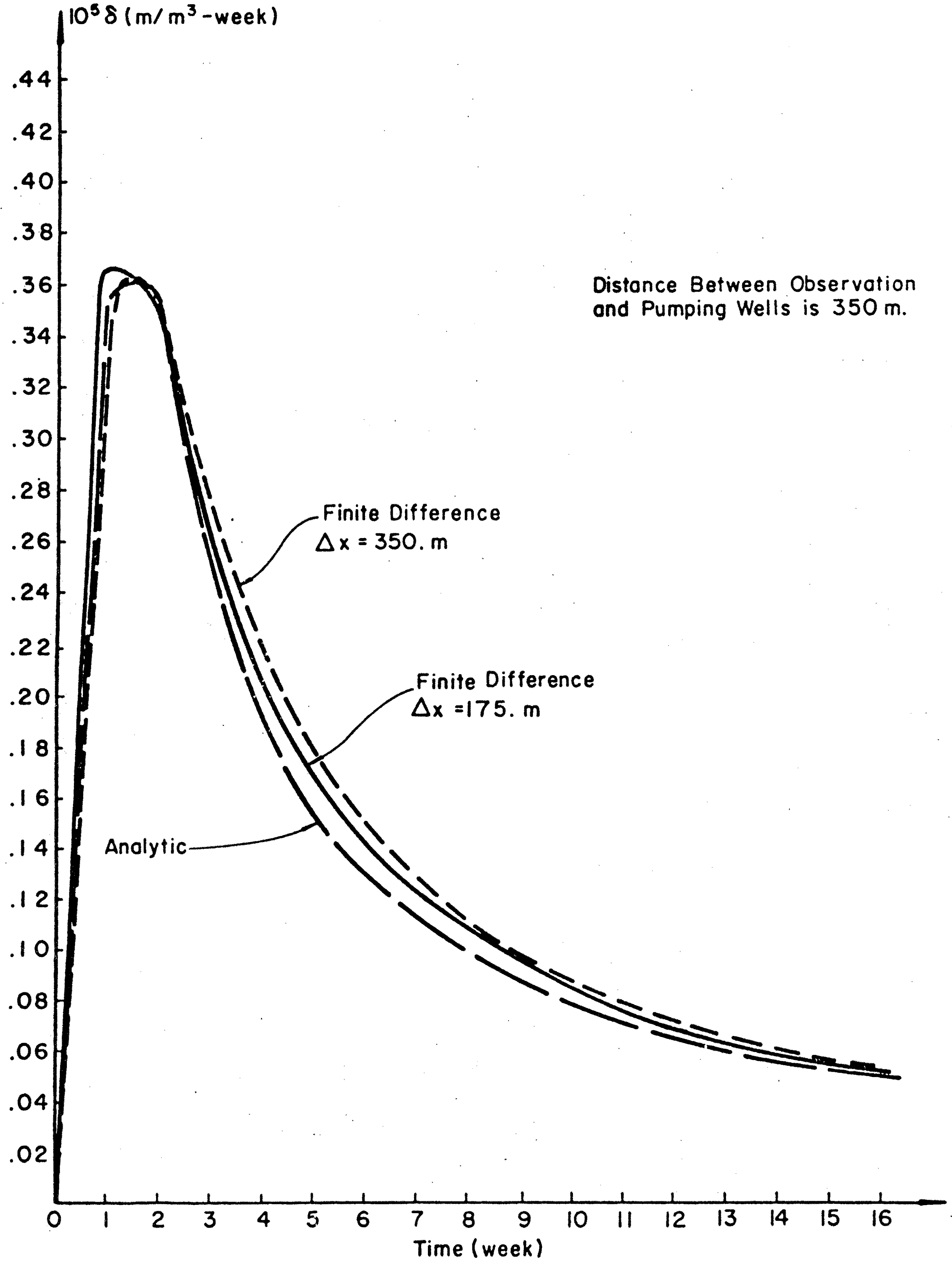
$$s(4) = \delta(4)Q(1) + \delta(3)Q(2) + \delta(2)Q(3) + \delta(1)Q(4) = 2.0 \times 0.2 + 3.6 \times 0.1 = 0.76 \text{ m}$$

The other values are shown in Table 1, and the drawdowns plotted on Figure A-3.



Pumping Well Location
I
J
3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29

Figure A-1



$10^5 \delta$ (m/m^3-week)
.44
.42
.40
.38
.36
.34
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
Distance Between Observation and Pumping Wells is 350 m.
Finite Difference Δx = 350. m
Finite Difference Δx =175. m
Analytic
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Time (week)

