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Simple Methods for Estimating Outflow Salinity from Inflow and Reservoir Storage

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Simple methods for estimating outflow salinity from inflow and reservoir storage

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1. Introduction

Salinity of riverflow fluctuates daily, weekly and monthly. Reservoir storage is likely to buffer fluctuation in streamflow salinity, as inflow blends into the storage. It is important from an operational point of view to be able to project in advance monthly changes in salinity of outflow from the reservoir, using inflow and its salinity data. The hydrological estimates of runoff from snowmelt, for example, can be used to project salinity of the reservoir in advance of the irrigation season. In another situation, where saline water such as irrigation returnflow enters into irrigation water supply, water management strategies can be evaluated for its impact on reservoir salinity. Where there are several reservoirs along a river, another use possibility would be to forecast the impact of different discharge strategies from upstream reservoirs on downstream reservoirs. The residence time of the large reservoirs in the western states often exceeds a year, and salinity of outflow has a comparable time lag. A simple predictive equation is also useful for refining routing models, such as ROTO (Arnold, 1990) for riverflow simulation.

There are many sophisticated models, which describe changes in water quality of reservoirs or lakes (Imberger, 1981; Hamilton and Schladow, 1997). These models incorporate hydrodynamic dispersion, thermal stratification, as well as flow path in a reservoir. Application of these models requires the extensive input data, which are not readily available for most irrigation project areas. For example, one needs to collect the detailed geometry of the lake, factors which affect hydrodynamics of the reservoir such as wind speed, temperature besides rainfall and evaporation. Simpler methods based on the assumption of completely mixing or two-layer models (Killworth and Carmack, 1979; Zagona et al., 2001) are also available, and may offer an alternative to the sophisticated models, especially when detailed hydrologic data are not available. However, these methods were not developed specifically for simulating salinity, and their applicability to salinity prediction must be tested.

The objective of this study was to evaluate several simple models for estimating monthly outflow salinity from inflow salinity and quantity, and reservoir storage. Three scenarios were considered. The first scenario is that the data available are limited to quantity and salinity of inflow, and the initial reservoir storage and its salinity. The second scenario is that the reservoir storage is known on a monthly basis or can be computed from monthly inflow and outflow data, ignoring the evaporation and seepage losses. The third scenario is that the complete water balance is known, including evaporation, rainfall, and percolation losses.

2. Models considered

The first method tested is a steady-state flow model where reservoir storage is nearly constant for a duration of interest, which is usually an irrigation season or two. This means that the outflow rate approximately equals the rate of inflow. An additional assumption is that reservoir storage and inflow are mixed within a period of one month.

$$C_j = \frac{C_{j-1}S_0 + C_{\mathrm{IN}j}Q_{\mathrm{IN}j}}{S_0 + \alpha Q_{\mathrm{IN}j}} \tag{1}$$

where S_0 is the initial reservoir storage (L^3), assumed to remain a constant under the steady state assumption. C_j and C_{j-1} are salinity of the reservoir during the jth month and the $j-1$ month (ML^{-3}), respectively. C_{IN} and Q_{IN} are the monthly salinity (ML^{-3}) and the inflow per month (L^3T^{-1}). The coefficient α is an empirical matching factor, accounting for ungauged inflow, and water losses. This equation can be executed with three measurable parameters, S_0, C_{IN} and Q_{IN}.

The second method incorporates a water balance in Eq. (1)

$$C_j = \frac{C_{j-1}S_{j-1} + C_{INj}Q_{INj}}{S_{j-1} + \alpha Q_{INj}} \tag{2}$$

and

$$S_j = S_{j-1} + (Q_{INj} - Q_{OUTj}) \tag{2a}$$

where Q_{OUTj} is the outflow from the reservoir (L^3T^{-1}). The reservoir storage S (L^3) can be the gauged value or be estimated from Eq. (2a) if the monthly outflow data are available. Evaporation and percolation losses are excluded for simplicity, but are embedded in the empirical factor α.

