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Determination of Fresh-Water Discharge for an Oregon Estuary

Interest in coastal estuaries in the Pacific Northwest has mounted in recent years as conflicting interests, such as recreation and industry, have contended for their use. Increasingly heavy use is being made of these natural resources for waste receptacles. The capacity of an estuary to cope with discharged wastes is intimately tied to its circulation pattern. Circulation, in turn, depends on the fresh-water discharge, the physical dimensions of the estuary, and the amount of dissipated tidal energy available to mix the waters in the estuary (Blanton, 1969; Burt and McAlister, 1959). Fresh-water discharge must be known to calculate either the effectiveness of tidal energy dissipation or the distribution of a pollutant in an estuary, but one is indeed fortunate when sufficient measurements of runoff are available. One must often work in a rather complicated drainage network where only a small fraction of the network is monitored for rainfall and streamflow. This paper describes a method to estimate fresh-water discharge where measurements of precipitation and fresh-water discharge from a limited region must be extrapolated to a much larger region.

The Role of Fresh-Water Discharge in Circulation of Estuaries

The estuaries of Oregon were classified by Burt and McAlister (1959) into three groups, depending on the extent of vertical homogeneity in the estuary. The classification into which a given estuary fits depends on the amount of tidal energy available (which is relatively constant throughout the year) and the amount of fresh-water discharge (which fluctuates seasonally). At times of low discharge, tidal energy can vertically mix the fresh water with sea water so that little change in salinity occurs from top to bottom. As fresh-water discharge increases, greater tidal energy is required to mix the incoming fresh water and ocean water. Finally a point is reached where sufficient dissipated energy is not available to produce vertically homogeneous conditions, and either partially mixed or two-layered conditions prevail.

The amount of fresh-water discharge also affects the flushing time of the estuary, which is the average time required for a particle of fresh water or suspended matter to be moved out of the estuary. During periods of high discharge the flushing time

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will be short and pollutants in the estuary will be moved rapidly out to sea, but during periods of low discharge pollutants may reside in the estuary for a longer time.

The seasonal nature of rainfall in Oregon imposes variations in streamflow. In months of heavy rainfall in winter and spring, large amounts of water flow into the heads of the major Oregon estuaries, but in the summer and fall the runoff is low. For example, our calculations have shown that as much as 100,000 cfs flows into Coos Bay from the Millicoma and Coos rivers at maximum and less than 100 cfs at minimum. These extremes of fresh-water runoff, although modified in some cases by dams upstream from an estuary (Lockett, 1963), illustrate the seasonal variation to which all Oregon estuaries are subject.

The Problem

Runoff of fresh water from most small coastal streams into their estuaries is not well known. The standard method for determining stream discharge into an estuary is by stream-stage measurements because of the relationship between stream stage and flow rate. Small coastal streams, however, usually lack sufficient gauging stations. Furthermore, stream stages cannot be simply related to flow rate in the unsteady flow of tidally influenced streams. Unsteady flows can be analyzed only by complex simulations (Baltzer and Lai, 1968). Consequently, determination of stream discharge in small coastal streams must be accomplished by some indirect means.

The indirect determination of the fresh-water runoff into an estuary is complicated by the dendritic patterns of streams in the watershed, by the paucity of river gauging stations and weather stations, and by the uneven distribution of rainfall over the watershed. In particular, uneven distribution of rainfall creates a problem in mountainous regions such as in Oregon's Coastal Range where moist air masses lose much of their water as they rise over the mountains.

In addition to utilizing stream-discharge and rainfall data, the water-bearing capacity of the soil and the evapotranspiration rate must be considered in a calculation of stream discharge (Thornthwaite and Mather, 1955). The truly complicated interactions of these factors can be appreciated by consulting a good text on hydrology (*e.g.,* Linsley *et al.,* 1949).

The Coos Bay estuary, like most estuarine systems in Oregon, does not have a sufficient network of rainfall gauges and stream-discharge gauges for direct measurement of fresh-water discharge. Only one river in the entire drainage area is gauged, and rainfall is measured in only two locations. We therefore devised a systematic procedure to calculate stream discharge into Coos Bay estuary from limited data.

Calculation of Stream Discharge

Calculation of stream discharge by our method requires only the watershed area, rainfall data from representative stations, and at least one stream gauge to estimate the fraction of rainfall which is carried away in streams.

