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# Observations of the Specific Resistance in the Øresund

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The specific resistance and three other secondary coefficients in the instantaneous integral energy equation describing the flow in the Øresund strait, are accurately estimated from over two years of high resolution measurements. Parameter variation due to stratification, effectively insulating the flow from the effect of bottom friction, is demonstrated and quantified. Also, parameter variation with the flow direction is quantified. Residual error dynamics is discussed and described. The relevance of an additional linear resistance term in the flow energy equation is discussed.

## Introduction

The specific resistance (or total head loss coefficient) describes the integral effect of friction and expansion/contraction losses along the Øresund (Fig. 1). Recent estimates of the Øresund specific resistance differ from $160\times10^{-12}$ $s^2$ $m^{-5}$ in Stigebrandt (1992) to $203\times10^{-12}$ $s^2$ $m^{-5}$ in Mattsson (1995). The latter also provides some evidence of a weak linear resistance term in addition to the primary quadratic dependence of the north-south water level difference on the Øresund throughflow. Additionally, Jakobsen and Møller (1994) demonstrate that the specific resistance differs for northward ("less stratified") and southward ("more stratified") flows. During outflow from the Central Baltic Sea low saline water (~8-10 PSU) passes the Drogden Sill and contributes to the surface pool in the Kattegat (*e.g.*, Stigebrandt 1983; Mattsson 1997; Jakobsen 1997A), while during inflow more saline Kattegat water

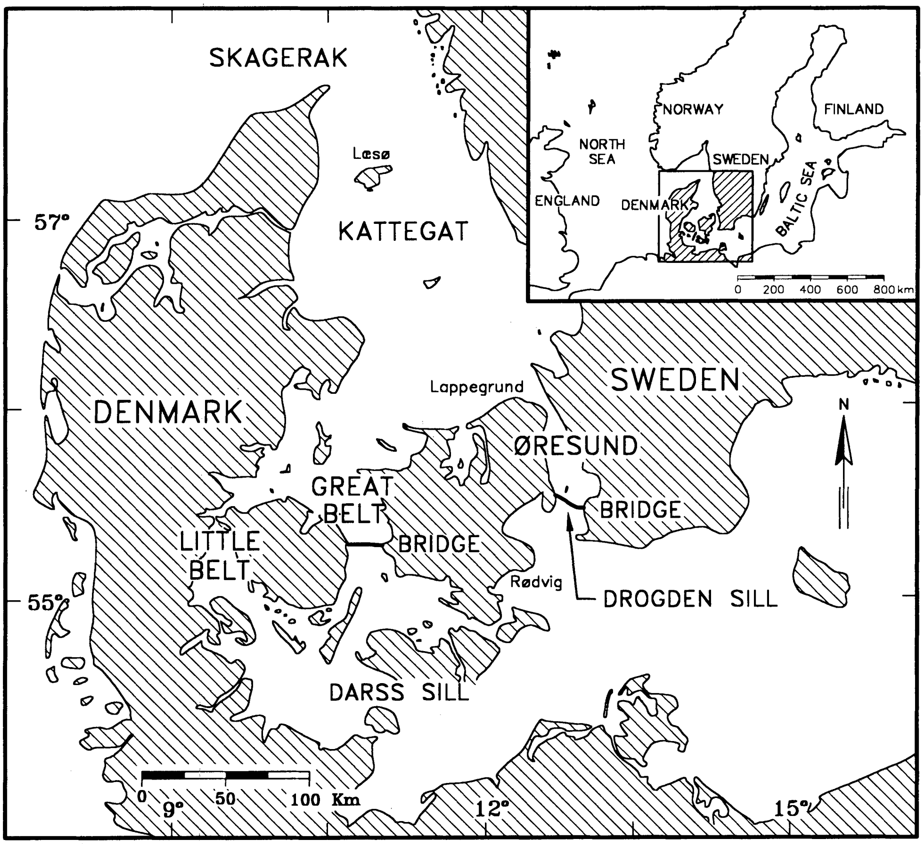


Fig. 1. The transition area between the Baltic Sea and the North Sea with indication of the Øresund and the Drogden Sill.

passes the sill and contributes to the bottom pool in the Central Baltic Sea (*e.g.*, Stigebrandt 1987; Jakobsen 1995; 1997B). An accurate estimate of the Øresund specific resistance is useful in connection with long-term simulations of flow through the Øresund, and is the key scaling parameter for blocking calculations in connection with the ongoing construction of the Øresund Link between Copenhagen (DK) and Malmø (S) (Ellegaard and Jakobsen 1992; Stigebrandt 1992; Møller and Hansen 1994).

