HYDROLOGIC STUDY FOR
SOUTH SLOUGH ESTUARINE SANCTUARY,
COOS BAY, OREGON

David W. Harris
William G. McDougal
William A. Patton
Nasser Talebbeydokhti

CLASS PROJECT FOR CE 527 APPLIED HYDROLOGY

Professor Peter C. Klingeman

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WATER RESOURCES RESEARCH INSTITUTE
OREGON STATE UNIVERSITY
CORVALLIS, OREGON 97331

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I. INTRODUCTION

No hydrologic study has previously been made of the South Slough Estuary drainage basin. Yet, since freshwater runoff is paramount to an estuary, it would seem that such a study is vital to the proper understanding -- and hence management -- of the estuary. Therefore, a brief hydrologic analysis of the South Slough basin has been conducted as part of a class project at Oregon State University. The results are presented on the following pages. This analysis consists of two major parts: (1) The freshwater streamflow that enters the estuary from the drainage basin; and (2) the mixing of that fresh water within the estuary.

It should be noted that hydrologic data for the South Slough basin are made conspicuous by their absence. For this reason, data from nearby collection stations outside the basin have been used in the analyses made for South Slough. This has permitted an estimate of precipitation and runoff. But the results presented here can in no way take the place of the analysis of data collected in the drainage basin itself. Nor should these results, based on monthly averages of precipitation, be compared indiscriminately with measured daily values.

II. FRESHWATER RUNOFF

Basin Description

For analytical purposes, the northern boundary of the South Slough Basin was chosen to be at the Charleston highway bridge across the estuary mouth. This closely represents the natural basin directly affecting the slough. It inlcudes the entire boundary of the South Slough Estuarine Sanctuary. Figure 1 shows a map of the Sough Coast drainage area within which South Slough is located.

The area of the land surface that drains into South Slough is approximately 31.0 square miles. The basin is generally forested. Drainage is accomplished chiefly by means of small streams, most of which enter the slough from the east or south.

Data Assembly

No hydrologic data are available on the contribution of fresh water runoff to South Slough from tributary streams. Hence, recourse was made to the development of an empirical relationship between precipitation and runoff for the drainage basin. Precipitation and streamflow data from two nearby drainage basins were employed for this purpose. Coefficients for the relationship were determined for each month of the year.

The available hydrologic data at different stations and the corresponding periods of record are shown in Table 1. Figure 2 shows the locations of all hydrologic stations used and other relevant information, such as contour lines of average annual precipitation (isohyetal lines).

The two listed gauging stations for streamflow were chosen for their proximity to Coos Bay. Other, more distant stations also exist. The drainage basins above the Millicoma River and Coquille River gauging stations are relatively small, being 45.0 and 73.4 square miles in area, respectively. This fits the need to simulate streamflows from relatively small tributary areas to South Slough. It is also assumed that the soil and vegetation in these two basins are similar to those found in the South Slough basin.

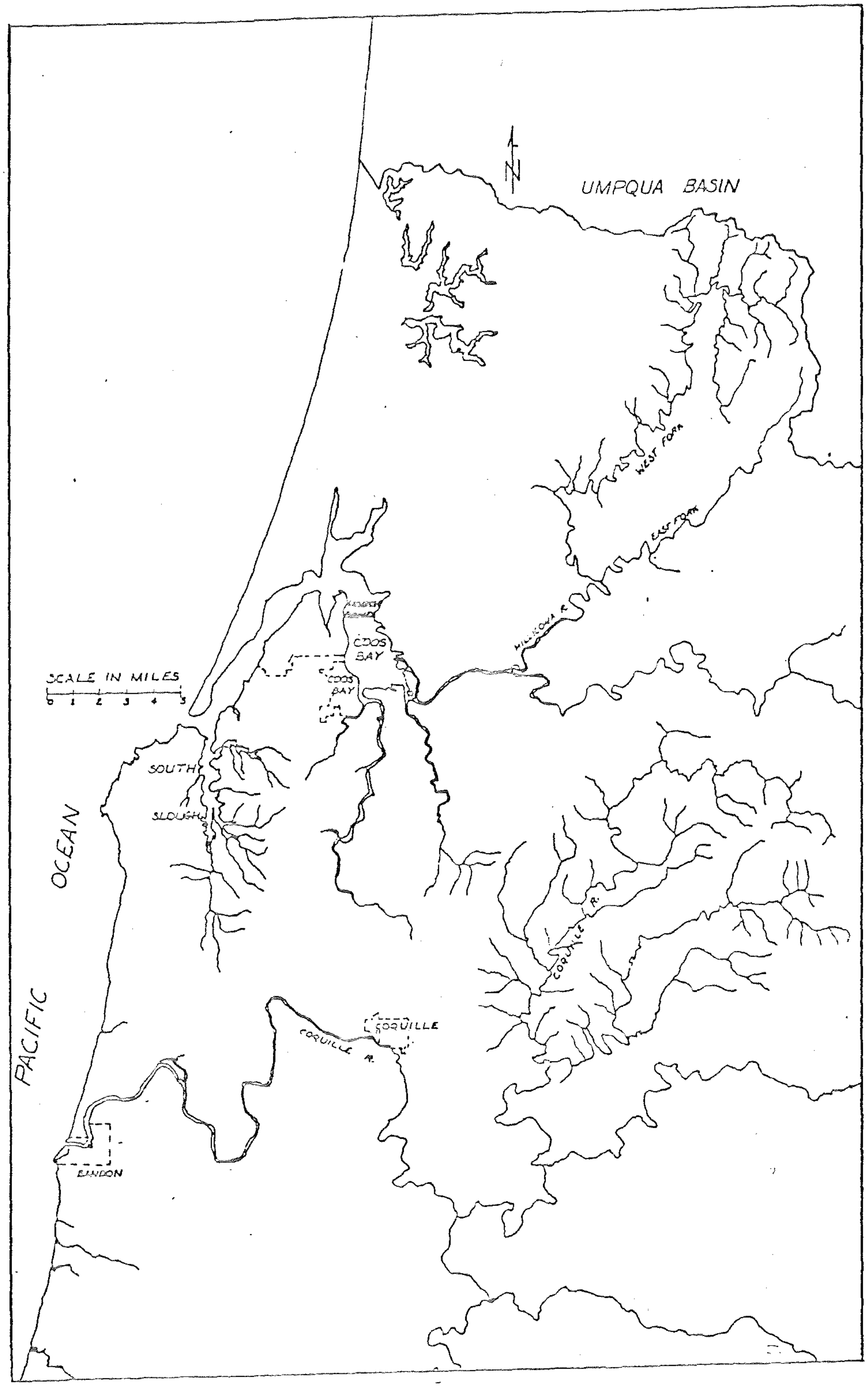


FIGURE 1. SOUTH COAST DRAINAGE BASIN, INCLUDING SOUTH SLOUGH

TABLE 1. AVAILABLE HYDROLOGIC DATA

STATION	DATA TYPE	REFERENCE	YEARS OF RECORD *
Bandon	Precipitation Temperature	1	1919 - present
Coquille City	Precipitation Temperature	1	1972 - present
Dora	Precipitation Temperature	1	1969 - present
Fairview	Precipitation Temperature	1	1974 - present
North Bend FAA AP	Precipitation Temperature	1	1902 - present
Sitkum	Precipitation Temperature	1	1944 - 1969
West Fk Millicoma near Allegheny	Streamflow	2, 3	1954 - present
North Fk Coquille near Fairview	Streamflow	2	1964 - present

*Note that streamflow records are kept by "Water Year", which extends from October 1 to September 30 and is identified by the calendar year in which the water year ends.

