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SALT TRANSPORT BY THE SOUTH PLATTE RIVER IN NORTHEAST COLORADO[1]

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ABSTRACT: The salinity of the lower South Platte River in Colorado is characterized by plotting the average annual flow, total dissolved solids, and salt mass flow against distance along the stream. The plots show that salts are being leached from the irrigated lands above Greeley and are being deposited on the irrigated lands below Greeley. The salt deposition on the lower lands will result in their salination. The plots show also that fall and winter stream flows carry most of the salt loads. These fall and winter flows are stored in off stream reservoirs for use during the irrigation season. Therefore these salts are transferred to the lower irrigated lands where they accumulate. The salt balance for these lands can be improved by permitting the fall and winter flows to leave the basin, or by providing adequate land drainage coupled with supplemental irrigation water.
(KEY TERMS: salt balance; salinity; South Platte River.)

BACKGROUND

In the history of irrigated agriculture there are many examples of decline in agricultural productivity due to salt accumulation. A well known case is in Iraq, where 60 percent of the land irrigated by the Tigris and Euphrates Rivers has become salinated. In the United States, large scale irrigated agriculture is only a century old, and salt balance problems are pervasive in virtually all irrigated land areas. Pillsbury (1981) mentions several problem locations, which include the San Joaquin Valley, the Rio Grande Valley, and the Colorado River. These cases illustrate a fundamental axiom of irrigated agriculture, i.e., that irrigation and drainage are inseparable. Pillsbury expresses this idea in terms of going upstream for supply and allowing the lower rivers to become brackish from the drainage water.

While salt concentration in the South Platte River system has been monitored for several decades there have been few attempts (e.g., Hurr, 1975; USBR, 1973) to interpret the large data base in terms of understanding the salt transport regime of the river. The assumption has been that because of the high salinity level in the water leaving the basin a salinity mass balance is being maintained. This is not true, as will be shown in this paper.

Content

The salt transport regime of the lower South Platte River is described using distance and time profiles of flow, total dissolved solids concentrations, and salt mass transport. From these profiles, recommendations were formulated for achieving a more favorable salt balance with respect to the irrigated lands in the lower portion of the basin and for protecting their long term productivity.

Scope

The study is empirical and utilizes published records of daily and monthly salinity and flow data for the 15-year period 1965-1979 (USGS, 1965-1979). The salinity characterization was confined to the lower South Platte River between Henderson and Julesberg, a distance of 343 km (213 mi). Records were summarized for five river stations and three tributary stations. The study is a descriptive characterization of the river salinity regime using a materials balance analysis for water and salt. All major inputs and outputs of water and salt to and from each reach such as return flows, diversions, tributary flows, and point source discharges are considered. Results are expressed as annual and seasonal averages.

THE SOUTH PLATTE RIVER

The South Platte River basin shown in Figure 1 covers 24,000 square miles in northeastern Colorado, southeastern Wyoming, and southwest Nebraska. The South Platte River originates in the mountains in the western portion of the basin and flows northeast across the plains to join the North Platte River in Nebraska. As the river flows north across the plains from Denver to Greeley the waters of six major tributaries are added to it. Table 1 provides a summary of statistics concerning water availability and distribution.

Approximately 70 to 80 percent of the surface runoff in the basin is due to winter snowfall in the mountains and occurs in spring and early summer. The total dissolved solids (TDS) concentration of this water is 50 to 100 mg/l. Most of this

