CHAPTER 217

SALT INTRUSION IN TIDELESS ESTUARIES

Ewa JASIŃSKA[1]

ABSTRACT

The data of several field measurements performed in different types of estuaries along the Polish Baltic Coast are presented here. The results of measurement showed how unsteady and changeable the flow conditions and the motion of salt water in tideless estuaries are. The salinity and velocity distributions in the tested estuaries demonstrate that the change of current direction occurs at different depth and different times. It has been stated that the dynamics of the flow in tideless estuaries is similar to that of the tidal estuaries. A method of determination of longitudinal dispersion coefficient for tideless estuary is presented. The results from calculations for tidless estuary using a threedimensional estuary model previously developed for tidal estuaries are presented.

1 INTRODUCTION

Most rivers enter the sea at the place where there is enough tidal rise and fall to modify flow near their mouths. The area where there is an interaction between river and sea waters is called an estuary. This paper deals with a penetration of salt waters into tideless estuaries which are typical of the Southern Baltic Coast.

Distributions of salinity and velocity in tideless estuaries are primary determined by variation of water level at both extremes of the estuary, flow rate, density of fresh and salt water and the geometry and bathymetry of water bodies. They are also affected by wind and wave and sometimes by the Coriolis force. The interaction of fresh and salt water in estuaries provides a circulation of water and transport typical of each estuary. The circulation and transport in estuarine waters are generally turbulent and time-dependent and often have threedimensional character. The relation between magnitudes of barotropic and baroclinic horizontal pressure gradients has a vital importance to the flow characteristic. The prediction of changes in salinity distribution in each estuary, caused by changes of some above mentioned parameters is a problem that often arises. The forecast requires the recognition of the physical processes and forces taking place in the estuary.

Some results of testing relevant physical processes by field measurements and numerical simulations in estuaries along the Polish Baltic Coast are presented in

[1]Ph.D., Institute of Hydroengineering Polish Academy of Sciences, Kościerska 7, 80–953 Gdańsk, Poland

this paper. To describe the above mentioned processes field measurements were conduccted in the following estuaries: Odra, Łeba, Łupawa, Piaśnica and Wisła (Fig. 1).

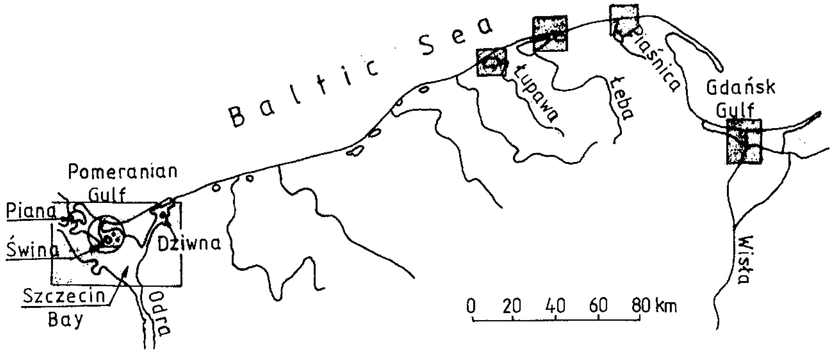

Fig. 1 Estuaries along the Polish Baltic Coast

It is proved that a profound knowledge of the hydrodynamic conditions and the character of motion of salt water in the estuaries are very important to water quality observation in these areas. A method of determination of the longitudinal dispersion coefficient for a tideless estuary and some results of calculations using a threedimensional baroclinic model adapted for the Odra estuary are also presented in the following sections.

2 CHARACTER OF FLOW AND SALT INTRUSION

The problem of intrusion of salt waters and character of flow was tested by the Institute of Hydroengineering in Gdańsk. It was done for several different types of estuaries along the Polish Baltic Coast. In this paper as the example is presented the data for two estuaries: Odra and Łupawa, whose size and topography are quite different. The Odra estuary (Fig. 1) is a very complex system in the western part of the Polish Baltic Coast. The river Odra flows into the sea through Szczecin Bay and three straits: Piana, Świna and Dziwna. The straits connecting the Szczecin Bay with Pomeranian Gulf, part of the Baltic Sea. The total area of Szczecin Bay together with the straits is 910 km^2. The area of the bay is 686.9 km^2 and the length of its coast line is about 243 km. The greatest extension of the bay along the east-west axis is around 50 km, the smallest width 7.8 km. Depths are small, except in the central part, where the depth reaches 6 m. Through the bay runs the navigational channel from Szczecin to the Baltic Sea which has a mean depth of 10 m and is 250 m wide (Jasińska et al. 1988).

