

# **Estimates of Seasonal Flushing Times for the Southern Georgia Basin**

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SOUTHERN GEORGIA BASIN

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## ABSTRACT

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We use three box-type mixing models to estimate the seasonal flushing times for the estuarine waters of the southern Georgia Basin situated between British Columbia and Washington State. These models are the salinity model of Ketchum (1950), the modified tidal prism model of Ketchum (1951), and the segmented tidal prism model of Dyer and Taylor (1973). For all three models, seasonal variations in the basin-scale flushing time -- the time to replace the existing volume of fresh water in the basin with runoff from the Fraser River -- are strongly related to seasonal differences in river discharge and vertical mixing. Calculated salinity distributions and flushing times for the tidal prism models vary widely with small changes to the imposed mixing scales, suggesting that these models are less well constrained by observations than the salinity model. The salinity model is considered to be the most reliable of the three models examined. Flushing times derived from the salinity model for the seasonal values of the observed input parameters are: 308 days (spring); 105 days (summer); 188 days (fall); and 241 days (winter). Except for summer, less than half of the resident fresh water is removed each season and complete replacement of the fresh water in the basin requires about 1.4 years.

## RÉSUMÉ

England, L. A., R. E. Thomson, and M. G. G. Foreman. 1996. Estimates of seasonal flushing times for the southern Georgia Basin. Can. Tech. Rep. Hydrogr. Ocean Sci.: 173, 24 p.

Trois modèles de mélange de type boîte sont utilisés pour estimer le temps de renouvellement des eaux estuariennes du détroit de Géorgie sud situé entre la Colombie-Britannique et l'état de Washington. Les modèles sont celui de salinité de Kechum (1950), celui de prisme modifié de marée de Kechum (1951) et celui de prisme segmenté de marée de Dyer et Taylor (1973). Pour les trois modèles, les variations saisonnières du temps de renouvellement à l'échelle du bassin -- le temps requis pour remplacer le volume total d'eau douce du bassin par l'écoulement du fleuve Fraser -- sont fortement reliées aux différences saisonnières du taux d'écoulement du fleuve et du mélange vertical. Les distributions de salinité et les temps de renouvellement calculés avec les modèles de prisme de marée varient grandement avec de petites variations des échelles de mélange imposées, suggérant que ces modèles sont moins bien contraints par les observations que le modèle de salinité. Le modèle de salinité est considéré comme le plus fiable des trois modèles examinés. Les temps de renouvellement dérivés du modèle de salinité pour les valeurs saisonnières des paramètres d'entrée observés sont: 308 jours (printemps); 105 jours (été); 188 jours (automne); et 241 jours (hiver). Sauf pour l'été, moins de la moitié de l'eau douce résidante est remplacée chaque saison et le remplacement complet de toute l'eau douce du bassin prends environ 1.4 ans.



## INTRODUCTION

The marine region of the southern Georgia Basin, formed by the Strait of Georgia, eastern Juan de Fuca Strait, Puget Sound, and adjoining passages (Figure 1) is part of an extensive estuarine system separating Vancouver Island from the mainland coasts of British Columbia and Washington State. The basin serves as a waterway for coastal and deep-sea marine traffic, supports major commercial and recreational fisheries, and is a receptacle for domestic and industrial waste from a regional population of roughly five million people. Contaminant loading of this increasingly populated and utilized region is strongly affected by freshwater inflow and aerolian transport. Since accumulation of toxic substances within the basin can cause short- and long-term (chronic) environmental damage, estimates of water renewal times are central to understanding the fate of these substances and their possible impact on the water quality and marine food web. Because of growing concerns about the general "health" of the shared waters, the basin was the focus of a recent bilateral study under the auspices of the British Columbia-Washington Environmental Cooperation Council (British Columbia-Washington Marine Science Panel 1994). Loss of shoreline habitat and concerns over increasing contaminant loading were two major issues identified in the report.

The circulation of the Georgia Basin is driven primarily by winds, river runoff, and tides (Waldichuck 1957; LeBlond 1983; Thomson 1994). Modification to the circulation results from fortnightly variations in tidal mixing over the shallow sills that separate the various sectors of the basin (Ebbesmeyer and Barnes 1980; Geyer and Cannon 1982; Griffin and LeBlond 1990) and from wind-induced reversals in the runoff-driven estuarine circulation (Frisch et al. 1981; Holbrook et al. 1983). Upwelling along the Pacific coast in summer, surface convection in the basin in winter, and the Coriolis effect also modify the primary flow patterns (Waldichuck 1957; Crean et al. 1988; LeBlond et al. 1994). Roughly 70 to 80% of the fresh water flowing into the basin enters via the Fraser River located south of Vancouver. Most of the fresh water eventually exits the system through the southern tidal channels before flowing into the Pacific Ocean at the mouth of Juan de Fuca Strait (Thomson 1994). Along its path, the fresh water is mixed vertically with the high salinity water that enters the system from the Pacific, resulting in a positive estuarine flow pattern in which net seaward flow in the upper layer ( $< 100$  m depth) is balanced by a net inward flow at depth (Godin et al. 1980; Labrecque et al. 1994). The degree of mixing between the upper and lower layers is determined primarily by the relative density difference between the layers and by the intensity of the tidal flow over the sills separating the various sectors of the basin (Griffin and LeBlond 1990; LeBlond et al. 1994). Surface wind stress and vertical convection in winter can also affect the mixing between the layers.

The purpose of this paper is to provide estimates of the seasonal flushing times for the southern Georgia Basin based on simple mixing models formulated for riverine flow in tidal estuaries. The flushing time for an estuary, defined mathematically as the ratio of the total volume of river water accumulated in the estuary to the volume of river flow introduced into the estuary per unit time (Dyer 1973), corresponds to the average time required to replace the existing fresh water in the estuary at a given river flow rate. Complete replacement is achieved when the volume of fresh water resident in the estuary has been removed or flushed

from the system by newly added river water. It is assumed that "all" of this volume of fresh water is removed when less than 1% of it remains in the estuary. Seasonal differences in flushing time arise from seasonal differences in river discharge and degree of vertical mixing. Results from three distinct mixing models are compared and best estimates given for the flushing times of the basin.

## FLUSHING-RATE MODELS

If we assume that the fresh water balance within the Georgia Basin is controlled primarily by Fraser River discharge and tidally-induced mixing, we can estimate the flushing times for the basin using three "classic" mixing models first developed in the 1950s for large river estuaries. Input to the simplest of these models, the "salinity model" (Ketchum 1950; Ketchum and Keen 1953), are the mean salinity distribution in the basin, the volume of the basin, and the flow rates of the main rivers entering the basin. The method has been applied to flushing times for the New York Bight (Ketchum 1950), the Mersey Narrows (Hughes 1958), and the Bay of Fundy (Ketchum and Keen 1953). The second model (Ketchum 1951) is based on a modified tidal prism method in which segmentation of the estuary is derived from the average travel time of a water particle during the flood. This model is more comprehensive than the salinity model in that it requires a detailed knowledge of the tidal range in addition to measurements of river flow and basin topography. The third model, developed by Dyer and Taylor (1973), is a modified version of the segmented tidal prism model. It uses a slightly different method for segmentation than the tidal prism model and introduces a spatially varying parameter meant to characterize mixing processes in the estuary.