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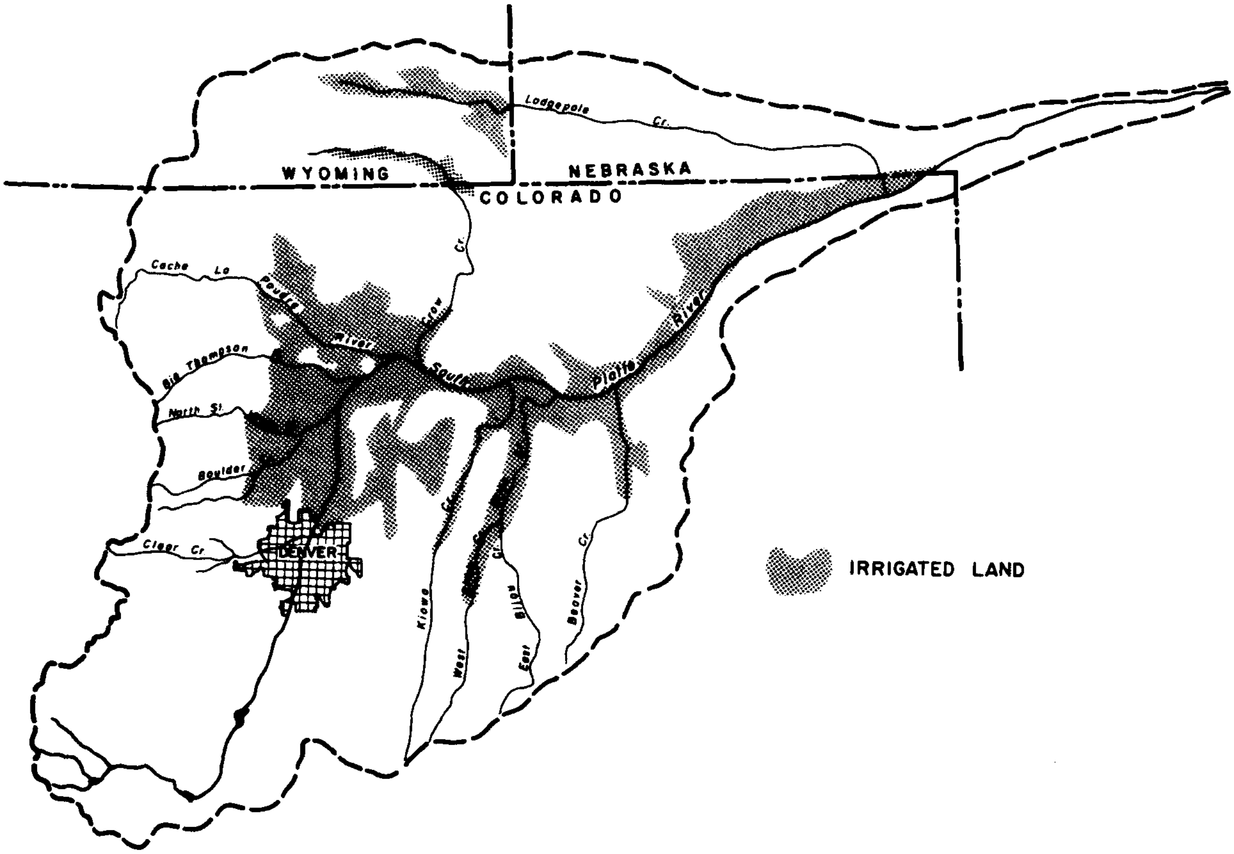


Figure 1. Irrigated Land in the South Platte River Basin (adapted from Hendricks, *et al.*, 1977).

runoff is captured and stored for use on irrigated crops in the summer.

TABLE 1. Statistics on Average Water Availability and Distribution, South Platte River Basin (from Hendricks, *et al.*, 1975).

Characteristic	Amount	Dimension
Native runoff, average	1,673 1,335,920	MCM acre-feet
Imported water	460 373,120	MCM acre-feet
Discharge at Colorado-Nebraska state line, average	457 370,200	MCM acre-feet
Consumptive use in basin	1,676 1,358,000	MCM acre-feet
Irrigation diversions between Henderson and Julesburg	1,164 943,600	MCM acre-feet
Ground water pumpage below Kersey	306 248,000	MCM acre-feet

After intensive use and reuse of the tributary and main stem waters for irrigation, the South Platte leaves Colorado at the Colorado-Nebraska border with an average TDS of 1600 mg/ℓ, which is equivalent to a specific electrical conductance of 2015 micro hmos/cm (Gomez-Ferrer and Hendricks, 1982). The sodium absorption ratios range typically from 2 to 4 (USBR, 1973). Thorne and Peterson (1954) give this water a classification of C-3, S-1, which means it is a medium to high salinity water which should be used only on soils of moderate to good permeability with regular leaching. The high salinity is caused by the saline return flows which find their way back to the tributary streams and enter the main South Platte River. In the lower South Platte, below Greeley, continued irrigation diversions occur with the salt laden water.

Of the total consumptive use shown in Table 1, approximately 85 percent is used by irrigated agriculture. Figure 1 shows the location of the irrigated lands in the basin. The irrigated land adjacent to the mainstem of the South Platte River between Henderson and Julesburg is shown in Figure 2. The irrigated land in the entire basin totals about 572,650 Ha (1,415,000 acres) (Bluestein and Hendricks, 1975). About 202,350 Ha (500,000 acres) of this irrigated land is located in the lower South Platte adjacent to the river, as shown in