This paper determines the average magnitude of the Øresund specific resistance with an accuracy of approximately ±3%. The specific resistance variation with the flow direction in the Drogden Channel is also quantified and a number of secondary parameters influencing flow in the Øresund are estimated. Finally, specific resistance variation with observed stratification is demonstrated and quantified. Stratification effectively insulates the upper layer from feeling the bottom friction and thus acts as a flow lubricant.

The flow parameters, and their variations, are determined on the basis of more than two years of continuous high resolution measurements of water levels, wind, and flow over the Drogden Sill.

The paper is structured as follows: first, there is an overview of the relevant basic theory (the energy equation), followed by a description of the various applied data series. Next, global estimates of the theoretical constant parameters are derived and the question of residual error dynamics and parameter uncertainty is discussed. Parameter variation as a function of the flow direction and observed stratification is outlined and concluding remarks are given.

## Theoretical Background

According to basic hydraulic theory the energy loss, $h_f$, in the Øresund due to bottom friction, expansion, contraction and turning may be taken to be proportional to the discharge squared (Chow 1986)

$$h_f = K\,Q|Q| \tag{1}$$

where $K$ is specific resistance, and $Q$ is discharge through the Øresund (positive towards north). Using this relation, the specific resistance can be introduced to the instantaneous, integral energy equation describing flow through the Øresund (Ellegaard and Jakobsen 1992). In many non-stratified straits the specific resistance is almost a constant (small variations can *e.g.* be caused by water level variations). However, the specific resistance in the Øresund varies between relatively wide limits, mainly due to the stratification variation in the sill area (it is noted that barotropic models do not show any important difference between northward and southward flows). When a water column is stratified, turbulence is damped and the velocity profile will be deformed and, for an unchanged headloss will result in a higher water discharge. In other words, stratification acts as a lubricant for the flow.

The energy equation may be conceived as a simple mathematical model. When appropriate measurements of water levels, wind, and Øresund discharge are available, it may be written in a linear form suitable for the estimation of model parameters by regression analysis. The energy equation will then read (*e.g.*, Jacobsen 1980; Stigebrandt 1980; 1992; Mattsson 1995; Jakobsen and Ottavi 1997)

$$H_s - H_n = K\,Q|Q| + a\,\frac{\partial Q}{\partial t} + b\,W^2\cos(\theta) + c + \varepsilon \tag{2}$$

where $H_s$-$H_n$ is the total head difference from south to north along the Øresund, which is taken to be equal to the water level difference, $W$ is wind speed over the Øresund, $\theta$ is the wind direction (angle measured from the north), $a$ and $b$ are regression coefficients of the secondary energy equation terms, which describe acceleration (inertia) and local wind forcing, $c$ is the level offset constant deriving from the salinity and density difference along the Øresund from south to north, and $\varepsilon$ represents model error.

Existing estimates of the specific resistance are primarily obtained during so called, "ideal" conditions, *e.g.* approximately steady conditions and/or negligible local wind forcing. Thus, even though the energy equation is arguably valid at all times there is a risk that existing parameter estimates are biased due to the choice of hydrographic conditions on which they are estimated, and/or that the energy equation coefficients are not truly constant but exhibit a second order variation between different flow regimes (as already proven for northward and southward flows).

Local estimates based on measurements of the effect of acceleration and local wind forcing in the Øresund – *i.e.* the secondary terms in the energy equation – hardly exist today. From theoretical sources the anticipated values of these parameters approximate (DHI/LIC 1997)

$$a \approx \frac{L}{whg} = 35\times10^{-3}\ \mathrm{s^2m^{-2}}$$

$$b \approx \frac{L}{hg}\ C_D\ \frac{\rho_a}{\rho_w} = 2.0\times10^{-3}\ \mathrm{s^2m^{-1}}$$

$$c \approx 0.5h_{\mathrm{sill}}\ \frac{\rho_n-\rho_s}{\rho_R} = 40\ \mathrm{mm}$$

where $L$ is length of the Øresund (≈90 km), $w$ is width of the Øresund (≈24 km), $h$ is the average depth (≈11 m), $g$ is the gravity, $C_D$ is the drag coefficient ($\approx 2\times10^{-3}$), $\rho_a/\rho_w$ is the ratio of air and water densities ($\approx 1.2\times10^{-3}$), $h_{\mathrm{sill}}$ is the typical sill depth (≈7 m), $\rho_n$ and $\rho_s$ are typical densities at the northern and southern boundaries (the salinities are typically 26 PSU and 10 PSU, respectively), and $\rho_R$ is the reference density ($\approx 1{,}010$ kg $\mathrm{m^{-3}}$). The anticipated parameter values and the empirical parameter estimates taken later are in satisfactory agreement.

