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Water exchange estimates derived from forcing for the hydraulically coupled basins surrounding Äspö island and adjacent coastal water

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Sammanfattning

En numerisk modellstudie som baserats på representativ fysisk drivning (statistiskt medelvärdesbildat under ca. 10 år) har genomförts i Äspö-området, vilket uppdelats i fem separata bassänger, som mellanförbundits med fyra sund och som satts i kontakt med Östersjökusten via tre sund. Vattenutbytet i den grunda Borholmsbassängen med sina förhållandevis små sundsektionsareor domineras kortsiktigt av snabba vattenstånd-fluktuationer medan de baroklina utbyteskomponenterna (estuarin och intermediär cirkulation) på längre sikt även ger bidrag. Den genomsnittliga uppehållstiden (medel-värdesbildad över bassängvolymerna under en hel årscykel) har befunnits vara något längre än 40 dagar för exogent vatten (dvs såväl kustvatten som tillrinnande sötvatten). Detta mått på vattenutbytet är av samma storleksordning som ensemble-medelvärdet av uppehållstiderna för 157 bassänger utmed svenska ost- och västkusten som analyserats på analogt sätt.

Utbytesmekanismerna och modellantagandena diskuteras. Påverkan på utbytestiderna av kort- och långsiktiga variationer i drivningen analyseras även. Standardavvikelsen för uppehållstiden under ett genomsnittligt år (inomårsvariationen) visas vara större än standardavvikelsen när olika år jämförs med varandra (mellanårsvariationen). Detta gäller för samtliga bassänger utom för Borholmsfjärden för vilken dessa två mått visar sig jämförbara. Om en extrem kombination av drivningens olika faktorer som styr mellanårsvariation konstrueras hypotetiskt, befinns det intervall som spridningen håller sig inom vara större ju längre från kusten bassängen befinner sig, mätt som det minsta antalet sund som befinner sig mellan bassängen och kusten. Resultaten från en tidigare undersökning granskas även.

Abstract

A numerical model study based on representative physical forcing data (statistically averaged from approximately 10 years) has been performed of the Äspö area, subdivided into five separate basins, interconnected by four straits and connected to the Baltic coast through three straits. The water exchange of the shallow Borholmsfjärden, with comparatively small section areas of its straits, is dominated by the sea level variations while the baroclinic exchange components (estuarine and intermediary circulation) also contribute. The average transit retention time (averaged over the basin volume for a full year cycle) is found to be a little over 40 days for exogenous water (i.e. coastal water and freshwater combined); this measure of the water exchange is comparable to the combined average of an ensemble consisting of 157 similarly analyzed basins distributed along the Swedish east and west coasts. The exchange mechanisms and model assumptions are discussed. The consequences for the retention times by short- and long-term variations of the forcing is also analyzed. The standard deviation (S.D.) of the retention time during an average year (intra-annual variation) is greater than the S.D. between years (interannual variation) for all basins except Borholmsfjärden for which these two measures are in parity. The range of the retention times that results from an extreme combination of forcing factor variation between years is found to be greater the farther a particular basin is located from the coast, measured as the minimal number of separating straits. The results of an earlier investigation are also reviewed.

Contents

1 Introduction

In the safety assessment of deep geological disposal of spent nuclear fuel, the potential effects on humans and the biosphere are subject to continuous evaluation. A dominating factor is the water turnover affecting dispersal and dilution of radionuclides in the biosphere. Since several possible disposal sites can be located in the vicinity of the coastal area it is important to understand the principles affecting the coastal water turnover. To exemplify, a computation of the water circulation around the island Äspö, where the hard rock laboratory of SKB is situated, naturally suggests itself. In May 1997 the present author was thus contracted by SKB to apply modern methods of coastal oceanography to compute the water exchange of the basins around the Äspö island, including the portion of the coastal zone containing a geological fault.

Notwithstanding that the water turnover is a key factor in determining the human dose of radiation from final repositories located along the coast, the circulation of radionuclides is completely disregarded in this analysis. The focus is set entirely on the water exchange expressed as transit retention times of exogenous water. The prospect of calibrating the actual numerical coastal model with independent radionuclide data presented itself as an attractive and unique opportunity. This has not been possible to realize in this study, however, because of a factually higher degree of data scarcity than was initially conceived. Comparisons with earlier results and to retention times of other coastal areas were also specifically requested by SKB as an integral part of the assignment. Furthermore it was agreed that the report should also entail estimates of the intra- and interannual variations including an analysis of hypothetical years with possible extreme retention times. This defines a range interval that with a high degree of confidence contains the interannual variations.

2 Evaluation of an earlier investigation

An explicit part of the present assignment includes an evaluation of the water exchange section of an investigation performed by Sundblad and Mathiasson (1994), which subsequently will be referred to as SM94. This review has been performed uniquely based on their report, without access to any auxiliary background data they might have used but not presented. Since their report does not reveal any details about how the actual measurements were performed, some hidden merits may thus not be given appropriate credit. An outline of the SM94 investigation is that on 30 occasions (910826 through 910828) the current velocities were measured one at a time (Table 2-1) in the two straits and one culvert that delimit Borholmsfjärden from the coast and adjacent basins (see map: Fig. 2-1). From these measurements in combination with the corresponding section areas, the volume flow was calculated to arrive at a daily average water turnover of $0.22 \cdot 10^6$ m^3. Exactly how this figure was calculated is not clear. This flow is equivalent to 2.6 m^3/s which, however, is almost exactly the average of the absolute (flow direction discarded) volume flow of the accounted exchange under the bridge. No instance of baroclinic (two-way) flow was reported.

From the figures presented by SM94 (reproduced in Table 2-1), one may estimate a measure of an associated section area for the three straits. These estimates vary considerably from one occasion to another, but their averages should reflect the value used by SM94. Since the presented values denote the maximal velocities, not the average, this certainly produces an underestimation of the areas. For checking purposes, the present author performed in early June 1997 a renewed investigation using both echograms and manual sounding methods. A comparison with the presently determined corresponding values confirms this assertion of systematic underestimation in SM94 (Table 2-2), the only exception being the Culvert (S8). The location of this and other items referring to the nomenclature in SM94 may be clearly seen in Fig. 2-2. During the present measurements the extremely low sea level was responsible for the small section area estimated, but is of little significance since this area is within a 5% inaccuracy deemed to apply to the appreciation of the other two straits. Only strait S7 has been estimated solely based on chart and map information. The presently determined value of the surface area has also been extracted planimetrically from charts by Leif Lundgren. For the one basin common to both investigations (Borholmsfjärden, B4), the present estimate coincides exactly with the value given by SM94. All relevant hypsographic basin data are presented in Table 2-3.

The sea level fluctuations have been gauged by a mareograph (operated by SMHI) located in the vicinity of Oskarshamn. The data record has 1-h temporal resolution. A graph of the long-term (1987–1995) development is presented in Fig. 2-3 which includes the time the SM94 investigation took place in late August 1991. A simple barotropic model (Engqvist, 1997) based on the sea level dynamics operating on the basin configuration in Fig. 2-2 (with the presently determined values of the strait section areas and basin surface areas) gives an appreciation of how well 19 of the totally 30 measurement instances in 1991 represent the flow.

Table 2-1. Original data from Sundblad & Mathiasson (1994) and the estimated section area associated with the three straits delimiting the Borholmsfjärden. For the last measurement in the Narrows no volume flux was indicated, and thus only 29 estimates of volume flux are effectively available for the evaluation.

Date	Time	Volume flux (m^3/s)	Max velocity (m/s)	Est. sect. area (m^2)
Bridge:				
910826	14:20	−3.00	−0.17	17.6
910827	10:00	−4.17	−0.25	16.7
910827	14:00	1.84	0.15	12.3
910828	08:10	−1.95	−0.15	13.0
910828	08:40	−2.30	−0.21	11.0
910828	09:10	−0.61	−0.12	5.1
910828	09:40	−1.10	−0.11	10.0
910828	12:00	5.90	0.45	13.1
910828	13:40	4.00	0.25	16.0
910828	15:30	2.50	0.20	12.5
			Mean:	12.7
Culvert:				
910826	15:10	0.22	0.18	1.2
910827	09:35	0.06	0.07	0.9
910827	14:25	0.23	0.18	1.3
910827	15:05	0.02	0.03	0.7
910828	08:30	0.00	0.00	–
910828	08:55	−0.27	−0.22	1.2
910828	10:00	0.00	0.00	–
910828	11:50	0.60	0.43	1.4
910828	13:42	0.40	0.30	1.3
910828	15:25	0.33	0.25	1.3
			Mean:	1.2
Narrows:				
910826	13:10	3.00	0.29	10.
910827	08:50	0.62	0.08	7.8
910827	11:30	1.69	0.23	7.3
910827	12:05	1.15	0.17	6.8
910827	15:10	0.00	0.00	–
910827	15:20	−0.02	−0.03	0.7
910827	15:30	−0.59	−0.09	6.6
910828	10:35	1.95	0.22	8.9
910828	11:00	2.38	0.30	7.9
910828	11:15	–	0.34	–
			Mean:	7.0

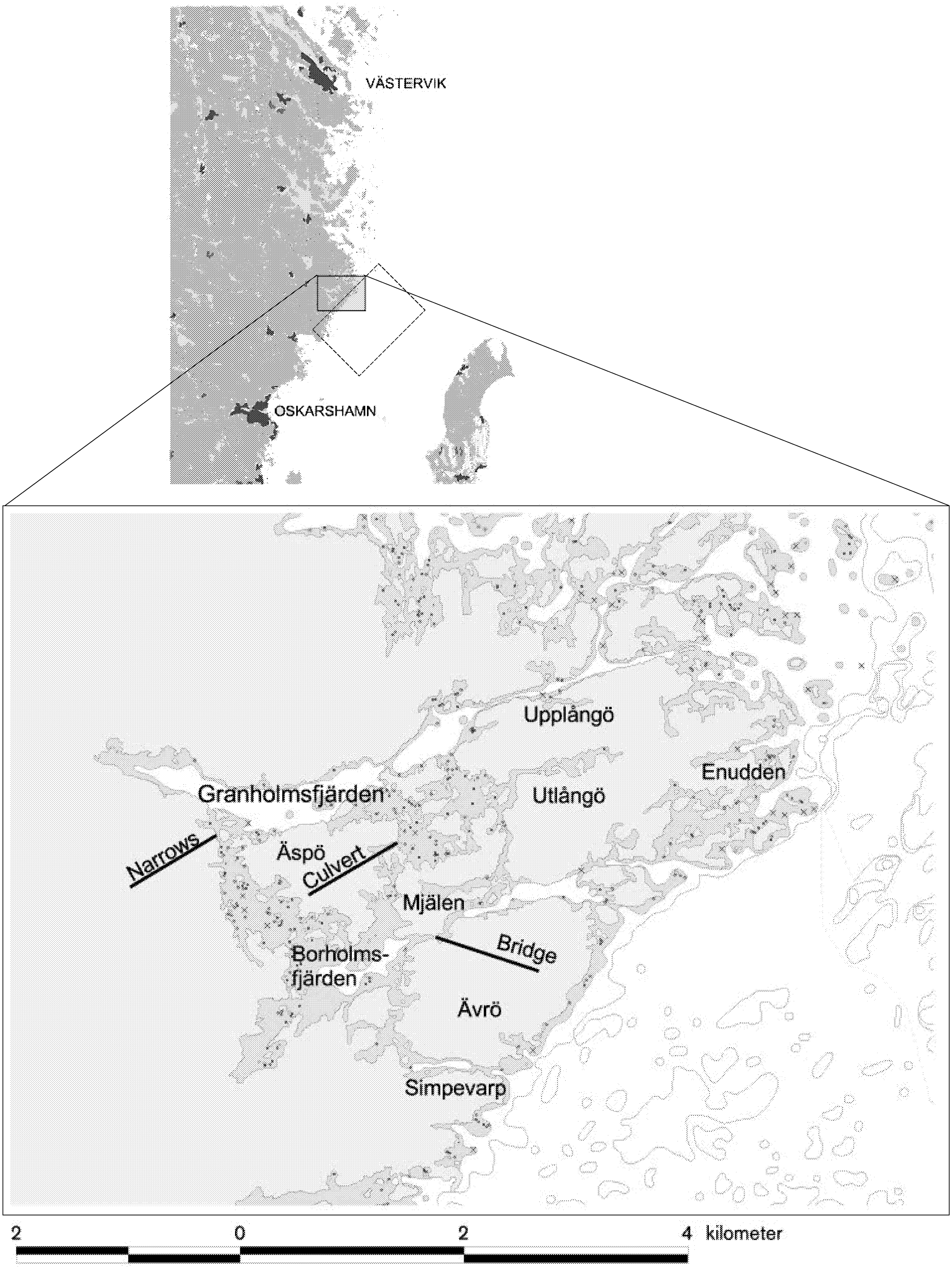


Figure 2-1. *Overview of the study area with the approximate location of the Simpevarp coastal area indicated with broken lines, partitioned according to the Swedish Water Archives (SVAR). A magnification of the Äspö area is also shown.*