### THE SALINITY MODEL

The salinity (or "fraction of fresh water") model uses observed basin salinity to compute the fresh water distribution and flushing time of the estuary. In this model, the estuary is divided into horizontal segments and each segment sliced into depth ranges. The vertically-averaged salinities,  $S_n^k$ , for each segment ( $n = 1, 2, \dots, N$ ) and depth range ( $k = 1, 2, \dots, K$ ) are specified and the flushing time,  $T_n$ , is calculated as

$$(1) \quad T_n = \sum_{k=1}^K Q_n^k / R = \sum_{k=1}^K f_n^k V_n^k / R$$

where  $Q_n^k$  is the volume of river water in the  $k$ th depth range of segment  $n$ ,  $V_n^k$  is the volume of segment  $n$  for the  $k$ th depth range, and  $R$  is the known rate at which river flow enters the estuary. The fractional concentration of fresh water in each depth range for a given segment,

$$(2) \quad f_n^k = (S_s - S_n^k) / S_s$$

is defined in terms of the salinity,  $S_s$ , of the undiluted seawater entering the system from the ocean. The variable  $Q_n^k = f_n^k V_n^k$  is calculated for each depth range and totaled for each segment to give the flushing time,  $T_n$ , for that segment.

To determine the flushing times for the Georgia Basin, the northern sector was ignored and the southern region divided into five segments (Figure 1). This assumes that all of the Fraser River discharge leaves the Strait of Georgia through Haro Strait, the largest of the southern passages. Omission of the northern passages is assumed to have a minor effect on the flushing times because, based on the observed volume transports in Juan de Fuca Strait and Johnstone Strait, only about 15% of the river water leaves the basin through the northern route (Thomson 1994). Similarly, Rosario Strait accounts for only about 15% of the fresh water discharge through the southern route. Boundaries of the segments were made to conform as closely as possible to the main oceanographic regions as defined by the locations of major sills and water property structure (Thomson 1994). Haro Strait, which separates Vancouver Island from the San Juan Islands, was broken into two segments, as was the eastern and western sectors of Juan de Fuca Strait.

Depth-weighted salinities were derived from the observed salinity distributions obtained during monthly along-channel surveys conducted from 1967 to 1968 by Crean and Ages (1971) and were calculated for the following depth ranges: 0-20, 20-40, 40-80, 80-120, 120-160, 160-200, and 200-250 m. The mean salinity value for a given depth range was considered representative of the entire segment. Salinities in the near surface layer of Georgia Basin decrease with distance from the mouth of the Fraser River (segment 1), with the lowest salinities occurring during the freshet conditions of late spring and early summer (Crean and Ages 1971). Observed deep water salinities in segment 1 ranged from 30.5 to 31.0 psu (practical salinity units) in spring and summer and from 31.0 to 31.5 psu in autumn and winter. Slightly higher deep water salinities were observed in segments 2 and 3. Undiluted oceanic water enters the estuary at depth at its seaward entrance and, because of the Victoria-Green Point and Boundary Passage sills, appears to extend only to segments 4 and 5 (Figure 1). A study of deep water intrusions in the system reveals that deep water passes over the sills as gravitational flows (density currents) at fortnightly and monthly intervals determined by the occurrence of significant neap tides (LeBlond 1983; Thomson 1994). In general, the salinity increases monotonically with depth, with well-mixed regions confined to the vicinity of shallow sills where tidal currents are strongest.

To account for seasonal variability in the water property structure and forcing functions, data collected in December, March, July, and October (Table 1) were used to characterize the four seasons. Values of river flow rate for each season (Table 1) were determined from 25-year (1955-79) means for the discharge at Hope, British Columbia, located approximately 100 km upstream of the river mouth. Since salinity distributions in the basin represent an accumulated response to freshwater discharge, and to account for annual variations in the Fraser River discharge, we used the average river discharge rather than the discharge for 1968, the time period of the Crean and Ages survey. We note that river discharge during 1968 was similar to the 25-year mean.

## THE MODIFIED TIDAL PRISM MODEL

In this model, flushing times for the estuary are derived from the observed rate of freshwater discharge to the estuary and the specified tidal heights (Ketchum 1951). The estuary is divided into segments, with the distance between the inner and outer boundaries of consecutive segments set equal to the mean excursion of a parcel of water on the flood (Figure 2). The average excursion is obtained from the volume of water entering each part of the estuary on the flood and the known topography of the estuary. The length of each segment, and hence the total number of segments, changes with the rate of freshwater discharge and imposed tidal elevations. Along the length of the estuary, each segment is defined such that the high tide volume in the landward segment is equal to the low tide volume in the adjacent seaward segment. This requires detailed knowledge of the depth. The intertidal volume,  $P_0$ , of the innermost segment (segment "0") is supplied entirely by the river flow, which has a volume flow  $R$  over one tidal cycle. On the flood, there is no exchange and mixing of water across the seaward boundary of segment "0" and the intertidal volume upstream (landward) of this boundary consists of river water only. Assuming that the low tide volume,  $V_1$ , of the first seaward segment (segment "1") is equal to the high tide volume of the segment located immediately up-estuary, we find

$$(3) \quad V_1 = V_0 + P_0 = V_0 + R.$$

Continuing seaward with this formulation, the low tide volume of segment  $n$  is equal to the combined low tide volume and intertidal volume of the adjoining up-estuary segment, segment  $n-1$  such that

$$(4) \quad V_n = V_0 + R + \sum_{j=1}^{n-1} P_j$$

where  $P_j$  represents the intertidal volume of the  $j$ th segment.

If we assume that complete mixing takes place within each segment at high tide, the proportion of water removed on the ebb is given by the exchange ratio,  $R_n$ , defined as

$$(5) \quad R_n = P_n / (P_n + V_n).$$

The flushing time (in tidal cycles) for the  $n$ th segment is then,

$$(6) \quad T_n = 1/R_n = Q_n/R,$$

where  $Q_n$  is the total volume of river water accumulated in the segment over many tidal cycles. The total flushing time is the sum of the flushing times for each segment. If the salinity of the undiluted sea water is known, the high-water salinity in each segment also can be calculated.