The watershed area of the Coos Bay drainage system (Fig. 1) was determined from topographic maps from the U.S. Geological Survey. The watershed area was divided into two areas: a lowlands area with runoff based on the rainfall at North Bend and a highlands area with runoff based on the rainfall at Allegany (Fig. 1). Rainfall records of the U.S. Weather Bureau were examined for North Bend and Allegany for the years

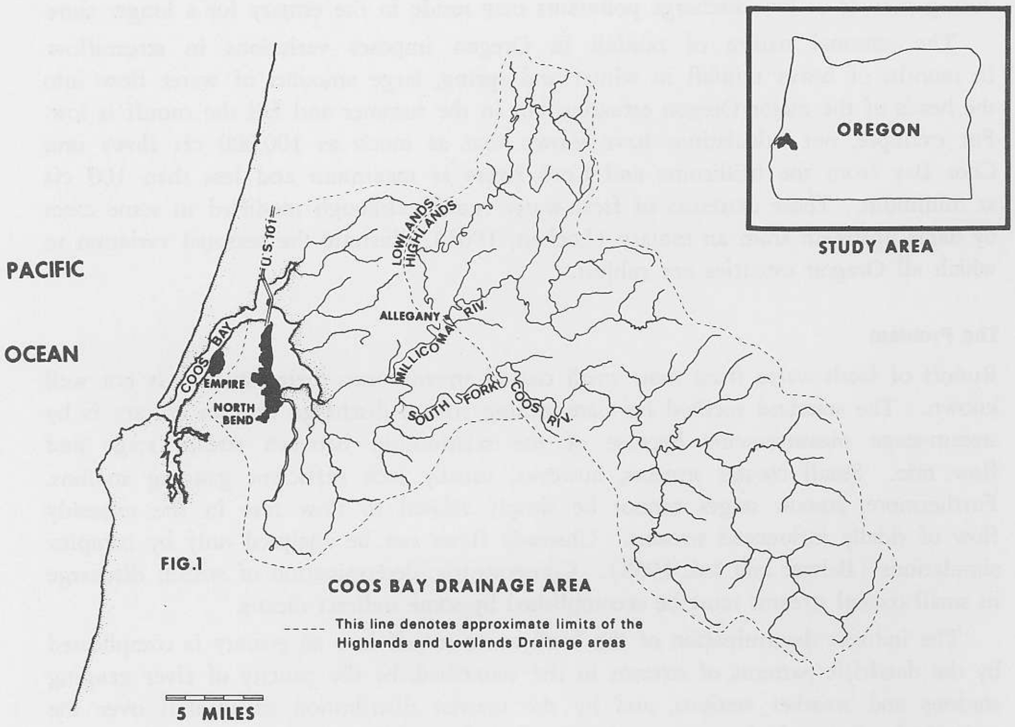

Figure 1. Coos Bay drainage area, modified from U.S.G.S. Maps of Coos Bay and Roseburg quadrangles.

1955 through 1961. The mean annual precipitation over the seven years at Allegany exceeded that at North Bend by 24.7 inches. We are confident that there is additional rainfall in the upper regions of the highlands area. Thus, 10 inches were added to the recorded annual rainfall at Allegany to compensate for the heavier rainfall occurring in the mountainous region upstream from Allegany. This increment may be set rather arbitrarily because it increases the total rainfall by only 10 per cent and in the subsequent calculations it is nearly cancelled out. Its only effect is to increase slightly the weight of highlands rainfall. The effect of the 10-inch increment on the calculated runoff factor will be discussed below.

The West Fork of the Millicoma is the only gauged river in the entire Coos Bay drainage area. The gauge is located just upstream from Allegany. The stream-gauge data plus the precipitation data at Allegany were used to estimate the percentage of rainfall that runs off through the West Fork of the Millicoma. This estimation was assumed valid for the entire drainage area for Coos Bay. The calculation used was

$$\text{Runoff factor (expressed as a percentage of local rainfall)} = \frac{\text{Runoff through gauging station}}{\text{Rainfall at Allegany} + 10''} \times 100\%$$

Runoff and rainfall may be expressed in inches.