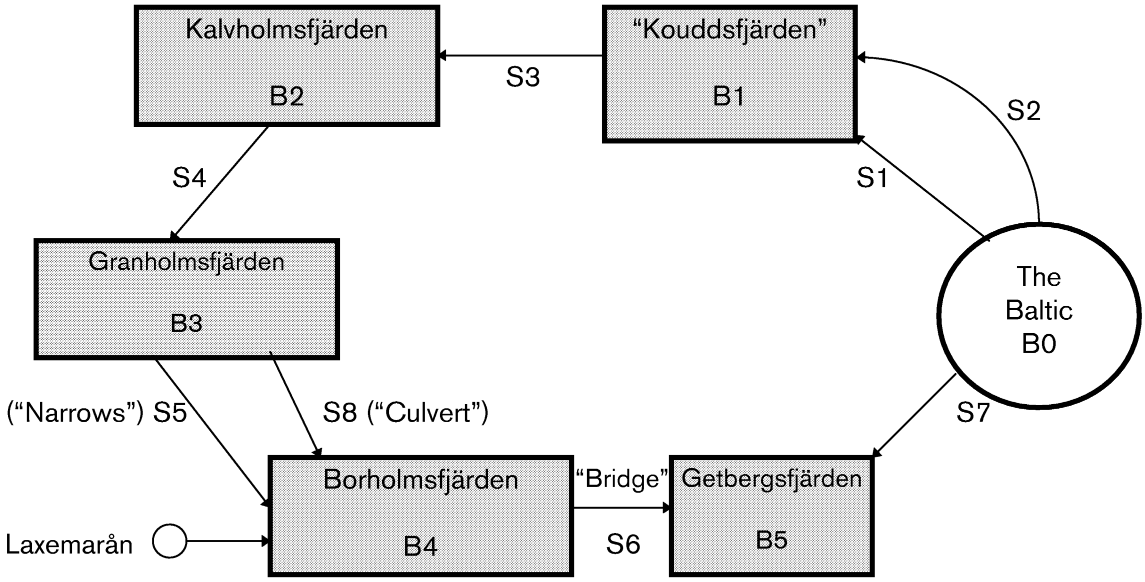


Figure 2-2. *Sketch of the Äspö area configuration, partitioned into five basins (B1–B5) with names according to economic map (6H 3a ÄVRÖ). B1 has been named arbitrarily from a place in the middle of the basin. The arrows define a flow direction denoting positive flow from a basin with a lower ID-number to one with a higher number. The straits occurring in parallel (S1 & S2 and S5 & S8) are conjoined in the simulations.*

Table 2-2. Overview of the hypsography of the straits with reference to Fig. 2-2.

Strait	Name	Max depth (m)	Mean depth (m)	Width (m)	Area (present) (m^2)	Area (SM94) (m^2)	Method
S1		6.5	4.3	58	252		Echogram
S2		4.5	3.5	42	145		Echogram
S3	Djupesund	4.0	2.8	42	116		Echogram
S4		4.7	2.9	44	126		Echogram
S5	Narrows	2.6	1.8	7.4	13.1	7	Echogram
S6	E of Bridge	2.5	1.2	14	16.2	13	Sounded
S7		2.7	2.0	75	150		From chart
S8	Culvert	0.1	0.1	2.7	0.27	1.2	Sounded

Departing from the numbering of the basin configuration in Fig. 2-2, the volume flux Q_{ij} (m^3/s) is counted positively from Basin i to Basin j if i<j. This direction is indicated in the figure. The sea level in Basin i is denoted H_i (m).

$$Q_{ij} = a_{ij} \cdot \frac{H_i - H_j}{\sqrt{|H_i - H_j|}}; \qquad (1)$$

The matrix a_{ij} is defined according to whether the two basins are connected or not:

$$a_{ij} = \begin{cases} \sqrt{2g} \cdot A_{ij}; \text{ if connection } i \leftrightarrow j \text{ exists.} \\ 0 ; \qquad \text{if not.} \end{cases} \qquad (2)$$

Aij denotes the section area of the strait connecting Basin i with Basin j.

The dynamics of this non-linear system are governed by the emptying and filling flows in relation to the surface areas, Y_i (m^2), of the respective basins. If the time derivative is denoted by a supercritical dot, the differential equation becomes:

$$\dot{H}_i = \sum_j Q_{ij} \cdot Y_i^{-1}; \qquad (3)$$

The resulting flow and sea level dynamics are presented in Fig. 2-4. The sea level forcing from the Oskarshamn data has been linearly interpolated so as to achieve a smoother curve, and it can be seen that the basins respond to this by adopting a filling or emptying flow that is maintained over most of the 1-h period while the same forcing regime lasts. Small deviations occur by the shift when the filling (or emptying) rate becomes too steep and the transport capacity of the straits becomes choked.

For the flow at the Bridge it is clearly seen from Fig. 2-4 that the measurements coincide acceptably with the simulated flow, except for the two occasions with outgoing (emptying) flow. For these exceptions the difference is presumably compensated by the baroclinic flow component. For the Narrows the similitude is less striking. The barotropic component would probably match the measured data better if not only the amplitude-attenuating effect for which the simulation accounts, but also the time delay factor had been included. The lag is produced by the transport time of the long surface wave ultimately responsible for the filling/emptying process. Estimates of these time delays are given in Table 2-4, and are small compared to the temporal resolution (1 h) of the sea level measurements.

A good point of SM94 is that the hypsographic data for Borholmsfjärden are decisively more articulate than the information from charts. For example, it gives the maximum depth to 8 m while the chart (No. 624) indicates only 4 m. Therefore the hypsographic figures of SM94 will be subsequently used for Basin 4. Their calculation of the volume from this curve ($3.3 \cdot 10^6$ m^3) seems however to be erroneously exaggerated by 10%. It is also puzzling how they can state “An inflow to the bay through the eastern straits (the bridge and the culvert) will cause, as expected, an outflow in the western narrows” when no simultaneous measurements were made. With the given basin configuration and

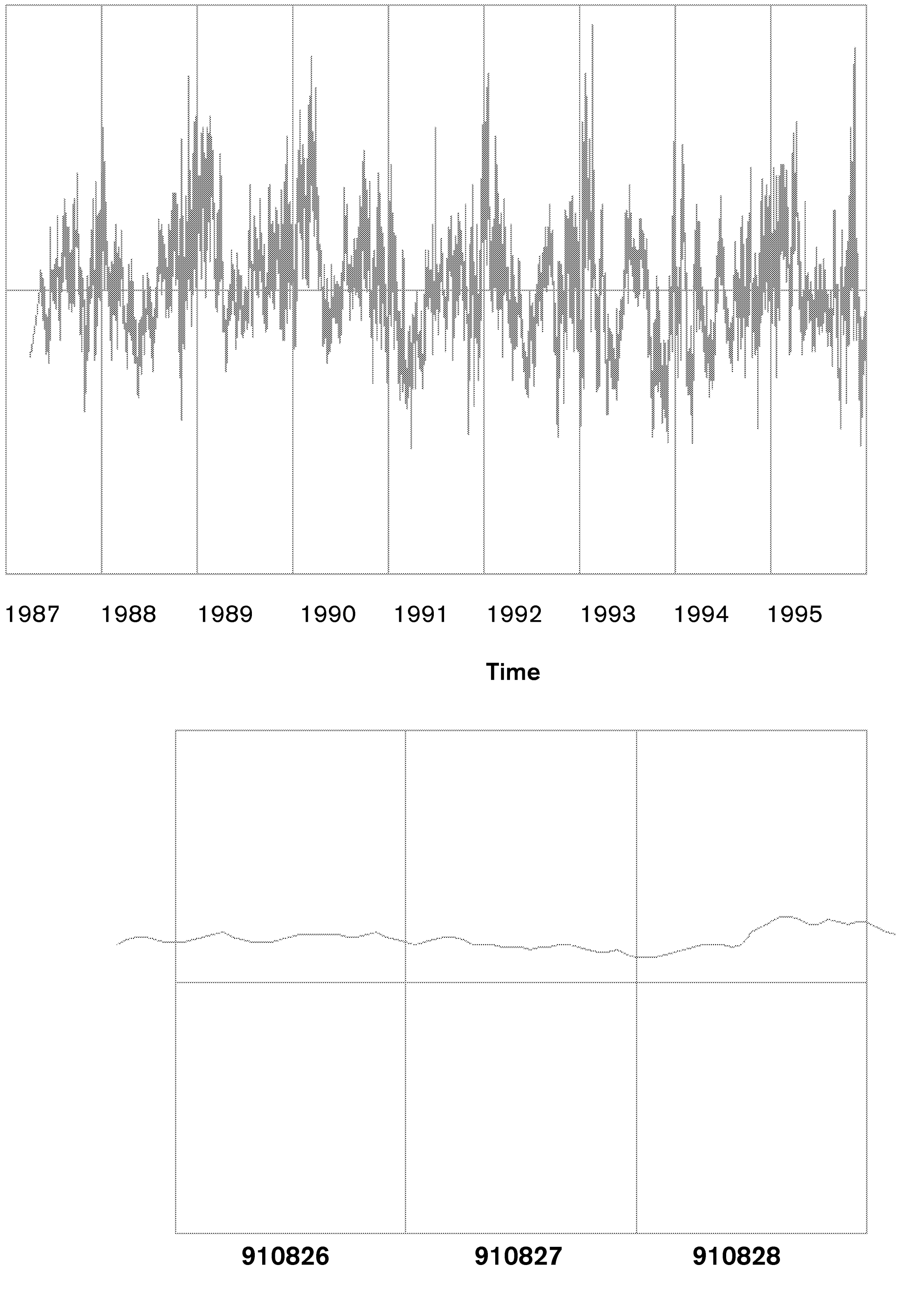


Figure 2-3. Sea level fluctuation at Oskarshamn 1987 through 1995 (upper diagram). The amplitude range is ± 1 m in relation to mean sea level. A time expansion of the study period of Sundblad and Mathiasson (1994) is also shown (lower diagram)

Table 2-3. Hypsography of the Äspö area basins presented as horizontal areas with regard to depth, planimetrically extracted from charts by Leif Lundgren.

