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THE FLUCTUATIONS OF WATER LEVEL IN THE ODRA ESTUARY

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Abstract

The work presents the results of studies on hydrological and meteorological determination of water level fluctuations in the Odra Estuary. Firstly there has been found the evident continuous increase of average water level at the gauge Świnoujście from the beginning of observational series (1811) due to eustatic changes and gradual land decreasing. Next the study revealed that seasonal fluctuations of sea level are determined by the quantity of sea basin filling which is dependent on circulation conditions. Then examined storm surges (1993-1995) emphasised the important role of sea surface distortion caused by the dynamical movement of low-pressure system. Finally there was found that circulation conditions modify relations between water discharge of the Lower Odra River and water level differences data as measured at the coastal stations of the Szczecin Lagoon and the Świna Strait. Especially during the Odra flooding events there were found statistically significant relations between them.

Key words: water level fluctuations, the Odra Estuary, circulation conditions, water discharge of the River Odra

INTRODUCTION

Water level fluctuations present an important geophysical, oceanographical and climatological problem. They have a significant impact on the changes of water depth and on the location of characteristic elements of coastal zone, which cause the erosion of seashore and the movement of coastline into the land. As a consequence the ecological changes, the disturbance of work in harbours and a danger of human existence can take place. Hence hydrological and meteorological determination of water level fluctuations is worth studying by all means.

In the Pomeranian Bay a great variability of water level fluctuations is observed. It is a result of interactions between different types of periodical and non-periodical fluctuations. Among periodical ones are long-term, annual, semi-annual oscillations as well as tides and seiches. Among non-periodical ones are storm surges and decreases of water level caused by wind and changes of atmospheric pressure as well as fluctuations caused by irregular amount of river input during the year. Some water level fluctuations are the result of annual precipitation and evaporation distributions as well as water density (Dziadziuszko and Jednorał 1987, Kożuchowski and Boryczka 1997, Majewski 1974, Robakiewicz 1993, Wiśniewski 1978).

In the Szczecin Lagoon variability of water level fluctuations is significantly smaller and is the result of water level fluctuations in the Pomeranian Bay as well as wind conditions over them. Water level increases in the Szczecin Lagoon caused by brackish and river water inputs amount to 50-80% of the increase of water level in the Pomeranian Bay and occur with a lag in relation to dynamic changes of water level in the Pomeranian Bay. In the Świna, Dziwna and Piana Straits water level fluctuations depend on water level fluctuations mainly in the Pomeranian Bay, to a lesser extent in the Szczecin Lagoon (Buchholz 1990, Buchholz *at al.* 1990, Majewski 1980, Robakiewicz 1993).

The work presents the results of studies on hydrological and meteorological determination of water level fluctuations in the Odra Estuary. First long-term variability of water level fluctuations at the gauge Świnoujście was studied. The station is in possession of the longest series of water level elevation data in the Baltic area (since 1811). The statistical compilation was performed and trend analyses were applied. Then seasonal and short-term variability of water level fluctuations in the Odra Estuary were studied. Air circulation and wind conditions were taken into consideration in order to find meteorological determination of water level fluctuations at the gauge Świnoujście. Finally water discharge of the Lower Odra River at Gozdowice was taken into analysis in order to find hydrological influence on water level difference data as measured at Trzebież, Karsibór and Świnoujście gauges. As high water discharge of the Odra has an effect on water levels in the Odra Estuary the Odra flooding events in the years 1970-1982 were studied (Buchholz 1991). Cross-correlation, simple and multiple regression analyses were performed. The data were taken from published sources and from Institute of Meteorology and Water Management in Gdynia.