The third method considered is a form of two layer models. The top layer is assumed to be subject to evaporation and rainfall, and the second layer is to percolation losses. Initially, the inflow was assumed to blend with the storage which is adjusted to percolation losses P_j (L^3T^{-1}).

$$C_j = \frac{C_{j-1}S_{j-1} + C_{INj}Q_{INj} - C_{j-1}P_j}{S_{j-1} + Q_{INj} - P_j} \tag{3}$$

The outflow is assumed to occur from the top layer, which is subject to evaporation E_j (L^3T^{-1}) and rainfall R_j (L^3T^{-1}).

$$C_{OUTj} = \frac{dA_jC_j}{dA_j - E_j + R_j} \tag{3a}$$

where C_{OUTj} is the outflow salinity (ML^3), d is the depth of the reservoir subject to evaporative concentration (L), A is the water surface area (L^2), and E, R, and P are the evaporation, the rainfall and the percolation losses, respectively. The percolation loss is assumed to occur from the bottom layer and

$$S_j = S_{j-1} + (Q_{INj} - Q_{OUTj}) - (E_j - R_j) - P_j \tag{3b}$$

Eq. (3) is essentially the same as Eq. (2), but the coefficient α is no longer used, and is replaced by a descriptive parameter d. The thickness of the top layer d is to be estimated by solving Eq. (3a), by applying available historical data.

3. Testing the equations

3.1. Reservoirs selected

The three equations were tested by using inflow and outflow data from three reservoirs; Amistad, Falcon, and Elephant Butte, all located along the Rio Grande. These reservoirs

Table 1
Estimates of the Annual Water and Salt Balance at the Selected Reservoirs[a]

Reservoir name	Elephant Butte		Amistad		Falcon	
Long term storage (Gm^3)	1.63		3.28		2.15	
Long term residence (mo)	20		21		12	
Years selected for testing water Balance	79/80	76/78	75/76	95/96	76/77	69/70
Storage (Mm^3)	1257	304	4667	1522	3185	1777
Residence time (mo)	20.6	7.5	19.2	12.2	10.2	11.3
Inflow (Mm^3/mo), actual	124	35	190	96	328	152
Inflow (Mm^3/mo), deduced	–	–	239	114	–	–
Outflow (Mm^3/mo)	61	40	243	124	311	158
Storage change (Gm^3)	37	−9	−36	−28	−17	−38
Percolation (Mm^3/mo)	14	0	10	4	9	6
Net evaporation (Mm^3/mo)[b]	12	5	22	14	25	25
Balance (Mm^3/mo), actual	0	−1	−49	−18	0	1
Balance (Mm^3/mo), deduced	–	–	0	0	–	–
Reservoir initial salinity (mg L^{-1})	369	427	607	824	581	564
Outflow salinity (mg L^{-1})[c]	317	520	631	857	582	595
Salt balance (kton/mo)						
Salt load, actual	43	19	162	91	198	91
Salt load, deduced	–	–	165	92	–	–
Storage change[d]	13	−3	−9	−24	1	−18
Percolation	4	0	7	3	5	4
Outflow	19	21	153	107	181	94
Balance	7	1	11	5	11	11

[a] mo denotes month.

[b] Net evaporation denotes evaporation minus rainfall.

[c] Flow-weighted average is used.

[d] Negative sign indicates loss of reservoir salt storage.

are managed under binational agreements, and have extensive flow and salinity records. Elephant Butte is located in New Mexico and was completed in 1916 with the initial capacity of 2.7 Gm^3. The residence time since 1975 averaged 20 months (Table 1). Amistad Reservoir, completed in 1968, has the maximum storage capacity of 6.9 Gm^3, but the actual storage since 1969 averaged 3.3 Gm^3. Falcon Reservoir has the storage capacity of 3.9 Gm^3 and the mean storage was 2.1 Gm^3 since 1969. The residence time of both reservoirs fluctuated widely: 1–75 months, with an average of 21 and 12 months for Amistad and Falcon, respectively. The monthly evaporation accounts for 12–20% of the inflow into these reservoirs.

