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Investigations into the hydrography and dynamics of suspended particulate matter and sediments in the Oder Lagoon, southern Baltic Sea

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Investigations into the hydrography and dynamics of suspended particulate matter and sediments in the Oder Lagoon, southern Baltic Sea

Untersuchungen zu Strömungs- und Transportprozessen sowie zur Sedimentologie des Oderhaffs (Stettiner Haffs)

von

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1 INTRODUCTION

1.1 Background and motivation

In many parts of the world, coastal areas traditionally have been a very important place for human activities. Around 70% of the world total population live along the shorelines. Half of the world's large cities over one million are sited near tide washed river mouths (UNEP, 2001). In particular, coastal zones located adjacent to large river systems play an important role for trade, transport, agriculture, fisheries as well as tourism. At the same time these areas are of extraordinary ecological values and a transformer and sink for terrestric nutrients and pollutants. Due to intensive human activities and heavy population pressure, coastal areas are suffering from heavy pollution. Municipal, industrial and agricultural wastes are brought by the rivers and discharged directly into coastal waters, causing ecological disturbances, environmental degradation and environmental disasters.

The Baltic Sea located in the northern part of Europe is one of the largest brackish water bodies in the world. Connection to the open Atlantic Ocean is almost entirely cut off and the only interlink are through the Danish Straits. Human activities such as fishery, shipping, industry, urban development, agriculture, forestry, tourism and military activities are occuring in the Baltic Sea region and have caused the degradation of the Baltic marine environment. Chemical and biological pollution as well as load of nutrients have lead to a destruction of marine habitats and ecosystems.

In the southern part of the Baltic Sea, particularly the areas at the border between Germany and Poland lies the Oder Lagoon a large lagoon which is in the focus of this study (see figure 1.1. and figure 2.1.). The Oder Lagoon is a part of the Oder river estuary. In German the Oder Lagoon is called the Oderhaff (Stettiner Haff) which is divided into the Kleines Haff in the west and the Grosses Haff in the east and in Polish it is named as the Zalew Szczecinski (also called Szczecin Lagoon or Szczecinski Lagoon) which is divided into the Maly Zalew in the west and the Wielki Zalew in the east. This lagoon has an area of about 686 km² (Buckmann et al., 1998), nearly the same as the areas of the country of Singapore which is 682 km² and slightly smaller than Hamburg State in Germany which is 755 km².

Throughout the world, lagoons have a high ecological value because of their protected environment and abundant food that provide vital habitats for thousands of marine species. They have a great diversity of marine life because of a wide range of habitat. Some fish species spend some part of their life cycles in the estuaries. Besides, it provides an important place for many species of birds for their food and nesting areas. Migratory birds use the estuaries for their resting and fooding place before continuing their journey. Estuaries act as as a filter and transformation area of the pollutant and nutrients before they reach the oceans, as a buffer between ocean and the land decreasing the effects of flooding and storm surges. They are also the place for coastal activities, commercial and recreational fishing, boating, tourism and a recreational destination area. These activities provide jobs and generate a large income each year.

The Oder Lagoon with its diverse geomorphology, unique landscape and beautiful sandy beaches has long been an important place for human activities and posesses a high ecological value too. There are at least 29 extremely valuable species of avivauna which can be found in the Oder Lagoon areas (Glowacinski, 1992 in Chojnacki, 1999). The lagoon is known as the favorable area for living and breeding conditions and its location is on the route of extensive avian north-south migrations. Tourism industry, recreational activities, fishing and transportation had been occuring for the last centuries. Furthermore, the coastal part of the Oder Lagoon has a long tradition for summer bathing and is an important economic factor for the regional economic development.

The Oder Lagoon receives its water mainly from the Oder river with its large catchment area. Human activities in the catchment area produce pollution that is transported by the river to the lagoon. At present, the Oder Lagoon is suffering from heavy pollution brought mainly by the Oder river. Due to high nutrient loads from that river, the lagoon suffers from heavy eutrophication. The input of N and P into the Oder Lagoon has approximately tripled between 1960 and 1980, this has caused the reduced water transparency and a change from a macrophyte dominated to phytoplankton dominated ecosystem (Lampe, 1993).

Figure 1.1. The Baltic region countries (left) and the locality of the Oder Lagoon (right) (modified from http://maps.grida.no/baltic/).

Andren (1999) has recorded the change of composition of the diatom assemblages attributable to anthropogenic factors in the Oder Lagoon. Particularly during the warm season, intensive algal blooms are occuring and have reduced the water quality of the lagoon. Negative impact of fish killed due to this blooms had occurred for example on May 1, 2000 (Schernewski, 2000). According to the HELCOM hotspots list, the Oder river basin is one of the high priority contaminated sites in the Baltic Sea catchment area (http://www.inem.org/htdocs/eco-baltic/hotspots.html). At present, the entire basin is characterized by intensive resuspension of the surface sediment layer (soft and fluffy material) during times of enhanced wind speed and wave action on the seafloor (Leipe et al., 1998).

In the regional development plan, the Oder Lagoon area is devoted to sustainable environmental protection and touristic development (Regionaler Planungsverband Vorpommern, 1998). This is contradictory to the present lagoon water quality as described. The poor water quality of the lagoon is the main obstacle for development efforts in this direction.

In the Baltic Region, the convention on the protection of the marine environment of the Baltic Sea Area known as HELCOM has been signed by all the states bordering the Baltic Sea, and the European Community in 1992. The HELCOM's main goal is to protect the marine environment of the Baltic Sea from all sources of pollution, and to restore and safeguard its ecological balance (http://www.helcom.fi/helcom.html). Furthermore the European Union has declared the European Water Framework Directive (WFD) in 2000 and stated that in the year 2015 all waters including the coastal water of the contracting parties should have achieved a good water status. Therefore, measures to increase the water quality of the lagoon need to be taken.

One important step to overcome this problem is to reduce the pollution load from the Oder river, which is the main source and the cause of pollution in the lagoon. To increase the water quality can be done by decreasing the nutrient input from the Oder river. However the result using ecological box model applied to the lagoon to simulate the nutrient level and the resulting conditions showed that the maximum possible nutrient reduction will keep the lagoon in an eutrophic state (Wielgat and Schernewski, 2002). This result indicated the importance of additional alternative measures to increase the water quality of the lagoon.

Wind induced currents or flow in the water bodies play an essential role in the transport of dissolved and particulate materials such as fine grained sediments (Ziegler and Lick, 1988), pollutants (Murthy, 1986), organic matter and nutrients (Sheng and Lick, 1979) and suspended particulate matter (Algan et al., 1999; Edelvang et al., 2002). The transport of those materials within the basin depends on the water movement. Currents also play an important role in the vertical mixing processes (Reynolds, 1994), distribution and resuspension of sediments (Bloesch, 1995), processes in macrophyte stands, reed zones and benthic systems (Commito et al., 1995). The intensive investigations on the spatial heterogeneity of phytoplankton and zooplankton during the last decades have shown the close relationship between water flow and lake biology (Podsetchine and Schernewski, 1999). As have been demostrated above, currents are the basic factor of understanding the transport processes of dissolved and particulate matter in the water bodies. Hence understanding the hydrodynamics of the Oder Lagoon is a very important basis for further studies as described.

Beside the material from the adjacent shores, atmospheric fallout and the input from the river, the resuspended materials from the bottom sediment are an important source for the turbidity in many shallow water bodies like lakes, bays and lagoons. Phytoplankton blooms occur as happened in the Oder Lagoon during the warm season, providing additional materials to the bottom sediment. The information about materials involved in the resuspension are very important to understand the origin and resuspension processes in the Oder Lagoon.

1.2 Aims of the study

In order to know the materials that are resuspended in the Oder Lagoon, the study started with the identification and determination of the types of bottom sediment and suspended particulate matter of the lagoon. Beside bottom sediments, core sediments were taken to provide insight of historical input material from the Oder river basin into the lagoon.

The importance of water flows in many processes in the water bodies has been pointed out by the previous studies. In order to provide a basis for understanding the transport processes in the Oder Lagoon, investigations on the the water flow were conducted. To achieve this goal the hydrodynamic and transport model Femflow2D developed by Dr. Victor Podsetchine of the Pirkanmaa Regional Environment Centre (PREC), Tampere, Finland was applied. To improve the ability of the model, the existing Femflow2D model was modified and updated during this study. This new version was tested and used. Particularly, the new suspended particulate matter module that has not been applied as yet was examined and applied in this study. This new suspended particulate matter module was used to simulate the dynamics of suspended particulate matter in the Oder Lagoon. In addition, the conditions and intensity of the water mass exchange between the Kleines Haff and the Wielki Zalew were investigated to provide a basis for further ecological studies of these two large parts of the lagoon.

Finally, the present conditions of the suspended particulate matter mass balance in the lagoon was studied.

Overall aims of this study are as follow:

A. To determine the type and composition of the sediments and suspended particulate matter of the Oder Lagoon.

B. To support the development of Femflow2D hydrodynamic and transport model through the model validation. The model application includes, B.1. Flow simulations and validation

B.2. Assessment of the water mass exchange between the Kleines Haff and the Wielki Zalew for further ecological studies in these two large parts of the lagoon.

B.3. Suspended particulate matter dynamic simulations and validation.

B.4. Tracking of particulate materials entering the lagoon from the Oder river. This covers tracking under different wind conditions and tracking of anthropogenic heavy metals particles.

C. To state the present conditions of the suspended particulate matter mass balance in the Oder Lagoon.

2 GENERAL OVERVIEW OF THE STUDY AREA

The Oder Lagoon is located in the north-eastern part of Germany, south of Pomeranian Bay which is a part of the Baltic Sea. The shape of the lagoon is oval and parallel to the Pomeranian Bay shorelines. Several small restricted bays can be found in the central southern part, north-west and north-east of the lagoon (see figure 2.1.). The western part of the lagoon which covers about 40 % of its total area belongs to Germany while the eastern part belongs to Poland and covers about 60 % of the total area. To the Baltic Sea, the lagoon is separated by the Usedom Island in the west and the Wolin Island in the east. Geographically, the lagoon is located between 54.14° to 53.60° North and 13.70° to 14.80° East. The distance from west to east is about 46.5 km and maximum distance from north to

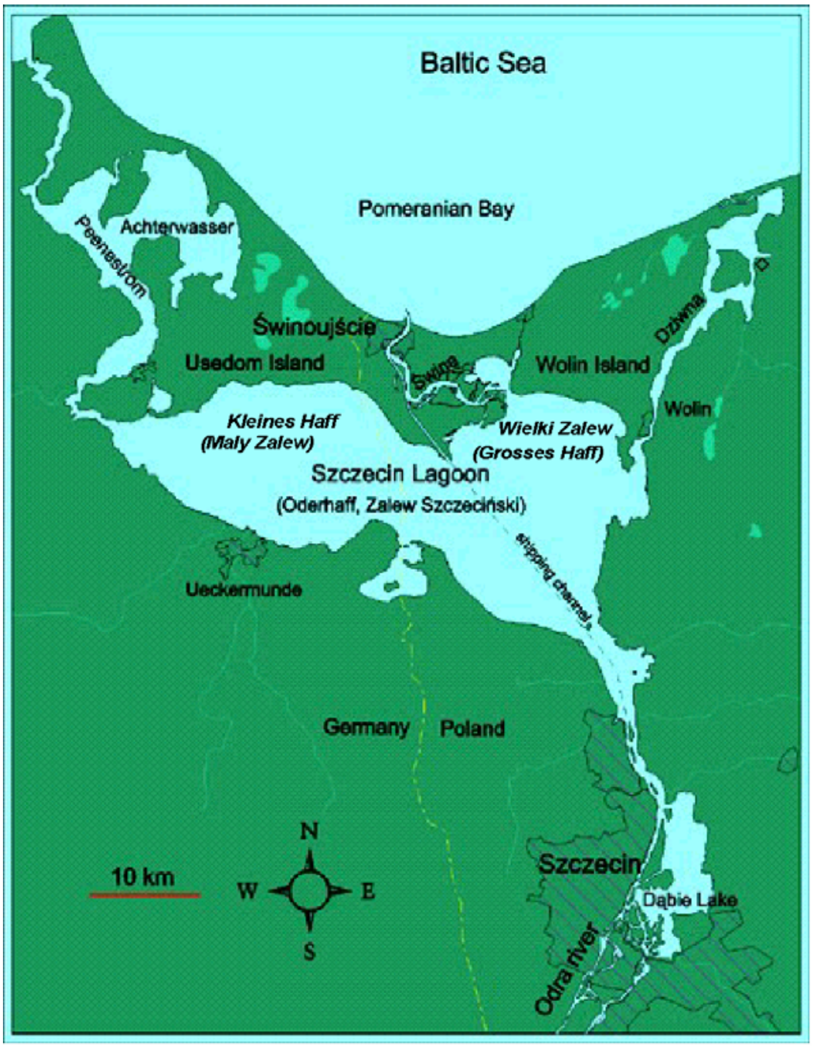


Figure 2.1. The Oder Lagoon and adjacent areas (modified from Institute of Marine Sciences, University of Szczecin, http://sus.univ.szczecin.pl/WNP/ZGM/ estuary.jpg).

south is about 14.7 km and 21.75 km in the Kleines Haff and the Grosses Haff respectively. The Oder Lagoon and adjacent areas can be seen in figure 2.1.

2.1. Geology and geomorphology

The Baltic region morphology was created by the Quaternary glaciations (Harff et al., 2001). Glacial erosion shaped the relief of Scandinavia while the West European Platform including the Oder Lagoon and adjacent areas were covered by glacial sediments (Harff et al., 2001). The factors that have considerably affected the distribution of late-glacial and post-glacial sediments in the Baltic Sea area are the differential uplift of the Baltic Sea basin, together with the multiple transgressions and regressions that have occurred during the various phases of the evolution of the Baltic Sea (Voipio, 1981). The distributions of various sediments depend on a number of factors such as water depth, wind fetch, distribution of currents and the supply of material. There are five zones of sedimentation that can be differentiated in the Baltic Sea region (Voipio, 1981):

1. Coastal accumulation zone particularly in the southern and south-eastern part of the Baltic Sea.

2. Relict clastic deposits, for example glacial drift with only a minor evidence of reworking of the uppermost layer of sediments.

3. Zone of retarded sedimentation, also as non deposition, increasing exposure to wave and current-induced water motion following crustal uplift or eustatic sea level change,

4. Zone of erosion, not to be confused with local erosion in deep channels and on and on the flank of topographic highs, the latter being the case of local increase in current velocities due to topographic flow restrictions.

5. Zone of sedimentation (silts and muds), generally located below the permanent halocline and the wave base level including internal wave in the permanent halocline.

According to the Guidelines for the Integrated Coastal Zone Management of the Szczecinski Lagoon, the Polish Side (2000) the geology and geomorphology of the Oder Lagoon area can be described as the following. Historical geology of the Oder Lagoon and adjacent areas began when huge continental glaciers in Scandinavia began to melt about 16000 years ago. The glacial erosion had brought enormous amounts of erratic blocks and moraine formations. In the vicinity of the withdrawing edges, new complexes of post glacial and fluvioglacial deposits came into existence, both accumulative and erosive forms. Rising of sea level occurred around 8000 years ago which sculptured the area. At about 6000 years ago the sea invaded the Pomeranian Bay and the lagoon and its waters formed the present shape of the shores.

The geomorphology of the area adjacent to the lagoon is quiet diverse. To the south-west, south and south-east the lagoon is surrounded by sandy plains being remnants of the outflow of post glacial waters in the final stage of the last glaciations when flat mud and peat plains were developed. Dunes, post glacial depressions and young river valleys with terrace levels diversified their surfaces. In the north-eastern part of the lagoon a flat or hilly ground moraine built of clays and post glacial sands can be found. The elevation is up to about 20 meter above sea level with only 5 meter drops. The northern parts of the lagoon are surrounded by the islands Usedom and Wolin which are elevated to the height of more than 100 meter above sea level. Holocene sandbars formed after the glacier had receded as well as accompanying dunes, beaches, cliff sea precipices, river valleys, river accumulation plains and lagoon accumulation plains.

2.2. Bathymetry

The Oder Lagoon is a shallow basin whose natural depth does not exceed 8.5 meter and in which 95.8% of the bottom area lies at a depth of less than 6 meter, while shallow water less than 2 meter deep occupies more than 25 % of its area (Osadczuk, 1999). The lagoon's bottom is relatively flat and featureless at depths of 4 to 6 meter (Osadczuk, 1999). The western part of the lagoon has an area of 277 km^2, an average depth of 3.7 m and a water volume of 1026 km^3 while the eastern part has an area of 410 km^2, average depth of 3.8 m and water volume of 1557 km^3 (Meyer and Lampe, 1999). A trough like depression occurrs in the middle part of the lagoon between the western and eastern part of the estuary. Across the eastern part of the lagoon, a long and narrow trough with a depth of about 10 to 11 meter and 90 to 130 meter wide can be found. This is a man made shipping channel that was built across the lagoon initially in the years 1875 – 1880 (Piastowski Canal) and in the 90's (Mielinski Canal). The channel is at present stretching south-east north-west about 70 kilometres long from Swinoujscie at the Swina Gate to the Oder river mouth area and up to the city of Szczecin in Poland (a large city about 20 kilometres south of the river mouth).

2.3. Climate

The climate of the Oder Lagoon and adjacent areas are influenced by three distinctive air masses approaching from the various regions of Europe (Guidelines for the Integrated Coastal Zone Management of the Szczecinski Lagoon, the Polish Side, 2000) as follows:

- Polar-maritime air masses from the Atlantic Ocean characterised by precipitation, higher humidity, increased cloudiness, significant air temperature cooling in summer and by warming up and sudden snow melting in winter. These air masses are the most common ones.

- Polar-continental air masses approaching from central Russia, characterised by low humidity. This usually happens during winter and spring time and causes cooling and keeps up sunny weather. Sporadically air masses from northern Russia and the very cool Arctic region might come causing ground frosts during late spring. These polar continental air masses are more seldom.

- Tropical air masses, which are more seldom, approaching from south-west as hot and humid air from the area of Azores or from south (North Africa and Asia Minor) which are hot, dry and not very transparent due to the particles desert dust. These air masses cause sporadic, sudden heating up in spring and autumn. The hottest heat waves in the summer are connected with these air masses.

Two different distinctive types of the dynamic change can be described as follows: the cool one with large variability (April to October) and a warm one (April to September) less changeable.

Winds of the southern Baltic are affected by the atmospheric circulation of moderate latitudes, modified by pseudo monsoon exchange of air masses with those from Atlantic Ocean and the European Continent. The superposition brings about the predominance of south-west and west directions, throughout the year and in most months, with the exception of spring (Zeidler et al., 1995).

The most common winds in the Oder Lagoon area are westerly and south-westerly winds. The strongest winds are blowing from the north-west direction. The most rare wind direction is the northerly wind but during the winter time they may reach the highest velocities, cause storm and flood in the lagoon.

2.4. Hydrology and hydrography

The Oder Lagoon receives its water mainly from the Oder river with its large drainage basin entering from the south-east of the lagoon. Other small rivers are the Peene the river in the west; Zarow, Uecker and Randow rivers in the south-west of the lagoon. The Oder river drainage basin has a total area of 118861 km^2 (Petr, 2000) with a total population of more than 13 million people (Humborg et al., 2000). The drainage basin is mainly located in Poland (about 89 % or 106057 km^2) and a small parts of the area belongs to Germany (about 5 % or 5587 km^2) and Czechia (about 6 % or 7217 km^2), see figure 2.2. (Petr, 2000).

The Oder river is one of the largest rivers flowing to the Baltic Sea. The average river discharge is 560 m^3/s or equal to be approximately of 17.7 km^3 water per year containing 80000 to 100000 tons of total Nitrogen and 5000 to 8000 tons of total Phosphorus (Meyer and Lampe, 1999). Meyer and Lampe (1999) also described that based on the monthly Oder river discharge and the volume of lagoon basins, the theoretical water residence times were 3 to 6 months in the Kleines Haff and 0.5 to 2 months in the Grosses Haff.

The Oder river has a length of 645.3 km with an average discharge of 535.58 m^3/s during the period of 1951 to 1990 and 546.63 m^3/s during the period of 1990 to 1994 (Fal et al., 1997). Yearly average discharges of the river during the period of 1951 to 1990 were between 314 and 819 m^3/s. Graphically, the monthly average discharge of the Oder river

Figure 2.2. The Oder river drainage basin and the Oder Lagoon (modified from Petr, 2000 in http://www.riob.org/ag2000/vhs_ang.htm).

can be seen in figure 2.3. In the yearly cycle, the Oder river shows a average high discharge during spring time with its peak in April and a lower discharge during summer and autumn. Minimum average discharge during the period of 1951 to 1990 is between 156 m^3/s in

November and 271 m^3/s in April. Maximum average discharge during the same period is between 1200 m^3/s in November and 2170 m^3/s in September. The outflow to the Pomeranian Bay is through three long and narrow outlets: to the west via Peene, to the east via Dzwina and to the north via Swina.

Mohrholz and Lass (1998) investigated the transport between the Oder Lagoon and the Pomeranian Bay using a barotrophic box model (barotrophic pressure gradient due to the sea level difference) and found that 77 % of the water was transported via Swina, 14% via Peenestrom and 9% via Dziwna. They found that if the model considered also the pressure gradient due to the salinity differences between the bay and the lagoon, the values were decreased to 68% for Swina, 19% for Peenestrom and 13 % for Dziwna. Furthermore if the wind effect (wind stress) on the sea level of the lagoon is also taken into account, the value would be 69%, 17% and 14% for Swina, Peenestrom and Dziwna respectively. The influence of the wind to the Swina is not significant while to the Peene and Dziwna it depends on the geographical orientation of the outlets in relation to the wind direction. The water exchange between the Pomeranian Bay and the lagoon, forced by the sea level of the bay, the Oder discharge and local wind stress on the surface of the lagoon occurs as pulse-like in-and outflow events with a duration of a few days (Mohrholz and Lass, 1998). The Swina governs the water exchange between the lagoon and the bay, it covers 60 – 70% of the mass transport while the Peene and Dziwna contribute 15 – 20% to the water exchange. Theoretical water residence time is 1 month in the eastern part of the lagoon and 3 months in the western part of the lagoon (Meyer and Lampe, 1999).

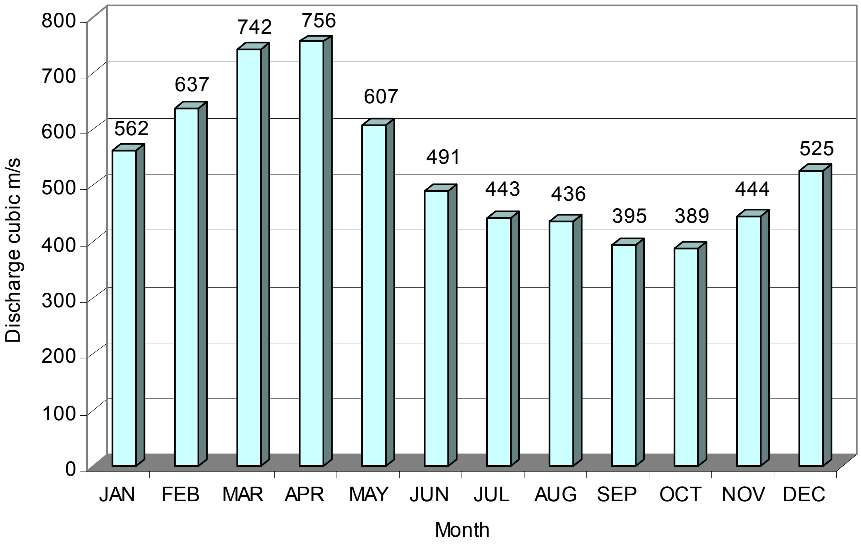


Figure 2.3. Monthly average discharge of the Oder river for the period of 1951 to 1990. The river discharge was measured at Gozdowice, Poland (52.76 North and 14.32 East). Data from Fal et al. (1997).

The Oder Lagoon has a low salinity ranging between 0.5 psu (practical salinity unit = ppt) to 2 psu. Episodically, saltwater from the Pomeranian Bay with salinities of about 7 to 8 psu can reach the inner part of the lagoon, driven by the water level differences between the bay and the lagoon. These saltwater bodies normally leave the lagoons within some hours to days, often with only a narrow mixing front (Meyer and Lampe, 1999).

According to the data from LUNG (Güstrow), StAUN Ueckermünde and WIOS (Szczecin) in Bangel (2001) the yearly average salinity in the lagoon during the period of 1980 to1999 ranges from 0.2 to 0.4 ppm at the mouth of the Oder river, between 0.6 to 3.3 in the western lagoon and between 0.4 to 3.3 ppm in the eastern part of the lagoon.

Leipe et al. (1998) described the hydrographical parameter (salinity, temperature, oxygen, Secchi depth and pH) of the Oder Lagoon (see table 2.1.). Based on the salinity, the water can be classified as brackish water, typical of lagoons. In the warm season, the pH in the lagoon can increase up to 9 due to the primary production that consumes dissolved CO_2 in the water. This causes intensive settling of $CaCO_3$ from the water column to the sediment (Leipe et al., 1998).

According to the data from The University of Greifswald (in Leipe et al., 1998), in extreme case, the Secchi depth particularly in September, can be up to 3 meter. This phenomenon is local and limited to the late summer algal bloom and calm hydrographical period and also due to the filtration by the mussel banks.

According to Kjerve (1994) classification, the Oder Lagoon is classified as a restricted lagoon. This type of lagoon is characterised by a large and wide water body, usually oriented shore parallel, and exhibits one or more entrance channels or inlets. As a restricted coastal lagoon it has a well defined tidal circulation, is influenced by winds, is mostly vertically well mixed and exhibits salinities from brackish to oceanic ones. Flushing times are considerably short.

Table 2.1. Variation of hydrographical parameter in the Oder Lagoon period 1993 – 1996, measured at depth 1 meter (original data from Geographic Institute, University of Greifswald) (from Leipe et al., 1998).

Parameter	**Unit**	**Minimum**	**Average**	**Maximum**
Salinity	psu	0.56	1.39	2.91
Temperature	°C	1.2	15	22.8
Oxygen	mg O_2/l	7.9	11.8	17.6
Oxygen	% saturation	84	117	199
Secchi Depth	meter	0.2	0.9	1.7
pH		6.8	8.4	9.5

2.5. Sediment and suspended particulate matter of the Oder Lagoon

The sediment and suspended particulate matter (SPM) in the lagoon have been investigated previously for example by Osadczuk et al. (1996), Müller (1997), Burkhardt and Breitenbach (1997), Fenske et al. (1998), Osadczuk (1999), Leipe et al. (1998), Osadczuk and Wawrzyniak-Wydrowska (1999), Breitenbach et al. (1999), Fietz (1996) and Klutentreter (2000).

Müller (1997) described the reconstruction of the sedimentation history in the Oder Lagoon based on the geochemical analysis of core samples taken from the lagoon. The cores revealed the sedimentation history since the Alleröd to the present time. At the beginning the low C_{org}/S ratios of the sediment suggest an additional input of dissolved sulphate into the sediments. High C_{org}/S ratios of the sediments were found in the eastern part of the lagoon between 7800 and 5500 BP and are considered to reflect fresh water conditions. There was an increased biological activity during this lacustrine period and the C_{org}/N ratios showed a broad range with mostly high values of more than 12 at that time. At the end of the lacustrine period the first signs of eutrophication are noticed in the eastern part of the lagoon. In the western basin there was possibly a change from macrophytes to phytoplankton being dominant in the water body at approximately since 1200 BP.

Osadczuk and Wawrzyniak-Wydrowska (1999) investigated the sediment of the Oder lagoon and found that based on the amount of the less than 63 micrometer fraction in the sediment samples from the lagoon, four granulometric sediment types could be separated: silts, sandy silts, silty sands and sands. Silts and sandy silts together cover 54 % or about 360 km^2 of the lagoon bottom surface and are common in the area below 3.5 meters. In some parts of the basin at depths below 5 to 6 meter, sandy silts can also be observed which were found mainly in the trough between Grosses and Kleines Haff. Silty sediments of the Grosses Haff are poorly and very poorly sorted while sands are usually medium to poorly sorted. The granulometric features indicate a sedimentary environment of higher dynamics characterised by frequent resuspension and redeposition. In the northern part of the Grosses Haff sandy sediments are predominant while the central and southern parts are predominated by silty sediments except in the near shore zones. A sediment map of the Oder Lagoon which shows the spatial distribution of sand to silt fraction can be seen in figure 2.4.

Osadczuk (1999) distinguished four geochemically different areas of the bottom sediment in the Oder Lagoon:

- Southern and western parts of the Wielki Zalew (Grosses Haff) are characterised by high proportions of organic matter and heavy metals in the sediments, showing the dominant type of sediment closely connected with the inflow of suspended and dissolved substances from the Oder river.
- The north-eastern part of the Wielki Zalew (Grosses Haff), where the sea water plays a significant part in sedimentation, sediments are characterised by a low

content of organic matter, calcium carbonate and heavy metals and a higher proportion of sulphur and magnesium.

- Kleines Haff (Maly Zalew), where silt sediments exhibit the smallest geochemical differences, which is indicative of a relative stability of sedimentary processes caused by equilibrium between the river and the sea influences, the sediments have a high proportion of calcium carbonate as a result of high primary production.
- The narrow shipping channel, characterised by the highest phosphorus and manganese contents caused probably by frequent changes in the redox conditions due to big ship traffic.

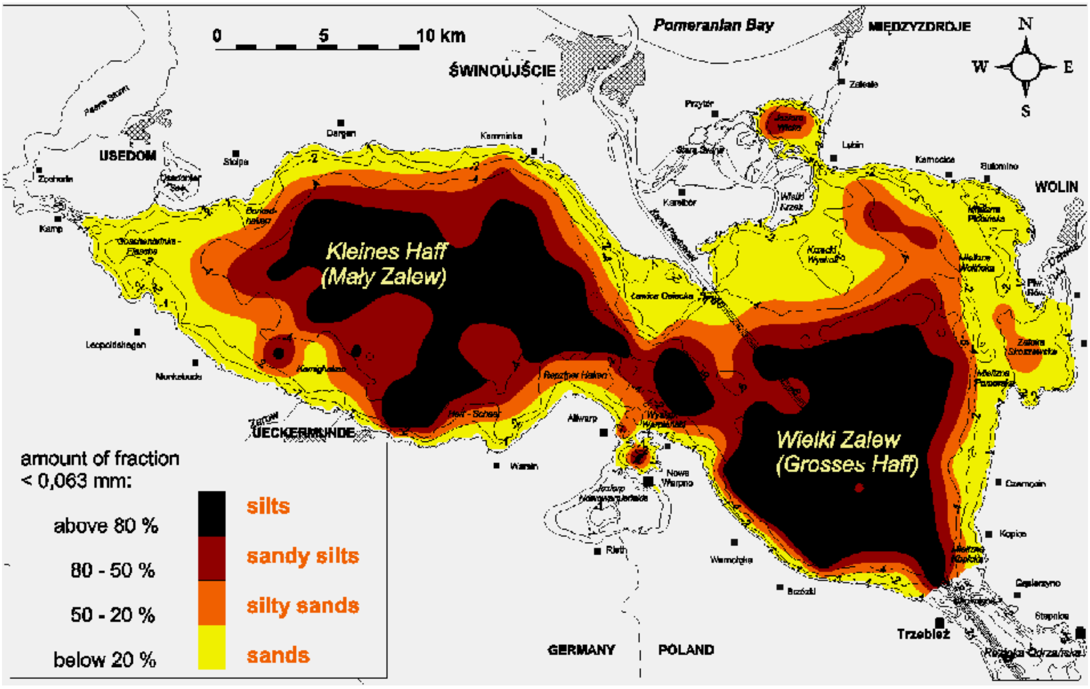


Figure 2.4. Sediment of the Oder Lagoon showing the distribution of sand to silt fraction (Osadczuk and Wawrzyniak-Wydrowska, 1999).

Burkhardt and Breitenbach (1997) investigated the suspended particulate matter (SPM) of the Oder Lagoon and found that it is composed mainly of organic matter, biogenic opal, quartz, calcite, clay minerals and others. Lateral and seasonal changes of these components can be observed in which the lateral variations are more important and caused by the decreasing influence of the Oder river with the growing distance from the river mouth. Breitenbach et al. (1999) described that the amounts of quartz, smectites, Ba, Cr, K_2O, P_2O_5, and SiO_2 are decreasing following the greater distance from the Oder river mouth. Generally, in autumn and in winter-time the content of organic matter is the lowest and the content of silicate-bound elements, terrigenous compounds (TiO_2, Al_2O_3, Fe_2O_3 and Cr) and heavy metals is the highest. This situation is inverse in the summer time. Similar changes were expected too for the Oder Lagoon. Fietz (1996) described that the suspended particulate matter of the Oder Lagoon consists in average of 21% Silicate, 10% Carbonate, 30% Opal and 36% organic substances. The quartz content is lower in the eastern part of the lagoon and the highest Opal content is found near the Oder river mouth.

Intense ore mining was carried out in the Oder catchment area from 1945 to 1970 (Neumann et al., 1996) and this gave an elevated heavy metals discharge, which in turn led to high metal accumulation rates in the sediments of the lagoon and its offshore basins. Due to restricted connection to the open Baltic Sea, the lagoon serves as an effective trap for nutrients and contaminants and reduces the pollution load of the river water before it reaches the sea (Leipe et al., 1998). The increase of heavy metal concentrations in the sediment (the heavy metal record) could serve as a proxy for human impact occurring in around AD 1850 coincides with an increased organic carbon content (Andren, 1999). The distribution of heavy metals are very specific, the highest concentrations of such metals as zinc, copper and lead (see figure 2.5.), nickel, cobalt and chromium are located in the south-western part of the Grosses Haff (Osadczuk and Wawrzyniak-Wydrowska, 1999). The average residence time of heavy metals and organic contaminants is only 10 to 20 years in the Oder Lagoon (Leipe et al., 1998).

The Oder river transports the suspended and dissolved substances from the Oder river basin into the lagoon. Based on the data from Instytut Meteorologii I Gospoderki Wodnej, Second Baltic Sea Pollution Load Compilation and Landesumweltamtes Brandenburg, Leipe et al. (1998) defined the input load from the Oder river to the Oder Lagoon as seen in table 2.2. The values are based on the data from the 80’s.

The concentration of suspended particulate matter (SPM) of the Oder Lagoon is 20 to 25 mg/l in average which is similar to the concentration of the Oder river (Dehmel, 1992 in Leipe et al., 1999) and about ten times higher than the average SPM concentration in the open Baltic Sea (Georgi, 1985 and Niedermeyer, 1987 in Leipe et al., 1998). Suspended particulate matter concentration is higher near the Oder river mouth and decreasing to the western Oder area.

The suspended particulate matter concentrations are closely related to wind speed but the wind speed does not show a good correlation with the suspended particulate matter composition (Breitenbach et al., 1999). During the Oder flood investigation in the period of 18 July to 18 August 1997, Fenske et al. (1998) also found that the amount of suspended matter is correlated with the wind velocity.

Varying behaviour of erosion and settling of the sediments in the Oder Lagoon as observed by Burkhardt and Breitenbach (1997). They explained that organic material will be eroded easier than minerals particles. The critical shear stress depends on the contents of organic material and water in the sediments. They also found that there is a correlation between the settling velocity and the content of organic matter in which the fastest and slowest settling fractions showed the highest content of organic material. While the latter is normal for purely organic particles, the former is a consequence of flocculation with mineral particles in an organic matrix. The suspended particulate matter shows a clear dependence on wind force.

Table 2.2. Estimation of the input load from the Oder river to the Oder Lagoon (Leipe et al., 1998).

Oder Discharge		17 km^3/year
	Concentration	**Load (ton/year)**
SPM - total	25 mg/l	425000
Particulate	(%)	(ton/year)
TOC	15.3	65025
Lost On Ignition	32.6	138550
TIC	0.4	1700
$CaCO_3$	3.0	12750
SiO_2	41.3	175525
Al_2O_3	8.5	36125
Fe_2O_3	6.8	28900
MnO	1.1	4675
MgO	0.8	3400
CaO	3.2	13600
K_2O	1.4	5950
P	0.9	3910
S	0.4	1700
Particulate	mg/kg	ton/year
Pb	200	85
Zn	1700	700
Cu	120	50
Cd	9	4
Hg	2.5	1
Particulate and Dissolved	mg/l	ton/year
N-total	2.94	50000
P-total	0.47	8000

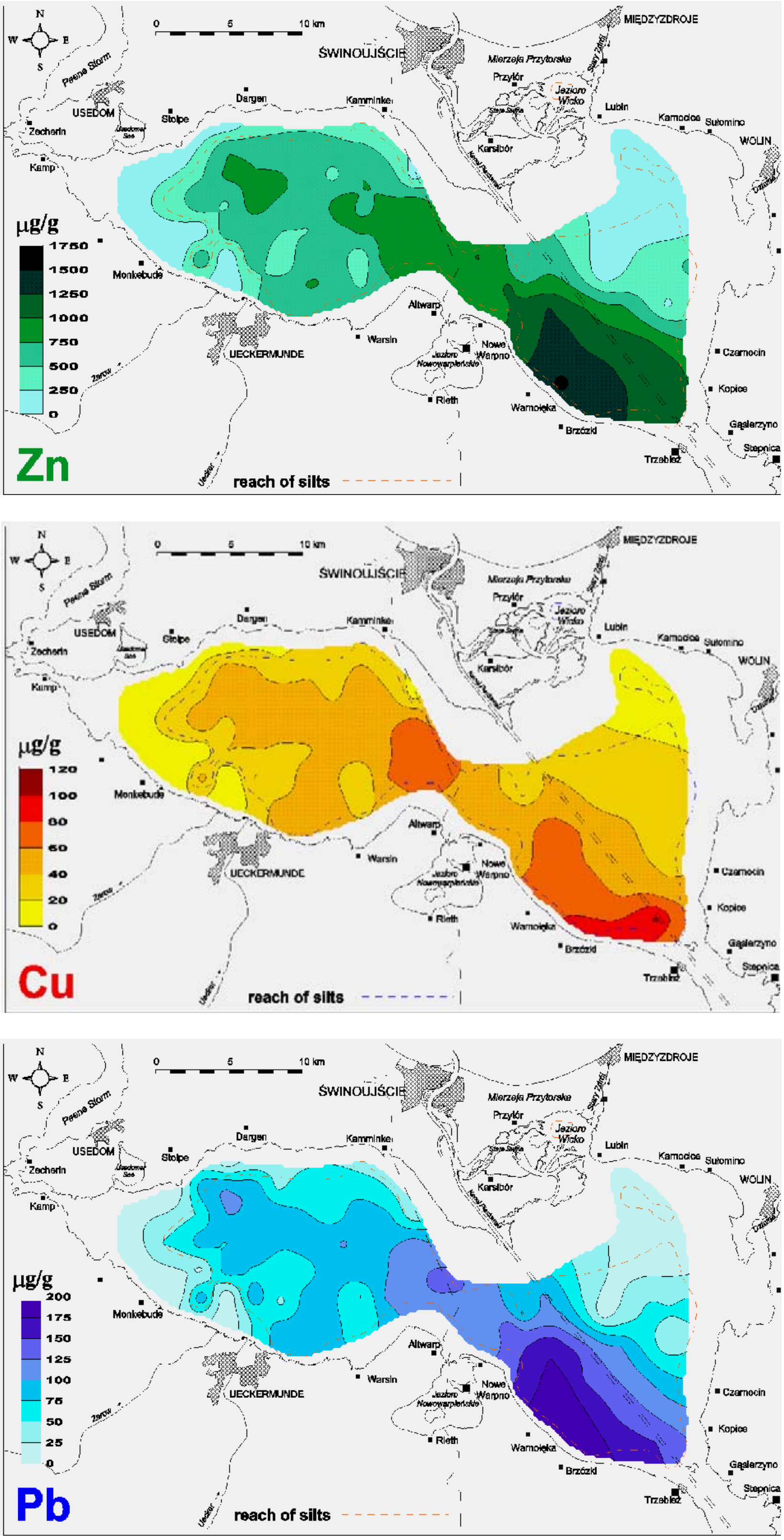


Figure 2.5. Spatial distribution of anthropogenic heavy metals Zn (top), Cu (middle) and Pb (bottom) sediments in the Oder Lagoon (from Osadczuk and Wawrzyniak-Wydrowska, 1999).

The sediments deposited in the Oder Lagoon are occasionally resuspended through wind mixing (Lampe, 1993; Leipe et al. 1999) and the final sinks for the load are the Arkona and Bornholm basins in the Baltic Sea. Edelvang et al. (2002) using the MIKE3 modelling system showed that the sediment was transported from the mouth of the Oder river at Swina to these basins. They found that the transport was episodic and mainly governed by wind events. There was a general tendency that the sediment was transported diversely into a pathway either to the north towards the Arkona Basin (2/3) or to the east towards the Bornholm Basin (1/3) over time scales of several months. The primary sedimentation from the Oder to the Arkona Basin generally takes place in the form of easily resuspended fluffy material.