RESULTS AND DISCUSSION

Long-term variability of water level

There has been evident continuous increase of average water level at the gauge Świnoujście from the beginning of observational series due to eustatic changes (the general positive balance of world ocean waters) as well as to the gradual land decreasing. The computed trend came to 0.045 cm a year for the period 1811-1990 (Fig. 1). The value is a little different than that computed by Dziadziuszko and Jednorał (1987) which was 0.07 cm a year. In recent a few dozen years the tendency of sea level increase has intensified at Świnoujście. For the period 1949-1990 the computed trend rose up to 0.07 cm a year. For comparison for the period 1951-1985 the calculated trend by Dziadziuszko and Jednorał (1987) is 0.14 cm a year. Our analysis revealed also that the maximum water level values rose significantly (0.27 cm a year) and the minimum water level values deepened considerably as well (- 0.17 cm a year). It seems to certify clearly about the increase of fluctuations of sea level during the year as well as about the increase of the long-term variability of sea level (Fig. 2). Probably the great variability of sea level is caused by the increase of climatic variability in the recent semi-century. However it can't be excluded that the increase rate of sea level increase at the gauge Świnoujście, apart from the eustatic increase of the average ocean level, is the tendency of vertical motions of the earth's crust with negative sign. So the decrease of banks in the coastal zone was found.

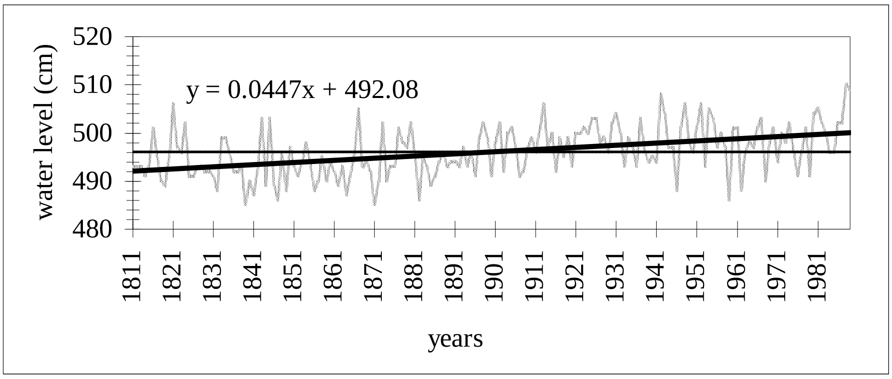

Fig. 1. The average trend of water level at the gauge Świnoujście (1811-1990)

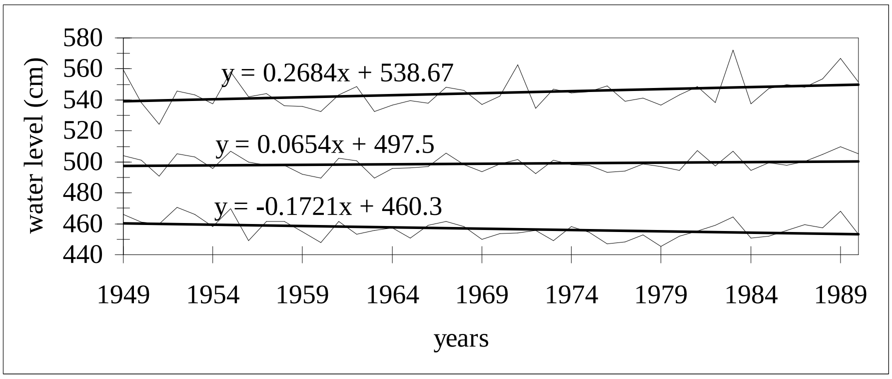

Fig. 2. Maximum (A), average (B) and minimum (C) water level trends at the gauge Świnoujście (1949-1990)

Seasonal variability of water level

Seasonal changes of sea level can be defined as mean water level changes during the year. They cause filling of a reservoir. At the gauge Świnoujście the minimum of water level is observed between March to May, while the maximum - between July to September. The secondary minimum in November and secondary maximum in December are recorded as well. Such distribution of seasonal changes is caused originally by annual and semi-annual oscillations connected with radiation changes of the Sun as well as annual and semi-annual solar and lunar tide. The atmospheric circulation is under dominating influence of the Sun radiation. Hence the annual rhythm of sea level changes is also affected by the Sun radiation. The magnitude of semi-annual solar tide can be described according to the equation of I.W. Maksimov:

$$\Delta H_S = 53.2(1 - 3\sin^2\phi)\cos 2h$$

where: ΔH_s is an amplitude of sea level fluctuations due to semi-annual solar tide wave in mm, h - the average Sun length, ϕ - the latitude. The maximum of ΔH_s is recorded in January and July and the minimum of ΔH_s is observed in April and October.