Name	ID	Area (10^6 m^2) at various depths					Estimated max depth (m)
		0 m	3 m	6 m	10 m	20 m	
"Kouddsfjärden"	B1	0.15	0.08	0.03			9.4
Kalvholmsfjärden	B2	0.78	0.20	0.13	0.05		15
Granholmsfjärden	B3	1.15	0.62	0.40	0.25	0.03	21
Borholmsfjärden	B4	1.43	0.13				4
Getbergsfjärden	B5	0.30	0.27	0.15	0.01		12
Sum:		3.81	1.29	0.70	0.31	0.03	

Table 2-4. Estimation of the lagtime associated with a long surface wave between the midpoint of the basins indicated in Fig. 2-2.

Section	Length (km)	Depth (m)	Velocity (m/s)	Lagtime (min)	
B0→B1	2.0	6	7.7	4.3	
B0→B2	0.3	6	7.7	0.6	
B2→B3	1.5	5	7.1	3.5	Sum= 7.6
B3→B4	1.0	15	12.2	1.4	
B4→B5	1.5	15	12.2	2.0	
B0→B5	1.4	6	7.7	3.0	3

hypsography, their statement does not either seem to make much sense from a physical point of view. Thus there seems to be room for reasonable doubt about many of the factors involved in the estimation of the residence time of 15 days:

1) The resulting volume flows cannot be derived from presented data in any physically obvious way. The long-term average was most likely overestimated.

2) The calculated volume of the basin is approximately 10% too high. Even though these two errors partly cancel one another when computing the turnover time, they leave the reader less assured about the overall accuracy.

3) Totally well-mixed conditions are unreasonably assumed, thus neglecting the influence of the stratification. According to their colleagues (Persson & Håkansson, 1996) this means a "gross oversimplification".

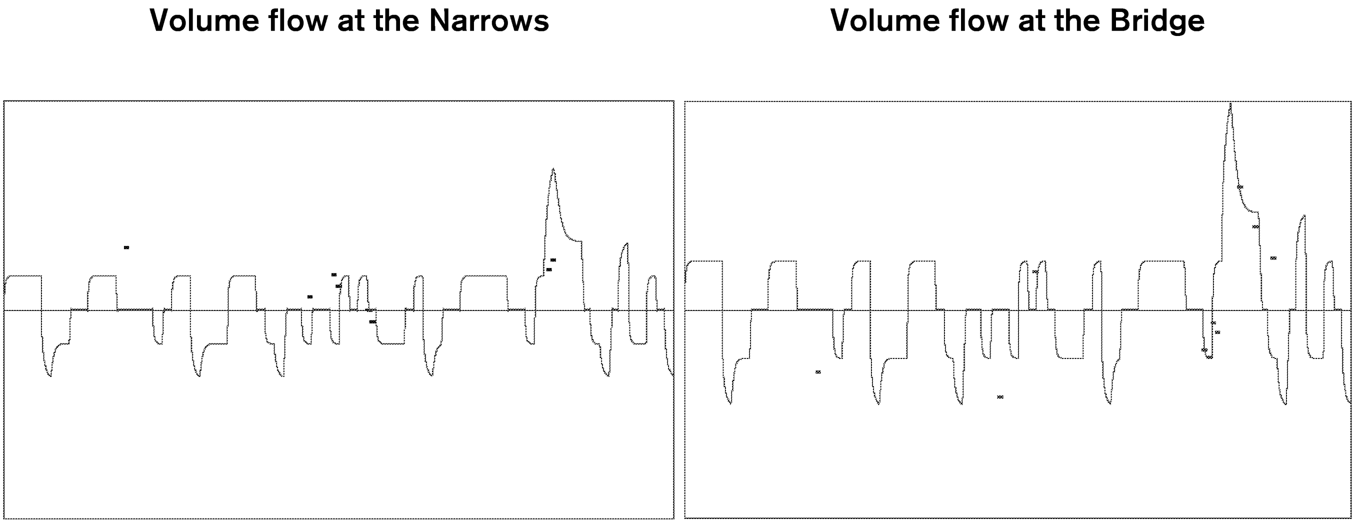


__Figure 2-4.__ Measured and simulated barotropic volume flow through the Narrows (left diagram) and the Bridge (right diagram). The measurements are indicated with filled rectangles while the simulated data form an unbroken curve. The time periods depicted are the same as in Fig. 2-5. The vertical range depicted is ±10 m³/s.

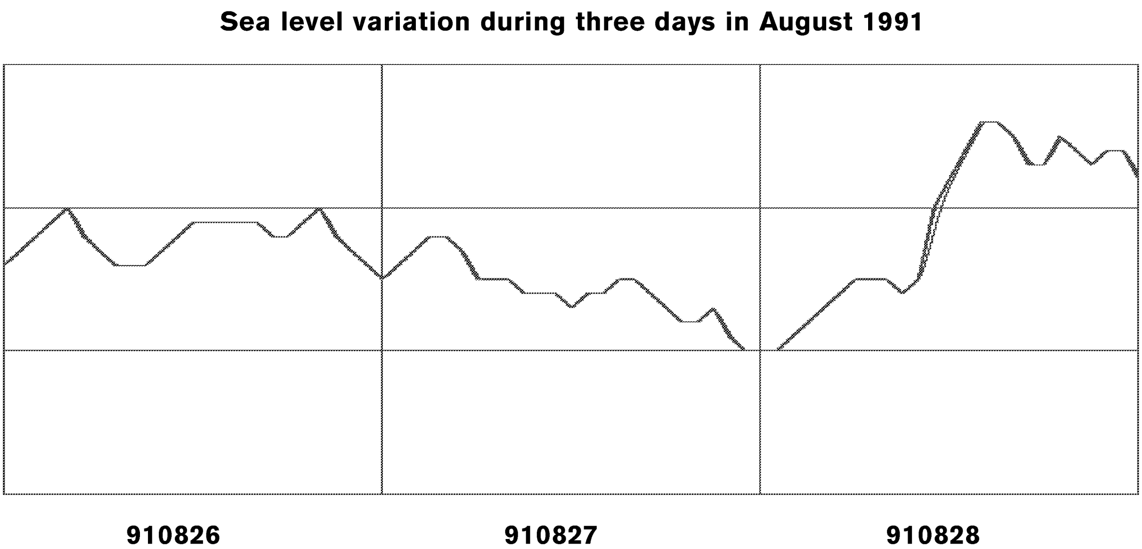


__Figure 2-5.__ Measured and simulated sea level variation at Oskarshamn and the Äspö area subdivided into five basins. The sea level in the basins followed quite closely the forced variations even during the steep rise around noon 910828 when a small deviation was noticeable for the innermost basins. The vertical range is 0–3 dm above the mean sea level.

3 Hypsography of the area

Since the previous section necessitated an introductory discussion of the basic hypsographic features, it seems appropriate here to give only a few additional comments. The primary purpose for the model construct is to achieve the volume (at times of mean sea level) of 1-meter strata from surface to bottom for all five basins and the section areas for the corresponding 1-meter slabs of the straits. This approximation into rectangular geometry is a standard procedure. The result is presented in Tables 3-1 and 3-2.

Table 3-1. Section areas (m^2) utilized in the modelling of the Äspö area.

Depth	S 1	S 2	S 3	S 4	S 5	S 6	S 7
0.5	55.1	39.9	39.5	40.5	6.9	10.8	74
1.5	49.2	35.6	34.6	33.5	4.9	5.4	50
3.5	37.4	27	24.7	19.4	1.6	–	26
4.5	31.6	11.3	9.8	6.2	–	–	–
5.5	25.7	–	–	–	–	–	–
6.5	9.9	–	–	–	–	–	–
7.5	–	–	–	–	–	–	–
Sum:	252.1	145	116	126	13.4	16.2	150

There are some canal-like channels in the area (e.g. Djupesund) with a length of approximately 1.5 km. It could be argued that friction in addition to the form drag flow resistance would be a motivation for including these as a singular basin elements. It will be shown in Section 5 that their influence is negligible even when allowing for the delay of a long internal wave. The same argument applies to the shallower but wider elongated Basin 5 that connects Strait 7 to the coast.

Table 3-2. Hypsography as utilized by the modelling of the Äspö basins, expressed as mean horizontal area (10^6 m^2) at the indicated depth. This value is valid in the model ±0.5 m above and beneath this depth, except for the topmost surface stratum for which the sea level sets the upper limit.

	"Kouddsfjärden"	Kalvholmsfjärden	Granholmsfjärden	Borholmsfjärden	Getbergsfjärden
Depth (m)	**B 1**	**B 2**	**B 3**	**B 4**	**B 5**
0.5	0.14	0.68	1.06	1.30	0.30
1.5	0.11	0.49	0.89	0.85	0.29
2.5	0.09	0.30	0.71	0.40	0.28
3.5	0.07	0.19	0.58	0.15	0.25
4.5	0.05	0.16	0.51	0.10	0.21
5.5	0.03	0.14	0.44	0.07	0.17
6.5	0.02	0.11	0.38	0.05	0.13
7.5	0.02	0.09	0.34	0.02	0.10
8.5	0.01	0.07	0.31	–	0.06
9.5	–	0.05	0.27	–	0.03
10.5	–	–	0.24	–	–
11.5	–	–	0.22	–	–
12.5	–	–	0.19	–	–
13.5	–	–	0.17	–	–
14.5	–	–	0.15	–	–
15.5	–	–	0.13	–	–
16.5	–	–	0.10	–	–
17.5	–	–	0.08	–	–
18.5	–	–	0.06	–	–
19.5	–	–	0.04	–	–
20.5	–	–	–	–	–
Sum:	0.54	2.28	0.61	2.94	1.81

4 Water exchange in relation to physical forcing

The water exchange mechanism may be subdivided into barotropic-based exchange (i.e. induced by mere freshwater run-off or coastal sea level changes) and baroclinic-based exchange (i.e., estuarine circulation and intermediary circulation). Sea level tilting in a basin may be induced by stress of the local wind so that a net sea level difference across a strait occurs during the duration of the wind surge. The associated slushing of the top layer between basins may, however, be ignored since it normally contributes only insignificantly to the water turnover (Engqvist & Omstedt, 1992).

The barotropic exchange mechanism is very simple indeed. A forced sea level difference produces currents to diminish this difference because "water seeks it own level". This occurs regardless of how the sea level difference has been induced, whether by adding fresh water to a basin or by low-frequency fluctuations of the sea level at the adjacent coast (Fig. 4-1a). The process of diminishing the sea level differences for any given stationary forcing normally reaches an equilibrium with the sea level differences exactly maintained for adapting the resulting flow to the sources (e.g. freshwater discharge) or possible sinks. The exception to this process is when long channels store a sufficient amount of kinetic energy as to be capable of overshooting the equilibrium point, producing a resonance phenomenon called (Helmholz-) *seiches*. The process of sea level adaptation is not instantaneous as has been already mentioned in Section 3, since it is mediated by a long surface wave with finite velocity. Any constriction along the path of this surface wave will also attenuate its amplitude. The Äspö basins behave regularly in the sense that both these lag time constants are short in comparison to the resolution of the forcing. The sea level in all basins thus effectively follows in unison the sea level fluctuations at the coast.

The baroclinic mechanisms are somewhat more complicated. If freshwater were to be carefully added on top of a basin which is homogeneously filled with denser (brackish) water when there is no wind (or other sources of vertical mixing), no mixing takes place. In this steady-state situation exactly the same volume flow of fresh water would exit the basin as a thin layer on top of all straits (Fig. 4-1b). If, on the other hand, there is a wind blowing (Fig. 4-1c), the top layer will mix with the brackish water beneath the freshwater layer so that a thicker surface layer with an intermediate density (between the density of the fresh and the brackish water) is created. The more intense the mixing, the thicker the layer, until the whole basin is homogeneously well mixed. Even so, this layer must leave the basin in order to attain a new equilibrium for the flux of the fresh water added. On the other end of the straits there will be unmixed water with the originally assumed density. The pressure at a given point (depth and location) is equal to the weight of a water pillar (unit area) from this depth to the surface. On two locations at the same depth on opposite ends of the strait, the outside pressure will thus be greater since it contains proportionally more of the denser water. This presupposes that the additional height of the interior water column is sufficiently small. Then an inward flow of the denser bottom-most water driven by this pressure gradient will occur. This filling current increases the interior sea level and also replenishes the brackish water that has been entrained into the surface layer. In time, a stationary regime is reached, called the estuarine circulation, which is characterized by contra-flowing layers (Fig 4-1c).