During the analyses the crucial importance of water level measurements being mutually consistent with respect to the reference level, in order to obtain meaningful estimates of all energy equation secondary and/or differential features, was observed. A choice had to be made, particularly with respect to water level data, as to what constitutes north and south water levels. Mattsson (1995) argues that using Hornbæk water levels in the north and Skanör water levels in the south is optimal in accordance with the principle of geostrophic control in a strait connecting two basins, as described by Garrett and Toulany (1982), and Toulany and Garrett (1984). While this is undoubtedly theoretically correct due to the Coriolis effect, it was actually found to make very little difference overall, whether the Hornbæk and Skanör stations were used alone, or whether straight averages between the Danish and the Swedish stations were applied at both ends. And since the former option appeared to produce somewhat more erratic estimates of the specific resistance, the straight average option has been preferred in the following analyses.

## Measurements and Methods

Basic measurements of water levels, wind, and currents in the Øresund are identical to what has been described previously (Jakobsen and Castejon 1995; Jakobsen and Lintrup 1996). The discharge through the Øresund is determined on the basis of the method outlined in Jakobsen and Castejon (1995). The method is further discussed in Jakobsen and Lintrup (1996). The length of the period for this investigation is increased to just over two years: from 12 Oct., 1993 to 5 Nov., 1995; and the scope of analyses has been directed towards an accurate determination of the Øresund specific resistance and related parameters. In the investigated period the wind speeds were higher than 17.2 m $s^{-1}$ in 118 hours and higher than 24.5 m $s^{-1}$ in 2 hours. Thus situations with strong winds are considered in the investigation.

In short, the data employed are (Fig. 2): A) Water level measurements from Hornbæk and Viken to the North and from Rødvig and Skanör to the south of the Øresund; B) Wind data from Kastrup on the Island of Amager, Copenhagen; and C) Flow and salinity data from each of the Drogden and Flinten channels, west and east of Saltholm, respectively, station numbers 24 and 21. These data have been derived from fixed station ADCP (Acoustic Doppler Current Profiler) velocity measurements with a vertical resolution of 0.5 m, in combination with salinity measurements at depths of 6 and 5 levels in the two channels.

All data were measured with a temporal resolution of 1800 s on purpose. This was achieved roughly 90% of the time. When disturbances occurred lasting less than 10 hours, the flow and wind series (but not the water level series) were interpolated. The data series employed comprises some redundancy of information. Thus, there are two water level stations both north and south of the Øresund and the correlation between the flow in the Drogden and Flinten channels on either side of Saltholm is very high. In order to carry out these analyses at least one water level observation from each end of the Øresund, at least one set of current/flow data from one of the two channels and wind data are required. The overall data coverage achieved is 95.7% (17,335 of 18,120 hours). Of the 785 hours of missing data, 678 hours are attributable to missing current measurements, 75 hours to missing wind data, and 32 hours to missing water level observations. Individually, the four water level series were not quite as complete. At each station periods with missing data spanned: 506 hours (2.8%) at Hornbæk, 333 hours (1.8%) at Viken, 216 hours (1.2%) at Skanör, and 523 hours (2.9%) at Rødvig.

In accordance with Eq. (2) original series were calculated with a time resolution of 1800 s for $(H_s\text{-}H_n)$ and each of the "independent" variables: $Q|Q|$, $\Delta Q/\Delta t$, $W^2\cos(\theta)$, and $Q$. Subsequently, coarser series were derived by ordinary time averaging to resolutions of 1, 2, 4, 12, 16, 24, and 48 hours. As the main analyses item, the set of 12 hourly values is used in the following, except where otherwise stated. This was preferred in order to almost eliminate semidiurnal tidal influence while preserving information content, since the integral time scale of the processes involved is roughly 15 hours (Mattsson 1995).