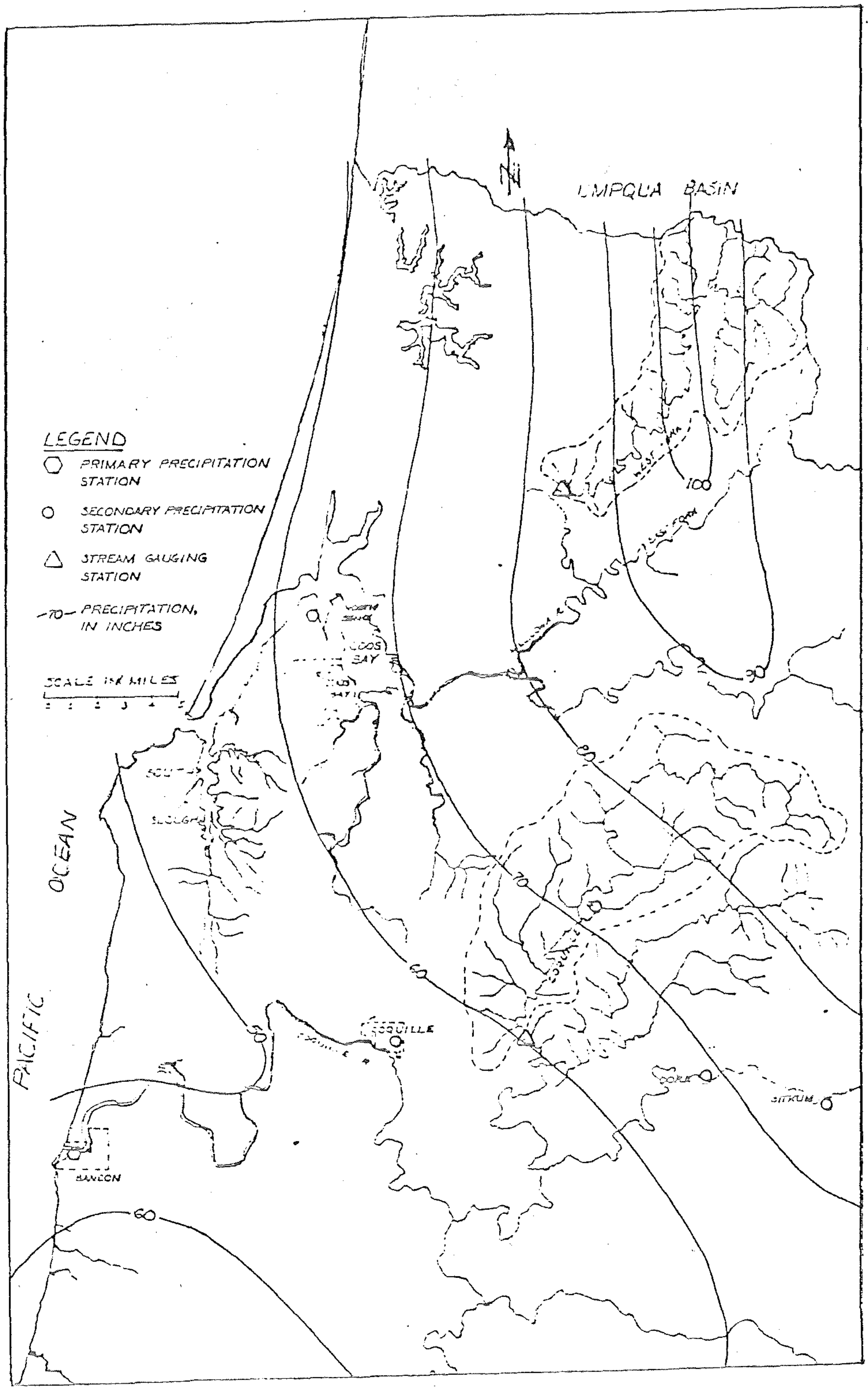


FIGURE 2. PERTINENT STREAMS, HYDROLOGIC STATIONS AND AVERAGE ANNUAL PRECIPITATION NEAR SOUTH SLOUGH

Calculation Methods

A schematic representation of the method used to drive fresh water runoff values for South Slough is shown in Figure 3. Precipitation and discharge data for the two nearby basins (identified as x and y in Figure 3) were combined and used to determine coefficients for the runoff equations. These monthly runoff equations, along with derived values of precipitation, were used to predict the average monthly runoff from the South Slough drainage basin.

Monthly precipitation values were estimated for each basin by use of the Normal Weighting Method (4),

$$P_x = \frac{1}{3}\left[\frac{N_x}{N_a} P_a + \frac{N_x}{N_b} P_b + \frac{N_x}{N_c} P_c\right] \qquad \text{Eq. 1}$$

in which

P_x = average monthly precipitation over drainage basin x

P_a = monthly precipitation at gauging station a

P_b = monthly precipitation at gauging station b

P_c = monthly precipitation at gauging station c

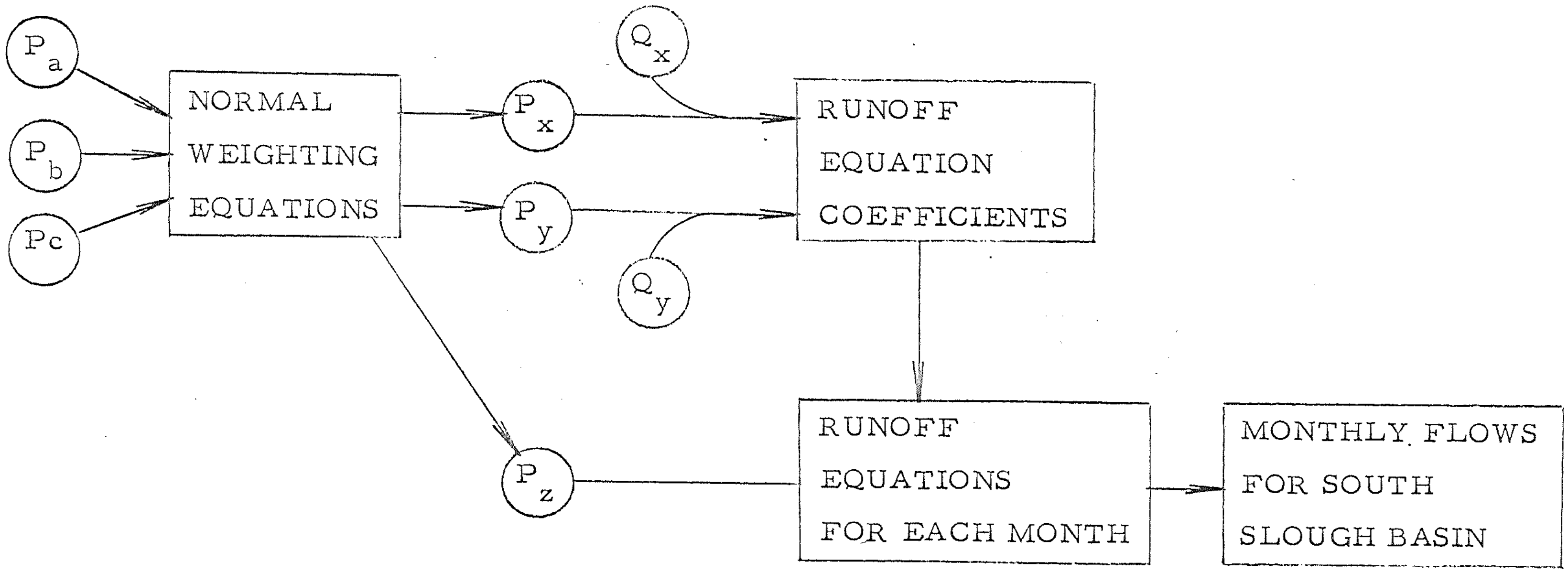
N_x = normal annual precipitation over drainage basin x

N_a, N_b, N_c = normal annual precipitation over drainage basins a, b, and c, respectively.

For this study, station a was chosen to be Bandon (N_a = 59.8 inches), station b to be North Bend (N_b = 61.7 inches), and station c to be Sitkum during 1960-69 (N_c = 74.7 inches) and Dora during 1969-76 (N_c = 66.6 inches). Monthly precipitation for that period 1957-1976. Note that during that period 1957-1959 only two stations (Bandon and North Bend) were used. Equation 1 was adjusted accordingly.

The values for N_x and N_y (y replacing x in the above equation) were determined from the isohyetal lines for each basin (see Figure 2). Two sets of monthly precipitation values were thus obtained, one for each of the two nearby drainage basins.

Monthly data for streamflow were available for the West Fork of the Millicoma near Allegany and the North Fork of the Coquille near Fairview. All precipitation and streamflow data used are summarized in Appendix I.