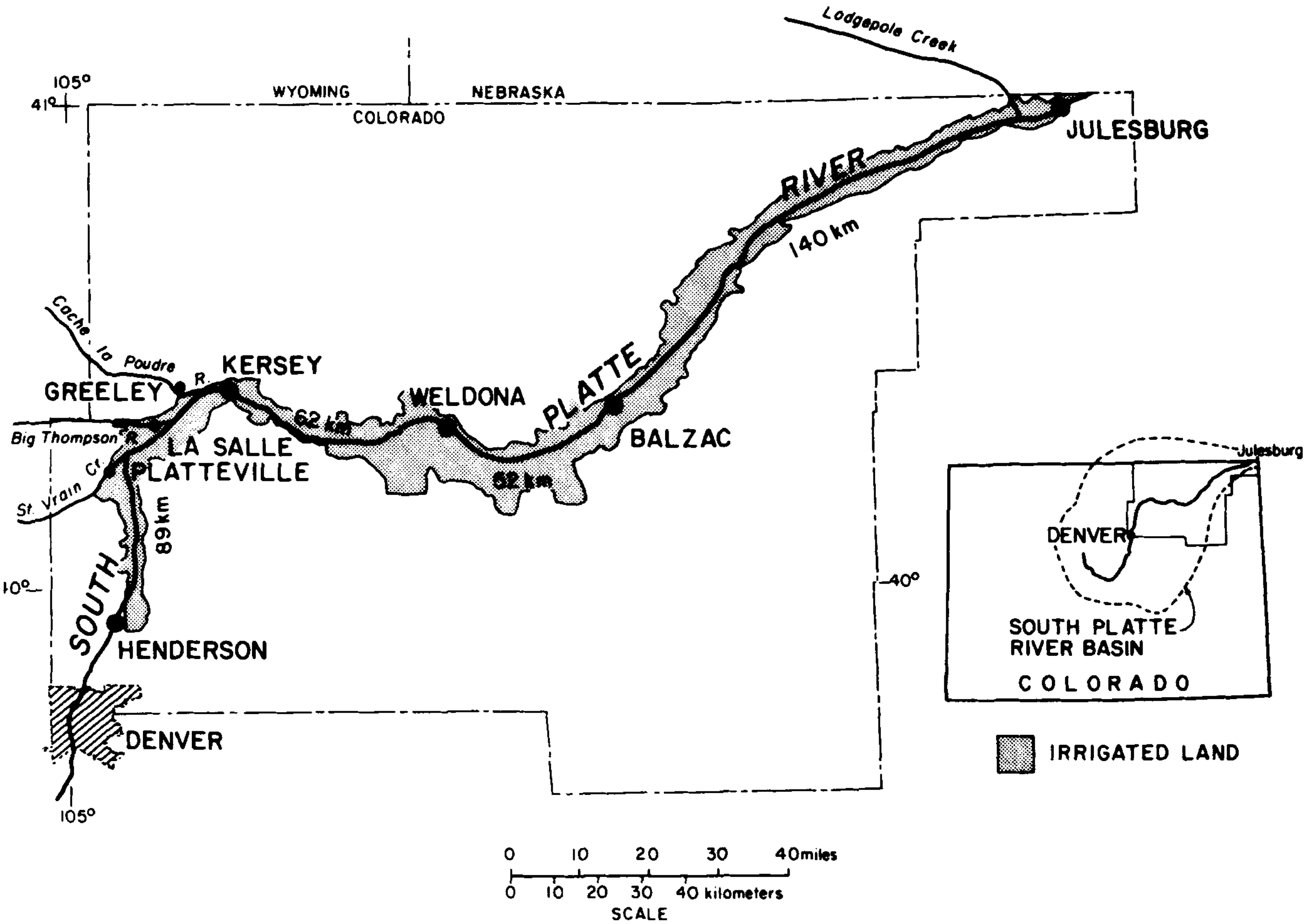


Figure 2. Lower South Platte River in Colorado (adapted from Hurr, *et al.*, 1975).

Figure 2. The irrigation diversions between Henderson and Julesburg are from about 50 canals.

Most of the tributaries below Kersey are ephemeral and were not considered in this study. Lodgepole Creek is the exception and was considered. The largest tributaries, St. Vrain Creek, the Big Thompson River, and the Cache La Poudre River, are between Henderson and Kersey. Because of the extensive irrigated land adjacent to these tributaries, their fall and winter discharges into the South Platte River are mostly return flows. The monitoring stations for these tributaries are located at Platteville, LaSalle, and Greeley, respectively. These stations provided the flow and salinity data used in this study. In addition to these tributaries, several point source discharges from canals are significant and were considered. Waste water discharges from municipalities and industries comprise only 7 percent of the total diversions and do not have significant effects on river salinity.

METHOD

Characterization of Salt Transport for River Stations

The averages of river discharge, total dissolved solids (TDS), and salt mass flows were determined by Gomez-Ferrer and Hendricks (1982) for each month, season, and year for the five river stations and three tributary stations for the period 1965-1979 using published data of the U.S. Geological Survey (1965-1979). These averages were plotted as distance profiles from Henderson to Julesburg.

The steps were as follows:

1. Total dissolved solids (TDS) was used as the parameter of salinity. These data were available for each station along with specific electrical conductance (EC) data. The EC measurements are easier to make than TDS determinations and are commonly used in lieu of the latter. Since a direct relationship exists between EC and TDS measurements, the former were converted to the latter.

2. A linear TDS-EC regression relationship was fitted to the data for each of eight stations. The R^2 values were greater than 0.9.