Percentages were tabulated for the years 1955 to 1959. For this period an average 83 per cent of the rainfall was discharged as runoff. The evapotranspiration is included in the 17 per cent of the rainfall which does not appear as runoff. In this empirical approach evapotranspiration is thus accounted for without involved calculations.

In view of the uncertainties in the actual distribution of rainfall in the highlands, the runoff factor is actually better to no more than one decimal place or 0.8. If we omit the 10-inch increment to rainfall at Allegany, the runoff factor is 0.9. If we add as much as 30 inches to the recorded rainfall at Allegany, the factor is reduced to only 0.7.

The annual runoff for each drainage area was calculated and summed. The total was used to estimate the annual runoff under the U.S. 101 Bridge over Coos Bay. The runoff for each area was calculated as

$$\begin{array}{lll} \text{Annual runoff} = & \text{Rainfall} \times & \text{Surface area} \times 0.8 \\ (\text{ft}^3/\text{year}) & (\text{ft}/\text{year}) & (\text{ft}^2) \end{array}$$

Runoff data for specific days were needed for comparison with salinity data at the U.S. 101 Bridge. Based on mean flow rates in the river and in the upper reaches of Coos Bay, it was estimated that it would take 24 to 48 hours for the runoff at the Allegany gauge to appear at the U.S. 101 Bridge in Coos Bay. An average was taken of the gauge readings two days prior to the day being analyzed. This average was used for the "daily gauge discharge," thus

$$\text{Daily freshwater discharge} =$$

$$\text{Annual runoff} \times \frac{\text{Daily gauge discharge } (\text{ft}^3/\text{sec})}{\text{Annual gauge discharge } (\text{ft}^3/\text{year})}$$

We have assumed that the fluctuations in daily gauge discharge at Allegany are representative of fluctuations that would be found over the entire Coos Bay system.

Table 1 summarizes the runoff figures obtained by this method for 12 dates of interest. The effects of the dry summers and wet winters are apparent.

Differences between bottom and surface salinity at the U.S. 101 Bridge were averaged over two tidal cycles from data published by McAlister and Blanton (1963). Large salinity differences indicating partial mixing were clearly correlated with high runoff.

TABLE 1. Fresh-water runoff under U.S. 101 Bridge

Date	*Runoff* *(feet^3/sec)*
21-22 June 1960	388
12-13 July 1960	164
16-17 August 1960	58
20-21 Sept. 1960	66
22-23 Oct. 1960	76
20-21 Dec. 1960	6720
28-29 Jan. 1961	865
25-26 Mar. 1961	5380
20-21 May 1961	1220
18-20 June 1961	170
20-21 July 1961	94
2- 3 August 1961	69

Discussion

We have compared our calculation method of stream discharge (the stream-gauge method) with a method based on a calculation of the water balance by Thornthwaite and Mather (1955) (Fig. 2). Both curves have the same general shape as the salinity-difference curve. It is apparent, however, that the water-balance method which is based on monthly averages of precipitation and temperature filters out the abrupt changes indicated by the daily data of streamflow and precipitation. The stream-gauge method is particularly responsive to the day-by-day changes because only two-day averages of streamflow are used in the calculation. The water balance could be made more responsive to daily changes in precipitation and runoff but only at the expense of considerably more calculation.

Because the stratification of the estuary undoubtedly responds to daily fluctuations in runoff, the stream-gauge method is advantageous for use in estuarine hydrography. For example, the runoff in the summer calculated by the water-balance method was consistently higher than that calculated by the stream-gauge method. This discrepancy

