HYDROLOGIC EFFECTS OF REDUCING IRRIGATION TO

MAINTAIN A PERMANENT POOL IN JOHN MARTIN

RESERVOIR, ARKANSAS RIVER VALLEY, COLORADO

By Richard R. Luckey

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CONTENTS

ILLUSTRATIONS

TABLE

CONVERSION FACTORS

For use of those readers who may prefer to use metric units rather than English units, the conversion factors for the terms used in this report are listed below:

Multiply English unit	By	To obtain metric unit
inches	25.40	millimetres (mm)
feet	.3048	metres (m)
cubic feet per second (ft^3/s)	.0283	cubic metres per second (m^3/s)
miles	1.609	kilometres (km)
square miles	2.590	square kilometres (km^2)
acre-feet	1233	cubic metres (m^3)

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ABSTRACT

The U.S. Geological Survey has evaluated a plan by the Colorado Division of Wildlife to maintain a permanent pool of 10,000 acre-feet (1.2×10^7 cubic metres) in John Martin Reservoir on the Arkansas River. The proposed pool would be maintained through the use of water formerly diverted by the Catlin Canal Company to irrigate land in the Arkansas River valley. This plan was evaluated using a mathematical simulation model developed to test management alternatives in a stream-aquifer system. A 25-year period from 1949 through 1973 was simulated using monthly time intervals. Based on this simulation, it is concluded that (1) the proposed change in water use would be adequate to maintain a permanent pool of the proposed size, (2) surface-water diversions by most other canals in the study area would increase slightly under the proposed plan, (3) the flow of the Arkansas River at the Colorado-Kansas State line would increase slightly under the proposed plan, and (4) the ground-water system would not be significantly affected by the proposed change in water-use plan.

INTRODUCTION

The Colorado Department of Natural Resources, Division of Wildlife, acquired 11.24 percent of the shares in the Catlin Canal Company in 1972. This company operates a canal to divert water for irrigation from the Arkansas River below Pueblo, Colo. In 1974, the Division of Wildlife petitioned the District Court to change the type of water use for the water available in connection with the shares owned by the Division of Wildlife. The supply would be used to maintain a permanent pool of about 10,000 acre-feet (1.2×10^7 m³) in John Martin Reservoir for recreation purposes rather than to irrigate fields above the reservoir.

The U.S. Geological Survey was asked by the Division of Wildlife, through the Colorado Water Conservation Board, to evaluate the hydrologic effects of the proposed change in water use on the lower Arkansas River valley in Colorado. The Geological Survey already had developed a model of the system for testing management alternatives (Taylor and Luckey, 1974). This model, which uses a digital computer to account for all of the major components of the hydrologic system, was used to evaluate the effects of the proposed change in water use. The model and data used in this evaluation were the result of previous studies conducted in cooperation with the Colorado Water Conservation Board; Division of Water Resources, Office of the State Engineer; and the Southeastern Colorado Water Conservancy District.

1

HYDROLOGIC SYSTEM

The Arkansas River valley system that is modeled is a 150-mile (240-km) reach from above Pueblo in southeastern Colorado to the Colorado-Kansas State line (fig. 1). The system consists of the river, its tributaries, and 450 square miles (1,200 km^2) of alluvial aquifer in hydraulic connection with the river. This valley, which is one of the major agricultural areas of Colorado, produces alfalfa, corn, barley, sorghum, sugar beets, and truck crops. Because the mean annual precipitation ranges from only 12 to 14 inches (300 to 360 mm), irrigation is necessary to raise the crops.

Water for irrigation is obtained from 23 canals diverting from the river and about 1,400 wells diverting from the ground-water system. The mean annual flow of the Arkansas River at Pueblo is 514,000 acre-feet (6.3×10^8 m^3) and the mean annual flow of the tributaries between Pueblo and the State line is about 320,000 acre-feet (3.9×10^8 m^3).