3. All EC data for each station were expressed as TDS values using the respective regression equation.

4. A linear log salt mass flow-log flow regression relationship was fitted to the data for each of the eight stations. This relation was developed for the 15 years of data and grouped by season for the fall, winter, spring, and summer. The R^2 values generally were above 0.9 for the river stations. The statistical analyses described above were performed using a regression program called Minitab II which was developed by the Statistics Department of Pennsylvania State University.

5. Using daily flow as an argument the corresponding daily salt mass flow was computed. These daily mass flows were then used to obtain monthly, seasonal, and annual averages.

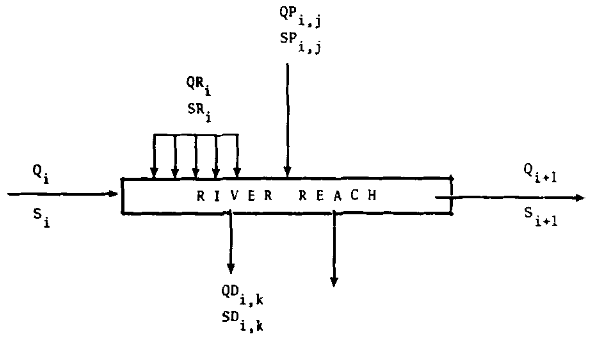
Materials Balance Analysis

Four river reaches, e.g., Henderson-Kersey, Kersey-Weldona, Weldona-Balzac, and Balzac-Julesburg, were used as the basis for material balances with respect to water and salt. All inputs and outputs of water and salt were determined on a monthly basis for each reach. These included river flow into the reach, return flows from irrigated lands, tributary flows, point source inflows, diversions, and river flow from the reach.

Figure 3 illustrates the mass balance computational scheme used for each of the river reaches. The stream flow, Q_i, carrying a salt concentration S_i, enters the reach at its upper end. Within the reach there are diversion flows, $QD_{i,k}$, point source inflows, $QP_{i,j}$, and return flows, QR_i, carrying salt concentrations, $SD_{i,k}$, $SP_{i,j}$, SR_i, respectively. The resultant stream flow, Q_{i+1}, carrying a salt concentration, S_{i+1}, leaves the reach at its lower end. The diversion flows are those of irrigation canals. Point source inflows include tributary flows, impoundment spillages, discharges from irrigation outlet canals, and municipal and industrial discharges. Return flows include both surface and subsurface agricultural return flows, and excess surface and subsurface water runoff.

Figure 4 is a schematic representation of the four reaches. All point source inflows are shown. Fifty-two diversion flows were considered but are not shown. All flows except the return flows are known from published data or are assumed. The return flows were computed as the residual of all known inflows and outflows to the reach using the materials balance relation in the form of Equation (1) in Figure 3. The salt mass flows were computed for the stream flows of the three major tributaries, i.e., St. Vrain Creek, Big Thompson River, and Cache la Poudre River, using measured TDS and flow data. The flow weighted mean annual TDS levels for these rivers are 867 mg/ℓ, 1393 mg/ℓ, and 1018 mg/ℓ, respectively. For the other point source inflows, the TDS concentration levels are unknown. Therefore reasonable assumed values were used based upon available information.

Measurements were not available for salinity levels of the diversion flows. Therefore the salinity associated with all diversion flows from a reach in a given time period was assumed to have a concentration close to the average concentration of the reach.



Reach flow balance for computation of return flow to reach

$$QR_i = Q_{i+1} - Q_i + \sum_{k=1}^{K} QD_{i,k} - \sum_{j=1}^{J} QP_{i,j} \qquad (3\text{-}1)$$

Reach salt balance for computation of return salt mass flow to reach

$$(QR_i)(SR_i) = (Q_{i+1})(S_{i+1}) - (Q_i)(S_i) + \sum_{k=1}^{K} (QD_{i,k})(SD_{i,k}) - \sum_{j=1}^{J} (QP_{i,j})(SP_{i,j}) \qquad (3\text{-}2)$$

<u>Notation</u>

Q_i	:	Streamflow at the upstream end of the reach i
Q_{i+1}	:	Streamflow at the downstream end of the reach i
$QD_{i,k}$	:	Flow in diversion k of reach i
$QP_{i,j}$	:	Flow in point inflow j of reach i
QR_i	:	Flow in return flows of reach i
S_i	:	TDS concentration of upstream end of reach i
S_{i+1}	:	TDS concentration of downstream end of reach i
$SD_{i,k}$	:	TDS concentration in diversion k of reach i
$SP_{i,j}$	:	TDS concentration in point inflow j to reach i
SR_i	:	TDS concentration in return flows to reach i

Figure 3. Flow Diagram of a Typical River Reach in the South Platte Showing Material Balance Computations for Water and Salt.