3.2. Data and computational procedures

Streamflow and salinity data below Elephant Butte were obtained from the International Boundary and Water Commission (IBWC), and those above Elephant Butte from US Bureau of Reclamation (BOR). Salinity data were derived from the electrical conductivity using conversion factors assigned to various gauging stations (Miyamoto et al., 1995). The conductivity records were available daily at several key gauging stations, and once a week at some locations. Evaporation data at Elephant Butte were downloaded from the National Climatic Data Center (NCDC), and those at Amistad and Falcon reservoirs estimated from the pan evaporation data obtained at several stations nearby. The pan coefficient of 0.70 was used to estimate evaporative water loss from the reservoir, following the calibration made by the Texas Water Development Board. The pan coefficient of 0.70 was also found suitable in the other studies (Khan and Bohra, 1990).

The flow and salinity data were screened for testing, based primarily on two criteria: (i) availability of salinity data which were taken at least twice a week and (ii) at least 12 consecutive months of high or low storage. These criteria are arbitrary, but were used mainly to assure quality of the salinity data under two different storage regimes. Examples of the data set used are shown in Table 1. Additional data used for testing were high and low storage periods at Amistad (1/78–12/79 and 1/99–12/00), and high storage periods (5/73–4/75 and 1/80–3/81) at Falcon.

The inflow into Elephant Butte is gauged at one location, San Marcia, and that into Amistad at three locations, each covering three main tributaries: the Devils, the Pecos, and the Rio Grande. The inflow into Falcon is gauged at Laredo, and at the confluence of Rio Salado from Mexico. The inflow into Falcon was adjusted to the estimated annual diversion of 192 Mm^3 per year to irrigate croplands between the gauging station and the reservoir.

The recorded data were then subjected to the water and salt balance check. In the case of Elephant Butte, the gauged inflow during high storage years (1979/80) exceeded the gauged outflow plus calculated evaporation losses and changes in storage volume by 14 Mm^3/mo or 11% of the inflow. This difference was attributed to percolation losses between the gauging stations and the reservoir outlets. The distance between the inflow and the outflow gauging stations is 20 km. In the case of Amistad, the gauged flow includes the three major tributaries, but not any other sources, thus creating a significant shortfall on the water balance. The ungauged deduced flow was estimated from the recorded outflow, the recorded reservoir storage, the estimated evaporation losses, plus the gauged spring flow below the reservoir, which was considered percolation losses from the reservoir. The water balance at Falcon was in good agreement.

The salt balance calculated by using the initial storage, the salt load, the outflow, and the changes in reservoir storage was generally positive, indicating that salt load exceeded that of outflow. The magnitude of the excess ranged from 5 to 25% of the salt load. This discrepancy may be accounted for by the over-estimation of initial reservoir storage, and salt storage in reservoir bank when the shoreline recessed, since the evapotranspiration loss from the bank was not accounted for. The over-estimation of initial reservoir salt storage seemed to be the largest cause at Elephant Butte as well as at Amistad. The salinity of the outflow from Elephant Butte, for example, changed from 398 to 260 $\mathrm{mg\,L}^{-1}$ in one month, due to large inflow of storm-water. Likewise, salinity at Amistad decreased from 607 to 497 $\mathrm{mg\,L}^{-1}$ during the initial period. If the lower salinity readings were used as the initial storage, the salt balance was nearly zero. In the case of Falcon, salinity data from the Rio Salado from Mexico were limited, and could have affected the balance estimate.

For testing Eqs. (1) and (2), both the gauged inflow, and the deduced inflow were used at Amistad (in the case of Elephant Butte and Falcon, there was no difference between the gauged and the deduced inflow). For testing Eq. (2), we also used the gauged storage, besides the estimated storage using Eq. (2a). The full accounting of water balance, is needed for testing Eq. (3). For Amistad Reservoir, the deduced inflow was used for testing.

The concentration of the initial reservoir storage was assumed to be equal to salinity of the outflow, as was the basic assumption used in Eqs. (1) and (2). Salinity of subsequent months was then computed as a moving average, and the empirical coefficients determined through the best fit. The computed salinity of outflow was then compared to the measured, and the standard error of the estimate computed. The empirical coefficients determined for each data set were then averaged, and salinity of the outflow was recalculated using the mean value in order to appraise the sensitivity of the salinity projection.

