Calculation of runoff to an estuary. Ria de Vigo*

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SUMMARY: Runoff that reaches an estuary was estimated as a function of daily rainfall in the drainage basin when the daily measurements of river flows are not available. This method is applied to the rivers flowing into the Ría de Vigo and compared with the River Deza that reaches the Ría de Arosa where the daily flow and rainfall are known. The optimum value of the retention coefficient (k = 0.75) is calculated. The distribution of flow calculated from the equation obtained and the surface salinity of the Ría de Vigo were related and a significant correlation (0.69) obtained. The values of estimated flows obtained by the proposed method are enough reliable to be used in studies of estuarine residual currents using the box model.

Key words: Runoff, drainage basin, flows, rivers, Ría de Vigo (NW of Spain).

RESUMEN: CÁLCULO DE APORTES DE AGUA DULCE A UN ESTUARIO. RÍA DE VIGO. — Se hace el cálculo de los aportes de agua dulce que recibe un estuario en función de la precipitación diaria de la cuenca hidrográfica cuando no se dispone de medidas diarias de los caudales de los ríos que vierten en él. Se aplica este método a los ríos que vierten en la ría de Vigo comparándolos con el río Deza tributario a la ría de Arosa del que se conocen diariamente la precipitación y el caudal, y se calcula el valor óptimo del coeficiente de retención (k = 0.75). Se relacionan las distribuciones de los caudales estimados a partir de la ecuación obtenida y las salinidades superficiales de la ría de Vigo obteniéndose una apreciable correlación (0,69). Los valores de los caudales estimados aplicando el método propuesto, son lo suficientemente fiables para ser utilizados en estudios de corrientes residuales estuáricas empleando el modelo de cajas.

Palabras clave: Aportes, cuenca hidrográfica, caudales, ríos, Ría de Vigo (NO de España).

INTRODUCTION

One of the methods for the study of water bodies fluxes and the budgets of biogenic elements in partially mixed estuaries, is the box model proposed by PRITCHARD (1969). This model was applied in the Rías Bajas of Galicia by OTTO (1975), FRAGA and MARGALEF (1979), PREGO (1988), and PREGO *et al.* (1990). In it the runoff is used as a "piston" moving the whole system according to the following equation:

$$Q_F = Q_R {*} S_S \,/\, (S_F - S_S)$$

where the entering oceanic water (Q_F) is a function of river flow (Q_R) and of the salinities of the water entering in the lower layer (S_F) and water leaving in the upper layer (S_S).

To solve this equation, once the salinities are known, it is necessary to obtain the flow of fresh water that reaches the estuary. The aim of this paper is to estimate this flow as a function of the daily rainfall on the drainage basin when the daily measurements of river flows are not available.

There are a few studies of the volume of fresh water input to the Rías Bajas (OTTO, 1975; LÓPEZ-JURADO, 1985), but they refer mainly to monthly or annual variations. These scales are too large when a quantitative study at a smaller scale is attempted.

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MATERIAL AND METHODS

The most direct way to calculate river flow is to obtain the daily measurements at a gaging station in the course of a principal or subsidiary river using Horton's Law (STRAHLER, 1984). Using this law, the estimated flow reaching the sea is obtained by proportionality. This method was used recently by ROSÓN *et al.* (1991) for flow calculations in the Ria de Arosa.

When this method cannot be used due to lack of daily gauge heights, the river flows reaching an estuary can be estimated using the drainage as a function of the rainfall on the drainage basin, in agreement with the following normalized geometrical progression:

$$A = (1-k)/(k-k^{365+1}) * \sum_{n=1}^{365} P_n * k^n \qquad \text{(I)}$$

This equation shows the sum of rainfall corresponding to the 365 days prior to the day under consideration, taking this day as n = 0, to obtain a complete annual cycle. The factor appearing in the equation, is the independent term of the geometrical succession that normalizes the sum. Drainage is expressed in $l \cdot m^{-2} \cdot d^{-1}$ (A), rainfall collected during the day n, in $l \cdot m^{-1}$, (P_n), the retention coefficient (k) is the proportion of water not discharged to the river with regard to rainfall the previous day in the drainage basin. When k trends to 1, the sum represents the average of 365 previous days, if k trends to zero, the drainage is given by the rainfall of the day before.

To apply this method to the Ría de Vigo, flow measurements of the rivers Oitabén, Verdugo, Redondela and Ullo, tributaries of Ría de Vigo, were made between July 1987 and December 1988 every 15 days at the gauging stations shown in figure 1. The stations were situated at bridges and the measurements were made using "Detectronic" current meters with ultrasonic detection. The gauge heights were measured. Then, measurements of currents at 20 % and 80 % of the heights at 6 points along the bridge were made. All these data have were integrated to obtain the corresponding flows.