From the computations of monthly flows, seasonal and annual averages were obtained. The annual averages of the individual components were plotted for each reach in terms of the time variations for the period 1965-1977.

RESULTS

Annual Variation of Flow, TDS, Salt Mass Flow

The annual variation in flow, TDS, and salt mass flow at Julesburg is shown in Figure 5. The mean annual flow varies over a wide range from 2.8 to 43 m^3s^{-1} (99 to 1519 cfs). The mean annual salt mass flow in metric tons per day ranges from 400,000 T/d to 3,700,000 T/d. Similar patterns of mean annual flow and mean annual salt mass flow are evident in Figure 5. The flow weighted mean annual salt concentration varies between 1000 mg/ℓ TDS at the highest flow and 1600 mg/ℓ TDS at the lowest flow. The pattern of salt concentration showed less variation than the other two parameters.

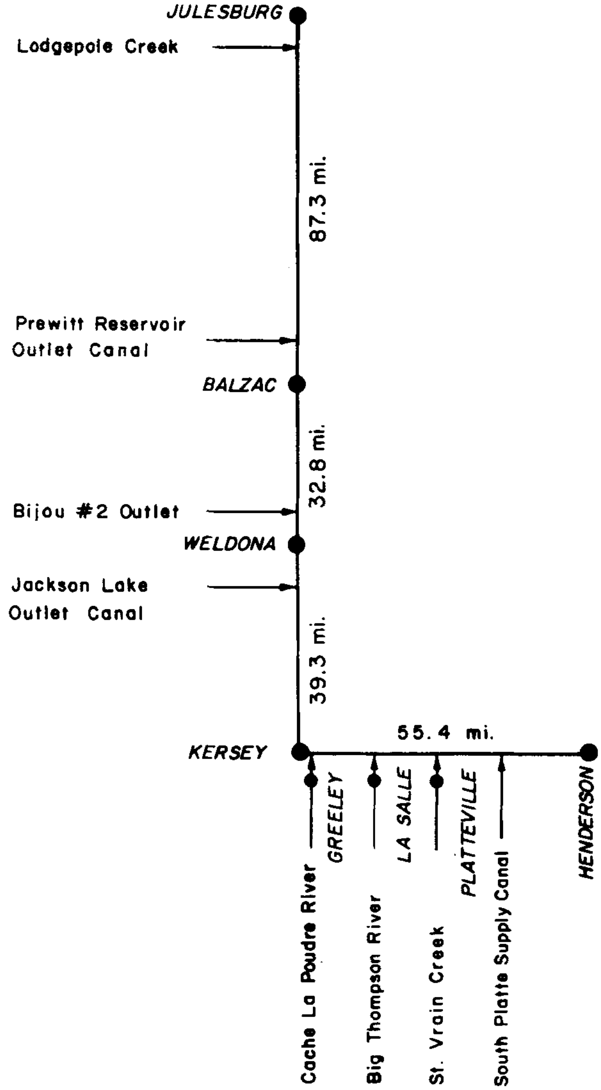


Figure 4. Schematic Representation of South Platte Between Henderson to Julesburg.

Distance Profiles of Salt Flows

Figure 6 shows the distance profiles of average annual flow in the river, salt concentration, and salt mass flow for the years 1975-79. As seen, the profiles of each parameter are similar from year to year, including those for the period 1965-74 which are not shown.

The flow profiles show an increase from Henderson to Kersey. The flow is essentially doubled between these stations for any given year. This is due to the large tributary flows coming into the reach from St. Vrain Creek, the Big Thompson River, and the Cache la Poudre River. From Kersey to Weldona the flow declines sharply due to irrigation diversions. The river flow continues to decline to Balzac and then it stabilizes from Balzac to Julesburg.