River systems and canals in Colorado are operated under the Doctrine of Prior Appropriation. Under this doctrine, the right to use the water belongs to whomever first puts the water to beneficial use. Canals were constructed as early as the 1860's to divert the Arkansas River water for irrigation. A list of appropriation dates and the associated rights to divert a rate of flow is maintained for each river system. This list determines how the available water will be distributed among the various users. The first water right in the system that was modeled has an appropriation date of April 1861. A change in water use on a canal may affect upstream users as well as downstream users depending on the location of the junior and senior water rights along the river.

The unconfined alluvial aquifer associated with the Arkansas River consists of from 0 to 300 feet (0 to 90 m) of gravel, sand, silt, and clay. The average saturated thickness is 30 feet (9 m). The hydraulic conductivity of the aquifer averages about 600 feet (180 m) per day and the specific yield averages about 0.20. About 1.7 million acre-feet (2.1×10^9 m^3) of water is stored in the aquifer. In general, the river acts as a drain for the aquifer, but the river may supply water to the aquifer in some areas. The primary source of recharge to the aquifer is from applied irrigation water. The alluvial aquifer was extensively developed in the 1950's and 1960's as a supplemental irrigation supply because of periodic water shortages.

John Martin Reservoir, which is about 90 miles (140 km) downstream from Pueblo, was constructed to store irrigation water and control floods and began storing water in 1943. The reservoir is normally emptied early in the irrigation season and remains dry until late fall. The current capacity of the reservoir is a little more than 600,000 acre-feet (7.4×10^8 m^3), of which 351,000 acre-feet (4.3×10^8 m^3) is reserved for irrigation storage. The long-term mean annual storage in the reservoir at the beginning of the irrigation season is 75,000 acre-feet (9.3×10^7 m^3), but the median storage for the same time is much lower.
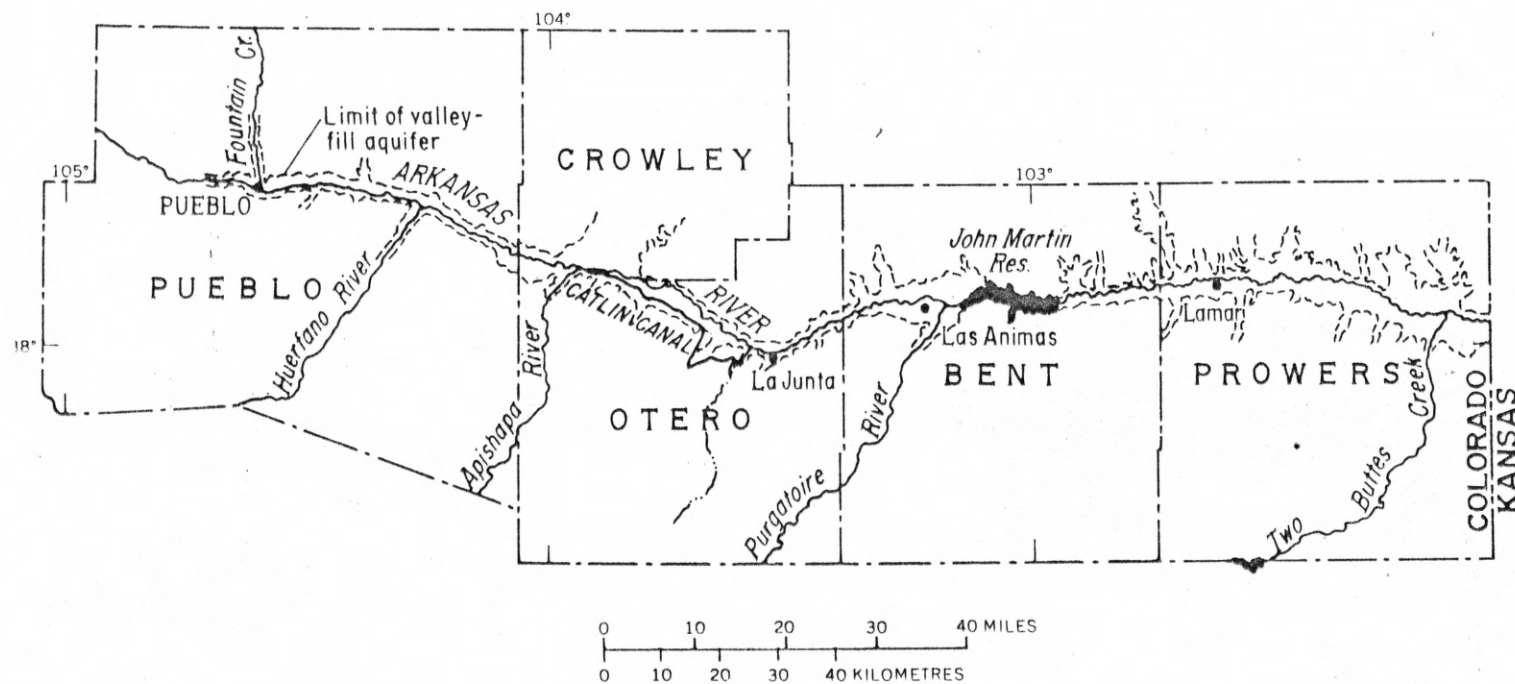
Figure 1.--Arkansas River valley in southeastern Colorado.

