Water and Salt Transfers in Sutter Basin, California

K. K. Tanji, D. W. Henderson, S. K. Gupta, M. Iqbal, A. F. Quek

THERE is an excess of water and salts being discharged from Sutter Basin, California, more than can be accounted for by surface water and salt inputs. Since drain water is discharged as a point source, more information on return flow quantity and quality is essential to evaluate current water quality control plans (SWRCB 1971) and any future controls such as the proposed point-source waste discharge permit system (EPA 1972).

Water quantity and quality in this basin have been measured in the past by several local, state, and federal agencies, but the data collected are inadequate for comprehensive analysis. For these and other reasons, extensive and detailed water quality and quantity data have been obtained during the past 3 years.

Surface water samples from over 50 stations (Fig. 1) in supply and drainage canals were taken twice a month for electrical conductivity (EC) and chloride (Cl). Water flows for diverted river water, basin drain discharge, and recaptured drain waters were estimated from pumping records. Flows in drain laterals and stations along the main drain are now available, but not for the study period reported herein. Additionally, water samples were subjected to detailed chemical analysis four times a year and soils were analyzed to 1 m depth from 32 sites for salinity appraisal before and after irrigation season. Shallow groundwaters were obtained from piezometers and deep groundwaters from wells.

This preliminary investigation on analysis of water and salt transfers is being further pursued with hydrosalinity modeling. The data base being generated will be used to calibrate and verify the simulation model.

The conditions in Sutter Basin, namely the presence of high water table, need for drainage, maintenance of salt balance in the crop root zone, and reuse and disposal of return flows, represent some of the problems facing irrigated agriculture in low-lying basins. Previous water quality-hydrologic models for irrigated basins have been generally di-