4. Results and discussion

Monthly salinity of the incoming flow into the reservoirs fluctuated widely (Fig. 1). Inflow salinity during the low storage periods was often higher than the salinity during the high storage periods, and fluctuated just as much as it did during the high storage periods. As hypothesized at the onset, outflow salinity fluctuated to a lesser extent than did inflow salinity in all cases tested. The applicability of each equation differed somewhat depending on the reservoirs tested.

4.1. *Elephant Butte*

Salinity of the inflow into Elephant Butte during 1979 and 1980 (high storage period) varied from 220 to 600 mg L^{-1} (Fig. 1a), and salinity during 1976 and 1977 (low storage period) fluctuated between 350 and 1150 mg L^{-1} (Fig. 1b). Salinity measured in the outflow from Elephant Butte ranged from 260 to 350 mg L^{-1} during the high storage period, and 400–700 mg L^{-1} during the low storage period. It is evident that reservoir storage effectively buffered salinity fluctuation during both high and low storage periods.

All three equations provided good estimates of outflow salinity from Elephant Butte with the standard error of estimate of less than 10% (Fig. 1a and b and Table 2). The empirical coefficient α of Eq. (1) was found to be 0.98 during the high storage period, and 0.79 during the low storage period. The low coefficient during the low storage period corresponds to the reduction in storage, which makes it necessary to artificially lower inflow. Eq. (2) provided the coefficients, which did not differ greatly between the high and low storage periods or between the measured and the estimated storage. The slightly smaller value of α, when the estimated storage is used, is a result of ignoring the evaporation and percolation losses. It appears that salinity of outflow can be well simulated with inflow data (flow and salinity) and the initial storage without having the full account of the water balance. As mentioned in the method section, it is not easy to establish the full account of water balance.

Eq. (3), a two-layer model, also provided a good estimate of outflow salinity. However, the depth of influence (d), which serves as a matching factor, was different between the