Figure A-2

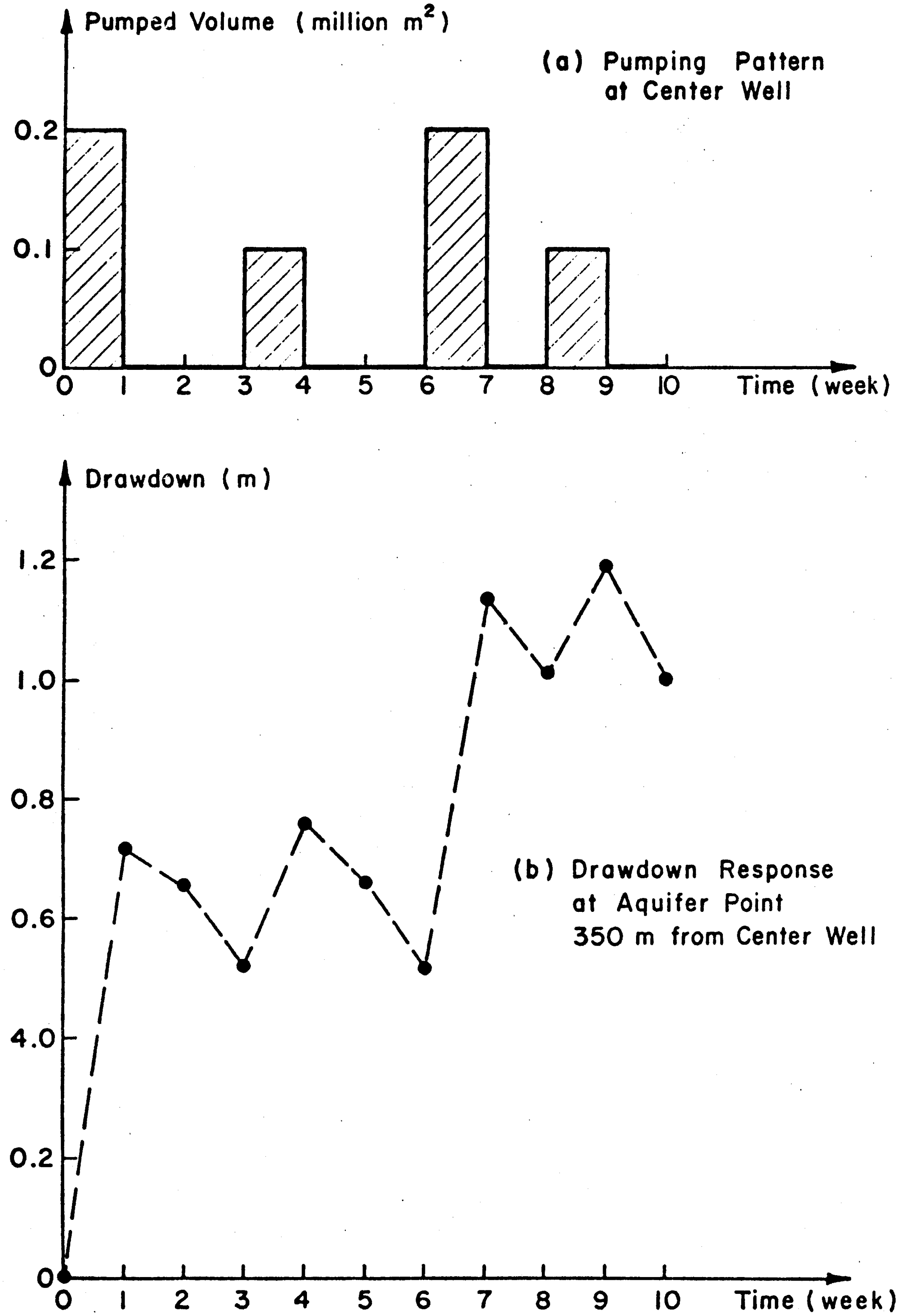

Pumped Volume (million m²)
(a) Pumping Pattern at Center Well
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10
Time (week)
Drawdown (m)
1.2
1.0
0.8
0.6
4.0
0.2
0
(b) Drawdown Response at Aquifer Point 350 m from Center Well
0 1 2 3 4 5 6 7 8 9 10
Time (week)

Figure A-3

Once the δ coefficients have been calculated then it is an easy matter to calculate drawdown anywhere at any time. Note that contrary to usual finite difference procedure it is possible to calculate drawdown at the end of week 8 for example without calculating drawdowns for the previous weeks. Also it is possible to calculate drawdown at one point without calculating it at other points. In other words, drawdowns are calculated only at points and times of interest. Therein lies a reason for the (relative) cost-effectiveness of the "discrete kernel" approach. On the other hand, the drawdown at one point does depend upon the entire history of pumping since time zero at all withdrawal points.

Aquifer-stream interaction

Considering the stream to behave mathematically as a long and narrow withdrawal strip, then net drawdown in an aquifer cell is the combined effect of withdrawals from wells, from the river (return flow, base flow) and recharge from field irrigation (negative withdrawal). Then Eq. (2) applies provided $Q_p(\nu)$ be interpreted as the net withdrawal volume from the cell p for week ν. If return flows in a reach were known as a function of time then application of Eq. (2) would yield drawdown at point w. Of course, the $\delta_{wr}(\ )$ coefficients of drawdown at point w due to return flow into reach r must be known.