Directly water level changes at Świnoujście are determined by the quantity of sea basin filling which is dependent on the kind and the direction of air circulation as well as wind systems. During the periods of the air circulation coming from west due to inflows from the North Sea the increase of water cubic volume of the Baltic Sea as well as sea level at Świnoujście were to be found. Such situations happen especially during periods of autumn winds with the strong western component. During the periods of the air circulation coming from east due to outflows from the Baltic Sea the decrease of sea level is observed. Such situations happen especially during periods of spring winds with the strong eastern and northeastern component. The results confirmed earlier studies by Dziadziuszko and Jednorał (1987) and Majewski (1974).

Meteorological determination of short-term variability of water level

Short-term changes of sea level can be defined as water level changes detected in the range of time between a dozen or so minutes to a few days. Intermediate oscillations between wind wavy motion and seasonal fluctuations belong to this group. Storm surges are the most important among them. A storm surge can be defined as a dynamic increase of water level, above the warning or alarm water level, caused by storm winds and low-pressure systems on a sea surface. Sometimes they can cause the flooding events. Storm surges, recorded in the years 1993-1995, confirmed their complicated nature and emphasised the important role of sea surface distortion caused by the dynamic movement of low-pressure system (Wiśniewski 1997).

During the examined period of time there were recorded eight significant periods of storm surges. One kind of storm surges was observed on 14^{th} of January 1993. It surrendered clearly to the dynamic effect of low-pressure system and created by it so-called barotropic wave (Fig. 3). The active low-pressure system, so-called „junior", with atmospheric fronts was moving over the North Sea, the Danish Straits and finally over the Baltic Sea. The minimum pressure reached 976 hPa. During the storm surge the sea surface distortion occurred due to the barotropic wave effect with its positive and negative phase. The speed of the low-pressure system (about 115 km an hour), that considerably affected the magnitude of wave dynamic component, was an important factor. The sudden increase and decrease of water level up to 70 cm an hour were the distinctive features of that storm surge (Fig. 4). The storm lasted only 5 hours but caused heavy financial losses along the Polish coast of the Baltic. It also caused the catastrophe of the ferry „Jan Heweliusz".

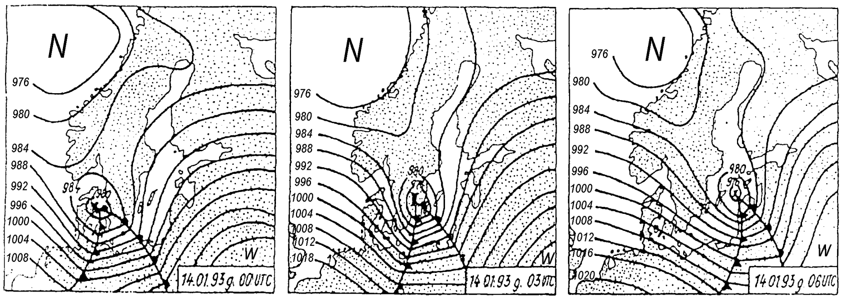

Fig. 3. The movement of storm low-pressure system over the Baltic Sea on 14th of January 1993 (from Dziadziuszko and Malicki 1993)

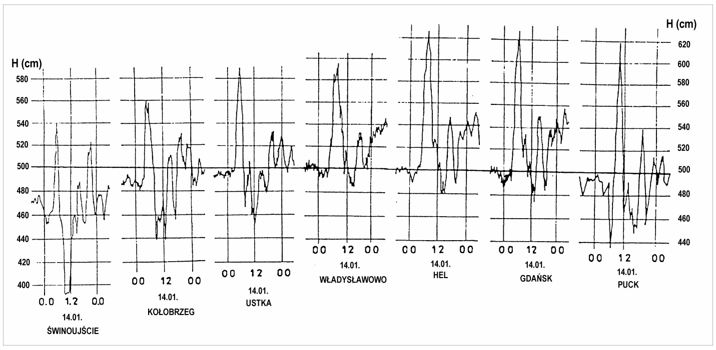

Fig. 4. Sea level changes along Polish coast of the Baltic Sea for the period 13th of January, six p.m. to 15th of January, six a.m., 1993 (from Dziadziuszko and Malicki, 1993)