A rain station is located in Fornelos de Montes, headwaters of the River Oitabén, and always gives the highest rainfall values in the whole of Galicia, according to the data of the Boletín del Servicio Meteorológico Nacional. On the other hand, according to figure 2b of PREGO (1988), the rainfall collected at this station is proportional to that at Peinador. Therefore, the rainfall data used in this paper were obtained from the Meteorological Observatory of Peinador Airport between July 1986 and February 1989. These data show better quality and are more reliable and available.

As a check on the model, it was applied to another river where the daily flows and rainfall are known. The flow measurements obtained by the river Deza gauging station no. 552 were used. This River is the biggest tributary of the River Ulla and the mentioned station is located close to the confluence of both. These data, from October 1982 to October 1984, were supplied by the Confederación Hidrográfica del Norte de España. The rainfall from October 1981 to October 1984 were collected by the Meteorological Observatory of Convento de los PP. Franciscanos of Herbón-Padrón.

RESULTS AND DISCUSSION

To determine the k value, we used the rainfall data from July 1986 until February 1989 and the flow data of the rivers Oitabén, Verdugo, Redondela and Ullo tributaries to the Ría de Vigo, between July 1987 and December 1988, measured at the gauge heights shown in the map (Fig. 1). The value of k for the River Deza, tributary to the river Ulla, has been also estimated to check if the model fits applying the data of daily flows and rainfalls. The data used for this river correspond to the period between October 1982 and October 1984, that is not the same period as for the rivers reaching the Ría de Vigo.

Linear correlations were made between the measured flows of the rivers and the drainage calculated with the equation (I), varying the retention coefficient between k = 0.05 and 0.70 at intervals of 0.05 and between k = 0.70 to 0.99 at intervals of 0.01. We have obtained a set of equations with its corresponding correlation coefficients and the k with the highest coefficient was chosen. A river with the behaviour of a torrent will have a low k, whilst a river having a steady discharge will have a high k.

Figure 2 shows the correlation coefficients (r) of each river versus their retention coefficients (k). The values of k, given in table 1, increase as the surface area of the drainage basin become greater. The River Verdugo behaves in a more natural way than the other rivers tributary to the Ría de Vigo because it is not controlled like the Oitabén. On the other hand, the River Redondela shows a strong peak at k = 0.97, due to the influence of the annual average wave, because being a small river it has a longer response to the low-water stage. The River Ullo also shows the

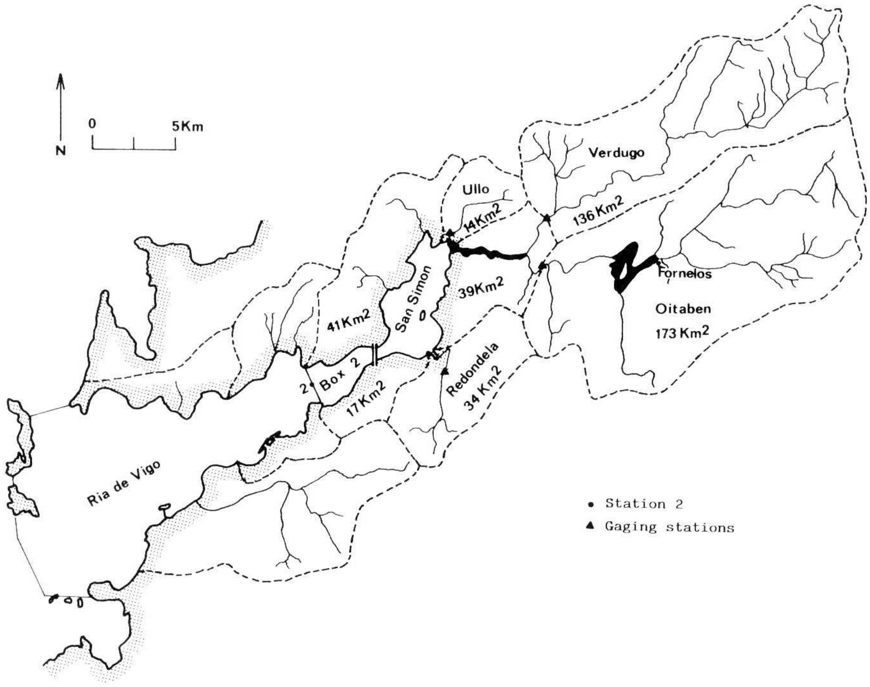

FIG. 1. — Map of Ría de Vigo, showing drainage basins and locations of hydrographic and gauging stations.

TABLE 1. — Retention coefficients and drainage surfaces upstream of gauging stations.

River	*k*	*Drainage basin (km^2)*
Deza	0.82	543
Oitabén	0.79	173
Verdugo	0.75	136
Redondela	0.72	34
Ullo	0.71	14

same peak for the same reason but it is more attenuated.