Reach transmissivity

In practice return flows may be known between two stream gauging stations some 100 miles apart but not at much smaller intervals. The return flows over the reaches within an aquifer cell (zone of influence) are not known and in fact depend on the relative position of the water table with respect to the water level in the river. It has been postulated (Morel-Seytoux and Daly, 1975; Morel-Seytoux, 1975a,b) and verified with reasonable accuracy (Peters and Morel-Seytoux, 1978) that the return flow, Q_r, into a reach within a cell was proportional to the difference between the mean aquifer drawdown and mean river drawdown (river level measured from a high datum) in the cell or mathematically:

$$Q_r = \Gamma_r \, (\sigma_r - s_r) \qquad (3)$$

where Γ_r is the reach transmissivity and σ_r is the river drawdown. The reach transmissivity can be estimated from the stream and the aquifer properties by the relation (Peters and Morel-Seytoux, 1978; Illangasekare, 1978):

$$\Gamma_r = \frac{TL \, (\frac{W_p}{2} + e)}{e \, (L + \frac{e}{2})} \qquad (4)$$

where T is aquifer transmissivity, L is reach length, W_p is wetted perimeter of the stream, and e is saturated thickness.

South Platte study

Grid system. Figure 1 displays the river section of interest, with diversion canals, storage reservoirs and wells and the selected grid system. Previously developed computer programs (Morel-Seytoux et al., 1975) were used to calculate the δ coefficients. The number of δ coefficients to be stored is very large and would be prohibitive if the δ were calculated on a weekly basis over 15 years. Instead only a limited number of δ on a weekly basis are calculated (say 4), then a limited number of δ on a monthly basis (actually 4 weeks) are calculated (say 4) and 15 yearly values are calculated. Thus to calculate drawdown after 90 weeks, a modified version of Eq. (2) is used. Let

$Q_p(\nu)$ be the weekly pumping rates. Let $Q_m(\lambda)$ be the monthly pumping rates occurring at integer multiple number of months prior to the date of interest. For example for the date of 90 weeks then $Q_m(1)$ is:

$$Q_m(1) = \sum_{\nu=83}^{86} Q_p(\nu)$$

and similarly:

$$Q_m(2) = \sum_{\nu=79}^{82} Q_p(\nu); \quad Q_m(3) = \sum_{\nu=75}^{78} Q_p(\nu); \quad Q_m(4) = \sum_{\nu=71}^{74} Q_p(\nu)$$

Let $Q_y(\alpha)$ be the yearly pumping rates occurring at integer multiple number of years prior to the date of interest. For example again for the date of 90 weeks, then:

$$Q_y(1) = \sum_{\nu=19}^{70} Q_p(\nu)$$

$$Q_y(2) = \sum_{\nu=1}^{18} Q_p(\nu)$$

The modified form of Eq. (2) is:

$$s(90) = \sum_{\nu=87}^{90} \delta_w(90-\nu+1)Q_p(\nu) + \sum_{\lambda=1}^{4} \delta_m(\lambda+1)Q_m(\lambda) + \sum_{\alpha=1}^{2} \delta_y(\alpha+1)Q_y(\alpha)$$

Instead of 90 weekly δ coefficients, only $4 + 4 + 2 = 10$ coefficients are needed. For a date corresponding to 15 years when $15 \times 52 = 780$ weekly coefficients would be needed, still 23 coefficients suffice. However, there is a computer price for this storage saving because the monthly and yearly pumping volumes must be recalculated every week (like a moving average).

Initial conditions. The original computer programs were developed to solve aquifer operational management problems using optimization on a seasonal basis. They were not designed to simulate long periods of time nor to calibrate system parameters. For simulation purpose it is necessary to superimpose upon the effect of the withdrawals on drawdown as given by Eq. (2) an additional term corresponding to the natural evolution of the aquifer if initially not at rest. A very promising and partially tested methodology has been developed but the computer program was not operational at the beginning of this study. Due to the serious time limitation of the study (then relaxed somewhat) it was decided to treat the effect of the initial condition with the introduction of a warm-up period. At the beginning of the warm-up period the aquifer is in flat equilibrium. As time proceeds the water-table builds up due to a net recharge from river diversions and field irrigation. By gradually increasing the return flows through the warm-up period until they reach actually observed values at the end of the warm-up period, an initial condition is recreated for the simulation period. If the calculated return flows (using Eq. 3) match the observed values during the early part of the simulation period then an acceptable initial condition was recreated. If not the trial and error calibration must be repeated.

APPENDIX B

DESCRIPTION OF CALIBRATION PROCEDURES AND RESULTS OF SOUTH PLATTE COMPUTER MODEL

Available Data

The entire area under study was divided into 35 subareas referred to as "*service areas*". A *service area* consists of a set of farms (and associated land area) supplied by a *common* ditch bringing to the area water diverted from the stream and/or by a *common* outlet from a reservoir and/or from wells. For each of the service areas the following data were gathered and compiled on a weekly basis for the period 1947-1961:

(a) surface water made available,

(b) total amount of ground water pumped from wells,

(c) amount of precipitation received,

(d) an average irrigation efficiency for the farms.

For the same period the following South Platte streamflow data were compiled on a weekly basis:

(a) Stream flow at a point upstream of Balzac gaging station (upper boundary of the study area).

(b) Stream flow at a point downstream of Julesburg gage at the Colorado-Nebraska state line (lower boundary of the study area).

(c) Return flow to the stream between diversions.