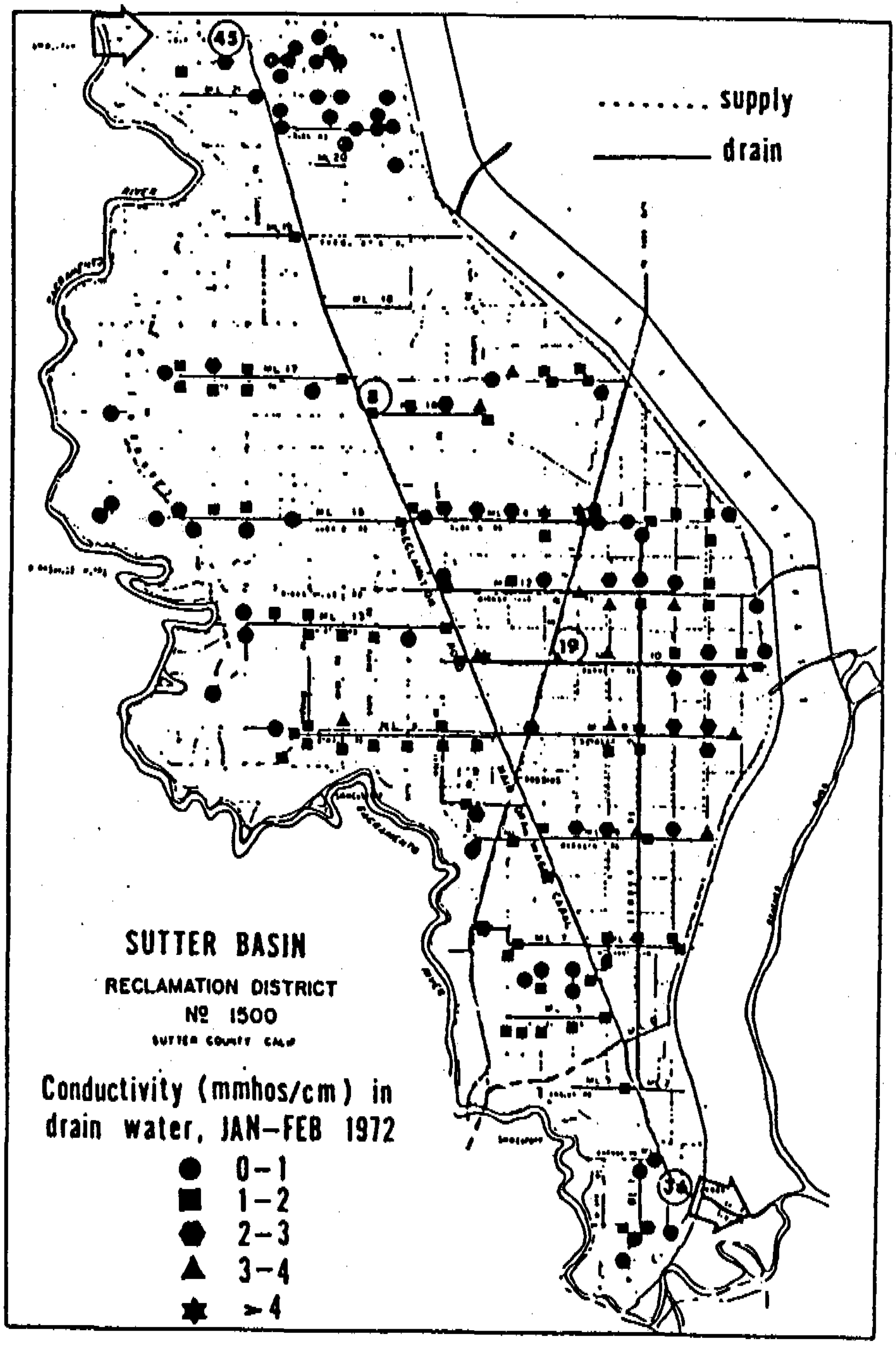

FIG. 1 Study area: locations of surface water inflows and outflows, stations for which detailed water analyses are reported, and spatial variability in electrical conductivity of drain waters.

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The authors are: K. K. TANJI, Lecturer, D. W. HENDERSON, Professor, S. K. GUPTA, Research Assistant, M. IQBAL and A. F. QUEK, Staff Research Associates, Water Science and Engineering Dept., University of California, Davis.

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Year	Rainfall	River water diversion	Surface supply	Recycled drain water	Drain Discharge	Evapotranspiration†	Rising groundwater ‡	Drainage index §
	ha-m							
1964	8 320	31 983	40 303	4 361	15 940	30 485	6 122	0.40
1965	11 041	28 230	39 270	4 675	16 980	29 873	7 492	0.43
1966	7 122	31 477	38 599	6 447	14 226	30 771	6 398	0.37
1967	16 870	25 907	42 776	5 279	20 609	27 779	5 611	0.48
1968	8 804	29 452	38 256	10 202	13 038	30 857	5 597	0.34
1969	15 807	27 339	43 146	8 700	21 521	30 271	8 646	0.50
1970	11 799	31 276	43 075	6 484	19 847	30 488	7 260	0.46
1971	10 875	30 319	41 194	5 611	19 421	29 866	8 094	0.47
1972	6 815	31 095	37 909	5 185	14 090	29 722	5 902	0.37
Ave.	10 828	29 675	40 503	6 349	17 287	30 012	6 791	0.42

* October of preceding year to September of current year.
† Based on potential evapotranspiration data for Davis furnished by W. O. Pruitt (1972); 90 percent PET (Apr-Oct) and 70 percent (Nov-Mar) on 99 percent of land surface in basin.
‡ Estimated by difference, i.e., (drain outflow + ET) – (rainfall + river diversion); comprised of river seepage, subsurface inflow from surroundings and rising connate waters.
§ Defined as surface drain output/surface inputs.

rected to conditions of net downward flux of water and salts. In Sutter Basin, however, and perhaps in other basins, the net flux of water and salts is from the subsurface to the land surface. This phenomenon causes rapid and dynamic changes in the quantity and quality of surface return flows.

BASIN DESCRIPTION

Sutter Basin (Fig. 1) is a levee-protected 26,585 ha basin located in the axial trough of the Sacramento Valley north of the City of Sacramento. It is surrounded by the Sacramento and Feather Rivers and Tisdale and Sutter Bypasses which are artificial floodways. Sutter Mutual Water Company diverts water from the Sacramento River, primarily at the Tisdale Pumping Plant (near Station 45, Fig. 1), to supply irrigation water to about 24,300 ha of crop lands. Reclamation District No. 1500 was formed in 1911 for flood protection and drainage in this basin.