In relation to the River Deza, using the daily flow data, the model fits and k is higher since the drainage basin is about three times greater that of the River Oitabén. As we can see, the correlation coefficients are low because the rainfall data have been taken at a single point for the whole basin as it was not possible to obtain data at other points.

The k values calculated are close to those given by CHOW (1964), although this author, working with drainage faces bigger than 30 300 km^2, obtains retention constants (k) between 0.85 and 0.98. In order to use the drainage data to calculate the flows of the tributary rivers to the Ría de Vigo, we take a value of $k = 0.75$ corresponding to the River Verdugo due to its most natural behaviour. With this method, and because we have directly measured the river flows, the k value obtained is more reliable than that obtained in a previous paper (PREGO *et al.*, 1990). Figure 2 shows the lag time to discharge 99 % of the water retained in the drainage basin. This lag time for $k = 0.75$ is 16 days. According to SÁIZ *et al.* (1961), the lag time to 99 % flow is 8 days, which corresponds to a retention coefficient of 0.6. This is a good value when average values are used.

The four equations obtained for $k = 0.75$, that relate flows to drainage, are given in table 2. It also shows the correlation coefficients and surface areas of the drainage basin.

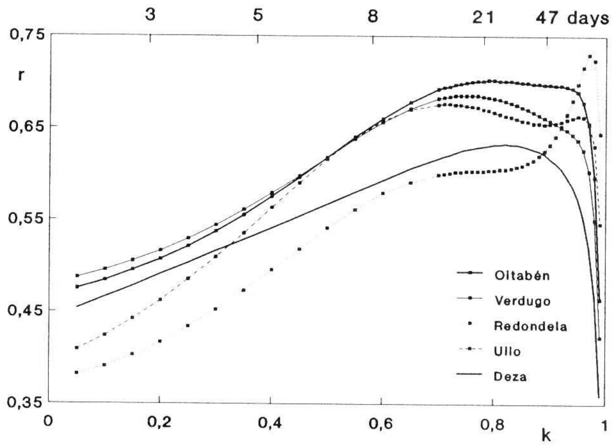

FIG. 2. — Correlation coefficient (r) versus retention coefficient (k) for Oitabén, Verdugo, Redondela, Ullo and Deza rivers. The lag time to 99 % flow of runoff is shown on the upper x-axis.

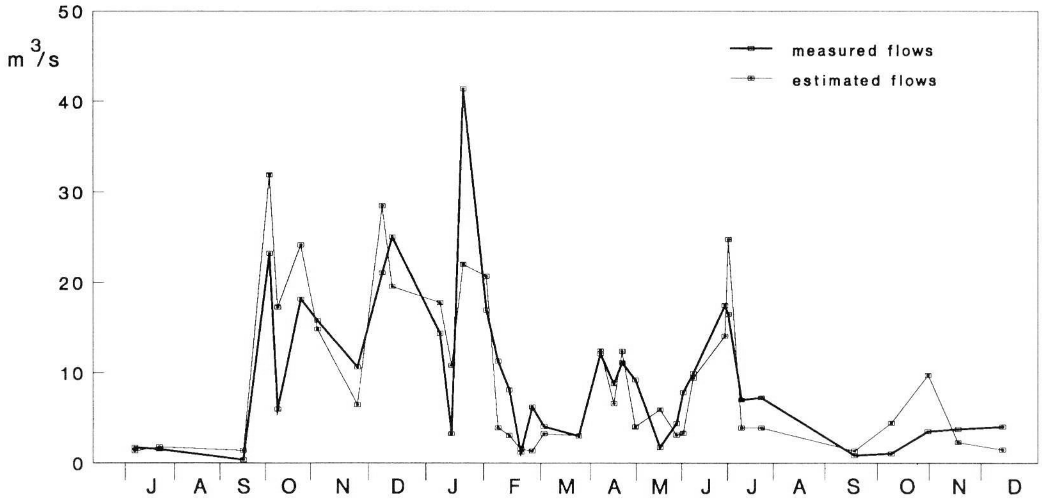

FIG. 3. — Distribution of measured and estimated fresh water flows from equation (II) for River Oitabén.

To obtain a unique equation for the whole drainage basin of the Ría de Vigo, a weighted average of the equations in relation to their correlation coefficients and the basin surfaces, was calculated and divided by the basin areas corresponding to the four rivers; we obtain the following equation.

$$Q = 0.007538 + 0.007889 * A \qquad \text{(II)}$$

where Q is the flow of fresh water in m^3/s for an area of 1 km^2 and A is the drainage expressed in $l \cdot m^{-2} \cdot d^{-1}$.

This equation is valid when the rainfall data recorded at Peinador are used. If data of other pluviometric stations are used, one must calculate first the relations between stations. For a value of $k = 0.75$ it is not necessary to use the rainfall corresponding to the 365 prior days. One month is enough for practical purposes.