To estimate the flushing times, the Georgia Basin was sub-divided into segments starting from the head of the estuary at New Westminster and extending to the mouth of Juan de Fuca Strait (Figure 1). The low tide volume of a given segment was set equal to the high tide volume of the adjoining upstream segment. To define the boundaries of each segment, we used a computer program that incorporated digitized depths from detailed hydrographic charts and tidal elevations derived from a high-resolution finite-element (triangular grid) model for the region (Foreman et al. 1993). In plan view, segments were generally rectangular in shape with horizontal boundaries defined by the width of the estuary and the mean excursion of a parcel of water on the flood. The number of segments generated ranged from 7 to 21 and varied according to the input parameters of river discharge and mixing depth. The hourly tidal elevations for twenty-one grid points located along the central axis of the model were obtained from the combined elevations generated using the eight largest diurnal and semidiurnal tidal constituents, which typically account for about 85% of the tidal range. Computed elevations were averaged over a spring-neap cycle (15 days). Starting with the high-tide volume of segment "0" and the digitized bottom topography for the basin, we determined the mean tidal excursion for each adjoining segment and hence the positions of the low-tide boundaries. Matching the tidal volume by adjusting the boundaries of the segment was accurate only to about 1% because of the finite areas of the digitized depth elements. Most of the difficulties were encountered near Roberts Bank at the mouth of the Fraser River where segments widen abruptly.

The model assumes complete mixing in each segment over one tidal cycle. To account for limited downward mixing of the brackish surface water with the underlying oceanic water, calculations for each segment were made only to a specified mixing depth. The mixing depth replaces the bottom of the estuary and can be determined in two ways. The most straightforward approach is to equate the mixing depth with the depth of the mean halocline observed for each segment of the basin for the season of interest. Alternatively, the mixing depth can be selected as that value which yields a salinity structure which most closely resembles the observed salinity structure. Both estimates were tried and their respective results discussed below.

## **THE DYER-TAYLOR SEGMENTED PRISM MODEL**

Internal inconsistencies in Ketchum's (1951) tidal prism model, due to a simplified mixing assumption and segmentation of the estuary, lead Dyer and Taylor (1973) to formulate a more general segmented prism model. Ketchum's model forces the entire low tide water column of segment  $n$  to move landward on the flood, thereby causing the concentration of river water to remain the same in that column of water when it occupies segment  $n-1$  at high tide. This can lead to concentrations of unity (100% river water) in downstream segments,

which is incompatible with the model requirements. In their segmentation of the estuary (Figure 3), Dyer and Taylor set the intertidal volume of the innermost segment,  $P_0$ , to be half the river flow  $R$  over one tidal cycle. On the flood, there is no flow across the lower seaward boundary of this segment. The low tide volume,  $V_1$ , of the first down-estuary segment is supplied by the river on the ebb and is entirely made up of river water at low tide. Segments 1, 2, ...,  $N$  are defined consecutively so that:

$$(7a) \quad V_1 = R; \quad \alpha V_2 = P_1, \quad n=1$$

$$(7b) \quad \alpha V_{n+1} = \alpha V_n + P_n, \quad n = 2, 3, \dots, N-1$$

where the parameter  $\alpha$  ( $0 < \alpha < 1$ ) is associated with mixing. On the flood, the whole system can be thought of as acting like a piston, pushing a volume of water  $\alpha V_{n+1}$  upstream to occupy  $\alpha V_n$  plus  $P_n$  (or just  $P_1$  for  $n=1$ ) at high tide. This water mixes with the volume  $(1-\alpha)V_n$ , which is the water remaining in segment  $n$  during low tide. On the ebb, an extra volume equal to  $R$  must also pass downstream.

High and low water concentrations of river water,  $C_n^H$  and  $C_n^L$ , respectively, are defined for each segment,  $n$ , by assuming that undiluted sea water enters the mouth of the estuary on the flood ( $C_n^L = 0$ , when  $n$  is the last segment) as follows:

$$(8a) \quad R C_0 = (R + \alpha V_{n+1}) C_n^H - \alpha V_{n+1} C_{n+1}^L, \quad n=1, 2, \dots, N$$

$$(8b) \quad C_n^L - C_n^H = [R / (1-\alpha) V_n] (C_0 - C_n^H), \quad n = 2, 3, \dots, N$$

where  $C_0 (= 1)$  is the reference concentration of the river. The flushing time, in tidal cycles for each segment is

$$(9) \quad T_n = Q_n / R.$$

The total flushing time for a region of the basin is the sum of the flushing times for each segment.

Segmentation of the Georgia Basin system was achieved in a similar manner as for the Ketchum model, with the above noted differences at the estuary head incorporated into the computer program. Input values of river flow rate and tidal heights were identical to those used in Ketchum's model. Criteria for choices of mixing depth and mixing parameter values are discussed in the following section.

## RESULTS

The flushing times for the southern Georgia Basin, including western Juan de Fuca Strait, have been simulated for each season using the three mixing models. In this section, we focus on summer and winter estimates since these represent the annual extreme conditions.

### THE SALINITY MODEL

The portion of fresh water,  $f_n^k$ , and associated volume of fresh water,  $Q_n^k$ , in each depth range for each of the five specified segments has been determined from (2) for each season. Fresh water estimates were based on the values for the undiluted sea water listed in Table 1 and the along-channel, depth-averaged salinity data from Crean and Ages (1971). For all seasons, the total percentage of river water was highest for segment 1, ranging from 13.5% in summer to 7.2% in winter, and decreased seaward to segment 5, where it ranged from 3.0% in summer to 2.8% in winter. The entire water column was diluted with river water throughout the estuary except for the deep waters ( $> 120$  m) of segment 5. Substitution of the sum of derived values of  $Q_k^n$  for all depth levels and seasonal river flow rates (Table 1) into (1) yielded the total flushing time,  $T_n$ , for the entire segment. Table 2 shows values of flushing time and depth-averaged flow for each segment for summer and winter. Estimates of the depth-averaged mean flow rate,  $U_n = L_n/T_n$ , have been calculated from the segment length  $L_n$  and the flushing time.

Table 3 provides a summary of the total fresh water accumulated in the basin and the flushing times needed to maintain a steady state balance of fresh water within the entire basin for all seasons. The summer and winter flushing times correspond to the vertically-integrated values presented in the last row of Table 2. According to these results, fresh water is flushed out of the estuary most rapidly in summer, the time of maximum river input to the system. Assuming that each season is about 91 days duration, roughly 87% of the fresh water in the system is replaced during the summer. The longest flushing times ( $> 240$  days) occur in winter and spring when less than 40% of the fresh water is replenished in a season. The depth-averaged flow rates for the entire estuary are 2.7 cm/s in summer and 1.2 cm/s in winter.

We can estimate the long-term flushing time,  $T_\infty$ , for the basin by examining the progressive removal of fresh water that enters the basin in early spring. By the end of spring, 70% of the original fresh water remains in the system. This is reduced to 9% by the end of summer, to 5% by the end of fall and to 3% by the end of winter. Continuing, we find that by the end of the next spring, less than 2% of the fresh water that had entered the basin the previous year remains in the system. If we set 0.01 (1%) as the fractional limit for complete flushing, then  $T_\infty \approx 1.4$  years, which is equivalent to the value of 1.3 years obtained by Waldichuck (1957) using observed water property structure and 1.4 years derived by Crean et al. (1988) using the GF6 finite-difference numerical model.