The water exchange between the bay and the sea through the straits varies from one to another and depends on the water level differences on the ends of straits and meteorological conditions. The water levels in Pomeranian Gulf are mainly caused by storm surge and in extreme situations they changed in range + 1.96 m and - 1.34 m. The tide range in the Baltic Sea in this region is around 0.04 m and is negligible. The velocities of the water rise may reach 0.20 m/h and about 1 m within 10 – 12 hours. Water levels in the Szczecin Bay oscillated from + 1.29 m to - 0.72 m. Average water level in the Szczecin Bay is a little bigger than in the Pomeranian Gulf.

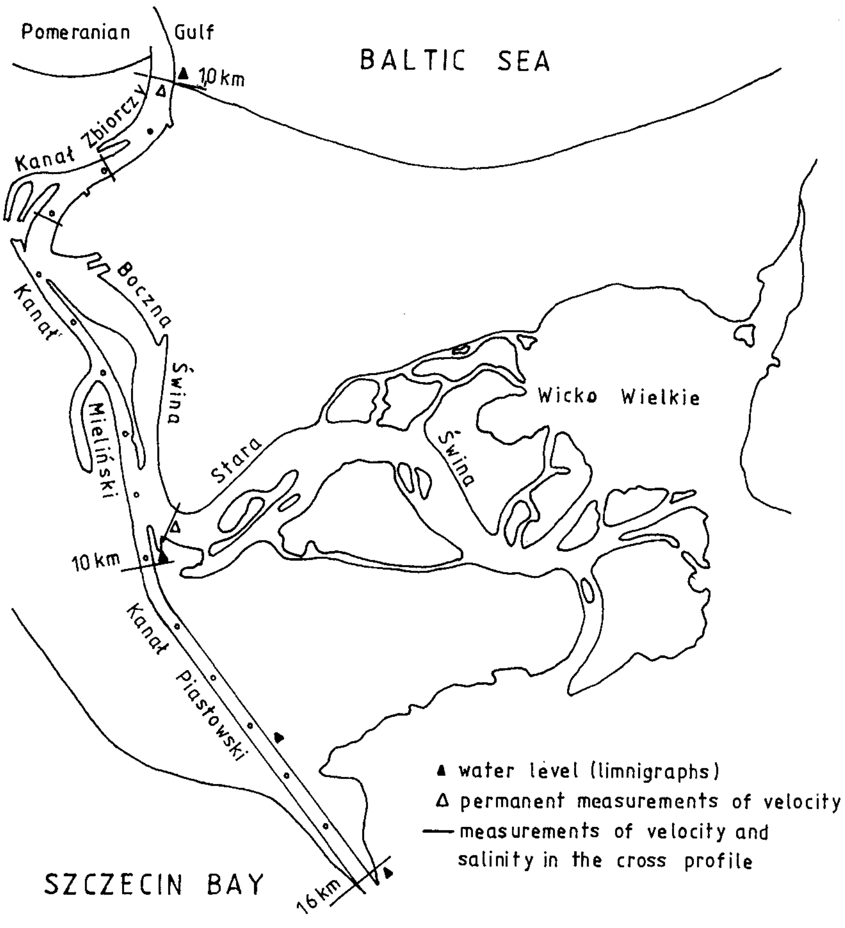

Fig. 2 The Świna Strait

The Świna Strait (Fig. 2), the main connection of the Szczecin Bay with the sea, consists of natural canals and man-made canals. Its length is 16.3 km and water areas are 13.2 km^2. Particular part of Świna Strait are of the following depths: Kanał

Zbiorczy (KZ) 15 - 17 m (at some places up to 21 m), Kanał Mieliński (KM) 10 - 12 m, Kanał Piastowski (KP) 10 m and Boczna Świna and Stara Świna 5 - 6 m.

The field measurements mainly concerned the water level and the distributions of velocity and salinity in so many points as possible. Very interesting results were obtained from continuous registration of velocity and water level during a longer period of time. In the analysis of the measurement data (Jasińska 1987) cyclic changes of the directions and values of currents and the distributions of salinity were noticed. Small changes of the water level and of its slope (Δh) caused a considerable oscillation of the value and direction of the velocity and in the distribution of salinity (Fig. 3).