In addition the following information was also gathered:

(a) Phreatophyte losses,

(b) Seepage from canals under average flow conditions,

(c) Seepage from reservoirs, and

(d) Stage discharge relationships at Balzac and Julesburg gages.

Calibration Criterion

Historical data for two types of state variables were available for the stream-aquifer system for the purpose of calibration, namely: the aquifer return flows and the stream outflow measured at the downstream boundary of the system. The observed return flows in the subreaches are functions of the stages in the stream (state of stream) and the aquifer water table elevations (state of the aquifer). The observed downstream flows show the aggregated effect of the state of the total system. The observed outflows were selected as a measure of calibration, taking into consideration the fact that more reliable weekly outflow data compiled from *daily* flow data were available as compared to the weekly return flows compiled from *monthly* estimates. Also, the outflow which is also the flow into Nebraska becomes an important parameter to be analysed in drawing major conclusions from the study.

Calibration Runs

A simulation period of 350 weeks, starting from the first week of July, 1951 to the last week of February, 1958, was selected for calibration. An important consideration given in the selection of this period was that it includes the drought years 1953 through 1956. These drought years with fairly low observed downstream flows are bounded by the wet years of 1952 and 1957 with observed high flows. The main objective was to calibrate the model for the low flow drought years for which the overall project objective of studying the impact of different physical and/or managerial strategies was addressed. The 46-weeks wet period

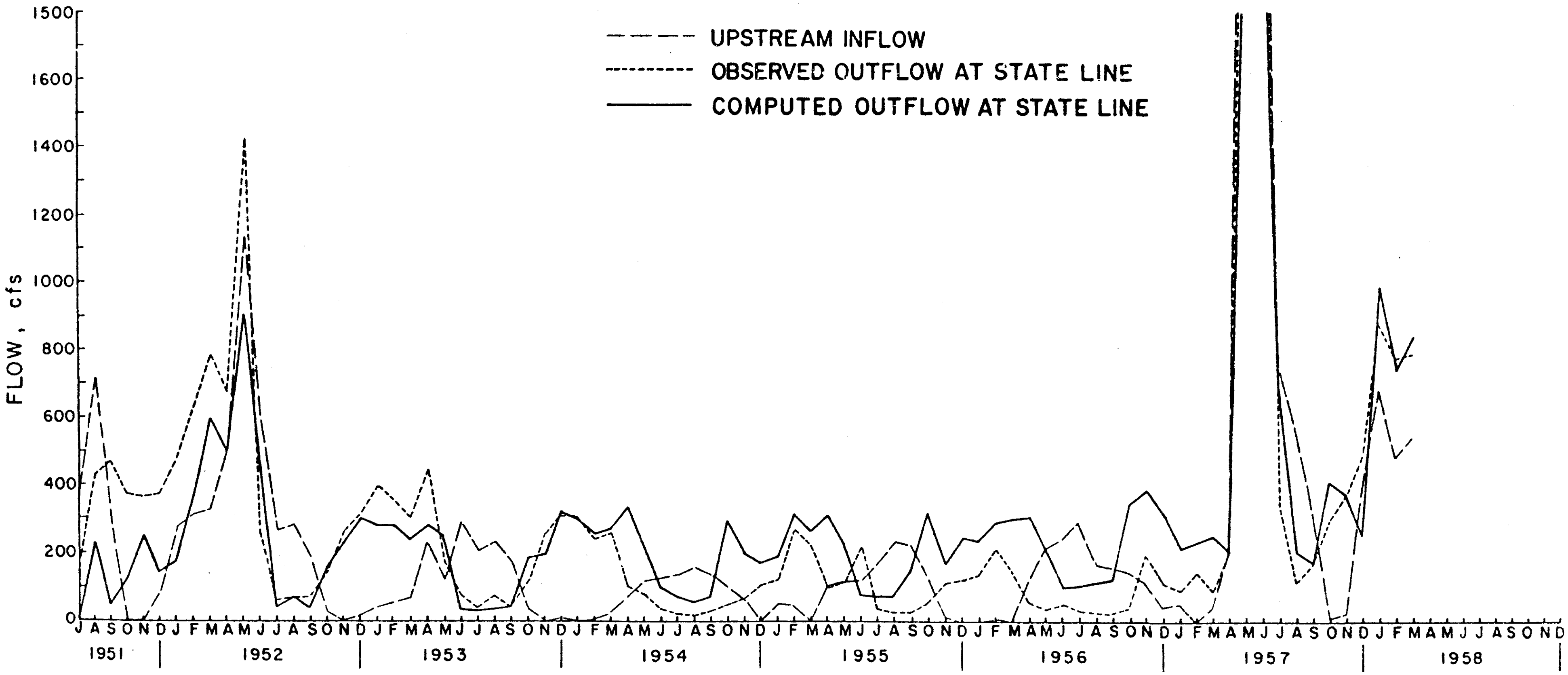


Figure B-1 Comparison of monthly observed and calculated flows at stateline starting from the first week of the simulation period and ending at the beginning of the 1952 irrigation season was treated as a "*stabilization period*" for the model. During this period the responses of the system due to the different excitations were allowed to stabilize. No attempt was made to calibrate the system to match the observed and computed outflows during the *stabilization period.*