Another kind of storm surges was recorded between 3rd to 4th of November 1995. The increase and the decrease of sea level at the gauge Świnoujście lasted for 34 hours. The storm surge was connected with an extensive wind field over all the Baltic Sea. The storm situation developed due to well-developed high-pressure system with the centre over the Norwegian Sea (pressure more than 1030 hPa) and two less-developed low-pressure systems (the minimum pressure of 990 hPa), which moved south of the Scandinavian Peninsula with the velocity of 45 km an hour. Due to one-dimensional stream of air masses coming from NE the southern and south-western parts of the Baltic Sea were being filled up for a long time. Along the Polish coast of the Baltic an occluded front came. Hence changes of wind directions followed. Winds coming from NW, N and NE were recorded mainly at Świnoujście whereas winds coming from SE and then E were recorded at other coastal stations. When the wind direction over the Baltic Sea had generally changed from NE to ENE and the wind speed had increased rapidly the increase of sea level in the Pomeranian Bay took place. Further change of the wind direction to N caused the increase of sea level up to 689 cm, while the warning sea levels were hardly exceeded at the eastern Polish coast. It was the biggest storm surge in the period 1995-1996 and caused the serious damage of the western Polish coast (2/3 of all the financial losses in that period). 75% of all the length of the coast was destroyed. The cliffs and sand dunes with the cubic volume of 871 775 m^3 were damaged. Dune berms were brought at Międzywodzie, Dziwnów, Niechorze and Mrzeżyno. The beaches were significantly narrowed and decreased, sometimes they disappeared entirely. The fishery landing stages were destroyed and foundations of the Amber Baltic Hotel at Międzyzdroje were unbalanced.

Generally storm periods in the Baltic area cause increases as well as decreases of sea level. Rapid decreases of sea level are difficult in forecasting of water reserve under a keel of a ship during making port or putting out to sea.

Hydrological determination of short-term variability

During the Odra flooding events water discharge of the Lower Odra River has an effect on shaping free surface of water in the Szczecin Lagoon as well as in the Świna Strait. During three high water periods of the Odra in the winter 1974-75 (19 October 1974 - 8 March 1975), the summer 1977 (4 August - 25 October 1977) and the spring 1979 (27 February - 5 June 1979) statistically significant relations were found. During the Odra flooding events in the spring 1979 as well as in the winter 1974-75, when the air circulation from the south sector was prevailing, the synchronous relations between water discharge values and water level differences data were the closest. On the contrary during the high water period in the summer 1977, when the air circulation from the north sector was prevailing, the lag of maximum correlation coefficient was 1-8 days. For instance, during high water period in 1979 the highly statistically significant coefficient of correlation, $r = 0.803$, was obtained as a result of relating water discharge values of the Lower Odra to water level differences data as measured at Karsibór and Świnoujście. In that case the equation of polynomial regression explained almost 65% of all the cases (Fig. 5).

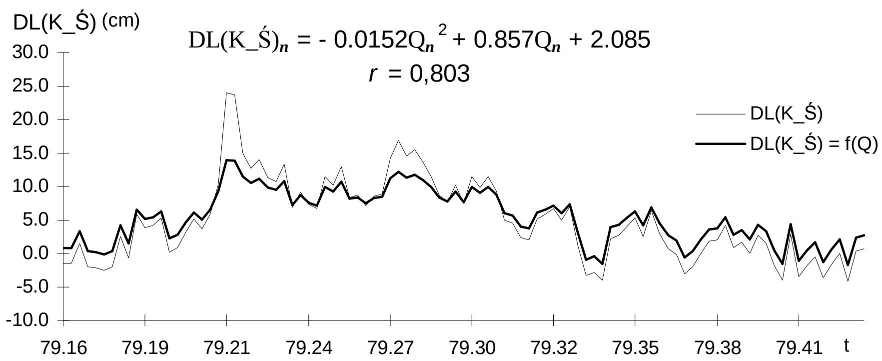

Fig. 5. The plot of water level differences as measured at Karsibór and Świnoujście (observed and calculated from the equation of polynomial regression) during the Odra flooding event in the spring 1979