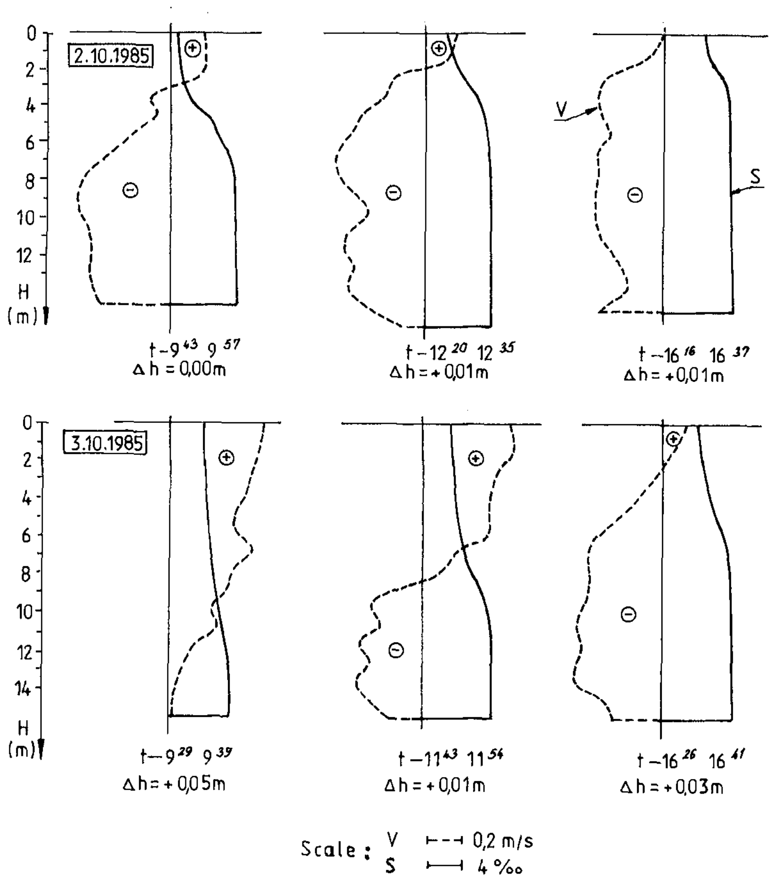

Fig. 3 Distributions of salinity and velocity at the small Δh in the Świna Strait

The strong inflow changed the conditions of flow and salt water filled the whole Świna Strait (Fig. 4) and also the part of Szczecin Bay within a short time.

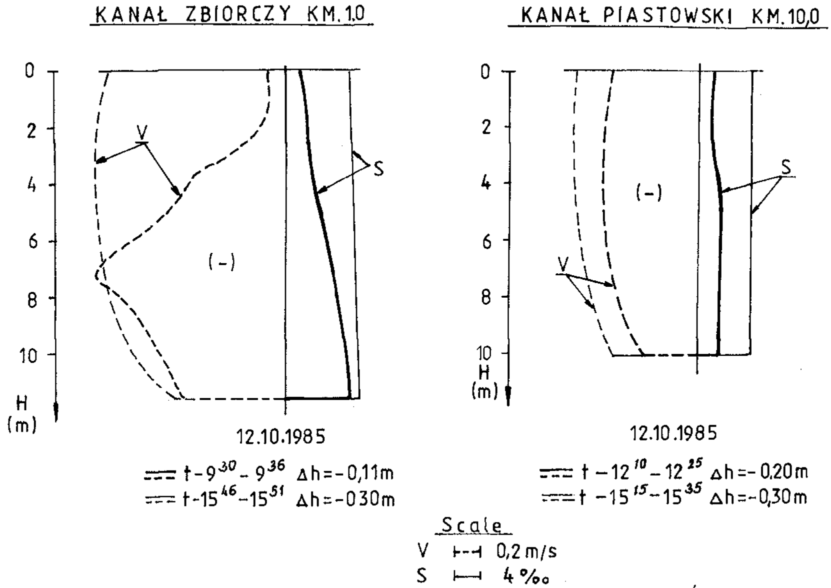

Fig. 4 Distributions of salinity and velocity at strong inflow in the Świna Strait

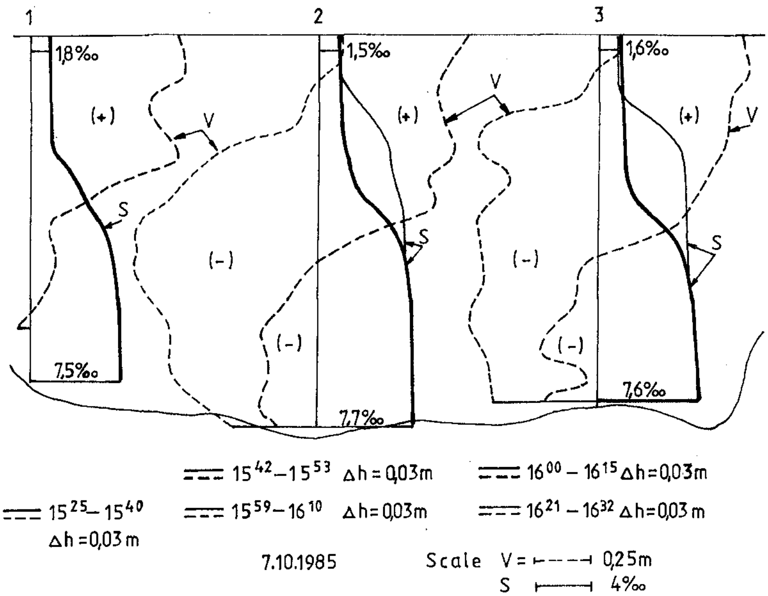

Fig. 5 Example of dynamic changes of flows and water salinity in cross-section, KZ - 1.00 km