There is another baroclinic exchange mechanism of importance, most noticeable by the current induced at an intermediary level of a coastal basin (mainly coinciding with the depth of the lowest threshold) and is thus called intermediary circulation (Stigebrandt, 1990). This process may be best described departing from a lock-exchange type situation when a sluice gate is suddenly opened (Fig. 4-1d) so that two homogeneous water masses with differing densities suddenly meet. To make the reasoning simpler it may be assumed (contrary to a real lock) that the sea levels are initially the same. At the moment of opening the gate, the denser water will instantaneously be forced by the pressure gradient to fill the side with the lower density. This will increase the sea level

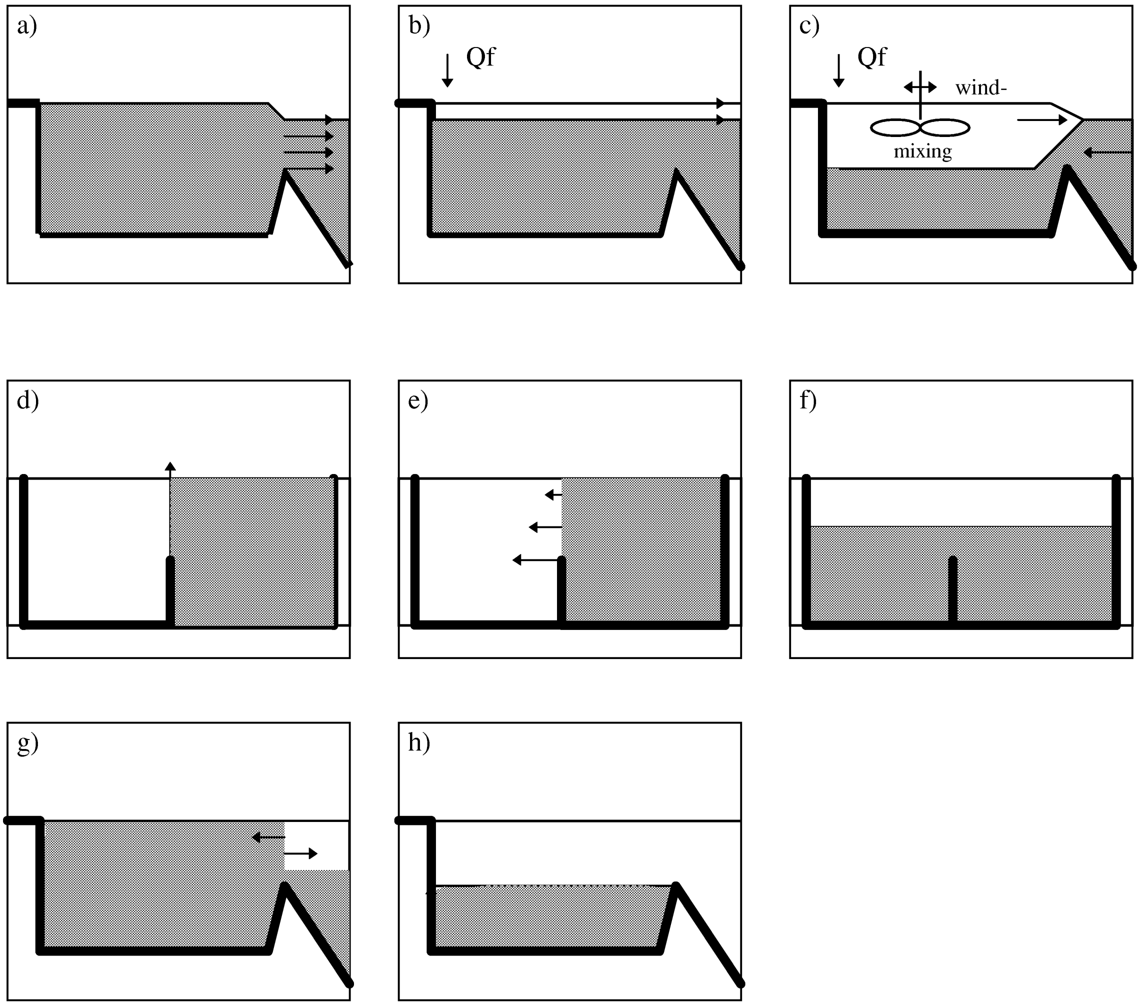


Figure 4-1. *Sketches of various flow regimes with relevance to water exchange in a coastal embayment:*

a) Barotropic flow induced by sea level lowering at the coast.
b) Barotropic flow induced by freshwater disharge. No mixing occurs.
c) Barotropic flow as in b) but vertical wind mixing present. Estuarine circulation occurs in steady state.
d) Lock exchange situation – before lifting the sluice gate.
e) Lock exchange situation – at the onset of the intermediary water exchange.
f) Lock exchange situation at rest equilibrium after passage of sufficient time in order to dissipate the transiently produced kinetic energy.
g) Intermediary exchange at down-welling situation – early stage.
h) Intermediary exchange at down-welling situation – equilibrium state after extended time period.

on the lighter side and eventually this water will start to flow on top into the basin with the denser water (Fig. 4-1e). Note that no freshwater needs to be added. If the basins connected by the lock gate are sufficiently large, this process can continue for a long time. The exchange will cease only when the two water bodies are evenly distributed over the two basins (Fig. 4-1f), the lighter on top, the denser on the bottom, with an exactly horizontal interface between them. This exchange mechanism occurs all along the coasts in up-welling situations, with the only difference being that the resulting vertical stratification is less homogeneous. The final result is the same. If a sufficiently long time is allowed for the adjustment, the coastal water density will be attained by all the coastal basins, provided that there are no freshwater discharges. If this is the case, then the estuarine and the intermediary processes must compete, which would mean a similar but yet altered flow regime. The same intermediary process works on down-welling occasions, but then the denser bottom water of the coastal basins is refrained from flowing back out if there is a sill obstacle blocking the passage (Fig. 4-1g).

The advantage of the model approach is that all these water exchange processes are permitted to act simultaneously and in concert as they do in reality. The water exchange may be computed without the arbitrariness which occurs when the mechanisms are treated separately and eventually must be weighed together. The underlying theory of the water exchange mechanisms is based on Stigebrandt (1977, 1981, 1989, 1990); details of the model formulations can be found in Engqvist (1996a) and Engqvist and Omstedt (1992).

The measurements used for the forcing are always limited by a finite temporal resolution. The long waves associated with the sea level fluctuations only temporarily choke the flow. The long-term variations are considerably smaller and can be computed from the monthly averages of the sea level rate of change given in Table 4-1. To evaluate the variations on a monthly basis, two consecutive monthly averages must be divided by the intervening number of days. This gives a considerably smaller rate of change, meaning that the compared short-term temporal resolution is adequate. For the temporal resolution of salinity and temperature the situation is different. These data were measured by the Swedish Coast Guard at Kungsgrundet, located clearly offshore approximately 30 km northeast of the study area. The average temporal resolution of the available data is on

Table 4-1. Monthly averages of the short-term sea level rate of change as gauged by SMHI in Oskarshamn expressed as (cm/day). The S.D. of the interannual variation is 1.7 (cm/day). Data are missing the first four months of 1987.

	Month												
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Yearly average:**
1987	–	–	–	–	19.3	22.9	20.5	20.3	31.9	23.6	23.6	40.8	25.4
1988	34.4	33.0	18.1	25.2	17.0	21.0	26.9	20.9	36.0	35.5	40.9	49.2	29.8
1989	41.9	40.5	32.7	21.9	19.7	20.6	22.3	26.3	21.0	34.8	32.7	43.7	29.8
1990	35.2	45.4	44.0	23.5	18.8	19.6	23.7	20.6	28.9	34.4	31.5	31.6	29.8
1991	41.5	24.8	22.0	19.8	19.8	31.0	16.1	21.6	28.4	22.4	37.0	47.3	27.6
1992	50.8	36.3	33.9	25.5	22.0	18.6	22.5	29.8	21.0	28.5	36.3	36.8	30.2
1993	65.1	42.6	28.8	18.5	18.3	21.0	23.9	23.4	21.9	30.6	19.8	35.5	29.1
1994	37.5	19.4	32.1	21.0	18.7	26.6	4.2	22.1	34.1	33.7	35.5	30.0	27.1
average:	43.8	34.6	30.2	22.2	19.2	22.7	21.3	23.1	27.9	30.4	32.2	39.4	28.9

the average a little over two weeks. The intermediary circulation process adapting the Äspö area basins to this varying density is mediated by an internal long wave in analogy to the long surface wave responsible for barotropic adaption. From a spectral point of view, the variations may be resolved into equivalent sine waves. The highest frequency that may be resolved (the Nyquist frequency) is thus about one month. It is very likely that there are short-term fluctuations present with a considerably more intense rate of change. To compensate for these fluctuations, a short-term sinusoidal component has been added to the forcing data. An overview of the forcing and the added harmonic sine waves with a time period shorter than the resolved period (one month) is presented in Table 4-2. The amplitudes associated with the basic data are founded on spectral analysis. The higher frequencies that are relevant for the short-term forcing are added by a superimposed sine wave with an amplitude multiplied by $\sqrt{2}$ so as to produce the same standard deviation (denoted δ in the table) in accordance with the actual measurements. The sea level fluctuation is an exception: The amplitude of the 2-day time period is so chosen that the average rate of change ($d\overline{Wl}/dt$) comprises the contribution of the higher frequencies down to 0.5 h^{-1}. The superimposed, extremely slow 1-year time period long-term variation with an amplitude of 0.5 m does not significantly contribute to water exchange but is merely added for model-checking purposes.

From measurements of salinity and temperature at opposite ends of Djupesund, the speed of the long internal baroclinic wave could be appreciated to amount to 9 cm/s in conditions measured in June 1997. The barotropic flow would then typically amount to 3 cm/s at the average short-term mean rate of change. This means that the baroclinic exchange on this occasion dominated the barotropic exchange even though it would take about 3 h to pass Djupesund. Meanwhile the short-term variation of the sea level fluctuations could be reversed. The result of such non-linear interaction is mainly that the oscillating barotropic flow enhances the barotropic component (Stigebrandt, 1977). Since the baroclinic component is dominant, the actual short-term flow regime can be replaced, without more than marginally changing the long-term averages, by allowing the barotropic filling rate to persist one full 24-h period followed by a period of equal length of emptying at (almost) the same flow rate. A small amplitude long-term drift with a time period of one year may certainly be admitted merely for checking purposes.

If there is a sufficiently intense coastal current so that a net sea level is formed between different geographically separated entrance straits, a net circulation through the entire basin cluster may emerge. Because of the short distance between the entrance straits, approximately 2 km, there seems to be no reason to assume that this mechanism would contribute significantly to the Äspö area circulation.

Table 4-2. The highest frequency resolved (Nyquist frequency) of the forcing data is 0.5 month^{-1} for all data except for the sea level fluctuation for which it is 0.5 day^{-1}.