$P_{a, b, c}$ - monthly precipitation at index stations (Bandon, North Bend, Sitkum/Dora)

$P_{x, y, z}$ - derived monthly precipitation over drainage basins (W. Fk. Millicoma, N. Fk. Coquille, South Slough)

$Q_{x, y}$ - monthly streamflow at "known" gaging stations (W. Fk. Millicoma, N. Fk. Coquille Rivers)

FIGURE 3. METHOD FOR DERIVING MONTHLY RUNOFF FROM SOUTH SLOUGH DRAINAGE BASIN

The precipitation-streamflow data sets were arranged by individual month (January, etc.). They were then subjected to least-squares regression analyses to fit the data with power equations of the form:

$$Q_{mo_i} = a[P_{i^{mo_i}} \cdot DA]^b \qquad \text{Eq. 2}$$

in which

Q_{mo_i} = average monthly discharge for the ith month, in cfs

P_{mo_i} = monthly average precipitation for the ith month, in inches

DA = drainage basin area, in square miles

a,b = coefficients to be determined.

Results of Analyses

The 12 sets of coefficients obtained from the combined data of both drainage basins are shown in Table 2. Values of r^2, the coefficient of determination, are also presented. Low values indicate a poor "fit" of the power equation whereas high values indicate a better "fit".

Average monthly precipitation values were derived for the South Slough drainage basin by use of the Normal Weighting Method (see Appendix I). Normal annual precipitation over South Slough basin were estimated as 55 inches (see Figure 2). No areal variation or precipitation over the basin was assumed.

Monthly runoff flows were then obtained by use of the derived South Slough basin precipitation values and the runoff equation (see Appendix I). These values represent the sum of contributions from all drainage basin sources into South Slough.

Estimated average monthly values of precipitation and runoff for the South Slough drainage basin for the period 1957-1977 are shown in Figure 4. Runoff is represented as an equivalent depth, in inches.

A fresh water budget for South Slough drainage basin is shown in Table 3. Overall, precipitation is in excess of runoff, as expected. Losses, presumably through evapotranspiration, represent 22% of the total annual precipitation. However, the magnitude of precipitation in excess of runoff for the months August to January, and runoff in excess of precipitation during February, April, June, and July cannot be fully explained by evapotranspiration. Probably, soil moisture and groundwater recharge and depletion take place on a yearly cycle and account for the above patterns.

TABLE 2. COEFFICIENTS FOR SOUTH SLOUGH DRAINAGE BASIN MONTHLY RUNOFF EQUATIONS (EQUATION 2)

MONTH	a	b	r^2
January	0.4545	1.0864	0.7963
February	2.5818	0.8400	0.7076
March	1.5054	0.8927	0.8201
April	3.2846	0.7428	0.5872
May	1.2654	0.8580	0.6388
June	12.1942	0.2683	0.1998
July	11.8854	0.0798	0.0805
August	4.9419	0.1466	0.2248
September	2.9523	0.3072	0.2853
October	0.0053	1.5729	0.7304
November	0.4672	0.9951	0.5604
December	0.3376	1.1221	0.8122

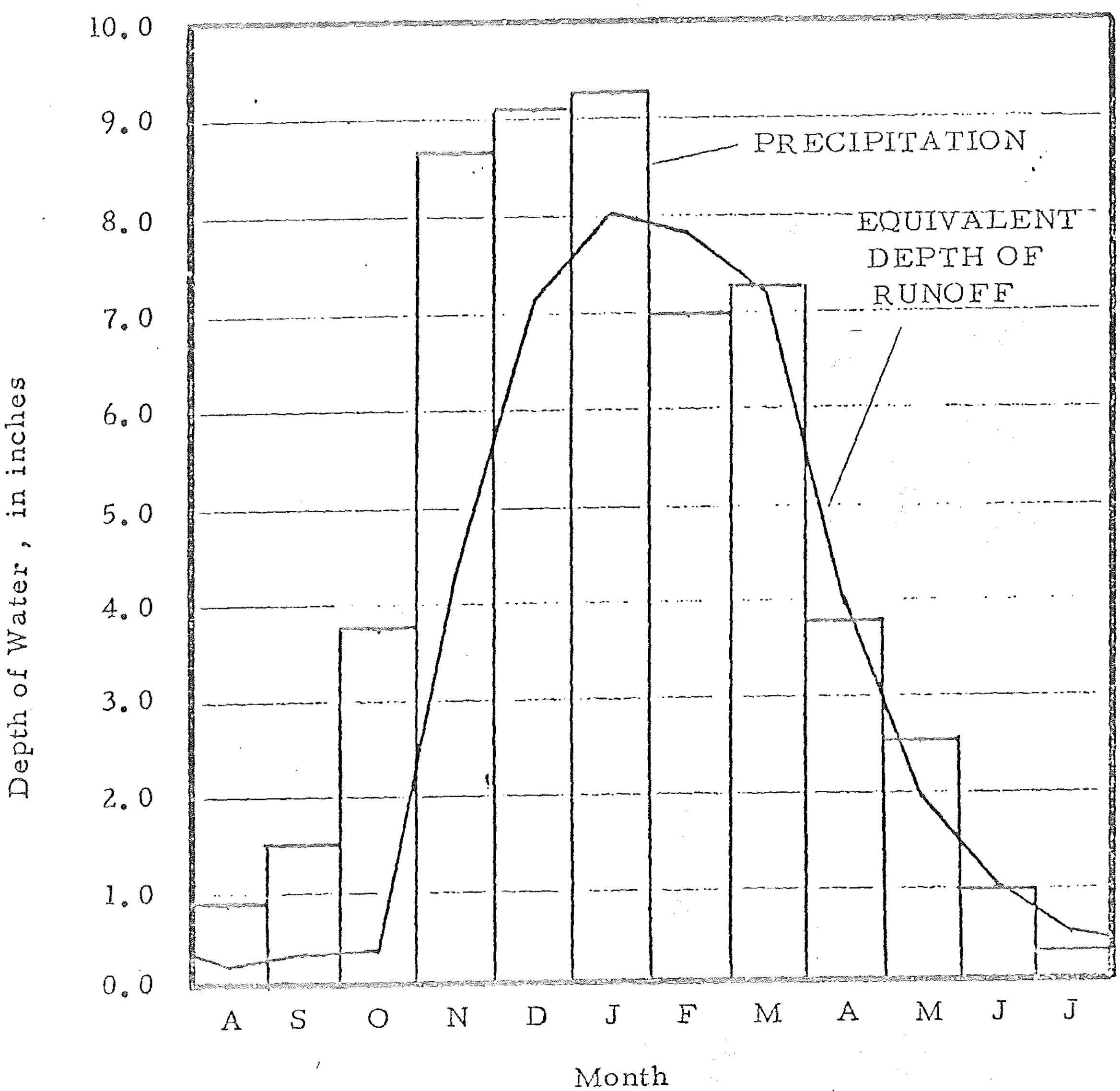


FIGURE 4. ESTIMATED AVERAGE MONTHLY PRECIPITATION AND EQUIVALENT DEPTH OF RUNOFF FOR SOUTH SLOUGH DRAINAGE BASIN

TABLE 3. FRESH WATER BUDGET FOR SOUTH SLOUGH DRAINAGE BASIN

MONTH	AVG DEPTH OF PRECIPITATION IN INCHES	AVERAGE RUNOFF IN CFS	EQUIV DEPTH OF RUNOFF IN INCHES	LOSS THROUGH ABSTRACTIONS IN INCHES
January	9.26	215	8.00	1.26
February	6.94	232	7.80	-0.86*
March	7.26	188	6.99	0.27
April	3.77	110	3.96	-0.19*
May	2.52	52	1.93	0.59
June	0.97	28	1.01	-0.04*
July	0.31	14	0.52	-0.21*
August	0.86	6	0.22	0.64
September	1.50	9	0.32	1.18
October	3.70	10	0.37	3.33
November	8.65	120	4.32	4.33
December	9.08	192	7.14	1.94
ANNUAL	54.82	98	42.58	12.24

* Represents net gain of water from source other than precipitation (e.g., from ground water base flow) Abstractions include interception, evaporation, transpiration, infiltration.

A flow-duration curve based on the monthly values of runoff for the South Slough drainage basin is shown in Figure 5. The median flow (exceeded 50 percent of the time) is about 50 cfs. The mean flow of 98 cfs (see Table 3) is exceeded about 40 percent of the time. The shape of the curve indicates that the basin is characterized by moderately high seasonal flows and a low-flow regime that is poorly sustained at the end of the dry season.