Mean annual precipitation is about 18.1 inches 46 cm. Other natural sources of water are seepage from the Sacramento River system, subsurface inflows from higher elevations, and rising groundwaters from deeply-seated origins (CDWR 1954, Gianelli 1962).

About one-third of the irrigated acreage is devoted to rice production and the remainder to field and row crops such as safflower, grain sorghum, tomatoes, melons, and beans. Smaller acreages are devoted to pears and walnuts. Various methods of irrigation are practiced, depending upon the kind of crop and soil properties. Surface irrigation methods range from contour-levee flooding of rice fields to furrow and sprinkler irrigation of other crops. Subirrigation is practiced to some extent by raising the water surface elevation in drainage ditches.

The dominant soils in Sutter Basin are the coarse-textured Columbia and related soil series (Sycamore, Colusa) along the rivers, and the very fine-textured Sacramento and related series (Marvin, Marcuse) in the interior of the basin (Gowans and Lindt 1965). Much of the basin is underlain at 1 to 4 m depths by a thin layer of sandstone-like material which readily conducts water and appears to act as a built-in underdrain. Although the basin is affected by high water table conditions the only drains are at field boundaries spaced at about 0.8 km intervals (tile drainage is not utilized). miles 279.6

Sutter Basin is criss-crossed with 450 km of supply canals and 563 km of 349.8 miles drain ditches (see network in Fig. 1). Some of the drain water is reused for irrigation. A main drain canal conveys return flows in a southerly direction across the 31 km length of the basin. Drain waters are discharged at one location, the Karnak Pumping Plant (Station 36, Fig. 1), and into the Sacramento River via Sacramento Slough.

HYDROLOGIC TRANSFERS

Table 1 gives a summary of estimated water balance for the 1964-72 hydrologic years. The surface water supply, rainfall and river diversions constitute the major water inputs to Sutter Basin. Rising groundwater is another input, consisting of river seepage, subsurface interbasin inflow from the surrounding area, and rising connate water under artesian pressure (Curtin 1971). Groundwater is not used, except in limited amounts along the Sacramento River, because of its high salt content. Some of the drain water is recaptured and reused. When drain waters are reused, electrical conductivity is maintained at or below 750 micromhos/cm, if necessary, by dilution with fresh river water.

The major outputs are surface drain outflow and evapotranspiration losses to the atmosphere. There is no net deep percolation of water into the substrata.

The drainage index, defined as the ratio of drain output to surface water inputs, ranges from 0.34 to 0.50 with a 9-year average of 0.42. Wilcox (1947) reported for the calendar years 1931, 1932, 1933, and 1946 drainage indices of 0.52, 0.63, 0.59, and 0.61, respectively. The Wilcox data considered only river diversion for surface inputs; if rainfall were included, the drainage indices

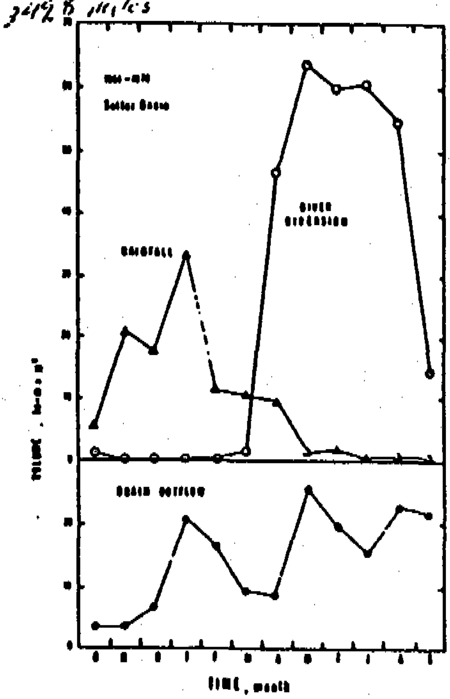

FIG. 2 Mean monthly precipitation, river diversion for irrigation, and return flow drain discharge.