Forcing	Long-term variation Time period	Short-term (added harmonic) Amplitude	 Time period
sea level	1 year	$\pm 0.5 \cdot d\overline{Wl}/dt$	2 days
wind (cubic mean)	2 months	±10%	15 days
salinity	2 months	$\pm\sqrt{2}\cdot\delta S$	30 days
temperature	2 months	$\pm\sqrt{2}\cdot\delta T$	30 days
fresh water discharge	2 months	±10%	10 days

5 Model study of the water exchange of the Aspö basins

The numerical model employed has evolved from an original "one basin-one strait" version (Engqvist, 1993). The number of basins and straits has successively been increased to reach eight basins and 11 straits in a study of the Stockholm archipelago (Engqvist 1996b). The barotropic formulation is based on Engqvist (1997). The calculation of the barotropic flow component for estuaries with no internal circulation loops (the number of basins equals the number of interconnecting straits) is straightforward (Engqvist & Omstedt, 1992). In the case of Äspö when the number of straits (7) exceeds the number of basins (5), two internal circulation loops occur. One such loop (S1 & S2) can trivially be resolved into an equivalent section area of the sum of these two. For the other loop, the scheme has been used which together with continuity equations resolves the flow (Engqvist, 1997).

The baroclinic formulation, the basin response of the flushing of in- and outflowing water, as well as the well-mixed layer dynamics are given in detail by Engqvist and Omstedt (1992) and Engqvist (1996b). During ice cover periods (January and February) the wind mixing has been reduced by a factor 10. Such a reduction also applies to the sea level fluctuation (Omstedt, 1994) and both these mechanisms have been incorporated in the model. All the modeled areas are sufficiently confined by land to meet the basic model assumption of controlled intermediary exchange.

The α-parameter, denoting the fraction of the total acceleration that takes place upstream of a strait, has been adopted from the coastal exchange theory (Stigebrandt, 1990). This parameter has throughout been given the value 0.4 indiscriminately, whether the actual strait hydraulically controls the flow or not. This may for some time duration result in an exaggerated internal circulation, but is, however, compensated by lowered flow as the baroclinic wave subsides. This procedure works acceptably well in the Stockholm inner archipelago (Engqvist, 1996b). The diffusivity of the waters below the well-mixed layer was modeled according to Stigebrandt (1987) and the maximum value of the diffusivity constant is set to $1 \cdot 10^{-6}$ m^2/s. The depth strata (beneath the varying surface stratum) for all areas are modeled with a thickness of 1 m. This also applies to the utilized section area of the straits with the slight error occurring that stems from the approximation of the real section area into rectangular slabs.

Prior to each yearly cycle simulation, the model was run idly for three months in order to reach a quasi-stationary equilibrium and to rid itself of initial transients.

The average retention time (*sensu* Bolin & Rodhe, 1973) is computed by giving the incoming water, whether from the sea or from freshwater run-off, an age of zero days per unit volume. Such incoming water will subsequently be called collectively "*exogenous*." The aging of the water contained in the various basins is increased by one day for every day passed (Engqvist, 1996a). The quality modeled is thus "age per volume," with the dimension [days$\cdot m^{-3}$]. The quasi-stationary equilibrium reached by the aging, slushing and mixing processes produces the presented age distribution which is mainly inversely proportional to the intensity of the ventilation of the exogenous water.

The result of this primary simulation, run with hydrographical and forcing parameters identical to those for 157 other coastal embayments in another study, is presented graphically in Fig. 5-1. It is clearly seen that the denser water enters the basin from below by filling the bottom-most layers first. By the same token this water will have a rejuvenating effect on the age of the basin's contained water. The average for the one-year simulation period for the 1-m strata is presented in Table 5-1, as is the average over the basin volume (age/m^3). Because of the hypsographic curve, the surface-most layers carry more weight since these represent a larger volume of water than the bottom-most ones.

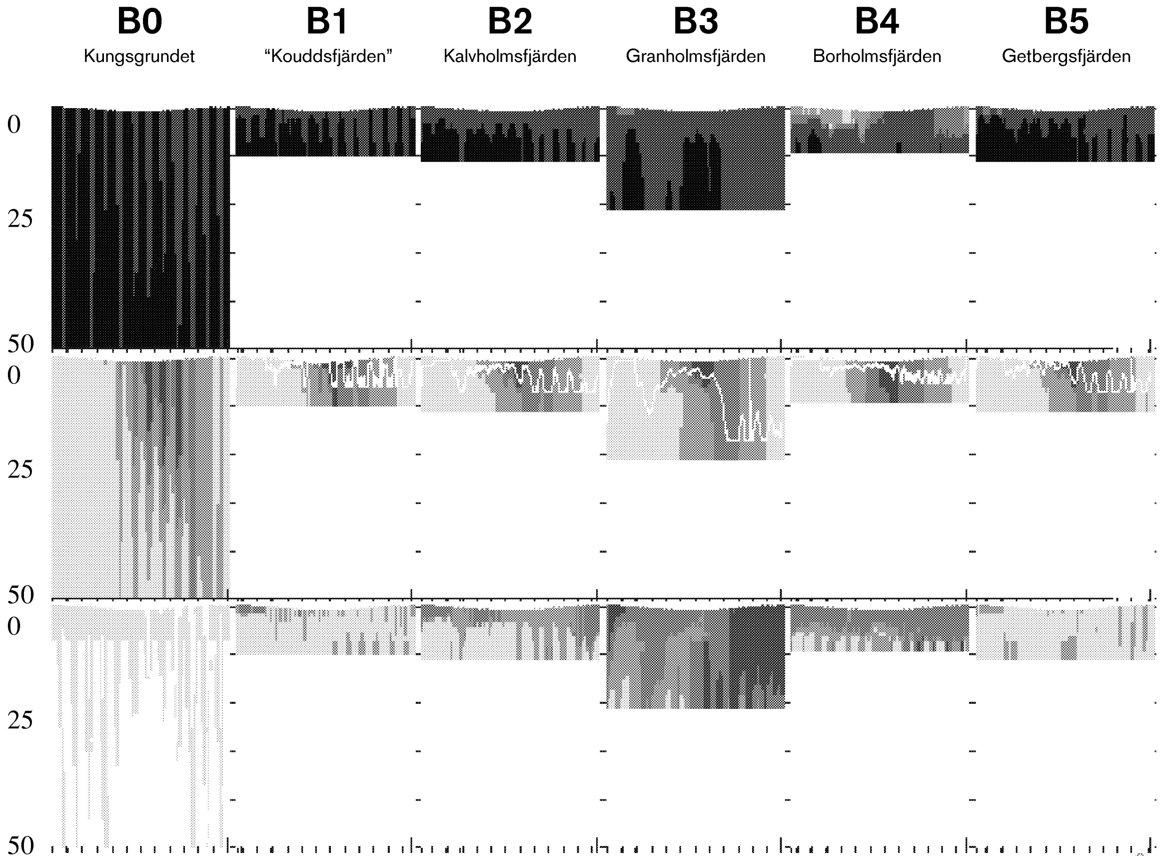


Figure 5-1. Overview of one-year standard simulation of the four Äspö-basins depicting: salinity (upper diagram), temperature (middle diagram) and retention time (lower diagram) as functions of time (horizontal axis) and depth (vertical axis) spanning 0–50 m. The white line in the middle diagram marks the depth of the well-mixed layer (see text). Darker shades indicate more elevated values of salinity, temperature and retention time (age).

Table 5-1. Average retention time (days) of exogenous water for the five basins into which the Äspö area has been subdivided according to Fig. 2-2.

Depth	B1	B2	B3	B4	B5
1	22	39	57	48	18
2	15	38	57	49	16
3	8	34	56	48	13
4	4	26	54	46	12
5	4	19	52	41	11
6	5	17	50	35	10
7	6	16	50	31	10
8	9	16	51	30	12
9	9	15	51	30	12
10	9	15	51	0	11
11	0	15	50	0	11
12	0	0	50	0	0
13	0	0	50	0	0
14	0	0	49	0	0
15	0	0	48	0	0
16	0	0	47	0	0
17	0	0	46	0	0
18	0	0	44	0	0
19	0	0	42	0	0
20	0	0	40	0	0
21	0	0	40	0	0
Average:	12	31	53	47	13

For comparison purposes, the forcing applied is identical to the set used to compute the other coastal basins whose retention times are presented in Fig. 6-1. The youngest water appears at the bottom because the denser water from Baltic coast is interleaved there due to the intermediary circulation. The small influence by the fresh water on rejuvenating the surface water of Basin 4 (Borholmsfjärden) is barely noticeable by rendering the topmost layer a somewhat lower retention time than the adjacent stratum. The averages with regard to volume are presented on the last line and are the quantities compared in Fig. 6-1. Non-applicable strata are indicated by zero.

6 Comparison to the retention time of other coastal embayments

The present simulation results may be compared with those of a study of retention times aimed at producing retention time estimates for a selection of 157 coastal basins (selected for their relevance in judging ecological quality criteria). Although the final selection in retrospect turned out to be complicated, an overall ambition was to make the chosen basins as evenly distributed along the Swedish coast as possible and as representative from an *a priori* water turnover point of view. In Fig. 6-1, a histogram is presented of the volume and time average retention times of exogenous water for this set of basins. The two major basins of the present study (Borholmsfjärden and Granholmsfjärden) with an average retention time of 40 and 52 days respectively, fall very close to the grand average (37 days) of this 157-basin ensemble.

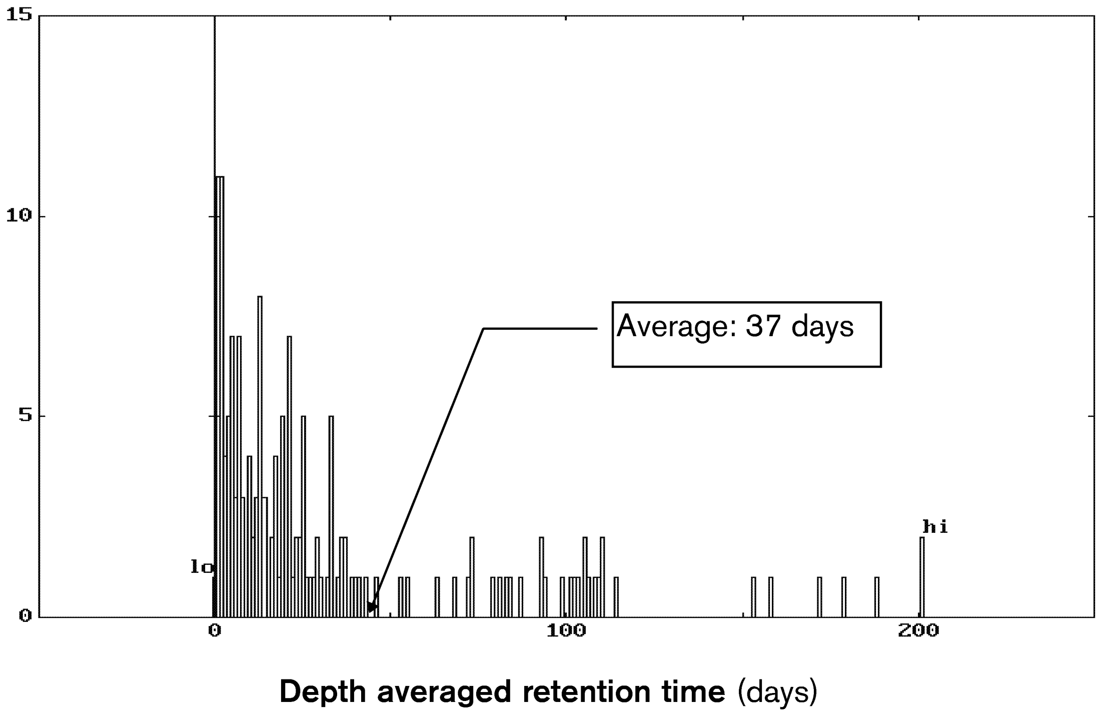


Figure 6-1. *Histogram over retention times for a representative selection of 157 coastal basins distributed along the entire Swedish coast. The retention times of the two major Aspö area basins Borholmsfjärden (45 ±3 days) and Granholmsfjärden (50 ±3 days) fall just above the average 37 days of selected basins.*

One may also like to take into account the age profile of the retained water. One way of achieving this is to plot the retention time of the bottom water against that of the surface water, producing a scatter diagram such as that given in Fig. 6-2. Basins below the separating line indicate those that are deeper and those with more intense freshwater flow where the retention time of surface layers is comparatively lower. Normally, but not invariably, the volume average falls in between the retention times of the surface and bottom strata. The exceptions are basins with moderate freshwater discharge together with a marked sill that are separated from the coast by at least one basin in between. For these basins the entering bottom water will on the average be densimetrically interleaved, not at the bottom, but at an intermediary level. In Fig. 6-2, the Äspö basins fall above the line denoting basins for which these retention times of the bottom and surface waters are equal. As has been stated above, this is a consequence of the feeble freshwater forcing admitting the intermediary circulation to act freely with minute inhibiting interaction.