Dynamic changes of flows are reflected in changes of water salinity (Fig. 5). As a result of a systematic increase of slope the salt water was gradnally displaced out of the surface layers. Between 16.00 and 16.30 a sudden change in water salinity as well as in velocity was recorded within a few minutes. Measurements were taken directly succeeding one another and in vertical 3 an increase in the thickness of the salty layer from 5 m to 10 m (from the bottom) was recorded. The difference of water level between the two end of estuary changed from 0.0 m to 0.05 m and it was a typical example of salinity and velocity distributions under conditions of twodirectional flow of unsteady character.

When the water level difference between the sea and the bay under calm weather conditions is smaller than about 0.05 m the baroclinic pressure gradient has the main effect on the current causing two layer stratified flow. When the differences (Δh) are bigger than $\pm$ 0.05 m there is an outflow or inflow, when the differences are between + 0.05 m and -0.05 m may take place outflow, inflow or twodirectional flow.

Sometimes fronts between the salt Baltic and the brackish bay water in horizontal and vertical plane appear. As a result of the intensive turbulence after inflow the salinity gradients in the vertical plane quickly disapper.

The Łupawa estuary is located in the middle part of the Polish Baltic Coast. In the lower part of the Łupawa river (Fig. 6) there is a shallow lake Gardno. The two km long section of the river joins the lake with the sea. Between the bridge (500 m from the mouth) and the sea there is a fish harbour Rowy. The river in this part is a harbour chanel with concrete walls on both sides. There is continuous dredging work in this region because of the strong sedimentation in the river mouth. The depths are 1.5 m to 2.0 m and the average width is 20 m.

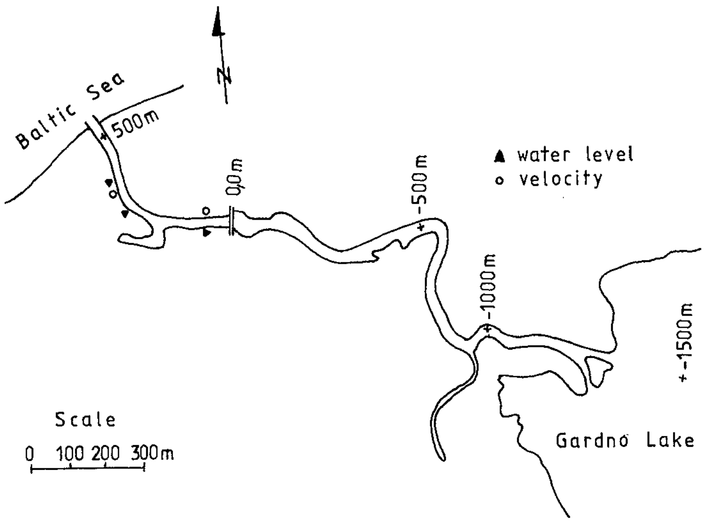

Fig. 6 The Łupawa estuary

The measurements were carried out in May 1989 in the area between the lake and the sea. In Fig. 6 there are shown profiles and verticals where the measurements were performed. The water levels in the lower part of the Łupawa during the measurements and in the period before were slightly changeable but had an oscillating character. The periods of oscillation were from a few minutes to several hours. The water level difference between the bridge and the sea were very small from + 0.12 m to - 0.03 m but most of them were close to zero. In May and particularly at the time of expedition winds were weak but changeable in their directions.

In spite of such small variations of water level and weak winds very substantial changes of flow conditions with strong inflows of salt waters into Łupawa estuary were noticeable. The flows were noticed in the whole profile towards the sea or towards the Gardno lake. The two-direction flows with a wedge of salt water were observed too. The existence of homogenous fresh or salt water in the whole profile was noticed. There were also completely or partially mixed waters with stratification. The salinity of the water in the Łupawa estuary changed from 0.8‰ to 9.2‰ (Jasińska 1990).

As an example of the penetration of salt water into the Łupawa estuary the situation abserved on May, 15th is presented (Fig. 7 and Fig. 8). At the almost zero gradient of the barotropis pressure there was a typical baroclinic inflow. At 8 o'clock in the morning there was a beginning of a set of measurements in the profiles and verticals. The measurements were started in profile 400 m towards the bridge, the velocities were small up to + 0.10 m/s, the salinity of water was about 1.2‰ in the whole area (Fig. 7). The wind was from NE with the velocity from zero to 2 m/s. Because of the observed change of flow conditions at 9.40 a set of continuous measurements was begun. It was made in profile 230 m in the vertical near the west pier.