Data in the form of aquifer water table elevations were not available to define the initial conditions of the system at the beginning of simulation. The only available information was the observed return flows. As mentioned previously, the return flow depends on the state of the system. In the absence of initial aquifer drawdown data the observed initial return flows were used to define the initial conditions. This was achieved indirectly by using an artificial history referred to as the "*warm-up period*". The *warm-up period* includes an assumed excitation history of 20 years during which the aquifer excited in such a way to bring the aquifer from an assumed initial steady state to the observed initial state. The selected 20-year period was approximately the memory period of the aquifer. The artificial history during the warm-up period was manipulated to create approximately the observed return flows at the beginning of the simulation period. The data from actual observed history for the period of 1947-1961 was used as an initial approximation for the artificial history during the warm-up period. The system was calibrated to obtain a reasonable match between the observed and computed outflows by manipulating the excitations during the warm-up period. A few changes in the (somewhat) known historical excitations were made to create the artificial history. First, it was observed that the historical excitations created a mining situation in the downstream section of the aquifer. This resulted in high negative return flows at the downstream reaches. This was corrected by setting all the net withdrawal excitations to be zero during the warm-up period. Second, a mass balance comparison of the net aquifer recharge and net aquifer return flow to stream during the warm-up period showed that the latter was in excess by $.17 \times 10^{10}$ cubic meters. This quantity is equivalent to an average depth of 6 meters distributed throughout the aquifer. To allow for this unaccounted quantity of water the aquifer level was raised throughout the aquifer. A raise in mean water table elevation of 7.8 meters gave the best match for the calibration.

The system was simulated using the artificial warm-up period and the observed history on a weekly basis. The observed outflows and the computed outflows for the final calibration run are shown on Figure B-1.

Calibration Results

The observed and computed outflows do not match perfectly but there are several positive results, which can be readily seen from the figure. The most critical period is that of low downstream flows, occurring regularly in June, July, August and September of each year. These low flows are predicted reasonably well. During the period of high downstream flows occurring regularly in December, January, February and March, the comparison between observed and computed flows is quite good in 1953 and in 1954. Starting in 1955 there is a tendency for the model to *over-predict*. However, by 1958 following the wet 1957 year, the agreement for the months of January and February was even a little better than 1953. Note that even though through the years (1954-1955-1956) the difference between predictions and observations increases *cumulatively*, the two curves show very similar patterns.

One interpretation of the results is that the downstream low flows in August and September occur when return flows are small because: (1) the aquifer level has been lowered as a result of pumping, (2) upstream inflows are fairly high, and (3) surface diversions are extensive. The downstream outflows are conditioned mostly by the diversions. The small return flows do not affect significantly the streamflow. On the other hand, in December, January, February and March the upstream inflow is quite low. The river stage is at its lowest through the stream and the downstream flows are conditioned by the return flows and diversions, diversions being possible only from the existence of return flows. The drift in the predictions during these months may be caused either by overprediction of water-table elevations in the aquifer, thus causing higher return flows from the aquifer to the stream or by underprediction of diversions from the stream. Overprediction of water-table elevations in the aquifer could be due to underestimation of pumped volumes (Bureau of Reclamation data are used in the study) or underestimation of irrigation efficiency (i.e., overprediction of recharge) or underestimation of evapotranspiration losses (or losses from phreatoph tes). The purpose of the calibration runs was mostly to check the possibility of errors in the programs and to check that the values of reach transmissivities and of the stage-discharge relations in the stream. The results indicate that the reach transmissivities and the stage-discharge curves require no adjustments.

As indicated previously, a possible cause of apparent drift in the prediction of the high downstream flows could be that the Bureau of Reclamation data on pumping, diversions and return flows are somewhat in error, but it could be due to errors in estimation of irrigation efficiency. One could have played on these factors to obtain a better fit but it is difficult to time the impact of a correction and many trial and error runs would have been required. It was too costly to do with the resources allocated to this study. However, with *hindsight* looking at the results of the Series IV run it is clear that by progressively increasing values of pumping for the historical period 1953-1956 over the estimated Bureau of Reclamation values one could have obtained a better match between predicted and observed outflows in 1955 and 1956.