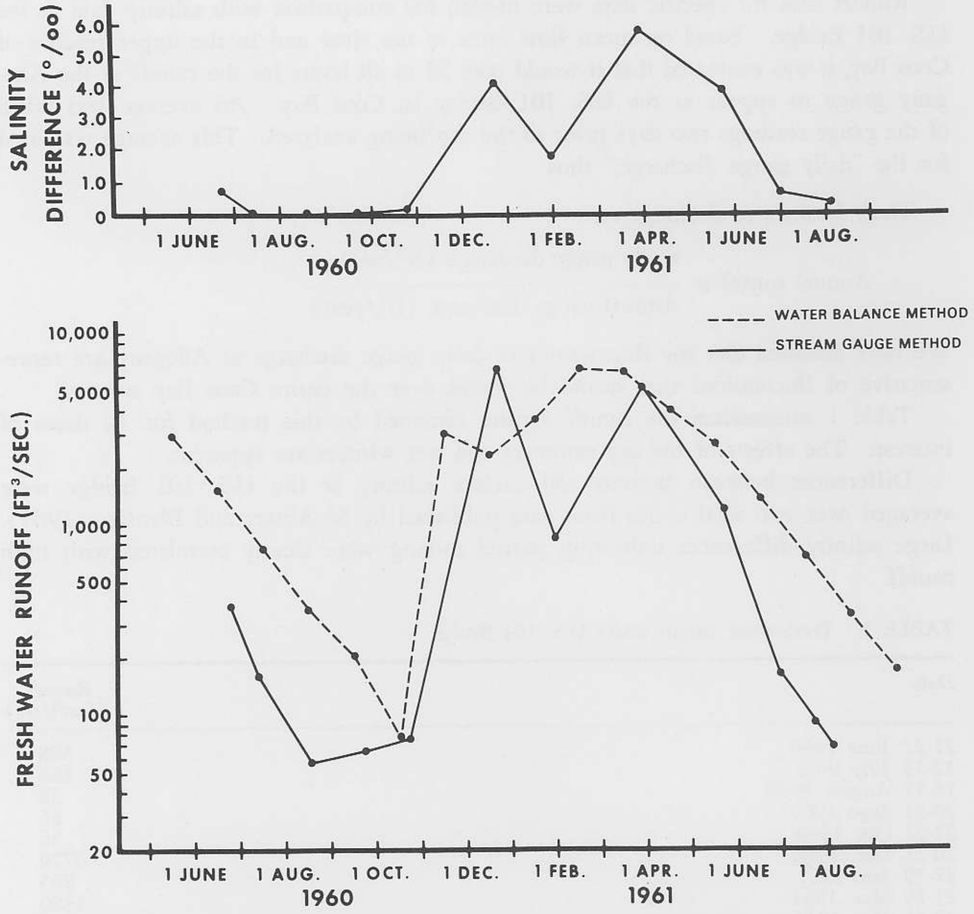

Figure 2. Salinity difference between surface and bottom at U.S. 101 Bridge (upper graph) and fresh-water runoff into Coos Bay (lower graph). On the lower graph, the points for the stream-gauge method represent two-day averages; the points for the water-balance method represent monthly averages.

occurs because the water-balance method gives an average flow whereas the stream-gauge method gives a daily flow. Many of our sampling days occurred during periods of lower than average rainfall, resulting in lower runoff than would be typical of that month. Extremes during a month are thus masked in the water-balance method.

Conclusions and Summary

Responsiveness to fluctuating meteorological conditions makes runoff calculations based on stream-gauge data particularly useful in studies of estuarine hydrography. Its real advantage, however, is that its application is simple and straightforward and can be applied in areas where data are scarce. The stream-gauge method compares favorably with the more sophisticated water-balance method.

The method described here is no panacea. It is certainly no substitute for other established techniques in localities where there is coverage of precipitation and runoff measurements sufficiently adequate to represent hydrological conditions throughout the drainage network. For Coos Bay, the hydrological data have been stretched to the limit by extrapolating data from one or two points over the entire drainage basin. This procedure implicitly assumes that conditions at Allegany and North Bend are representative of the entire Coos Bay drainage basin. Obviously, the assumption becomes more valid if more data points are available, but for this case as well as most cases for the Pacific Northwest coast, we are fortunate if we have one or two points.

The test of this method on one series of salinity data is not as good a test as one would like, although the independent check using the water-balance method (Fig. 2) gives the stream-gauge method a good degree of credibility. Hopefully, the method will be evaluated for more estuaries as suitable salinity data become available.

Knowledge of the magnitude and fluctuations of fresh-water discharge is indispensable when considering mixing and circulation patterns. The estimates of discharge assume even greater importance when assessing the possible effects of diversion projects or dams which may alter the fresh-water supply to an estuary. The method described here offers rough estimates of fresh-water discharge into estuaries in areas where limited measurements of streamflow and rainfall are available. The input data for such a study are usually readily available through the U.S. Geological Survey streamflow records, and U.S. Weather Bureau (ESSA) precipitation records.

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