DURING, AND AFTER IRRIGATION SEASON

Description and Station No.	Date	EC micromhos/cm	Na	Ca	Mg	HCO_3	Cl	SO_4
			meq/liter					
Supply Water (Stn 45)	7/14/72	120	0.24	0.40	0.59	1.12	0.01	0.08
	9/1/72	139	0.31	0.54	0.62	1.22	0.07	0.07
Main Drain outflow (Stn 36)	2/15/72	1594	6.0	3.9	5.9	6.9	7.6	0.9
	7/14/72	624	2.2	1.5	2.0	3.8	2.1	0.4
	9/1/72	714	2.8	2.2	2.7	4.4	2.5	0.4
	10/16/72	1417	5.4	3.6	5.6	6.4	7.8	0.6
	2/20/73	1237	4.5	2.9	5.1	-	4.8	0.8
Drain Lateral ML-10 (Stn 19)	2/15/72	4048	14.0	12.5	14.5	6.6	31.0	0.5
	7/14/72	992	3.6	2.3	3.2	3.9	4.8	0.4
	9/1/72	850	2.8	2.1	3.1	3.8	4.0	0.1
	10/16/72	2757	10.0	7.2	10.2	6.1	21.0	0.3
	2/20/73	3432	13.2	9.5	14.0	-	28.6	0.4
Drain Lateral ML-18 (Stn 8)	2/15/72	750	1.6	2.6	4.8	7.3	0.7	0.6
	7/14/72	349	0.8	1.2	2.0	3.3	0.1	0.3
	9/1/72	392	0.9	1.3	1.8	3.6	0.2	0.2
	10/16/72	704	1.5	2.4	4.1	6.8	0.8	0.5
	2/20/73	549	1.1	2.0	2.9	-	0.5	0.4

would be lower.

Fig. 2 shows the monthly mean rainfall, river water diversion, and surface drain outflow for the 1964-70 hydrologic years. Much of the precipitation occurs during the winter months. The irrigation season, as indicated by river diversions, starts in April and ends in September. The drain discharge first peaks in January and February which normally are the high rainfall months. The next peak occurs after rice germination in May when flood water depths in the rice fields are lowered from about 15-25 cm to about 5-10 cm. Deep water culture is practiced early in the season to protect water-seeded rice from birds and to minimize weed growth. Another peak occurs in August and September as rice fields are drained prior to harvesting and water levels in the drains are lowered. In addition to the latter two peak flows, rice culture in the Sacramento Valley involves continuous spilling and seepage to drains throughout the growing season. There are some damping effects on drain outflow due to drain ditch and bank storage as well as flooding and draining of rice fields.

SALT TRANSFERS

Table 2 contains typical water quality data for supply and drain waters before, during, and after the irrigation season. The locations of the water sampling sites are shown in Fig. 1. The Sacramento River supply water is a low-salt, high-quality irrigation water. The main drain outflow at the Karnak Pumping Plant is a composite of all return flows from the basin. Electrical conductivity of water in the main drain before and after the irrigation season is typically about 10-fold greater than that of the supply water, and during the irrigation season about 5-fold greater. Fig. 3 gives a more detailed trend in EC levels in the drain outflow. It shows the distinct lowering during the irrigation months of May through September. These seasonal quality changes are mainly attributed to continuously-flooded rice culture and the spilling and percolation of flood waters into drains.

Fig. 1 shows the spatial variability in the quality of drain waters in terms of EC. This particular sampling period, during an uncommonly dry winter, is thought to represent the quality of rising groundwaters at or near the land surface, unaffected by surface inputs of precipitation or river diversion. A particularly high-salt area is located to the east and northeast of Robbins.

Additional chemical data for drain water are given in Table 2. Station 19 on main lateral 10 (ML 10) is located in the high-salt area. EC levels are substantially higher than at Station 8 on main lateral 18 (ML 18), which is located in a low-salt area. In both drain laterals, salt concentrations are diluted by runoff and seepage waters from flooded rice fields.