2.6. Coastal zone management and tourism

According to the Landscape Framework Plan (LAUN 1996), the German part of the Oder Lagoon is regarded as a National Park (Island of Usedom), land protection and natural protection areas. The area of Oder lagoon is devoted for natural protection and tourism area both for the German part and the Polish part of the lagoon. The same as to the Polish part of the eastern lagoon areas in which Wolin Island is regarded as a naturally separated physiographic unit. The area of Wolin Island is over 250 km^2, 50 km^2 of which belong to Wolin National Park and together with the adjacent waters of the Oder Lagoon and the Baltic Sea, the total area of the Wolin National Park is over 100 km^2 (Jakuczun, 2002), see figure 2.6.

The coastal area of the lagoon has a unique landscape due to its geological development involving areas of accumulative and erosive post glacial forms of moraine elevation, terminal moraines, marginal plains, drumlins, sanders, proglacial stream valleys, subglacial gullies, Holocene sandbars, dunes, beaches, cliffs, river and lagoon plains. The area of the Oder Lagoon is an important place for procreation and rest of international importance during the migration and wintering of fish, birds and mammals. Plant communities on the island of Wolin are protected as reserves. The local population amounts to approximately 30000 inhabitants; about 5000 in winter time and about 90000 during the summer peak: tourists, holidaymakers and health resort visitors stay on the island (Jakuczun, 2002). The area has unique natural qualities of an international importance. Furthermore, according to the Guidelines for the Integrated Coastal Zone Management of the Szczecinski Lagoon, the Polish Side (2000), the Oder river and the Oder Lagoon area are of a special importance due to its economic functions: the existing commercial, ferry and naval harbours, shipyards, fishery, attractiveness for tourism, water tourism, nature tourism and hiking, health resorts, shipping line between the Oder river, the Oder Lagoon and the Swina Channel.

The water quality problems of the Oder Lagoon have to a certain degree affected the tourism growth. This is particularly obvious for the tourists in the inner coastal part toward the Oder Lagoon with a relatively bad bathing water quality compared to the outer coastal part of the lagoon (outer coasts toward the Baltic Sea) that has a higher bathing water

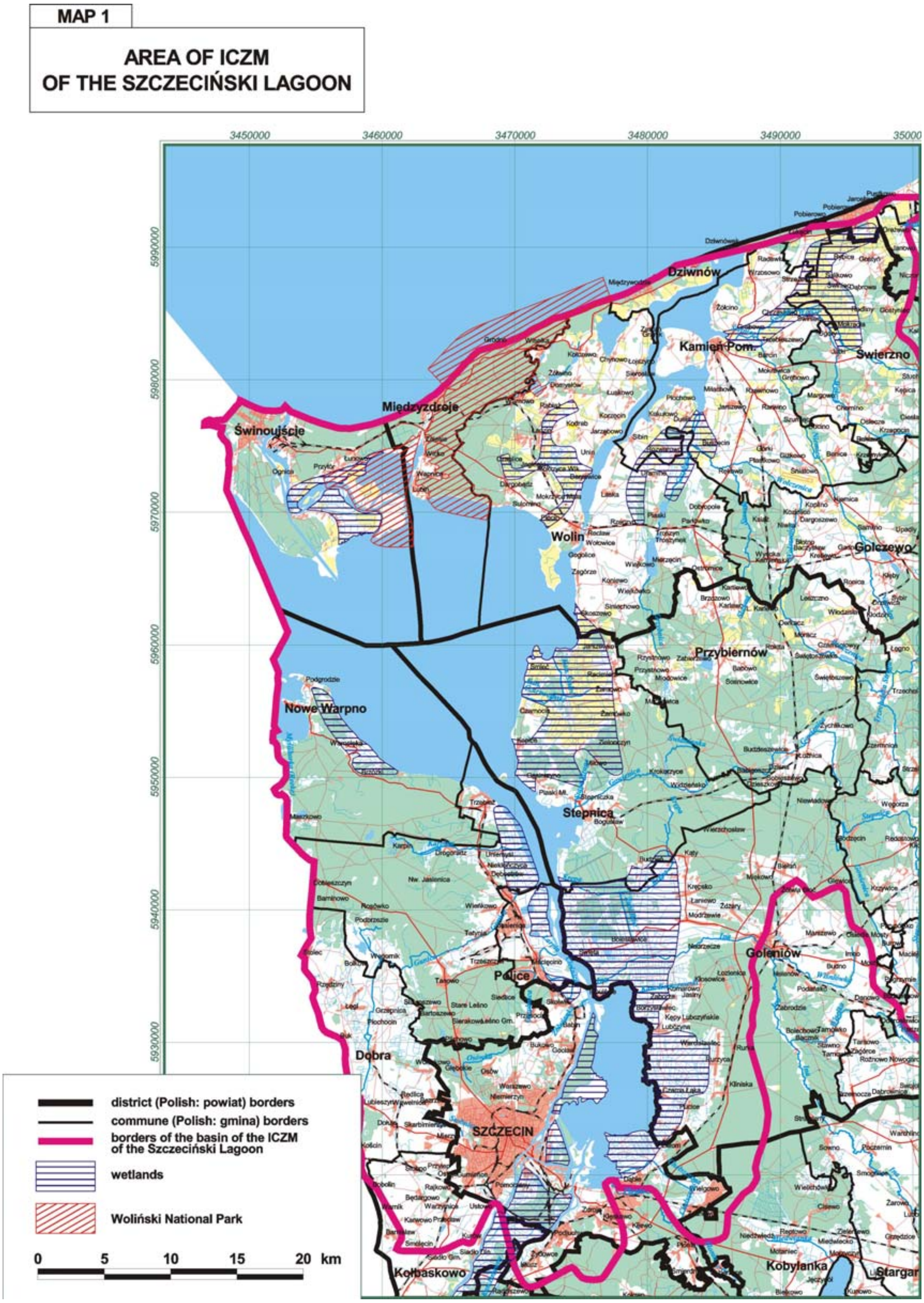


Figure 2.6. The area of Integrated Coastal Zone Management of the Oder Lagoon at Poland site (from the Guidelines for the Integrated Coastal Zone Management of the Szczecinski Lagoon, the Polish Side, 2000).

quality. According to the Statistisches Landesamt Mecklenburg Vorpommern (2001) the overnight stay have dropped from 28.2% to 22.5% in 2000 in Uecker Randow County (including Mönkebude and Ueckermünde) compared to stable utilization rates of 36% to 37% at the Ostvorpommern County (Usedom Island, including the northern coastal part toward the Baltic Sea).

Dolch and Schernewski (2002) described that a good water quality is regarded to be important or even very important for the selection of a holiday resort by tourists on Usedom Island. From their survey they found that the tourists are aware of water quality problems shown by the tourist's evaluation in both coastal parts of the lagoon. Their survey showed that tourists of the inner coastal part of the Oder Lagoon voted the water quality of this area for very good (2.7%), good (26.4%), reasonable (47.8%), acceptable (17%) and poor (6%) compared to the tourists of the outer coast of the lagoon that voted this area for very good (21.8%), good (26.4%), reasonable (17.6%), acceptable (0.8%) and poor (0.8%). Tourism is an important economic factor along the Oder Lagoon, especially bathing tourism during summer. Overnight stays of 6.6 million and an annual growth rate of 14.5% (2001) were registered in Usedom Island. In contrast to this, tourism at the southern coast of the lagoon is poorly developed (121377 overnight stays in 1999).

The water policy for the European Union Countries in the form of the Water Framework Directive (WFD) was established by the European Parliament and entered into force since 22. December 2000. The purpose of this directive is to protect all waters (surface waters, transitional waters, coastal waters and groundwater) to prevent further deterioration of water resources, promote sustainable water use, enhancing protection and improvement of the aquatic environment. Overall, the Directive aims at achieving a good water status for all waters by 2015.

3 MATERIALS AND METHODS

The work during the study covered literature collection and review; field observation, measurement and sampling; laboratory work and analyses; Femflow2D model testing and application as well as analyses of the model results. Literature directly and indirectly related to the study was collected and documented using EndNote program. Altogether the work is described in three main activities: field observation, measurement and sampling; laboratory work and analyses; and the Femflow2D hydrodynamic and transport model application.

3.1 Field observation, measurement and sampling

The field work and observation during the study was conducted in three different times. First field work was mainly devoted to core and bottom sediment sampling at several localities in the southern part of the Kleines Haff. The second field work was done in cooperation with PREC, Tampere, Finland. The third field work covered observation of the eastern part of the lagoon at the Polish side.

3.1.1 Core and bottom sediment sampling

First field observation and sediment sampling was done on 9 and 10 May 2001 at Mönkebude beach, offshore east of Altwarp, and at the reed zones east of Mönkebude and west of Altwarp. This field work aimed at taking bottom and core sediment samples. A rubber boat was used to reach the reed zone areas and offshore sampling localities.

Bottom sediment sampling at Mönkebude beach, was done by using a small plastic tube of 5 cm diameter and 30 cm length. The sediment samples were taken by pressing the tube into the sediment up to a depth of about 20 cm, the top part of the tube was then closed using a rubber plug, and the sample was pulled out. The bottom part of the tube then can be closed by using another rubber plug. Samples were then placed in a plastic container after the water has been removed.

A grab sediment sampler (see figure 3.1.) was used for taking offshore sediment samples east of Altwarp, close to the border between Germany and Poland. During the sampling, the grab sampler was released from the boat until it reached the bottom sediment. As soon as it reached the bottom, the sampler closed and grabbed the sediment. The grab sampler was then pulled up to the boat and the sediment sample was taken by using a small spade to be placed in the plastic container.

At the littoral zones, core samples were taken by using a stainless steel drill tube corer with 10 cm diameter (see figure 3.2). A polyvinylchloride (PVC) tube (see figure 3.2.) was installed in the inner part of the corer before sampling. Sampling was done in the reed

Figure 3.1. Grab sediment sampler used for taking offshore sediment samples.

Figure 3.2. Drill corer and PVC tube (left) and core sampling at the Reed zone east of Mönkebude (right).

zone where undisturbed sediment with higher sedimentation rates was expected to occur. After sampling, the samples were cut in the laboratory into 5 cm thick intervals and the slices were placed in a separate plastic container. In the laboratory, the samples underwent weighing and drying procedures as described in chapter 3.2.1.

3.1.2 Field measurement and sampling

The second measurement campaign was done in the lagoon area from 13 to 17 August 2001 in cooperation with PREC, Tampere, Finland. A small boat named Sirius belonging to PREC was used during the measurements and sampling (see figure 3.3).

The Sirius boat was equipped with Acoustic Doppler Current Profilers (ADCP) Sensortec UCM –50 broadband 600 kHz ADCP (see figure 3.3.); Global Positioning System (GPS) satellite receiver Garmin 128; depth finder of Echo scan as well as digital (Azimuth 100) and magnetic compass (Suunto C 65). Additional equipment used were Secchi disc (see figure 3.4.), water sampler (see figure 3.5.), grab sediment sampler (see figure 3.1.) and mobile anemometer.

The Acoustic Doppler Current Profilers (ADCP) Sensortec UCM –50 broadband 600 kHz, was used to measure the horizontal and vertical flow speed and direction of the water bodies of the lagoon at the site or track of measurements.

The Secchi disc was used to estimate the lagoon’s water quality. The disc is lowered into the water until it just disappears from the sight and this depth measurement is recorded. The deeper the measurement, the clearer the water. This measurement provides a general indication of problems with algae, zooplankton, water colour and silt.

GPS was used to determine the latitude and longitude positions at the measurement or sampling sites.

A grab sediment sampler was used during this measurement campaign for taking offshore bottom sediments. The samples obtained after sampling were stored in a plastic container. Sampling procedures are described in chapter 3.1.1.

A water sampler was used for taking water samples at particular depths.

The water for suspended particulate matter (SPM) analysis was sampled from the boat by using plastic bottles at a water depth of about 50 cm.

A mobile anemometer was used to measure the wind speed and direction at each point of measurement. The measurement was done by raising the anemometer up to the highest possible observation position on the boat.

An Inductive Flow Meter ISM-2000 was used to measure the flow or current at localities close to the reed zone offshore Mönkebude area. A small speed boat was used to reach the point of measurement.

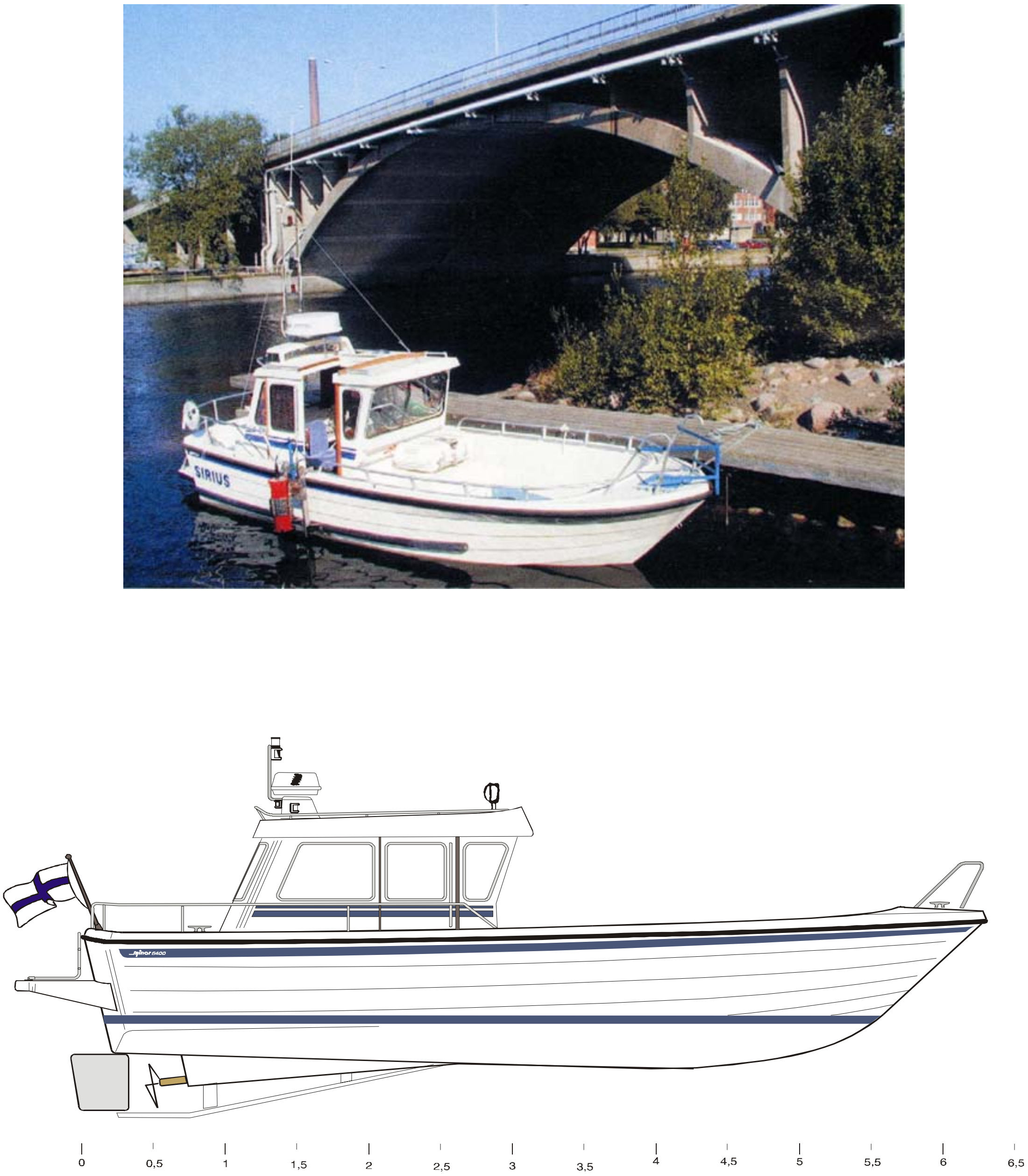


Figure 3.3 Sirius boat used during the second field work (above) and the boat schematic cross section (below) (figures courtesy PREC, Tampere, Finland). Note the red ADCP mounted at the side of the boat.

During the cruise, samplings were done at several localities particularly across the lagoon from Mönkebude in the south-west to Kamminke in the north-east of the western Oder Lagoon. The locality of sampling in the littoral zone and offshore the lagoon as well as the sample number can be seen in figure 3.6.

3.1.3 Field observation in the eastern part of the lagoon

The third field work was done from 14 to 17 November 2001. During this trip the eastern part of the Oder Lagoon was observed and documented. The area covered during this trip were Szczecin City and adjacent areas (large city by the Oder river, about 25 kilometres southeast of the lagoon; see figure 2.1.); Stepnica and Lubczyna Beaches; Wolin and Swina outlets; Lubin, Karsibor and Swinoujscie areas; the coastal areas in the northern part of Usedom Island and Pomeranian Bay.

Figure 3.4. Secchi disc for measuring Secchi depth.

Figure 3.5. Water sampler used for taking water sample at particular depths.

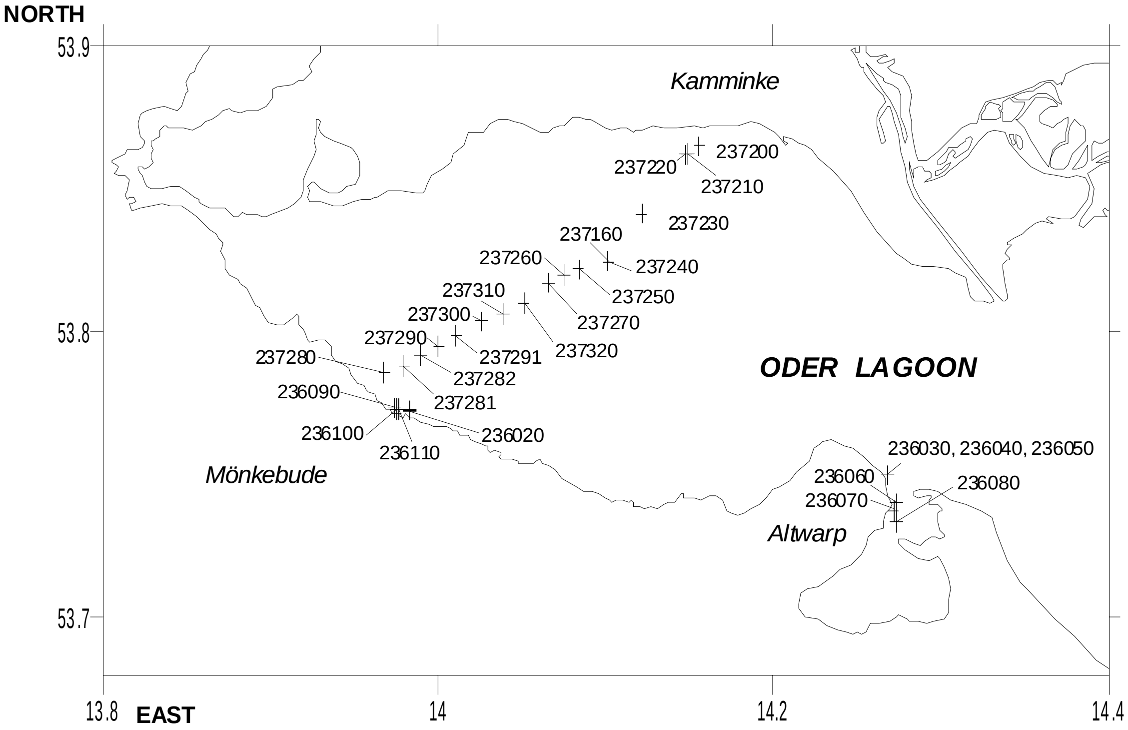


Figure 3.6. Sampling localities and sample number.

3.2 Laboratory work and analyses

Laboratory work was done at the Insitut für Ostseeforschung Warnemünde (IOW). The laboratory analyses comprised the suspended particulate matter (SPM) concentration and carbon content measurements, grain size analysis; Total Organic Carbon (TOC), Total Inorganic Carbon (TIC), Sulphur (S) and Nitrogen (N) content analyses; geochemical analysis; mineral analysis as well as the phytoplankton and biomass analyses.

3.2.1 Sediment samples treatment

All sediment samples which were taken from the field were weighed to know their water saturated weight. The samples were dried using freeze dryer (see figure 3.7.) to removed the water content. The water content can then be calculated from the weight differences between dry and saturated conditions. Similarly to the bottom sediment samples, the core samples that had been cut into 5 cm slices were also freeze dried so that the water content can be obtained. Since the freeze dryer was limited to only several samples in one run, then the other samples were put in the freezer with temperature of −18 °C in order to keep their water content before they were dried.

Water samples for SPM analysis were stored in a cooling box as soon as they were sampled. Lugol was added to water samples intended for biomass analysis in order to

Figure 3.7. Freeze dryer used for drying the sediment samples.

preserve the biological part of the particulate matter. For SPM analysis, the water samples were soon analysed in the base camp while for mineral and grain size analysis the water was kept in the cooling box during transportation to the lab, in the refrigerator and freezer before analysis.

3.2.2 Suspended particulate matter concentration and carbon content

Glass microfiber GFF Whatmann 7.0 micron filters with a diameter of approximately 2.5 cm were prepared. First, the filters were placed in the oven at 550°C for 2 hours in order to remove the moisture and small carbon particles. Then they were put in the glass for few minutes for cooling down while preventing access of moisture to the filters. The filters were then weighed and stored in a plastic compartment as ready to use filters. The filter weight at this stage is called dry weight. Three filters remained unused as an error control.

Water samples taken from the lagoon were filtered directly in the field by using standard filtration for SPM. All water samples were filtered by pouring 50 ml of each water sample via a funnel into the Erlenmeyer glass which contained filters that had been prepared. If the water sample is not very turbid then another 50 ml water sample were added for filtering. Distilled water was used to wash the funnel so that the salt that they may contain could be flushed. A small pump connected to the Erlenmeyer glass was installed to help the filtering process. After filtering the filters were placed in the plastic container and in the fridge before further processing in the laboratory.

In the laboratory, these plastic containers were placed in the oven with 60°C temperature for 12 hours in order to remove the moisture. The filters were then weighed, and the weights are the filter weighed plus SPM weight. To know the organic (total carbon) and inorganic components of the samples or the SPM, the filters were then burned in the oven with 550°C temperature for two hours. The organic material will be lost from the filters because of the burning. The filters were again weighed and the organic content of the samples can be calculated by the weight differences of each filter before and after burning. The weight differences of the unused filters that were meant for error control were also calculated and these values were used to correct the results of the filters that had been used.

3.2.3 Grain size analysis

Grain size analysis was done for the sediment samples using two methods depending on the type of the sediment. Sieve analysis was done for sand dominated sediment samples while laser particle analysis was done for silt dominated sediment samples. To keep the samples dry, they were put in the oven with 60°C temperature before the analysis. Before the analysis, the samples were sieved manually using 2 mm sieve size in order to remove the mussels and the roots or plant fragments contained in the samples.

Sieve analysis was done by using a RETSCH AS 200 sieving machine that contains 12 sieves each with a particular mesh size. Fractions used were as follows (in micrometer): < 63, 63 – 75, 75 – 90, 90 – 106, 106 – 125, 125 – 150, 150 – 180, 180 – 212, 212 – 250, 250 – 400, 400 – 630 and > 630. Before sieving, the sediment samples were mixed manually by a small spoon and only about 50 grams were used from each sample for this analysis. To do the sieve analysis, the sieve pans were weighed one by one using weighing machine that is connected to a computer. The pans were put together according to the size from fine sieve mesh size at the bottom to coarse at the top. 50 grams sample were poured into the top part of the pans which were then placed in the RETSCH vibrating machine. The sieving process took 10 minutes and the machine vibrates electromagnetically every 10 seconds. The computer connected to a weighing machine is provided with SP1000 program to calculate the weight of the sieve pans before and after sieving as well as the overall sieve analyses results. The results of the sieve analyses were then analysed by using Microsoft Excel program.

A laser particle analyser Galai WCIS-50 (photo optical counting) was used to analyse the grain size of silt dominated sediment samples. The sample preparation started by sieving the samples manually using 150 micrometer sieve size and 0.5 gram sample were needed for the analysis. The sieved samples were placed in a glass and 30 to 40 ml Aquadest were added. The glasses were then placed in a ultrasonic bath for 10 to 15 minutes to disperse the samples. One to three ml Calgon was then added to each sample. The samples were shaken and left for one day before they were analysed. The samples were again shaken before they were analysed by the laser particle analyser.

3.2.4 Total Carbon (TC) and Nitrogen (N) analyses

Total Carbon (TC) and Nitrogen (N) were analysed by using Eltra Analyser EA 1110 (CHN Analyser). The machine was attached to a computer provided with software Eager

2000 for analysis. A small amount of samples was wrapped with aluminium and placed in the machine. Several samples were prepared and were analysed in one session automatically.

3.2.5 Total Inorganic Carbon (TIC) and Sulphur (S) analyses

TIC (Total Inorganic Carbon) and S (Sulphur) were analysed using ELTRA CS 500 analyser. 50 mg sample were placed in an Erlenmeyer glass container. The glass container was then placed above the heated plate, a magnetic cylinder was placed in the glass which can rotate and keep the sample mixed. Two times 2.5 ml of 50% H_3PO_4 were added to the glass and heated with 50°C temperature in order to disintegrate the carbonate and hydrogen carbonate. The CO_2 gas resulting from the reaction was measured with the detector. The infrared detector will measure the amount of CO_2 and the total carbon can be calculated. A $CaCO_3$ standard was used for calibration.

To measure the TC and S content, 50 mg samples were taken and placed in a small elongated ceramic plate. The ceramic plate will then be put in a high temperature oven of 1200°C. The gas resulting from burning at this temperature was measured by a detector in the ELTRA. The TOC can be calculated by the value differences between TC and TIC in which TC is equal to TIC plus TOC.

3.2.6 Geochemical analysis

Geochemical analyses for major and trace elements were done by using an Inductive Coupled Plasma ICP AES Emission Spectrometer Liberty 200. Analyses include major elements (Fe, Al, Mg, Mn), trace elements (Ca, K, P) and heavy metals (Cu, Zn, Pb, Ni, Co, Cr, Li).

Samples were prepared before the analysis by taking 500 mg samples and placed in the PFA containers. Two times, 5 ml HNO_3 were added to the samples and the samples were heated to remove the organic material. After the samples had been dried, 4 ml HF (40%) were added as well as 4 ml Aqua Regia (Nitro hydrochloric acid) (HNO3/HCl, 1:3). The samples were reheated until they were dry. The PFA containers were then inserted into the pressure digestion containers, locked up and placed for 8 hours in the drying chamber at 180°C temperature and 35 bar pressure. After this, the pressure digestion containers were taken out and the material in the PFA containers were added by 1 ml HClO4 (60%) and reheated. Two times, 10 ml HCl (18%) were then added to remove the Fluoride and again heated. The residues were added by 5 ml HCl in a 50 ml flask and with 50 ml demineralised water. These liquids were then placed in 50 ml PE glass containers and were ready for ICP AES measurement.

The principle of measurement with ICP AES Emission Spectrometer Liberty is that the Spectrometer detects trace amounts of elements, which after being atomized and heated, show characteristic sharp emission lines.

3.2.7 Mineral analysis

Scanning electron microscopy (SEM) and x-ray micro-analyses (EDX) were used to investigate the mineralogical composition of selected samples from the sediment surface (fluffy layer material) and from the SPM, collected from 0.5 m water depth. The samples were prepared by filtration on a 0.45 µm nucleopore filter, rinsed by H_2O to remove salt, dried and coated with carbon for electron conductivity. 500 to 600 individual particles per sample, in the size range from 1 to 50 µm, were analysed automatically by their elemental composition. Based on these results, a statistical rework and classification was used for identification and quantification of major mineral components of the samples. A detailed description of the method was given by Leipe et al. (1999).

3.2.8 Phytoplankton and biomass analyses

The phytoplankton and biomass analyses were conducted following the HELCOM procedure as described in http://www.helcom.fi/Monas/CombineManual2/PartC/CFrame.htm. Sampling of water for phytoplankton and biomass analyses was done at locality 237240 (see figure 3.6.) at one meter depth. The sampled water was stored in a glass bottle. Lugol solution was added to the sample so that the biological particulate matter in the water can be preserved. In the laboratory, first, the sample was shaken slowly so that the particles in the water were distributed evenly. An amount of 50 ml of the sample was taken and placed in the glass. Aquadest was then added to dilute the sample. 10 ml of this sample was then placed in the microscope counting chamber, closed by a glass plate and left for 24 hours in order to let the particles settle down on the bottom part of the chamber. After 24 hours, the sample can then be analysed using an inverted microscope Axiovert S 100 Zeiss.

3.3 Femflow2D hydrodynamic and transport model

The Femflow2D hydrodynamic and transport model was developed by Dr. Victor Podsetchine of PREC, Tampere, Finland and has been applied for example in the study of water exchange in the northern part of Lake Ladoga (the largest lake in Europe, located in Karelia, north-western http://www.wikipedia.org/wiki/Russia Russia, near the Finnish border) (Podsetchine et al., 1999) and in the study of the influence of spatial wind inhomogeneity on flow pattern in Lake Belau (located in the northern part of Germany) (Podsetchine and Schernewski, 1999).

In this study the existing Femflow2D model was modified and updated. This new version was tested and used. In particular, the new SPM module that has not been applied before was examined and applied in this study. Therefore the works in this study include testing, application, calibration and validation of the modified and new Femflow2D model version.

The flow module is based on vertically integrated equations of motion and continuity known as shallow water equations (Weiyan, 1992). The system of shallow water equations is discretised with the modified Utnes scheme which is characterised by a semi-decoupling algorithm, the continuity equation is rearranged to Hemholtz equation form and the upwinding Tabata method is used to approximate convective terms (Podsetchine and Schernewski, 1999). Details of the equations as well as the exemplary application of this flow model to Lake Belau, Schleswig Holstein, Germany can be found in Podsetchine and Schernewski (1999). The Femflow2D hydrodynamic and transport model is a two dimensional model therefore the flow in the lagoon calculated by the model in all points (see figure 3.11.) were the depth-averaged flow values. Hence the water column was regarded as a single layer and the values of the flow velocity and direction are described at each points (see figure 3.11.). The ratio of depth to area is very small in the Oder Lagoon, therefore, the lagoon can be classified as a shallow water system. In this shallow water system, the wind speed and wind direction are expected to play a significant role in the transport and circulation of the water masses.

To validate the Femflow2D simulations, results of flow and SPM concentration simulations were compared with the field measurements. Flow measurement data from the field work, raw hydrographic data from GKSS buoy (http://meteo.gkss.de/sgdaten.html), sediment input parameter values from laboratory measurements and previous studies were used to investigate and validate the flow and SPM conditions in the Oder lagoon. The validations confirm the reliability of model simulations that provide a reliable basis for application of the model for coastal water management of the Oder Lagoon.

3.3.1 Femflow2D model features

The new version of Femflow2D model runs under Windows 95/98/NT/ME/2000 and XP operating systems and contains eight main menus as follow: file, model, particle tracking, view, graph type, options, animate and help menus. The features of the Femflow2D model can be seen in figure 3.8.

The file menu is used to start the work, for choosing the working directory and opening the files. Saving the files, printing and exit from the model are included under this menu. The model menu prescribes the input parameters for running the model consisting of wind scenario, bottom roughness, erosion stress as well as edit parameters. Under this menu there is a tool to start or run the model when all input parameters had been set. The particle tracking menu is used for running the particle tracking module. It consists of options to choose the particular flow data file for running the particle tracking module. There is a tool for entering the parameter values before starting the particle tracking simulation in this menu. The view menu enables to fit and zoom the working figure as well as to show the rectangular grid and the triangular points number. Graph type menu item gives the opportunity to select different types of graphics to be displayed: coastline, triangular mesh, flow field, wind measured, wind interpolated, roughness measured, roughness interpolated, bathymetry, SPM concentration, erosion stress measured and erosion stress interpolated, bathymetry, SPM concentration and water level. Options menu has four sub menus to be chosen: default and user defined minimum and maximum contours, draw filled contours (with options to choose black and white or colour contours) and bathymetry editor.

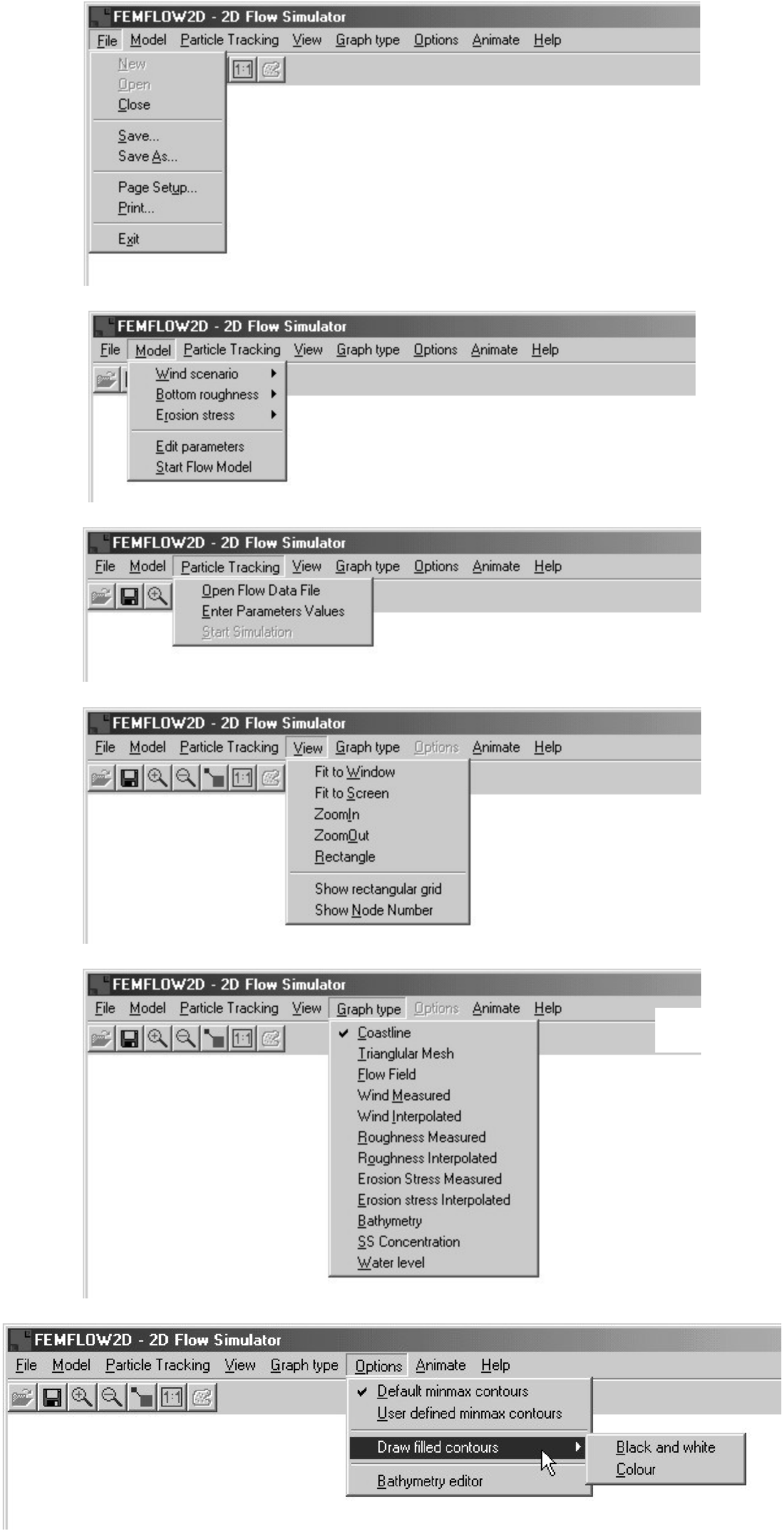
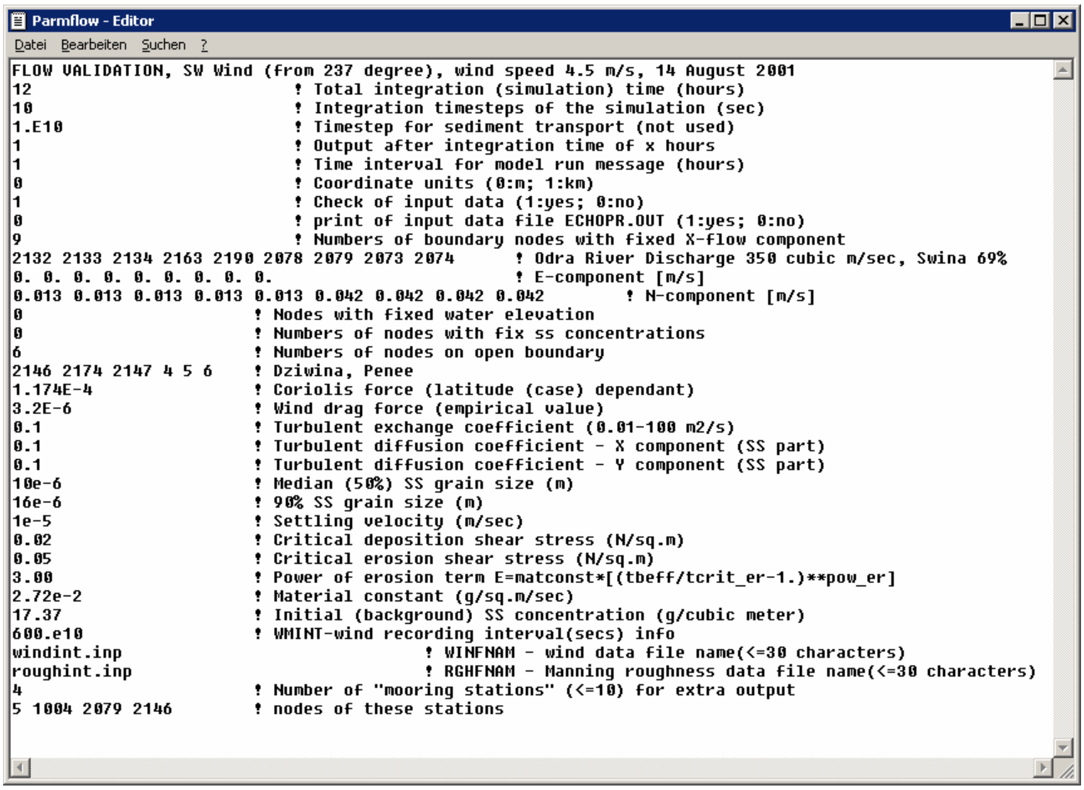


Figure 3.8. The features of Femflow2D showing file, model, particle tracking, view, graph type and options menus.

Animate menu is used to animate the flow or SPM in the lagoon. The first and last frames for the animation as well as animation speed can be chosen under this menu. The help file describes the instructions for a user and a brief information about the model.



```
FLOW VALIDATION, SW Wind (from 237 degree), wind speed 4.5 m/s, 14 August 2001
12                          ! Total integration (simulation) time (hours)
10                          ! Integration timesteps of the simulation (sec)
1.E10                       ! Timestep for sediment transport (not used)
1                           ! Output after integration time of x hours
1                           ! Time interval for model run message (hours)
0                           ! Coordinate units (0:m; 1:km)
1                           ! Check of input data (1:yes; 0:no)
0                           ! print of input data file ECHOPR.OUT (1:yes; 0:no)
9                           ! Numbers of boundary nodes with fixed X-flow component
2132 2133 2134 2163 2190 2078 2079 2073 2074      ! Odra River Discharge 350 cubic m/sec, Swina 69%
0. 0. 0. 0. 0. 0. 0. 0. 0.                        ! E-component [m/s]
0.013 0.013 0.013 0.013 0.013 0.042 0.042 0.042 0.042        ! N-component [m/s]
0                       ! Nodes with fixed water elevation
0                       ! Numbers of nodes with fix ss concentrations
6                       ! Numbers of nodes on open boundary
2146 2174 2147 4 5 6    ! Dziwina, Penee
1.174E-4                ! Coriolis force (latitude (case) dependant)
3.2E-6                  ! Wind drag force (empirical value)
0.1                     ! Turbulent exchange coefficient (0.01-100 m2/s)
0.1                     ! Turbulent diffusion coefficient - X component (SS part)
0.1                     ! Turbulent diffusion coefficient - Y component (SS part)
10e-6                   ! Median (50%) SS grain size (m)
16e-6                   ! 90% SS grain size (m)
1e-5                    ! Settling velocity (m/sec)
0.02                    ! Critical deposition shear stress (N/sq.m)
0.05                    ! Critical erosion shear stress (N/sq.m)
3.00                    ! Power of erosion term E=matconst*[(tbeff/tcrit_er-1.)**pow_er]
2.72e-2                 ! Material constant (g/sq.m/sec)
17.37                   ! Initial (background) SS concentration (g/cubic meter)
600.e10                 ! WMINT-wind recording interval(secs) info
windint.inp                              ! WINFNAM - wind data file name(<=30 characters)
roughint.inp                             ! RGHFNAM - Manning roughness data file name(<=30 characters)
4                       ! Number of "mooring stations" (<=10) for extra output
5 1004 2079 2146        ! nodes of these stations
```

Figure 3.9. Main input parameter of Femflow2D model.

The structure of the files in the model can be divided into two groups, the input and output files. Input files comprise depth, geometry of the water body, parameters for modelling, bottom roughness and wind. Output files are modout (velocity x, velocity y, resultant velocity as well as SPM concentration), info file (information about volume of water body and CPU time), check file (information about elements), “velts.dat” (velocity time series) and “wlevts.dat” (water level velocity time series) file.