CONCLUSIONS

1. There has been found the evident continuous increase of average water level at the gauge Świnoujście from the beginning of observational series (1811). For the period 1811-1990 the computed trend came to 0.045 cm a year. For the period 1949-1990 the computed trend rose up to 0.07 cm a year. Probably the great variability of sea level is caused by the increase of climatic variability in the recent semi-century.
2. Seasonal fluctuations of sea level are determined by the quantity of sea basin filling which is dependent on circulation conditions. During the periods of the air circulation coming from west (especially during periods of autumn winds) the increase of sea level at Świnoujście were to be found. During the periods of the air circulation coming from east the decrease of sea level is observed (especially during periods of spring winds).
3. Storm surges in the years 1993-1995 emphasised the important role of sea surface distortion caused by the dynamical movement of low-pressure system. They caused heavy financial losses along the Polish coast of the Baltic Sea and were dangerous on sea. Rapid changes of sea level cause problems in maritime navigation.
4. Circulation conditions modify relations between water discharge of the Lower Odra River and water level differences data as measured at the coastal stations of the Szczecin Lagoon and the Świna Strait, especially during periods of high water of the Lower Odra River. The closest synchronous relations between them were found during the Odra flooding events with prevailing air circulation from the south sector. On the contrary when the air circulation from the north sector was prevailing, the lag of maximum correlation coefficient was 1-8 days.

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ZMIENNOŚĆ STANÓW WODY W ESTUARIUM ODRY

Streszczenie

Praca przedstawia wyniki badań nad hydrologicznymi i meteorologicznymi uwarunkowaniami zmienności stanów wody w estuarium Odry.

W Świnoujściu od początku serii obserwacyjnej (1811) zaznacza się stały wzrost średniego poziomu morza. Wyznaczony trend za okres 1811-1990 ma wartość 0,045 cm rok^{1}. W ostatnich kilkudziesięciu latach w Świnoujściu wyraźnie nasiliły się tendencje podniesienia poziomu morza. Trend wyznaczony dla okresu 1949-90 osiąga wartość 0,07 cm rok^{-1}. Jednocześnie zauważa się wyraźny wzrost wahań rocznych.

W Świnoujściu minimalne roczne stany wody występują wiosną - od marca do maja, maksymalne zaś w miesiącach lipiec - wrzesień. Również zauważane są ekstrema drugorzędne. Pierwotną przyczyną takiego rozkładu zmian sezonowych poziomu morza jest charakterystyka rocznej i półrocznej oscylacji związanej ze zmianą radiacji Słońca oraz rocznym i półrocznym pływem słonecznym. Bezpośrednio na kształtowanie się poziomu morza w Świnoujściu ma wpływ wielkość wypełnienia przez wodę basenu morskiego zależna przede wszystkim od rodzajów cyrkulacji atmosferycznej i wygenerowanych przez nie systemów wiatrów.

Zmiany wywołane warunkami sztormowymi podczas wezbrań sztormowych należą do najważniejszych zmian krótkookresowych. Rejestracja wezbrań w okresie 1993-95 potwierdza ich złożoną naturę oraz podkreśla ważną rolę zniekształcenia powierzchni morza przez dynamicznie przemieszczający się układ obniżonego ciśnienia atmosferycznego. Okresy sztormowe powodują zarówno wezbrania poziomu morza jak i jego obniżenia powodując ogromne straty na wybrzeżu i na morzu. Bardzo szybki spadek poziomu wód może spowodować brak rezerwy pod stępką statku.

Wielkość przepływu wody w Odrze jak i warunki cyrkulacyjne mają istotny wpływ na układ zwierciadła wody w Zalewie Szczecińskim. Zwłaszcza w okresach wysokich przepływów wody w Odrze wielkość przepływu determinuje układ zwierciadła wody w Zalewie Szczecińskim, co potwierdziły istotne statystycznie związki. W czasie wezbrań Odry w 1979 i na przełomie 1974-75, o przewadze cyrkulacji południowej, najsilniejsze okazały się związki synchroniczne. W okresie wezbrania letniego w 1977, o przewadze cyrkulacji północnej, przesunięcie czasowe współczynnika maksymalnej korelacji wynosiło 1-8 dni.