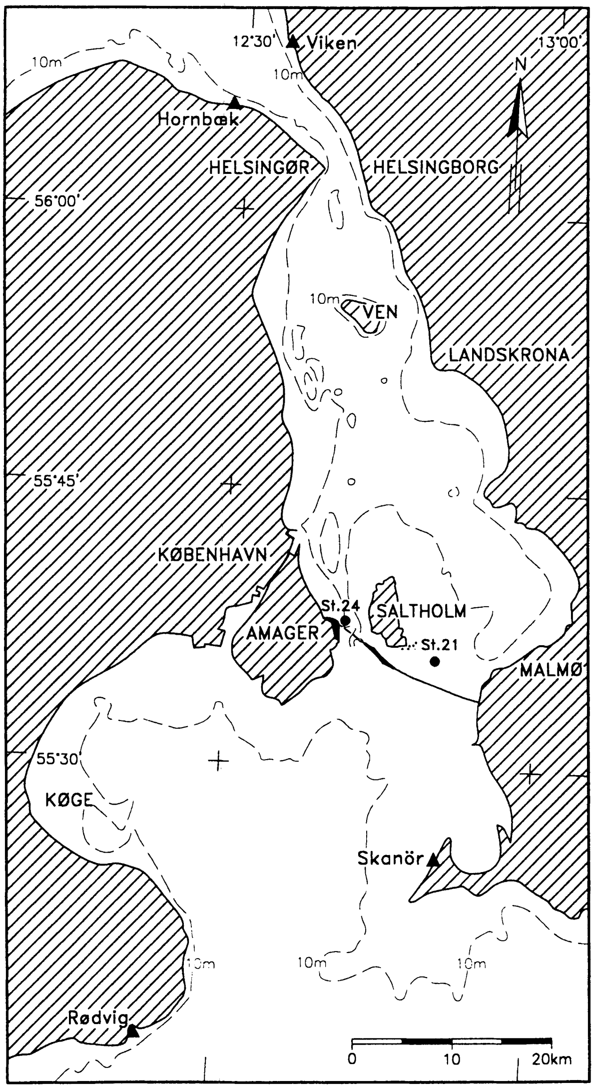


Fig. 2. Map of the Øresund with position of the fixed stations.

Traditional least squares regression was used throughout, but only after ascertaining that it made very little difference whether this method or a non-parametric method (so called robust regression method based on observation ranks) was applied. Linear regression with reverse parameter estimation was not applied since the type of system dynamics implied by such methods was not considered a physical representative of the physical properties studied.

## Global Parameter Estimates

Parameters *K, a, b,* and *c* in Eq. (2) were estimated for the entire data set by ordinary least squares regression after it was found to make little difference whether this classic and efficient method, or so called robust regression (with a linear penalty function) was applied. Parameter uncertainties (±2 standard deviations) were estimated using the Monte Carlo simulation, as described later. Resulting estimates are summarized in Table 1. The coefficient of determination in the estimation was $R^2$ = 92.2%.

When running the regression without regard for the secondary terms, *i.e.* effectively assuming $a$=$b$=0, the specific resistance estimate decreased from $K = 226\times10^{-12}$ s$^2$ m$^{-5}$ to K = $216\times10^{-12}$ s$^2$ m$^{-5}$ and the level offset decreased from $c$ = 58.2 mm to $c$ = 49 mm. At the same time the coefficient of determination was reduced to $R^2$ = 88.3%.

The basic analyses were carried out for all series of different resolutions. Within the range 4-24 hours the choice of resolution had little influence on parameter estimates. Only for series with resolutions 1, 2, and 48 hours did problems with parameter identifiability become evident. Results of parameter estimations for series with different resolutions are shown in Fig. 3, where individual estimates are normalized relative to the 12 hourly values presented in Table 1. In moving from a resolution of

Table 1 – Parameter estimates in Eq. (2) with uncertainties (95% confidence level).

| Effect | Symbol | Unit | Estimate | Uncertainty |
|---|---|---|---|---|
| Øresund specific resistance | $K$ | $10^{-12}$ s$^2$ m$^{-5}$ | 226 | 6.2 |
| acceleration (inertia) | $a$ | $10^{-3}$ s$^2$ m$^{-2}$ | 63.7 | 8.0 |
| local wind forcing | $b$ | $10^{-3}$ s$^2$ m$^{-1}$ | 1.40 | 0.18 |
| level offset | $c$ | mm | 58.2 | 5.6 |

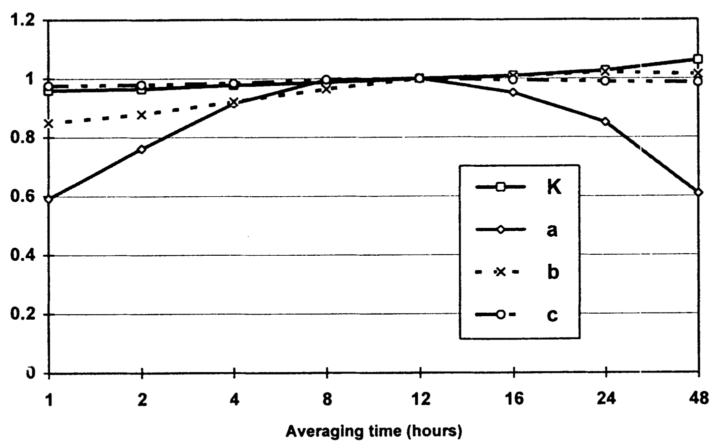


Fig. 3. Normalized parameter estimates for various resolutions, relative to $\Delta t$ = 12 hours.