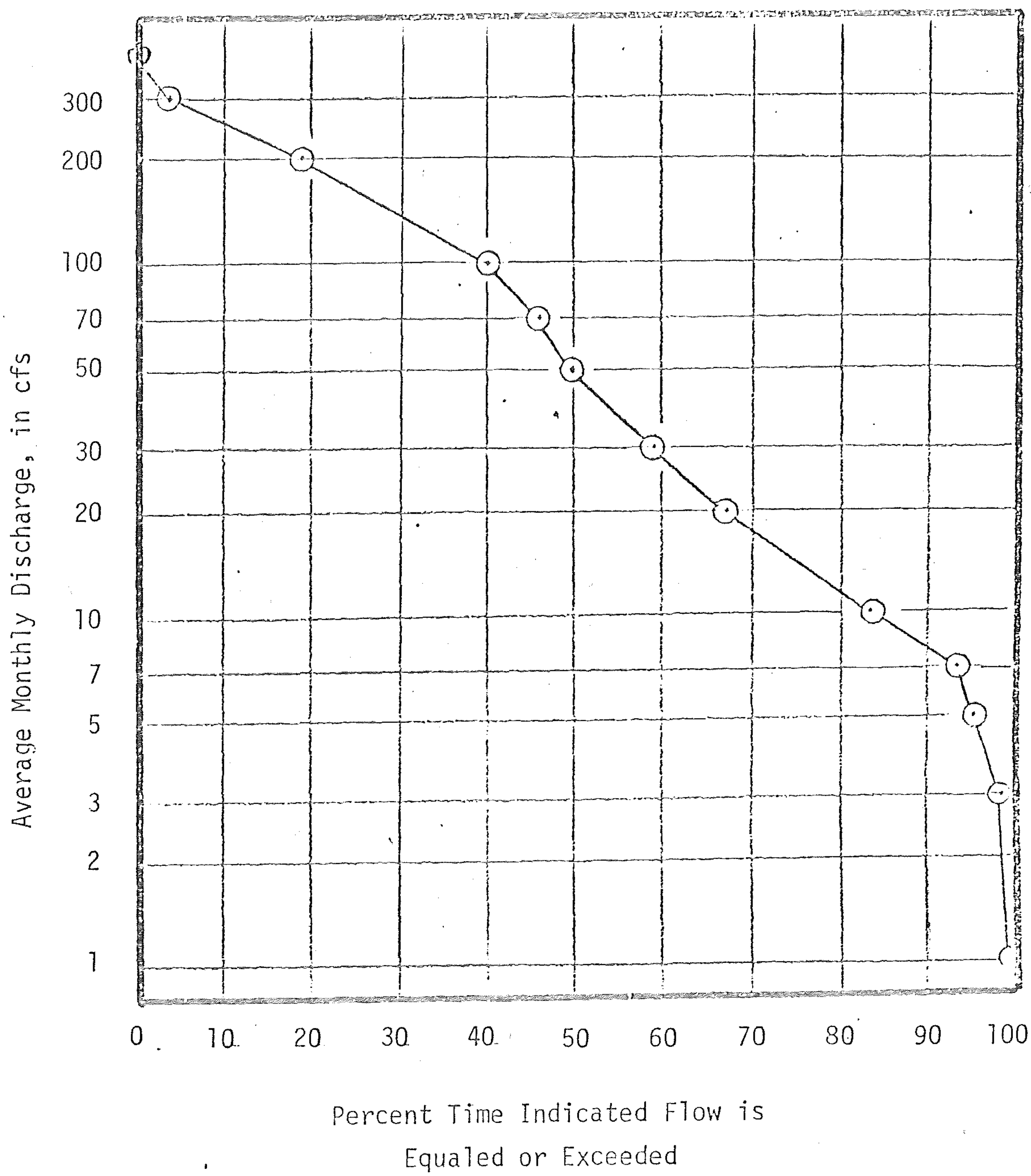


FIGURE 5. FLOW DURATION CURVE FOR SOUTH SLOUGH DRAINAGE BASIN DISCHARGE

III. ESTUARINE FLUSHING

Estuary Description

The South Slough estuary is fairly long and narrow, with its long axis running mainly north-south, as shown in Figure 6. Its mouth opens onto Coos Bay approximately one mile upstream from the mouth of Coos Bay at the Pacific Ocean. The surface area of South Slough south of the bridge at Charleston is 2.04 square miles and the mean tide range is 5.7 feet (6). Fresh water enters the slough from several small streams, mostly flowing from the east and south.

Tidal Prism Volume

Calculation Methods

The tidal prism volume and the flushing and mixing characteristics are each calculated here in three ways. The results are then compared.

The first method of finding the tidal prism volume involves the assumption that the sides of the estuary are steep. In this case, the prism volume is simply the product of the plan area of the estuary and the tide range.

The second method is based on a trapezoidal approximation. Boyce (2) presented field data on the mean cross-sectional depth at several stations in South Slough. The station locations are identified in Figure 6. By means of these measurements a trapezoidal approximation for the prism volume is obtained. These data are presented in Table 4.

The third method is based on a two-dimensional, non-linear circulation model developed by the Corps of Engineers (3). The volume flow rate is calculated across several cross sections. Integrating the volume flow rate at the entrance to South Slough over a rising or falling limb of the tide gives the volume of the tidal prism. This flow rate was integrated over four limbs and averaged. An 8.2 foot tide was used in the numerical model. Therefore, this was linearly scaled to the 5.7 foot mean tide range for use with South Slough in this study. The scaling is accurate if the tide flats are planar.

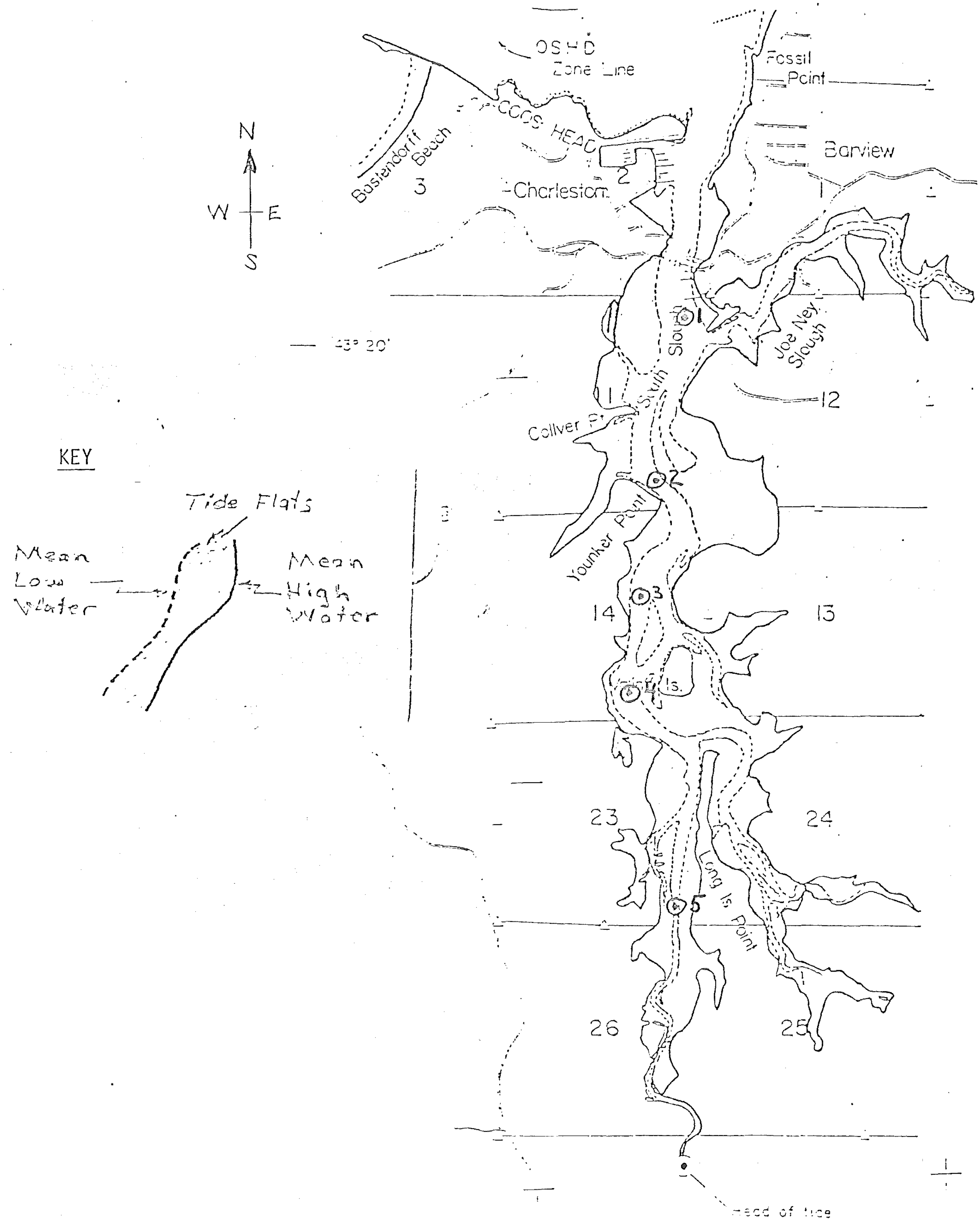


FIGURE 6. SOUTH SLOUGH ESTUARY, INCLUDING STATION LOCATIONS [From State of Oregon Division of State Lands Map (1973)]