MATHEMATICAL MODEL

The model used in this study has been described in earlier reports (Taylor and Luckey, 1974; Jenkins, 1968a, 1968b). Briefly, the model is a mathematical model that simulates the temporal and spatial distribution of both surface and ground water based on a functional relationship between stress on the aquifer and response by the stream. The stream-aquifer system is subdivided into 27 reaches perpendicular to the trend of the river and as many as 10 bands on each side parallel to the river. Ten response functions are necessary to describe the interrelationship between the river and the aquifer.

The model simulates a 25-year period from 1949 through 1973 using 1-month calculation periods. The following data are needed for the model:

Water supply:

    1. Monthly streamflow at Pueblo.

    2. Monthly tributary inflow.

    3. Monthly imported water for several canals.

    4. Initial contents of John Martin Reservoir.

    5. Monthly precipitation by reach.

    6. Initial ground-water storage by reach and side of the river.

    7. Ground-water inflow to each reach.

Water losses:

    1. Evapotranspiration from the shallow water table by month and reach.

    2. Consumptive use of applied water by reach.

    3. Monthly municipal use.

Water distribution:

    1. Monthly demand by each canal.

    2. Water rights and appropriation dates for each canal.

    3. Location of each canal headgate and irrigated land under the canal.

    4. Pumping capacity of wells in each reach-band-side of the river combination.

Each month of simulation, the stream outflow from a reach is calculated by adding the main-stem inflow, tributary inflow, steady ground-water inflow, and return flow from recharged irrigation water and precipitation, and subtracting canal diversion and stream depletion caused by wells and evapotranspiration from the shallow water table. The functional relationships between aquifer stress and stream response are used to determine the timing between the stress and the response. The relationships also determine the change in ground-water storage in each reach and side each month.

The model distributes the available surface water according to the Doctrine of Prior Appropriation. Each water right on the priority list is allowed to divert its right, provided that (1) the canal has a demand for water that month, (2) the water is available at the canal headgate, and (3) the diversion will not harm any canal diverting under an earlier water right. If any of these restrictions apply, the diversion is reduced until all restrictions are met. After the proper diversion under a particular water right is determined, the effect of this diversion on the entire system is calculated. After all available surface water has been distributed, those areas supplied by canals with deficient supplies are allowed to pump supplemental water according to their needs and pumping capacities.

John Martin Reservoir is operated under the rules set forth in the Arkansas River Compact. This compact specifies that the reservoir will start storing water on November 1 and will release the water upon demand to Colorado and Kansas users starting on April 1. Sixty percent of the release goes to Colorado users and 40 percent goes to Kansas users if these users demand water. The measuring point for water delivered to Kansas is the Colorado-Kansas State line. During the winter, Colorado users may demand the release of as much as 100 ft^3/s (2.8 m^3/s) of the inflow to the reservoir for use within Colorado. Excess inflow to the reservoir during the summer may be stored. Evaporation from the reservoir is calculated each month based on the area-capacity relationship of the reservoir and pan evaporation at the reservoir. A pan coefficient of 0.7 is used to convert pan evaporation to lake evaporation (Chow, 1964).