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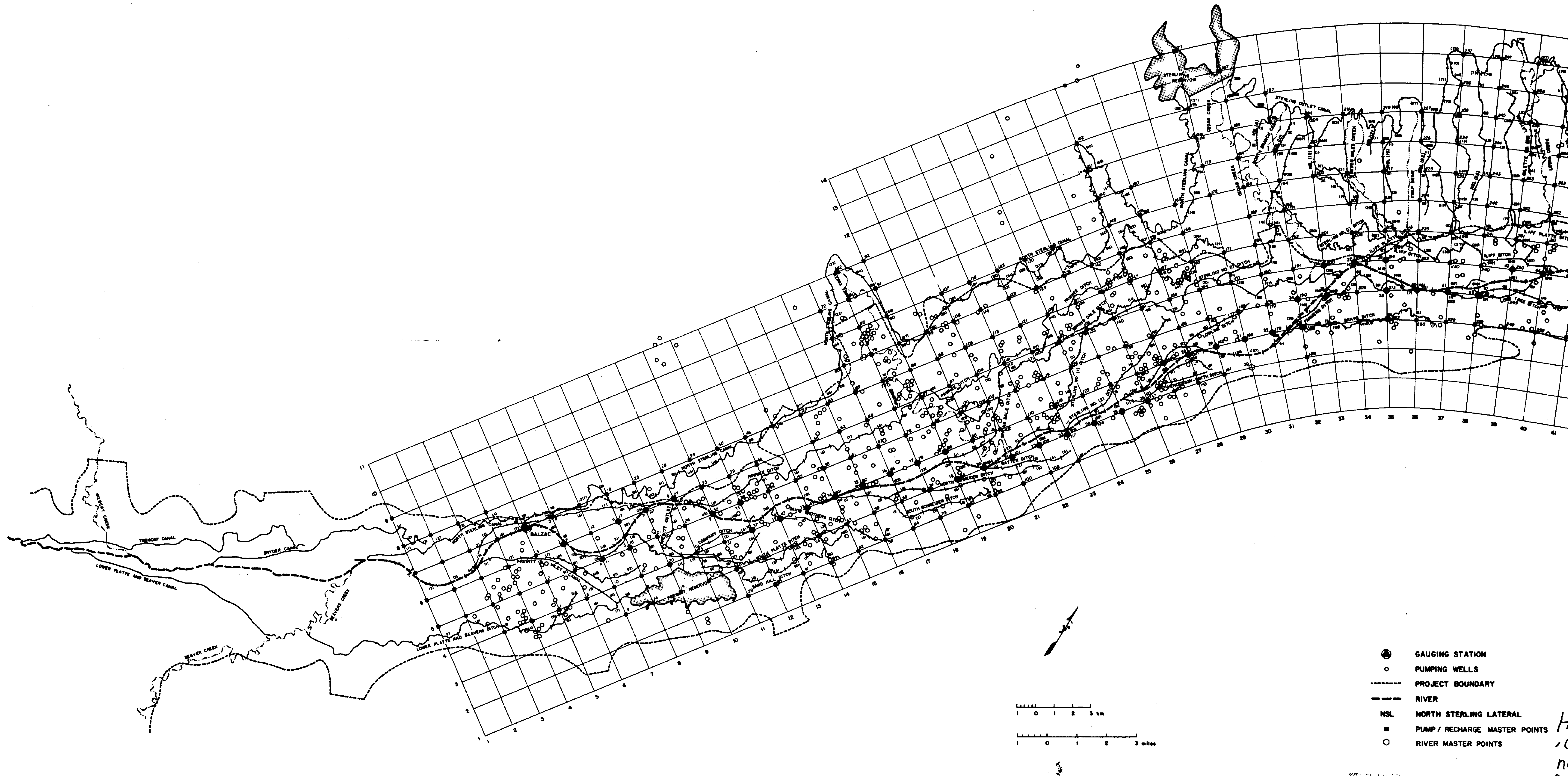
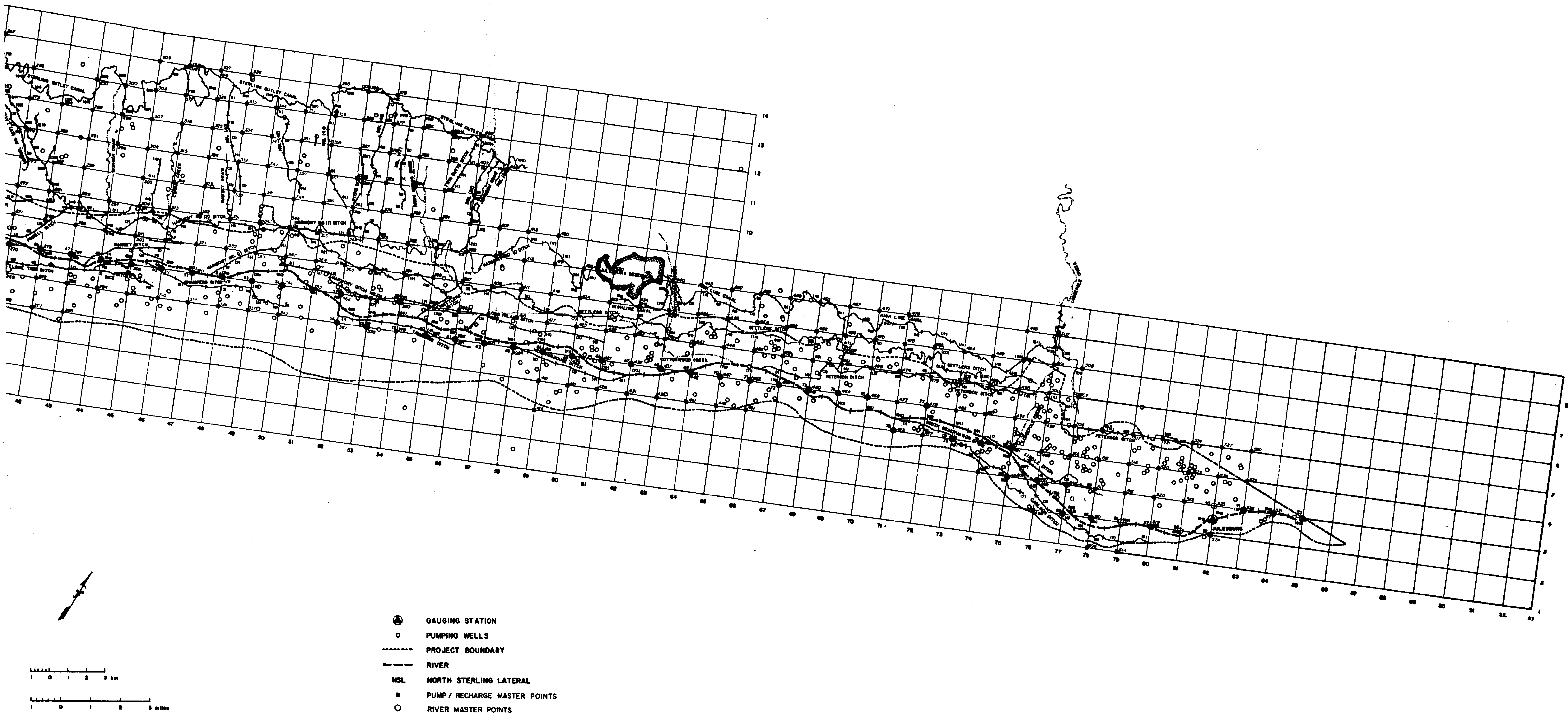
FIGURE V-1 MAP SHOWING DITCHES, CANALS, RESERVOIRS AND PUMPING WELLS IN BALZAC - JULESBURG REACH OF THE SOUTH PLATTE RIVER