TABLE 4. ANALYSIS OF BOYCE (1977) FIELD MEASUREMENTS

Station	HW Depth	LW Depth	$\bar{w}$	x	L	¥$_{LW}$	¥$_{P}$
1	6.6 ft.	0.9 ft.	2750 ft.	4800 ft.	6850 ft.	17.0 (10^6) ft^3	107.4 (10^6) ft^3
2	21.3	15.6	3100	8900	3600	174.1 (10^6)	63.6 (10^6)
3	6.2	0.5	1350	12000	2550	1.7 (10^6)	19.6 (10^6)
4	16.1	10.4	2750	14000	3250	93.0 (10^6)	50.9 (10^6)
5	11.2	5.5	1700	18500	7710	72.1 (10^6)	74.7 (10^6)
						3.58 (10^8)	3.16 (10^8)

Results

The three independent techniques all give similar results for the volume of the tidal prism. These are:

method	tidal prism
steep sides	3.25×10^8 ft^3
field data	3.16×10^8 ft^3
numerical model	3.46×10^8 ft^3

The calculations were based on a volume of the estuary at low water (V_{LW}) of 3.58×10^8 ft^3 (see Table 4).

The good agreement increases the confidence in the estimates. A representative value for tidal prism was selected from the above comparison to be used in flushing calculations. This is

$$V_p = 3.3 \times 10^8 \text{ ft}^3$$

where

V_p = tidal prism volume.

Flushing and Mixing

Anticipated Conditions and Calculation Approach

South Slough is very long with respect to its width. This suggests that there is little lateral variation in salinity. The depth is generally shallow. These conditions, combined with significant winds and tides, suggest that little vertical stratification will be found.

The river inflow is small, so longitudinal gradients should also be small. Furthermore, the length of the bay is small with respect to the tide wave length so there is little phase lag, if friction is neglected.

All of the above suggest that a "well-mixed box model" may be appropriate.

For a well-mixed-box estuary, the mass of a conservative tracer remaining in the basin at the n^{th} tide cycle after an initial injection is given by:

$$\frac{M_n}{M_o} = \left[\frac{1}{V_P/V_{LW} + 1}\right]^n \qquad \text{Eq. 3}$$

in which

M_o = the initial mass of tracer

M_n = the remaining mass of tracer after the nth tidal cycle

n = the number of tidal cycles

V_p = estuary tidal prism volume

V_{LW} = estuary low-water volume.

For South Slough, using the representative values for V_p and V_{LW} obtained above, substitution into Equation 3 gives:

$$\frac{M_n}{M_o} = [0.52]^n \quad .$$

M_n/M_o is plotted against the number of tide cycles, n, in Figure 7.

A technique proposed by Arons and Stommel (1) offers a second method for examining the mixing or longitudinal stratification in an estuary. The downstream advection of a tracer is balanced by its upstream diffusion. Stratification is a function of the flushing number, F, where F is given by

$$F = \frac{\bar{u}h^2}{2BA_o^2WL} \qquad \text{Eq. 4}$$

in which

$\bar{u}$ = mean velocity due to stream inflow

h = mean depth

B = dimensionless numerical constant

A_o = tide amplitude

W = tidal frequency

L = estuary length.

For South Slough this becomes (see Appendix II)

$$F = 0.000129\ Q$$

in which Q in the streamflow in ft^3/second. To apply this we need only select representative values for streamflow. Use of the extreme monthly flows shows the likely range for the flushing number. The maximum and minimum freshwater inflows occur during February and August, respectively. The corresponding average monthly values are:

Q_{Feb} = 232 cfs,

Q_{Aug} = 6 cfs.