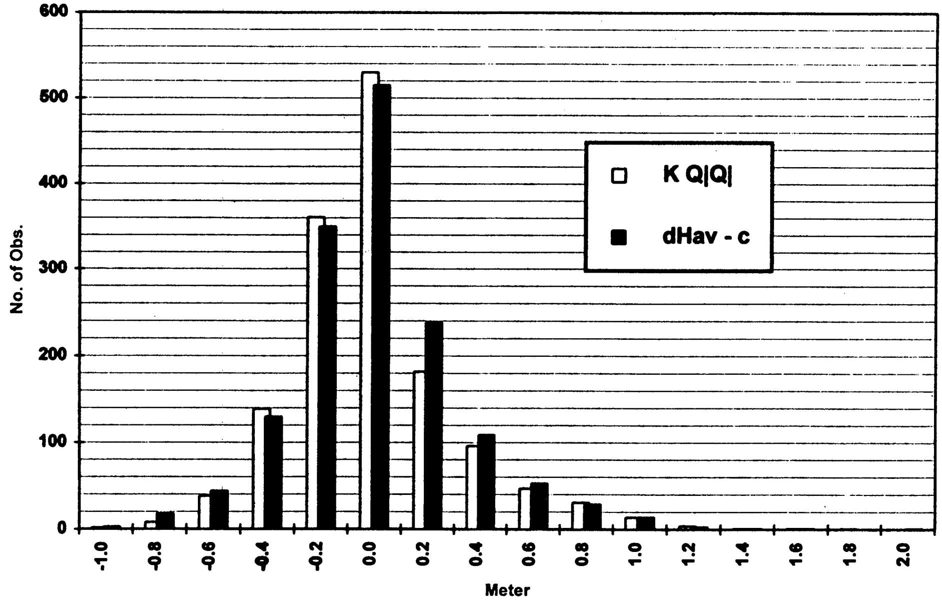


Fig. 4. Normalized variable distributions: Discharge squared, $K\,Q|Q|$, and south to north water level difference less density offset, $H_s$-$H_n$-$c$.

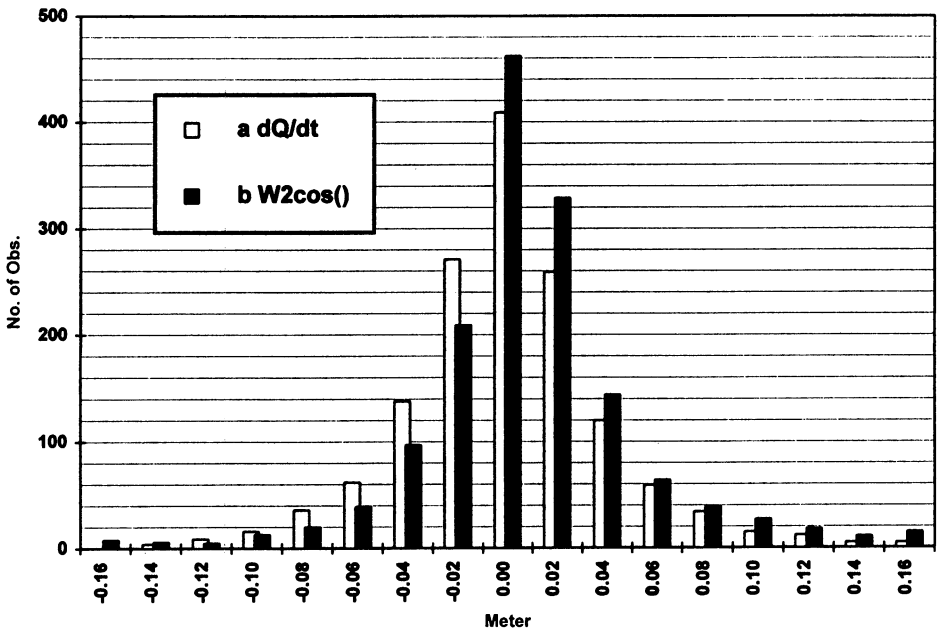


Fig. 5. Normalized variable distributions: Acceleration term, a $\Delta Q/\Delta t$, and wind term, $b\ W^2\cos(\theta)$. The latter actually extends to ±30 cm but the long tails have been wound up and are lumped in with the ±16 cm values.

1 hour to a resolution of 48 hours the regression coefficient of determination, $R^2$, increases from 88.2% to 94.0%.