The results from each month of simulation include the following quantities:

   1.   Surface-water diversions for each canal.

   2.   Ground-water diversions from areas supplied by each canal.

   3.   Streamflow at the State line.

   4.   Change in ground-water storage by reach and side of the river.

   5.   Contents of John Martin Reservoir and the amount of water assigned to the permanent pool.

   6.   Return flow to the river and change in storage in the ground-water system for all future months of the simulation due to operation during all preceding months and the present month.

The model was used to simulate the hydrologic system under normal operation and with the proposed change in use of water. All data and operating procedures were the same for both simulations except as noted below. The differences between the results of the two simulations are a measure of the hydrologic effects of the proposed change in water use.

It is recognized that any model cannot provide a perfect representation of a complex real hydrologic system. However, based on various tests made in comparing this model with observed field conditions, it is believed that this model provides a sufficiently accurate representation of the real hydrologic system to provide a useful measure of the effects of this proposed change in water use.

Assumptions

The Division of Wildlife has a right to 11.24 percent of the water diverted by the Catlin Canal. Under the change in water-use simulation, 11.24 percent of the direct diversion by the canal was assigned to the Division. However, because this water was historically applied as irrigation water with resulting return flow to the Arkansas River, only the consumptive use of this water was allowed to be transferred to the Division of Wildlife in the simulation. The consumptive use was estimated to be 77 percent (Taylor and Luckey, 1972). The remaining 23 percent of the water was returned to the river to replace the historical return flow.

Under the proposed change in water use, the Division of Wildlife's supply would be diverted at the Catlin headgate and carried through the canal system. The water would then be discharged into one or two tributaries to the Arkansas River at the lower end of the canal system. The water then would travel about 35 miles (56 km) down the Arkansas River to John Martin Reservoir. Under Colorado law, a natural stream can be used to convey water for reservoir owners, but natural transmission losses must be deducted (Radosevich and Hamburg, 1971). The Colorado State Engineer charges a transmission loss of 0.07 percent of the conveyed water per mile for the Arkansas River, which results in a transmission-loss charge of 2.5 percent against the water still assigned to the Division of Wildlife. The water deducted for transmission loss was allowed to remain in the river and the remaining water was delivered and stored in John Martin Reservoir.

The Catlin Canal imports water from the Arkansas basin upstream from the modeled area. Imported water is not subject to the priority system and was not deducted from the canal's demand by the model. In the simulation, imported water was delivered and applied but the Division of Wildlife did not claim 11.24 percent of the imported water.

The Catlin Canal was not allowed to increase its demand for water because of the change in use of part of the water, nor were well owners in the canal system allowed to pump additional ground water to substitute for the water assigned to the shares that were sold to the Division of Wildlife.

The proposed permanent pool was assumed to contain 10,000 acre-feet (1.2×10^7 m^3) of water at the start of the simulation and, hence, the initial total volume in John Martin Reservoir was increased from 116,500 acre-feet (1.4×10^8 m^3) to 126,500 acre-feet (1.6×10^8 m^3). The permanent pool was limited to 15,000 acre-feet (1.9×10^7 m^3), but was not allowed to invade the flood-control pool by more than 10,000 acre-feet (1.2×10^7 m^3). Neither of these limitations was encountered in the simulation, but the latter condition may occur during times of major flooding.

The Division of Wildlife's water stored in John Martin Reservoir is subjected to evaporation losses which are calculated each month on the basis of the surface area resulting from the total volume of water in the reservoir. This evaporation is then deducted from the permanent pool and the nonpermanent pool on the basis of their respective volumes. Because the model assumes that water is added to the reservoir at a constant rate, during any month in which water is being transferred to the reservoir the evaporation losses for the month are calculated on the basis of the average volume in the reservoir during the month.