## THE MODIFIED TIDAL PRISM MODEL

The segmented tidal prism model has been used to calculate flushing times and salinity distributions for the study region. With the exception of the mixing depth, the required input parameters for the model (tidal elevations, bottom topography and river flow) are known with considerable accuracy. Since the function of the mixing depth is to simulate the vertical extent of surface entrainment processes within the estuary, it varies considerably with location and season. The results for summer and winter data reveal a strong dependence of the flushing times and depth-averaged transport velocity on the specified mixing depth (Table 4), detracting from the usefulness of the model.

We applied several values of the mixing depth for the summer and winter regimes. Both constant and variable mixing depths were used in the computer program but, due to the nature of the model, only small ( $< 20$  m) changes in the mixing depth produced realistic results. Results for three different values of the mixing depth for both winter and summer are presented in Table 4.

Initial values (model run 1) were equated to the main halocline depth and determined from the along-channel salinity distributions published by Crean and Ages (1971). Summer mixing depths associated with the upper halocline are shallow ( $< 10$  m) throughout the estuary. A mixing depth of 6 m was chosen for run 1. Simulated flushing time and freshwater volume were much lower than those values produced by the salinity model while average transport rates were considerably larger. Although the simulated salinities were 10 to 20% lower than observed, the salinity distributions generated by run 1 compared quite favourably with observed salinities. Winter mixing depths vary markedly along-channel; the estuary is well-mixed to about 60 to 80 m depth in Haro Strait and Boundary Passage but only to about 10 to 20 m in the Strait of Georgia and Juan de Fuca Strait. The largest change in the winter mixing depth, used in run 1, was 20 m. The variable mixing depth of 20/40/20 represents, approximately, a mixing depth of 20 m for the Strait of Georgia (segment 1, Figure 1), 40 m for Boundary Passage and Haro Strait (segments 2 and 3, Figure 1), and 20 m for Juan de Fuca Strait (segments 4 and 5, Figure 1). The resulting model results, including exchange ratio, accumulation of river water and salinity distribution do not agree well with corresponding data generated by the salinity model or with observed salinity distributions. The exchange ratios are much lower and the percentages of river water are higher, especially near the estuary head, producing lower salinities than those observed. The mixing depths chosen are too large, indicating that vertical mixing was not complete to these depths. Where the mixing depth was increased to 40 m the exchange ratio became very low, causing the salinity to drop in these areas. Observations indicate that salinities gradually increased down-estuary. The flushing times for this run and for the salinity model were comparable, except for segment 3 (Haro Strait), where the deep mixing zone resulted in a much longer flushing time than for the salinity model.



The second set of mixing depths (run 2, Table 4) corresponded to those depths which produced a simulated salinity distribution that most resembled that observed. As was mentioned previously, a mixing depth of 6 m for the summer regime gave the best salinity match. Presumably, a smaller mixing depth would have provided an even closer match. However, the estimated flushing times of 25 days or less are much shorter than those predicted by the salinity model and are unrealistic. For the winter regime, a constant mixing depth of 8 m produced a salinity distribution most closely resembling that observed. The simulated salinity values were 0.2 to 5.5 % lower than observed values. Once again, run 2 produced freshwater volumes and flushing times considerably lower and average transport rates considerably higher than those of the salinity model.

The third set of mixing depths in Table 4 correspond to those depths which produced flushing times and river water volumes that most closely resembled those of the salinity model. To obtain a summer flushing time similar to that of the salinity model ( $\approx 104$  days), the summer mixing depth had to be increased to 18 m. The resulting salinity distribution was then 15 to 30% lower than observed. Similarly, for a winter flushing time similar to that of the salinity model ( $\approx 241$  days), the mixing depth had to be increased to 25 m. The resulting winter salinity distribution was 25 to 45% lower than observed. Thus, we cannot match simultaneously both the flushing times and salinity distributions of the two models. Average transport rates for both winter and summer were almost identical for the two models (compare Tables 2 and 4).

Exchange ratios  $R_n$  given by (5) did not vary greatly throughout the estuary. All model simulations revealed higher exchange ratios near the estuary head, decreasing gradually seaward, and then rising slightly near the mouth of the estuary. Larger mixing depths resulted in lower exchange ratios. For a summer mixing depth of 6 m, exchange ratios ranged from 0.24 to 0.35. For a winter mixing depth of 14 m, they ranged from 0.12 to 0.19.

## DYER-TAYLOR SEGMENTED PRISM MODEL

Flushing times and salinity distributions have been computed for specified input parameters, including the mixing depth and mixing parameter (Table 5). The low and high water concentrations of river water,  $C^L$  and  $C^H$ , also were computed for each segment. Several different values of  $\alpha$ , the mixing parameter, were used in the model. A constant value of  $\alpha = 0.15$  produced the most reasonable and stable (i.e. non-oscillating) values of freshwater concentrations and the most acceptable salinity distributions throughout the estuary. Unstable solutions, when concentrations of fresh water oscillate about unity and salinities become negative near the head of the estuary, occurred if a large ( $> 0.3$ ) mixing parameter was combined with a small ( $< 10$  m) mixing depth. The model allows  $\alpha$  to vary along-estuary; however, for the southern Georgia Basin, it was found that even small down-estuary increases in the value of the mixing depth produced a salinity profile that was too "fresh", especially near the estuary head. According to our computer simulations, the larger the value of  $\alpha$  the higher the concentrations of fresh water, and thus the lower the salinity values throughout the estuary. The model results need to be constrained by the observed salinity values which indicate that the southern Georgia Basin is composed mostly of high-

salinity water except very close to the Fraser River delta. This topic is discussed further in the following section.

Three sets of mixing depths are presented in Table 5 for both the summer and winter regimes for a value of the mixing parameter,  $\alpha = 0.15$ . Run 1 used those values of mixing depth (50 m for summer and 60 m for winter) which gave flushing times, freshwater volumes, and average transport rates that most closely resembled those produced by the salinity model. Simulated salinity values from run 1 also closely matched the observed salinities. For the summer regime, salinity values were 3 to 10% lower than observed and winter values were 0.6 to 5% lower than observed. These differences are much smaller than those produced by the Ketchum model. It is obvious from these results that the Dyer-Taylor model leads to improved simulations of estuarine regimes. The mixing parameter allows the model to involve a greater portion of the water column in the calculations while only allowing a small portion of the water column to be transported on the flood. We remark that the product of the mixing depth and the mixing parameter used in run 1 produces depths (7.5 m for summer and 9 m for winter) that are similar to the mixing depths used for run 2 in the Ketchum model (6 m for summer and 8 m for winter), which produced the best match to the observed salinity distribution. Not only did run 1 generate a strong similarity in salinity distribution, but it also yielded excellent agreement in all other derived values (compare Table 5 to Table 2 and 3) which was not the case for the Ketchum model. As suggested by the observed salinity data, it is not unrealistic to include the top 50 to 60 m of the water column in the vertical entrainment process. Unfortunately, there appears to be no method for choosing the values of mixing depth except through matching simulated with observed salinities.