The distribution of each variable, scaled to the unit m by Table 1 parameter estimates, is shown in Figs. 4 and 5. Note the different scales of the $x$-axes indicating the relative importance of the variables. Actually, the distribution of the wind term, $b\ W^2\cos(\theta)$, extends to ±30 cm, but in Fig. 5 the long tails have been rolled up and lumped in with the ±16 cm end values.

## Model Error Dynamics

Obviously, Gaussian linear regression as used in the global parameter estimation can be applied only as a least squares estimator since assumptions of independence between observations and normal distribution of variables are violated, *cf.* Figs. 4 and 5.

It may be noted that a single parameter autoregressive error model, AR(1), adequately describes dynamics of the regression model residuals. The single autoregressive model parameter takes on a value of 0.58. The autocorrelation function, as well as the partial autocorrelation function of the residuals, is shown in Figs. 6 and 7, both before and after fitting of the AR(1) error model. The adequacy of the AR(1) model is apparent from the figures. Any possible remaining information content in the AR(1) residuals is minimal. The applied statistics software, MINITAB, does not allow for joint estimation of regression coefficients and the single AR(1) error model parameter, but it is indicated that inclusion of the error model can increase the coefficient of determination from 92.2% to well over 94%. In view of the later de-

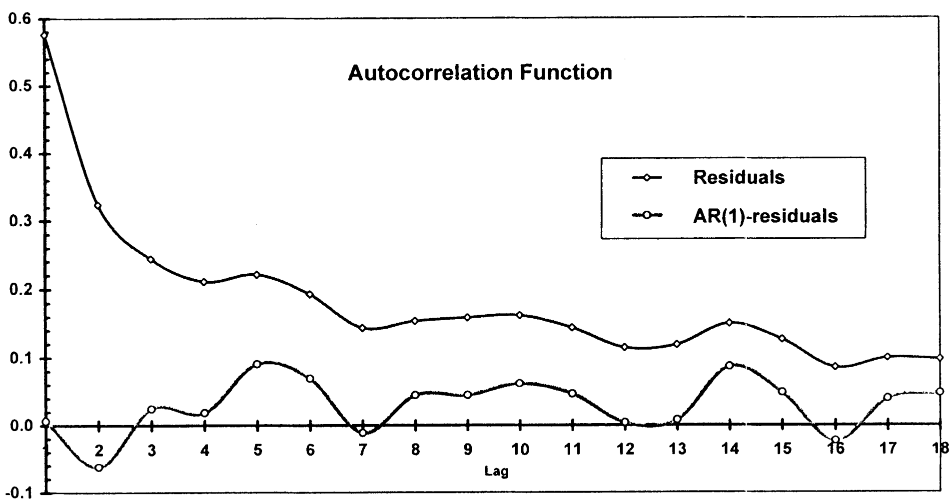


Fig. 6. Autocorrelation function of residuals, before and after fitting of an AR(1) error model.

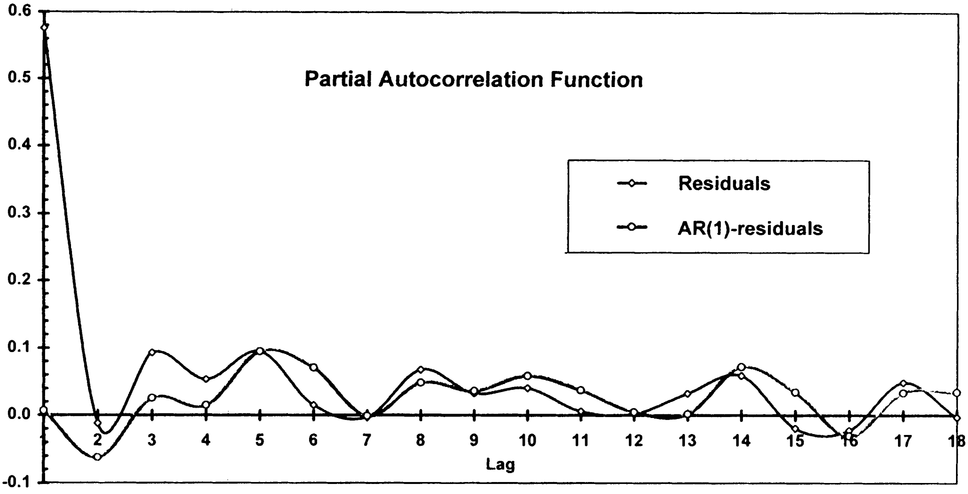


Fig. 7. Partial autocorrelation function of residuals, before and after fitting of an AR(1) error model.

scribed parameter variability, the AR(1) error model may be perceived as a versatile and parsimonious adaptation to momentary physical conditions.