Results

Through this change in water use, a permanent pool is maintained in John Martin Reservoir. A graph of the simulated contents of the permanent pool is shown in figure 2. The pool, which would initially contain 10,000 acre-feet (1.2×10^7 m^3), would have reached a minimum storage of 7,600 acre-feet (9.4×10^6 m^3) in the winter of 1956–57, a maximum storage of 13,800 acre-feet (1.7×10^7 m^3) in the summer of 1966, and a final storage of 11,200 acre-feet (1.4×10^7 m^3) at the end of 1973. The mean storage in the permanent pool would have been 10,900 acre-feet (1.3×10^7 m^3) and the mean annual evaporation would have been 3,500 acre-feet (4.3×10^6 m^3). A simulation starting with no initial storage in the permanent pool indicates that it would take 2 or 3 years to initially fill the pool under normal conditions.

The impact of the proposed change in water use on other water users in the Arkansas River valley was determined by comparing simulated surface-water diversions by canal, the flow of the Arkansas River at the State line, and ground-water storage under normal operation and under the transfer plan.

Surface-water diversions under both plans and the differences between plans are shown in table 1. Booth Orchard Canal and Town Canal no longer have any surface-water rights, but of the 21 remaining canals, 18 would be affected by the transfer. The largest effect of the change in water use would be on the Fort Lyon Canal, where average annual diversions would be increased 660 acre-feet (8.1×10^5 m^3), an increase of about one-half of 1 percent. The largest relative effect would be on the Excelsior Canal, where diversion would increase about 1.3 percent. All canals affected would have an increase in mean annual surface-water diversions. The total mean annual increase in canal diversions would be 1,770 acre-feet (2.2×10^6 m^3).
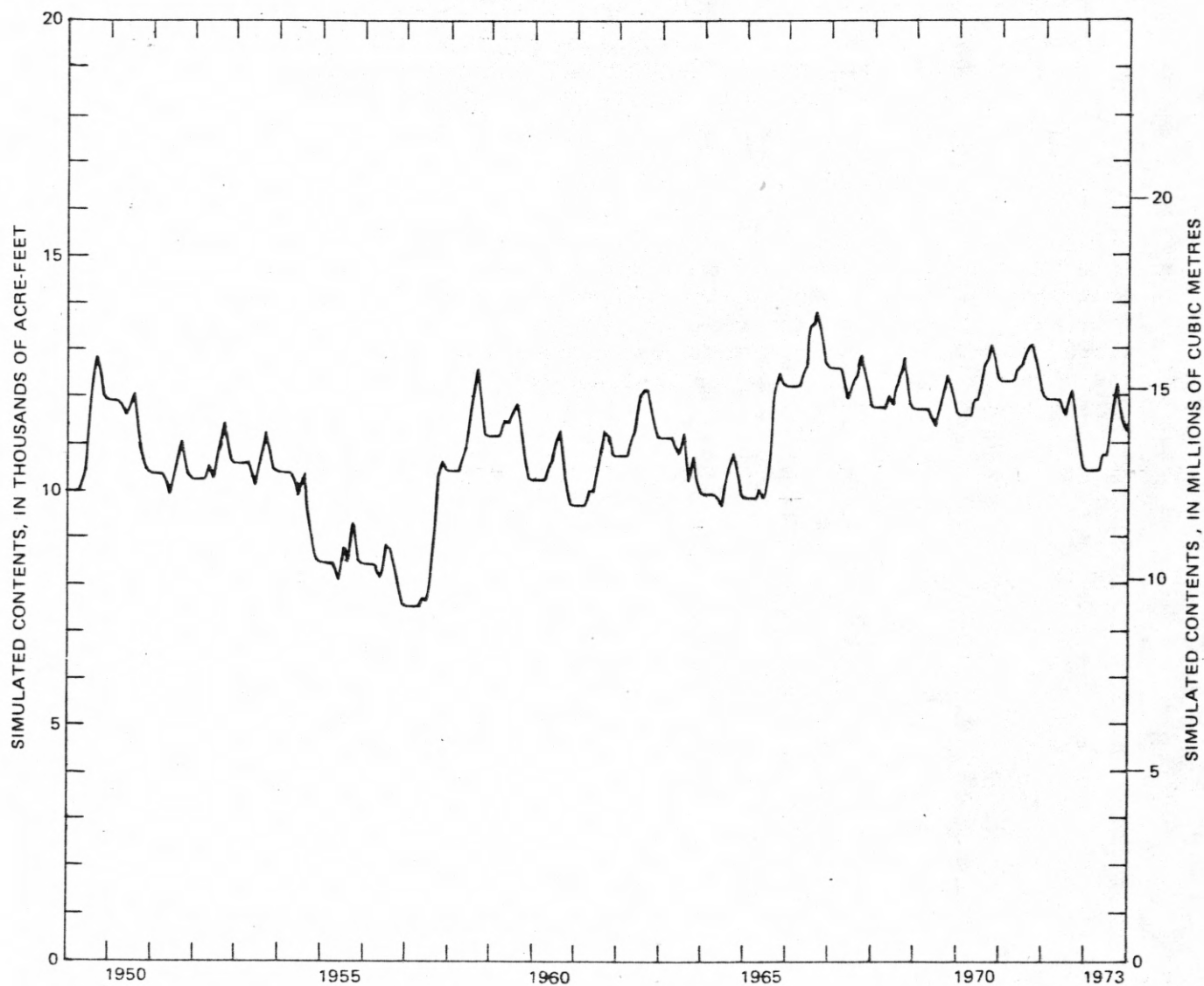
Figure 2.--Simulated contents of the proposed permanent pool,
John Martin Reservoir, 1949-73.