When the mixing depth was increased or decreased by 20 to 30% (runs 2 and 3, Table 5) we observed large changes in output parameters, namely the flushing time, freshwater volume and average velocity. For flushing time prediction purposes, this indicates the importance of determining the mixing depth to an accuracy of at least 10%. Changes in the salinity distribution were not as pronounced.

## DISCUSSION

### SALINITY MODEL

The three principal factors affecting the salinity model are the river flow, the salinity structure and the undiluted (background) salinity. Seasonal mean river flows vary markedly from year to year so that it is important to know how discharge variations change the nominal flushing rates. Estimates of the flushing time varied most at small flow rates ( $< 5 \times 10^3 \text{ m}^3/\text{s}$ ), making the model most sensitive to small changes in winter river discharge (Figure 4a). For summer, when flow rates are high ( $> 5 \times 10^3 \text{ m}^3/\text{s}$ ), there was much less dependence on flow rate variations. For a given flow rate, summer flushing times were slightly longer than winter flushing times.

The relationship of the estimated flushing time to the salinity distribution was calculated as a percentage change in salinity for the entire estuary relative to nominal values derived from

the observations (Figure 4b). Results clearly indicate that the flushing time was most dependent on winter decreases in salinity and least affected by summer increases in salinity. A 5% decrease in salinity in winter more than doubled the flushing time while in summer the corresponding change was less than a factor of 1.5. Within Juan de Fuca Strait, large departures in salinity are unlikely so that the nominal values presented in the previous section are probably representative of the region. In particular, comparison of the observed salinity data collected in the strait in 1967-68 (Crean and Ages 1971) and 1989-90 (R. Birch, ASL Environmental Sciences, Sidney, B.C., personal communication) shows basin-wide differences of less than 1%. As for basin-wide changes in salinity, the impact of background oceanic salinity changes on flushing times was much greater in winter than in summer (Figure 4c). For example, a change from 32.0 psu to 33.0 psu increased the flushing time by 130 days in winter (from 180 to 310 days) but only by 25 days in summer (from 50 to 75 days).

### THE MODIFIED TIDAL PRISM MODEL

Based on our findings, the modified tidal prism model works best when: (1) the estuary is well-mixed; and (2) the cross-sectional area increases fairly quickly downstream. Although neither of these conditions strictly apply to the Georgia Basin, the model was useful for acquiring approximate estimates of the flushing time and for determining factors which most affect such calculations. One advantage of the model is that only the topography, river flow and tidal range need to be known in detail. A major limitation of the model is the inability of the segmentation method to accommodate large changes in mixing depth. In order for the freshwater volume,  $Q_n$ , in each segment to remain less than the total high tide volume ( $P_n + V_n$ ) of that segment (substitute (5) into (6) and solve for  $Q_n$ ), the ratio of river flow,  $R$ , to the intertidal volume,  $P_n$ , must remain less than unity; put another way, we require  $P_n > R$ . If there is a sudden increase in the mixing depth, matching of volumes between segments forces a reduction in the surface area of the segment and hence the intertidal volume,  $P_n$ , is also reduced. To ensure  $P_n > R$ , the increase in mixing depth must remain small.

Flushing times for the tidal prism model (Figure 5a) indicated a much weaker dependence on river flow than the salinity model at low discharge rates ( $\leq 5 \times 10^3 \text{ m}^3/\text{s}$ ). However, at high discharge rates, the dependence on river discharge was similar for both models. As with the salinity model, winter flushing times (low river discharge) were longer than those for summer (high discharge). The rates of change of the flushing time as a function of river flow (slope of the curves) were similar in winter and summer. As with the salinity model, summer flushing times were slightly longer than winter flushing times for the same river discharge rate. The dependence on tidal range, measured relative to the nominal values obtained from the numerical simulation of Foreman et al. (1993), had little effect on flushing times (Figure 5b), and differences in tidal range as high as  $\pm 10\%$  did not substantially change the results. In contrast, the flushing time for the basin was strongly dependent on the specified mixing depth (Figure 5c). For example, increasing the depth from 10 to 20 m increased the winter flushing time from 60 to 190 days and the summer flushing time from 45 to 110 days.

## DYER-TAYLOR SEGMENTED PRISM MODEL

The effects of river flow, mixing depth, and mixing parameter variability on flushing times have been examined for the Dyer-Taylor model. Nominal values for the latter two parameters are 40 m and 0.15, respectively. Model sensitivity to changes in river discharge (Figure 6a) was similar to that of the modified prism model in that flushing times gradually increased with decreasing flow discharge. At the lowest flow rates, the relative change of flushing rate as a function of river discharge was much lower than for either the salinity or modified tidal prism models. Unlike the previous two models, winter flushing times exceeded those for summer for a given river discharge rate.

The effect of mixing depth variation on flushing times in the Dyer-Taylor model (Figure 6b) was similar to that of Ketchum's model (Figure 5b), with greatest rates of change occurring during winter when flow rates are low. It appears that large alterations (10 to 20 m) in nominal mixing depths less than 60 m do not greatly affect the salinity distribution but do create large changes in the flushing time. This may be due, in part, to the model requirement that the salinity of the last segment at the mouth of the estuary match that of the deep oceanic water.

For both summer and winter, flushing rates were strongly dependent on the mixing parameter,  $\alpha$  (Figure 6c). This dependence was especially pronounced for winter runoff values when large flushing times in excess of one year are predicted for mixing parameters  $\alpha > 0.3$ . Such large values are unrealistic. To maintain reasonable (close to observed) salinity distributions and freshwater concentrations within the estuary, the mixing parameter in the model must remain small. The value  $\alpha = 0.8$  suggested by Dyer and Taylor (1973) as a reasonable value for typical estuaries is not applicable to the Georgia Basin. At such high mixing values, the model predicts basin-wide salinities that are much lower than observed. Specifically, segment 1 became composed entirely of river water for high mixing parameters, contrary to what is observed even during summer when river runoff is high. At low values of  $\alpha$  ( $0.1 \leq \alpha \leq 0.2$ ), salinities are at their highest values throughout the estuary and most closely match observed values. In their study of the Raritan River, Dyer and Taylor (1973) found that the salinity distribution varied from an entirely seawater estuary for  $\alpha \rightarrow 0$  to an entirely freshwater estuary for  $\alpha \rightarrow 1$ . Based on the observed salinity distributions, we would expect the value of  $\alpha$  for the southern Georgia Basin to be low.