Fig. 4 shows the vertical change in EC and Cl of groundwaters located in the high-salt area. At about 30 to 100 m beneath the land surface, groundwaters typically have EC's of 8 000 to 13 000 micromhos/cm and 100 to 135 meq/l Cl. These rather saline groundwaters apparently represent the chemical quality of rising connate waters (Cl concentration of about 360 meq/l) which are being diluted by surface inputs and shallow subsurface inflows. As the connate water rises upwards to the land surface it tends to become further diluted so that EC levels at 3 to 7 m are less than 1 000 to about 4 000 micromhos/cm and chlorides are correspondingly lower. A linear relationship between EC and Cl is suggested by the data in Fig. 4.

Fig. 5 illustrates a more definitive linear relation between EC and Cl in the drain outflow at Karnak. Chloride content in drain waters from this basin is about 2 to 3 meq/l during the irrigation season and about 4 to 8 meq/l during the non-irrigation season. It appears that

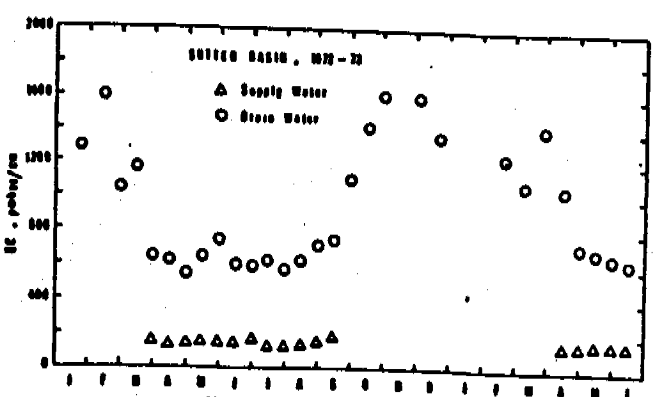

FIG. 3 Seasonal trends in electrical conductivity of irrigation water and basin drain outflow.

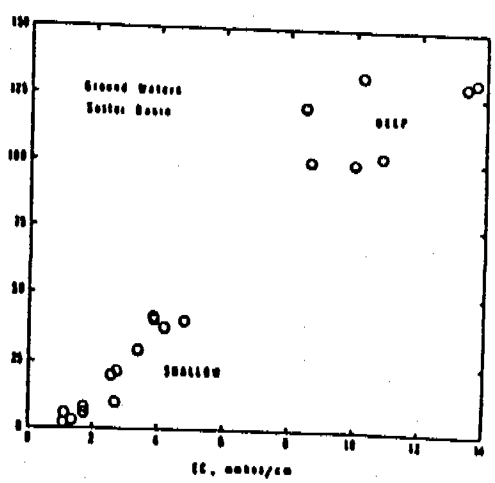

FIG. 4 Relations between chloride and electrical conductivity of deep (30-100 m) and shallow (2-7 m) groundwaters.

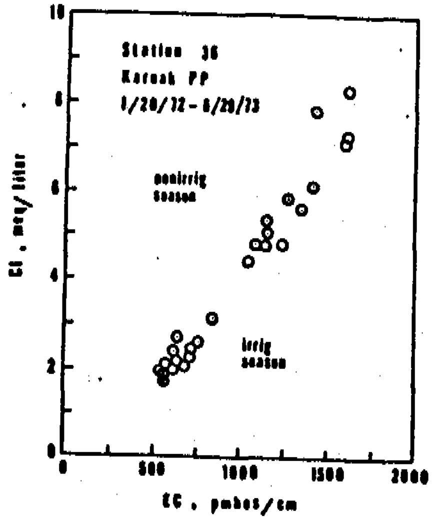

FIG. 5 Relations between chloride and electrical conductivity of drain outflow during irrigation and nonirrigation season.