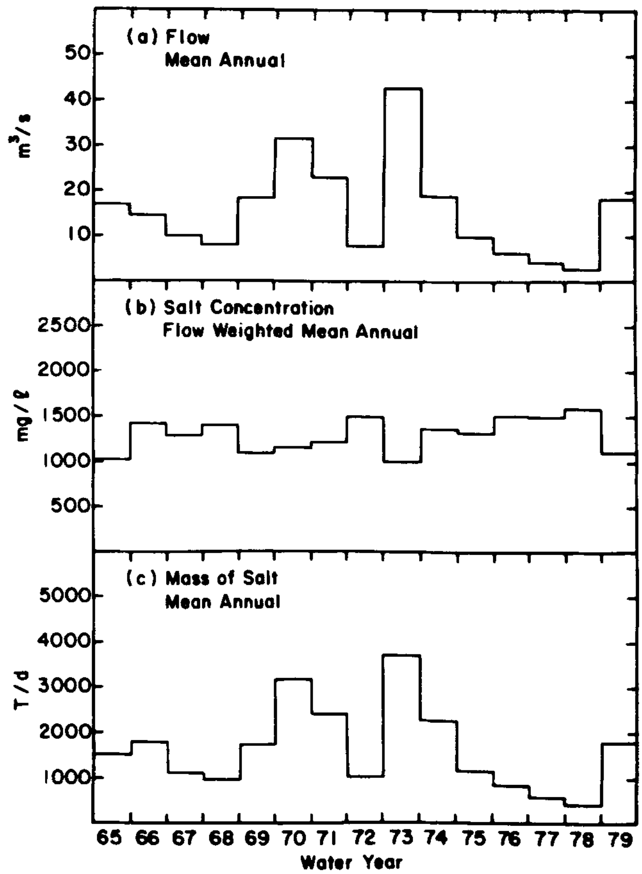


Figure 5. Annual Variation in Flow, Salt Concentration, and Salt Mass Flow at Julesburg, 1965-1979.

The salt concentration increases sharply from Henderson to Weldona. This is due to the tributary inflows which are comprised largely of irrigation return flows. The exception is during the spring when snow melt comprises a large portion of tributary inflow. During the years with high flows, such as 1979, the TDS level increases from 450 mg/ℓ to 950 mg/ℓ between these stations. For low flow years, such as 1977, the TDS level increases from 600 mg/ℓ to 1400 mg/ℓ between the same stations. The salinity levels increase slightly at Julesburg where the seasonal range is between 1000 mg/ℓ and 1600 mg/ℓ. The distance profiles of mean annual salt mass flows are similar to those of mean annual flows, except they are accentuated by the increasing salt concentration levels.

It should be noted that the annual distance profiles, seen in Figure 6, are the average of a wide range of daily, monthly, and seasonal behavior. Figure 7 illustrates the influence of seasonal variation in the distance profiles for the 1979 water year. Similar seasonal resolution could be shown for mean annual flow, TDS, and salt mass flow, seen in Figure 5.

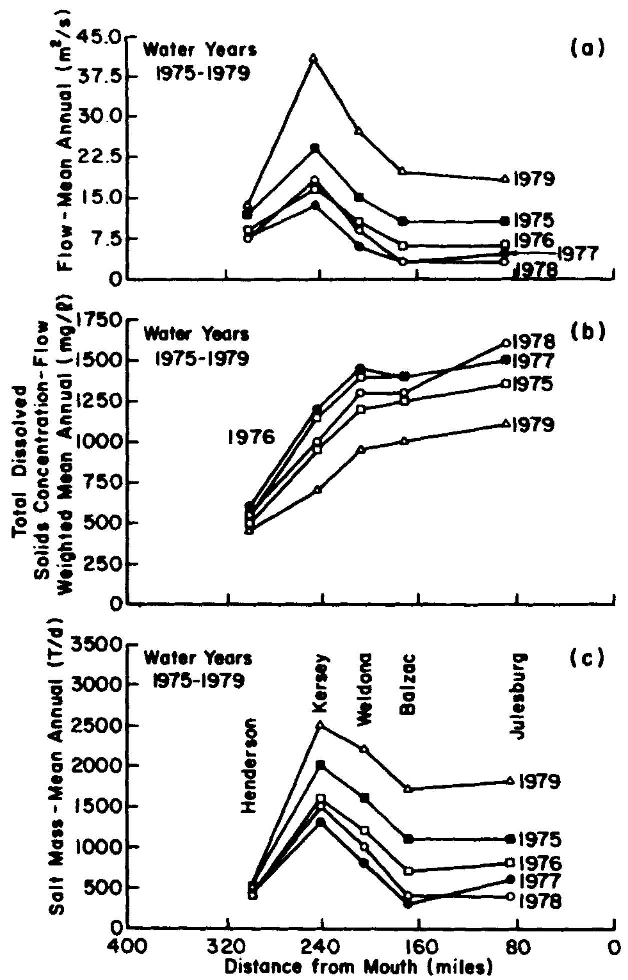


Figure 6. Distance Profiles of Flow, Salt Concentration, and Salt Mass Flow, Averaged by Year, 1975-1979, Lower South Platte River.

Figure 6 and 7 both illustrate one feature of critical importance to irrigated agriculture. An accumulation of salts occurs from Henderson to Kersey, but salt mass is being lost between Kersey and Balzac. Between Kersey and Julesburg there is a net loss of salt to the land. The salt mass accumulation between Henderson and Kersey comes from the salts in the irrigation return flows in the three tributary streams, while the loss to the land between Kersey and Balzac is due to irrigation diversions. Table 2 gives the salt mass flows for each station averaged over the period 1965-1979. The net loss to the land is seen as the difference in salt mass flows between Kersey and Julesburg, which amounts to 380 metric tons per day.