Table 1.--*Surface-water diversions under normal conditions and with proposed change in water use*

Canal	Simulated mean annual surface-water diversion (in acre-feet)		Difference (col. 1 minus col. 2)	Downstream order number (below Pueblo)
	With proposed change in water use[1]	Under normal conditions[1]		
Amity Canal---------	79,200	78,900	250	17
Booth Orchard Canal-	0	0	0	2
Buffalo Canal-------	16,500	16,400	24	22
Catlin Canal--------	52,000	52,000	10	9
Collier Canal-------	374	374	0	4
Colorado Canal------	62,700	62,600	110	5
Consolidated Canal--	20,200	20,000	0	13
Excelsior Canal-----	1,450	1,430	19	3
Fort Bent Canal-----	14,500	14,400	36	15
Fort Lyon Canal-----	127,400	126,800	660	12
Highline Canal------	57,100	56,800	328	6
Holbrook Canal------	9,810	9,740	65	10
Hyde Canal----------	2,980	2,950	36	19
Keesee Canal--------	3,260	3,260	0	16
Lamar Canal--------	17,200	17,200	24	18
Otero Canal---------	3,770	3,750	24	8
Oxford Canal--------	12,600	12,600	7	7
Manvel Canal--------	3,500	3,460	45	20
Rocky Ford Canal----	29,300	29,200	72	11
Sisson-Stubbs Canal-	2,200	2,190	10	23
Town Canal----------	0	0	0	14
West Pueblo Canal---	897	896	1	1
X-Y Graham Canal----	7,090	7,040	50	21

[1]These numbers are rounded, differences were taken before rounding.

Even though most canals would be affected by the transfer plan under certain hydrologic conditions, in any given year most canals would not be affected. In the first year, six canals would be affected; in the second year, five canals would be affected; in the third year, three canals would be affected. A number of factors determine which canal would be affected any given month by the transfer plan, but the most important factors are main-stem streamflow, tributary inflow, and return flow or stream depletion caused by prior operation.

Amity, Catlin, and Fort Lyon Canals would divert slightly less stream-flow in some months under the proposed change in water use. The Fort Lyon Canal would have diverted slightly less streamflow in 10 months of the 300-month simulation. Eight of the decreases would have occurred in April and the remaining two in September. The average decrease during the 10 months would have been 13 acre-feet (1.6×10^4 m^3) compared to an average annual gain of 660 acre-feet (8.1×10^5 m^3). The 13 acre-feet (1.6×10^4 m^3) is about one-tenth of 1 percent of the mean monthly surface-water diversion of the Fort Lyon Canal. The Catlin Canal would have diverted less streamflow in April of 4 years, July of 2 years, and August of 2 years. The average decrease during these 8 months would have been 10 acre-feet (1.2×10^4 m^3). The mean annual simulated surface diversion of the Catlin Canal is 52,000 acre-feet (6.4×10^7 m^3). The Amity Canal would have diverted less streamflow in August and September of 1 year. The average decrease for these 2 months would have been 46 acre-feet (5.7×10^4 m^3). The mean annual simulated surface diversion of the Amity Canal would be 79,000 acre-feet (9.7×10^7 m^3).