The main input parameter of the model available under model menu (edit parameters tool) is a very important part of this model (see figure 3.9.). It consists of several controls and input values for running the simulation such as time integration and control; flow, water level, SPM and liquid boundary conditions; physical parameters of the flow model and SPM block (only for non cohesive sediments) and additional flow model parameters. To run the model, three scenarios of wind can be chosen; constant, time series and spatially variable wind. The input parameters of bottom roughness and erosion stress have also two options: constant and spatially variable.

3.3.2 Input data construction

The input data needed by the Femflow2D program were depth information (depth.inp), geometry of the lagoon water body (geom.inp), geometry of the water body for particle tracking (geompt.inp), bottom roughness (roughint.inp), wind speed and direction (windint.inp), erosion shear stress (erosionint.inp), velocity of water from the Oder river entering the lagoon (velint.inp) and parameter for modeling (see figure 3.9.). The depth and geometry of the lagoon formed the basic information required by the model. Detailed depth data of 100 times 100 meter grids for the reconstruction of the lagoon bathymetry was received from K. Buckmann (Greifswald) (see figure 3.10.).

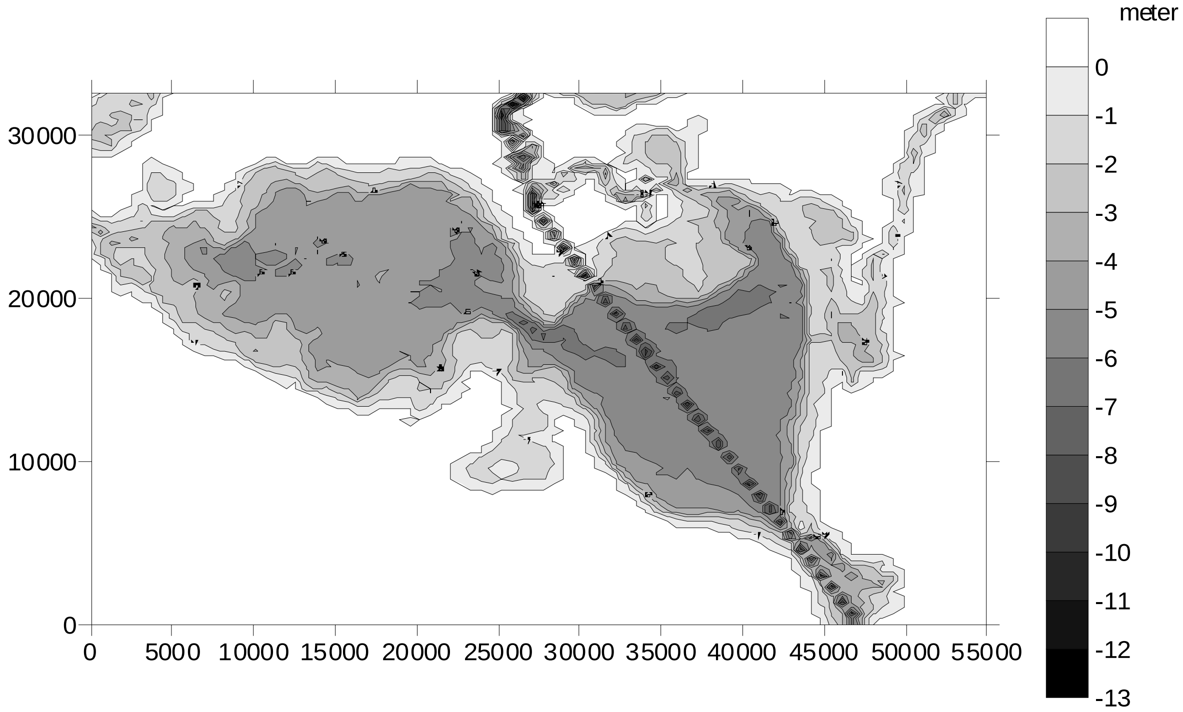


Figure 3.10. Bathymetry data that are used for bathymetry data construction for the model (data from K. Buckmann, Greifswald).

Altogether there were 3845 elements and 2240 points created by the ArgusONE for the Oder Lagoon (see figure 3.11.). These depth data were interpolated to the geometry and the triangular map that had been created before in the Argus program so that each points of the lagoon corresponded to the depth information. A depth file which contains the depth of each node hence can be created (see figure 3.12.).

The input data constructions began by digitising the map of the Oder Lagoon using Arc Info program. The digitized file was then imported into the Surfer program and saved as an ASCII file. This file was then imported to the map layer of the ArgusONE program (www.argusint.com). Using this program the triangular mesh for further basis data for model calculation can be created.

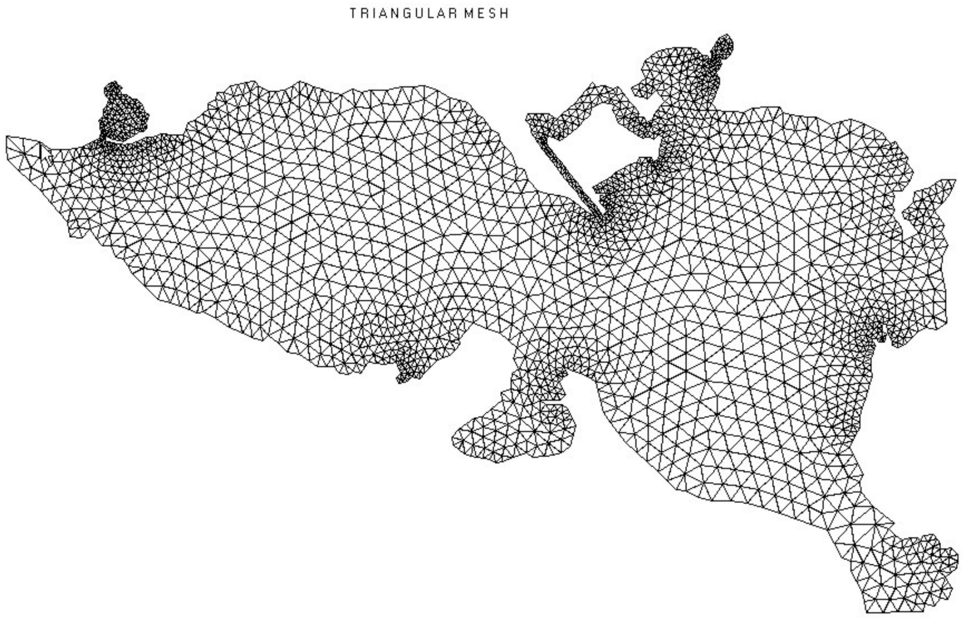


Figure 3.11. Triangular meshes used for model calculation in the Oder Lagoon comprising 2240 points and 3845 elements.

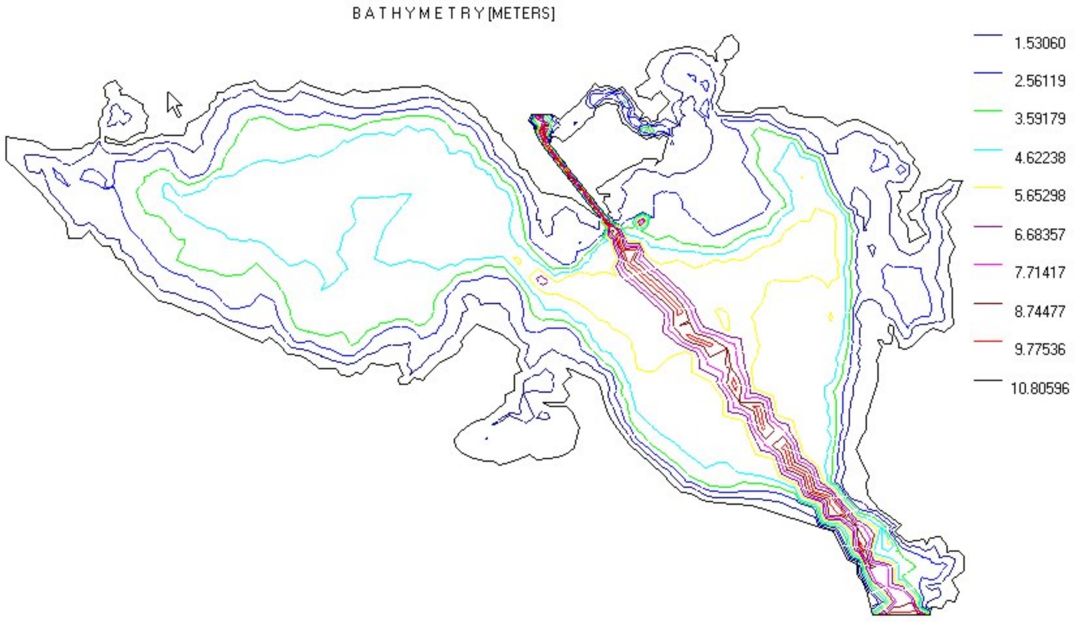


Figure 3.12. Bathymetry of the lagoon generated by Femflow2D used in the model calculations.

3.3.3 The flow module

The flow module was designed to investigate and simulate the flow conditions in the shallow water bodies. Parameters used to run this module include the time integration control, output control, flow boundary conditions, liquid boundary conditions, physical parameters of the flow model, wind parameter and bottom roughness.

Total integration time defined the duration of integration time in hours. Integration time step controlled the calculation interval of this flow module. The smaller the integration time step the longer the time is needed to complete the simulation. The frequency of output data is governed by the output control (in hours).

The flow boundary conditions described the input data of flow velocity from the Oder river and the output flow velocity from Swina, Peene and Dziwna. The numbers of boundary points with a fixed X-flow component which is the input flow from the Oder river to the lagoon needed to be entered according to the selected river discharge. The liquid boundary conditions at Swina, Peene and Dziwna can be chosen as open or fixed X-flow boundaries.

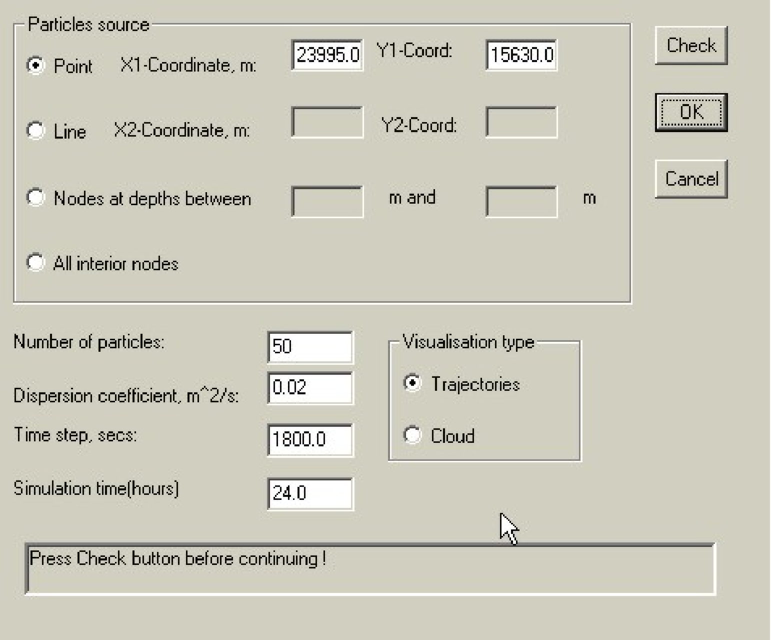
The model runs under certain wind conditions that can be selected from three options; constant, time series and spatially variable wind prevailing in the Oder Lagoon. Input of bottom roughness can be selected from two options, constant and spatially variable bottom roughness.

3.3.4 The particle tracking module

The Femflow2D model was equipped with a particle tracking module that can be used for studying the behaviour of particulate matter in the lagoon. The results can be interpreted as the concentration distribution or transport probability. Options in this module are available under the particle tracking tool option. Tracking of the particles starts with the selection of a flow data file produced by the flow simulation. This was done by choosing the open flow data file tool (see figure 3.8., particle tracking menu). The flow field in the lagoon is used by this module for further tracking of particles moving in the lagoon under this prevailing flow. Particle tracking parameters are then needed to be prescribed after choosing the flow data file. These are particles source, number of particles, dispersion coefficient, time step and simulation time and visualisation type (see figure 3.13). There are four options of particle source types for beginning the tracking. They are points (by entering the x and y model coordinates), lines (by entering two values of x and y coordinates of the ending point of the line), nodes at depth between (assigned for nodes at certain depth) and all interior nodes.

The particle tracking parameters can be seen in figure 3.13. The larger the number of particles the more time is needed to run this module. This is also the case for time step and simulation time. The dispersion coefficient determines the behaviour of particles moving in the water column. The higher the dispersion coefficient the more disperse are the particles moving in the water column.

In this study, the particle tracking module was used to study the behaviour of particles entering from the Oder river to the lagoon under different wind conditions. Particularly, the module was used in this study to assess the anthropogenic heavy metals pollution in the lagoon brought by the Oder river from the river basin.


Particles source

● Point X1-Coordinate, m: 23995.0 Y1-Coord: 15630.0

○ Line X2-Coordinate, m: Y2-Coord:

○ Nodes at depths between m and m

○ All interior nodes

Number of particles: 50

Dispersion coefficient, m^2/s: 0.02

Time step, secs: 1800.0

Simulation time(hours) 24.0

Visualisation type

● Trajectories

○ Cloud

Press Check button before continuing !

Figure 3.13. The particle tracking parameters in Femflow2D model.

3.3.5 The suspended particulate matter module

The suspended particulate matter module is another block in the Femflow2D model. This module can be used to study the dynamics of SPM concentration in shallow water bodies. Dr. Victor Podsetchine used and described the equations for this module as the following. The depth-averaged convective-diffusion equation of sediment transport is:

$$\frac{\partial S}{\partial T}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}=\frac{1}{H}\frac{\partial}{\partial x}\left(K_x H\frac{\partial S}{\partial x}\right)+\frac{1}{H}\frac{\partial}{\partial y}\left(K_y H\frac{\partial S}{\partial y}\right)+\frac{1}{H}(E-D),$$

where S is the depth-averaged concentration of SPM, u,v are x and y velocity components of the flow, K_x and K_y are turbulent diffusion coefficients, H is water depth, E is the erosion term and D is the deposition.

The module is limited that it can only simulate one particular sediment type with its physical properties. Input data needed for this module are D_{50} and D_{90} grain sizes, settling velocity, critical deposition and erosion shear stresses, a power of erosion term and material constants. In the main parameter menu this block is prescribed in the lower section, starting from median 50% grain size until the initial background of SPM concentration (see figure 3.9.). The erosion of the sediment calculated by the model can be described as follows;

$$E = M\left[\sigma_{beff} / \sigma_{crit.eros} - 1\right]^{P}, \sigma > \sigma_{beff}$$
$$E = 0, \sigma \leq \sigma_{beff}$$

where, E is erosion, M is material constant, σ b_{eff} is bottom effective shear stress, $\sigma_{crit.eros}$ is the critical erosion shear stress and P is the power of the erosion term.

The deposition term is written in the following form:

$$D = \beta S, \sigma < \sigma_{dcrit},$$
$$D = 0, \sigma \geq \sigma_{dcrit},$$

where β is the settling velocity of sediments, σ_{dcrit} is the critical deposition shear stress.

The total shear stress is given as a vector sum of current and gravity waves stresses (Van Rijn, 1990)

$$\sigma = \frac{1}{T}\int_{0}^{T_s}\left|\bar{\sigma}_c + \bar{\sigma}_w\right| dt,$$

where σ is the bottom shear stress vector averaged over one wave cycle. The current induced shear stress is calculated using an empirical relation

$$\sigma_c = \frac{\rho_w g}{C_c^2}(\bar{V}^2)^{1/2}\left|\bar{V}\right|,$$

where ρ_w is the water density, g is the gravity acceleration, C_c is the Chezy coefficient, V is the velocity vector, resultant from the x and y vertically averaged components u and v. The shear stress due to gravity waves is paramaterized using linear Airy wave theory:

$$\bar{\sigma}_w = \rho_w f\frac{U^2}{2},$$

where ρ_w is the water density, f is the wave friction factor, U is the maximum orbital velocity at the bottom.

The model assumes the existence of the same value of initial background SPM concentration in mg/m^3 over the lagoon and calculates both erosion and sedimentation depending on fetch length, wind speed, depth and sediment properties. It is also assumed that SPM concentration is small enough so that these processes do not alter the bathymetry. This approach can be justified, since short-term processes are considered.

3.4 Input parameter values

The values for the input parameter prescribed in the model (see figure 3.8. and 3.9.) were obtained by several different ways as follow: by using data from previous studies, using theoretical values, the application of box models, calibration against measurement and calibration parameter.

- The values for the grain sizes were taken from the results of grain size analyses of the sediment samples from the lagoon. Therefore the grain size input parameters were calibrated against measurement.

- The inflow from the Oder river to the lagoon, the outflow via Swina, Peene and Dziwna, were prescribed as the boundaries with fixed x – flow components in the model. The flow velocity from the Oder river to the lagoon was calculated by dividing the discharge of the river and the cross section of the river at the mouth of the Oder river (points number 2132, 2133, 2134 and 2163, total area 27555 m^2, see figure 3.14.). Discharge of the Oder river used in the calculation was equal to 350 m^3/s and was kept constant. This value is within the range of yearly Oder river mean discharge in the period 1951 – 1990 (see chapter 2.4). The output flowing via Swina (points number 2078, 2079, 2073 and 2074, total area 5763 m^2, see figure 3.14.) was calculated as 69% of the Oder river discharge (Mohrholz and Lass, 1998) while the outflows via Peene (points number 4, 5 and 6) and Dziwna (points number 2146, 2147, 2174) were set as open boundaries.

- The wind drag force value used in the model is an empirical value. The value is calculated from the wind drag coefficient equation as follows:

$$k = \gamma \rho a / \rho w$$

where, k is wind drag coefficient, ρ_a is density of air, which is 1.26 kg/m^3, ρ_w is density of water which is 1000 kg/m^3 and γ is a drag coefficient which is 2.6 x 10^{-3} (dimensionless). Therefore the wind drag coefficient is 3.2 x 10^{-6} and this value was used in this study.

- The Coriolis parameter in the model describes the effect of a moving water body over the earth's surface drifting sideways from its course because of the earth's rotation. In the northern hemisphere the deflection is to the right and to the left in the southern hemisphere. The Coriolis parameter can be described as follows:

$$f = 2\omega \sin \mu$$

where ω is the angular velocity of the earth ($\omega = 2\pi / 86400$) and μ is the latitude of the object. The lagoon position of 53°37'60" North was taken for the calculation and therefore the Coriolis parameter of the Oder Lagoon is 1.174 x 10^{-4}. This value was used in the model simulations.

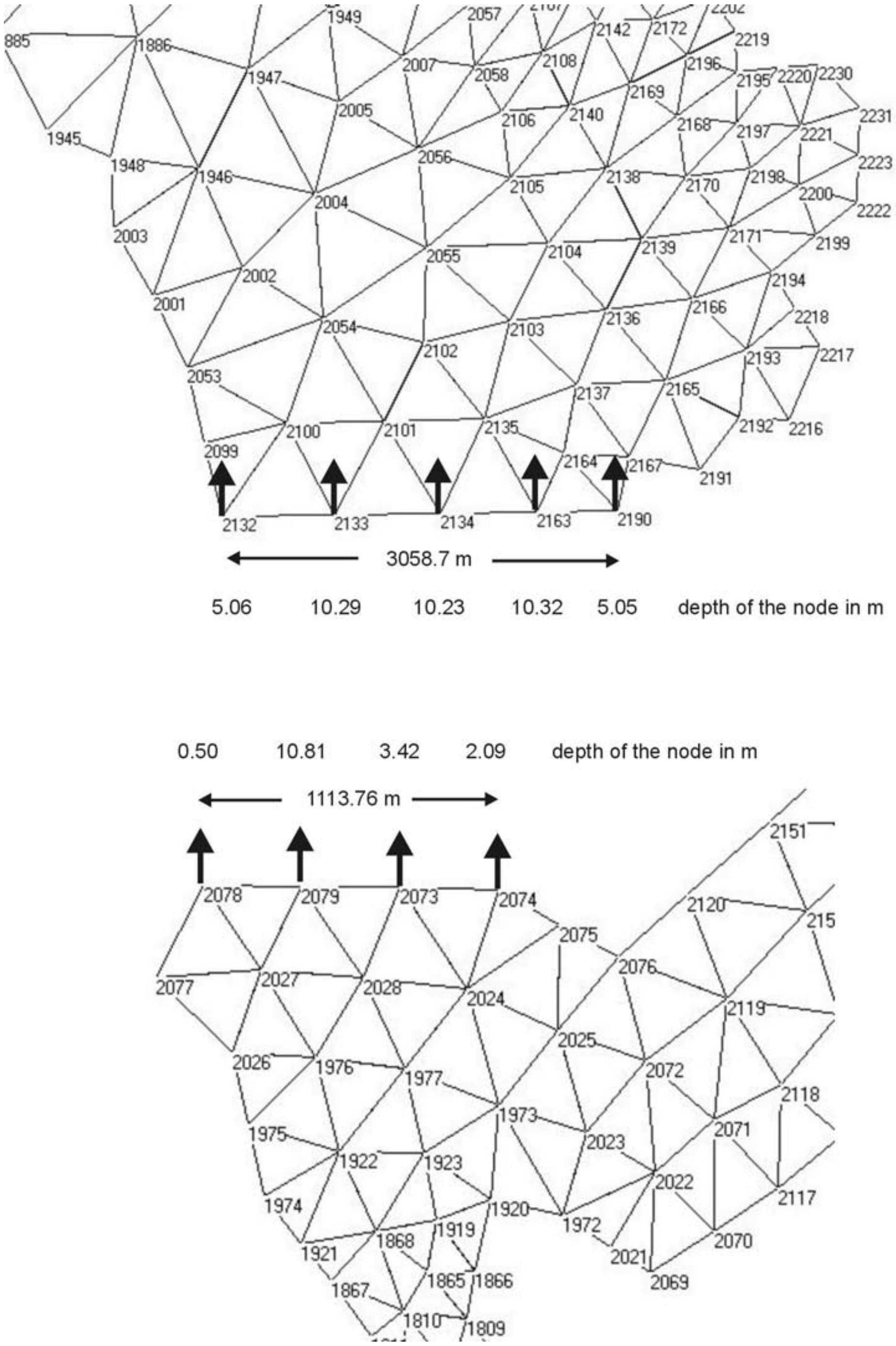


Figure. 3.14. Boundaries with x – flow components at Oder inflow (top) and Swina outflow (bottom) with corresponding points number and depth.

- A constant Manning roughness coefficient of 0.015 $m^{-1/3}s$ was used for the bottom roughness value in the model simulations.

- Wind speed and direction data for model simulations were taken from the Oder Buoys 01, 02 and 03 (http://meteo.gkss.de) and Ueckermünde Weather Station.

- Settling velocity is the measure of how fast is the particle in the water column to settle down. The values of settling velocity for input of the model were calculated by two different methods, the Stokes Law and the simple box optimisation model of Dr. Victor Podsetchine. Both values obtained by these methods were tested in the model.

The Stokes law describes that the settling velocity of a particle in the water column depends on the density, the weight and shape of the particle and the viscosity of water. The relationship of those factors can be written as follows:

$$v = \frac{2(ds - df)gr^2}{9\eta}$$

where v is velocity of the particle in cm/s, ds and df are particle and fluid densities in g/cm^3, η is the viscosity in poise, g is the acceleration of gravity in cm/sec^2 and r is the radius of the particle in cm. Soil particle in water at 20°C: ds = 2.65 g/cm^3 (for sand particle, quartz), df = 0.998 g/cm^3, η = 0.1005 poise, g = 980 cm/sec^2, and the particle radius which is in this case the grain size. Graphics of the Stokes law was obtained from Van Rijn (1989). Grain sizes from the measurements were plotted in this graphics to know the settling velocity that was used in the model simulations.

The box optimisation model of predicting the settling velocity value for SPM of the Oder Lagoon was described by Dr. Podsetchine as the following. In this box model, the original model of Luettich et al. (1990) is derived from the three-dimensional mass transport equation by integrating it over the vertical direction and applying the corresponding boundary conditions on water surface and bottom. As result an ordinary differential equation is obtained,

$$\frac{dS}{dt} = \frac{1}{H}\left(-\beta \cdot S + E\right), \tag{1}$$

where S is the SPM concentration (mgl^{-1}), H – is the depth of the water column (m), β is the settling velocity, and E is the erosion term. The last term is usually parameterised as a function of bottom stress. Assuming the existence of a threshold value of shear stress and taking only wave-induced shear stress into account it can be written as follows,

$$\begin{aligned} &E = 0, h < h_c \\ &E = K\left[\frac{h - h_c}{h_{ref}}\right]^n, h > h_c \end{aligned}, \tag{2}$$

where h is the wave height (m), h_c is the critical value of wave height, h_{ref} =0.01 m is the reference wave height, K is the empirical factor, n – is the power exponent. The concept of critical shear stress $\tau_c > 0$ and respectively $h_c > 0$ was criticised by Lavelle et al. (1984) who showed that experimental results can also be interpreted with $\tau_c = 0$ ($h_c = 0$) due to the random nature of bottom stresses and particle movement. Since the wave height depends mainly on the square of the wind speed, the equation (1) can be rewritten as follows:

$$\frac{dS}{dt} = \frac{1}{H}\left(-\beta \cdot S + \alpha W^{p}\right), \qquad (3)$$

where W is the wind speed (ms^{-1}), α is the empirical wind factor and p is the power exponent.

An analytical solution of the equation (3) can be found in a form of the convolution integral

$$S = \frac{\alpha}{H} e^{-\frac{\beta t}{H}} \int_{0}^{t} W^{p}(\tau) \cdot e^{\frac{\beta \tau}{H}} d\tau + S(0) \cdot e^{-\frac{\beta t}{H}} \ , \qquad (4)$$

where S(0) is the initial SPM concentration at t = 0. The numerical solution can be obtained by replacing the integral in (4) with suitable quadrature formula or using the standard numerical method to solve the ordinary differential equation (3). The standard fourth-order Runge-Kutta method was used in this work in combination with a direct search optimisation method (Nelder and Mead, 1965) to obtain the best combination of model parameters α, β and p.

- The values of the critical erosion and deposition shear stresses were obtained from previous studies for example by Ziervogel and Bohling (2003), Bohling (2003) and Christiansen et al. (2002). Lund-Hansen et al. (1999) in Edelvang et al. (2002) measured the critical erosion shear stress of the fluffy layer using a LABEREX chamber. The undisturbed sediment samples for this measurement were collected from Pomeranian Bay and were analysed on board of the ship. In principle, the method used was to increase the shear stress until critical shear stress had been reached, which was determined by the light attenuation in the chamber. The critical erosion shear stress varied from about 0.024 N/m^2 at a shallow water station to about 0.016 N/m^2 in the Arkona Basin (Edelvang et al., 2002). Ziervogel and Bohling (2003) measured the critical erosion shear stress velocity of sand, silt and fluffy surface materials of the Mecklenburg Bay area using a microcosm device. They described that the critical shear stress velocity for sand was 1.2 cm/s, 3.75 cm/s for cohesive mud and 0.39 cm/s for the fluffy surface layer. Bohling (2003) measured the critical erosion shear velocity for fluffy surface layer as well as for several types of sand and found that the values were between 0.4 and 0.7 cm/s for fluff, between 0.9 and 2.6 cm/s for muddy fine sand, between 0.8 and 1.6 cm/s for well sorted fine sand, between 1.2 and 1.9 cm/s for bad sorted fine to medium sand, between 1.4 and 2.0 cm/s for well sorted medium sand and from 1.4 to 2.1 cm/s for well to moderately sorted medium to coarse sand. The critical erosion shear stress can be calculated by using the formula, τ_c = density of water * $(U_c)^2$. The water density is equal to 1 g/cm^3. The values of critical deposition shear stress (the values below which the sediment will settle) were obtained by estimation. This value was below the critical erosion shear stress. Christiansen et al. (2002) described that the fluff layer of the south-western Baltic Sea have a low resuspension threshold of less than 0.023 N/m^2.

- The input values for total integration time, integration time steps of the simulation, turbulence exchange coefficient, turbulent diffusion coefficient, material constant (erodability coefficient) and power of erosion used in the simulations were the calibration parameters. Several integration time step of simulations were applied for example 600, 300 and 100 seconds and the resulting flows in the lagoon were observed. The input values for a material constant used by Lee et al. (1994) were used as a starting point in the simulations.

- To obtain a high resolution of measured SPM data (in mg/l), the data of SPM measurement of 12 hours resolution received from Prof. M. Pejrup of The University of Copenhagen was analysed. The existing online transmission data from the GKSS Oder Buoys 01, 02 and 03 (http://meteo.gkss.de) were calibrated against the SPM measurement data. The regression formula obtained from the calibration was used to extrapolate the transmission data from the buoys into SPM in mg/l unit. The input value for the background concentration in the model was taken from the available transmission data of those buoys that was converted into a mg/l unit using the regression formula obtained.

3.5 Statistical analyses

Statistical analyses covering percent frequency, minimum, maximum and average were done to characterise the meteorological conditions of the Oder Lagoon. Data analysed were from the period of 1991 – 2000.

Linear regression analyses were used to assess the correlation between wind speed and SPM concentration. Logarithmic regression analysis was performed to assess the relationship between transmissivity and SPM in the lagoon. The regression results obtained were used to calculate the concentration of SPM in mg/l from the available transmissivity data which were in percent unit. Pearson’s correlation was used to analyse the relationships between wind speed and SPM concentration in the lagoon as well as between transmission and SPM. The Pearson’s correlation measures the correlation between those variables and reflects the degree of linear relationship between those two variables.

3.6 Flow measurement

Measurement data of flow speed and direction from ADCP and ISM-2000 as well as the data from the drifters were processed. The Femflow2D model calculates the flow in the lagoon as the depth averaged flow, therefore vertical flow speed and direction measured by ADCP and ISM-2000 at each point of measurements were averaged for the entire water column. The ADCP measured the flow speed and direction at every 25 cm depth. The measurement results were plotted in the map so that they can be compared with the flow simulation results. The ADCP started the measurements from the depth of 70 cm to the bottom of the lagoon. Therefore the data of the first 70 cm water depth were not measured.

For the calculation of the depth average flow speed and direction, this depth needs also to be included. The flow speed and direction of this section was calculated based on the assumption that the wind blowing above a water body generates a flow on the water surface with approximately 1% of the wind speed. It's direction follows the wind direction. The drifter measurements showed that the flow direction of 10 cm drifter depth was deflected 20° to the right away from its true direction indicating the Coriolis force that worked on the lagoon water mass flow.

3.7 Flow simulation

Several different values of input parameters were applied to investigate the hydrodynamic conditions in the lagoon. The values for the input parameter used were described in chapter 3.4. The results of simulations showed that the flow field in the lagoon reached a stable flow field starting at 6 hours integration simulation time. To get stable flows in the lagoon, 12 hours integration simulation time was needed. The time needed for completing one flow simulation depends on the integration timestep of the simulation and the total integration simulation time. Using 100 seconds integration timestep of the simulation time it took approximately 8.8 minutes to complete 12 hours integration simulation time and by applying 300 seconds integration timestep it took about 2.8 minutes. The computer used for those runs has the speed of 1 GHz (Intel Pentium 3). Several integration timestep of simulations were applied for example 600, 300 and 100, 30, 20 and 10 seconds and the resulting flows in the lagoon were observed. The results showed that the larger the integration timestep of simulation the lower the flow speed in the lagoon.

4 RESULTS

4.1 Meteorological conditions

Meteorological conditions of the Oder Lagoon which include wind speed and wind direction as well as air temperature were analysed for the basis of Femflow2D model application. Data of wind speed and direction as well as air temperature were obtained from Ueckermünde Weather Station. Ten years data from the period of 1991 – 2000 were selected for the analyses. The wind direction data were summarised on the basis of eight 45° sectors: north wind (337.5° - 22.5°), north-east wind (22.5° - 67.5°), east wind (67.5° - 112.5°), south-east wind (112.5° – 157.5°), south wind (157.5° - 202.5°), south-west wind (202.5° - 247.5°), west wind (247.5° - 292.5°) and north-west wind (292.5° - 337.5°). The data are available in an hourly basis but they do not cover completely over the entire period. 4.88% of the total data were not recorded and analysed. The results of frequency analyses of wind speed and direction as well as air temperature can be seen in figure 4.1., figure 4.2., table 4.1., appendices 1-A and 1-B.

The results of wind direction analyses through the ten years period of 1991 – 2000 at Ueckermünde Weather Station showed that the most frequent wind directions in the Oder Lagoon were south (21.69%), south-west (21.58%) and west (17.11%) winds which comprised totally of 60.38 % frequency. The average direction of those winds (south, south-west and west winds) was 225° whereas the average direction of all winds of the ten years period was 223°. The frequency of other wind directions from higher to lower frequencies were east (11.24%), north-east (9.19%), south-east (7%), north (6.93%) and north-west (5.26%) winds.

Wind speeds at the Oder Lagoon were moderately calm with mostly below 6 m/s (84.50% frequency). Wind speeds higher than 6 m/s comprised 15.50 % frequency. The average wind speed through the ten years period was 4 m/s. Average wind speeds of more than 4 m/s occurred from November to April (see table 4.1.). The maximum wind speed happenned on 4 October 1996 with a wind speed of 44.8 m/s and direction 0°. The main directions of wind speed > 10 m/s were from west (43.4 %) and south-west (36.93%). Both directions sum up to 80.33%. Other wind directions for that wind speed occurred in less than 10% of all measurements (see figure 4.3.).

If the wind data was analysed on the basis of daily average then the south-west wind was the most frequent wind direction in the lagoon with 25.05% frequency followed by the south wind with 17.19% and the west wind with 16.01% frequencies (see figure 4.1.). These winds remain the most frequent wind directions that totally made 58.25% frequency. Other winds were north-east (11.05%), east (10.55%), south-east (7.79%), north (6.2%) and north-west (6.17%) directions. Wind speeds in the Oder Lagoon were mostly below 6 m/s (84.93% frequency) and wind speeds of higher than 6 m/s comprised 15.07% (see

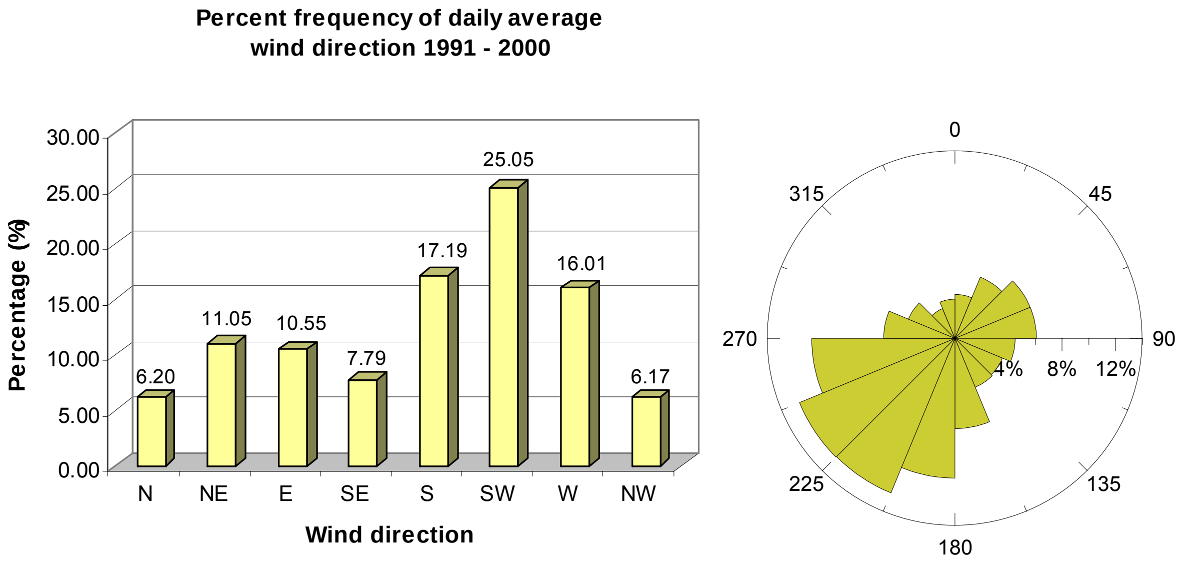


Figure 4.1. Percent frequency of daily average wind directions through the ten years period of 1991 - 2000 at Ueckermünde Weather Station and its wind chart.

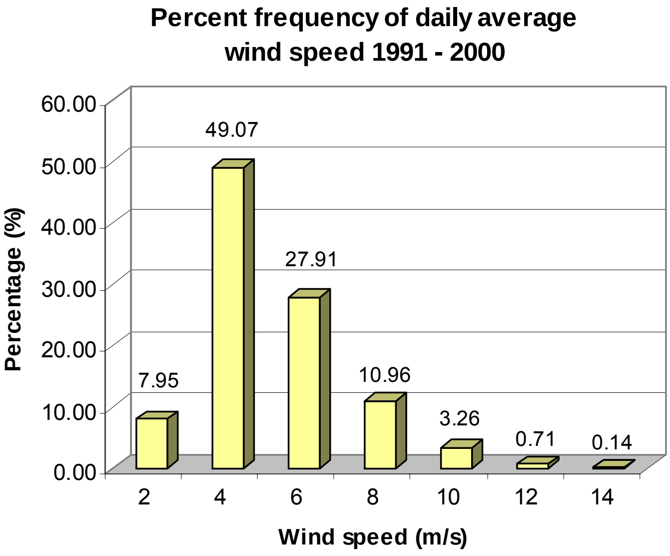


Figure 4.2. Percent frequency of daily average wind speeds through the ten years period of 1991 – 2000 at Ueckermünde Weather Station.

figure 4.2.). In the ten years period of 1991 – 2000, wind speed of > 4 m/s, > 6m/s, > 8m/s and >10 m/s occurred in 1566, 553, 153 and 31 days and the average directions of those

wind speeds were 233°, 238°, 242° and 248° respectively. Wind speeds of > 4 m/s were mostly from the south-west (37.42%) and west (23.12%) (see figure 4.4.). Similarly, wind speeds of > 6 m/s were mostly from the south-west (47.2%) and west (28.93%) (see figure 4.4.). Strong wind speeds of > 8 m/s were predominantly from the south-west (54.25%) and west (35.29%) whereas the main direction of wind speed > 10 m/s was west (51.61%) and south-west (35.48%) winds (see figure 4.4.).

The seasonal variations showed that during winter there were the highest monthly average wind speeds (4.72 m/s) and during summer the lowest (3.47 m/s) average wind speeds. In spring and autumn the average wind speeds were 4.13 m/s and 3.82 m/s respectively. The winter contained the greatest number of strong wind events of > 10 m/s with 935 hours or 4.4% followed by spring (501 hours or 2.3%), autumn (275 hours or 1.3%) and summer

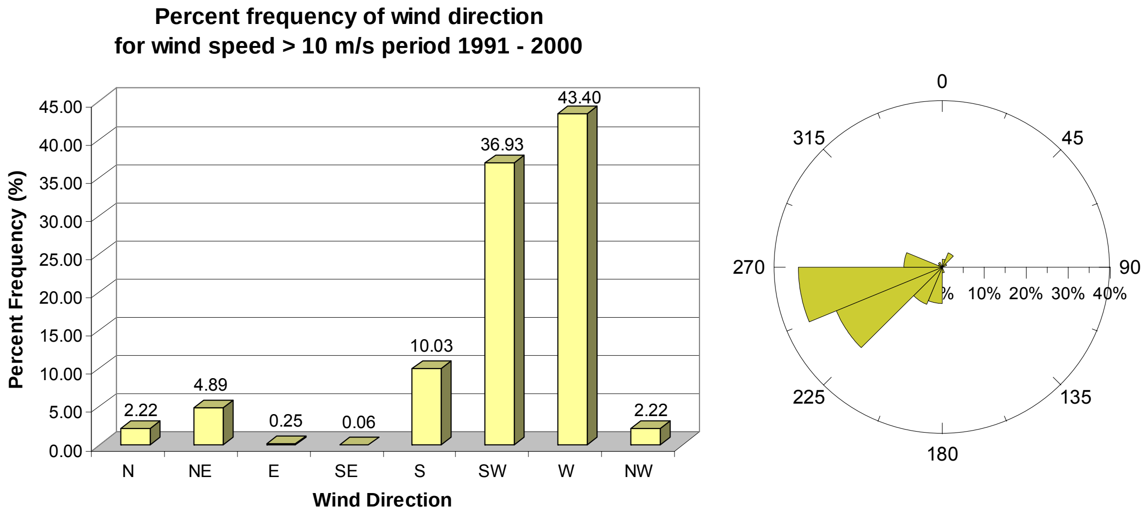


Figure 4.3. Percent frequency of wind direction of wind speed > 10 m/s through ten years period of 1991 – 2000 at Ueckermünde Weather Station and its wind chart.

(84 hours or 0.39%). If daily average is considered then winter had the largest number of days with strong wind events of > 10 m/s with 17 days followed by spring (9 days) and autumn (6 days). In summer no strong wind events of > 10 m/s have been recorded. For wind speeds of > 8 m/s, the number of days with these strong wind events were: winter (82 days), spring (38 days), summer (8 days) and autumn (22 days). The monthly and seasonally wind charts for Ueckermünde Weather Station through the ten years period of 1991 – 2000 are presented in appendices 1-A and 1-B.