Approximately 133,550 Ha (330,000 ac) of land are irrigated between Kersey and Julesburg along the South Platte River. If the salt load is evenly distributed on this cropland the average rate of accumulation would be 0.42 metric tons of salt per acre per year.

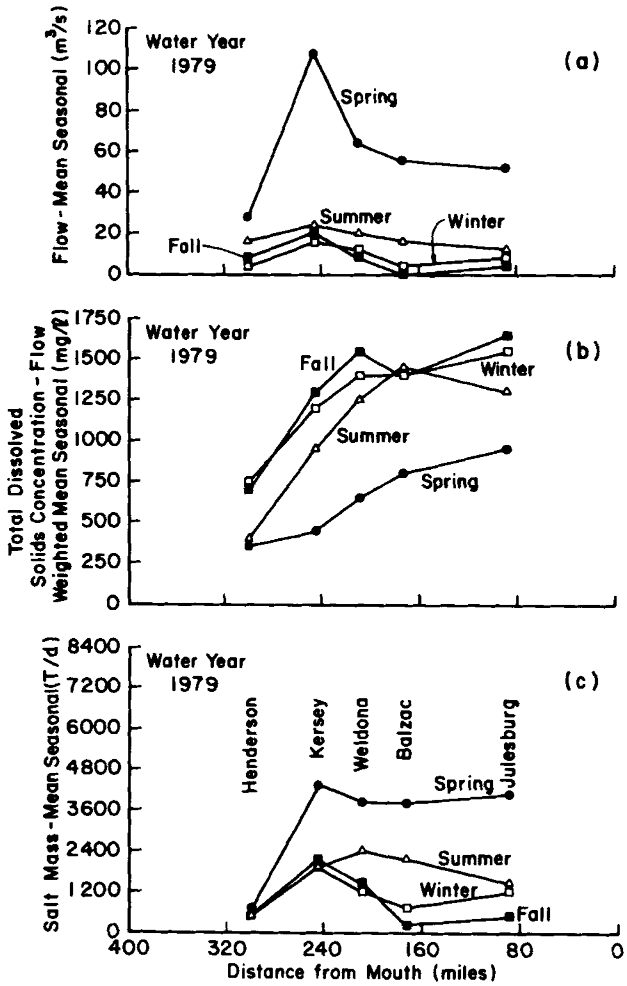


Figure 7. Distance Profile of Flow, Salt Concentrations, and Salt Mass Flow, Averaged by Season, 1979, Lower South Platte River.

ANALYSIS

A distance profile of average salt mass flows at different points along the South Platte River is shown in Figure 8. The data were obtained from Table 2. The base salt load of the native flows coming from the mountains plus imported water is about 400 metric tons per day and is seen in the plot as "g." The increments of salt mass flows due to the tributaries are shown as the salt load increases between Henderson and the Cache La Poudre River designated as a, b, c, and d, respectively. Except during the spring runoff, the waters in these tributary streams are mostly return flows. Therefore, the salts carried into the mainstream of the South Platte River below the Cache La Poudre River are leached from the irrigated lands along the tributaries. The salt pickup by the main stem between the Cache La Poudre River and Kersey is shown as "e." The aggregate salt pickup is shown as "f." The stream loses salt to the land between Kersey and Balzac, due to canal diversions and water storage, which is shown as "h." Some of this salt may reappear in the return flow salt load between Balzac and Julesburg, which is shown as "j." The net minimum salt loss to the land is shown as "k." If some or all of "j" is leached between Balzac and Julesberg, the net loss to the land could be as large as "h" which is equivalent to 640 tons per day.

TABLE 2. Mean Daily Salt Mass Flows at Stations in the South Platte River and Tributaries, Averaged Over the Period 1965-1979.

Station	Mean Daily Salt Mass Flow (tons/day(metric))
Base salt load of native and imported water at mouths of canyons (2,097MCM/yrx70mg/L)	400.0
South Platte River at Henderson	523.0
St. Vrain Creek near Platteville	464.3
Big Thompson River near LaSalle	312.7
Cache la Poudre River near Greeley	327.7
South Platte River near Kersey	2007.8
South Platte River near Weldona	1713.2
South Platte River near Balzac	1368.0
South Platte River at Julesberg	1627.9

From Figure 8 it can be seen that an average of 1700 metric tons per day of salts are leached from the upper irrigated lands (as "f"), with a net deposit to the lower lands of 380 metric tons per day as a lower limit ("k"), and 640 metric tons per day as an upper limit ("h"). In other words a great deal of salt is being washed from the upper irrigated lands each year and about one-third of it is being deposited on the lower irrigated lands.

CONCLUSIONS AND RECOMMENDATIONS

There must be a salt balance for the lower irrigated lands between Kersey and Balzac if they are to be maintained in production. This assertion is consistent with established principles of irrigated agriculture that lands irrigated with C-3 waters should have regular leaching. This requires improved drainage so that the return flows from these lands find their way back to the river. The profile of annual salt mass flow in Figure 8 shows a decreasing slope from Weldona to Julesburg indicating that salts are being deposited on the land.