The simulated difference in streamflow at the Colorado-Kansas State line between normal operation and the proposed change in water use is a way of measuring the effect of the transfer on Kansas users. With normal operation, the simulated mean monthly streamflow at the State line would be 9,260 acre-feet (1.1×10^7 m^3). With the proposed change in use of water, the mean month-ly streamflow would increase to 9,290 acre-feet (1.1×10^7 m^3). The increase in mean monthly flow of 30 acre-feet (3.7×10^4 m^3) would be accompanied by a slight increase in the variability of the streamflow at the State line. In general, there would be a substantial increase in the streamflow to Kansas in the spring when John Martin Reservoir is releasing water and a minimal increase during the rest of the year. There are some months when the streamflow to Kansas would decrease as a result of the change in use of the water.

Comparing simulated change in ground-water storage between normal oper-ation and the proposed change in water-use measures the effect of the change in water use on water levels as well as the response of the system after the 25-year period that was simulated. In both simulations, ground-water storage would be decreased, but the total decrease under the transfer plan would be 400 acre-feet (4.9×10^5 m^3) less. Ground-water storage would decrease slight-ly under the Catlin Canal system while it would increase slightly or remain the same in the rest of the area because of the change in water use. How-ever, none of the effects of the change in water use on the ground-water system could be considered significant.

Under all the measures used to evaluate the proposed change in water use, the plan would give a slight benefit to most water users in the Arkansas River valley. Surface diversions would increase, State-line streamflow would increase, and ground-water storage would be virtually unchanged.

Several factors would contribute to produce this overall benefit. The 2.5-percent river-loss charge on the transferred water appears to add previously unavailable water to the system, primarily during the middle of the irrigation season. The transportation-loss charge generally amounts to less than 200 acre-feet (2.5×10^5 m^3). With repeated reuse, this amount could increase the supply to as much as 250 acre-feet (3.1×10^5 m^3) (Taylor and Luckey, 1974).

Under the change in water-use plan, only the consumptive use of the transferred share of the Catlin diversion would be claimed by the Division of Wildlife. The remaining part would be returned to the river to replace the return flow lost by not applying 11.24 percent of the Catlin diversion. The replacement would not add any new water to the system, but it would alter the timing of the availability of the water. Under normal operation, the simulated annual return flow of about 1,300 acre-feet (1.6×10^6 m^3) would reach the river at an approximately steady rate of 110 acre-feet (1.4×10^5 m^3) per month. Under the simulated change in water use, most of the 1,300 acre-feet (1.6×10^6 m^3) would reach the river during the middle of the irrigation season and would be available to other irrigators. Under normal conditions, 550 acre-feet (6.8×10^5 m^3) of the return flow of this water would reach the river in the winter and would be stored in John Martin Reservoir. Upon release, 220 acre-feet (2.7×10^5 m^3) would flow to Kansas. Reuse of the 220 acre-feet (2.7×10^5 m^3) could increase the total new supply for Colorado to about 280 acre-feet (3.5×10^5 m^3). Another very noticeable effect of the change in timing of return flow would be seen in the early spring of most years. Streamflow would be down slightly in the spring and under the change in water-use plan most of the decreases in surface-water diversions would take place at this time.