During the first period only the salinity and water temperature were measured because the velocities were close to zero. The time of measurements in the whole vertical (H = 1.90 m) every 0.20 m was about three minutes. The inflow with the salinity changing at the bottom from 1.2‰ to 9‰ (Fig. 8) was registered. The conditions were changing very quickly and the whole process lasted to 11 o'clock. The velocities increased up to - 0.15 m/s at the bottom, but at the surface they were still close to sero. The water slope was almost constant close to zero and all the time was towards the sea. It appears from the continuous registration at profile 310 m that the direction of the flow was changed and it took place at 9.40 and again at 12.40 and the velocities were about - 0.10 m/s.

After 11 o'clock there was a gradual decrease in salinity in profile 230 m. The velocities there were close to zero. At 11.10 a new set of measurements was begun in the longitudinal profile in the Łupawa in order to define the range of inflow. The salt water filled the whole cross section of the Łupawa up to the profile 310 m (Fig. 7), further the salinity gradually decreased in the surface layer but at the bottom it was still about 9‰ in the distance – 100 m (above the bridge). The velocities changed from – 0.20 m/s near the sea to zero in the region of the profile 60 m. They were two-directional above the bridge. The water slopes were still very small.

The similar situations repeated a few times during the measurements. These results confirmed the intrusion of salt water into the tideless estuaries in spite of small variations of water level in the sea.

On basis of the results of field measurements the classification of the tested estuaries was performed. The estuaries are classified according to two basic quantities:

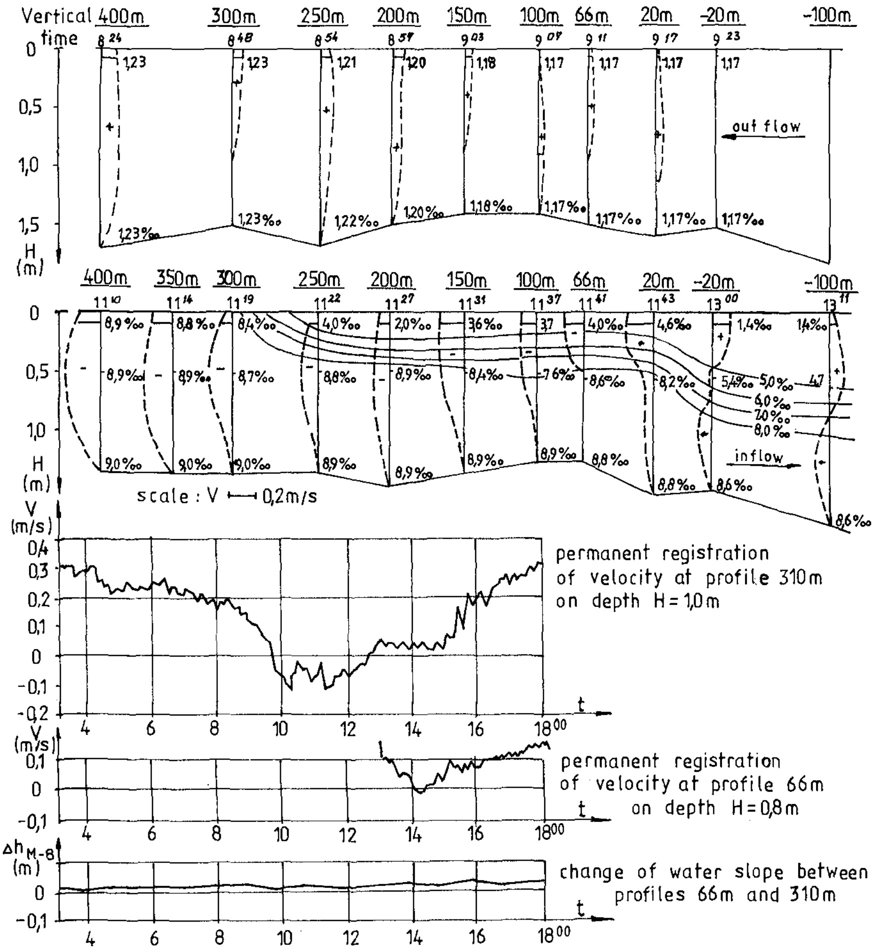

Fig. 7 The change of conditions of flow and salinity in the Łupawa – 15.05.1989

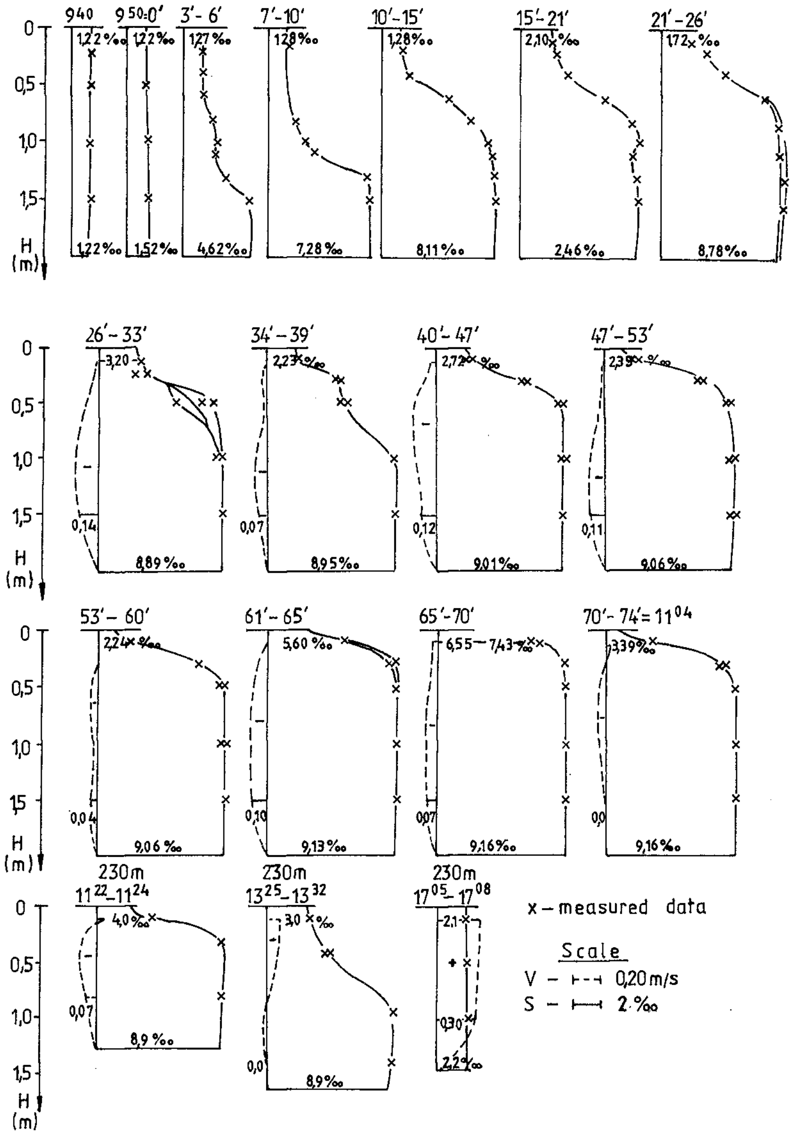

Fig. 8 The baroclinic inflow of salt water into the Łupawa – 15.05.1989

topography and structure of salinity. The estuaries along the Polish Baltic Coast are well or partially mixed and also temporary highly stratified with a salt wedge. The type of an estuary may change when there are changes in the river flow or in the dynamics of the inflow of the salt water.

3 RESULTS OF NUMERICAL SIMULATION

Parallely to the field measurements theoretical analysis and calculation based on one- two- and three- dimensional numerical models were carried out. First results were obtained from the onedimensional model. For this calculation it was necessary to determine the longitudinal dispersion coefficient. A method of determination of the longitudinal dispersion coefficient for a tideless estuary (Jasińska 1983) has been based on the Ippen and Harleman's (1961) approch made for a tidal estuary. The analysis of the field data has exposed a new dimensionless parameter L_u

$$L_u = \frac{D_o}{v_f\ Z}$$

where: L_u – the Estuary Number, D_o – the dispersion coefficient at $x = 0$, v_f – the fresh water velocity, Z – the distance in the seaward direction, where the salinity is equal S_o – sea water salinity. During an analysis of the field data it was found that the Estuary Number maybe correlated with the dimensionless values $\overline{S}/S_o$, v_f/v_s and Z/D charakterizing the estuary and its processes, where $\overline{S}$ – instantaneous salinity averaged over the cross-section, v_s – the salt water velocity, D – the depth in $x = 0$. The correlations (Fig. 9 and Fig. 10) were established for the conditions of tideless estuaries along the South Baltic basing on the results from the field measurements of Łeba and Dziwna. The effect of estuary depths, fresh water flow rate and changes in salt water in the flow into the estuary on the dispersion coefficient may be described from these correlations.