TABLE 3. SUMMARY OF ESTIMATED SALT BALANCE FOR THE 1970-72 HYDROLOGIC YEARS AND FOR SELECTED HISTORICAL CALENDAR YEARS

Year	Rainfall	River Water Diversion	Surface Inputs	Drain Discharge	Rising Groundwaters*	Salt Balance† Index
		tons salt				
1931‡	-	30 121	-	113 464	-	3.77§
1932‡	-	30 727	-	201 376	-	6.55§
1933‡	-	31 226	-	124 403	-	3.98§
1946‡	-	36 106	-	128,519	-	3.56§
1970	1286	34 774	36 060	113 219	77 159	3.14
1971	1395	35 254	36 649	101 298	64 649	2.76
1972	819	36 987	37 806	71 593	33 787	1.89
Average 1970-72	1167	33 599	36 838	121 982	58 532	2.59

*Estimated by difference: (drain discharge) - (rainfall + river diversion).
†Defined as drain output/surface inputs.
‡Reported by L. V. Wilcox (1947).
§Salts in rainfall not considered.

increases in Cl content in drain waters cannot be attributed only to concentration of applied waters by evapotranspiration. Moreover, analyses of soil samples taken during 1971-73 indicate Cl is not accumulating to any substantial degree in the soil profiles above the water table. Therefore, it appears that Cl and other salts must also be coming from sources other than surface inputs or the soil zone.

Table 3 contains a summary of the salt balance for selected historical calendar years as reported by Wilcox (1947) and the 1970-72 hydrologic years. Historical salt balance indices, defined as the ratio of drain output to surface input, were reported to be as low as 3.56 for 1946 to as high as 6.55 for 1932. The 1932 salt balance index appears to be out of line. The only unusual information available is that 1932 was an extremely dry year, but in spite of this condition the amount of river water diverted was nearly the same as the previous and succeeding calendar years.

The more current data indicate salt balance indices are between 1.89 and 3.14 (i.e., about 2 to 3 times more salts were discharged than could be accounted for by surface inputs). Although the recent salt balance indices appear to show a downward trend, it is not known if this trend will persist in the future. It should be noted that the margin of error in estimating drain outflow and salt load is considerable. The unit mass emission rates (drain outflow) were 66 ha-cm/ha/yr and 3.58 metric tons salt/ha/yr for the 1970-72 hydrologic years.

WATER AND SALT TRANSFERS

Fig. 6 summarizes basin-wide salt and water fluxes for the 1970 hydrologic year. This flow sheet shows that the average salt load in surface water inputs was 0.74 tons per ha-m (thm), and the drain outflow was 5.08 thm, a 7-fold increase. The salt load in the unaccounted subsurface inflows was estimated at 9.57 thm. The unaccounted subsurface inflows contributed about 40 percent of the drain water outflow and 70 percent of the salt outflow. It is very evident that water and salt transfers in this basin cannot be evaluated solely on the basis of surface input-surface output relations.

GEOHYDROLOGIC INFORMATION

The earlier reports on the hydrogeology of Sacramento Valley (Bryan 1923, Olmsted and Davis 1961) were very sketchy for Sutter Basin. But more recently, Curtin (1971) provided information which supports the findings reported herein. Fig. 7 shows that a fault line bisects a portion of Sutter Basin. It should be noted that within the Sutter Basin the fault line occurs in the high-salinity drain water area (Fig. 1).

The Sacramento Valley trough contains one of the thickest sediments and most nearly complete late Mesozoic sections in North America (Olmsted and Davis 1961). The Upper Jurassic, Lower Cretaceous, and Upper Cretaceous sequences have a thickness in excess of 17 000 m. Fig. 8 shows a geologic section of Sutter Basin including the vertical fault with the south block displaced upward about 170 m in relation to the north block.

The Forbes Formation, about 1 000 m thick, is predominately a gray marine shale. The Kione Formation is a massive, friable sandstone of granitic origin. The other formations are of lesser interest. Apparently during the Late Paleocene Period, an inland sea was trapped in the Sacramento Valley leaving a mound of connate water in the Kione Formation.