## CONCLUSIONS

Our findings suggest that the salinity model of Ketchum (1950) provides more reliable estimates of the Georgia Basin flushing times than the Ketchum (1951) modified tidal prism model or the Dyer-Taylor (1973) segmented prism model. The Ketchum tidal prism model failed for the southern Georgia Basin. Model results which produced flushing times close to those predicted by the salinity model yielded unrealistic estuarine salinity distributions. Conversely, those model runs which produced realistic salinity distributions gave flushing times much lower than those predicted by the salinity model. The Dyer-Taylor model was

more successful. Using reasonable values of the mixing depth and the mixing parameter, model results compared favourably with those for the salinity model. Simulated salinity distributions were within 10% of those observed, and flushing times were within 11% of those simulated by the salinity model. For both tidal prism models, small changes to mixing scales caused large changes in the computed flushing times. This "sensitivity" of the Dyer-Taylor segmented prism model and the difficulty in determining a more well-constrained mixing depth for input to the model, detract from its usefulness for the complex estuarine system of the southern Georgia Basin.

The salinity model has the advantage that it is strongly controlled by the along-channel freshwater dilution of the background salinity field. Collection of along-channel salinity data for all seasons is expensive and time-consuming, but if these data exist they can be used to considerable advantage in the salinity model. The salinity model sets the standard against which the other models are to be compared. If we assume an average duration of 91 days for each season, the salinity model results imply that, for the southern Georgia Basin, roughly 29.6% of the water is replaced in spring (flushing time,  $T = 308$  days), 86.9% in summer ( $T = 105$  days), 48.5% in fall ( $T = 188$  days), and 37.9% in winter ( $T = 241$  days). Complete replacement of the fresh water in the Georgia Basin requires about 1.4 years. Since contaminants transported into the basin by the Fraser River can be lost through flocculation, chemical transformation, sedimentation, and other processes, the total estimated flushing time is a conservative estimate for the removal of non-conservative material from the basin.

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Table 1. Input parameters for the salinity model. The undiluted salinity was obtained from salinity data collected near the entrance to Juan de Fuca Strait by Crean and Ages (1971). The flow data for the Fraser River (R. Birch, ASL Environmental Sciences, Sidney, B.C., personal communication) was measured at Hope, British Columbia.

	Spring	Summer	Autumn	Winter
Undiluted salinity, $S_s$ (psu)	32.90	33.85	33.80	32.50
River flow, $R$ ( $m^3/s$ )	1750	5750	2750	1500

Table 2. Summer and winter flushing times for each of the five segments used in the salinity model. The last two columns give the mean flushing rates,  $U_n$ , for the various segments.

Segment	Length (km)	Flushing Time (days)		Depth-averaged velocity (cm/s)	
		summer	winter	summer	winter
1	63.0	63.4	129.2	1.2	0.6
2	18.4	4.2	8.4	5.1	2.5
3	36.2	6.8	11.9	6.2	3.5
4	39.4	11.6	25.2	3.9	1.8
5	91.4	18.7	66.1	5.7	1.6
Total	248.4	104.6	240.7	Mean 2.7	Mean 1.2

Table 3. Net flushing times for all seasons (sum of flushing times for all segments) using the salinity model.

Season	River Discharge ( $m^3/s$ )	Freshwater Volume ( $\times 10^{10} m^3$ )	Flushing Time (days)	Fraction Replaced
Spring	1750	4.66	308	0.30
Summer	5750	5.20	105	0.87
Autumn	2750	4.47	188	0.48
Winter	1500	3.12	241	0.38



Table 4. Summer and winter flushing times and vertically-averaged transport velocity using the modified tidal prism model. The first mixing depth (model run 1) for each season was based on the depth of the halocline; the second (model run 2) was that depth which gave the best salinity distribution match to the observed data; the third (model run 3) was that depth which gave mean flushing times equal to those from the salinity model.

Model Run	Mixing Depth (m)	Freshwater Volume ( $\times 10^{10} \text{ m}^3$ )	Flushing Time (days)	Average Velocity (cm/s)
Summer 1	6	1.25	25	11.5
2	6	1.25	25	11.5
3	18	5.14	104	2.8
Winter 1	20/40/20	2.60	201	1.4
2	8	0.62	48	6.0
3	25	2.96	229	1.3

Table 5. Summer and winter flushing times and mean vertically-averaged transport rates for the segmented tidal prism model for various values of the mixing depth and freshwater volume. The mixing parameter  $\alpha = 0.15$ .

Model Run	Mixing Depth (m)	Freshwater Volume ( $\times 10^{10} \text{ m}^3$ )	Flushing Time (days)	Average Velocity (cm/s)
Summer 1	50	4.97	100	2.9
2	40	4.10	82	3.5
3	60	6.09	123	2.3
Winter 1	60	2.78	215	1.3
2	40	1.52	117	2.4
3	80	4.14	319	0.9

## Figure Captions

Figure 1. The Georgia Basin region. Boxes denote the borders of the five domains used in the salinity model calculations.

Figure 2. Segmentation of the Georgia Basin for Ketchum's (1951) modified tidal prism model. The low tide volume,  $V_n$ , of the  $n$ th segment is equal to the high tide volume,  $V_{n-1} + P_{n-1}$  of the adjacent upstream segment. River water enters the region from the left and exits to the right.

Figure 3. Segmentation of the basin for the Dyer and Taylor (1973) segmented tidal prism model. Similar to Figure 2 except that the amount of vertically mixed water in each segment is determined by the specified mixing parameter,  $\alpha$ .

Figure 4. Flushing times (days) for the Georgia Basin derived from the salinity model. (a) Flushing time versus rate of river inflow ( $\text{m}^3/\text{s}$ ); (b) Flushing time versus mean estuary wide salinity (ppt); (c) Flushing time versus background (oceanic) salinity (ppt).

Figure 5. Flushing times (days) for the Georgia Basin derived from segmented tidal prism model. (a) Flushing time versus rate of river inflow ( $\text{m}^3/\text{s}$ ); (b) Flushing time versus tidal range as a percentage of computed tidal range from the finite element numerical model of Foreman et al. (1993); (c) Flushing time versus mixing depth (m). For (b) and (c), we assume nominal summer and winter river discharge rates of 5750 and 1500  $\text{m}^3/\text{s}$ , respectively (Table 1). The nominal mixing depths are 6 and 14 m, respectively.

Figure 6. Flushing times (days) for the Georgia Basin derived from modified tidal prism model. (a) Flushing time versus rate of river inflow ( $\text{m}^3/\text{s}$ ); (b) Flushing time versus mixing depth (m); (c) Flushing time versus mixing parameter,  $\alpha$ . For (b) and (c), we assume nominal summer and winter river discharge rates of 5750 and 1500  $\text{m}^3/\text{s}$ , respectively (Table 1). The nominal mixing depth and mixing parameter are 40 m and 0.15, respectively.