During the period of 1991 – 2000, a minimum air temperature of –22.5° C in 1 January 1997 and a maximum temperature of 37.7° C in 1 August 1994 were recorded. The

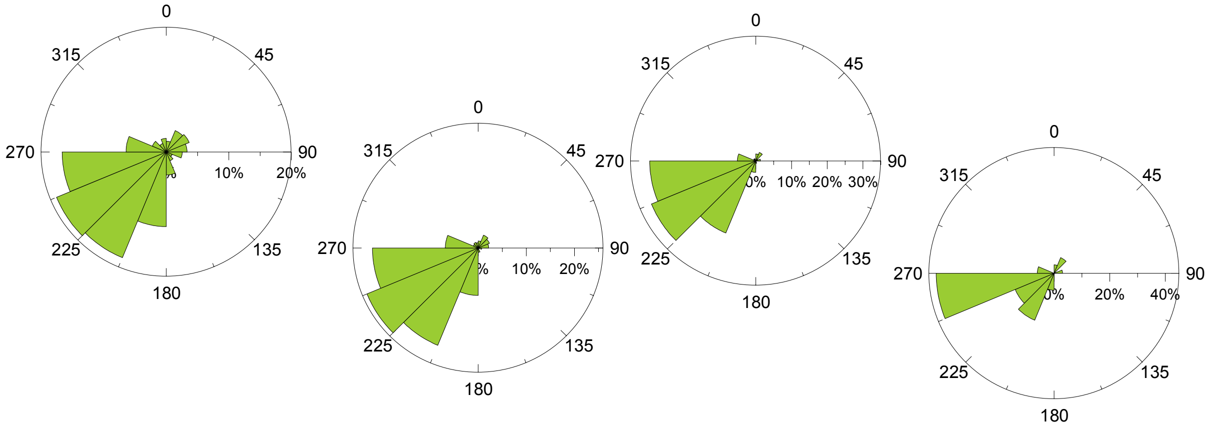


Figure 4.4. Wind chart of daily average wind direction for wind speed > 4 m/s, > 6 m/s, > 8 m/s and > 10 m/s (left to right).

Table 4.1. Summary of monthly wind speed and air temperature analyses for the period of 1991 – 2000 at Ueckermünde Weather Station.

PERIOD **1991 - 2000**	**Wind Speed** **(m/s)**		**Air Temperature** **(°C)**		
	Average	Maximum	Average	Maximum	Minimum
JANUARY	4.76	21	0.84	14.6	-22.5
FEBRUARY	4.98	16	1.51	16.7	-17.9
MARCH	4.62	15.9	3.84	19.8	-10.8
APRIL	4.08	26.2	8.10	28.7	-4.9
MAY	3.68	26.7	12.53	30.8	-0.1
JUNE	3.69	37	15.71	35.5	2.7
JULY	3.47	30.9	17.04	35.8	7.2
AUGUST	3.25	37	17.85	37.7	7.1
SEPTEMBER	3.41	13.4	13.72	27.2	2.1
OCTOBER	3.97	44.8	9.13	24.1	-4.0
NOVEMBER	4.06	28	3.70	15.7	-11.7
DECEMBER	4.43	19	0.85	12.7	-21.9

monthly average temperature was between 0.84° C in January and 17.85° C in August. The two lowest monthly average temperatures were in January and December with 0.84° C and 0.85° C while the two highest average temperatures were in August with 17.85° C and July with 17.04° C (see table 4.1.).

4.2 Sediments of the Oder Lagoon

Sediments of the Oder Lagoon were studied as a background for the flow and suspended particulate matter model. Several sediment samples were taken from the western part of the lagoon (Kleines Haff), at Mönkebude and Altwarp areas as well as along the section from Mönkebude to Kamminke. Along the Mönkebude to Kamminke section, several sediment samples were not able to be taken due to the existence of mussel banks. No sediment samples could be obtained by grab sampler but dead and living mussels of predominantly *Dreissena polymorpha*. These mussel banks were found offshore of Mönkebude at three stations: 237281, 237282 and 237291 (see figure 3.6. for the localities).

To classify the grain size, the grain size classification by Udden – Wentworth (Wentworth, 1922 in Dyer, 1986) was used. In this classification, grain size classes (in micrometer or µm) were: very fine silt (3.9 to 7.6 µm), fine silt (7.6 to 15.6 µm), medium silt (15.6 to 31.3 µm), coarse silt (31.3 to 63 µm), very fine sand (63 to 125 µm), fine sand (125 to 250 µm), medium sand (250 to 500 µm) and coarse sand (500 to 1000 µm). During the sieve analyses, a 400 µm mesh size was used instead of 500 µm. Therefore for practical purposes, the grain size range of medium and coarse sand described in the following section are 250 to 400 µm for medium sand and 400 to 1000 µm for coarse sand.

Two main types of sediment along the Mönkebude - Kamminke cross section were found, sand and silt dominated sediments. The sediment types changed from sand to silt and back to sand dominated sediments from Mönkebude to the central part of the lagoon and to Kamminke. Silt sediments occurred in the central and deeper part of the lagoon. The results of sediment analyses are described in the following sections and the results summary of the laboratory analyses can be seen in appendices 2-A, 2-B, 3 and 4. The localities of sediment sampling can be seen in figure 3.6.

4.2.1 Water content

Along the section from Mönkebude to Kamminke, two distinct groups of the sediment water content can be identified, the lower and the higher groups of water content (see figure 4.5.). Sediments from the coastal area to about -2.9 meter water depth had the lower water content ranging from 12.52% to 17.53%. The water content of the sediments from the deeper part of the section (central part of the lagoon), from about -2.9 to -5.3 meter water depth had the higher water content ranging from 62.36% to 70.76%.

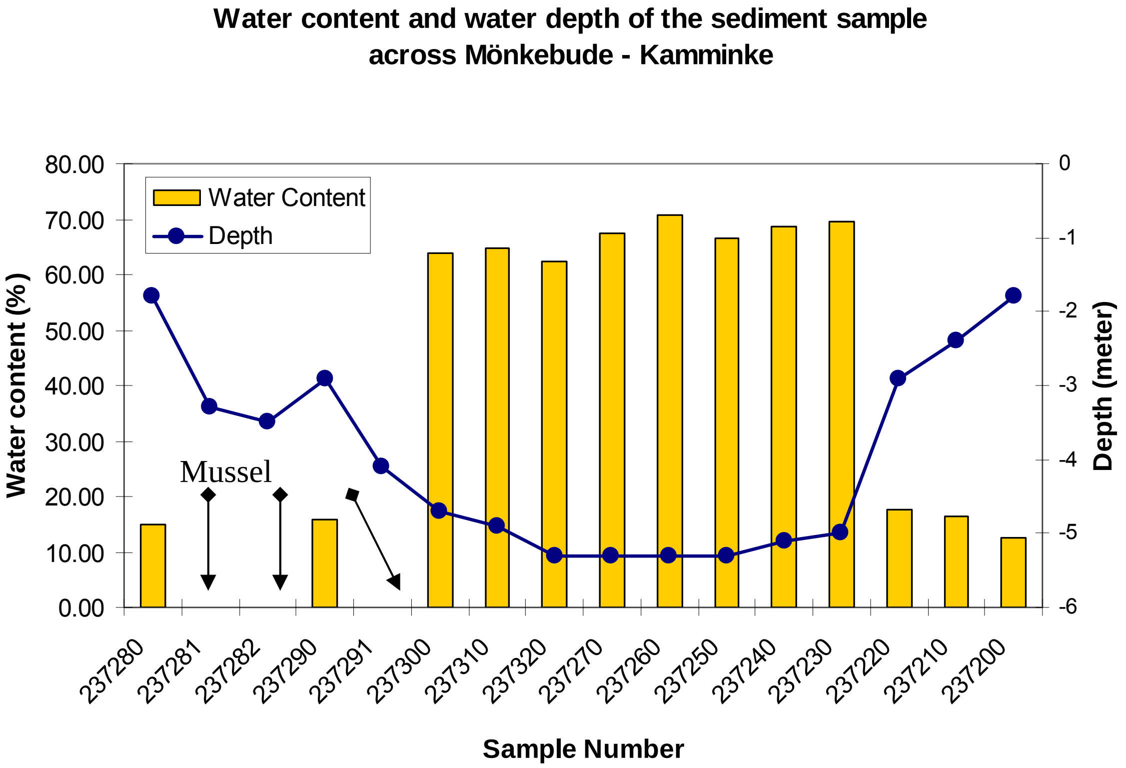
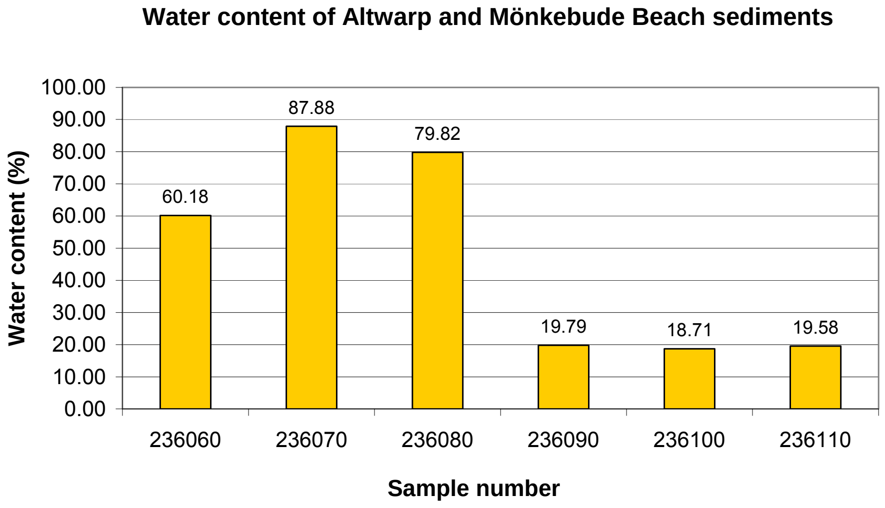


Figure 4.5. Water content and water depth of the sediment samples across the section of Mönkebude to Kamminke.



236060 = Altwarp Port 236070 = Altwarp Bay I 236080 = Altwarp Bay II
236090 = Mönkebude Beach East 236100 = Mönkebude Beach Central
2366110 = Mönkebude Beach West

Figure 4.6. Water content of the sediments from Mönkebude Beach and Altwarp areas.

The water content of the sediments from Mönkebude beach, samples 236090, 236100 and 236110 were 19.79%, 18.71% and 19.59% respectively whereas the sediments from the bay east of Altwarp, samples 236070 and 236080, had a water content of 87.88% and 79.82% (see figure 4.6.). The Altwarp Port sediment sample (236060) showed a water content of 60.18% (see figure 4.6.).

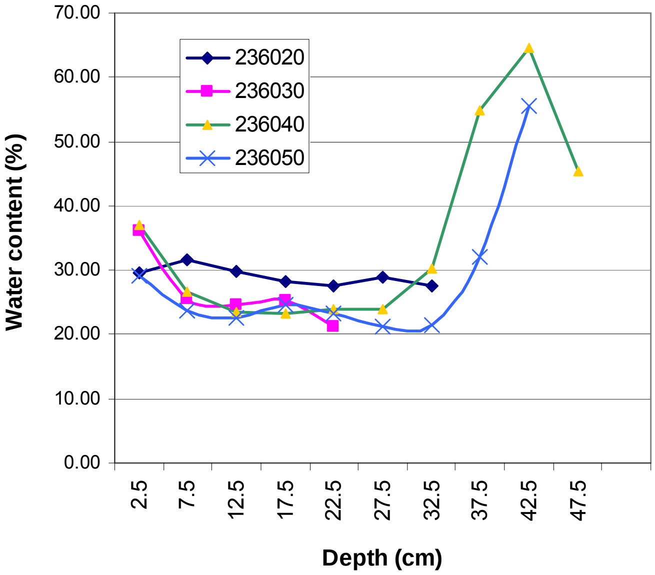


Figure 4.7. Water content of the core sediments from the reed zones of Mönkebude and Altwarp.

Figure 4.7. displays the water content of the core sediments from the reed zones of Mönkebude and Altwarp. The water content of the core sediment from the reed zone east of Mönkebude (sample 236020, thickness of 35 cm) were between 27.54% and 31.67% whereas the core sediments from Altwarp, samples 236030 (thickness of 25 cm) had the water content between 21.16% and 36.06%. The Altwarp core samples 236040 (thickness of 50 cm) and 236050 (thickness of 45 cm) had the higher water content at the deeper part of the cores. In sample 236040 the water content ranged from 23.53% to 64.66% and in sample 236050 ranged from 21.23% to 55.62%.

4.2.2 Grain size

Based on the grain size analyses, the sediments along the section from Mönkebude to Kamminke can be divided into two main types, sand and silt sediments. The sizes changed from sand at localities closer to Mönkebude, to silt in the central part of the lagoon and again to sand sediment towards the Kamminke area. Silt sediments were found in the deeper part of the lagoon. The general trend of sand found at the shallower part and silt in the deeper part of the lagoon was observed. Figure 4.8. shows the average grain size and the water depth of the sediments across Mönkebude – Kamminke. The average grain size of sediment samples from the central part of the Oder Lagoon (samples 237300, 237310, 237320, 237270, 237260, 237250, 237240 and 237230) was between 31 µm and 63 µm (coarse silt). Sediments closer to Mönkebude (samples 237280 and 237290) had the average grain size of 266 µm and 322 µm (medium sand) whereas the average grain size of sediments towards Kamminke (samples 237220, 237210 and 237200) was 181 µm, 177 µm and 190 µm (fine sand). Based on Folk and Ward's (1957) sorting classification, the silt sediments were poorly to moderately sorted and the sand sediments were very well to well sorted.

At the western, central and eastern part of Mönkebude beach (samples 236110, 236100 and 236090 respectively) the grain size of the sediments was predominantly fine sand that comprised 68.8% to 86.4% (see figure 4.9., sieving analyses results). At the central part of the beach (sample 236100) more medium sand compared to the samples of the western and eastern part was observed. The medium sand in the central part of the beach composed 22.2% of the total fractions compared to 6.2% and 11.1% in the western and eastern parts of the beach. In all Mönkebude beach sediments, the fractions of very fine sand were between 7% and 19.6% with the highest proportion in the eastern part of the beach

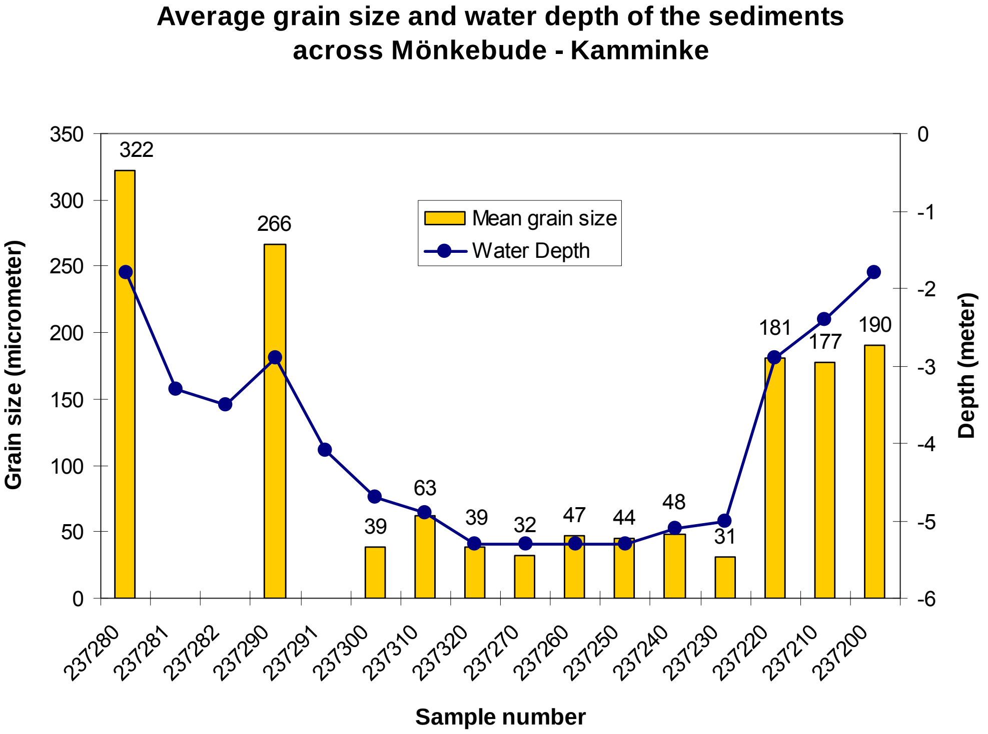


Figure 4.8. Average grain size and water depth of the sediments across Mönkebude – Kamminke.

(see figure 4.9.). Silt to clay fractions were absent in those sediment samples. Based on Falk and Ward (1957) sorting classification, the Mönkebude beach sediments were well sorted sands.

In Altwarp Bay, the sediments (samples 236070 and 236080) were sand with similar proportions of grain size fractions from very fine to coarse sand. In those sediments, very fine, fine, medium and coarse sands made up 12% to 19%, 18% to 25%, 19% to 21% and 19% to 47% respectively (see figure 4.9.). Unlike the sediment in Altwarp Bay, at Altwarp Port (sample 236060), fine sand predominated (64%) followed by medium sand (20%), very fine sand (11%) and coarse sand (4%). The average grain size of the Altwarp sediment samples was between 216 and 375 μm. Based on Folk and Ward's (1957) sorting classification, the Altwarp Port sediment was moderately well sorted and the sediments of the Altwarp Bay (samples 236070 and 236080) were very poorly and poorly sorted respectively.

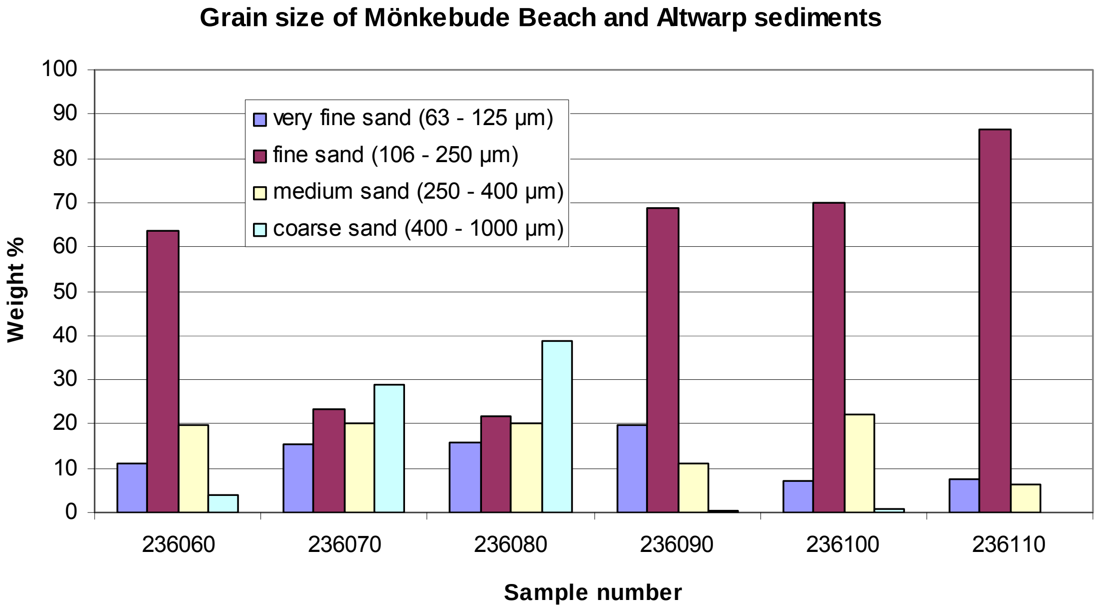


Figure 4.9. Sieving analyses results of the Mönkebude beach and Altwarp sediments.

The core sample from east of Mönkebude beach (35 cm long core, sample 236020) consisted of predominantly fine sand sediment (between 76.15% to 85.67%) with a few fractions of very fine sand and medium sand and minor fractions of coarse sand and silt (see figure 4.10., sieving results of core sediment samples). Same few hundred meters west of Altwarp, at the reed zones, a 23 cm long sediment core (sample 236030) showed a

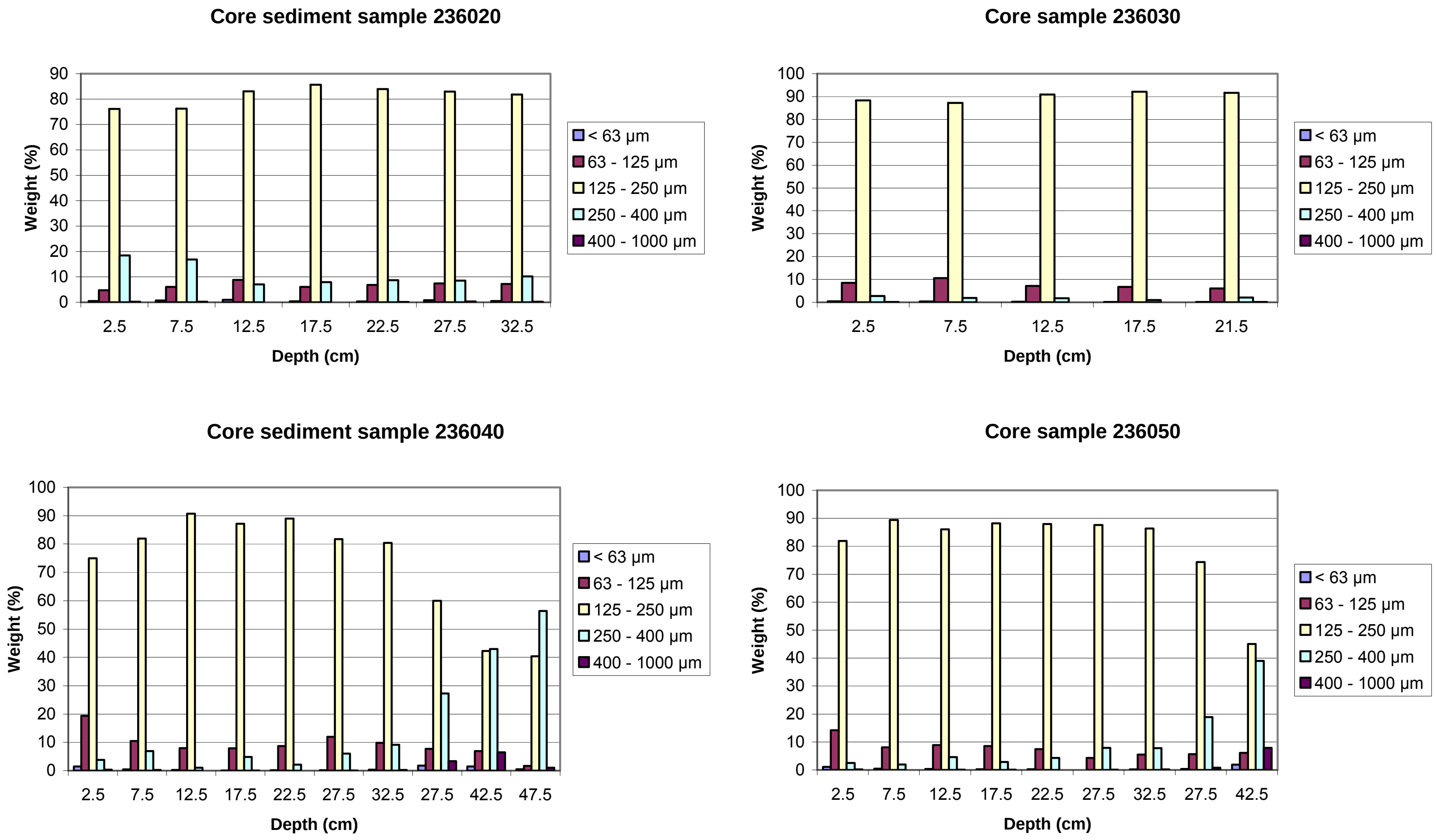


Figure 4.10. Sieving results of core sediment samples.

similar grain size to the core sediment at Mönkebude. The sediment at this locality was predominantly fine sand (87.23% to 92.08%) followed by very fine sand (6.02% to 10.59%) with minor fractions of medium sand (1% – 2.78%), silt (0.12% to 0.42%) and coarse sand (0% to 0.06%). The core sediments 236040 and 236050 were slightly different to the core sediments 236020 and 236030 in which the medium and coarse sands as well as the silt fractions occurred in higher proportions at the deeper core sections (see figure 4.10.). The average grain size of the core sediments were between 154 µm and 179 µm for sample 236020, 139 µm to 144 µm for sample 236030, 135 µm to 281 µm for sample 236040 and 138 µm to 287 µm for core sample 236050 (see figure 4.11.).

For the Femflow2D model application, the value of D_{50} (particle size at which 50% by weight is finer) and D_{90} (particle size at which 90% by weight is finer) were required as input parameter for the model. Values of D_{50} and D_{90} of all surface sediment samples are summarized in table 4.2.

Table 4.2. D_{50} and D_{90} values of the Oder Lagoon sand and silt sediments

Sand		**Silt**	
D_{50}	161 – 310	D_{50}	28 – 57
D_{90}	210 – 750	D_{90}	53 – 116

values are in micrometer (µm)

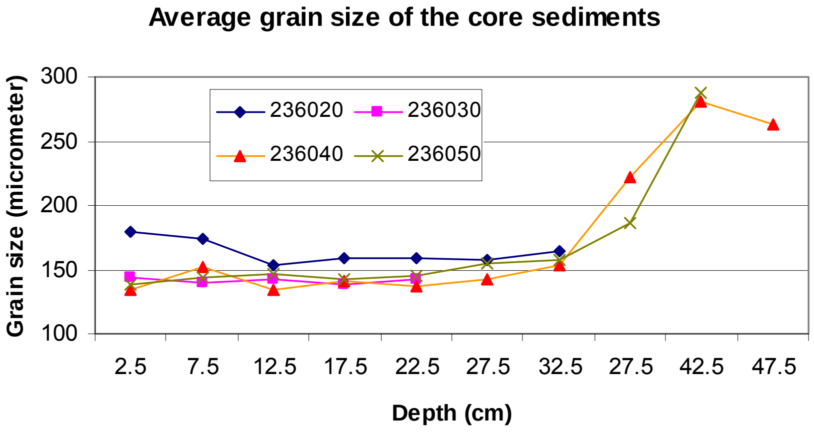


Figure 4.11. Average grain size of the core sediments.

4.2.3 TC, TIC, S, N and TOC/N ratio

The results of TC and N as well as TIC and S analyses are presented in appendix 4. TOC was calculated by substracting the TIC values from the TC values. The TOC/N ratio can then be calculated. This ratio is an indicator of the origin of the carbon material in the sediment. A ratio above 10 indicates terrestrial origin whereas a ratio below 10 means that the carbon was originating from the freshwater phytoplankton.

The analyses and calculations showed that Altwarp sediment samples has a TOC/N ratio of 9.25 (sample 236070, Altwarp Bay 1), 8.88 (sample 236080, Altwarp Bay 2) and 10.87 (sample 236060, Altwarp Port). Along the Mönkebude - Kamminke section the TOC/N ratio of silt samples were ranging from 5.61 to 7.64 (see figure 4.12.). Those values except Altwarp Port sample were below 10 which is indicative of freshwater phytoplankton origin of the carbon material in the sediments. The Altwarp Bay sample which has a ratio of above 10 means that the origin of the carbon material in the sediment was terrestrial.

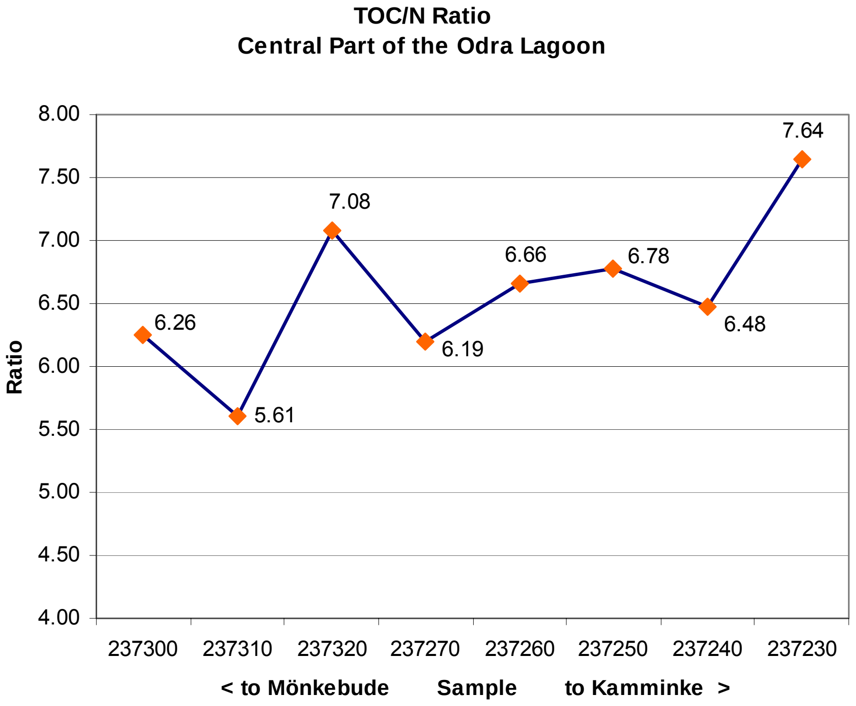


Figure 4.12. TOC/N ratio of the silt sediments of Mönkebude - Kamminke section.

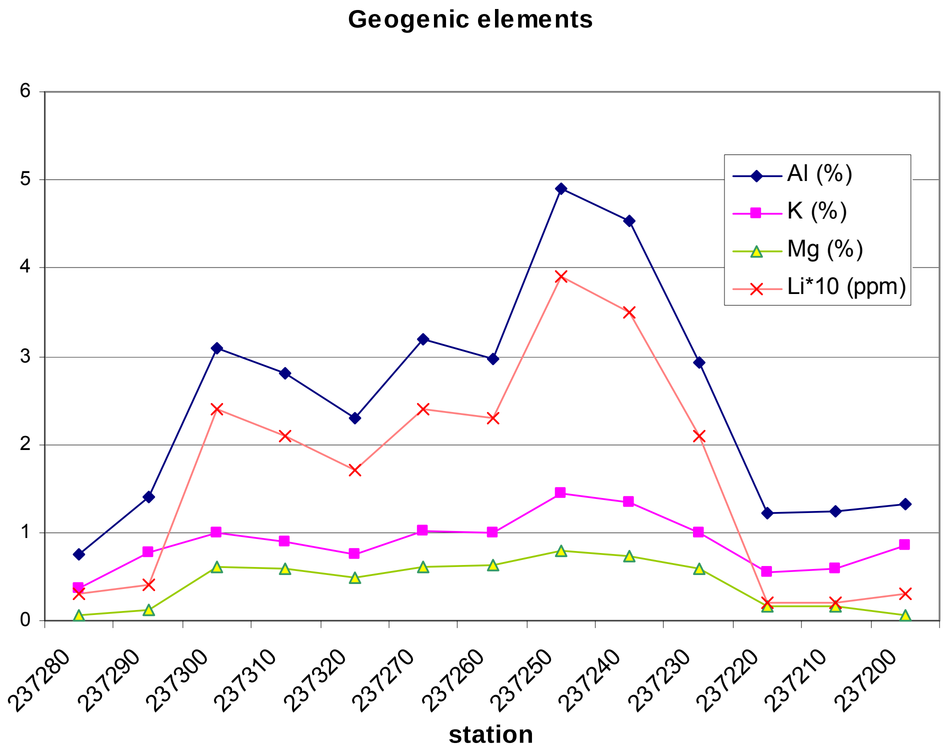
4.2.4 Geochemical elements

The results of geochemical analyses of the sediment samples from the Mönkebude to Kamminke section are presented in figures 4.13. and 4.14. The geochemical elements can be classified into four groups of elements: geogenic (Al, Mg, K, Li), anthropogenic metals (Pb, Zn, Cu), redox (Fe, S and Mn) and nutrient – eutrophication (P, TOC, N, $CaCO_3$) elements. Each group of elements showed a similar graphic trend across Mönkebude to Kamminke.

Generally, the concentration of all elements is significantly higher in the silt sediments (at the central part of the lagoon – samples 237300, 237310, 237320, 237270, 237260, 237250, 237240 and 237230) compared to that of the sand sediments (closer to Mönkebude and Kamminke areas – samples 237280, 237290, 237220, 237210 and 237200) (see figures 4.13., 4.14. and figure 3.6. for the locality). The geogenic elements showed a relatively higher concentration in the northern part of the section in the silt sediments. This higher concentration might be caused by the steeper slope in the northern part of the section compared to the southern part (see water depth profile in figure 4.8.). The steeper slope in this area may cause the sand sediment from the coastal areas to be transported to the deeper part more easily and accumulated in the deeper part.

Similar results were found for the redox elements. Within the sand sediments slightly higher concentrations of nutrient eutrophication and redox elements were found at the locality 237280. In the Mönkebude to Kamminke section, particularly at the localities 237250 and 237240, a slightly higher concentration of Fe and S was observed and this was coincident with a lower concentration of P and N as well as of the anthropogenic metal elements at the same localities (see figure 4.13. and 4.14.). These slightly higher values for redox elements with lower P and N concentrations might be caused by the sampling in the field in which during sampling more deeper parts of the sediments were taken out from those localities. If the sand sediments are neglected a general slight increase of anthropogenic metal concentrations from Mönkebude to Kamminke can be seen except at localities 237320, 237250 and 237240. At these localities the concentrations were lower (see figure 4.13.).

The nutrient eutrophication elements showed the highest concentration in the central part of the lagoon at locality 237260. At the localities 237250, 237240 and 237270 the concentration of those elements were lower compared to the other localities except in the sand sediments which were the lowest (see figure 4.14.). The concentration of nutrient eutrophication elements were slightly higher in the samples near Mönkebude compared to the ones taken near the Kamminke area.



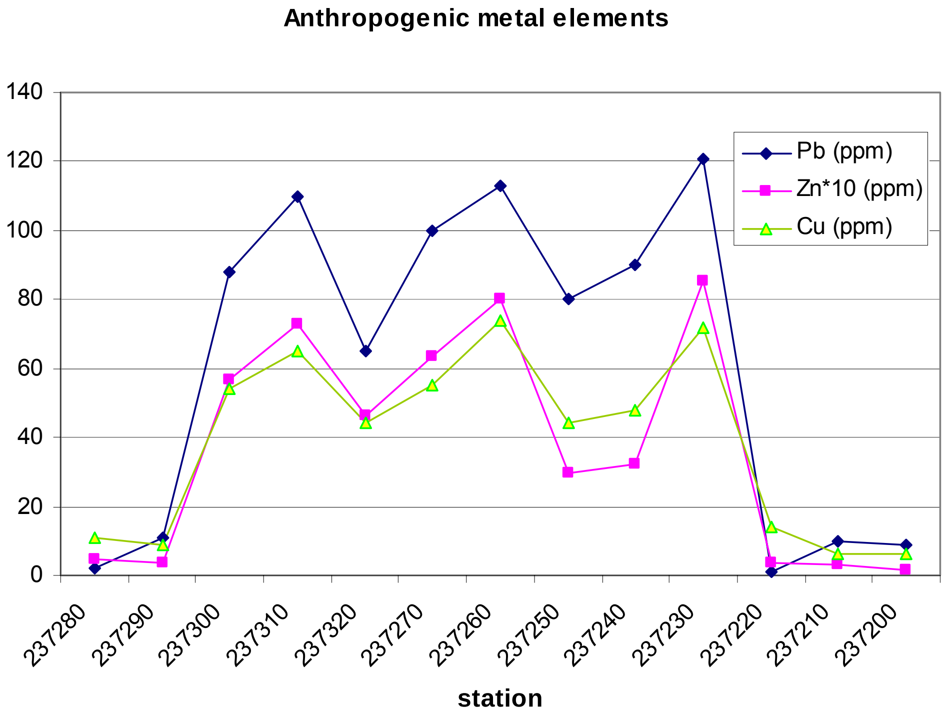
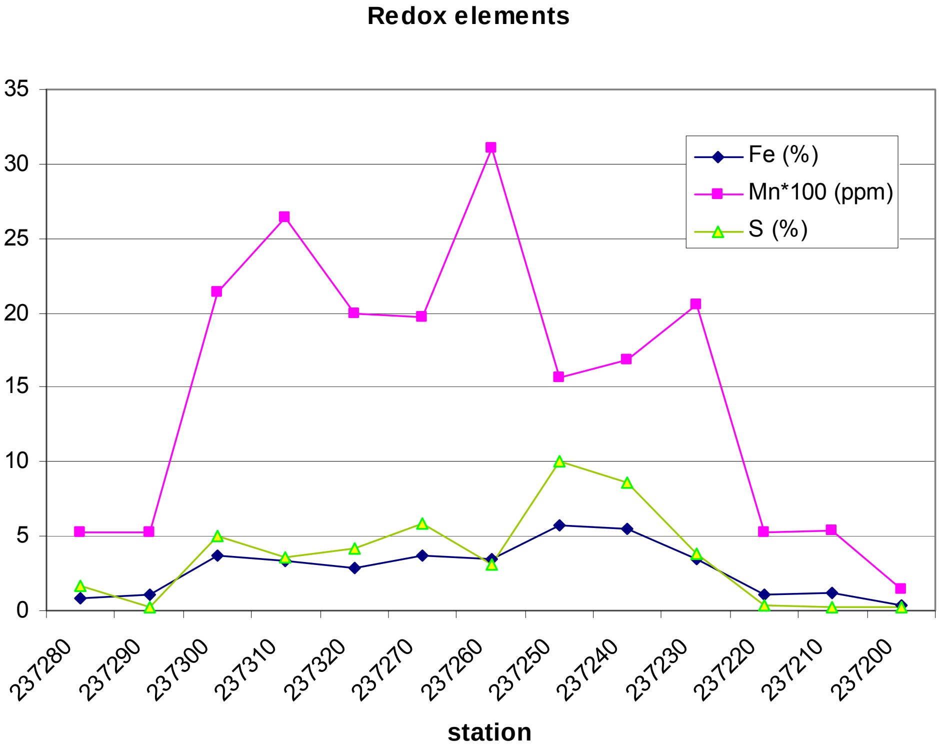


Figure 4.13. Geogenic and anthropogenic metal elements of the sediments of the Mönkebude - Kamminke section.



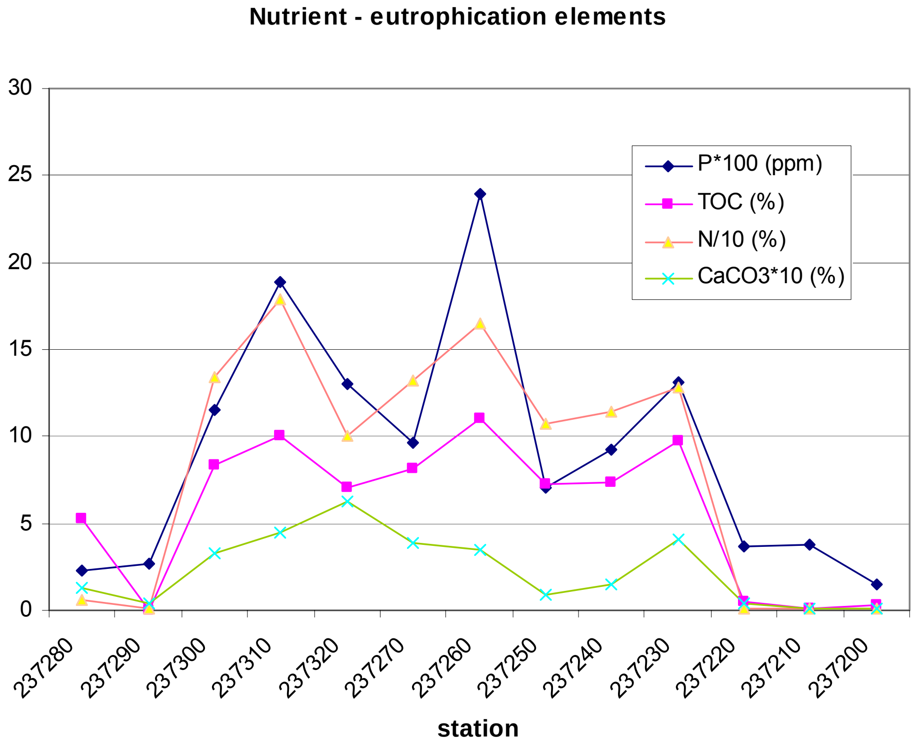


Figure 4.14. Redox and nutrient eutrophication elements of the sediments of the Mönkebude - Kamminke section.

4.3 Core sediment analyses

The longest sediment core which was the Altwarp sediment core (sample 236040, thickness 50 cm) was analysed in more detail compared to the other core samples. The analyses did not cover the water content and grain size only, but also the TOC/N ratio and the geochemical composition of the core at intervals of 5 cm.

The results revealed that there is a general increase of the geochemical element’s and heavy metal’s concentrations toward the deeper part of the core. The peaks were found at the depth between 40 and 50 cm (see figure 4.16. and appendix 8) except for Co, Cr and Mn which showed higher concentrations at 22.5 cm and Ca and K which showed higher concentrations in the first 5 cm of the core. The general trend of increasing concentration of those elements to the depth is related to the higher portion of fractions < 63 µm (clay to silt) (see the clay to silt fraction in figure 4.15. in relation to the figures in appendix 8 and the heavy metals concentration of Zn, Cu and Pb in figure 4.16.).