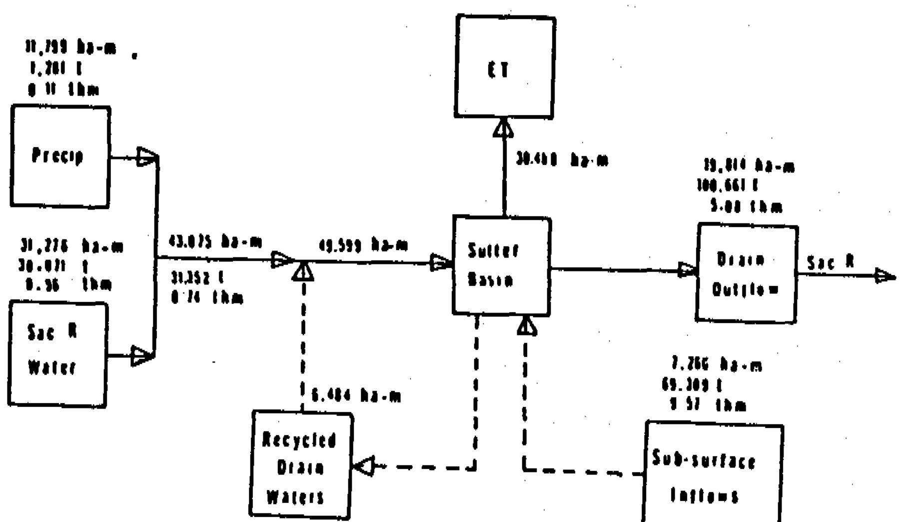

FIG. 6 Basin-wide water and salt transfers for the 1970 hydrologic year (ha-m, t, and thm denote hectare-meter of water, metric tons of salts, and metric tons of salts per hectare-meter of water, respectively).