All least squares analyses were only applied to simultaneous observations. The inclusion of lagged variables, lag1($Q|Q|$), lag1($\Delta Q/\text{-}\Delta t$) and lag1($W^2\cos(\theta)$), in the analysis, only increased the coefficient of determination by 0.6% to 92.8%. Thus, it hardly warranted including the lagged variables.

## Parameter Uncertainty

Since least squares estimations do not provide directly relevant estimates of the uncertainty of the model parameters for serially correlated data, parameter uncertainties were instead estimated by Monte Carlo simulation (also denoted the Bootstrap method, see Press *et al.* (1992)). Thirty-five samples of 1,510 observations each were extracted from the original series of 1,510, (necessarily by extraction with replacement, allowing duplication of individual observations in the 35 artificial samples). The least squares parameter estimation was applied to each of the 35 samples. Inter-sample parameter variability is assumed equal to the uncertainty of the original parameter estimates.

The Bootstrap procedure assumes that the original series fully represents the true, natural joint distribution of all measured variables. This is clearly not the case, but the amount of measurements is sufficiently large, that the error is probably minimal. It should, however, be noted, that the method normally tends to underestimate parameter variability, since the original series can never span all possible values of the measured variables.

Systematic errors (bias, if any) have previously been judged to be less than 5% when determining the discharge, see Jakobsen and Lintrup (1996). Irrespective of the non-linear character of the present analyses with regard to discharge, it is still expected that they are biased by less than 5% overall.

## Parameter Variability

As previously mentioned, flow parameters vary with flow direction. The variation is caused by changing conditions on the Drogden Sill: the Drogden Sill is more often stratified during southwards flow than during northward flow. Jakobsen and Møller (1994) provide the following estimates: A) for northward flow (64% frequency) $K = 210\times10^{-12}$ $s^2$ $m^{-5}$; B) for southward flow (36% frequency) $K = 145\times10^{-12}$ $s^2$ $m^{-5}$; and C) on average (weighted by frequency) $K = 190\times10^{-12}$ $s^2$ $m^{-5}$. These values were found from cross-profile ship measurements during quasi-steady conditions, assuming $a$=0, but taking into account the local wind. In Jakobsen and Møller (1994) the ship measured discharges were increased by 5% to correct for the unmeasured discharge near the coastlines, but this correction has later been shown to be too large, and thus the resistances found should be increased by approximately 10%.

Similarly, the present data set was separated into situations with northward ("less stratified") currents and situations with southward ("more stratified") currents. Additionally, an alternative separation of data on the basis of possible stratification, as indicated by measured salinities at station 24 (Nordre Røse) was tried. Stratification criterion demands an observed salinity gradient higher than 0.75 psu $m^{-1}$ and a velocity gradient higher than 0.08 $s^{-1}$ (Jakobsen and Castejon 1995). For the 12 hourly data series a distinction was made between entirely "homogenous" basic conditions at st. 24, predominantly (8-12 hours) "stratified" conditions, and indeterminate/changeable conditions not qualifying for either of the pure categories.

Results of parameter estimations for each of the five groups of flow regimes described are shown in Table 2. In all cases, parameter variation is seen to be quite substantial and significant. The difference by flow direction identified by Jakobsen and Møller (1994) is supported, but specific resistance estimates are somewhat higher.

Parameter variability by stratification is seen to be even stronger than by flow direction. As would be expected, flow resistance is weaker and wind influence is stronger during stratified conditions. Likewise, the density offset appears to be smaller during stratification. This may be interpreted as the system only "feeling" the upper layer difference in densities between north and south.

Finally, data was separated according to both flow direction and observed stratification simultaneously. Results of parameter estimation for each of the six groups are shown in Table 3. The effects already shown in Table 2 are repeated and partially emphasized.

Data was also analysed for seasonal parameter variation, but no such seasonal variation was found.

Table 2 – Results of parameter estimations for distinct flow regimes. The flow regime homogenous, changeable and stratified refer to flow conditions in the Drogden Channel.

| Flow regime: | Parameters/Coefficients | | | | |
|---|---|---|---|---|---|
| | $K$ $10^{-12}\,s^2\,m^{-5}$ | $a$ $10^{-3}\,s^2\,m^{-2}$ | $b$ $10^{-3}\,s^2\,m^{-1}$ | $c$ mm | $R^2$ % |
| North dir. | 245 | 43 | 1.24 | 43 | 81.3 |
| South dir. | 210 | 81 | 1.81 | 34 | 89,8 |
| Homogenous | 248 | 55 | 1.21 | 76 | 93.2 |
| Changeable | 228 | 70 | 1.22 | 40 | 94.0 |
| Stratified | 197 | 71 | 1.66 | 39 | 91.7 |