The average grain size and the sediment water content are increased toward the depth of the core (see figure 4.15.). The higher water content is related to higher clay to silt fractions (< 63 micrometer). Poorly sorted grains occurred at the bottom of the core which are coincident with the higher clay to silt fraction in the sediment. TOC/N ratios ranged between 5.9 and 21.6 and were mainly above 10 indicating the varying predominance of

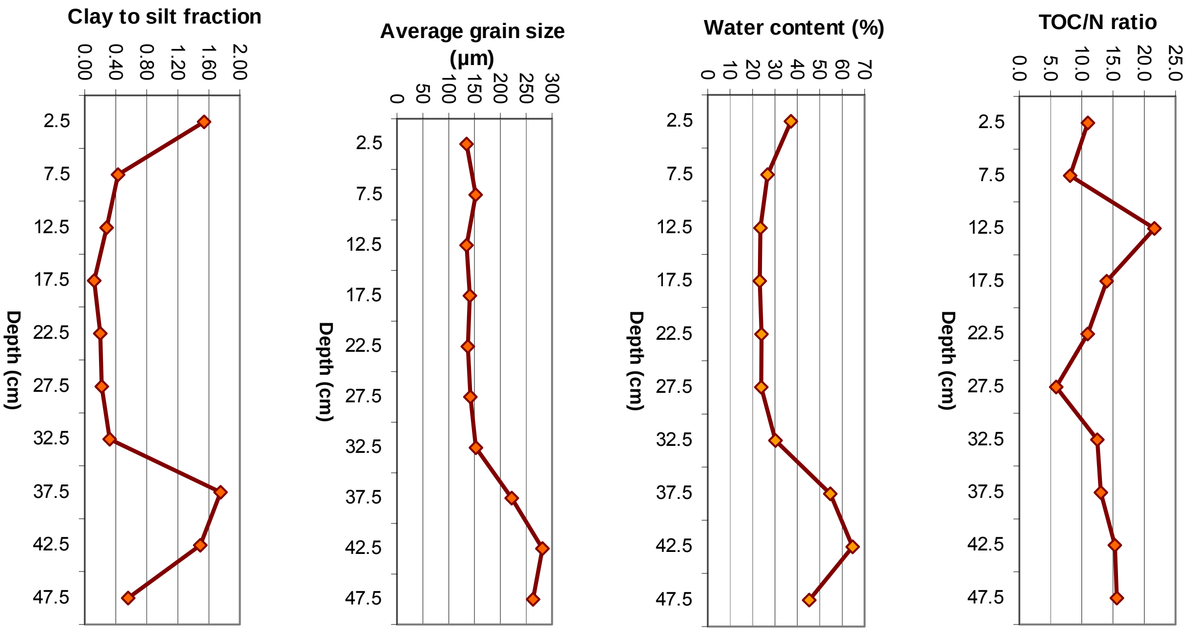


Figure 4.15. Clay to silt (< 63 µm) fraction, water content, average grain size and TOC/N ratio of the Altwarp core sediment 236040.

phytoplankton and terrestrial carbon sedimentation at the core site (see figure 4.15.). Carbon having originated from the phytoplankton was more dominant at the core depths 7.5 and 27.5 cm while at the other depths the terrestrial carbon was more dominant. Anthropogenic heavy metals are bound to the clay to silt fraction (see figure 4.15. the clay to silt fraction; Zn, Cu, Pb concentrations in figure 4.16. and the other elements such as Co, Ni, Zn, Cu, and Li in appendix 8). To assess the concentration profile of the anthropogenic heavy metals, the concentration of heavy metals Zn, Cu and Pb were normalised to Li. In this way the effect of higher concentrations of these metals in fine grain sizes of silt to clay was removed. Normally, the relation between those metals and Li is constant. The results of the normalisation showed a peak of the anthropogenic heavy metals Zn, Cu and Pb at the depth of 22.5 cm (see figure 4.16.).

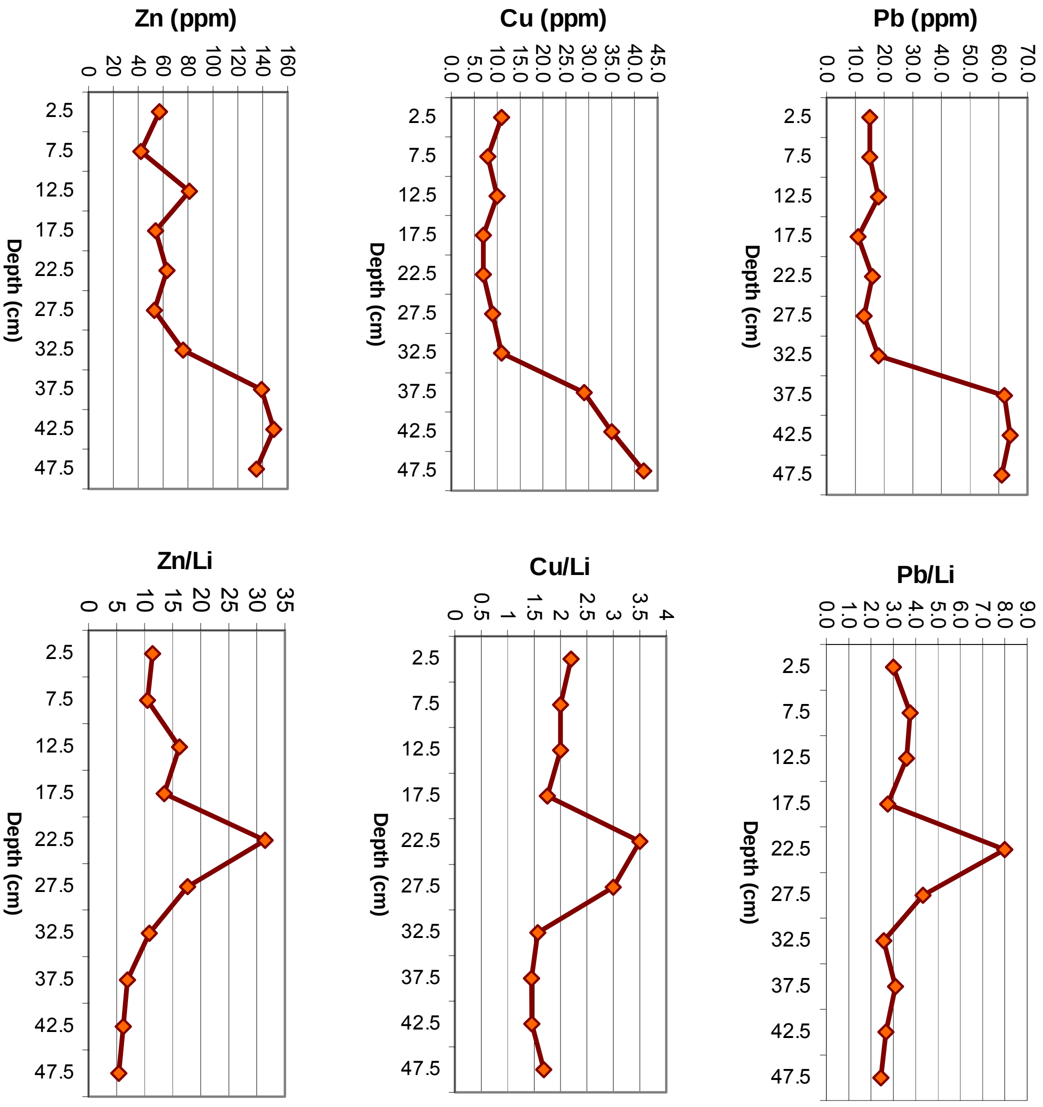


Figure 4.16. Zn, Cu, Pb in comparisons to Zn/Li, Cu/Li and Pb/Li of the Altwarp core sediment 236040.

4.4 Suspended particulate matter of the Oder Lagoon

The suspended particulate matter of the Oder Lagoon were analysed to determine their grain sizes, concentrations and compositions. Water samples for the analyses were taken from several localities in the western part of the lagoon (Kleines Haff). The results of the grain size analyses were used for the input of the Femflow2D model. The suspended particulate matter concentration were measured to know the amount of material in the water suspension both horizontally and vertically. The suspended particulate matter compositions were analysed to determine the material involved in the resuspension. The results of the analyses are described in the following sections.

4.4.1 Grain size

The grain size of Oder Lagoon suspended particulate matter was obtained by grain size analyses using the laser particle analyser GALAI CIS100. Two samples taken from the section of Mönkebude – Kamminke were selected, sample 237300 in the southern part and sample 237230 in the northern part (see figure 3.6. for localities). The results showed that grain sizes were dominated by silt with minor fractions of clay and very fine sand. The average grain size for sample 237300 was 29 µm (very fine silt) and for sample 237230 it was 37 µm (very fine silt).

4.4.2 Suspended particulate matter concentration

Water samples for suspended particulate matter concentration measurements were taken from several localities along Mönkebude - Kamminke in the western part of the lagoon (see figure 3.6. for localities). The samples were taken from about 0.5 meter depth and filtered by silicon microfibre filter. Filters were dried and weighed before analyses. The results of suspended particulate matter concentration measurements can be seen in appendix 5 and the graphic is presented in figure 4.17.

The suspended particulate matter concentrations along Mönkebude to Kamminke showed a range of values between 13.7 and 23 mgl/l with an average of 16.4 mgl/l (see figure 4.17.). The suspended particulate matter are composed of organic and inorganic components. Organic components appeared to be the main part of the suspended particulate matter of the Oder Lagoon at these localities, ranging from 73.4 % to 97.2 %. Inorganic components composed a smaller part ranging between 2.8 % and 26.6 %.

At locality 237240, in the central part of the lagoon, a vertical water sampling was done at depths of 1, 4 and 5 meters and the results are presented in figure 4.18. The suspended particulate matter value was ranging from 17 mg/l at 1 meter depth and slightly decreasing to 12 mg/l at 4.9 meter depth.

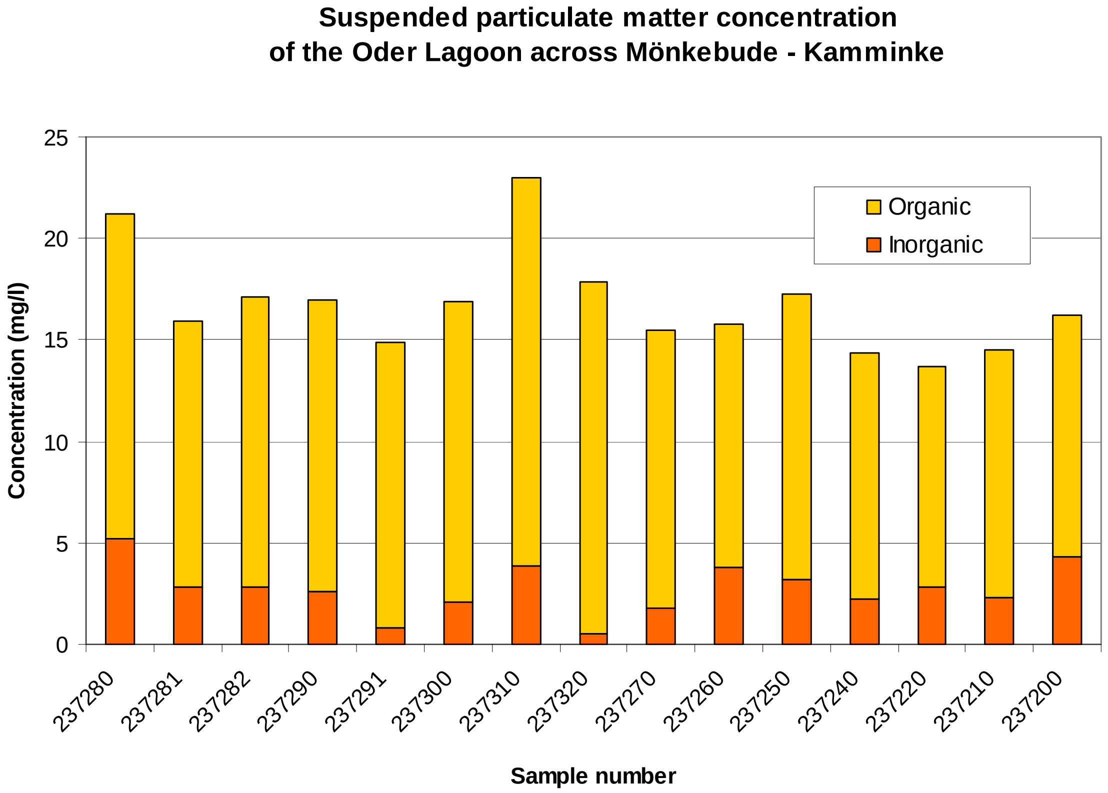


Figure 4.17. The Oder Lagoon suspended particulate matter concentration along the Mönkebude – Kamminke section.

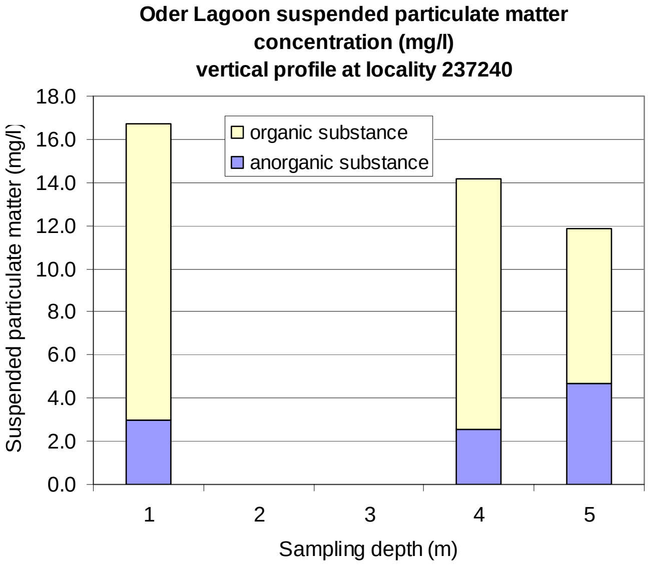


Figure 4.18. The Oder Lagoon suspended particulate matter concentration at locality 237240 (vertical profile).

4.4.3 Suspended particulate matter composition

To know the composition of the Oder Lagoon suspended particulate matter, several water samples were taken for the analyses. One water sample taken from locality 237240 (buoy H2) was subject to phytoplankton and biomass analyses. Three samples taken from the Mönkebude - Kamminke section (sample 237280 in the southern, sample 237240 in the central and sample 237200 in the northern sections) which represent three different localities were analysed by their elemental compositions to know the mineralogical composition.

The suspended particulate matter of the Oder Lagoon composed mainly of organic materials. The results of phytoplankton and biomass analyses showed that not less than 25 species of phytoplankton were detected from the sample. They belong to four classes and according to abundances were as follows: Cyanophyceae, Chlorophyceae, Diaptomophyceae, and Cryptophyceae. The five most abundant phytoplankton species were: *Planktothrix sp.*, *Anabaena sp.*, *Mycrosistis sp.*, *Anabaenopsis sp.* and *Pseudanabaena / Limnothrix sp.* The dominance of organic components of the Oder Lagoon suspended particulate matter is displayed in figures 4.19. and 4.20. The first one was taken by the SEM and the latter one by an inverted microscope.

Figure 4.19. Inverted microscope picture showing the dominance of organic components within the Oder Lagoon suspended particulate matter.

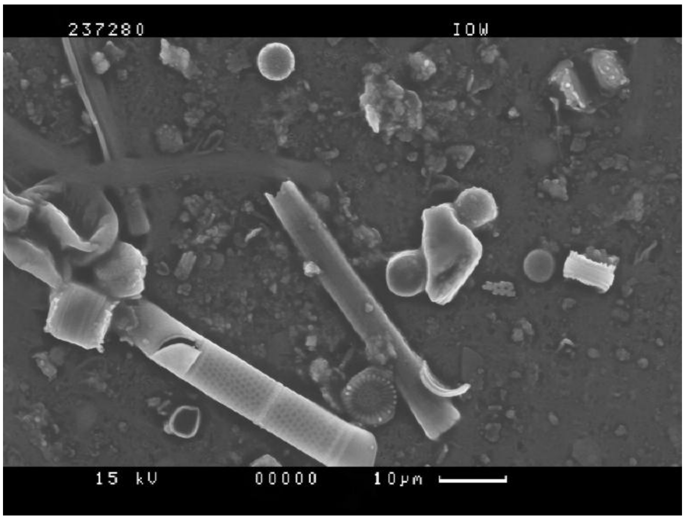


Figure 4.20. Scanning electron microscope picture showing mainly organic components of the Oder Lagoon suspended particulate matter (sample 237280).

The results of the Oder Lagoon suspended particulate matter analyses using SEM – EDX showed that Biogenic Opal was the dominant mineral in the water column (see figure 4.21.). It made up 43.9%, 46 % and 44.9% in the southern (237280), central (237240) and northern (237200) stations respectively without significant differences between the stations. Quartz was more abundant at the northern and the southern stations with 23.5% and 20.1% respectively. In the central station Quartz composed only 8.2%. The sum of the clay minerals which included Chlorite, Kaolinite (see figure 4.21.),

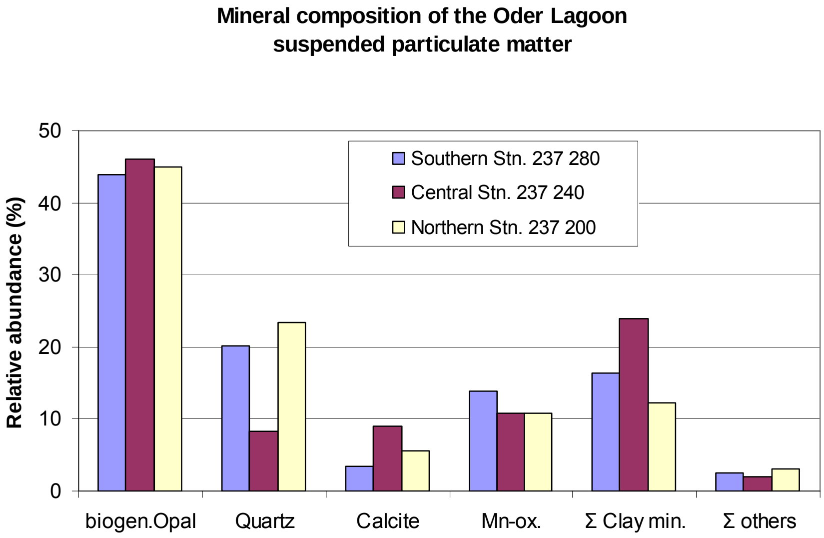


Figure 4.21. Mineralogical composition of the Oder Lagoon suspended particulate matter.

Illite, Illite-Mixed Layer (ML) and Smectite was the highest at the central station with 23.9% compared to the southern and northern stations with 16.2% and 12.2% respectively. Other minerals which covered Ti minerals, Fe-oxide and K-Feldspar were found at the southern, central and northern stations with 2.5%, 2.1% and 3.1% respectively.

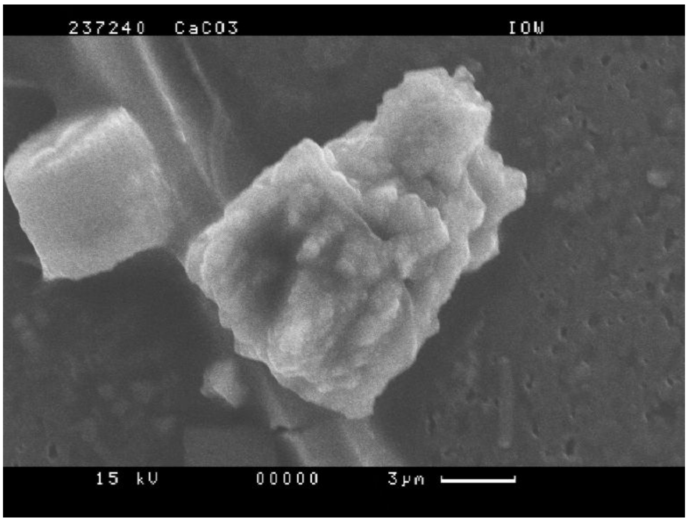


Figure 4.22. Scanning electron microscope picture showing Calcite particles in the Oder Lagoon suspended particulate matter (sample 237240).

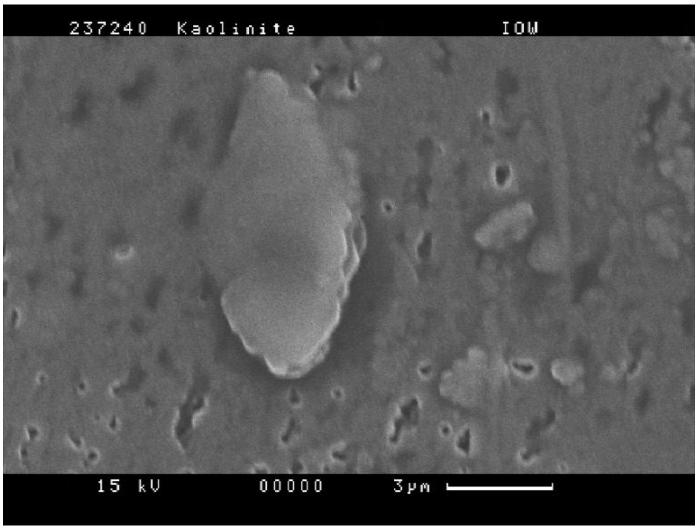


Figure 4.23. Scanning electron microscope picture showing Kaolinite particle in the Oder Lagoon suspended particulate matter (sample 237240).

Close to the sediment water interface, fluffy layer material was sampled and its mineral composition was analysed. The sample was taken from the central Oder Lagoon (sample 236160) which was the same locality as sample 237240. The result of the analyses can be seen in figure 4.24. The sum of clay minerals was dominant in the fluffy layer material (71.5%). The sum of other minerals of 13.1% is composed of biogenic Opal (2.3%), Quartz (2.3%) and Calcite (0.8%). Mn-oxide minerals appeared to be absent in this sample.

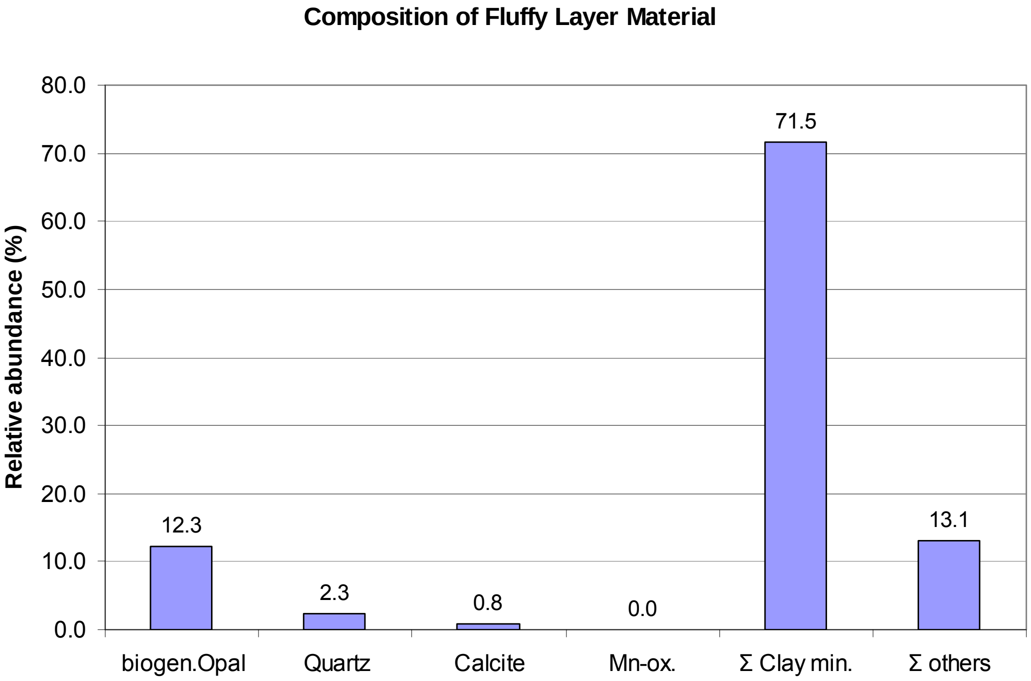


Figure 4.24. Mineralogical composition of the Oder Lagoon fluffy layer material.

Scanning electron microscopy pictures of the Oder Lagoon minerals can be seen in figure 4.22. and 4.23. as well as in appendix 6-A, 6-B and 6-C. The minerals in figures 4.22. and 4.23. were Calcite and Kaolinite found at locality 237240.

4.5 Flow in the Oder Lagoon

The flow module of the Femflow2D hydrodynamic and transport model was applied to study the flow or hydrodynamic conditions of the Oder Lagoon. Furthermore, the flow simulation results were an important basis for the calculation in the suspended particulate matter module.

The input data for model simulations were obtained from field measurements and by calibration during simulations (calibration parameters). To obtain reliable flow model calculations, flow simulation results were compared with the field measurements (validation). The values of input parameters applied in the validation provide a reliable basis for further investigations on the hydrodynamic conditions in the lagoon for example under eight different wind directions and strong wind events.

4.5.1 Flow validation

To compare the simulation with the field measurements, the simulation for 14 August 2001 was chosen. Data of wind speed and direction were taken from the GKSS Oder Buoy ODE-03 (http://meteo.gkss.de/sgdaten.html). The input data of the wind speed and direction used for 14 August 2001 simulation were 4.5 m/s and 237°. A constant wind in the lagoon was applied in the simulations (see figure 4.25.). The simulation result showed that the flow directions fit with the measurements but the flow speed in the lagoon was about 1/10 times lower compared with the measurements. The investigations revealed that if the coastline depth was increased by 10 times from 0.05 to 0.5 meter, the resulting flow field in the lagoon becomes similar to the field measurements. Therefore the 0.5 meter coastline depth needs to be used in the simulations. A good agreement between computer simulation and field measurements except the area closer to the shoreline at the southern part of the lagoon was achieved (see figure 4.26.).

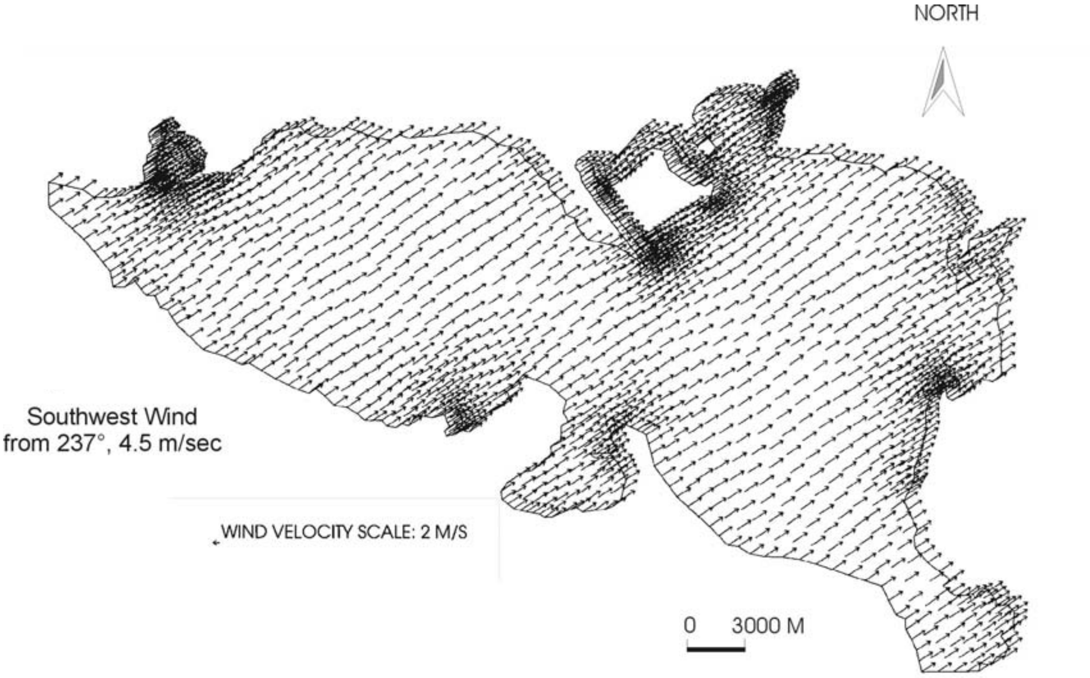


Figure. 4.25. Constant wind field used in the 14 August 2001 simulation.

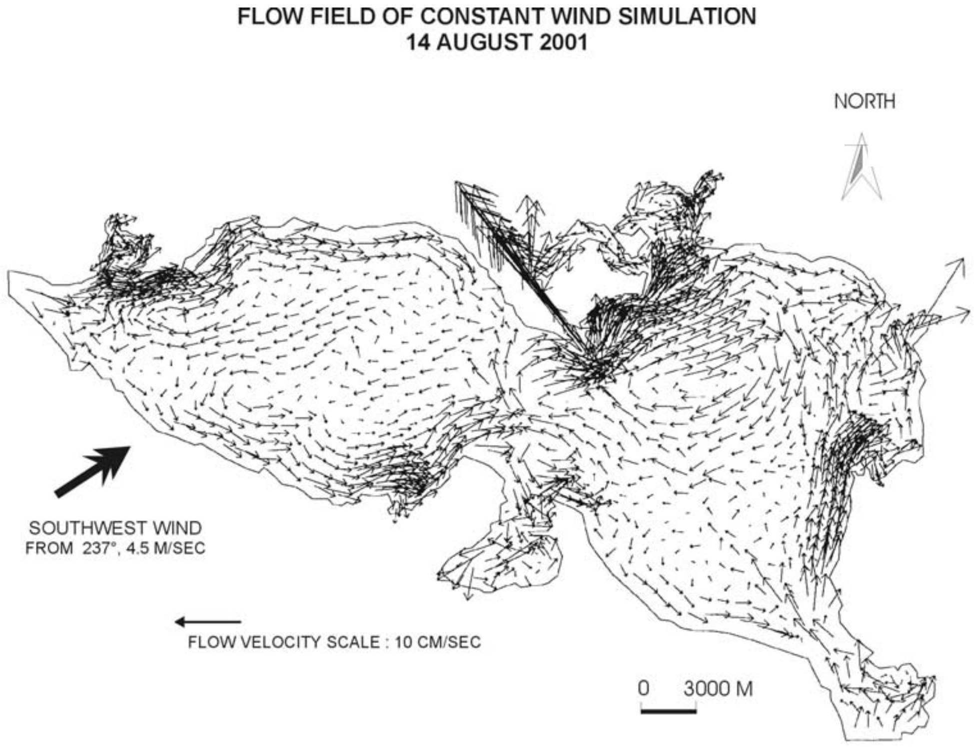


Figure 4.26. Flow field in the Oder Lagoon in 14 August 2001 using constant wind field.

Another simulation was done using the same input parameter values as used in the constant wind simulation but with a different wind field. A spatially variable wind speed was applied in this simulation in which the assumption of zero wind speed at the coastline was made. This assumption was considered because there might be sheltering effects along the coastline due to the topography, buildings and vegetation adjacent to the shoreline, as well as the reeds that grow along the immediate offshores. Because the wind was from south-west, the sheltering effect was occurring at the southern part of the lagoon coastline. The wind direction was kept constant and the wind speed was increasing off the coast (see figure 4.27.). As the spatially variable wind speed was applied, the flow adjacent to the southern lagoon coastline turned to the opposite directions and matched with the measurements conducted offshore Mönkebude (see figure 4.28.). The comparison between flow measurements and simulation results using the spatially variable wind can be seen in figure 4.29.

Flow simulations in the lagoon under constant winds resulted in general eastward flows along the shallower parts of the lagoon at the north and south coastlines. In the deeper parts the general flow is to the west. Using spatially variable wind, the simulation result showed the flow along the southern part of the lagoon going to the opposite directions. The flow directions were in a good agreement with the measurements conducted in that area, near the reed zones (see figure 4.29.) except that the flow speed was lower. The locality of flow

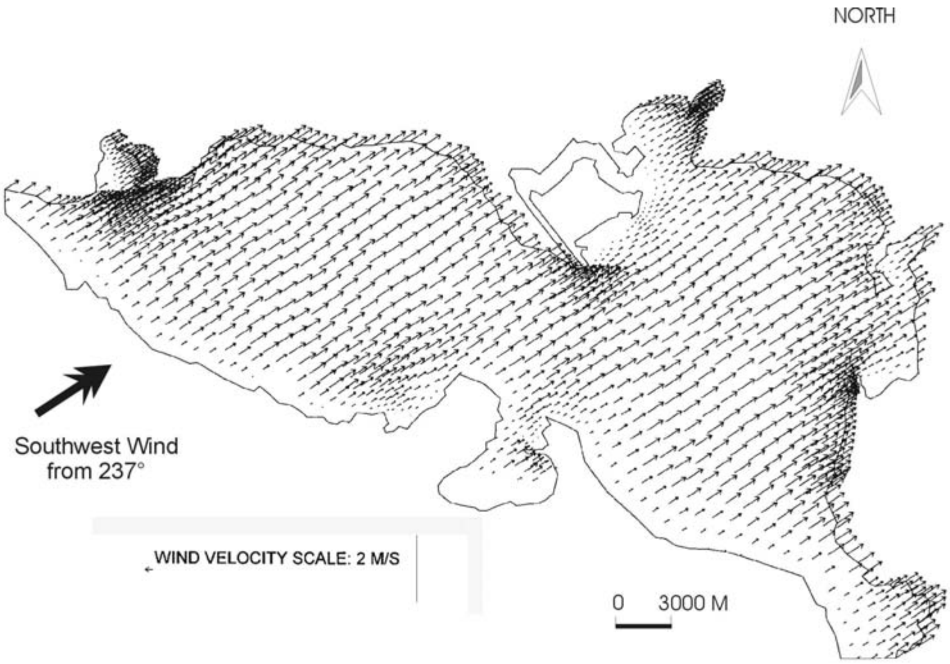


Figure 4.27. Spatially variable wind field used in the 14 August 2001 simulation.

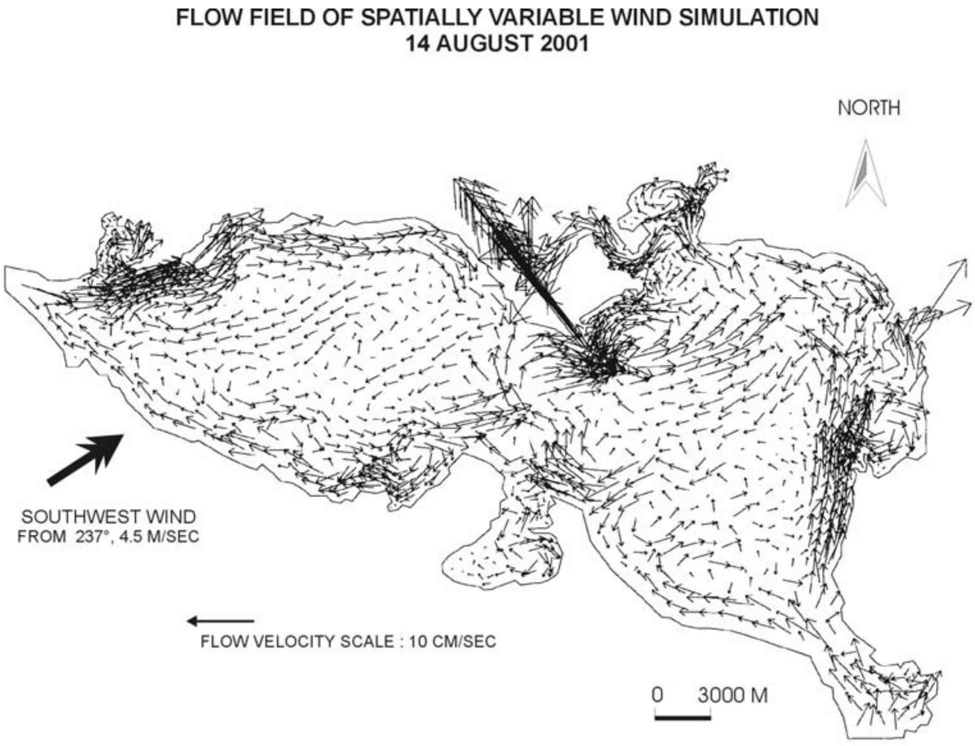


Figure 4.28. Flow field in Oder Lagoon in 14 August 2001 using spatially variable wind field.

measurement at S2 is the same as at S6 and so for S3 and S7 (see figure 4.29.). The differences were the time of measurements. S2 was measured at 11:30, S3 at 12:40 while S4, S5 and S6 were measured beginning at 17:10 and S7 at 17:50. At locality G3W and G3E, the flows were measured with current meter ISM-2000.

The validation of flow in the lagoon achieved from the simulation provides a reliable basis for further flow simulations to explore the general flow pattern in the lagoon under eight different wind directions and during strong wind events.

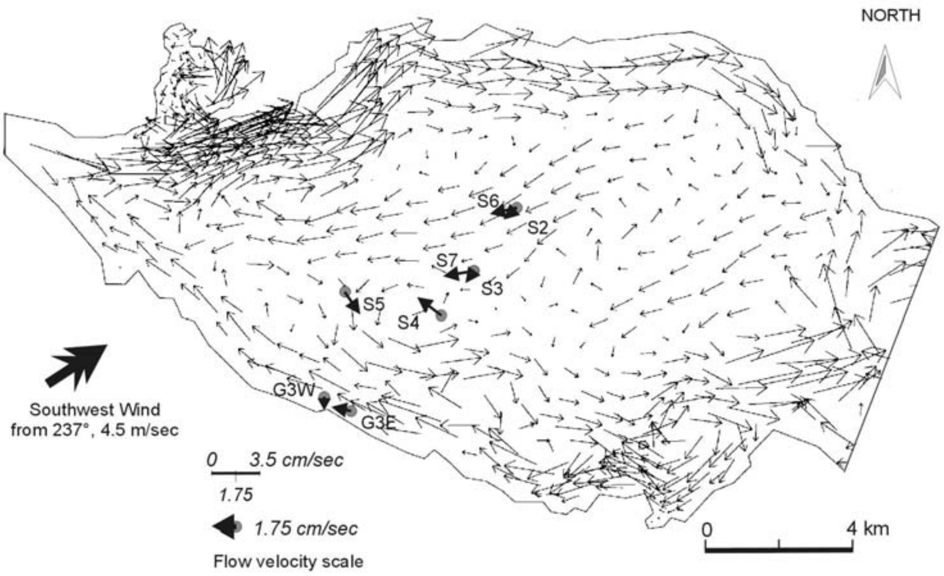


Figure 4.29. Comparison between flow measurements and simulation on 14 August 2001.

4.5.2 Flow patterns in the Oder Lagoon under eight different wind directions

In order to know the flow field in the lagoon under different wind conditions, eight flow simulations were done. The simulations covered the wind from the north, north-east, east, south-east, south, south-west, west and north-west directions. The input parameter values used were the same with the one that had been used in the flow validation except the wind directions. The constant wind speed of 4 m/s was applied. This is the average wind speed for the period of 1991 - 2000.

The results of south, south-west, and west winds which cover 60.38 % frequencies can be seen in figure 4.30. and the other wind directions are presented in the figures 4.31. and 4.32. It can be seen that the wind direction has a major impact on the flow field in the lagoon. Each wind direction had its own flow characteristics. The flow pattern in the lagoon as the result of eight wind directions, can be classified into four major flow patterns. The four major patterns can be described as follows:

1. East and west wind:

The flow pattern under an east wind direction was characterised by coastal jet flows to the west along the major part of the southern and northern coastlines particularly within the western part of the lagoon. Strong backflows can be observed in the central part of the western lagoon. Inflow from Dziwna to the lagoon was occurring and the outflows were via Swina and Peene. Several eddies can be seen particularly in the western part of the lagoon. In the central part of the shipping channel flows to the southeast direction were occurring. Under west wind direction, very similar flow patterns can be observed in the major part of the lagoon except that the flows were to the opposite directions. Under this wind direction, more eddies at the south-eastern part of the lagoon were developed. The outflow was via Dziwna and the inflow to the lagoon was from the Peene.

2. North and south wind:

The flow patterns under north and south wind directions exhibit relatively weaker flows in the central part of the western lagoon. At this locality many eddies of large and small scales developed under both wind directions particularly in the western part of the lagoon. Small eddies can also be observed at the mouth of the Oder river, Peene and Dziwna while large eddies can be observed in the north-eastern part of the lagoon. Coastal jet flows occurred in the western and eastern coastlines. In the central part of the shipping channel, south-east flows were occurring under south wind direction while the north wind direction resulted in the north-west flows at this locality.

3. North-east and south-west wind:

The flow pattern under south-west and north-east wind directions shows relatively stronger flows at the coastlines approximately parallel to the wind direction. This was particularly obvious in the north-western and south-eastern part of both the western and eastern part of the lagoon. Several eddies can be seen particularly in the south-western part of the eastern lagoon. Similar to the flow pattern under south and north wind directions, large eddies were occurring in the north-eastern part of the lagoon. The outflow direction was similar to the flows under east and west winds in which under the south-west wind the outflow was via Dziwna and under the north-east wind the outflow was via Peene. No distinctly directed flows along the channel can be observed under both wind directions.