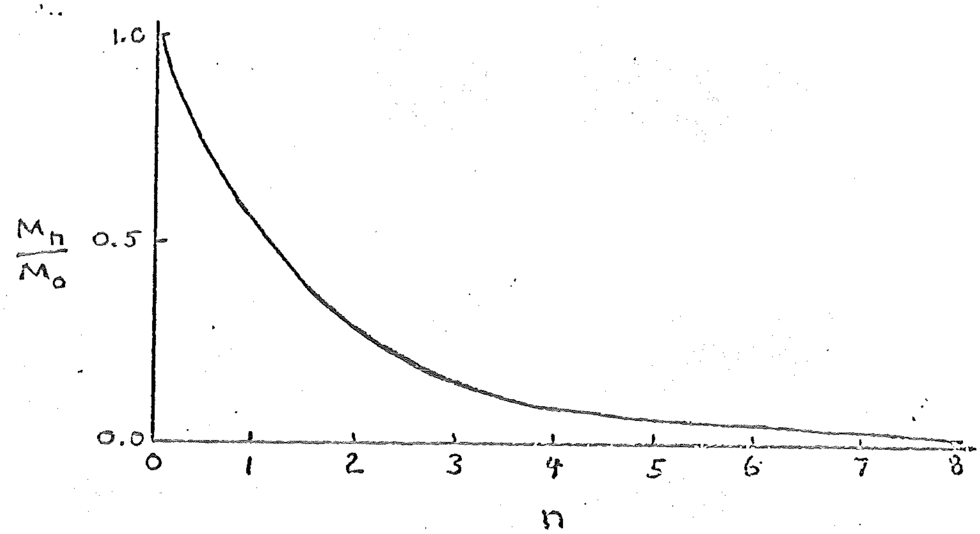


FIGURE 7. RELATIVE CONCENTRATION OF A CONSERVATIVE TRACER AS A FUNCTION OF TIDE CYCLES

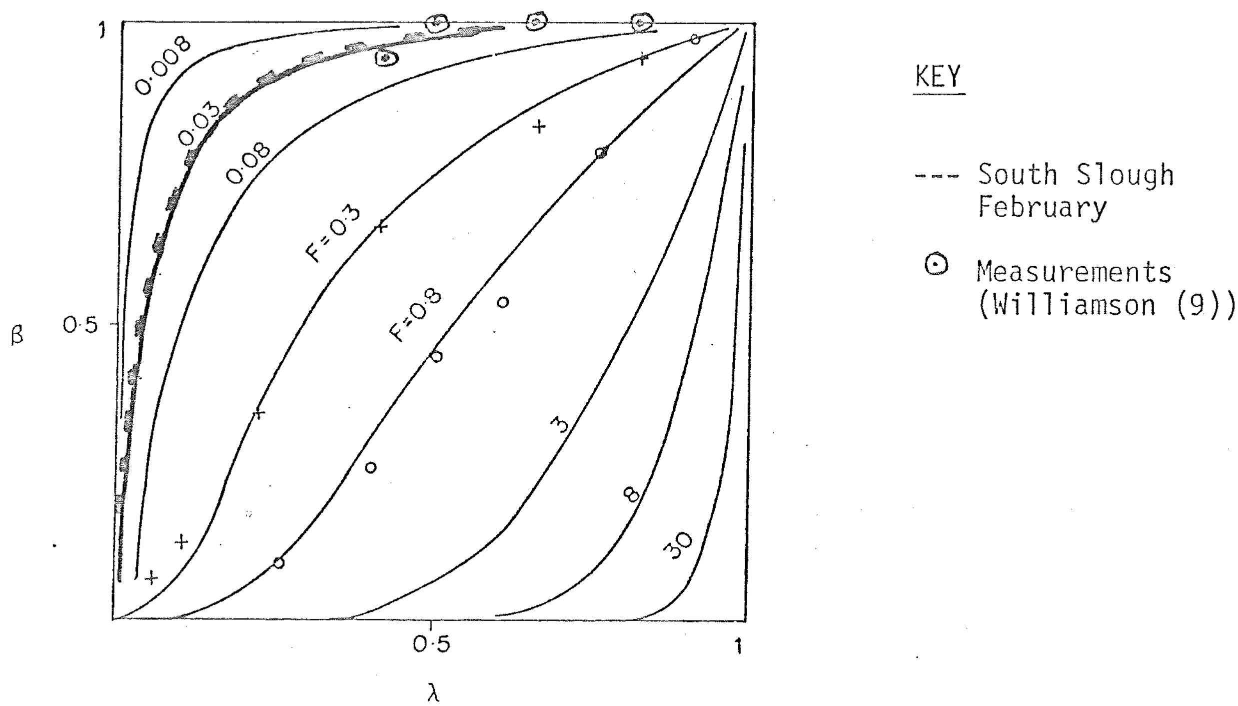


FIGURE 8. LONGITUDINAL RELATIVE CONCENTRATION PROFILES BASED ON THE FLUSHING NUMBER

For these extreme flows the flushing numbers are

$$F_{Feb} = 0.030$$
$$F_{Aug} = 0.001.$$

In Figure 8 the longitudinal relative concentration profile of the tracer is given as a function of the flushing number. The abscissa shows the relative position along the estuary ($\lambda = x/L$) and the ordinate shows the relative salinity compared to that of the ocean (β = local salinity/ocean salinity). South Slough data show that the majority of the estuary has near-ocean salinity. By the shape of the F curves it is inferred that the salinity would only be reduced locally at points of fresh water inflow.

As has been indicated above, the South Slough is well mixed. Based on this assumption, a third method of estimating mixing can be tried, involving fresh water inflow. The concentration of tracer in the estuary is assumed to be proportional to the ratio of the volume of fresh water in the estuary to the volume of sea water. This ratio is a function of the fresh water in flow rate.

For South Slough, this fresh water inflow rate is:

$$\text{Feb.} \text{ -- } \frac{V_{FW}}{V_P} = 3.05\%$$

$$\text{Aug.} \text{ -- } \frac{V_{FW}}{V_P} = 0.09\%$$

The small ratio of fresh water volume to tide prism over the range of encountered conditions indicates that the fresh water flow is of lesser importance to flushing.

The relative concentration of sea water, β is given by the total volume ratios:

$$\beta = \frac{\frac{1}{2}V_P + V_{LW}}{\frac{1}{2}V_P + V_{LW} + V_{FW}} \qquad \text{Eq. 5}$$

in which

V_{FW} = volume of fresh water.

For South Slough.

$$\beta_{Feb} = 98.09\%$$
$$\beta_{Aug} = 99.95\%,$$

The salinity of North Pacific water is around 34 parts per thousand ($^{o}/oo$). Using this and the above information, differences in salinity in the estuary due to fresh water inflow, Δs, would be

$$\Delta s_{Feb} = 0.649 \ ^{o}/oo$$

$$\Delta s_{Aug} = 0.017 \ ^{o}/oo \ .$$

Results

All three of these methods seem to imply the same thing regarding flushing and mixing in South Slough: mixing is fairly thorough and, in fact, the effect of the fresh water inflow is very small.

The box model shows that the fresh water is quickly carried out of the estuary. The mixing length theory of Arons and Stommel shows that the longitudinal gradients of salinity are small. Incidently, this method assumes that all fresh water entered at the estuary head. But for South Slough the inflow occurs at several points, which would seem to imply that stratification is even less than that calculated. Finally, the method of a well-mixed estuary indicates that the fresh water inflow is much less important to flushing than is tidal flow. It is also seen that even at the peak of fresh water runoff the change of salinity is less than one part per thousand.

IV. CONCLUSIONS

Average annual freshwater runoff from South Slough drainage basin was estimated to be 98 cfs. Monthly average values ranged from 6 cfs, in August, to 232 cfs, in February. An annual average precipitation of 54.82 inches resulted in 42.58 equivalent inches of runoff. Evaporation presumably accounts for the remaining 22%. Based on analysis of 20 years of data, the median monthly freshwater flow was estimated to be 70 cfs. Extreme values of monthly runoff were 1 cfs and 445 cfs, respectively.

These hydrologic data and results were used to characterize the degree of mixing and flushing of fresh water in South Slough. Three independent methods were used to estimate the volume of the tidal prism, yielding close agreement and a representative value of 3.3×10^8 ft^3. Mixing was also described in three ways: 1) an exponenential-decay, relative-concentration method, which showed that the concentration of a tracer is halved every tide cycle; 2) a longitudinal stratification, flushing number technique, which yielded extreme values of flushing numbers of $F_{Feb} = 0.030$, $F_{Aug} = 0.001$ (low values indicate little stratification); and 3) the ratio of fresh water volume per tide cycle to tidal prism, which gave extreme values of 3.05% and 0.09% fresh water for February and August, respectively.

Where calculations were made it was assumed that the salinity outside the entrance to South Slough was that of the open waters of the North Pacific. If, however, the salinity is less than oceanic due to freshwater flow into Coos Bay, the salinity in South Slough will drop correspondingly; but the effect of fresh water runoff directly into South Slough should remain small.

In general, it seems from this analysis that mixing is very thorough and that flushing is very quick: the effect of fresh water appears to be minor. In fact, the nutrients, pollutants or sediment associated with the fresh water may be more important to the estuary than the fresh water itself.

V. REFERENCES

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APPENDIX I:

PRECIPITATION AND STREAMFLOW DATA USED

PRECIPITATION DATA FOR "BANDON"

Monthly Precipitation, in Inches												
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1957	5.40	8.42	9.35	2.93	3.29	1.04	0.40	0.51	1.86	7.03	3.21	11.68
1958	8.89	13.34	7.03	5.79	0.99	0.72	0.84	0.21	1.37	3.47	10.73	6.67
1959	15.38	13.09	5.91	0.94	3.13	1.56	0.16	0.14	3.15	2.15	1.08	4.75
1960	7.99	8.14	9.39	5.09	6.82	0.09	0.03	0.24	0.12	E3.55	E13.98	4.96
1961	5.85	15.96	12.48	4.42	6.63	0.71	0.13	0.40	0.76	5.58	12.49	6.79
1962	3.12	8.23	10.64	3.61	2.47	0.86	0.12	1.12	1.16	7.59	9.01	4.51
1963	3.13	5.81	8.48	10.43	7.15	2.24	0.86	0.08	0.86	5.12	12.46	4.93
1964	13.45	2.26	7.71	2.29	1.57	1.47	1.09	0.69	0.74	1.70	10.87	14.81
165	11.83	2.70	1.57	5.75	1.70	0.55	0.13	0.34	0.08	2.18	11.72	13.34
1966	11.14	5.13	10.67	1.47	0.62	0.35	1.02	0.35	2.45	1.72	10.99	8.52
1967	3.91	4.05	8.98	6.80	2.72	0.34	0.00	T	1.19	4.84	5.40	8.53
1968	8.37	7.67	5.85	1.84	2.64	1.66	0.07	4.39	1.63	7.31	9.17	16.91
1969	15.78	7.36	2.89	4.46	1.58	2.71	0.21	0.01	2.27	5.15	4.94	17.24
1970	20.03	4.90	3.24	5.87	1.91	0.59	T	T	1.73	4.67	8.83	12.92
1971	11.19	4.77	8.57	6.49	1.71	2.72	0.25	1.62	4.03	4.15	8.16	14.47
1972	E12.12	7.49	10.90	6.11	1.31	0.41	0.05	1.44	1.30	1.33	8.56	9.66
1973	8.93	3.80	10.61	1.91	1.97	1.78	0.07	0.21	3.71	3.00	23.35	15.12
1974	13.33	9.95	11.23	3.39	1.50	0.77	1.21	0.01	0.17	0.59	7.40	10.61
1975	9.03	9.71	8.26	4.52	2.42	0.66	0.16	2.21	T	8.54	9.98	7.48
1976	6.91	6.90	6.28	2.48	0.72	0.50	0.51	1.97	0.67	1.11	2.54	1.63
1977	2.32	5.10	8.46	1.37	4.45	0.54	0.05	3.88	4.14	3.62	5.74	11.09