Figure 1

# ESTUARY SEGMENTATION FOR KETCHUM'S MODEL

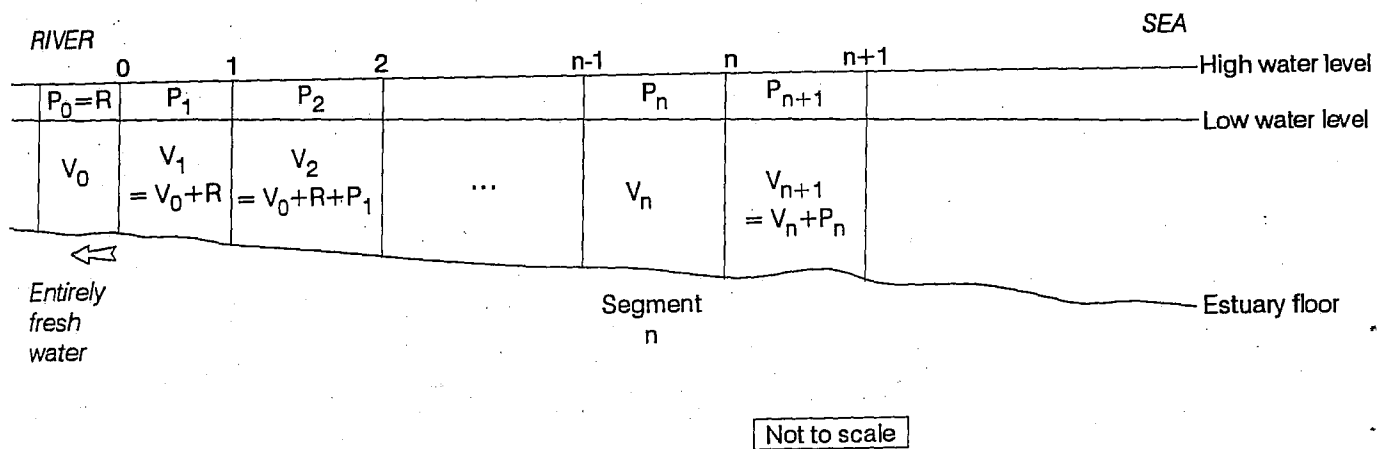


Figure 2

# ESTUARY SEGMENTATION FOR DYER - TAYLOR'S MODEL

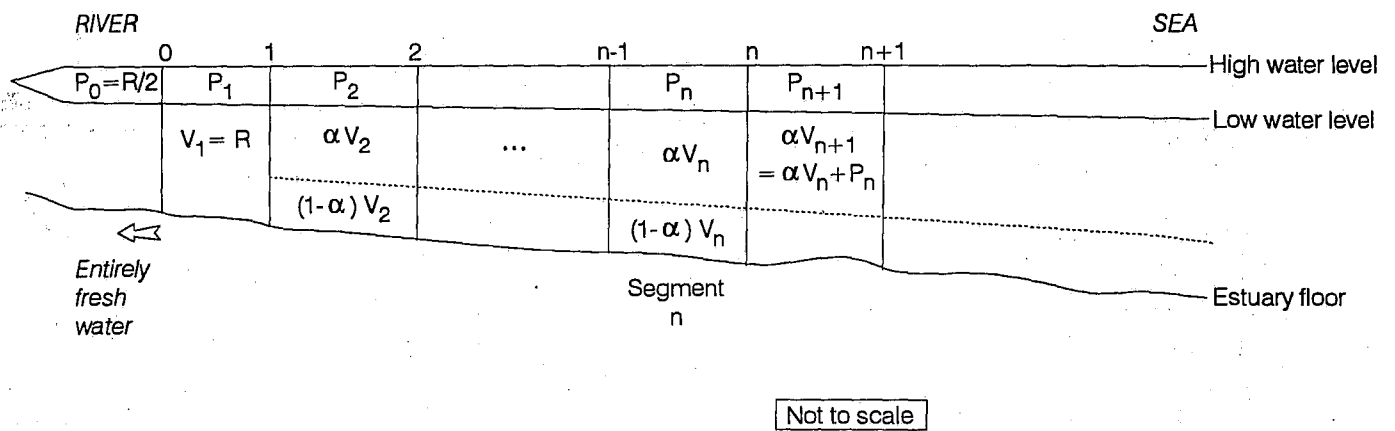