4. North-west and south-east wind:

The flow pattern under north-west and south-east wind showed relatively stronger flows at shallow depth localities and the areas which are approximately parallel to the wind direction. These stronger flows were particularly obvious along the southern, northern and

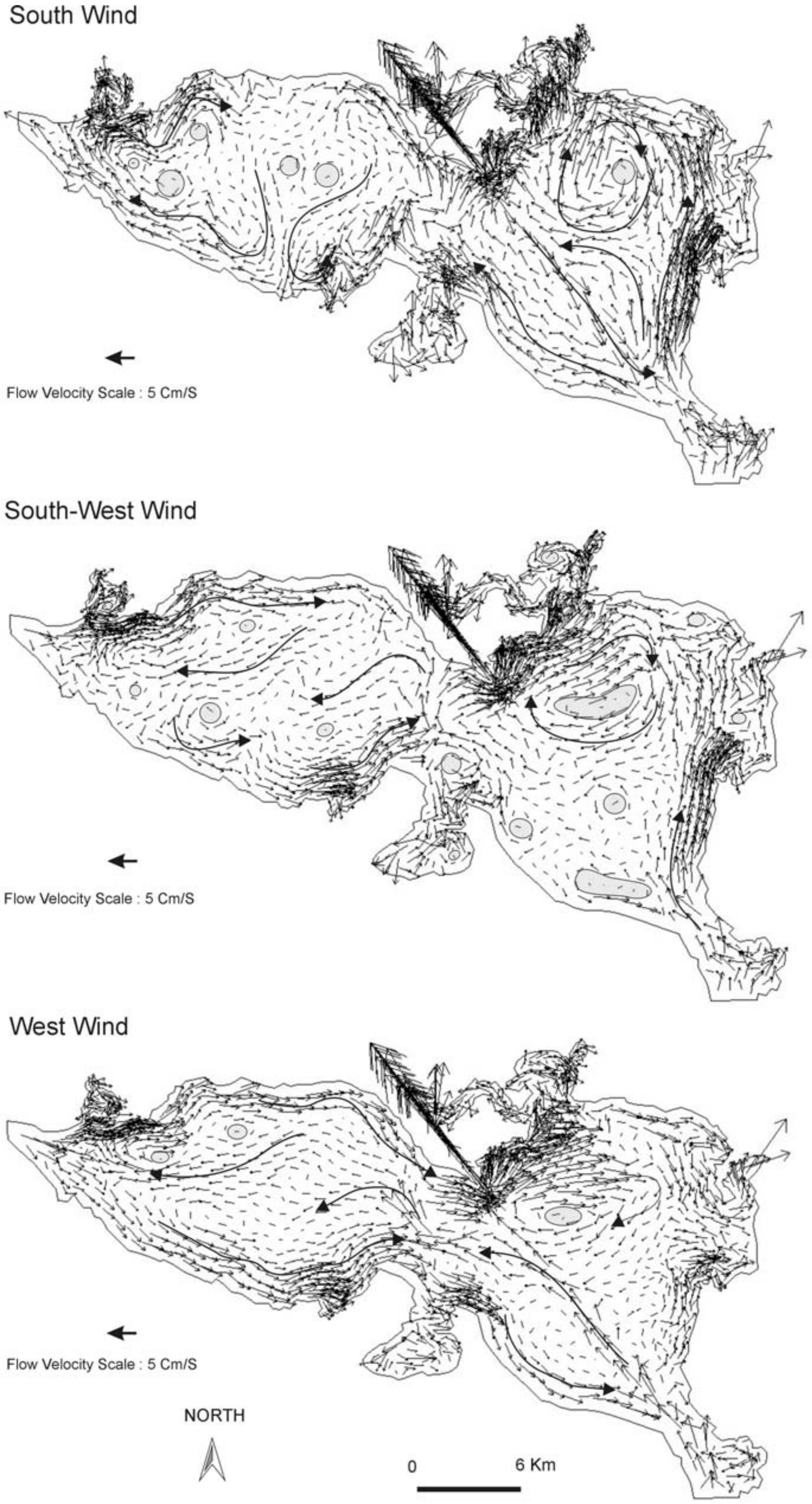


Figure 4.30. Flow pattern in Oder Lagoon under three most frequent wind directions: the south, south-west and west wind directions. Large eddies are indicated by the shadows and strong flows are highlighted in bold.

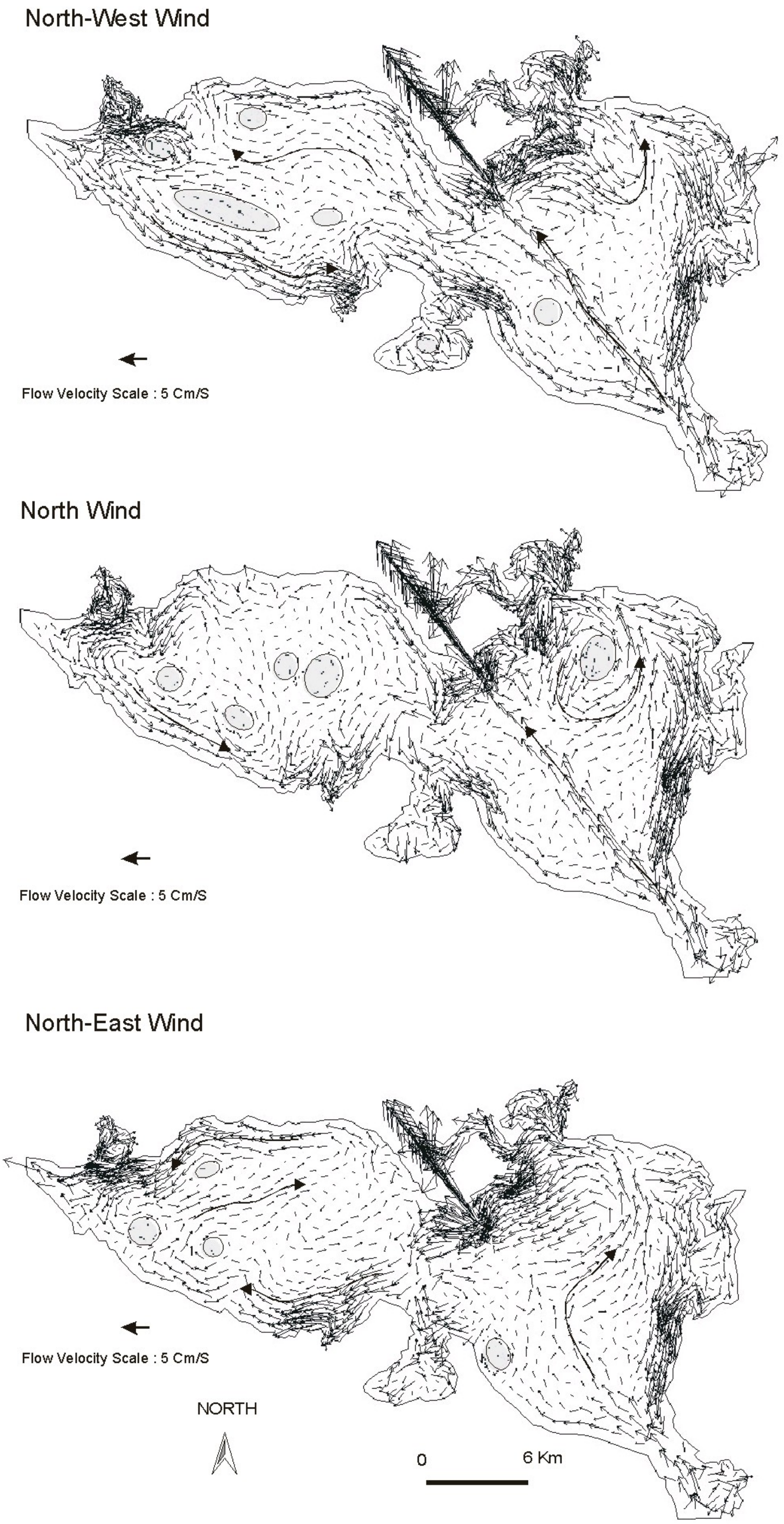
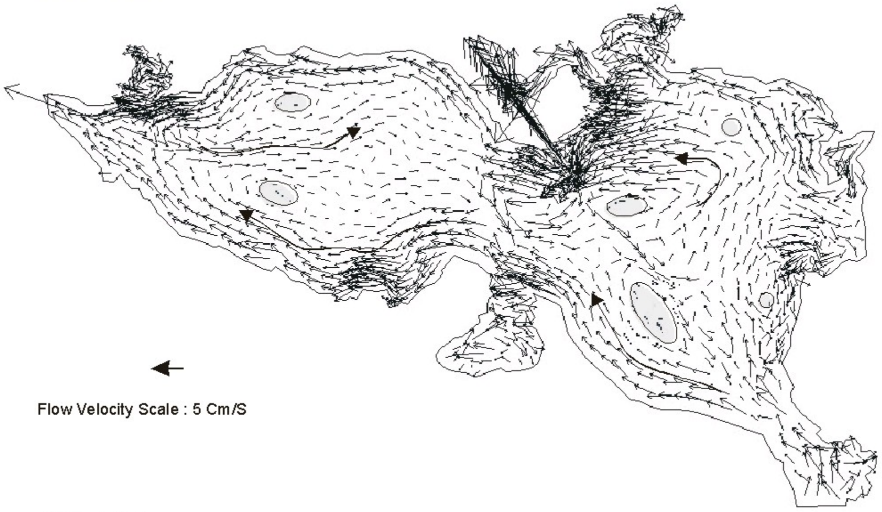


Figure 4.31. Flow pattern in Oder Lagoon under the north-west, north and north-east wind directions. Large eddies are indicated by the shadows and strong flows are highlighted in bold.

East Wind



South-East Wind

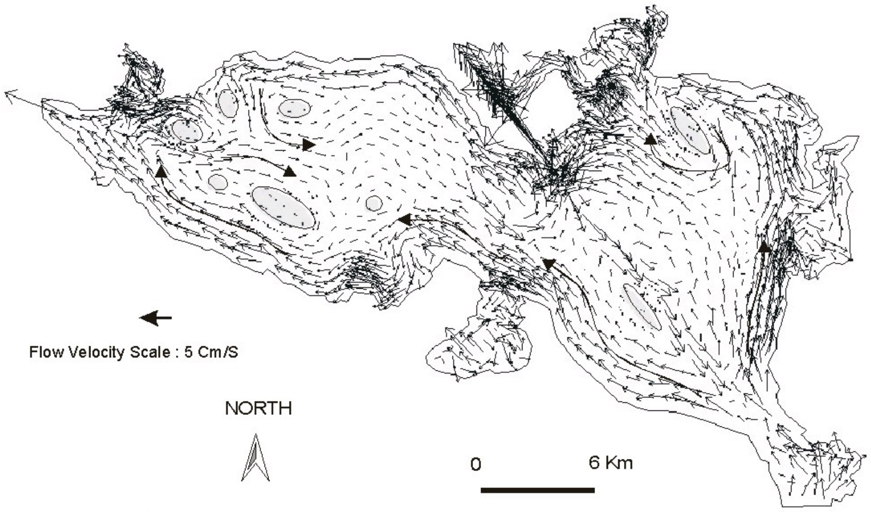


Figure 4.32. Flow pattern in Oder Lagoon under east and south-east wind directions. Large eddies are indicated by the shadows and the strong flows are highlighted in bold.

eastern part of the lagoon as well as along the shipping channel. Several eddies were developed in the deeper part of the western and eastern lagoon.

The results of flow simulation in the lagoon under eight wind directions showed that the north-west and south-east winds are the winds causing relatively stronger flows along the coastlines throughout the lagoon. More eddies are developing particularly during the north and south wind directions. Eddies are more commonly occurring in the western part compared to the eastern part of the lagoon under these eight wind directions.

4.5.3 Flow patterns in the Oder Lagoon under strong wind events

The flow patterns in the Oder Lagoon under strong wind events were investigated by conducting simulations using strong wind speed. All input parameter values used in the flow validation were used. West, south-west and east wind directions were chosen and a constant wind speed of 10 m/s was applied. The results of the simulations showed that the major flow pattern remained similar except the flow speed and directions. It can be observed that in many parts of the lagoon the flow speed under 10 m/s wind speed are about 2.5 times higher compared to the 4 m/s wind speed (see figure 4.33.).

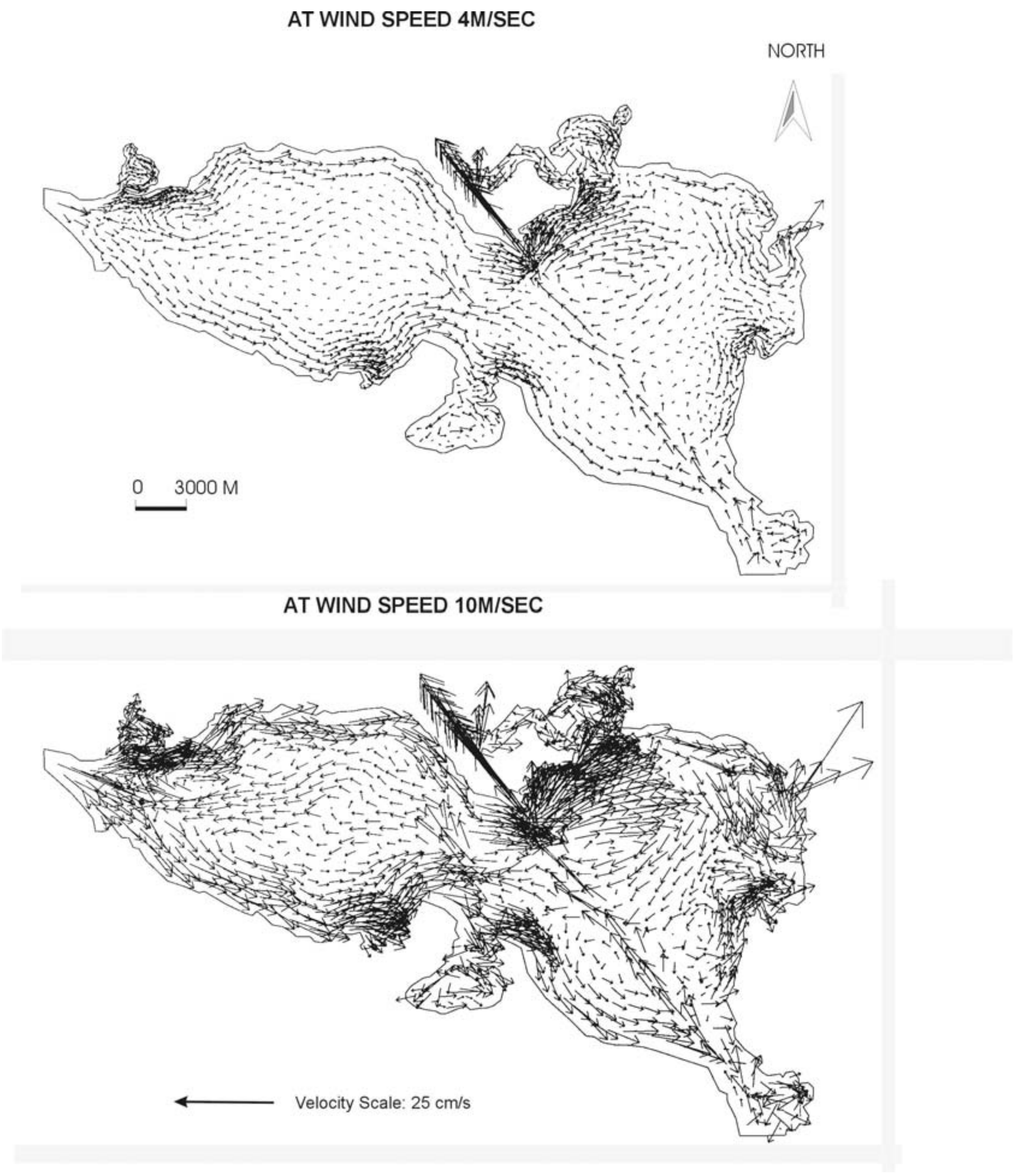


Figure 4.33. Comparison between average and strong wind speed of 10 m/s for west wind situation.

4.5.4 Water mass exchange between the Kleines Haff (Maly Zalew) and the Wielki Zalew (Grosses Haff)

The flow module of the Femflow2D model was used to study the water mass exchange under eight wind directions between two main parts of the lagoon, the Kleines Haff (Maly Zalew) and the Wielki Zalew (Grosses Haff). The study involved two conditions, under natural and under the artificial conditions. Under artificial a kind of blocking construction such as wooden piles were installed to reduce the water mass exchange rate between the Kleines Haff and the Wielki Zalew. Under artificial conditions, the nutrient input into the Kleines Haff could be reduced and further ecological studies can be conducted based on the calculation results.

A cross section between Kleines Haff and Wielki Zalew was drawn between triangular nodes number 765 and 960 (see figure 4.34.). The results of the flow simulation under eight wind directions, that have been conducted previously, were used in the discharge calculations at the cross section. The total cross sectional area was calculated based on the depth information and the distance of each node along the section. At the beginning, the area of the cross section was calculated at each node along the section. The total cross sectional area is the sum of the area of each node. There are 14 nodes altogether along the section involved in the calculations (nodes 765, 766, 767, 736, 737, 770, 803, 832, 857, 877, 902, 930, 961 and 960, see figure 4.34.). The cross sectional area was calculated by multiplying the depth of the node and the half distance between the nodes. For nodes 765 and 960 which occur at the coastline, the calculation started at these nodes to the following nodes. To reduce the complication in the calculations, a straight line between node 737 and 803 was drawn and taken into account in the calculations instead of along those nodes. The depth of these nodes used in calculations were the depth weight of nodes 770 and 771 as well as nodes 803 and 804. The same is true for the flow velocity at these nodes used in the calculations.

In order to calculate the discharge, flow velocities at each node along the cross section were obtained from the flow simulations. In the calculations, the value of the flow that is perpendicular to the cross section was used. The discharge is equal to the cross section of the area times the flow velocity at each node. The flows depending on the prevailing winds in the lagoon as were described in chapter 4.5. Therefore, the calculations were repeated eight times for all eight wind directions. Hence the water mass transport conditions under eight wind directions were obtained. The results of the discharge calculations along the section dividing the Kleines Haff and the Wielki Zalew are presented in table 4.3. (under natural conditions). The water mass exchange rate was calculated by summing up the amount of the discharge into the Kleines Haff (see B in table 4.3. and 4.4.) and the discharge into the Wielki Zalew (see A in table 4.3. and 4.4.). The theoretical water mass exchange time of the Kleines Haff can be calculated by diving the volume of the Kleines Haff which is 1026 km^3 (V) (Buckmann et al. 1998) by half of the sum of the discharge into the Kleines Haff, from the Kleines Haff and Peene (V/((A +B +C)/2)).

The result showed that the total area of the cross section was 21101 m^2. The discharge calculations revealed that the water mass exchange rate occurs most effectively under west wind direction (744 m^3/s) and least effectively under north-east wind direction (327 m^3/s). The average water mass exchange can be calculated by taking into account the wind frequency prevailing in the lagoon (see chapter 4.1). If the daily average wind frequency was used (see figure 4.1.), the average water mass exchange rate between the Kleines Haff and the Wielki Zalew was 506 m^3/s. This is equal to about 140% of the Oder river discharge which is 359 m^3/s that is used in the calculation. The results of the theoretical water mass exchange time for eight wind directions can be seen in table 4.3. In average the theoretical water mass exchange time of the Kleines Haff is 43 days.

Table. 4.3. Water mass exchange between Kleines Haff and Wielki Zalew as well as at Peene and Dziwna under natural conditions at eight wind directions.

Wind Direction	**Peene* (m^3/s) (C)**	**Dziwna* (m^3/s)**	**Flows from the Kleines Haff to the Wielki Zalew (m^3/s) (A)**	**Flows from the Wielki Zalew to the Kleines Haff (m^3/s) (B)**	**Error (%)**	**Water mass exchange rate (m^3/s)**	**Theoretical water exchange time (days)**
North	+ 11.5	+ 7.9	189	237	24	426	54
North-east	- 57.2	+ 29	123	205	17	327	62
East	- 83.1	+ 29.5	312	384	4	696	30
South-east	- 75.4	+ 11.1	287	407	13	694	31
South	- 33.7	- 20.9	156	214	14	370	59
South-west	+ 39.3	- 39.4	181	183	19	363	59
West	+ 69.2	- 40.6	365	380	19	744	29
North-west	+ 61	- 23.9	362	298	0.96	660	33

* Note: At Peene and Dziwna, plus indicate the water mass transport flowing into the lagoon and minus means leaving the lagoon.

In order to assess what is the effect of artificial installed along the cross section aimed at reducing the water mass exchange between these two main parts of the lagoon, another calculations at the same cross section were conducted. Bathymetry editor in the

Femflow2D model that was newly added during this study was used. The artificial were installed at the northern and southern parts of the section (see figure 4.34., bold lines), leaving only the middle and the deepest part of the section as before. At the localities of artificial , the depth were set to the same value as the depth of the lagoon coastline. In general the flow velocities near the artificial areas were reduced. An example of the flow velocity contours under natural and artificial conditions at south-west wind situation can be seen in figure 4.35. The figures are showing the flow conditions in the southern part of the cross section.

Table. 4.4. Water mass exchange between Kleines Haff and Wielki Zalew as well as at Peene and Dziwna under artificial conditions at eight wind directions.

Wind Direction	**Peene* (m^3/s) (C)**	**Dziwna * (m^3/s)**	**Flows from the Kleines Haff to the Wielki Zalew (m^3/s) (A)**	**Flows from the Wielki Zalew to the Kleines Haff (m^3/s) (B)**	**Error (%)**	**Water mass exchange rate (m^3/s)**	**Theoretical water exchange time (days)**
North	+ 8.9	+ 6.9	74	157	56	230	99
North-east	- 58.2	+ 29.3	36	71	66	107	144
East	- 84.8	+ 30.2	156	136	68	291	74
South-east	- 77.4	+ 12.2	164	146	59	310	61
South	- 35.2	- 20.2	49	76	45	126	148
South-west	+ 40.7	- 39.7	58	104	60	162	117
West	+ 71.1	- 39.6	127	218	56	346	42
North-west	+ 63.5	- 25	138	247	56	385	53

* Note: At Peene and Dziwna, plus indicate the water mass transport flowing into the lagoon and minus means leaving the lagoon.

It appeared that the total cross sectional area after the instalation equaled to 9889 m^2. This means the area reduction of 53%. Eight flow simulations were done to know the flow conditions under artificial at eight different wind directions. The result of the discharge calculations under the artificial and at eight wind directions can be seen in table 4.4. (see under artificial conditions).

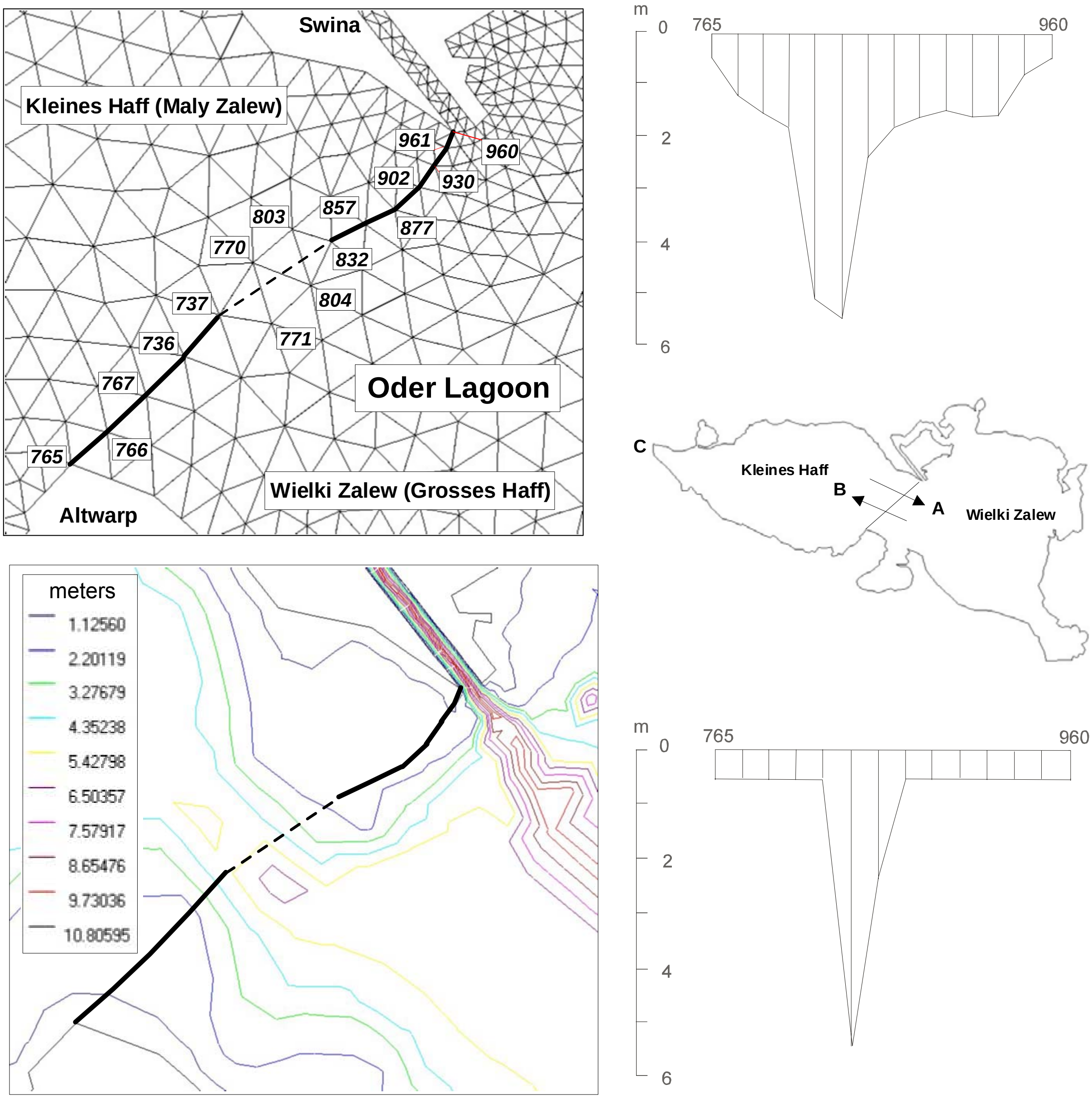


Figure 4.34. Cross section and bathymetry for the water mass exchange calculations between the Kleines Haff (Maly Zalew) and the Wielki Zalew (Grosses Haff). Bold lines indicate the blocked sections. Figures on the right show a sketch of the cross sections under natural conditions (top) and artificial conditions (bottom) (distances between nodes 765 and 960 are not to scale). The symbols used for water mass exchange calculations used in table 4.4. and 4.5 are drawn in the middle picture of the right figure.

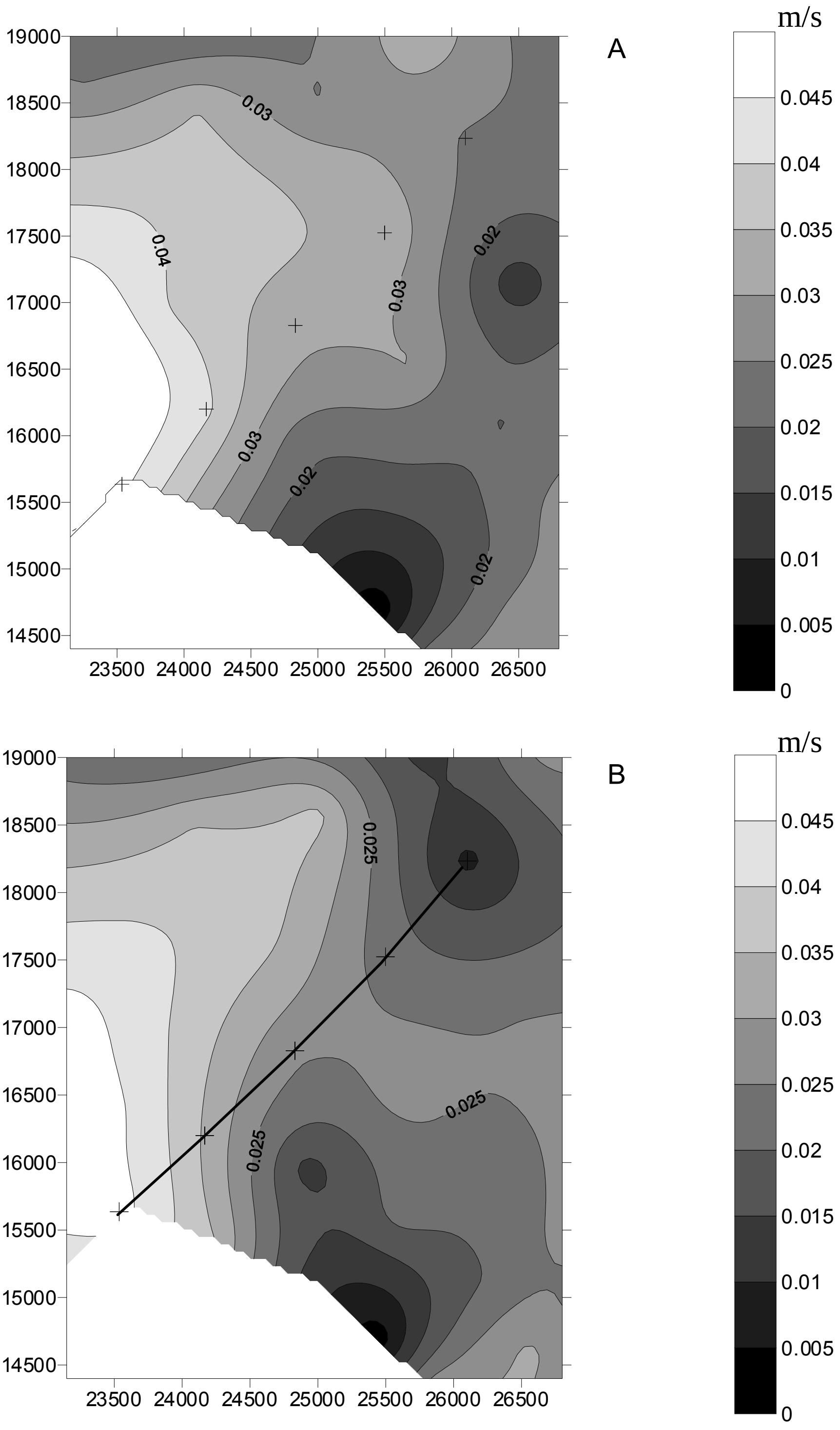


Figure 4.35. Flow velocity contours at normal (A) and artificial (B) conditions in the southern part of the cross section at south-west wind situation.

In the discharge calculations the error occurred. The error depended on the wind directions. Under natural conditions error of 0.96% to 24% (an average error of 14%) were found whereas under artificial conditions much larger error between 45% and 68% (an average error of 58%) occurred. In all flow simulations, the flow from the Oder river into the lagoon as well as the flow leaving the lagoon via Swina were set as the fixed x-flows. The outflow via Peene and Dziwna were set as the open boundaries. Based on the flow simulation results and the discharge calculations, the amount of water mass flowing from the Oder river into the lagoon was 359 m^3/s and the water mass leaving the lagoon via Swina was 216 m^3/s. The results of the discharge calculations at eight different wind directions (see table 4.3. and 4.4.) were recalculated taking into account the wind frequency analyses (see chapter 4.1). The discharge were weight averaged with the daily average wind frequency in the lagoon (see figure 4.1.). Based on this result, the net water mass transport at Peene and Dziwna could be calculated. The results of the calculations showed that on average the water mass leaves the lagoon via Peene at an amount of 68 m^3/s and an amount water of 48 m^3/s leaves the lagoon via Dziwna. These values are equal to 19% (at Peene) and 13% (at Dziwna) of the Oder river discharge into the lagoon. If the net transport via Swina and Peene are 19% and 13% then the transport to the Baltic Sea via Swina is 68% of the Oder river discharge.

Similar to the normal conditions, under artificial conditions the water mass exchange occurs most effectively under west wind direction (346 m^3/s) and least effectively under north-east wind direction (107 m^3/s). If the daily average wind frequency in the lagoon (see chapter 4.1 and figure 4.1.) were taken into account in the calculations, the average water mass exchange rate between the Kleines Haff and the Wielki Zalew under artificial conditions is 223 m^3/s. This means the reduction of 56% as compared to the natural conditions. The theoretical water mass exchange time of the Kleines Haff under this conditions are presented in table 4.4. In average, the theoretical water mass exchange time of the Kleines Haff is 81 days. This means the water mass exchange time under the artificial conditions was about two times longer than the water mass exchange time under natural conditions.

4.6 Suspended particulate matter dynamics in the Oder Lagoon

The suspended particulate matter module of the Femflow2D is a newly developed module and had not been applied before. In this study this module was tested and applied to investigate the dynamics of suspended particulate matter of the Oder Lagoon. The changes in the suspended particulate matter concentration of the lagoon under a particular and strong wind events were studied. To validate the suspended particulate matter simulation, the result of simulations were compared with the suspended particulate matter measurements.

4.6.1 Suspended particulate matter field measurement data

The hydrographical and meteorological conditions in the Oder Lagoon are monitored by three buoys of the GKSS Research Centre, Germany. The buoys are located at three localities in the western part of the lagoon; the western (Oderhaff 01), central (Oderhaff

02) and eastern buoys (Oderhaff 03). The data are kindly provided online and can be accessed via the internet at website http://meteo.gkss.de/. The water transparencies in the lagoon are recorded by the transmissiometers installed on the buoys and the transmission in the lagoon is measured in percent unit.

In the Femflow2D model, the input data needed for the suspended particulate matter modul calculation are the suspended particulate matter concentration (SPM) in mg/l. To obtain the values in mg/l from the available transmission data a calibration of the measured data is done. The calibration enables the conversion of transmission data in percent unit to SPM concentration in mg/l. Time series of SPM field measurement data of the Oder Lagoon were received from Prof. M. Pejrup of the University of Copenhagen, Denmark. The data covered the period of 26 August 1999 to 2 November 1999 in 12 hours resolution. The measurement was done at the locality buoy Oderhaff 03 (53°50’00 N and 14°06’00 E) which covered measurement of time, suspended particulate matter concentration as well as the wind speed and direction. A few data within that period were not available, therefore the data cover not completely the entire period. The time series graphic of suspended particulate matter concentration and wind speed can be seen in figure 4.36.

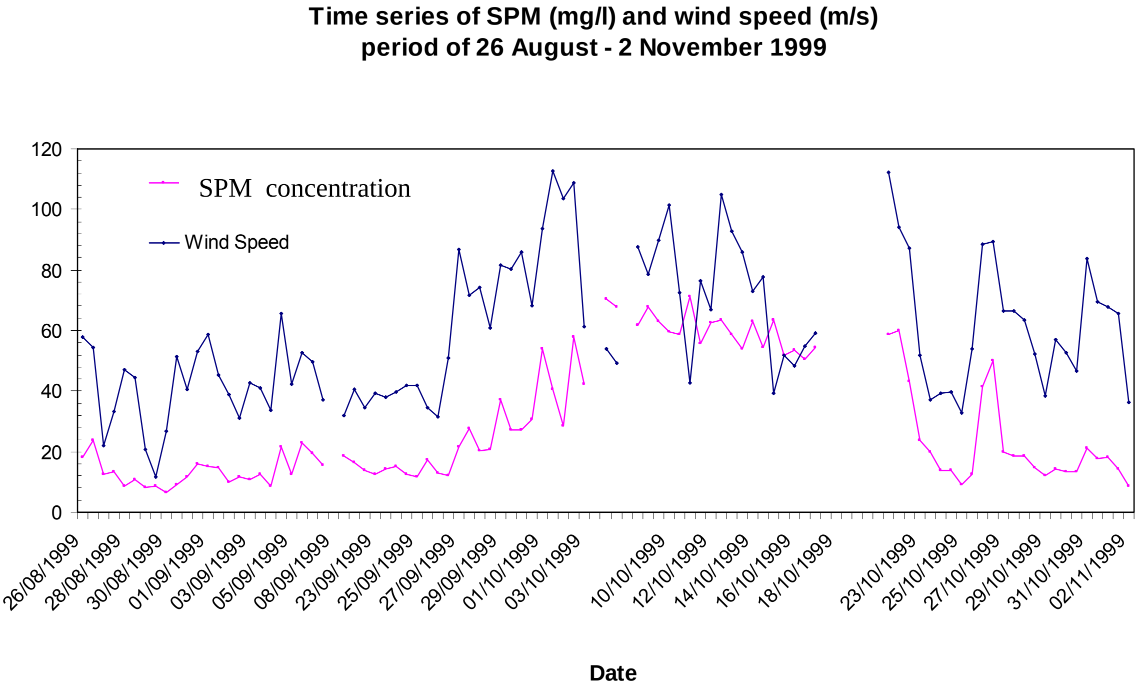


Figure 4.36. Time series of suspended particulate matter concentration and wind speed measurements in Oder Lagoon for the period of 26 August to 2 November 1999. Suspended particulate matter concentration drawn in the graphic is 10 times of the original values (data from Prof. M. Pejrup, the University of Copenhagen, Denmark).

Regression analyses were done to assess the relationships between SPM and transmission as well as between SPM and wind speed. All measured SPM data were plotted against the transmission data measured by the transmissiometer. The results showed a scattered plot indicating poor relationship between the transmission and the SPM. The data were then reanalysed by considering the error that might have occurred in the measurements, the wind directions that might have had impact and the changing of wind directions particularly when they had turned to the opposite directions. The results of reanalyses indicate the important role of the wind directions on the SPM. The data were classified into four sets of data according to their wind directions: quadrant I (1° - 90°), II (91° - 180°) , III (181° - 270°) and IV (271° - 360°). A strong correlation exists only for the SPM data with wind directions from quadrant II were considered ($p<0.001$, Pearson correlation, $R^2 = 0.96$). The regression formula obtained allows the conversion of transmission values measured by the transmissiometer to values of SPM in mg/l in which the transmission is equal to -21.34 Ln (SPM) plus 101.78 (see figure 4.37.).

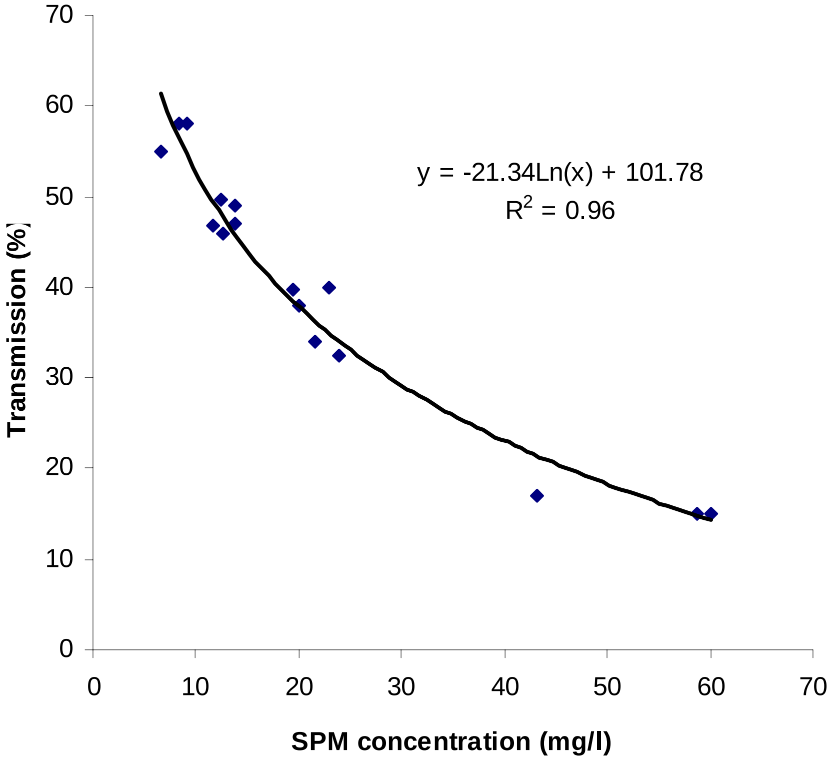


Figure 4.37. Logarithmic correlation between SPM and transmission.

Similar results were obtained in the regression analyses between wind speed and SPM. A significant correlation between wind speed and SPM ($R^2 = 0.89$) existed only for all SPM data with wind directions from quadrant II. Other wind directions revealed weak correlations (R^2 = 0.38, 0.21 and 0.54). To obtain a more reliable correlation result, the data of Prof. Pejrup measurements are combined with previous measurements by Burkhardt and Breitenbach (1997, and pers.comm.). The result showed a very good correlation when the SPM measurements during strong wind speeds (Prof. Pejrup's data) are combined with the Burkhardt and Breitenbach's data ($p<0.001$, Pearson correlation, R^2 = 0.91), see figure 4.38. From the graphics of SPM and wind speed correlation, it can be estimated that the critical wind speed for resuspension of the lagoon's sediment is about 5 m/s to 6 m/s (see figure 4.36.).