PRECIPITATION DATA FOR "NORTH BEND"

Monthly Precipitation, in Inches												
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1957	6.22	6.64	11.30	2.93	3.01	1.18	0.61	0.44	1.81	6.88	2.86	13.10
1958	11.70	14.98	7.06	5.33	1.24	2.42	0.74	0.16	1.52	3.39	10.48	7.31
1959	17.42	18.86	5.63	1.12	3.43	0.68	0.32	0.34	3.79	3.04	1.65	5.01
1960	8.65	8.63	10.25	3.44	6.47	0.10	T	0.45	0.19	3.88	15.56	4.18
1961	7.51	15.26	13.28	4.47	5.74	0.52	0.17	0.63	0.69	5.93	10.68	6.30
1962	2.41	8.24	9.05	2.55	2.00	0.65	0.09	0.57	1.38	6.54	7.36	4.10
1963	3.47	6.84	8.12	9.26	5.26	1.64	0.71	0.05	1.53	3.92	11.66	4.92
1964	12.75	2.63	6.97	3.10	0.91	1.91	0.88	0.70	0.81	1.54	12.88	17.77
1965	13.39	3.25	1.65	4.94	1.77	0.84	0.10	0.50	0.05	2.73	13.48	14.39
1966	12.74	5.65	11.14	1.67	0.72	0.47	1.09	0.15	2.08	2.55	11.00	10.33
1967	13.47	5.50	9.69	6.08	1.84	0.48	T	0.01	1.34	5.12	5.77	0.79
1968	11.77	6.33	5.73	2.06	2.67	1.78	0.13	5.49	2.44	7.13	10.38	18.56
1969	16.87	7.06	2.86	3.43	1.66	3.34	0.11	0.01	3.03	4.90	5.28	14.37
1970	20.23	8.34	2.61	5.78	3.05	0.73	0.02	0.04	1.43	4.22	8.10	11.98
1971	13.57	6.15	9.70	8.06	1.84	3.00	0.08	2.72	5.36	4.50	9.50	15.00
1972	9.90	6.92	10.61	7.73	1.13	0.87	0.14	1.10	1.82	1.14	5.85	11.91
1973	7.92	3.84	7.72	1.91	1.65	1.43	T	0.38	3.32	3.12	22.69	16.10
1974	11.63	10.33	12.58	2.91	2.07	0.56	0.92	T	0.17	1.24	8.67	11.76
1975	8.22	9.75	8.12	6.16	2.92	0.47	0.07	1.89	T	9.22	10.72	6.80
1976	6.73	7.39	5.84	2.88	0.76	0.29	0.79	2.12	0.76	1.61	2.55	1.80
1977	1.85	4.65	8.26	1.28	4.51	0.69	0.04	2.13	3.38	3.55	11.30	12.60

PRECIPITATION DATA FOR "SITKUM"

	Monthly Precipitation, in Inches											
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	8.20	13.51	14.07	6.61	10.25	0.11	0.01	1.75	0.56	4.29	16.42	4.81
1961	6.03	20.94	18.70	4.17	5.64	0.71	0.20	0.22	1.59	9.03	18.25	E9.03
1962	3.42	9.48	11.34	4.63	2.35	0.97	0.02	1.34	1.67	9.88	12.44	4.27
1963	3.52	8.95	11.28	11.84	8.00	4.35	0.88	0.07	3.33	4.44	15.88	6.50
1964	21.42	3.74	11.78	3.58	2.87	2.32	0.81	0.91	1.26	1.50	14.46	E 21.22
1965	—	—	—	—	E1.77	1.17	0.64	0.76	0.02	3.77	9.69	11.98
1966	15.37	6.67	12.34	2.16	0.63	0.84	1.52	0.43	1.67	6.74	14.82	13.21
1967	14.95	4.41	10.31	8.44	2.87	1.20	0.00	0.00	1.54	6.95	5.65	12.12
1968	12.62	9.29	9.65	3.16	4.38	1.51	0.49	5.07	2.77	8.76	14.54	E19.53
1969	21.73	7.59	5.56	5.64	—	—	—	—	—	—	—	—

PRECIPITATION DATA FOR "DORA 2W"

	Monthly Precipitation, in Inches											
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1969	NA*	NA	NA	NA	NA	2.99	0.01	T#	3.27	NA	3.46	13.49
1970	16.87	4.26	3.52	6.16	3.46	0.79	0.05	0.18	1.57	4.10	7.80	11.66
1971	13.25	4.64	10.49	6.26	2.37	2.56	0.03	1.64	4.71	3.50	12.35	14.17
1972	14.48	8.03	10.81	7.17	1.62	0.35	0.09	0.82	1.99	E1.73$	6.71	9.75
1973	8.75	3.22	8.35	2.59	1.43	1.35	0.05	0.48	4.52	3.46	24.47	13.62
1974	11.60	11.59	12.18	4.56	2.06	1.36	0.69	0.00	0.10	1.82	6.72	11.11
1975	10.42	11.30	8.93	5.53	3.25	0.43	0.19	2.53	0.01	9.47	E9.94	9.02
1976	10.85	7.05	E5.87	3.26	1.37	0.61	0.40	2.55	1.18	2.23	1.13	1.65
1977	2.08	5.52	8.83	1.86	5.99	0.53	0.20	2.62	3.31	3.04	13.85	12.56

* NA = not available   # T = trace $ E = estimated

STREAMFLOW DATA FOR

"NORTH FORK COQUILLE RIVER NEAR FAIRVIEW"

Monthly Average Instantaneous Streamflow, in CFS												
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1963	–	–	–	–	–	–	–	–	–	35.2	775	368
1964	1123	355	550	153	127	54.8	22.9	15.1	10.8	13.1	390	1530
1965	1142	323	160	226	103	41.0	18.3	8.71	5.16	13.6	144	516
1966	963	398	776	136	42.3	20.0	13.7	3.82	8.60	32.9	464	620
1967	866	493	446	410	170	43.6	12.9	4.98	3.90	60.9	99.4	511
1968	429	782	336	137	77.0	47.6	14.3	24.2	31.5	109	488	1269
1969	873	894	272	129	67.4	52.6	31.2	10.7	10.2	91.8	165	673
1970	1331	405	203	254	223	39.8	13.6	4.84	8.60	33.8	402	732
1971	1155	420	785	573	114	78.2	33.0	14.6	60.0	71.3	605	1228
1972	1105	503	832	312	102	34.5	11.7	6.70	7.91	9.28	111	600
1973	501	205	408	223	59.1	29.1	10.6	5.35	38.7	26.9	1121	1070
1974	916	792	987	400	128	70.0	22.1	7.59	5.10	4.92	74.9	491
1975	745	815	630	332	248	42.2	16.0	11.6	6.97	98.6	391	732
1976	860	402	372	246	78.9	33.6	13.6	14.9	6.96	–	–	–

STREAMFLOW DATA FOR

"WEST FORK MILLICOMA RIVER NEAR ALLEGHANY"

Monthly Average Instantaneous Streamflow, in CFS												
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1957	247	576	618	193	68.7	28.6	10.3	7.56	6.87	50.7	111	994
1958	554	853	247	370	46.3	23.2	9.42	3.43	6.10	11.4	612	316
1959	928	608	310	128	111	35.9	12.1	4.79	68.1	157	118	191
1960	352	716	566	294	358	53.6	12.5	6.59	6.53	31.0	743	229
1961	306	1152	809	215	193	32.6	11.1	4.52	7.64	93.6	424	627
1962	185	418	612	146	106	31.5	10.4	7.18	11.8	144	422	306
1963	101	569	359	571	292	34.0	21.1	9.11	19.0	49.5	679	289
1964	948	238	489	126	91.4	80.2	24.3	16.3	7.88	9.48	374	1357
1965	956	273	133	205	82.2	26.2	9.68	4.48	2.50	9.76	200	472
1966	909	305	617	92.2	26.8	16.1	11.2	3.56	7.38	36.6	332	570
1967	748	344	335	267	90.5	28.4	9.83	3.93	3.11	91.1	138	457
1968	393	623	239	97.0	65.6	70.7	13.2	57.1	48.2	177	504	1016
1969	652	612	245	124	61.4	84.3	35.7	9.27	19.8	115	169	698
1970	1063	361	144	191	154	26.9	9.03	3.52	10.8	51.4	384	596
1971	898	284	612	436	75.2	82.5	29.1	15.2	97.7	102	574	844
1972	955	527	635	676	76.2	22.5	8.07	3.77	7.79	8.04	114	611
1973	419	137	302	141	39.2	27.2	10.2	6.15	41.0	31.5	1065	916
1974	818	600	671	278	87.0	59.9	20.2	6.08	3.16	4.18	137	553
1975	573	691	529	277	173	25.9	12.5	12.3	7.99	181	476	593
1976	714	468	313	159	55.4	21.3	11.1	9.80	2.86	7.25	39.6	34.1
1977	52.8	143	450	83.1	93.7	41.2	11.4	15.0	37.1	–	–	–