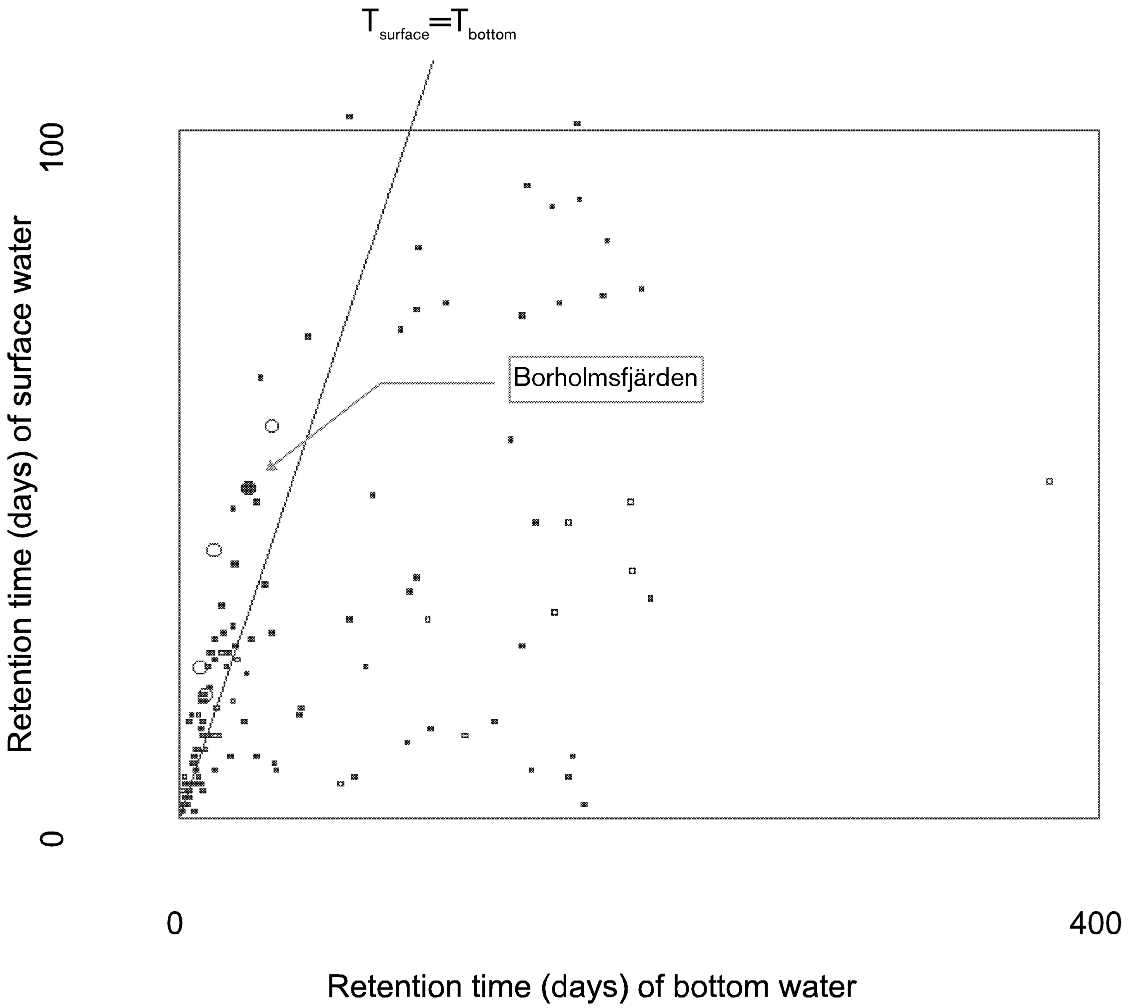


Figure 6-2. *Retention time (days) of surface water versus retention time of bottom water for 139 coastal basins along the Swedish coast (filled squares are located on the east coast; non-filled on the west coast). The circles denote the Äspö-area basins of which Borholmsfjärden has been explicitly marked. The range of the vertical axis is 0–100 days and 0–400 days for the horizontal. The diagonal line indicates the loci for which the retention times for bottom and surface exogenous water are equal. All the Äspö basins fall above this line which is a consequence of the marked sills and the baroclinic exchange, rejuvenating primarily the bottom water. The Norrland coast (18 basins) is excluded in this diagram.*

The variation of the retention time during the standard one-year simulation is depicted in Fig. 6-3; the corresponding average and standard deviation (S.D.) of the different basins' volume average retention times are presented in Table 6-1. These latter values represent a measure of the *intra*-annual variations, to be later compared to the estimates of *inter*annual variations in Section 9.

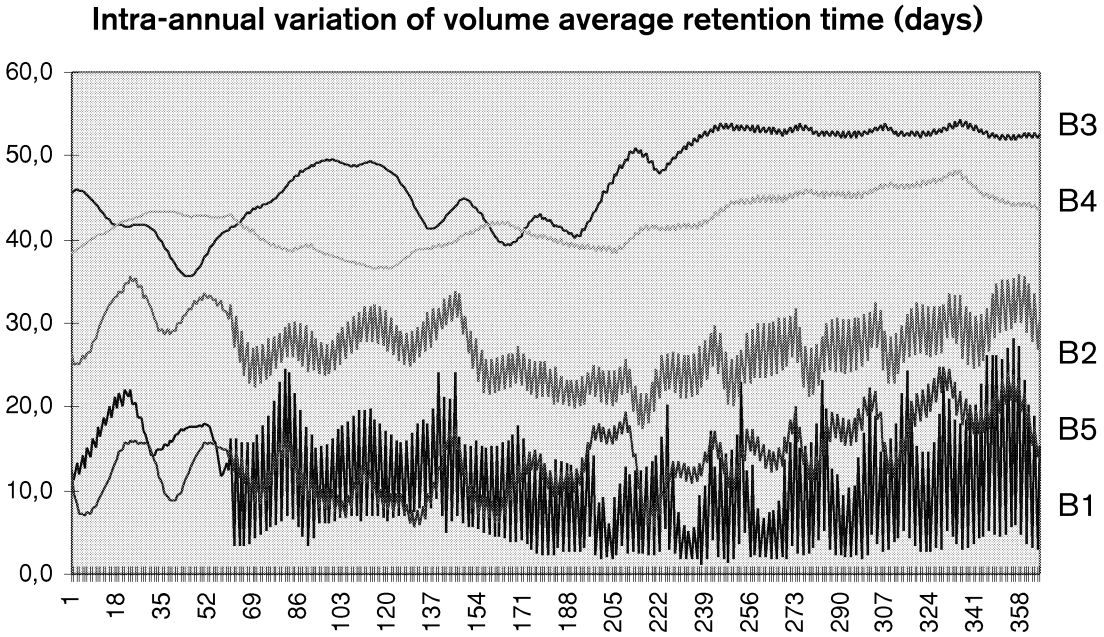


Figure 6-3. *Volume average retention time (days) for the five Äspö basins (B1–B5) for the one-year simulation with standard forcing parameters and with monthly resolved average sea level fluctuations. The ice cover period with reduced sea level fluctuation during the first two months of the year is conspicuous as is the slushing back and forth of the water in the outermost basins B1 and B5.*

Table 6-1. Volume average and standard deviation (S.D.) of retention time (days) estimates, averaged over volume and time of the five Äspö area basins B1–B5.

	B1	B2	B3	B4	B5	Comment
1) Vol. average: retention time	12	31	53	47	13	Parameters equal to compared basins
2) Vol. average: retention time	11	27	47	42	14	Short-term sea level rate of change adjusted
Range 1)–2)	±0.5	±2	±3	±2.5	±0.5	
S.D. of 2)	7.0	4.1	5.2	3.0	4.3	

Simulation 1) certainly overestimates the retention times while 2) most likely underestimates it by not taking the lag effects into full account. The range 1)–2), calculated as the difference between 1) and 2), gives an indication of the modelling precision and is smaller than the intra-annual variations expressed as one S.D.

7 Estimation of the retention time of the coastal water

The Simpevarp area of the SVAR (Swedish Water Archives) partitioning of the Swedish coast according to Lindkvist (1994) includes with broad margins the fault zone mentioned in Wikberg et al. (1991). The delimitation of the areas in SVAR is mainly organized by sills and underwater ridges – particularly essential in the open coastal zone – since without any morphometrical features to define an area, the retention time becomes dependent on the utilized scale and is thus essentially meaningless. This is because the forcing results in typical water current velocities and the choice of the length scale will then directly determine the turnover time. The mechanisms of water exchange in open coastal areas are certainly more complex because of the added degrees of freedom for the water movements. For example, an internal Kelvin wave (Walin, 1972a, b) may temporarily shift out water from beneath without much changing the water content after the wave has passed. The rate of change for the accompanying barotropic surface wave attributed to Kelvin waves is of the order of 1 cm/day (Carlsson,1997), implying that the internal waves at 10 m depth could have an amplitude inversely proportional to the relative density difference at this depth, i.e. an order of magnitude greater. In order to estimate the retention time for these more exposed areas, the following general observations may serve as guidelines, while keeping constantly in mind that these estimates will with necessity be coarse to the point of mainly reflecting the correct order of magnitude.

The mechanism denoted as the Ekman transport affects mostly the surface water by deflecting the bulk water movement to the right (northern hemisphere) of the wind so that a balance of the forces the direction of the wind is attained. The windstress, τ (N/m^2), which acts on the surface may be enumerated (e.g. Pond & Pickard, 1983):

$$\tau = 1.8 \cdot 10^{-3}\ W^2\ ; \qquad (4)$$

where W (m/s) is the windspeed. If the area flow (volume flow per unit span) is denoted Q_E (m^2/s) in the orthogonal direction of the wind, then the Coriolis force per unit span will eventually equal the windstress:

$$f \cdot \rho \cdot Q_E = \tau; \qquad (5)$$

where f ($\approx 1.4 \cdot 10^{-4}\ s^{-1}$) is the Coriolis parameter of the actual latitude and ρ (1000 kg/m^3) is a reference density. The depth of this wind-affected upper layer (Ekman layer) may be estimated as $2.5 \cdot W$ (m) according to Pond & Pickard (1983). For depths exceeding this depth from the open coast and landwards, the retention time of the surface layer may be estimated as the time at the average velocity it takes to travel this unimpeded distance perpendicular to the coast.

The result of this analysis is that for the Simpevarp area (with a linearly averaged wind from Ölands Norra Udde in the N/S-direction) this would take on the average about 2 days. This estimate should be representative for the water above the fault zone that is mainly unconfined by the bottom topography. It is important to note that there is certainly a considerable spreading of the retention time distribution over this average. Progressively closer to the coast, the archipelago-like underwater ridges will impede the circulation so as to produce longer retention times. These would typically be significantly longer than 2 days but also considerably shorter than the retention times of 2 weeks estimated for the outermost basins (B1 & B5) adjacent to the coast.