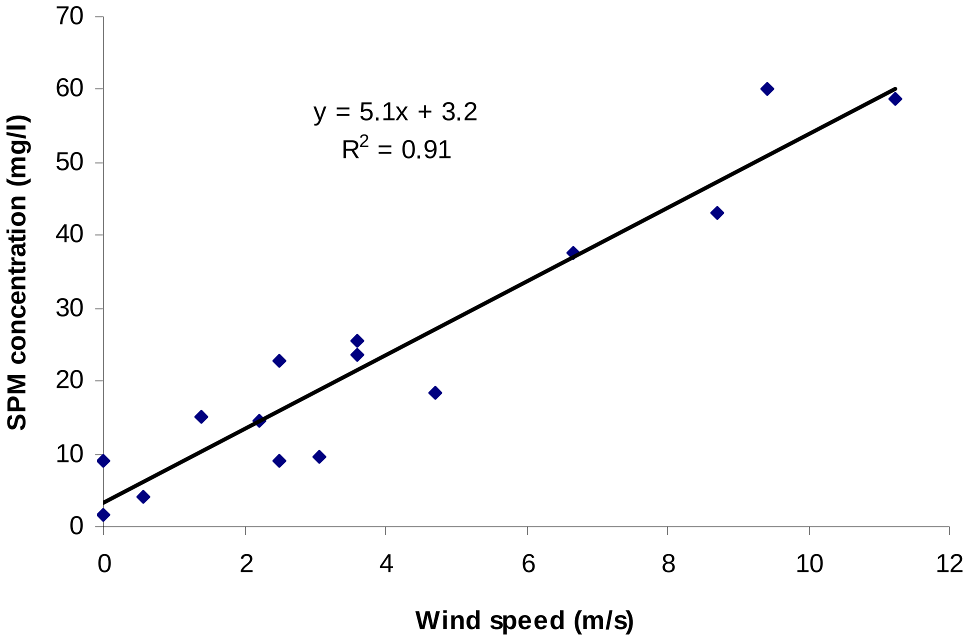


Figure 4.38. The strong correlation between wind speed and suspended particulate matter concentration in Oder Lagoon (data from Burkhardt and Breitenbach 1997 and Prof. M. Pejrup).

4.6.2 Input parameter values for suspended particulate matter simulation

The suspended particulate matter module in the Femflow2D model was used to simulate the dynamics of suspended particulate matter of the Oder Lagoon. To run this module, the prescriptions of the physical parameters of suspended particulate matter are required. This module runs along with the flow module, therefore the input parameters for the flow module also have to be prescribed. The input parameter as has been used in the flow validation was used in all suspended particulate matter simulations. However because the suspended particulate matter module is the newly developed module that has not been applied before, different input parameter values for both the flow and the suspended particulate matter were tested and the results of the simulations were compared to the suspended particulate matter measurements in the lagoon.

Input parameter values needed to run the suspended particulate matter module are D_{50} and D_{90} grain sizes, settling velocity, critical deposition and erosion shear stresses, power of erosion, material constant and the initial background of suspended particulate matter concentration. The model has the limitation that only one type of sediment can be simulated. Therefore if one type of the sediment has been chosen then the physical properties of that sediment need to be applied. The simulations can be divided into two periods of simulations, the long simulation period (several days) and the short simulation period (24 hours).

As in the simulation for the flow validation, a constant Manning roughness coefficient of 0.015 $m^{-1/3}s$, a wind drag force of 3.2×10^{-6} and a Coriolis parameter of 1.174×10^{-4} were used in all suspended particulate matter simulations. A turbulence coefficient equal to 0.1 m^2/s was first used but the calibrations of this parameter were made. Inflow discharge used was kept constant with the value of 350 m^3/s. Output discharge via Swina was calculated 69 % of the inflow river discharge whereas the Dziwna and Peene were prescribed as open boundaries. The grain size values obtained by the grain size analyses of the Oder Lagoon suspended particulate matter were applied. The input parameter for D_{50} and D_{90} grain sizes used were 28 μm and 53 μm. A settling velocity of 3.3×10^{-4} m/s was used. This value was obtained by the application of the simple box optimisation model of Dr. Victor Podsetchine for the estimation of settling velocity value based on the suspended sediment measurements data. From the simulations it was found that the suitable critical erosion shear stress values were 0.015 N/m^2 and 0.02 N/m^2. These values are in good agreement with the values of critical erosion shear stress of the fluffy layer from the Pomeranian Bay measured by Lund-Hansen et al. (1999) in Edelvang et al. (2002) which was between 0.016 and 0.024 N/m^2 and the fluffy layer from the Mecklenburg Bay by Bohling (2003) which was between 0.016 N/m^2 and 0.049 N/m^2. The critical deposition shear stress and the power of erosion term values were obtained by the calibration during simulations. It was found that suitable critical deposition shear stresses were 0.005 N/m^2 and 0.01 N/m^2.

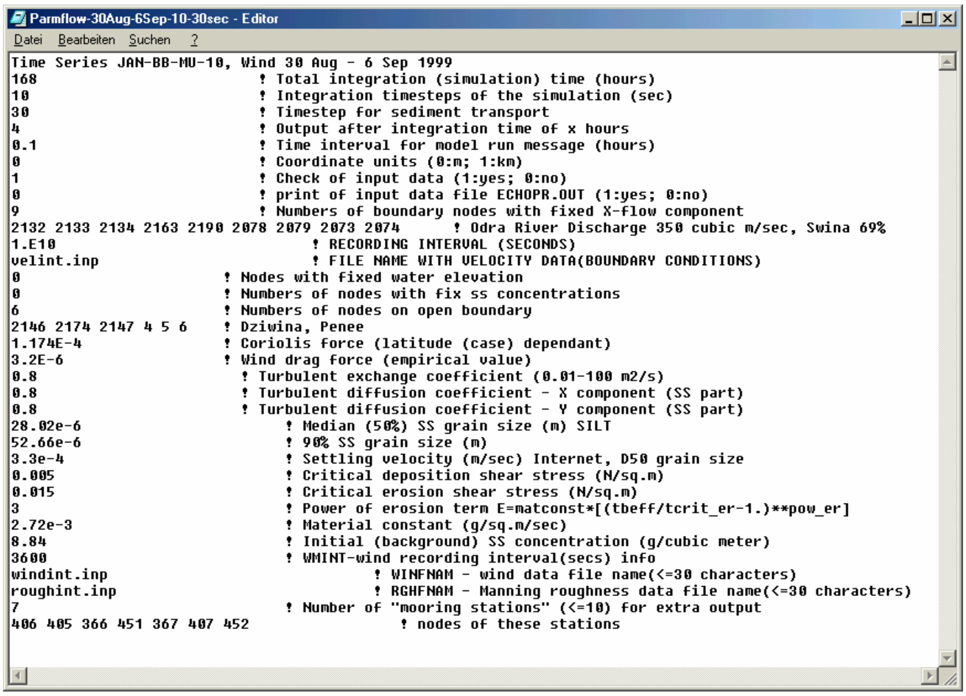
The power of erosion of 3 was found as the most suitable value to fit best with the measurements. The material constant was also calibrated during the simulations. Initially, the value used by Lee et al. (1994) was applied and the suitable values were 2.72×10^{-3} $g/m^2/sec$ for long simulation period and 0.55 $g/m^2/sec$ for short simulation period. The values of 0.8 m^2/s for turbulence exchange and diffusion coefficients appeared as the suitable values for the suspended particulate matter simulations. These values were different to the values that had been used in the flow validation. The value used as the background SPM concentration in the simulation followed the concentration at the beginning of the simulation.

For the long simulation period, both 10 seconds integration timestep of the simulation and 30 seconds timestep for sediment transport and 100 seconds integration timestep of the simulation and 300 seconds timestep for sediment transport can be used. For the short simulation period, 100 seconds integration timestep of the simulation and 300 seconds timestep for sediment transport need to be applied. The new option of spatially variable critical shear stress was added to the model during the study. This was found to be important for running the short simulation period.

4.6.3 Suspended particulate matter dynamics simulation

The dynamics of suspended particulate matter in the Oder Lagoon were investigated by running various simulations with different input parameters. The results of the simulations showed that the suspended particulate matter dynamics of the Oder Lagoon can be simulated quite reliably. The simulations are conform with the measurement results. To enable the comparison of the simulation results with the suspended particulate matter measurements, the periods for simulations were selected within the period of Prof. Pejrup's SPM measurements (26 August to 2 November 1999). For the long simulation period, the SPM dynamics of 30 August to 6 September 1999, 7 to 19 September 1999 and 23 to 31 October 1999 were chosen and for the short simulation period the SPM conditions of 1 October 1999 and 19 August 1999 were simulated.

The investigation showed that the model is very sensitive to a change of the critical erosion shear stress, the material constant and the power of erosion term values. Other parameters are not so critical as those parameters. Setttling velocity is more sensitive compared to the critical deposition shear stress. However, the change of the settling velocity by a factor of 10 results in small differences of the simulation results. The critical deposition shear stress value is not that sensitive. The computer simulation results showed that the dynamics of the suspended particulate matter of the Oder Lagoon is dominated by the fluffy materials. The simulation results showed that the sediment properties used in the simulations were related to the fluffy layer materials. In the long simulation period of 30 August to 6 September 1999, the input parameters used for the flow validation were similar to the input values for the flow validation except the turbulent exchange and diffussion coefficients which were 0.8 m^2/s. A constant critical erosion shear stress over the lagoon of 0.015 N/m^2 was applied in the simulations. The critical deposition shear stress value used was 0.005 N/m^2. The integration timestep of the simulation was 10 seconds and the timestep for sediment transport was 30 seconds. Time series of wind speed and direction of one hour resolution were used in the simulations. The wind data were taken from the Ueckermünde Weather Station. The input parameter values used in the simulation are presented in figure 4.39. The time series of wind speed and direction for the period 30 August to 6 September 1999 can be seen in figure 4.40. The result of the simulation was compared to the measured SPM at the locality buoy Oderhaff 03. The comparison of the computer simulation and the measured SPM for the period of 30 August 1999 to 6 September can be seen in figure 4.41.



```
Time Series JAN-BB-MU-10, Wind 30 Aug - 6 Sep 1999
168                          ! Total integration (simulation) time (hours)
10                           ! Integration timesteps of the simulation (sec)
30                           ! Timestep for sediment transport
4                            ! Output after integration time of x hours
0.1                          ! Time interval for model run message (hours)
0                            ! Coordinate units (0:m; 1:km)
1                            ! Check of input data (1:yes; 0:no)
0                            ! print of input data file ECHOPR.OUT (1:yes; 0:no)
9                            ! Numbers of boundary nodes with fixed X-flow component
2132 2133 2134 2163 2190 2078 2079 2073 2074       ! Odra River Discharge 350 cubic m/sec, Swina 69%
1.E10                              ! RECORDING INTERVAL (SECONDS)
velint.inp                         ! FILE NAME WITH VELOCITY DATA(BOUNDARY CONDITIONS)
0                        ! Nodes with fixed water elevation
0                        ! Numbers of nodes with fix ss concentrations
6                        ! Numbers of nodes on open boundary
2146 2174 2147 4 5 6     ! Dziwina, Penee
1.174E-4                 ! Coriolis force (latitude (case) dependant)
3.2E-6                   ! Wind drag force (empirical value)
0.8                        ! Turbulent exchange coefficient (0.01-100 m2/s)
0.8                        ! Turbulent diffusion coefficient - X component (SS part)
0.8                        ! Turbulent diffusion coefficient - Y component (SS part)
28.02e-6                        ! Median (50%) SS grain size (m) SILT
52.66e-6                        ! 90% SS grain size (m)
3.3e-4                          ! Settling velocity (m/sec) Internet, D50 grain size
0.005                           ! Critical deposition shear stress (N/sq.m)
0.015                           ! Critical erosion shear stress (N/sq.m)
3                               ! Power of erosion term E=matconst*[(tbeff/tcrit_er-1.)**pow_er]
2.72e-3                         ! Material constant (g/sq.m/sec)
8.84                            ! Initial (background) SS concentration (g/cubic meter)
3600                            ! WMINT-wind recording interval(secs) info
windint.inp                               ! WINFNAM - wind data file name(<=30 characters)
roughint.inp                              ! RGHFNAM - Manning roughness data file name(<=30 characters)
7                               ! Number of "mooring stations" (<=10) for extra output
406 405 366 451 367 407 452                  ! nodes of these stations
```

Figure 4.39. Input parameter values used in the simulation period of 30 August to 6 September 1999.

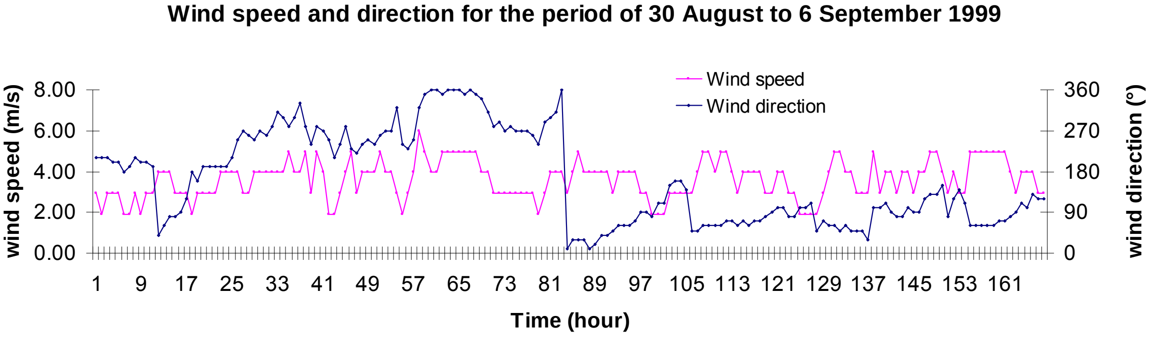


Figure 4.40. Time series of wind speed and direction for the period of 30 August to 6 September 1999.

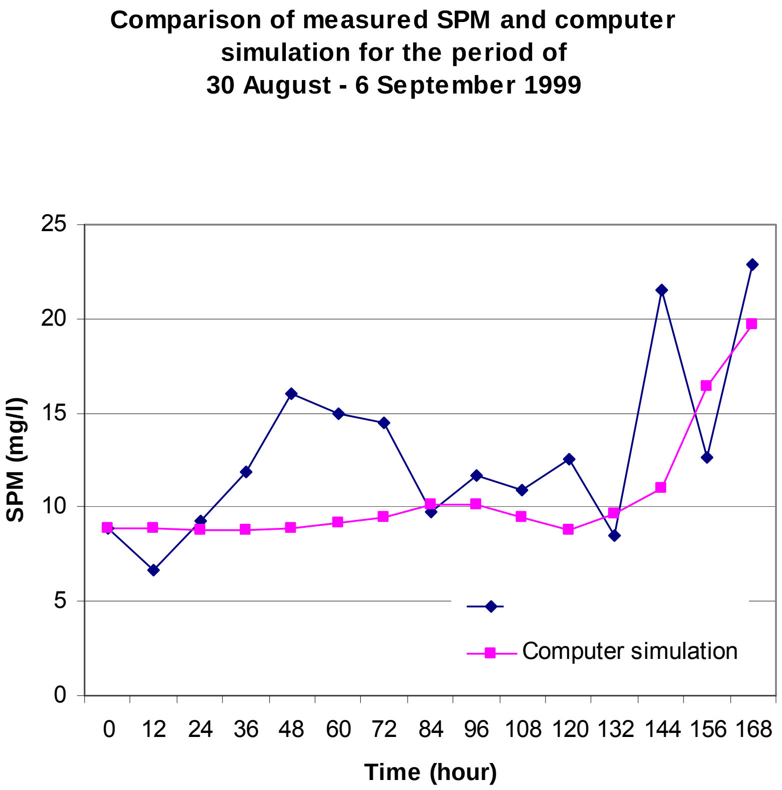
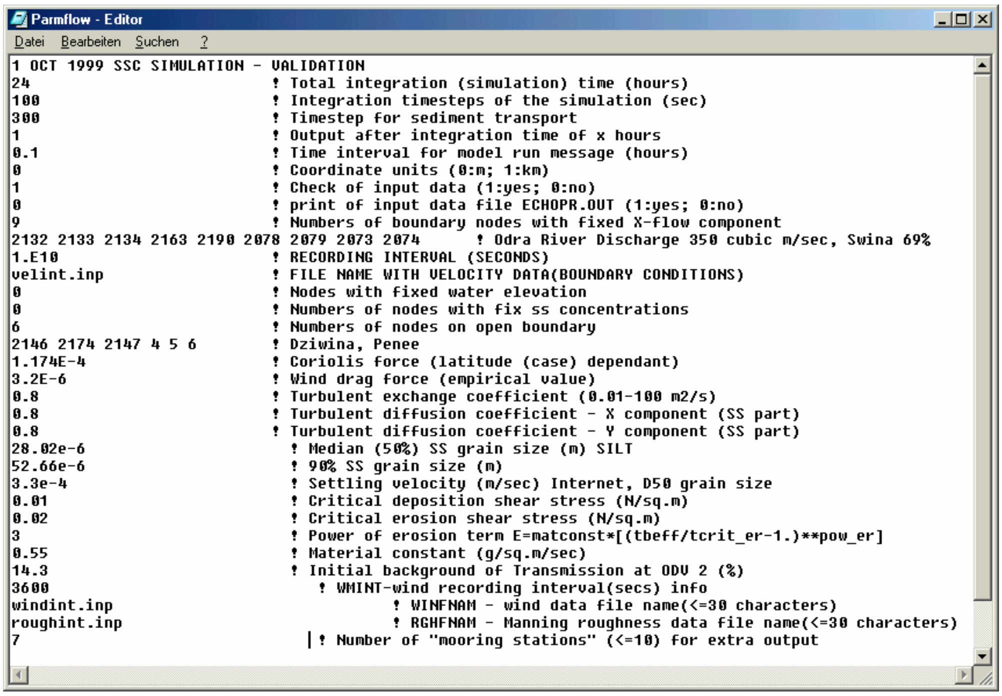


Figure 4.41. The comparison of measured SPM and the computer simulation for the period of 30 August to 6 September 1999.

In the short simulation period, the case of 1 October 1999 was chosen and the input parameter values used were as in the long simulation period except the integration timestep of the simulation, the timestep for sediment transport, the critical erosion and depositional shear stresses and the material constant. The integration timestep of the simulation used was 100 seconds and the timestep for sediment transport was 300 seconds. The input parameters used can be seen in figure 4.42. The scenario of the wind used in the simulations were time series of wind speed and direction in one hour resolution and the wind data were taken from the Ueckermünde Weather Station. The time series of wind speed and direction for the period of 1 October 1999 used in the simulation are presented in figure 4.43. The investigations revealed that spatially variable critical erosion shear stress needs to be applied in order to get a better fit to the measurements. The results of simulations using constant critical erosion shear stress did not fit with the measurement's results. The spatially variable critical erosion shear stress was based on the spatial distribution of the sediments in the lagoon (see figure 2.4.). The critical erosion shear stress applied ranged from 0.013 N/m^2 in the silt sediment to 0.12 N/m^2 in the sand (see figure 4.44. in relation to figure 2.4.). The suitable value for critical deposition shear stress was found to be 0.01 N/m^2.

The results of the 1 October 1999 simulations were compared to the suspended particulate matter measurements. There were no direct measured SPM values available for this period. The data of Prof. Pejrup were in 12 hours resolution, therefore it was not enough data to compare the simulation results. In Oderhaff 01,02 and 03 buoys, the turbidity in the lagoon was measured by using the transmissiometers installed in the buoys. The measurement’s values were recorded in percent units, but values in mg/l were needed to follow the requirements in the Femflow2D model. To convert the transmission values to SPM in mg/l, the regression formula obtained from the regression analyses between the transmission and the measured SPM concentration (see chapter 4.6.1) was used. Hence the transmission data measured by the buoys were converted into SPM values in mg/l.



```
1 OCT 1999 SSC SIMULATION - VALIDATION
24                          ! Total integration (simulation) time (hours)
100                         ! Integration timesteps of the simulation (sec)
300                         ! Timestep for sediment transport
1                           ! Output after integration time of x hours
0.1                         ! Time interval for model run message (hours)
0                           ! Coordinate units (0:m; 1:km)
1                           ! Check of input data (1:yes; 0:no)
0                           ! print of input data file ECHOPR.OUT (1:yes; 0:no)
9                           ! Numbers of boundary nodes with fixed X-flow component
2132 2133 2134 2163 2190 2078 2079 2073 2074      ! Odra River Discharge 350 cubic m/sec, Swina 69%
1.E10                       ! RECORDING INTERVAL (SECONDS)
velint.inp                  ! FILE NAME WITH VELOCITY DATA(BOUNDARY CONDITIONS)
0                           ! Nodes with fixed water elevation
0                           ! Numbers of nodes with fix ss concentrations
6                           ! Numbers of nodes on open boundary
2146 2174 2147 4 5 6        ! Dziwina, Penee
1.174E-4                    ! Coriolis force (latitude (case) dependant)
3.2E-6                      ! Wind drag force (empirical value)
0.8                         ! Turbulent exchange coefficient (0.01-100 m2/s)
0.8                         ! Turbulent diffusion coefficient - X component (SS part)
0.8                         ! Turbulent diffusion coefficient - Y component (SS part)
28.02e-6                      ! Median (50%) SS grain size (m) SILT
52.66e-6                      ! 90% SS grain size (m)
3.3e-4                        ! Settling velocity (m/sec) Internet, D50 grain size
0.01                          ! Critical deposition shear stress (N/sq.m)
0.02                          ! Critical erosion shear stress (N/sq.m)
3                             ! Power of erosion term E=matconst*[(tbeff/tcrit_er-1.)**pow_er]
0.55                          ! Material constant (g/sq.m/sec)
14.3                          ! Initial background of Transmission at ODV 2 (%)
3600                             ! WMINT-wind recording interval(secs) info
windint.inp                              ! WINFNAM - wind data file name(<=30 characters)
roughint.inp                             ! RGHFNAM - Manning roughness data file name(<=30 characters)
7                                ! Number of "mooring stations" (<=10) for extra output
```

Figure 4.42. Parameter input for SPM simulation and validation.

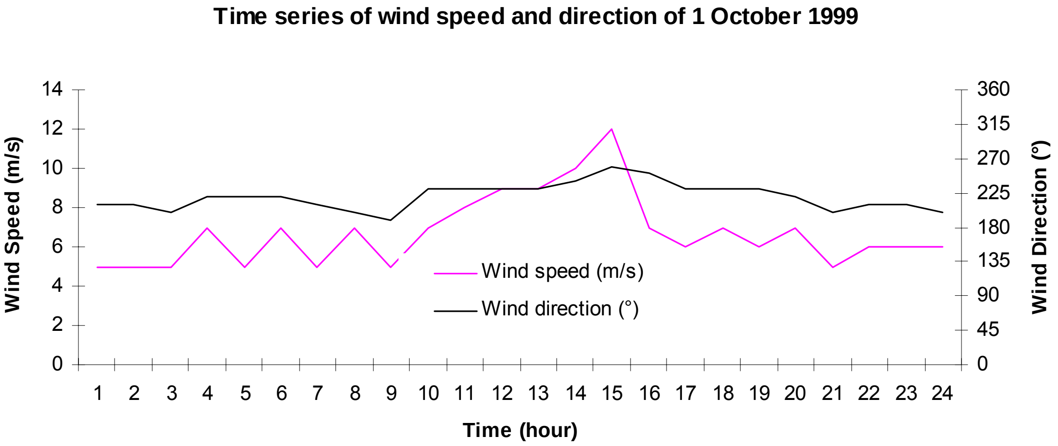


Figure 4.43. Time series of wind speed and wind direction of 1 October 1999 used in the simulation.

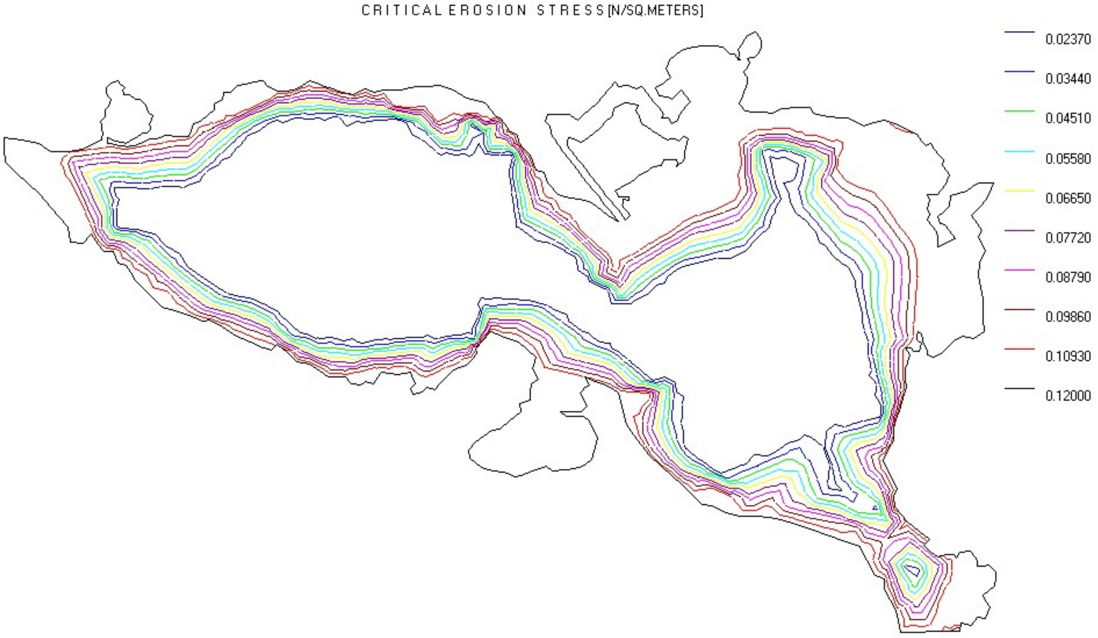
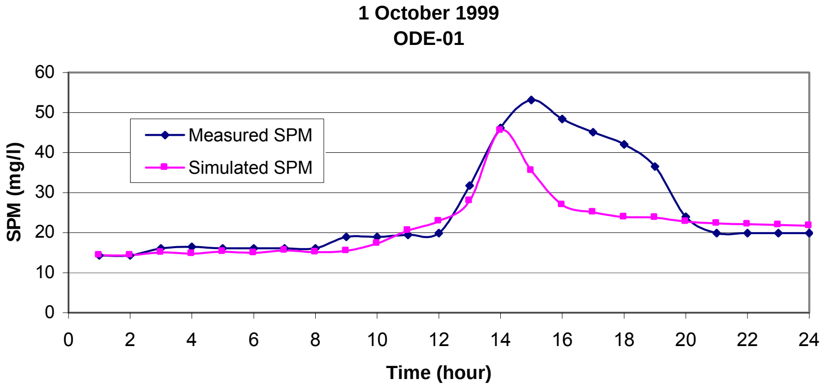
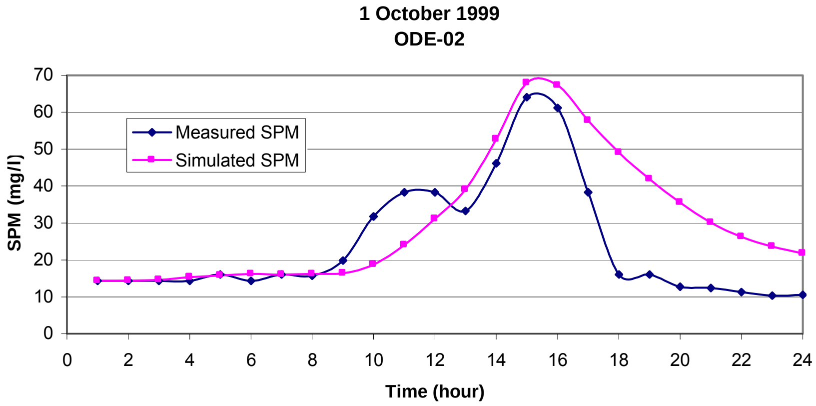


Figure 4.44. Spatially variable critical erosion shear stress applied for the short simulation period used for the cases of 1 October 1999 and 19 August 1999.





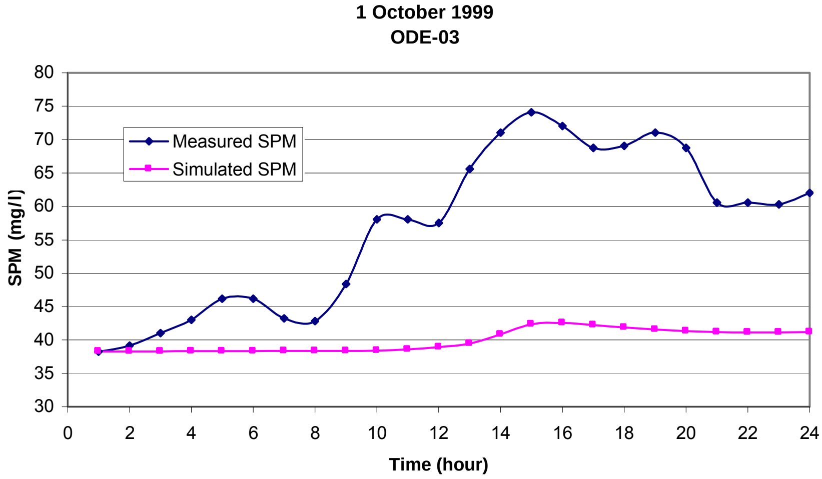


Figure 4.45. Comparisons of measured and simulated SPM at Oderhaff Buoys 01, 02 and 03 for 1 October 1999.

The comparisons of measured and simulated suspended particulate matter at Oderhaff buoys 01, 02 and 03 for 1 October 1999 are presented in figure 4.45. The simulation results show the good relationship between measured and simulated SPM in the Oder Lagoon. In Oderhaff Buoy 03, the simulated SPM was lower compared to the measured SPM. However, the graphic trend was similar. In other buoys a good relationship can be seen.

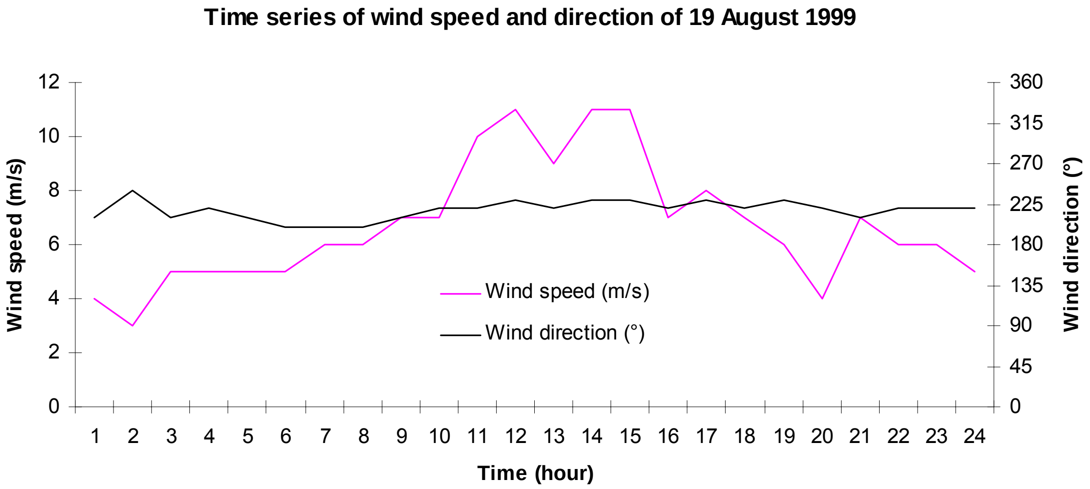


Figure 4.46. Time series of wind speed and wind direction used in the 19 August 1999 simulation.

To know wether the input parameter values used in the 1 October 1999 simulation were reliable another simulation was conducted to validate the results of the simulation. The high wind speed event of 19 August 1999 was chosen for the validation. Identical input parameter values as in the 1 October 1999 simulation were again used in the 19 August 1999 simulation. The results of the simulation again show good relationships between measured and simulated SPM in the lagoon. Wind speed and direction used in the 19 August 1999 simulation can be seen in figure 4.46. The comparisons between measured and simulated SPM at Oderhaff Buoys 01, 02 and 03 can be seen in figure 4.47.

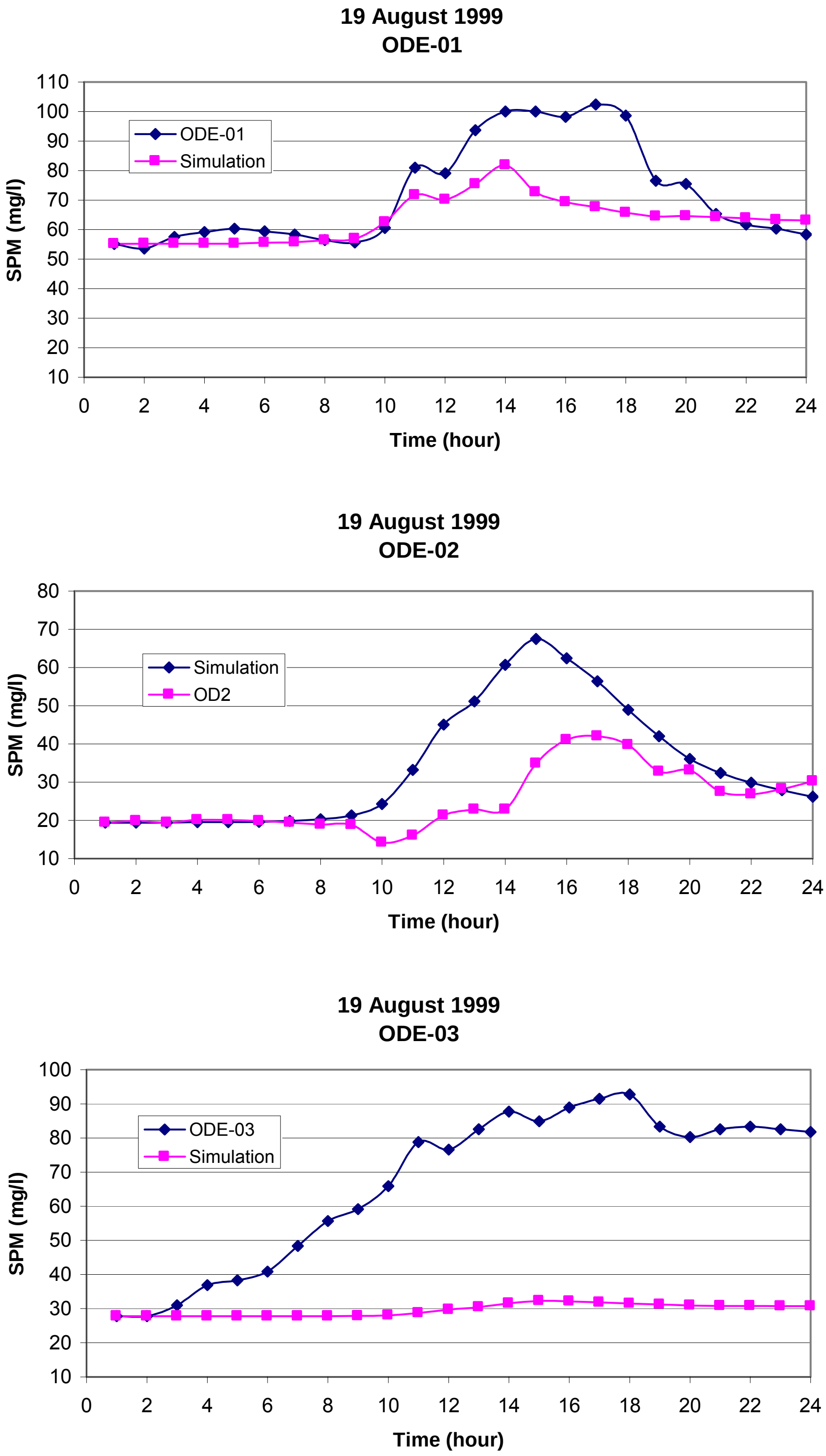


Figure 4.47. Comparisons between measured and simulated SPM at Oderhaff Buoys 01, 02, 03 for 19 August 1999.

4.7 Particle tracking module application

The Femflow2D model is equipped with a particle tracking module that can be used for analysing the behaviour of particulate matter in the lagoon. The particle tracking module was applied for the Oder Lagoon to investigate the behaviour of particles entering from the Oder river to the lagoon under eight different directions. The results may also be interpreted as the water mass flow from the Oder river to the lagoon. A particular application of this module was to investigate the anthropogenic heavy metal pollution brought by the Oder river to the lagoon. The goal was to assess the relationship between the water flow entering from the river and the accumulation of heavy metals in the eastern part of the lagoon.

4.7.1 Flow data and input parameter for particle tracking

To run the particle tracking module, a particular flow field should be chosen from flow simulation results. The tracking of particles is based on the selected flow field, and the limitation is that it can work only on one particular flow conditions. Simulations of eight wind directions using a constant wind speed of 4 m/s were done and the resulting flow fields were used for the investigation of particles that were released from the Oder river into the lagoon. To investigate the anthropogenic heavy metal particles brought by the Oder river to the lagoon, two flow simulations were conducted. The first simulation was done in an average wind conditions (wind speed 4 m/s and wind direction 233°). The other simulation was run to assess the movement of the particles under a strong wind event (wind speed 10 m/s and wind direction 248°). Both simulations were conducted in a spatially variable wind conditions. The probability of the particles that were transported from the river to the lagoon was investigated. It was assumed that one particle represented 1000 m^3 of water from the Oder river that has the cross sectional area of 27555 m^2 and 1 m width at the mouth of the river. Altogether 27 particles were used in the simulations. The dispersion coefficient applied was 0.03 m^2/s and integration timestep of 1800 seconds were used in all particle tracking simulations.

4.7.2 Tracking of particles entering the Oder Lagoon from the Oder river

The results of particle tracking for the two most frequent wind directions, the southern and south-western winds as well as for other wind directions are presented in appendix 9. In these figures the particles development after 2, 4, 8, 16 and 24 days can be seen.

The results of the tracking revealed that under the north-east and south-west wind directions and after 24 days, all particles were moving only within the eastern part of the lagoon. The similar situation was observed for the north and south wind directions. Under these wind directions, only a few particles entering the western lagoon (Kleines Haff) could be observed after 24 days. Under the east, south-east, west and north-west wind directions, at the beginning, the particles were entirely moving into the eastern part of the lagoon too. However, after 8 to 10 days the particles started entering the western part of the lagoon.

Similarly, the particles moving under the north and south wind directions in which after 24 days, only a very few particles entering the western part of the lagoon. Under the east, south-east, west and north west winds, the particles moving in the eastern part of the lagoon too and started entering the western lagoon after about 8 to 10 days. Similar patterns of particles movement were observed under east and south-east winds as well as under west and north-west winds (see appendix 9). Under east and south-east winds, the Oder river flows were directed both to the western and eastern side of the Grosses Haff whereas under north and north-west winds, the flows were mainly along the shipping channel and then to the Kleines Haff for the west wind and both to the Kleines Haff and Grosses Haff for the north-west wind. Under west, north-west and north winds, flows mainly along the shipping channel can be observed.

The flow fields used for tracking of particles entering the Oder Lagoon from the Oder river were the flow fields under constant wind direction. As has been described in the flow validation the flow fields under spatially variable winds more would be accurate. For detailed study the spatially variable wind need to be applied. However, to look on the general situation the flow field of constant wind can be used.

4.7.3 Assessment of anthropogenic heavy metal particles entering the Oder Lagoon from the Oder river

Anthropogenic heavy metals are especially bound to particles with a great surface such as clay minerals, Fe and Mn oxihydrates, carbonates and organic matter. The sources of these heavy metals are mainly from industrial wastes and the mining industry in the hinterland.

To assess the anthropogenic heavy metal particles entering the lagoon from the Oder river, two flow fields resulting from the flow simulations under average (wind speed 4 m/s and direction 233°) and strong wind conditions (wind speed 10 m/s and direction 248°) were used (see chapter 4.7.1). The probability of the particles moving in the lagoon under both winds can be seen in figure 4.48. Under average wind conditions, 62 % and 30 % of the particles were transported to the western and eastern sides of the river mouth area respectively. 3% of the particles remained in the river mouth area. Under strong wind events, 96 % of the particles were transported to the western side and 4 % were left in the river mouth area. No particles transported to the eastern side of the lagoon can be observed under this strong wind conditions (see figure 4.48.). The results showed that the probability of particles transported to the western side of the lagoon is higher compared to the eastern lagoon. As the wind speed increases the probability of westerly transport is increasing and nearly all particles were transported to the western side of the lagoon under a wind speed of 10 m/s (see figure 4.48.). If we compare the particle tracking results to the anthropogenic heavy metals Zn, Cu and Pb sediments distribution in the lagoon (see figure 2.5.), higher concentrations of those heavy metals were found in the western side of the

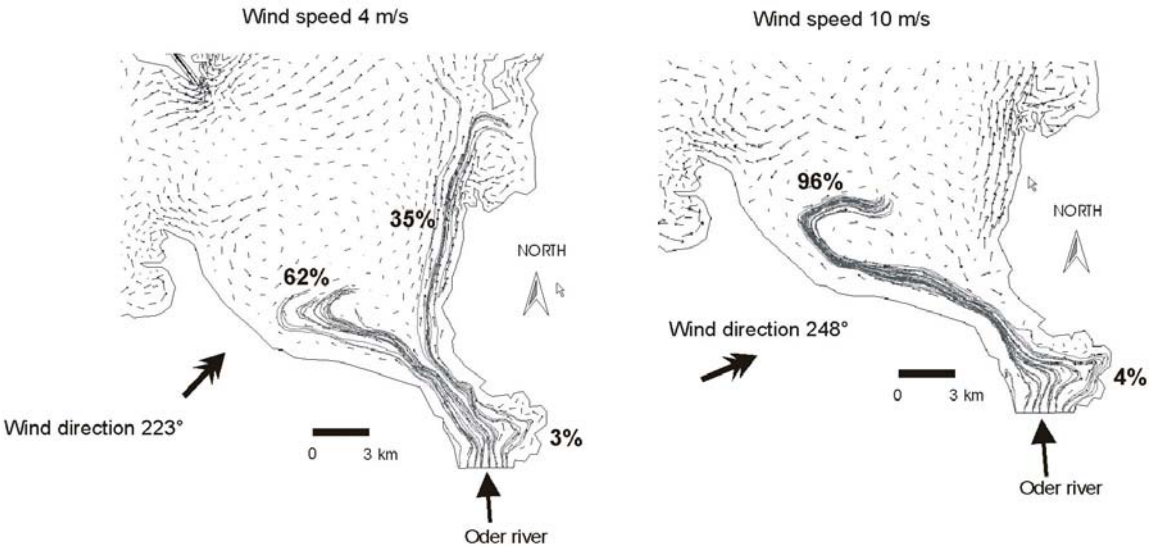


Figure 4.48. The probability of particles entering from the Oder river to the lagoon under average (left) and strong wind conditions (right).

river mouth area coincident with the higher probability as mentioned before. To further assess why the higher concentrations of heavy metals were found in the south-western area of the eastern part of the lagoon (see figure 2.5.), another particle tracking was conducted. Most of the particles were assumed to be resuspended and transported under the strong wind event and therefore the flow field of the strong wind conditions was chosen for the assessment. The particles from the higher concentration area are represented by a line and the movement of those particles was observed (see figure 4.49.).