Table 3 – Results of parameter estimations after data separation according to both flow direction and observed stratification in the Drogden Channel. The flow regimes refer to flow conditions in the Drogden Channel.

| Flow regime: | Parameters/Coefficients | | | | | |
|---|---|---|---|---|---|---|
| Main dir./ stratif. | $K$ $10^{-12}\,s^2\,m^{-5}$ | $a$ $10^{-3}\,s^2\,m^{-2}$ | $b$ $10^{-3}\,s^2\,m^{-1}$ | $c$ mm | $R^2$ % | Obs. 12 h. |
| N./Homogenous | 262 | 27 | 0.98 | 63 | 86.3 | 355 |
| N./Changeable | 207 | 60 | 0.90 | 59 | 81.0 | 216 |
| N./Stratified | 199 | 52 | 1.26 | 36 | 77.0 | 277 |
| S./Homogenous | 221 | 84 | 1.56 | 26 | 90.0 | 145 |
| S./Changeable | 239 | 90 | 1.81 | 43 | 94.9 | 130 |
| S./Stratified | 193 | 84 | 2.57 | 32 | 89.8 | 307 |

## Discussion

Finally, it was investigated and considered whether a linear resistance term, $d$, should be included in the basic model as suggested by Mattsson (1995)

$$H_s - H_n = K\,Q|Q| + a\frac{\partial Q}{\partial t} + b\,W^2\cos(\theta) + c + \varepsilon + d\,Q \quad (3)$$

In fact, all parameter estimations were made both with and without the linear term included, and in most – though far from all – cases, estimation results supported the theoretical significance of the linear term. However, a decision was made against extending the model. This was decided for two practical reasons. Firstly, unless strictly necessary it is not desirable to apply a model with strongly correlated variables, such as $Q|Q|$ and $Q$, since it imposes parameter identifiability problems. Thus, with the present data set, the standard deviation of $K$ estimates increased by a factor of 3 to 4 when parameters $K$ and $d$ were both included in the model. Secondly, including the linear parameter, $d$, did not appreciably improve the model fit. In the global estimation (Table 1 results) the specific resistance, $K$, and the constant offset, $c$, together provided for a determination coefficient of 88.3%. Adding the secondary terms, $a$ and $b$, describing flow inertia and local wind forcing, increased the coefficient of determination by 3.7% to 92.0%. Including parameter $d$ provided only a further 0.2% increase, which was less of an improvement than that obtained by discriminating between homogenous and stratified conditions, *cf.* Table 2. The claim made by Mattsson (1995) that local wind and baroclinic forcing are of only minor significance in the Øresund does not seem justified, at least not in comparison to any linear flow resistance effect.

Furthermore, instead of the simple AR(1) error model, an attempt was made to eliminate model residual dynamics by directly including physical state information concerning salinities and stratification in the Øresund in the formulation of the energy equation. It was carried out using a hybrid approach, incorporating genetic programming methods. Results of exploratory analyses were not encouraging, so this line of investigation was not pursued.

The energy equation can be used to determine long-term transports through the Øresund, but an empirical relationship between the discharge 12 h average and the discharge squared 12 h average is needed. This empirical relationship was found to be

$$\overline{|Q|Q} = e^2\ \overline{|Q|}\,\overline{Q} \qquad (4)$$

where $e$ = 1.043 is a constant. The coefficient of determination in the estimation was $R^2$ = 99.5%.

## Conclusion

The Øresund specific resistance, $K$, has been determined, as well as several secondary parameters influencing flow in the Øresund. This has been done generally and for several specific flow regimes. The average value found for $K$ is $226\times10^{-12}$ s$^2$ m$^{-5}$, which is somewhat higher than previous resistance estimates. This is probably because of the necessity for previous analysts to focus on specific conditions and to make convenient assumptions due to the lack of comprehensive data. The present analyses also show that the Øresund specific resistance varies in a systematic and identifiable way, at least spanning the range 190-$260\times10^{-12}$ s$^2$ m$^{-5}$, an interval comprising most earlier estimates in the lower range. Parameters vary with the flow direction and observed stratification. The latter effect has not previously been identified empirically in the Øresund. The values found for the secondary term coefficients are probably the first direct estimates of these parameters. They are in rough agreement with theoretical parameter estimates. Relative to the theoretical estimates, the estimated acceleration (inertia) effect and the estimated differential density offset are a little stronger than predicted, whereas the local wind forcing is somewhat weaker. The latter is hardly surprising considering the confined character of the Øresund.

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