Figure 3

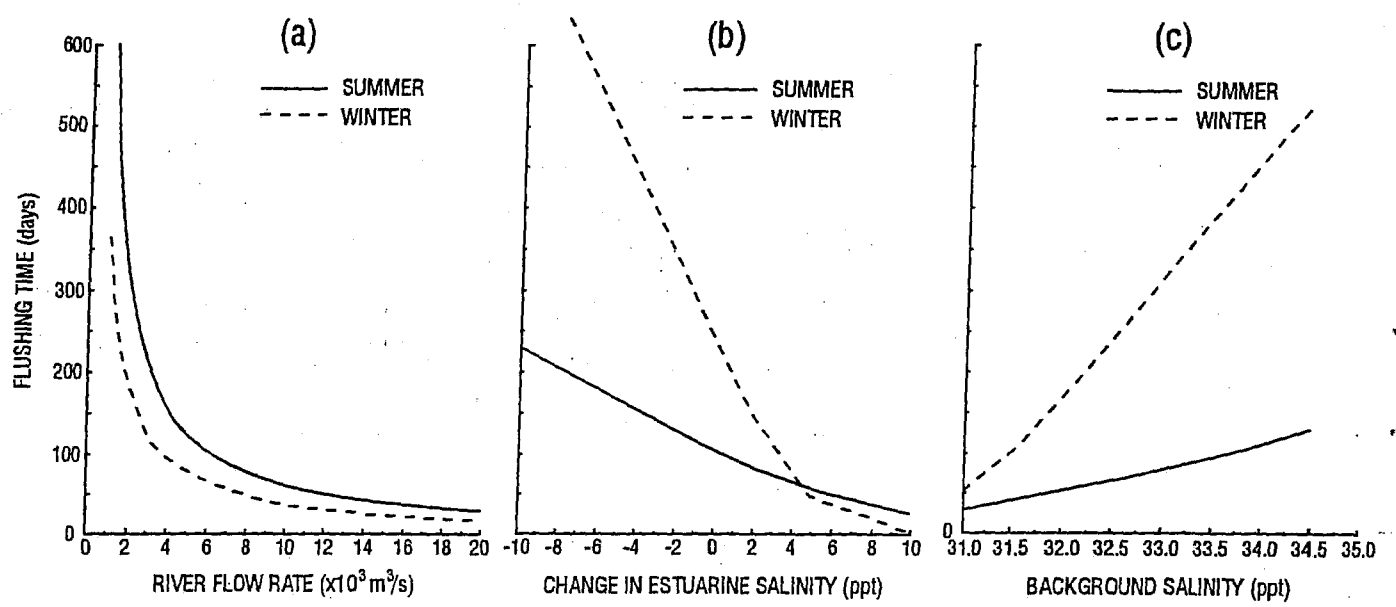


Figure 4

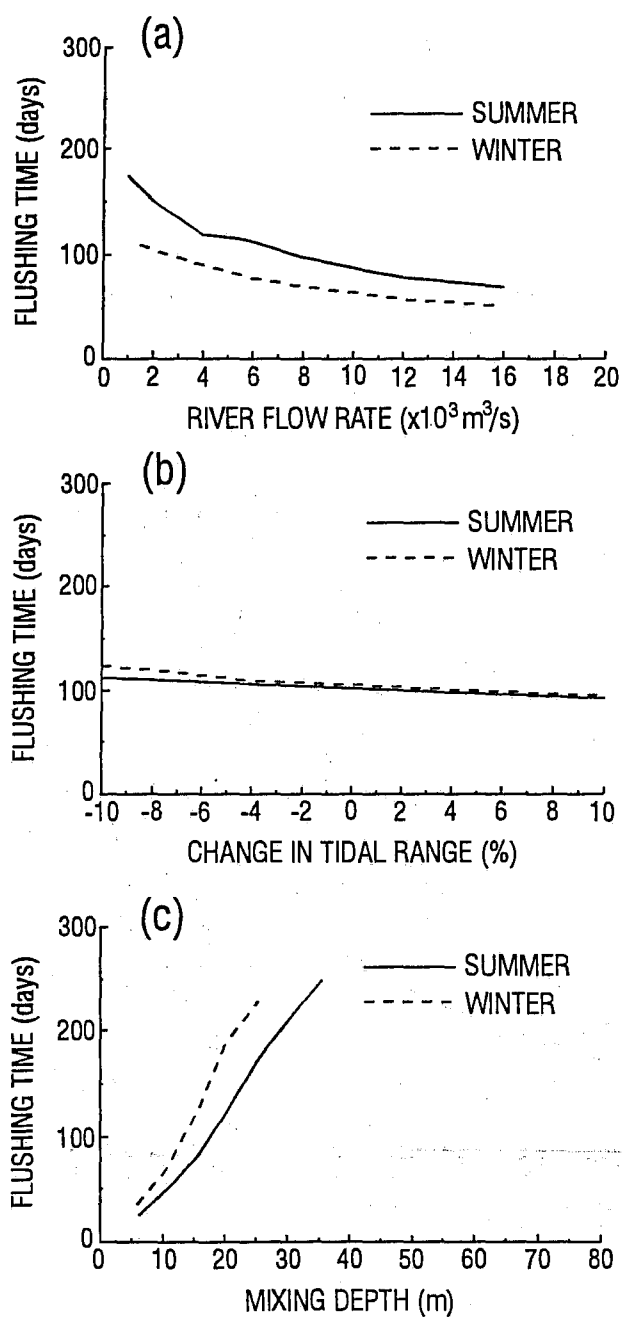


Figure 5

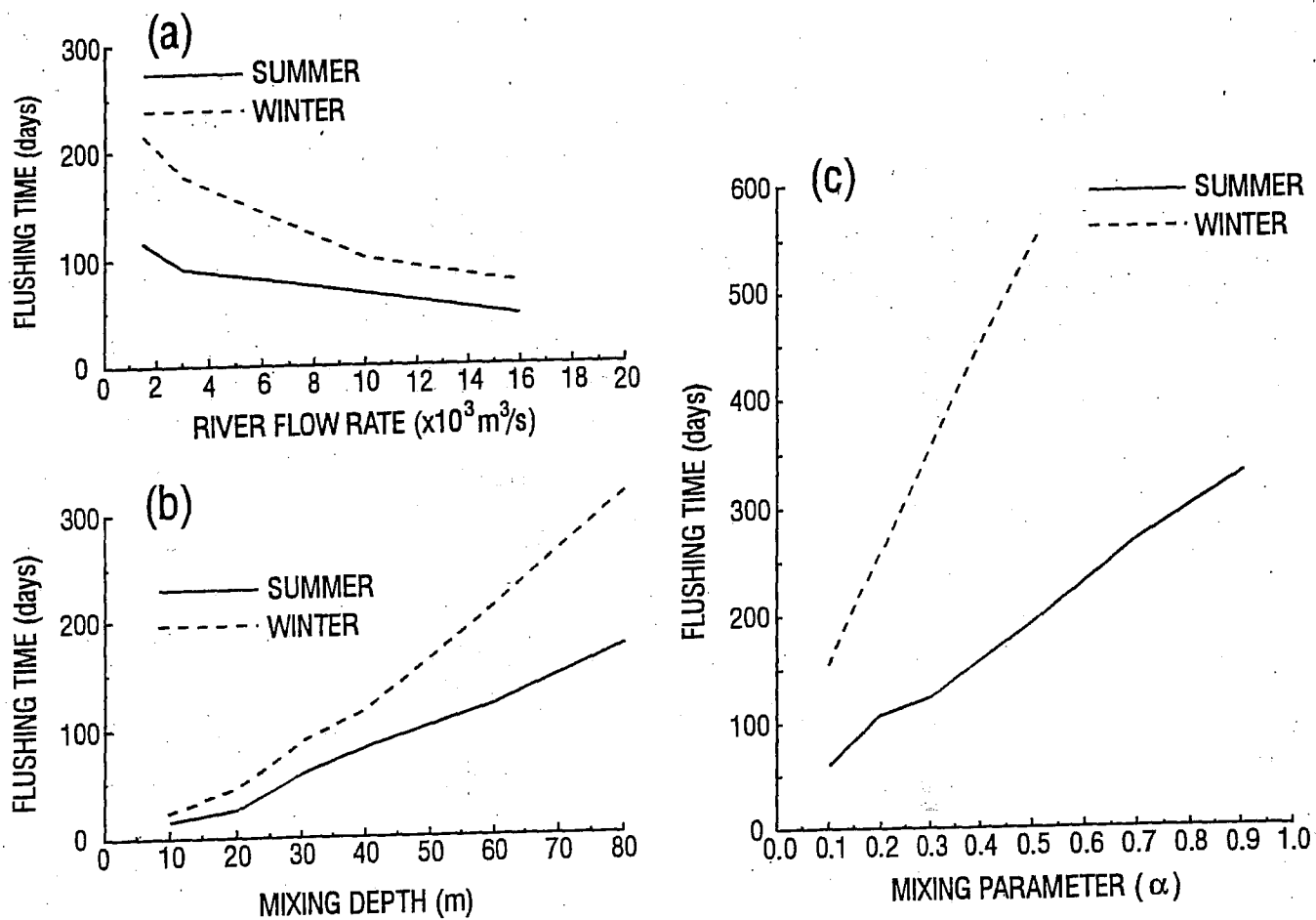


Figure 6