John Martin Reservoir would contain additional water as a result of the proposed change in water use. The surface area of the reservoir would increase and, hence, the evaporation loss would increase. However, because of the shape of the reservoir, the volume of the reservoir increases more rapidly than does the surface area. As stated in the assumptions, the evaporation from John Martin Reservoir is proportioned between the permanent pool and the nonpermanent pool, on the basis of their respective volumes. As a result of this assumption, the evaporation loss charged against the nonpermanent pool is generally less than what the evaporation from the nonpermanent pool would have been had the permanent pool not existed. For example, the simulated evaporation from the total pool in John Martin Reservoir during 1973 is 7,600 acre-feet (9.4×10^6 m^3). The permanent pool lost 4,300 acre-feet (5.3×10^6 m^3) to evaporation and the nonpermanent pool lost less than 3,300 acre-feet (4.1×10^6 m^3). Had the permanent pool not existed, the simulated evaporation from the nonpermanent pool in 1973 would have been about 3,650 acre-feet (4.5×10^6 m^3). The change in water-use plan thus would cause

a net reduction in simulated evaporation from the nonpermanent pool of 350 acre-feet (4.3×10^5 m^3). Evaporation is negligible during the winter and only the permanent pool would exist during the summer of most years, but during the spring and fall when both the permanent and nonpermanent pools would exist, the simulated evaporation from the nonpermanent pool would be generally less than it would have been without the permanent pool. This method of proportioning evaporation from the reservoir would give several hundred acre-feet per year extra water supply to other users in the basin at the expense of the permanent pool.

SUMMARY

The Colorado Department of Natural Resources, Division of Wildlife, has acquired 11.24 percent of the shares in Catlin Canal in order to maintain a permanent pool of about 10,000 acre-feet (1.2×10^7 m^3) of water in John Martin Reservoir. The U.S. Geological Survey was asked to evaluate the effects of this plan on the hydrologic system in the Arkansas River valley. A model developed for testing management alternatives was used to evaluate this change in water-use plan. Various tests indicate that this model provides a sufficiently accurate representation of the hydrologic system to provide a useful measure of the effects of the proposed change in water use.

The 25-year period from 1949 through 1973 was simulated. In simulating the change in water use, the following assumptions were made:

1. Only the consumptive use (77 percent) of the Division's water would be transferred to the reservoir. The recharge (23 percent) would be returned to the river.

2. The Division would be charged a river loss of 0.07 percent per mile (total loss 2.5 percent) for transporting the water down the river to the reservoir.

3. Evaporation from the reservoir would be proportioned between the permanent pool and the nonpermanent pool on the basis of their respective volumes.

4. Irrigators in the Catlin Canal system would not be allowed to pump additional ground water to substitute for water that was sold to the Division of Wildlife.

5. The Division of Wildlife did not claim any of the imported water that belonged to the Catlin Canal.

6. The pool size was limited to 15,000 acre-feet (1.9×10^7 m^3) provided that the flood-control pool was not invaded by more than 10,000 acre-feet (1.2×10^7 m^3).

The State has acquired sufficient shares in the Catlin Canal to maintain a permanent pool under the above assumptions. During the 25-year period, the

average volume of the permanent pool would have been 10,900 acre-feet (1.3×10^7 m³). The initial volume of the pool is assumed to be 10,000 acre-feet (1.2×10^7 m³).

The proposed change in water use would increase the mean annual surface-water diversion of 18 of the 21 canals in the area having surface-water rights. The remaining three canals would not be affected. The total increase in surface-water diversion would be 1,770 acre-feet (2.2×10^6 m³). Three canals would divert less streamflow during some months due to the change in water-use plan. The decrease would occur primarily during the early spring, but also would occur in the late summer.

The streamflow at the State line would increase an average of 30 acre-feet (3.7×10^4 m³) per month due to the proposed change in water use. This increase in streamflow would be accompanied by a slight increase in the variability of flow at the State line.

The simulated difference between change in ground-water storage under normal operation and with the proposed change in use would be insignificant.

The overall benefit to the water users in the basin would be produced by several factors. The most significant factor would be a decrease in the evaporation losses from the nonpermanent pool in John Martin Reservoir because of the maintenance of the permanent pool. A less significant factor would be the change in timing of return flows from water that had been historically applied, but was not transferred. The 2.5-percent river-loss charge also would increase the water supply for the system.

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