Figure 3 shows the measurements and estimated flows using equation (II) for the River Oitabén during the annual cycle. In general, a great similarity between the values is observed, except when larger runoff occurs. Then the estimated flows are smaller than the observed flows.

In table 3 average annual flows, estimated using equation (II) and the drainage surfaces, are given i) for all the Ría de Vigo, ii) in box 2, from station 2 to the head of the ría, iii) in San Simon Cove and iv) at its origin. SÁIZ *et al.* (1957, 1961) calculated the average flow in San Simon using the average isoyectes and the rainfall data, and obtained an annual average flow value of 16.6 m^3/s. This value is close to the average flow estimated in San Simon Cove although it is practically the same as to box 2 (16.4 m^3/s) which corresponds almost totally with San Simon Cove. In the same way, the average annual flow (13.1 m^3/s) that reaches the head of San Simon, whose drainage basin includes 96 % of the Rivers Oitabén and Verdugo, gives value close to the average annual flow (13.6 m^3/s) given by SÁIZ *et al.* (1957), and also close to the average annual runoff (13.2 m^3/s) according to the data recording by Metra/Seis (1976) for the same rivers. As we can see, using average runoff values, the differences are small even with different methods.

Using the calculation proposed in equation (II)

TABLE 2. — Drainage surfaces of Oitabén, Verdugo, Redondela and Ullo rivers, flows calculated using equation (I) and $k = 0.75$, and correlation coefficients.

River	*Surface* (km^2)	*Flows* m^3/s**	*r*
Oitabén	173.15*	Q = 1.665 + 1.427 * A	0.70
Verdugo	136.14*	Q = 0.826 + 1.096 * A	0.69
Redondela	33.81	Q = 0.264 + 0.107 * A	0.60
Ullo	14.27	Q =– 0.070 + 0.170 * A	0.67

* Surfaces upstream of gauging station
** Q in m^3/s if P in the equation (I) is in $l \cdot m^{-2} \cdot d^{-1}$.

TABLE 3. — Drainage surfaces and annual mean flows of fresh water in the Ría de Vigo.

	Drainage basin km^2	*Average flow of fresh water* m^3/s
i) Ría de Vigo	589	21.33
ii) Box 2	454	16.43
iii) San Simón Cove	430	15.58
iv) San Simón (origin)	363	13.13

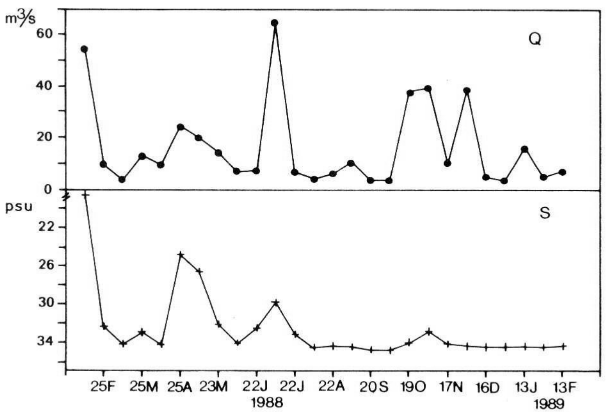

FIG. 4. — Distribution of fresh water flows (Q) that reach station 2 in the Ría de Vigo and the surface salinity (S) at the same station during a year.

and the surface data of drainage basin area, the runoff that reaches station 2 is estimated. This station was sampled from February 1988 until February 1989 each 15 days at high water neap tides, coinciding many times with sampling in the gauging station of the rivers. The calculated runoff values, in m^3/s, for the dates of sampling and the surface salinity values at the same station, are shown in figure 4. The great similarity between the distributions of fresh water flow and salinity is evident. The regression between them is:

$$S = 35{,}51 - 0{,}172 * Q$$

with a high correlation ($r = 0.69$), despite the fact that salinity depends on other environmental factors such as the wind. On the other hand, there is a connection because the south wind produces rain and diminishes salinity, and the north wind produces upwelling and increases the salinity due to the elevation of water from the bottom to the surface. The influence of runoff from 17 November is not reflected in a diminution of salinity. This fact is due to the penetration of the Ria by Eastern North Atlantic Central Water of subtropical origin ($ENAW_T$) with salinity and temperature characteristics higher than those of water of subpolar origin ($ENAW_P$) (Ríos *et al.*, 1992). This high temperature water coincides with the highest values of evaporation during the year, calculated for the ría water as far as station 2, to be about three times the average value.

The use of the proposed calculation is valid for period of less than one month, even though shorter periods diminish precision. This is proved by the correlation coefficient of 0.69 between daily flows and rainfall for the River Deza used to check the method. Rosón *et al.* (1991) applying Horton's law, obtain an increase of correlation coefficient as the data are grouped in blocks of 3 to 15 days.

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