Examination of the seasonal salt mass flows in Figure 7 reveals a method for achieving a salt mass balance for the river, and also for the adjacent lands. Figure 7 shows that flows are diverted from Kersey to Balzac in the fall and winter, in addition to the spring and summer seasons. The highest salinity occurs during the fall-winter period. If these winter and fall flows were not diverted but instead were allowed to flow downstream and transport salt loads from the basin, the salt mass balance would be improved significantly. The fall and winter profiles of salt mass flows would become essentially horizontal from Kersey to Julesburg. This, in turn, would cause the annual profile to become almost horizontal between these two stations. This means that the salt mass transport would be constant rather than losing along this reach of the stream.

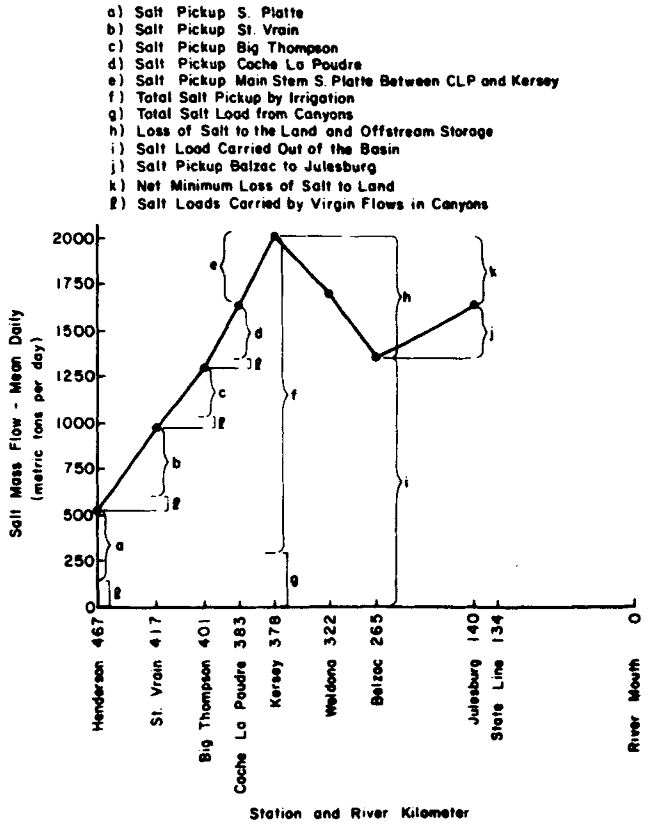


Figure 8. Profile of Average Salt Mass Flows Over Period 1965-1979, South Platte River Showing Analysis of Changes.

The amount of water diverted between Kersey and Balzac is seen in Figure 7 to average 20 m/s in fall and 10 m/s in winter; this amounts to 236,522 acre-feet in 1979, a year of high runoff. Currently, this water is diverted and stored in offstream reservoirs for use during the growing season. The bypass of 236,522 acre-feet of water in Colorado, a state with an appropriate water rights system, would be opposed by many water users. But if replacement water could be provided such opposition would diminish.

The proposed Narrows Reservoir near Weldona, or the alternate Hardin Reservoir, could be a source for replacement water. The Narrows Reservoir would provide an increase in annual water supply from 93,000 acre-feet to 120,000 acre-feet. This would be "new water" which currently flows into Nebraska. The project could be designed and operated to return the salt balance in the lower South Platte to an equilibrium state by providing replacement waters for the fall and winter diversions, which would be used to transport salts from the basin. To carry the salt laden water from the upper lands a bypass canal would have to be constructed around the reservoir. The alternative approach would be to improve drainage practices on the irrigated lands. Still another approach would be to attempt to reduce the salt leaching from the upper lands. This could be done by using more efficient irrigation practices, which become feasible when using the low TDS irrigation water available at the canyon mouths.

SUMMARY

Flow data and salinity data have been collected for many years in the western United States. Salinity data have been collected since about 1885 and since the 1920's on a regular basis. While casual inspection of these data will reveal trends, there are often conflicting indications of behavior. Utilization of all of these data, however, in statistical characterizations provide a more accurate picture of the salinity behavior of an irrigated river system. Such analyses if done more routinely could provide valuable policy guidance in further water resources development and operation for improved salinity management of irrigated river basins.

The message given by analysis of data for the South Platte River is that a large amount of salt is being leached from the upper irrigated lands is being deposited on the lower lands. Further, over half of this salt is diverted from the river in the fall and winter, when salt concentrations are highest and stream flows are low. One possible remedy is to pass these fall and winter flows out of the basin and use the proposed Narrows Reservoir to provide replacement water.

ACKNOWLEDGMENTS

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