DATA PRECIP, EST (inches) STATION S. Slough Basin

COMMENTS

YR \ MO	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	5.26	6.83	9.34	2.65	2.85	1.00	0.46	0.43	1.66	6.30	2.75	11.21
58	9.30	12.81	6.38	5.04	1.01	0.78	0.72	0.17	1.31	3.11	9.61	6.33
59	14.84	14.43	5.23	0.93	2.97	1.02	0.22	0.22	3.14	2.34	1.23	4.42
60	7.53	7.59	8.89	3.87	6.02	0.09	0.01	0.31	0.14	3.36	13.36	4.14
61	7.42	14.14	11.66	4.02	5.61	0.56	0.14	0.46	0.66	5.21	10.50	5.93
62	2.51	7.46	8.93	2.80	2.83	0.69	0.10	0.77	1.15	6.87	7.42	3.90
63	2.99	5.72	7.52	8.92	5.63	1.76	0.71	0.06	1.08	4.10	10.93	4.46
64	11.87	2.21	6.65	2.43	1.13	1.53	0.89	0.63	0.70	1.47	10.74	14.73
65	11.41	2.69	1.46	4.85	1.57	0.63	0.10	0.38	0.06	2.22	11.40	12.55
66	10.80	4.88	3.87	1.42	0.61	0.37	0.95	0.23	2.05	1.93	9.96	8.52
67	12.40	4.31	8.45	5.84	2.07	0.37	0.01	0.01	1.14	4.51	5.05	8.73
68	7.09	6.35	5.24	1.76	2.40	1.56	0.09	4.47	1.84	6.54	5.54	16.05
69	14.78	6.53	2.60	3.59	1.47	2.73	0.15	0.01	2.39	4.55	4.62	12.95
70	18.23	5.97	2.65	5.28	2.24	0.60	0.01	0.02	1.43	4.03	7.67	11.28
71	4.19	4.93	8.26	6.58	3.80	2.59	0.15	1.96	4.24	3.91	7.99	13.34
72	9.99	6.53	9.74	6.25	1.11	0.58	0.09	1.15	1.41	1.12	6.54	9.75
73	7.64	3.46	8.32	1.73	1.64	1.46	0.03	0.27	3.19	2.77	20.85	14.13
74	11.31	9.18	10.77	2.86	1.61	0.60	0.97	0.01	0.15	0.82	7.27	10.12
75	7.82	5.81	7.42	4.87	2.41	0.51	0.10	1.86	0.21	8.04	9.37	6.45
76	6.18	6.47	5.49	2.42	0.67	0.36	0.59	1.85	0.65	1.23	2.30	1.55
77	1.89	4.42	7.57	1.20	4.06	0.56	0.04	2.73	3.41	3.25	9.52	10.12
	9.26	6.94	7.26	3.77	2.52	0.97	0.31	0.86	1.50	3.70	8.65	9.08
			P_{AA} = 54.82									

DATA EST FLOW (cfs) STATION S. Slough

COMMENTS

YR \ MO	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	115	232	238	87	59	31	15	7	10	21	39	240
58	214	394	169	140	24	29	15	6	9	7	136	127
59	356	436	142	40	61	31	14	7	12	4	18	85
60	170	254	227	115	113	16	11	7	5	8	188	79
61	168	428	290	119	106	26	13	7	7	16	148	118
62	52	250	228	91	44	28	13	8	9	24	105	73
63	62	200	196	214	106	36	15	5	9	11	154	85
64	279	90	176	82	27	34	15	8	8	2	152	326
65	268	106	45	136	36	27	13	7	4	4	161	273
66	352	175	250	55	16	23	16	7	11	3	141	177
67	243	158	217	156	45	23	11	4	9	13	72	181
68	209	219	142	64	51	35	13	10	10	23	125	359
69	354	224	76	109	34	40	13	4	11	13	65	283
70	445	208	77	145	48	27	11	5	9	11	108	242
71	262	177	213	171	76	40	13	9	13	10	113	292
72	232	224	247	165	26	26	13	8	9	1	92	205
73	173	131	214	63	37	34	12	7	12	6	293	312
74	265	298	270	92	36	27	16	4	5	1	103	214
75	177	288	194	136	51	26	13	9	2	31	132	129
76	137	222	148	81	17	23	15	9	7	2	33	26
77	38	161	197	48	80	26	12	9	12	8	134	214
21 yr Mean →	215	232	188	110	52	28	14	6	9	10	120	192
	/											
depth of water over basin (inches) →	8.00	7.80	6.99	3.96	1.93	1.01	0.52	.22	0.32	0.37	4.32	7.14
Annual TOTAL Depth = 42.58"												

APPENDIX II: TIDAL PRISM AND FLUSHING CALCULATIONS

A. Tidal Prism

(1) Steep walled estuary

$$V_P = (\text{Area})\ (\text{Tide Range})$$
$$= (2.04\ mi^2)\ (5280\ ft/mi)^2\ (5.7\ ft)$$
$$= 3.24 \times 10^8\ ft^3$$

(2) Field measurements

See Table 4

$$V_P = 3.16 \times 10^8\ ft^3$$
$$V_{LW} = 3.58 \times 10^8\ ft^3$$

B. Flushing

(1) Box model

$$\frac{\text{estuary length}}{\text{tide wave length}} = \frac{L}{\sqrt{gh}\ T} = \frac{23960\ ft}{[6\ ft\ (32.2\ ft/sec^2)]^{1/2}\ (12.2\ hrs)\ (3600\ \frac{sec}{hr})}$$

$$\frac{L}{L_T} = 0.039$$

$$\frac{M_n}{M_o} = \left[\frac{1}{\frac{V_P}{V_{LW}} + 1}\right]^n = \left[\frac{1}{\frac{3.3 \times 10^8\ ft^3}{3.58 \times 10^8\ ft^3} + 1}\right]^n$$

$$\frac{M_n}{M_o} = [0.52]^n$$

(2) mixing length method (Arons and Stommel (1))

$$F = \frac{\bar{u}\ h^2}{2BA_o^2WL}$$

in which

$\bar{u}$ = mean velocity due to stream inflow

h = mean depth

B = dimensionless numerical constant (a value of 0.36 was determined from field data taken by Williamson (9))

A_o = tide amplitude

W = tidal frequency

L = estuary length.

By continuity,

$$\bar{u} = \frac{Q}{Area} = \frac{Q}{h\bar{w}}$$

in which

$\bar{w}$ = mean width of estuary

then $F = \dfrac{Qh}{2BA_o^2 W \bar{w} L}$

$$= \frac{Q\ (6\ ft)}{2(1)\left(\frac{5.7\ ft}{2}\right)^2 \left[\frac{2\ \pi}{(12.2\ hrs)\ (3600\ \frac{sec}{hr})}\right]\ (2300\ ft)\ (23960\ ft)}$$

$F = 0.000129\ Q$

(3) well mixed model

Feb. $\dfrac{V_{FW}}{V_P} = \dfrac{Q\ (duration)}{3.3 \times 10^8\ ft^3} = \dfrac{(232\ ft^3/sec)\ (12.2\ hrs)\ (3600\ \frac{sec}{hr})}{3.3 \times 10^8\ ft^3}$

$= 3.05\%$

Aug. $\dfrac{V_{FW}}{V_P} = \dfrac{Q\ (duration)}{3.3 \times 10^8\ ft^3} = \dfrac{(6\ ft^3/sec)\ (12.2\ hrs)\ (3600\ \frac{sec}{hr})}{3.3 \times 10^8\ ft^3}$

$= 0.09\%$