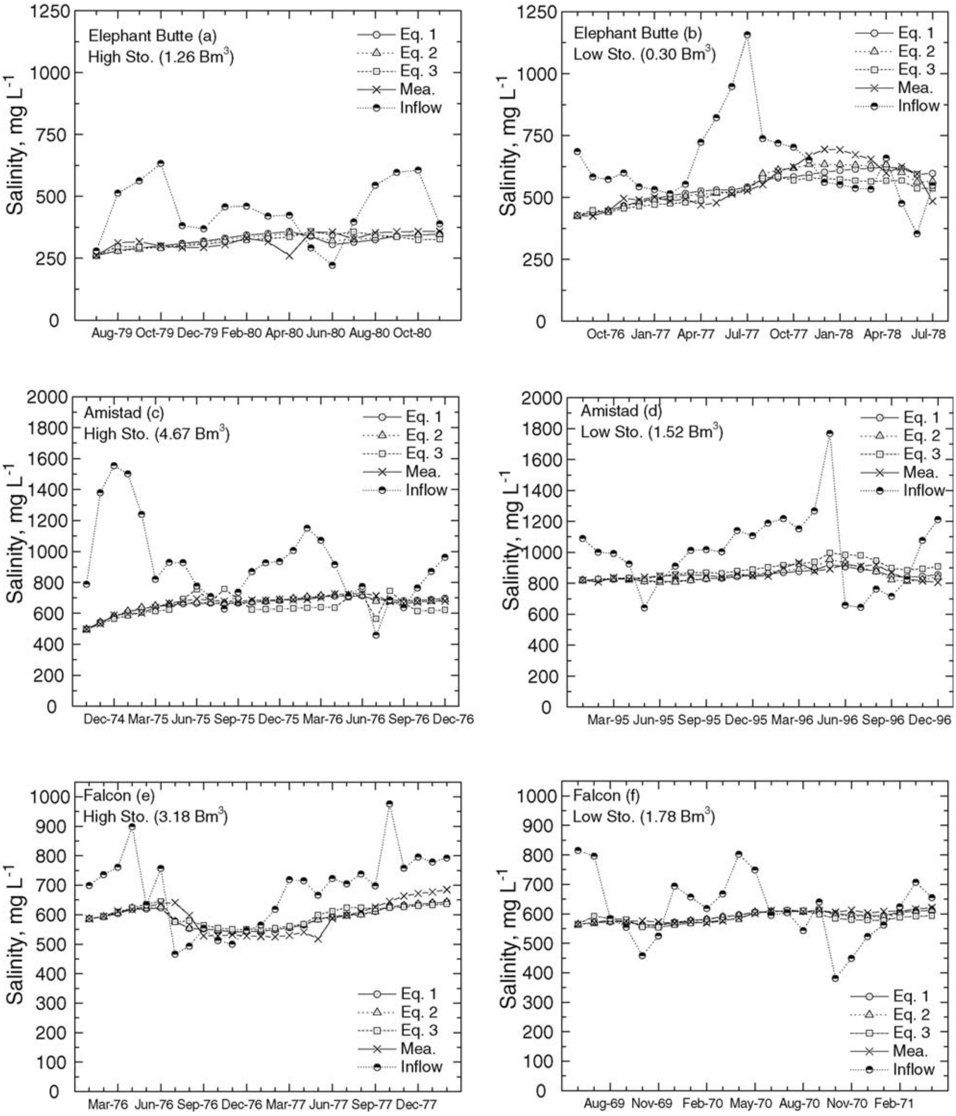

Fig. 1. Recorded inflow salinity (half-shaded circles), measured outflow salinity (*x*), and outflow salinity estimated by the three equations for three large reservoirs under low and high storages.

high and the low storage periods. The low value of *d* indicates that Eq. (3) underestimated outflow salinity unless the evaporative concentration is amplified. Recall that the initial salinity of the reservoir during the high storage period was conceivably overestimated. This means that the depth factor during the high storage period must be small. The standard error of the estimate was similar for the high and the low storage periods, and was mostly less than 10%, including the estimates by Eqs. (1) and (2).

Table 2
The empirical coefficients and the standard errors when estimated by the three equations

	Interval modeled	Storage (Gm^3)	The empirical coefficients				Standard errors (%)			
			α			d (m)				
			Eq. (1)	Eq. (2)	Eq. (2)[a]	Eq. (3)	Eq. (1)	Eq. (2)	Eq. (2)[a]	Eq. (3)
Elephant Butte										
High	07/79–11/80	1.26	0.98	0.93	0.91	2.3	10.9	9.6	9.2	8.3
Low	08/76–07/78	0.30	0.79	0.88	0.87	4.9	8.7	6.4	6.7	10.6
Amistad										
High	10/74–12/76	4.67	0.78	0.82	0.82	1.4	3.3	2.8	2.8	7.8
	01/78–12/79	4.25	1.03	1.02	1.02	5.7	2.6	2.4	2.3	2.7
Low	01/95–12/96	1.52	0.93	0.95	0.94	3.5	3.6	3.4	3.4	3.5
	01/99–12/00	1.58	0.92	0.91	0.91	3.1	3.5	3.4	3.5	4.3
Falcon										
High	01/76–02/78	3.18	1.01	1.01	1.01	7.5	4.9	4.9	5.4	5.4
	05/73–04/75	2.98	1.07	1.05	1.04	7.9	7.5	8.1	7.5	7.8
	01/80–03/81	2.59	1.08	1.08	1.08	15.0	1.9	1.7	1.7	3.5
Low	06/69–04/71	1.78	0.96	0.97	0.96	11.1	1.5	1.7	1.4	2.9
Projections using mean coefficients of each reservoir										
Elephant Butte										
High		1.26	0.89	0.91	0.89	3.6	12.1	9.6	9.2	8.6
Low		0.30	0.89	0.91	0.89	3.6	10.6	6.9	7.0	10.7
Amistad										
High		4.67	0.92	0.93	0.92	3.4	6.9	6.0	6.0	8.1
		4.25	0.92	0.93	0.92	3.4	6.3	5.3	5.4	3.6
Low		1.52	0.92	0.93	0.92	3.4	3.6	3.5	3.4	3.5
		1.58	0.92	0.93	0.92	3.4	3.4	3.6	3.7	4.4
Falcon										
High		3.18	1.03	1.03	1.02	10.4	5.3	5.2	5.6	5.4
		2.98	1.03	1.03	1.02	10.4	7.6	8.1	7.5	7.8
		2.59	1.03	1.03	1.02	10.4	2.4	2.5	2.7	3.6
Low		1.78	1.03	1.03	1.02	10.4	4.5	4.4	4.2	2.9
Grand mean			0.95	0.96	0.94	5.8	7.1	6.0	5.9	6.5