For extended periods with along-shore wind, this process continues for the duration of the wind surge and produces along-shore currents closer to the coast at such a depth that the bottom friction eventually will limit the intensity of the induced current which is geostrophically balanced by the tilt of the sea level in the direction perpendicular to the coast (e.g. Gill, 1982; Svansson, 1975). Such along-shore transport occurs as long-term residual surface currents mainly derived from lightship data measurements (Andersson et al., 1992). Their magnitude is typically 10–20 cm/s again indicating that they would even travel through the elongated Simpevarp costal area in a couple of days. This applies, however, mainly to the topmost surface layer, and the best estimate for the entire surface layer would still be obtained by the Ekman transport. For the bottom layer the dynamic response of the Baltic pycnocline to large-scale wind and air pressure differences is another mechanism of water renewal. The corresponding density variations are preferably available from measurements.

Interestingly, if one contra-factually assumes that such internal waves act over the entire area facing the sea (no rotational control) and are permitted to shift out water by the intermediary mechanism as for any of the more confined basins facing the coast, one arrives at exchange rates of the same magnitude as for the Ekman transport.

8 Interannual variations

The forcing parameters have so far been derived from monthly resolved averages of the available data. For example, from the monthly resolved sea level fluctuation averages in Table 4-1, it is obvious that there is a sea level variation between years. The procedure for arriving at an estimate of the interannnual variation is by simulating all seven years (1988 through 1994) with full data coverage and from these data extract a S.D. measure of the retention times for the individual basins. This would be directly comparable to the intra-annual S.D. estimates in Table 6-1. In addition to this, the range limits have been estimated by constructing two artificial years consisting of extreme combinations of the different measured forcing factors so as to produce maximum and minimum retention times.

In analogy to the barotropic dynamics for which the rate of change of the sea level has been shown to be one relevant factor in determining the exchange, the rate of change of the salinity for two depths is shown in Table 8-1. Since none of the coastal strait entrances is deeper than 10 m, an analysis of these two depth suffices. It is seen that the maximal recorded rate of change took place in 1988 and the lowest in 1994. For the surface value the rate of change was almost doubled in 1988 and more than halved in 1994 compared to the average value (Fig. 8-1). The ratio between the maximal and the minimal rate of change is approximately 5. The corresponding rate of change of the other factor determining the temperature varies considerably less, about half that of the salinity factor. Together with the difference of the linear expansion coefficients ($8 \cdot 10^{-4}$ for salinity and $7 \cdot 10^{-6}$ for temperature) it cannot be expected that the interannual variations of the temperature will have any substantial influence on the interannual retention time variations. In order to facilitate the analysis, in the following the volume average retention time will throughout be the quantity compared.

The interannual variation of two forcing parameters remains to be estimated: the wind mixing and the freshwater runoff. In Table 8-2 the monthly cubic mean values (cubic root of summed cubes) of the wind is projected in the two dominant directions (E/W and SE/NW) of the Äspö area. For both these directions the maximum (5.3 m/s) occurred in 1993 and the minimum (4.1 m/s) in 1988. From Table 8-2 it is obvious that the intra-annual variations of the wind are greater than those of the interannual. For the fresh water the long-term variations fall between –50% and +100% (Andersson et al., 1992). The mean intra-annual variations are once again greater than the interannual for the data period. The influence of the freshwater interannual variations can thus be expected to yield only a marginal influence on the interannual variations.

The simulations of the years 1988 through 1984 are straightforward. For each of the five forcing functions (salinity at 0 and 10 m, temperature at 0 and 10 m, sea level, wind and freshwater variations), a factor has been introduced relating the forcing of the particular year to the average forcing used for the standard year. It is thus tacitly assumed that the distribution of the forcing over the particular year remains the same as for the standard year. The rationale for this is that the short-term added harmonic forcing (Table 4-2) is similarly constructed and dominates the water exchange processes, while the influence of the long-term variations is considerably smaller.

Table 8-1. Rate of change of salinity (100·psu/day) for Kungsgrundet resolved into years and months for two depths: 0 and 10 m. The yearly and monthly averages are also given. For both depths the highest measured rate of change took place 1988 and the lowest 1994. In addition to these recorded time derivatives with an average temporal resolution of 16 days, there exist variations with a higher rate of change. A conservative estimate gives that this may amount to a factor four times greater than the rate of change of this resolution. Data from SMHI.

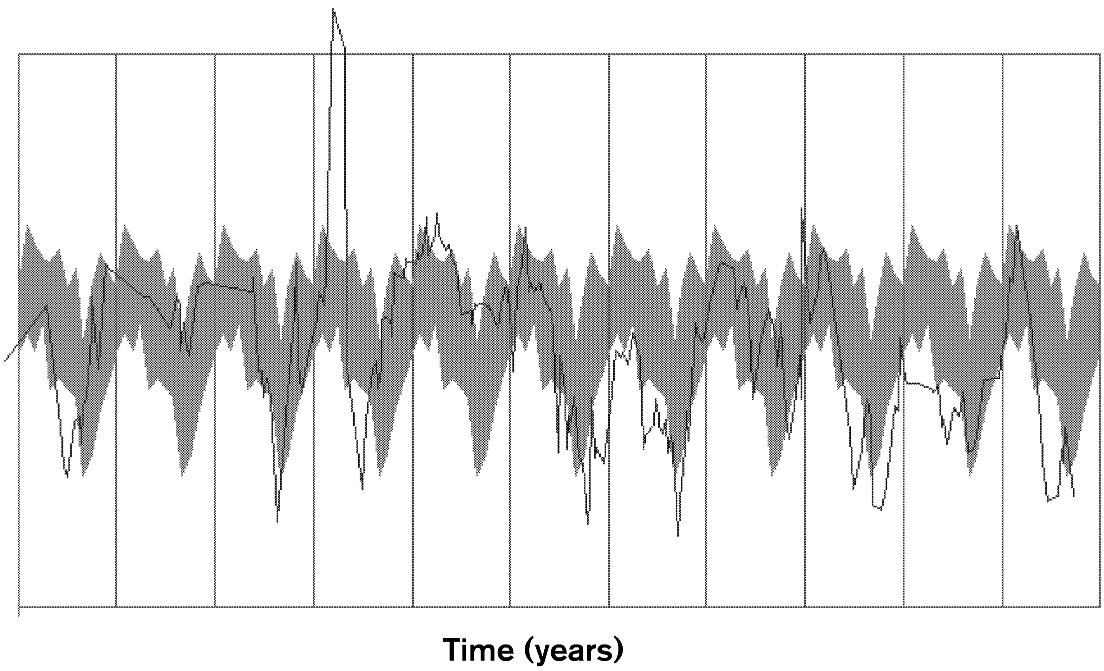
0 m:

	Month												
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Mean:**
1985	–	–	–	0.1	–	0.9	0.6	2.5	0.8	2.7	1.0	–	1.2
1986	–	–	–	0.0	–	–	0.2	2.0	0.7	0.8	0.0	–	0.6
1987	–	–	–	–	0.3	1.0	0.6	1.9	–	2.4	2.4	0.5	1.3
1988	0.7	2.3	3.2	0.3	7.5	–	1.8	0.8	2.5	1.0	0.0	0.5	1.9
1989	0.3	1.3	0.3	1.6	0.4	0.2	0.9	0.5	0	0.2	0.6	0.6	0.6
1990	2.0	0.7	0.9	0.4	–	1.3	2.4	0.7	0.8	3.1	1.2	0.2	1.2
1991	1.1	0.3	0.3	0.5	1.5	0.7	0.6	1.1	1.7	1.6	1.3	0.3	0.9
1992	0.6	0.3	–	0.5	0.3	1.3	0.9	0.3	1.3	1.2	0.6	5.9	1.2
1993	0.9	0.9	0.4	–	0.7	1.1	–	0.7	3.9	0.3	0.9	1.4	1.1
1994	0.5	0.0	–	0.1	0.6	0.6	0.3	0.9	0.3	0.8	–	0.0	0.4
1995	0.9	0.8	0.8	0.4	1.3	0.8	0.1	1.3	0.8	–	–	–	0.8
Mean:	0.88	0.83	0.98	0.43	1.58	0.88	0.84	1.15	1.28	1.41	0.89	1.18	1.03

10 m:

	Month												
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Mean:**
1985	–	–	–	0.3	–	1.8	1.5	4.4	1.3	5.7	5.3	–	2.9
1986	–	–	–	0.1	–	–	0.7	4.0	1.4	1.5	0.2	–	1.3
1987	–	–	–	–	0.7	1.9	1.1	3.8	–	3.7	4.8	0.9	2.4
1988	1.5	3.4	6.6	0.7	15.	–	3.5	1.4	4.1	2.0	0.1	0.9	3.5
1989	0.6	2.8	0.5	2.9	0.7	0.4	1.9	1.0	0.2	0.4	1.2	1.2	1.2
1990	2.8	1.2	1.8	1.0	–	2.3	4.6	1.3	1.5	6.3	2.4	0.3	2.3
1991	0.1	0.6	0.8	1.0	2.8	1.5	1.2	1.8	2.9	3.0	2.6	0.4	1.7
1992	0.2	0.5	–	1.1	0.7	2.7	1.6	0.9	2.6	2.4	1.1	12.	2.4
1993	1.8	1.8	0.7	–	1.5	1.7	–	1.2	7.9	0.8	1.8	2.7	2.2
1994	0.9	0.0	–	0.1	1.0	1.2	0.8	1.8	0.6	1.5	–	0.0	0.8
1995	2.1	1.9	1.5	0.8	2.4	1.9	0.1	2.2	1.6	–	–	–	1.6
Mean:	1.63	1.53	1.98	0.89	3.08	1.71	1.70	2.16	2.41	2.73	2.17	2.28	2.0

0 m:



10 m:

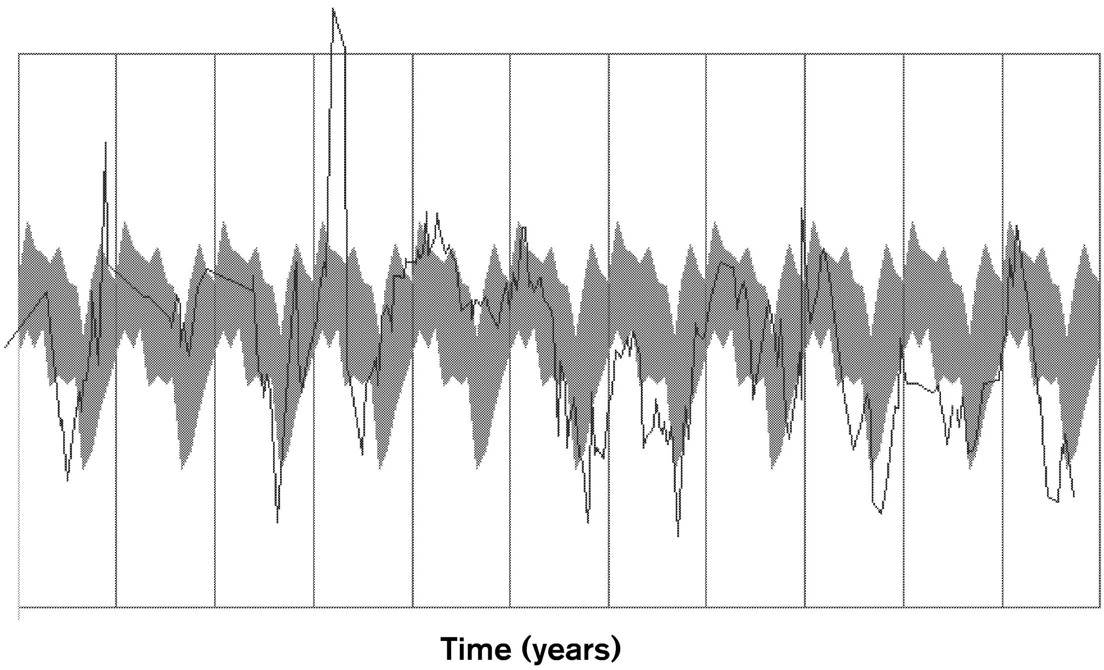


Figure 8-1. *Salinity variations 1985 through 1995 at Kungsgrundet for two depths (0 and 10 m). The estimated coastal variation (monthly average ± 1 S.D.) is also indicated as a shaded area. With a few exceptions, the particular year values fall within these variations. Vertical range is 5–7 psu.*

Table 8-2. Monthly resolved wind (cubic mean) average (m/s) 1985 through 1994 in the two cardinal directions into which the basins of the Äspö area approximately conform their elongation. The maximum wind mixing occurred 1993 and the minimum 1988 for both these directions. Based on original data from SMHI pertaining to Ölands Norra Udde with an average temporal resolution of 8 h.