GAUGING STATION
PUMPING WELLS
PROJECT BOUNDARY
RIVER
NSL NORTH STERLING LATERAL
PUMP / RECHARGE MASTER POINTS
RIVER MASTER POINTS
3 km
3 miles
STERLING OUTLET CANAL
HIGHLINE CANAL
SETTLERS DITCH
PETERSON DITCH
COTTONWOOD CREEK
SOUTH RESERVATION DITCH
JULESBURG

FIGURE V-2 COMPARISON OF OUTFLOWS AT STATE LINE

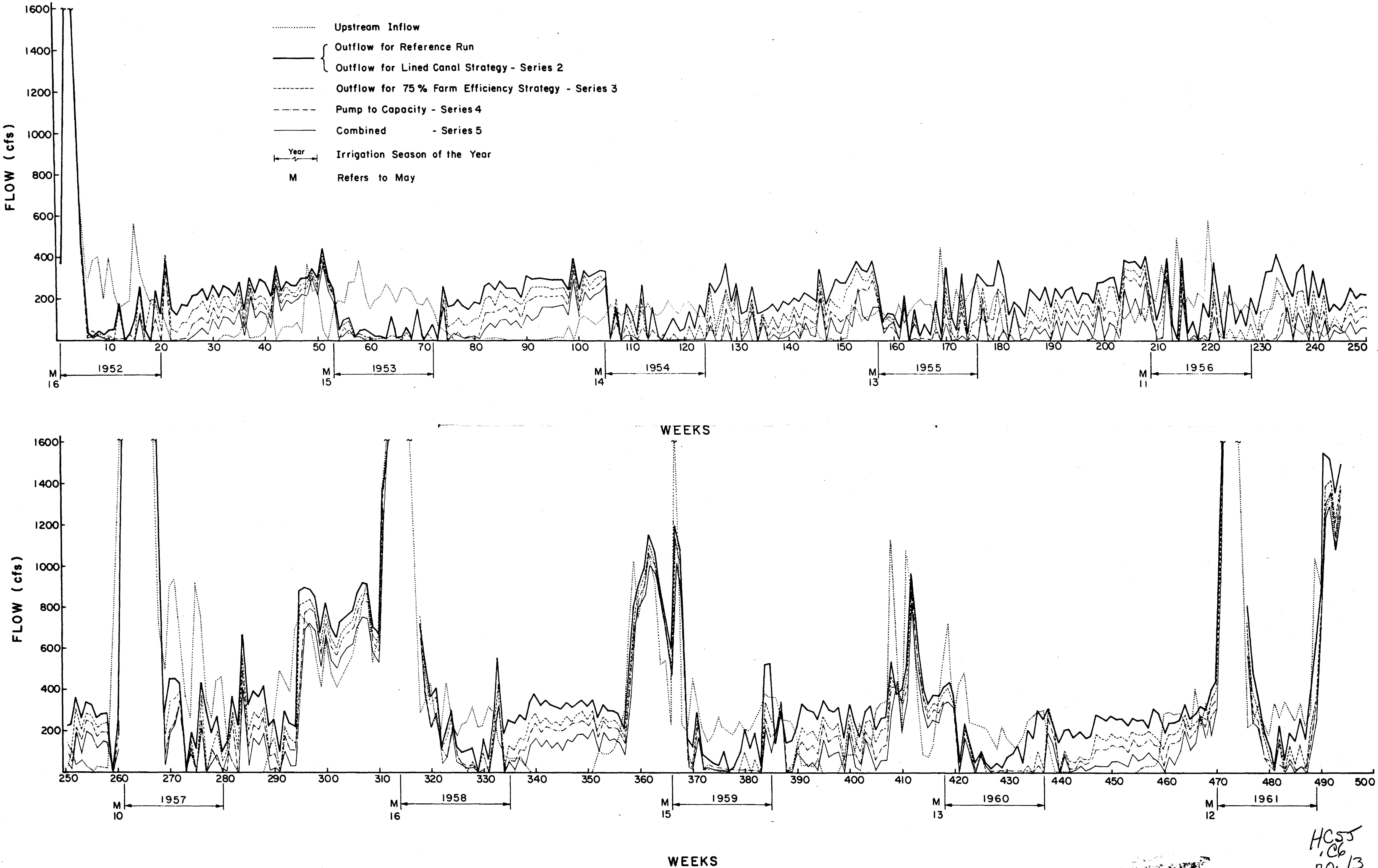


FIGURE V-3 PERCENTAGE SATISFACTION OF IRRIGATION REQUIREMENTS FOR THE STERLING NO. 1 AREA

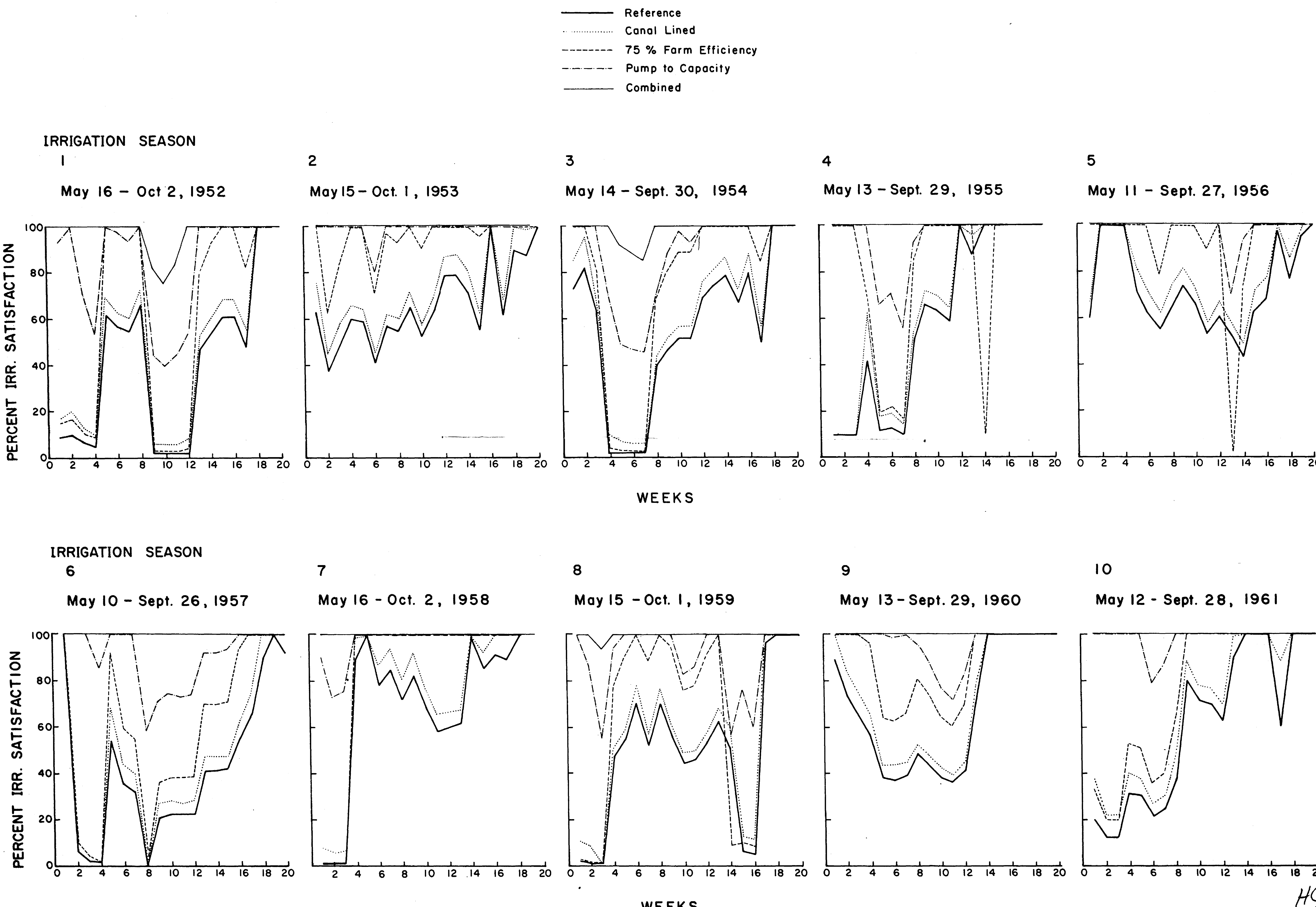


FIGURE V-4 PERCENTAGE SATISFACTION OF IRRIGATION REQUIREMENTS FOR THE SETTLERS DITCH AREA