[a] Using the estimated storage.

4.2. *Amistad*

Salinity of the inflow fluctuated widely between 500 and 1550 mg L^{-1} during the high storage period (Fig. 1c), and between 650 and 1800 mg L^{-1} during the low storage period (Fig. 1d). The measured salinity of outflow began at 500 mg L^{-1}, and steadily increased to 700 mg L^{-1} during the high flow period, and remained around 800 mg L^{-1} during the low storage period (Fig. 1c and d).

The empirical coefficient for Eqs. (1) and (2) was less than unity, ranging from 0.78 to 0.82 during the high period of 1976–1977. The inflow data used for Amistad Reservoir were the gauged flow only, and the amount of the gauged flow was considerably lower than that of the deduced flow from water balance during the period of 1976–1977. In other words, there was ungauged fresh runoff into the reservoir, which lowered reservoir salinity. In all other cases examined, the values of empirical coefficient were close to unity, ranging from 0.91 to 1.02. The standard error of estimate was less than 5%.

The estimate of outflow salinity by Eq. (3), using the deduced flow, produced a low value for d during the period of 1974–1976. As for the case of Elephant Butte, the overestimation of the initial reservoir salt storage is likely to be the cause. The standard error was the largest among the three equations tested, but still less than 10% (Table 2).

4.3. Falcon

Salinity of the inflow into this reservoir fluctuated between 400 and 1000 mg L^{-1}, whereas salinity of the outflow varied from 550 to 650 mg L^{-1} (Fig. 1e and f). All equations provided good estimates of the outflow salinity with the standard error of less than 5%, except for the period of 1973–1975. During this period, high outflow salinity was reported for a few months before or after flood events. It is possible that salt flushing has occurred which was not detected during the routine salinity measurements. In any case, these discrepancies might have produced the high standard errors.

4.4. Sensitivity

The use of the mean value of the empirical coefficients for Eqs. (1) and (2) led to increase in the standard error of estimate by a few percentages at Elephant Butte, during the high storage period at Amistad, and during the low storage period at Falcon (Table 2). The use of the grand means, 0.95 for Eq. (1) and 0.96 for Eq. (2) provided the mean standard error of 7.1 and 5.9%, for Eqs. (1) and (2), respectively. Eq. (2) is obviously preferred when reservoir storage changes.

The use of mean depth in Eq. (3) did not substantially change the standard error at Elephant Butte, and Amistad, and no effect at Falcon. When d exceeds about 5 m, the effect on the outflow salinity became negligibly small. The use of the grand mean depth, 5.8 m provided the mean standard error of 6.5%. The standard error is likely to decrease to less than 5% if the estimate of the initial reservoir salt storage can be improved.

5. Conclusions

The two-layer model, expressed in Eq. (3), is descriptive, and seems to offer a realistic estimate of outflow salinity from inflow and initial storage data. The mixing model, especially Eq. (2) can also simulate the process adequately with limited monthly inflow data. The accuracy of prediction by these equations is relatively insensitive to the empirical coefficient, as the reservoir storage, even being “low” storage, buffers salinity fluctuation. The choice of the methods would depend largely upon the availability of flow, salinity, and reservoir data. Any of these methods should help improve salinity routing for riverflow modeling.

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