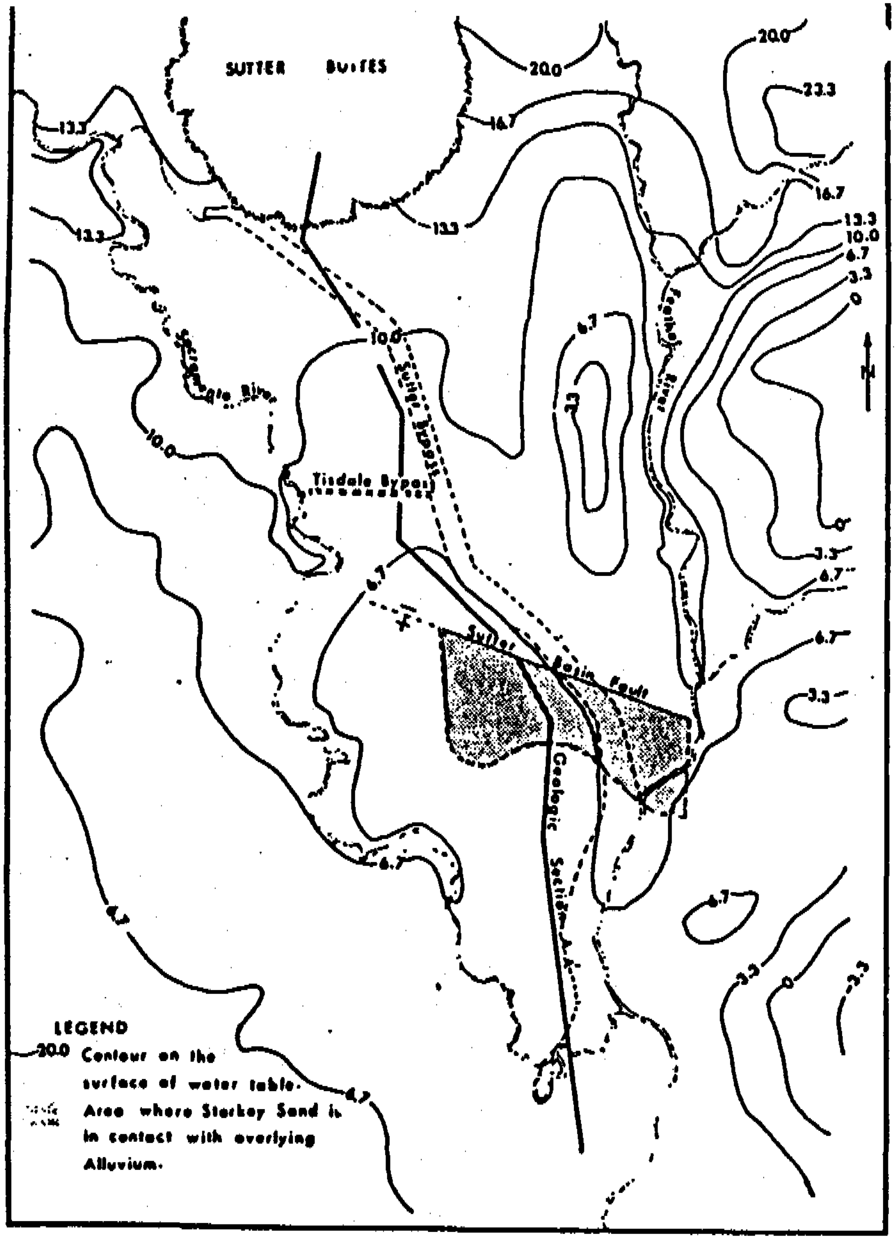

FIG. 7 Location of vertical fault and water table contours (meters) in the study area. Geologic section A-A' is given in Fig. 8.

It is believed that this connate water, made up principally of sodium and chloride, rises upwards through the fault line under artesian pressure. The pressure is created by inflows of fresh water into the Kione sand formation where it is tilted upwards at Sutter Buttes, a volcanic rock intrusion in the valley floor. The hydraulic head is estimated to be 80 to 130 m. Based on Curtin's (1971) study and the findings reported herein, it is apparent that the major source of salt load in the discharges at Karnak is rising connate water, altered somewhat in cationic composition due to ion exchange.

SUMMARY AND CONCLUSIONS

An analysis of water and salt transfers was conducted in Sutter Basin, California. The average drainage index for the hydrologic years 1964-72 was estimated to be 0.42 ± 0.08 and the average salt balance index for the hydrologic years 1970-72 as 2.59 ± 1.25.

For the 1970 hydrologic year, the flow-weighted average surface input of salts (precipitation + irrigation water) was 0.74 tons per ha-m and the surface output (return flow) 5.08 tons per ha-m. About 40 percent of the water and 70 percent of the salt load in the return flow is estimated to have originated from subsurface origins, mainly rising connate water.

Hydrogeologic evidence indicates that connate water is rising upwards under artesian pressure from about 830 to 1 000 m below sea level. There is no apparent net deep percolation of water and the net flux of water and salts is from the subsurface to the land surface.

This analysis shows that surface input-surface output relations do not always give an adequate assessment of water quantity and water quality in irrigated basins. When point source waste discharge permits are to be enforced in the future, due consideration should be given to natural geochemical sources like rising connate water.

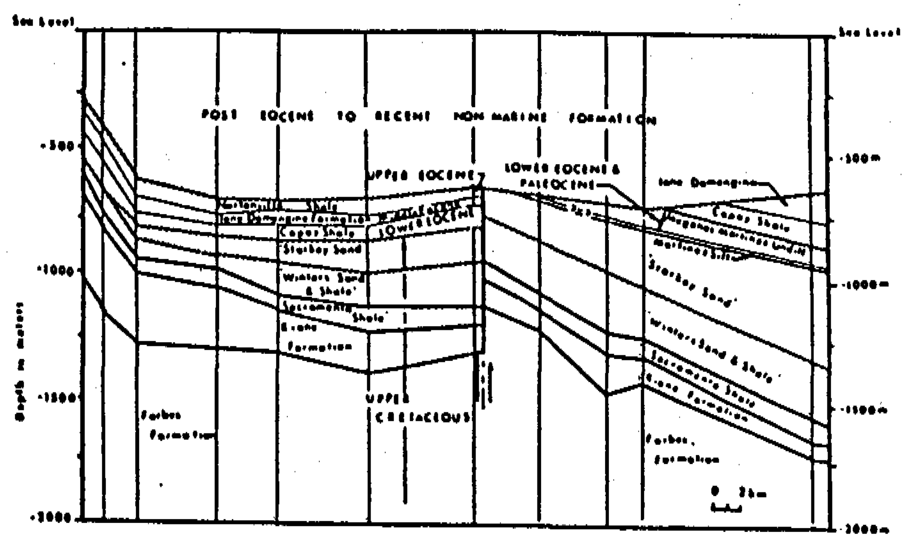

FIG. 8 Geologic formations and vertical faulting along geologic section A-A' (Fig. 7). Vertical scale is in meters.

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