The complexity of the hydrodynamic regime and their threedimensional characteristics require the use of a threedimentional model in order to get better results. For the Odra estuary a threedimentional baraclinic model of high resolution in the vertical and horizontal plane (Duwe et al 1983, Pfeiffer and Duwe 1987) has been used for the simulation of hydrodynamic conditions and the movement of salt water. The adaptation and verification of this model were done for the Odra estuary (Jasińska and Nöhren 1988) using the data of the above mentioned measurement. The calculations were done in cooperation with the Institute of Oceanography Hamburg University. This model taks into account the horizontal momentum equations, the continuity equation, the transport of salinity and an equation of state. Hydrostatic equilibrium, kinematic boundary conditions at the free surface and Newton-Taylor bulk - formulars for wind stress and bottom friction are applied additionally. Detailed description of the model and its numerical scheme were done by Duwe et al. (1983).

The area of the model extends over the straits of Piana, Świna and Dziwna, the Szczecin Bay and the Odra to Gozdowice. The horizontal grid size of the rectangular net is 250 m as the main waterway through Szczecin Bay is 200 m to 300 m wide. In the vertical there are eight layers with a thickness of 2 m each. The time step is chosen to be 600 s, which is sufficient to resolve the dominant oscillations.

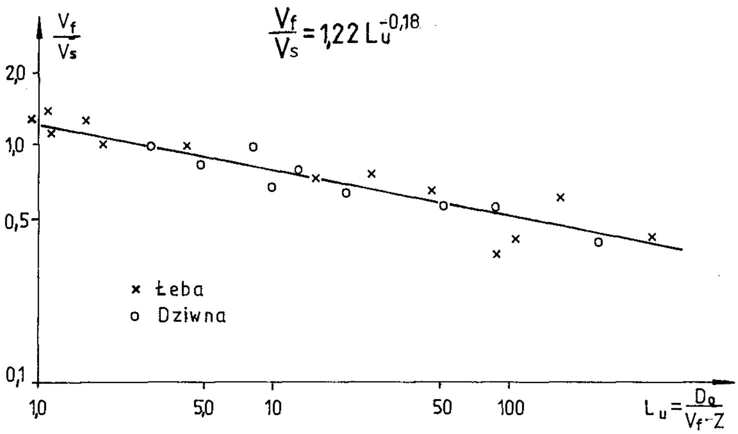

Fig. 9 Velocity distribution *vs* L_u

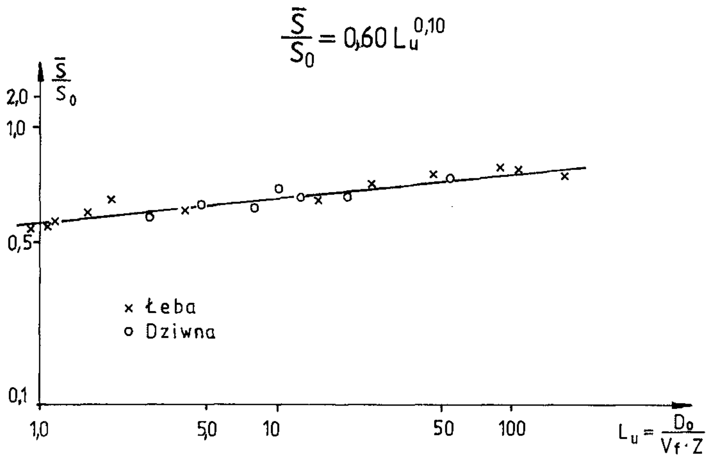

Fig. 10 Concentration *vs* L_u

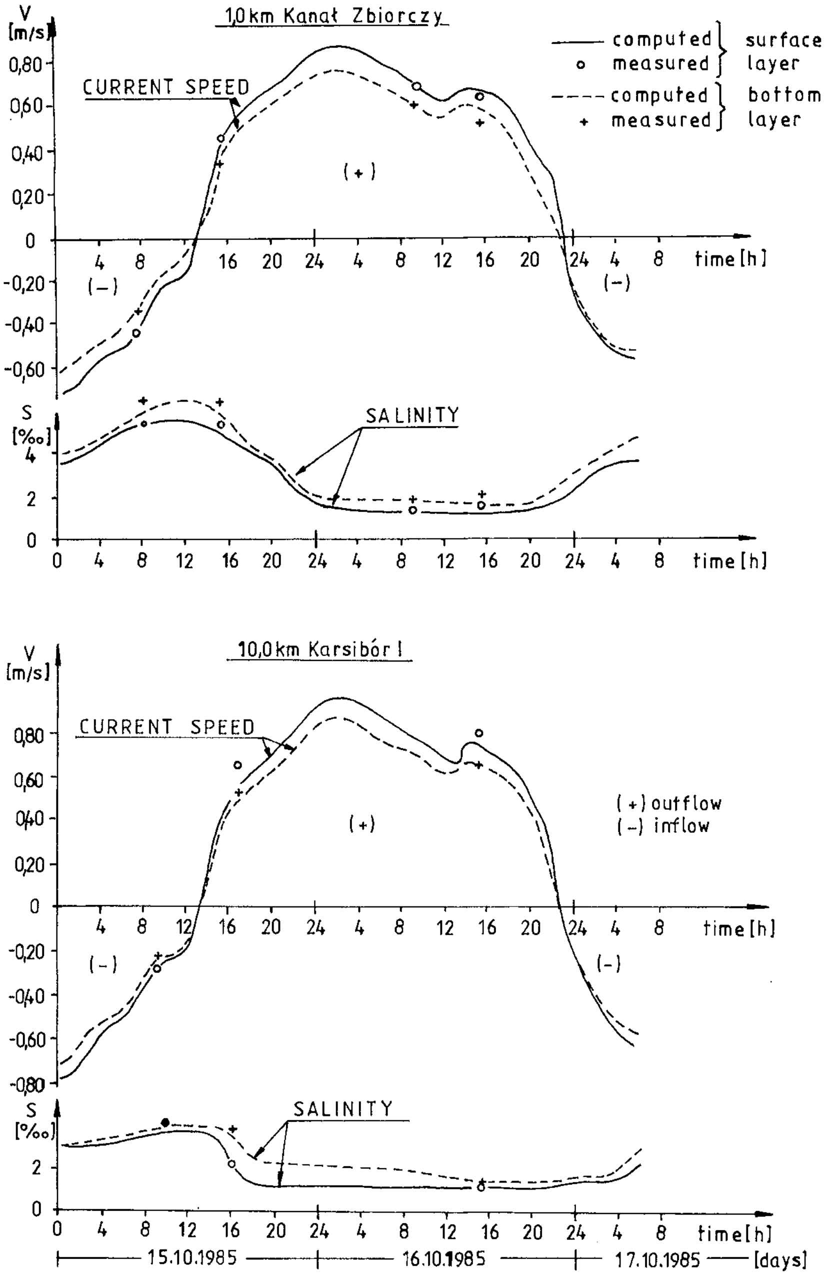

Fig. 11 Changes of salinity and velocity at points KZ - 1 km and KP - 10 km

As a boundary conditions water level elevations and time dependent vertical salinity distributions were given at the boundary to the Baltic Sea (the mouth of Piana, Świna and Dziwna). At the landward open boundary the Odra discharge in Gozdowice was given. For the wind field, the data set was taken from the measurements in Świnoujście and was assumed to be uniform in space.

The comparison of the computation with the measurement data showed a good accordance, some results are present in Fig. 11. In the figure time series of velocity and salinity in the surface and bottom layers for the points Kanal Zbiorczy - 1.0 km and Karsibór 1 – 10 km are shown. The difference between measured and computed results is small. The measured velocities, their values and directions, are correctly reproduced by the computation. The agreement between measured and computed values for the salinity is also very good. There is a very well reproduced change of salinity in the vertical as well as in longitudinal direction.