Direction: E/W

	Month												
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Mean:**
1985	7.7	4.6	5.4	5.7	4.8	4.1	5.1	4.1	4.2	4.6	5.4	4.9	5.1
1986	4.3	6.2	3.9	4.4	4.3	3.5	4.3	4.7	5.7	4.7	5.3	6.5	4.8
1987	7.5	5.0	3.1	4.5	3.9	4.0	4.4	4.0	5.0	3.1	4.7	5.2	4.5
1988	4.6	5.1	3.6	4.2	3.2	3.3	3.3	3.6	4.3	4.5	4.5	5.5	4.1
1989	6.1	5.9	4.6	4.1	3.7	3.3	3.4	4.7	3.9	5.3	4.1	5.0	4.5
1990	5.9	6.1	6.1	3.6	3.6	3.6	4.0	3.6	4.7	5.1	5.6	4.6	4.7
1991	5.1	6.0	4.0	3.6	4.2	3.8	3.3	4.2	4.9	4.1	3.4	6.9	4.5
1992	6.8	5.6	4.5	4.6	4.1	3.9	4.4	4.6	3.6	5.4	5.2	4.4	4.8
1993	7.8	5.4	5.8	3.9	3.4	4.2	4.6	4.6	6.5	5.7	5.8	6.3	5.3
1994	5.7	5.4	5.7	3.6	3.0	5.2	2.8	4.6	5.5	5.0	5.6	4.5	4.7
Mean:	6.2	5.5	4.7	4.2	3.8	3.9	4.0	4.3	4.8	4.8	5.0	5.4	4.7

Direction: SE/NW

	Month												
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Mean:**
1985	7.0	8.0	4.5	5.1	4	4.3	5.6	3.6	5.0	4.9	5.6	5.1	5.1
1986	6.4	5.3	4.6	4.2	4.1	4.1	4.8	4.4	5.2	4.9	5.7	7.5	4.8
1987	6.7	4.8	4.5	4.1	3.5	3.5	3.3	3.7	4.8	5.3	4.8	6.1	4.5
1988	5.5	4.2	4.8	4.4	2.9	2.5	3.1	3.2	3.6	4.6	5.6	6.5	4.1
1989	4.5	4.6	3.9	3.9	3.3	3.2	3.7	4.0	3.6	5.3	6.5	6.2	4.5
1990	4.8	4.6	5.6	4.4	3.7	3.7	4.5	4.2	5.3	5.7	5.9	5.3	4.7
1991	5.2	6.7	4.5	4.8	4.8	4.1	2.7	4.4	5.7	5.2	5.2	6.7	4.5
1992	6.8	6.4	4.8	5.1	3.7	3.3	4.2	3.5	5.3	6.1	6.4	4.7	4.8
1993	6.3	5.8	4.6	3.6	3.3	3.9	4.3	4.4	4.7	5.5	5.4	5.2	5.3
1994	5.4	4.1	4.8	4.1	4.1	4.2	3.0	4.1	4.5	5.4	6.0	4.8	4.7
Mean:	5.9	5.5	4.7	4.4	3.7	3.7	3.9	4.0	4.8	5.3	5.7	5.8	4.8

The results are presented in Fig. 8-2 from which it is apparent that the ± 1 S.D. confidence interval of the interannual variations is greater than the corresponding interval of the intra-annual variations for all peripheral basins except Borholmsfjärden. The averages in this diagram have been adjusted by adding the 2 days retention time estimated for the coastal water of the Simpevarp area.

The combination of the interannually varying factors does not occur independently in nature. These factors are undoubtedly correlated to an unknown but not negligible level. In order to achieve an estimate for maximal and minimal retention times one may, however, combine them freely as to arrange for the combination that increases or decreases the water exchange. The maximal exchange of exogenous water is produced when the rate of change of density variations is maximal. This means that the maximum salinity rate of change is combined with the maximum temperature rate of change, but operating in antiphase so that when the salinity increases, the temperature decreases. To enhance the estuarine circulation, maximal freshwater discharge is combined with maximal wind. Increased sea level fluctuation invariably leads to increased exchange and is also chosen. With all of the maximum values of the factors in Table 8-3 thus combined, the simulation that renders the minimum retention time is performed; reciprocally with all minimal values the maximum retention time is simulated. The result is presented in Fig. 8-2 as horizontal lines denoting the extreme range within which the retention time of the basins will confidently be contained even when a highly unlikely combination of the known forcing variations occurs.

Table 8-3. Factors influencing the interannual variations and their interannual relative variation with yearly average set to unity. The maximum and minimum relative values and S.D. are given.

	Minimun	1±S.D.	Maximum	Data period
Salinity rate of change (0 m):	0.38	1±0.41	1.84	1985-95
Salinity rate of change (10 m):	0.40	1±0.41	1.75	1985-95
Temperature rate of change (0 m):	0.59	1±0.32	1.63	1985-95
Sea level fluctuation	0.93	1±0.06	1.04	1987-94
Wind variation (E/W- & SE/NW-directions)	0.87	1±0.07	1.13	1985-94
Freshwater runoff	0.5	1±0.4	2.0	1985-94

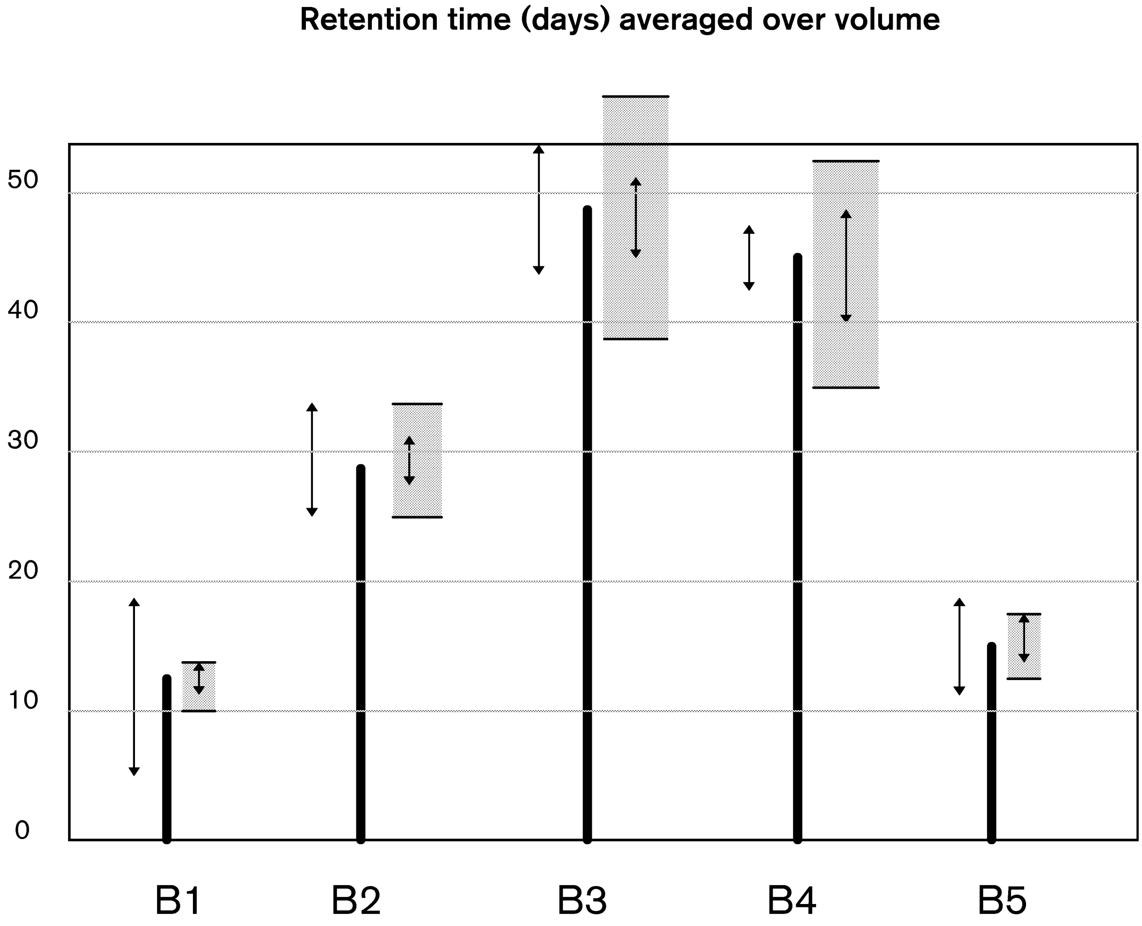


Figure 8-2. *Graphical display of retention times for the various basins. The coarse lines depict the yearly volume average of the standard run [case 2) in Table 6-1], adjusted by adding 2 days representing the average retention time of the coastal water. The intra-annual variations are indicated by ± 1 S.D. to the left and correspondingly the interannual variations for the seven years (1988 through 1984) to the right. The ranges produced by the extreme combination of the forcing (see text) are presented as shaded rectangles, covering the ± 1 S.D. interannual swing.*

9 Discussion

Notwithstanding that the present model is believed to represent the state of the art in coastal oceanography for models resolving material exchange on ecological time scales, it must be emphasized that no model can provide more than a few dominating aspects of an almost infinitely complex reality. The recommended method for validating the model with a time series record of tracer dynamics (Engqvist, 1990) has not been available in spite of the proximity of the study area to a nuclear power plant.

In particular this reflection applies to the retention time estimate of the Simpevarp coastal area. If it were desirable to improve the results of the present approach as to the resolution in time and space, the difficulties steepen rapidly and the necessity of 2- or even 3-dimensional models would arise.

The unknown short-time variability of border salinity and temperature does not seem crucial since numerical experiments unequivocally indicate that the Äspö basins are already at the point of being choked by the long-term recorded rate of change of these parameters.

There is little reason to suspect that the vertical mixing induced by local wind stress needs to be corrected by the additional source of mixing power provided by boat propellers, at least for the innermost basin Borholmsfjärden, for which the shallow sills effectively fence off larger motorboats.

The present land rise amounts to 3 mm/year according to chart information. This indicates that in less than 1000 years Borholmsfjärden will have evolved from a coastal embayment to become a lake, completely uncoupled from influences on the water exchange from the coast. Most likely this process will be accelerated by sedimentation processes. These are presently noticeable in the shallow areas in the northeast corner of this basin where the soft bottom characteristics are apparent. In time the volume of the pelagic water will thus undoubtedly diminish. The retention time of lakes is determined by the fresh water discharge, its volume and to a minor extent also modified by the thermal stratification. The latter two of these factors are subject to climate change, thus indicating that all three factors are under continuous long-term evolution. Depending on the relative intensity between the rate of change of the development of the volume and the freshwater discharge, the resulting retention time may either increase or decrease. This indicates that a prediction of future retention times of the Äspö basins is genuinely uncertain and must fall outside the scope of a downright coastal oceanography analysis.

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