Summarizing the results of calibration and verification it can be concluded that generally the flow phenomena and the motion of salt water in the Odra estary are well reproduced by this model. The results will be applied to determination of boundary conditions for more detailed model of the subarea of the Odra estuary which is now being made in the Institute of Hydroengineering in Gdańsk. In future the model will be improved by additional data from field measurement and numerical studies in order to get a better insight into the dynamics of estuaries along the Polish Baltic Coast and possibility of forecast.

4 CONCLUSIONS

The above described study increased considerably the knowledge of the circulation and the transport processes in the tideless estuaries along the Polish Baltic Coast. It has been stated that the dynamics of the flow in tideless estuaries is similar to that of the tidal estuaries. In spite of very small changes in the gradients of barotropic pressure and of weak wind there are significant changes in the flow conditions. The intrusion of marine waters appeared not only at a storm surge but also during calm weather conditions. During calm weather a weak balance of the barotropic and baroclinic pressure gradients is present which yields changeable inflow and outflow conditions. Under these conditions the intrusion of salt water in the tested estuaries is probably caused by the change of pressure conditions above the Baltic Sea. It is very difficult to define and predict the flow conditions when the water slope is small what happens very often. Under such conditions there may be an outflow, inflow or two-directional flow.

The continuous measurement showed how unsteady the flow conditions are. The velocity and salinity distributions in the tested esstuaries demonstrate that the change of current direction occurs at different depth and different times, thus there is a need of threedimensional numerical modelling. The applied threedimensional numerical model reproduces the flow phenomena and the motion of salt water in the Odra estuary very well.

The model can be advised for design and exploitational purposes as well as for the analysis of transport problems. It is planned to develop a separate section model for the Świna Strait with the boundary conditions obtained from the whole Odra estuary model which has been already verified.

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