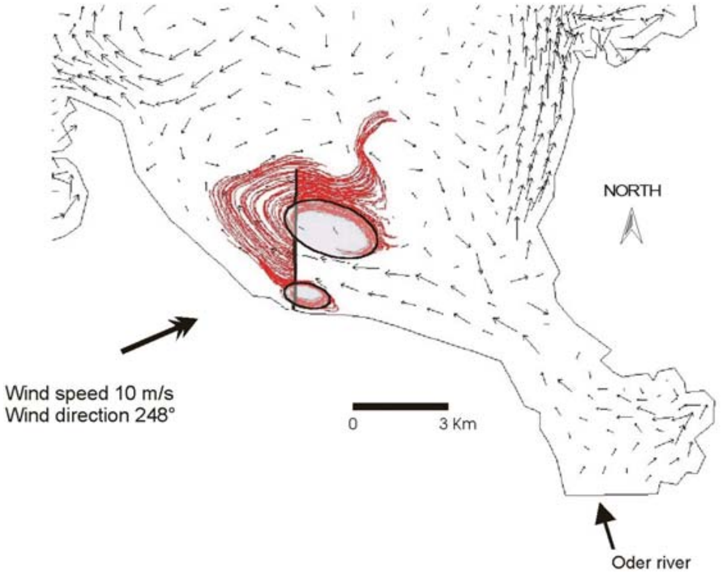


Figure 4.49. Particle's movement from the high heavy metals concentration area under a single strong wind event that lasts for 36 hours. The eddies act as the trap for these heavy metal particles.

A total duration of 24 hours of one strong wind event was chosen and the assumption that the particles were moving 6 hours before and after the strong wind event was used. The movement of the particles after 36 hours starting from the line can be seen in figure 4.49. The results show that eddies that developed in the south-western part of the eastern lagoon act as a trap for the resuspended heavy metal particles (see figure 4.49.). Most of the particles preferentially remained in this area despite the prevailing strong wind event. In the long term period, higher concentrations of anthropogenic heavy metals are therefore observed in this area as shown in figure 2.5.

4.8 The estimation of a suspended particulate matter mass balance of the Oder Lagoon

The suspended particulate matter mass balance of the Oder Lagoon can be predicted based on the relationship between wind speed and suspended particulate matter concentration as described in chapter 4.6.1 The linear relationship between wind speed and suspended particulate matter concentration is $y = 5.1x + 3.2$ in which y is the suspended particulate matter concentration in mg/l and x is the wind speed in m/s. The lagoon receives its water and suspended particulate matter mainly from the Oder river and the outlets to the Baltic Sea are via Swina, Peene and Dziwna. These main input and outlets were used in the estimation of a suspended particulate matter mass balance of the Oder Lagoon.

The amount of sediment transport into and out of the lagoon can be calculated by multiplying the discharge to the suspended particulate matter concentration. Leipe et al. (1998) calculated an input load of the sediment to the lagoon of 425000 tons per year. This is based on the average concentration of the Oder river which is 25 mg/l and the discharge of the river entering the lagoon which is 17 km^3 per year. The output load via three outlets: Swina, Peene and Dziwna was calculated based on 69%, 17% and 14% of the Oder river discharge respectively (Mohrholz and Lass, 1998). The average suspended particulate matter concentration in the lagoon is similar to the Oder river which is 25 mg/l (Leipe et al., 1998).

In this situation the sediment transport into and out of the lagoon is in a balance conditions. The input load from the Oder river which is 425000 ton/year is the same as the output load to the Baltic Sea via three outlets (Swina 293250 tons, Peene 72250 tons and Dziwna 59500 tons). According to the wind speed and suspended particulate matter relationship, the concentration of 25 mg/l in the lagoon is reached at the wind speed of 4.3 m/s (see table 4.5. and figure 4.50.). Therefore at this wind speed, the sediment transport in the lagoon is in a balance conditions. The average wind speed in the lagoon as shown by the wind analyses (see chapter 4.1) is 4 m/s. Therefore the Oder Lagoon is at present close to a balance conditions in which the sediment input load from the Oder river is about the same as the output load to the Baltic Sea. At wind speeds below 4.3 m/s the lagoon acts as a trapping system for the suspended particulate matter whereas at wind speeds higher than 4.3 m/s the lagoon acts as exporting sytem.

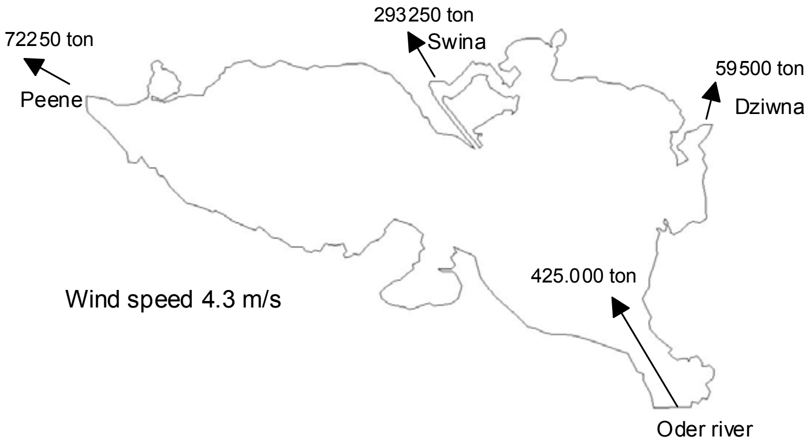
Table. 4.5. Wind speed and suspended particulate matter mass balance in the Oder Lagoon.

SPM (mg/l)	Wind Speed (m/s)	Oder Lagoon Function
5	0.4	trap
10	1.3	trap
15	2.3	trap
20	3.3	trap
25	4.3	balance
30	5.3	export
35	6.2	export
40	7.2	export
45	8.2	export
50	9.2	export
55	10.2	export
60	11.1	export
65	12.1	export
		Note
	4.0	Average wind speed
25	4.3	balance before dredging
7.47	0.8	balance after dredging

Dredging activities along the shipping channel have been going on in the lagoon for about a century. The average dredged amount is about 298062 tons per year (Minning et al. 2003). This was calculated based on the volume of the yearly average wet dredged materials and the dry bulk density of the dredged sediment which is 0.2 ton/m^3. If the dredging materials are taken into account, then the amount of sediment input to the lagoon would be much less, about 126938 tons/year. This amount is equal to the concentration in the lagoon of 7.47 mg/l. This concentration in the lagoon is reached at wind speeds of about 0.8 m/s (see table 4.5. and figure 4.50.). If the lagoon is in a balance conditions then this material will be exported to the Baltic Sea. The wind speed needed to export this amount of material is much lower, about 0.8 m/s. Hence the lagoon acts as an sediment exporting system at present.

The Oder Lagoon has an area of about 687 km^2 with an average depth of 3.8 meter. The volume of the lagoon calculated from those data is 2610060000 m^3. The dry bulk density of the sediment is between 0.2 and 0.3 ton/m^3 (Leipe et al., 1998). If the dry bulk density is used then the amount of sediment needed to fill up the lagoon is about 783180000 tons/year. If the input of 425000 tons/year is considered as the constant input of sediment to the lagoon, then the time needed to fill up the lagoon is 1843 years or about 2000 years. Theoretically, from the present time onwards it will take about 2000 years to fill up the lagoon with sediment.

Wind speed and suspended sediment mass balance in the Oder Lagoon before dredging activities



Wind speed and suspended sediment mass balance in the Oder Lagoon after dredging activities

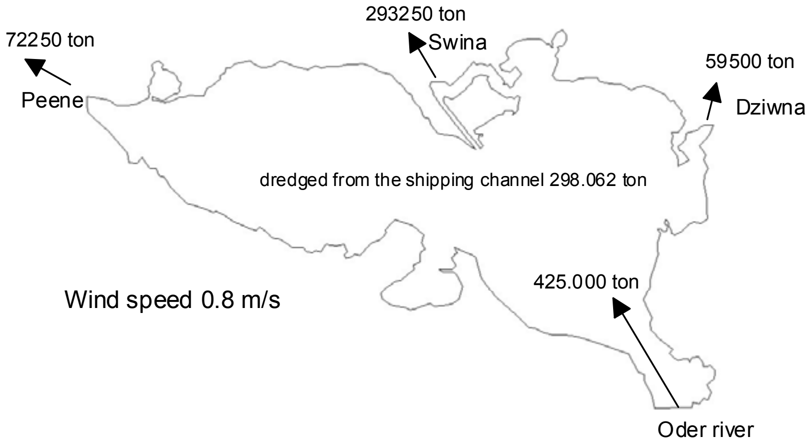


Figure 4.50. The wind speed and balance conditions in the lagoon before and after dredging activities.

5 DISCUSSION

5.1 Meteorological conditions of the Oder Lagoon area

Wind conditions are controlled by atmospheric pressure patterns, orography and thermal factors. The results of wind data analyses of the ten years period 1991 – 2000 at Ueckermünde Weather Station showed that the west to south winds were the most frequent wind directions which accounted more than 60 % of all wind directions (see figure 4.1.). The predominance of those wind directions was also observed for example by Schernewski et al. (2000) in Lake Belau (North Germany), and in accordance to Zeidler et al. (1995) who stated that the predominant winds of the Southern Baltic were south-west and west winds. As shown by the monthly wind chart of that ten years period (see appendices 1-A and 1-B), all months were showing a predominance of west to south winds except April and May. In these two months of spring, the wind directions showed a dominance of northern to eastern winds. The results of wind analyses also show that as the wind speed increases, from more than 4, 6, 8 and 10 m/s, the western to south-western winds become more significant (see figure 4.4.). Zeidler et al. (1995) also described that in spring time the wind directions were not dominated by the western to south-western winds which was the exceptional case. During this time the northern to eastern wind predominated.

The results of temperature analyses showed a higher and a lower temperatures occurred in summer (June to August) and winter (December to February) time. The differences between those two seasons were quite distinct with monthly average low temperatures of 0.84°C and 0.85°C in January and February respectively and a high average temperature of 17.85°C in August. The months within both the spring (March to May) and autumn (September to November) showed the opposite temperature trend. Increasing and decreasing temperature during spring and autumn. During low temperatures in winter time, the water surface in the lagoon, particularly at shallow areas may be frozen or covered with ice. The extent of this ice cover differs from year to year depending on the prevailing stronger or weaker winter. In the winter of 1995/1996 very strong ice covers developed along the German coasts of the Baltic Sea. The thickness of the ice in the Oder Lagoon was between 20 cm and 40 cm in 9 February 1996 and between 30 cm and 50 cm in 26 February 1996 (Strübing, 1996).

5.2 Sediment and suspended particulate matter of the Oder Lagoon

5.2.1 Sediment and water sampling

The sediment samples in this study were taken only from the western part of the Oder Lagoon and none was taken from the eastern part of the lagoon in the Polish territory. Therefore no direct and complete information of the sediment and water conditions in the lagoon were obtained in this study. Ideally the sediment sampling would also include the eastern part of the lagoon so that broader knowledge about the sediment could be obtained.

However due to the difficulties in the administration requirements for taking samples in the Polish part as well as limited resources to conduct the sampling in this very large lagoon the sampling was concentrated in the German part of the lagoon. The sediment and water sampling that were done across Mönkebude to Kamminke as well as at the beach and the reed zones areas aimed at covering different parts and depths of the lagoon from the southern to the northern areas of the Kleines Haff. The data and information from previous studies for example by Leipe et al. (1999) and Osadczuk (1999) were used to compare and to get more complete knowledge of the sediment in the Oder Lagoon.

The sediment core sampling was done to reconstruct the historical pollution in the Oder Lagoon. To get a good sample that can reveal this history, sampling were done at the reed zone of the lagoon. These reed zones were expected as areas of calm sedimentation in the low current regime of the lagoon and the area of low resuspension due the existence of the reeds that reduced the current speed. Difficulties occurred during the core sampling in Mönkebude and Altwarp, because the area was densely covered by the reeds that prevented the core to be drilled into the sediment. However a quite long sediment core of 45 cm length could be obtained from the reed zone west of Altwarp (sample 236040, see figure 3.6.) and this longest core was subject to geochemical analyses (see chapter 4.3).

5.2.2 Sediment grain size and water content

The grain size of the sediment in the lagoon clearly shows the larger grain sizes at the coastal areas of the lagoon and decreasing grain sizes towards the central or deeper part. Along the Mönkebude to Kamminke section this trend can be seen very clearly (see figure 4.8.). Distinct grain size differences can be observed in which in the coastal areas (0 to about 3 meter depth), the average grain sizes were between 177 and 322 micrometer (fine to medium sand) whereas in the central part of the lagoon, the average grain sizes were between 31 and 63 micrometer (coarse silt). Sand sediments closer to Kamminke area appeared to have a finer average grain size compared to the sands near Mönkebude area (see figure 4.8.). The average grain sizes were 177 to 190 μm and 266 to 322 μm respectively. This may be due to the differences in the sources of those sediments. Both sands may come from the adjacent land with different sands in Kamminke area compared to that of the Mönkebude area. In the Mönkebude area, an increasing average grain size from the beach towards the offshore area can be found. This may indicate that the finer sands were transported easier from the adjacent land to the deeper part of the lagoon than the coarser ones and a trend of larger grains in the beach area and smaller grains toward the deeper areas was found.

That sand sediments occur in the coastal areas was also shown by the grain size analyses of the sediments of Mönkebude beach and Altwarp Port. At these localities, well sorted and moderately well sorted sand sediments occurred. Hence, the sediment in the lagoon can be divided into two distinct sediment types, sand sediment occurring in the coastal areas and silt in the deeper parts starting from about 2.9 meter water depth.

The grain size of core samples from Mönkebude (236020) and Altwarp (236030, 236040, 236050) was predominantly fine sand towards the entire core depth (see figure 4.11.). In Altwarp core samples 236040 and 236050, beside fine sand, medium and coarse sands become more prominent with increasing core depth (see figure 4.11.).

The water content were found to be closely related to the grain sizes and the sorting of the sediments. Fine sediments have higher water contents compared to coarser sediments (see figure 4.5. and 4.8.). Silt samples occurring in the central lagoon had a significantly higher water content, between 62.36% and 70.76% compared to sands in areas closer to Mönkebude and Kamminke (between 12.52% and 17.53%). The relationships between water content and sediment sorting were shown by Altwarp Port and Altwarp Bay sediments. Very poorly to poorly sorted sands of the Altwarp Bay have a higher water content than the moderately well sorted sand of the Altwarp Port.

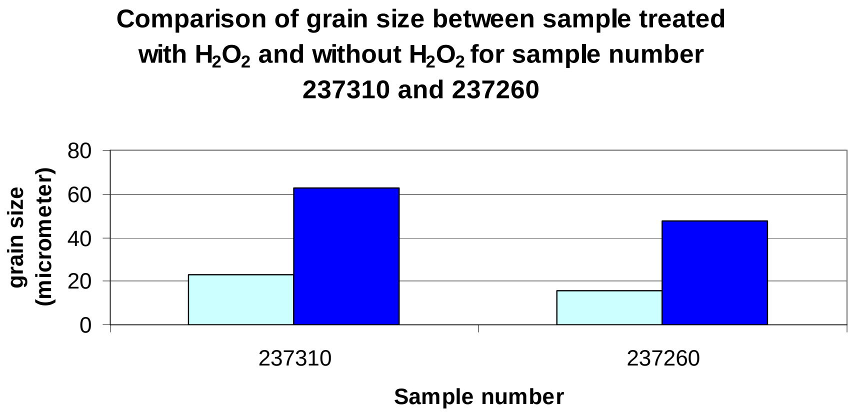


Figure 5.1. Comparison of grain size of sample treated with and without H_2O_2 (light and dark diagrams respectively).

The grain size analyses for silt sediments were done by using a Galai WCIS-50 particle size analyser in which the measurements of particle size were done through photo optical counting. Using this method errors may occur during the measurement particularly when the shape of the solids particles is long and narrow which means the grain size can be larger or smaller depending on the positions of the particles passing through the analyser. Normally, H_2O_2 solution was added to the silt sediments before they were analysed. This was done in order to breakdown the particles that might occur as flocs. To know how large were the effects of H_2O_2 addition on the grain size, two samples (237310 and 237260) were treated both with H_2O_2 and without H_2O_2 and the results of the laser analyses were observed. The grain size appeared to be three times larger in the samples without H_2O_2 treatment (see figure 5.1.). To obtain the grain size that is closer to the natural conditions, the silt sediments in this study were prepared without H_2O_2 treatment.

5.2.3 Suspended particulate matter concentration and grain size

The results of suspended particulate matter concentration analyses showed that the suspended particulate matter of the Oder Lagoon are mainly composed of organic materials. The organic materials were more than 70% of the total compositions whereas the inorganic components were below 27%. The organic components were mainly originating from the phytoplankton contained in the lagoonal water. This phytoplankton becomes more abundant due to the phytoplankton blooms that usually occur in the warm period (around April to October). The average suspended particulate matter concentration from the measurements (16.4 mg/l) showed a similar value to the median value of the suspended particulate matter concentration of the Oder river which was 17 mg/l (Lehman et al., 1999) and below the average suspended particulate matter concentration in the Oder Lagoon which was 23.3 mg/l (Fietz, 1996) and 25 mg/l (Leipe et al.,1998). The suspended particulate matter of the lagoon are a dynamic value in time and space. Different time and locality of suspended particulate matter measurements could result in different values as shown by the results of SPM measurements in this study. The currents may play an important role of the spatial variability of the suspended particulate matter in the lagoon. Errors during the measurements can also happen. The suspended particulate matter concentrations across Mönkebude to Kamminke (see figure 4.17.) showed values ranging from 13.7 to 23 mg/l. Several factors that may influence the spatial concentration of the suspended particulate matter were currents, the input source for the suspended particulate matter like from the Oder river and the occurring phytoplankton blooms. The importance of the input from the Oder river to the suspended particulate matter concentration could be seen clearly during the flood period in 1997. During the Oder flood event from 18 July until 18 August 1997, Fenske et al. (1998) measured the SPM and found that the suspended particulate matter concentrations in the western part of the lagoon or Kleines Haff were ranging between 15 and 45 mg/l. In the satellite images taken during this flood period (Siegel and Gerth, 2000a and 2000b) clear differences of spatial suspended particulate matter concentrations could be seen.

Vertically through the water column (see figure 4.18.), the suspended particulate matter measurements showed a slight decrease of concentration from 16.7 to 11.9 mg/l. In the natural conditions, the suspended particulate matter concentration in the lagoon as shown by the results of measurements was not homogeneously distributed throughout the water column. Hence, in detail, vertical SPM differences occurred. But, one can consider that the suspended particulate matter concentration differences were not very large and the water in the lagoon was relatively well mixed throughout the water column.

The result of the grain size analyses of the suspended particulate matter and sediments revealed the similar grain size of about 29 micrometer between suspended particulate matter and sediments from the central part of the lagoon. This might indicate that the suspended particulate matter particles originate from the bottom sediment of the lagoon. The suspended particulate matter were predominantly consisting of organic material. A part of these materials might also be deposited in the lagoon bottom and then be resuspended again which is reflected by the grain sizes.

5.2.4 Suspended particulate matter compositions

The compositions of the organic suspended particulate matter as shown by the phytoplankton and biomass analyses were controlled by the phytoplankton community. Some of the phytoplankton species are toxic and harmful to people and animals and may cause considerable impact on the tourism. *Mycrocystis sp.* is an example of toxic phytoplankton found in the lagoon during the measurement.

Besides of the “pure” organic substances, which are not measured by the automated particle micro-analysis, the major components of suspended particulate matter are displayed in figure 4.23. Biogenic opal, which mainly derives from diatom shells of the phytoplankton community, is the dominant mineral in the water column. It makes up about 45% without significant differences between the sampling stations. Quartz is more abundant at the northern and southern stations whereas the sum of clay minerals is higher at the central station. This is caused by the resuspension of sandy material in the shallower shore zone at the rim of the lagoon. Calcite is formed as a result of a pH-shift towards basic values (8-10) during periods of high primary production of phytoplankton. Mn-oxydes are a characteristic component of the suspended particulate matter inside the lagoon, which act as a kind of trap for Manganese because of its capacity for redox cycling (see comparison to the sediment, fluffy layer).

Figure 5.2. shows the main differences of the mineralogical composition between the fluffy layer material and the suspended particulate matter at the central station of the lagoon. The main process of formation of fluffy layer material is the aggregation of single particles from the water column and the so called “benthic boundary layer”. This aggregation is forced by sticky properties of organic substances mainly formed by microbiological processes (bacteria) which in fact lead to an organic matter - mineral particle complex of large aggregates. These aggregates have a higher settling velocity than single suspended particulate matter. The results of the analyses in the Oder Lagoon are well conform to the hypothesis of Leipe et al. (2000), who analysed the vertical distribution of minerals in the adjacent Pomeranian Bay. Among the clay minerals, the three layer silicates Illite and Illite-Mixed Layer minerals are preferentially included in aggregates because of their special properties and relations to the microbiological metabolism. More than 50 % of the fluffy layer inorganic material consists of these minerals. All the other minerals (with exception of Mn-oxydes) are present, but not preferentially included in the fluffy layer. Manganese oxides were absent in this layer because of the temporarily anoxic conditions of the sediment/water boundary in the lagoon.

During the sampling time (August 2001) a calm and warm weather prevailed. This was a typical situation for the formation of anoxic environments at the sediment surface. Manganese will be reduced to Mn^{2+} and dissolved and can be precipitated “back” to Mn^{4+} oxide particles in the oxic water above the redox cline. A destruction of the fluffy layer will happen during strong winds because of the resuspension effects of waves and currents. In such situations, the substantial differences between the suspended particulate matter and the fluffy layer will disappear and the material will be more or less homogeneously distributed in the water column.

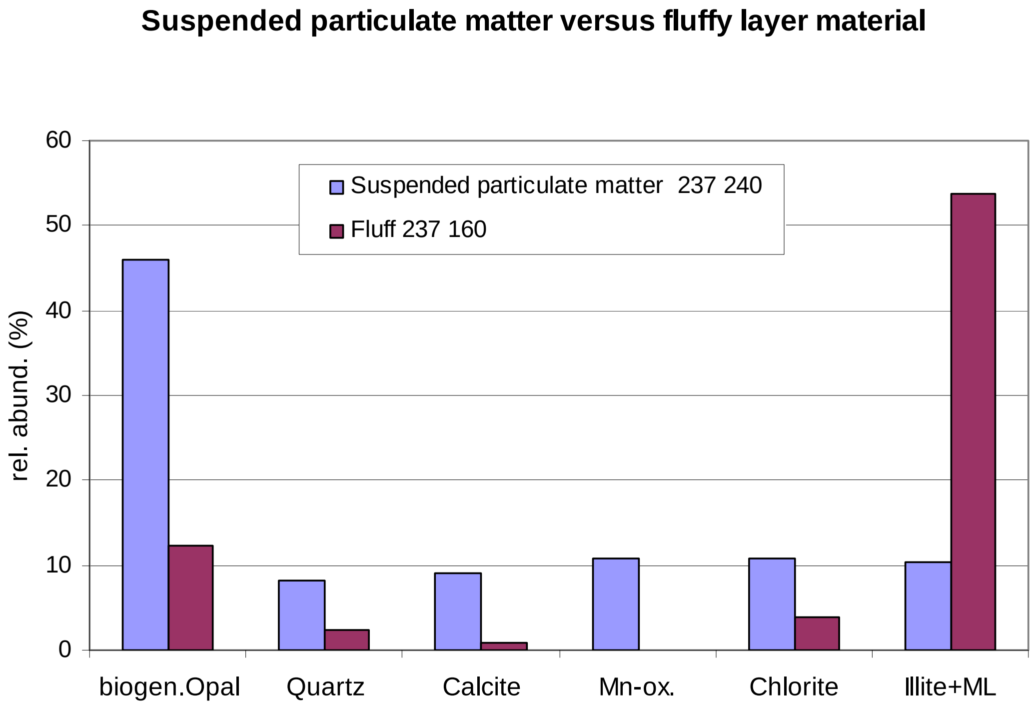


Figure 5.2. Suspended particulate matter versus fluffy layer material.

5.2.5 Wind speed and suspended particulate matter concentration relationship

A good correlation between wind speed and SPM in the Oder Lagoon had been shown previously for example by Burkhardt and Breitenbach (1997) and Fenske et al. (1999). In this study the close relationships were shown again by the analyses of the suspended particulate matter concentrations and the wind speeds (see figure 4.38.). This good correlation showed that the winds were able to resuspend the material quite easily and intensively due to the large area and the shallow depth of the lagoon. Therefore in general it is possible to derive the SPM of the Oder Lagoon according to the wind speed. There were differences in the data observed for the analyses of SPM and the wind speed. Burkhardt and Breitenbach (1997) investigated the relationship between SPM and wind speed in the lagoon in one year period from 8 July 1996 to 23 July 1997 and the data were in monthly resolution. Fenske et al (1999) recorded the SPM and wind data during the Oder flood period from 8 July to 7 August 1997.

In this study, a higher resolution of every 12 hours were used covering the period of 26 August to 2 November 1999. The results of analyses showed that the wind speed and SPM exhibited a high relationship when only the SPM data with the wind directions from east to south winds were considered. The reason for this was that the eastern to southern wind directions had a larger fetch length relative to the point of measurement compared to other wind directions. The resuspension intensity is larger as the fetch length increases.

The suspended particulate matter concentrations during the warm period (April to October) were found to be higher compared to the ones during the cold period (November to March). This is due to phytoplankton that becomes more abundant during the phytoplankton blooms usually occurring in the warm period (around April to October). Higher concentrations of suspended particulate matter in winter and lower concentrations during the warmer time were reflected in the measurements done by Burkhardt and Breitenbach (1997) in the period of 8 July 1996 to 23 July 1997. At the same wind speed of 0 m/s they measured a suspended particulate matter concentration of 9 mg/l in 8 October 1996 (during the warm period) compared to 1.7 mg/l in 20 January 1997 (during winter time). Similarly, at the same wind speed of 2.5 m/s they measured a suspended particulate matter concentration of 22.9 mg/l on 22 July 1997 (during the warm period) compared to 9 mg/l in 9 December 1996 (during winter time). The lower concentrations were due to the seasonal variations of the content of the organic matter. Generally, in autumn and winter time the content of organic matter is the lowest and the content of silicate-bound elements and heavy metals is the highest and in the warm seasons the situation is inverted (Breitenbach et al., 1999).

5.3 Femflow2D hydrodynamic and transport model

5.3.1 The flow module

The flow in the lagoon calculated by the model were the depth-averaged flow values. During the flow measurements in the lagoon it was found that the current velocity and direction were often divided into several layers with different flow velocity and direction. In the flow simulations, inflow discharge from the Oder river to the lagoon was kept constant and the same as the outflow to the Baltic Sea via Swina. In the real situation, slight variations of flow discharge may occur within a time period. The inflow of water from the Baltic Sea to the lagoon was neglected and was not taken into account in the model simulations. However for very large water bodies and shallow depths like in the Oder Lagoon, the application of the model is reasonable. The major target of this study was to understand the average transport conditions in the lagoon. Furthermore the flow measurements are in well agreement with the flow model simulation as shown by the simulation and measurement for the case of 14 August 2001 (see chapter 4.4). Despite the limitations in the model, the current simulation results and the comparisons with the field measurements showed that the Femflow2D can be applied to simulate the flow in the Oder Lagoon.

5.3.2 The particle tracking module

The particle tracking module in the Femflow2D hydrodynamic and transport model can be used to study the behaviour of particulate materials in the lagoon. The results of the particle tracking can be interpreted as the concentration distribution or transport probability. The particle tracking module has the limitation that it can only simulate the development of particles moving in the water bodies under one particular flow field. The flow field is the result of flow simulation using particular wind conditions. The flow field used can be from any flow simulation. The flow simulation results as presented in chapter 4.4. indicated that each wind condition could result in different flow conditions. One has to keep in mind that in the real situation, the wind speed and direction is not constant but changing over the time. Therefore to get more complete knowledge of the behaviour of the particles entering the lagoon from the Oder river under different wind conditions, the particle tracking was done using eight different wind directions. The wind speed used was 4 m/s (average wind speed of ten years period of 1991 - 2000).

In the investigation of heavy metal particles entering the lagoon from the Oder river, the flow fields of average wind and strong wind conditions were used. The particle tracking shows the transport of the particles only. Hence, the assumption that the particles were settled after six hours was taken.

5.3.3 The suspended particulate matter module

The suspended particulate matter module in the Femflow2D model was used to study the suspended particulate matter dynamics in the lagoon water bodies. The model has the limitation that it can only simulate one type of sediment class. The physical properties of the sediment need to be prescribed based on the selected sediment type.

At the beginning of the study there was only one option to describe the critical erosion shear stress in the lagoon with constant values over the entire lagoon. The option of spatially variable critical erosion shear stress in the model was newly added in order to better simulate the suspended particulate matter dynamics in the lagoon at short periods, for example during strong wind events that last for 24 hours.

In the model, the existence of the same background suspended particulate matter concentration for the entire lagoon is assumed. In the reality, as shown by the measurements, a variability of suspended particulate matter concentrations in time and space was observed. Therefore the model limits the existence of spatially variable suspended particulate matter concentrations at the beginning of the simulation. Like the flow module, the suspended particulate matter module calculates the concentration as a depth-averaged concentration of suspended particulate matter. Therefore the vertical variation of suspended particulate matter concentrations is not taken into consideration in the model.

5.4 The flow in the Oder Lagoon

The Femflow2D is a two dimensional model and therefore the results of the flow simulation show the average flow velocities in the lagoon from the surface down to the bottom. Despite the flow measurement results which were showing the existence of different flow layers, the model simulations are in well agreement with the depth-averaged measured flow. The model was able to simulate a sufficient spatial flow field with the existing model grid (see figure 3.11.). Eddies and flow structures could be presented quite well (see for example figure 4.30.) and different wind directions resulted in different flow patterns in the lagoon. A change of the wind speed but the same wind direction appeared to affect the flow speed rather than the general flow pattern in the lagoon.

In the coastal areas, at the area close to the reed zones, the discrepancies of model simulation results and current measurements were obvious. This shows the importance of wind sheltering effects due to coastal vegetation in those areas. Lower velocity and different direction of the measured flows compared to the flow simulation in these areas were the results of the combination between wind sheltering effects and higher bottom roughness of the reeds. In the simulation, the bottom roughness of the lagoon was considered as a constant value for the entire lagoon. Therefore the constant wind field was rather a simplification to know the general pattern of the flow in the Oder Lagoon.

The sheltering effects depend on the wind speed and direction relative to the coastline orientations as well as to the nature of the shelters (for examples: buildings, vegetation and geomorphology). For detailed studies along the coastlines and near the reeds, the spatially variable wind field needs to be taken into account in the model simulations. Zero wind speed can be assumed occurring along the coast and increasing linearly offshore up to its full value in terms of the fetch length. The spatially variable wind field gains more importance in the flow simulation of small sheltered lakes as has been pointed out by Podsetchine and Schernewski (1999) in Lake Belau, Northern Germany. The lake which is only 1.1 km^2 in area has a limited small fetch length and the influence of the surrounding topography on the wind field is greater than in a big lakes. Flow simulations showed the different pattern as the spatially variable wind field was applied. The results pointed out the importance of the wind field and roughness of the reeds on the coastal areas particularly for smaller lakes. Therefore for detail studies in the reed zone areas the bottom roughness should be taken into account. The spatial resolution of the Oder Lagoon model grid in the coastal areas used in this study was not that detailed. More detailed grids in the model need to be applied if detailed study on the reed zones are to be conducted. Important to keep in mind is that the depth of the lagoon’s coastline needs to be prescribed as 0.5 meter to get a reliable flow simulation result that fit best to the flow measurements. The depth of 0.05 meter that was used in the beginning of the model simulations yielded flow speeds that are approximately 0.1 time of the measured flow speed.

Large and small eddies can be found in several parts of the lagoon particularly under south west wind directions (see figure 4.30.). These eddies as shown by the tracking of heavy metal particles entering the lagoon from the Oder river were acting as traps for the suspended particulate matter.

In general, the flow in the Oder Lagoon has been successfully simulated and validated. Despite the limitation of the model, the current simulation results and validations with the field measurements showed that the Femflow2D can be used as a predictive tool of flow in the lagoon under different wind directions. The input parameters for the simulation used for the validation are reliable values and can be used for further detailed investigations of the hydrodynamics of the Oder Lagoon. The results proved that the Femflow2D model can be used to study the hydrodynamics of shallow water systems.

The water mass exchange between the Kleines Haff and the Wielki Zalew were studied to to understand the water mass transport condition and to know how intensive is the exchange within these two main parts of the Oder Lagoon. Up to present time, the information about this is lacking despite the importance of this information for understanding the internal lagoon biology, chemical, nutrient and particulate matter transport. The results of this study could be used for further ecological studies in the lagoon particularly in the Kleines Haff.

The cross section for the calculation was not a straight line. At nodes between 737 and 832 a straight line was drawn and the calculation was done based on this line instead of directly at nodes 770 and 803. The depth and flow velocity used in the calculation were wighted values between nodes 770 and 771 as well as 803 and 804. This was meant to reduce the complication and error in the calculations. However the error might still occur with this method.

Under artificial condition an average error of 58% was found in the discharge calculations. This error is much larger compared with the error under natural condition (13.76%). As an attempt to trace the error another flow simulation under blocked condition was done. The bathymetry at all nodes along the cross section dividing the Kleines Haff and the Wielki Zalew was set to 0.5 meter depth which was the same depth as the lagoon coastline. The west wind condition was chosen for the simulation. The result showed an error of 15.57% in the discharge calculation. If we assume that this was the error of the model simulation and should be taken into account in the discharge calculations between the Kleines Haff and the Wielki Zalew then the error under natural condition was minimum and the results of the calculation were more reliable. However the error under artificial condition remained large about 44%. One possible reason was the assumption in the model that the depth of the coastline and the new bathymetry along the cross section under artificial measures needed to be set to 0.5 meter depth. Nevertheless, the error cannot be traced.

The reliability of the water mass exchange calculation results was also shown by the calculation results of the water mass flow to the Baltic Sea via Peene and Dziwna. By taking into account the wind frequency prevailing in the lagoon, the net transport via Peene and Dziwna were 19% and 13% of the Oder Lagoon discharge respectively. This was in accordance with Mohrholz and Lass (1998) investigations on the transport between the

Oder Lagoon and the Baltic Sea. According to their results, if the wind stress on the sea level was taken into account, the transport via Peene and Dziwna were 17 % and 14% of the Oder river discharge respectively.

The water mass exchange between the Kleines Haff and the Wielki Zalew appeared to be quite intesive with an average discharge of about 506 m^3. This value is equal to about 140% of the Oder river inflow of 359 m^3/s that was used in this study. This exchange will be more intensive under strong wind. As has been shown in the results of flow in the lagoon under strong wind event (see chapter 4.5.3), at wind speed of 10 m/s the flow speed in the lagoon increased 2.5 times, as compared to the flow under average wind condition (4 m/s). Similar effect could be expected for the water mass exchange between the Kleines Haff and the Wielki Zalew which will be increase by about 2.5 times.

5.5 The dynamics of suspended particulate matter of the Oder Lagoon

5.5.1 Suspended particulate matter of the Oder Lagoon

The suspended particulate matter of the Oder Lagoon as shown by the analyses in this study are predominated by the organic materials (see chapter 4.4.2). The organic materials comprised 73.4% to 97.2% of the total suspended particulate matter of the lagoon at the localities and time of measurements of this study. The inorganic components were only between 2.8% to 26.6%. The very high organic material was mainly due to the phytoplankton bloom that normally occurs in the lagoon during the warm period, from April to October.

The sampling and analyses in this study were done in August which was in the warm period. The depth of the sampling might also contribute to the high concentration of the organic materials. As shown in figure 4.18. a slightly higher concentration was found near the water surface and the sampling was done at 50 cm depth. During calm wind conditions, some of the algae can be concentrated on the water surface or float as it was observed on 15 August 2001 (see figure 5.3.).

The very high concentrations of the organic materials in the suspended particulate matter also showed that the bloom during the warm period was enormous and contributed the main part of the suspended particulate matter of the Oder Lagoon. This also shows that the biomass production particularly during the warm period is the most important factor in the development of suspended particulate matter of the Oder Lagoon.

In the cold period (in autumn and winter), around November to March, the organic material in the suspended particulate matter become less. This has been shown by the Burkhardt and Breitenbach (1997) observations. The suspended particulate matter concentration differences between warm and cold periods as shown by their measurements were about 61% to 81% (see chapter 5.2.5).

Figure 5.3. Phytoplankton concentrated on the surface of the Oder Lagoon water in calm wind condition on 15 August 2001. Locality was in the northern part of the Kleines Haff near Kamminke.

5.5.2 The suspended particulate matter simulation study

The suspended particulate matter module in the Femflow2D model is a newly developed module and has not been applied before. Therefore before the model could be used, a series of model testing was done during the study. Several different input parameters were applied and the results were observed and compared to the measured suspended particulate matter. The option of spatially variable erosion shear stress was added to the model during this study due to the difficulties in the model calibration for strong wind simulations.

From the simulation results it was found that the model could simulate the dynamics of suspended particulate matter in the lagoon quite reliably with several restrictions. The dynamics of the suspended particulate matter under strong wind conditions can only be simulated for short periods of about 24 hours. The spatially variable erosion shear stress must be applied in this simulation. A suitable spatial erosion distribution pattern for the simulation was found when the values applied followed the spatial sediment distribution. The simulation for longer periods is suitable for more or less stable wind speeds of up to 7 days. A constant erosion shear stress needs to be applied in this simulation. It was also found that using the spatially variable erosion shear stress a higher material constant needs to be applied compared to the constant erosion shear stress.

The input parameter values for the suspended particulate matter module were obtained by the measurements and the calibration. From the suspended particulate matter simulation and validation results as presented in chapter 4.6. it was found that the suitable input parameter values were attributed to the fluffy layer materials. Hence, this result is supporting the statement of the present conditions of the Oder Lagoon by Leipe et al. (1998) who mentioned that the lagoon is characterised by intensive resuspension of the surface sediment layer (soft and fluffy material) during times of enhanced wind speed and wave action on the sea floor. During strong wind events a high suspended particulate matter concentration develops in the lagoon and the transport of sediment to the Baltic Sea is highly increasing.

The suspended particulate matter module is like the flow module. It is a 2D module, therefore the suspended particulate matter concentration is a depth-averaged concentration throughout the water column. The discrepancies between measurements and simulations as shown in figures 4.45. and 4.47. might be caused by this reason. The errors might occur during the measurements by the transmissiometer. Bunt et al. (1999) described several factors that might increase the transmissiometer response such as plankton (by 2 times), grain shape and surface roughness (by 2 and 10 times respectively), grain size changes (by over 100 times) and air bubbles. The discrepancies between measured and simulated suspended particulate matter concentrations particularly at the locality Oderhaff buoy 03 might because of these reasons particularly due to the plankton. The transmissiometer provides point measurements whereas the calculated suspended particulate matter concentrations by the model are depth-averaged values. This might be another possibility why the discrepancies between measured and simulated suspended particulate matter were observed.

5.6 Anthropogenic heavy metal pollution brought by the Oder river into the Oder Lagoon

The anthropogenic heavy metals brought by the Oder river into the lagoon have been described by the application of the particle tracking module of the Femflow2D hydrodynamic and transport model. High concentrations of anthropogenic heavy metals Zn, Cu and Pb were found in the south-western part of the Wielki Zalew (Grosses Haff). This is due to the eddies flow in that area. Hence in the long term period, high concentration developed in that area. During strong wind conditions these sediments with anthropogenic heavy metals can further be resuspended and transported within the lagoon and to the Baltic. Some of the particles were trapped and deposited in the Altwarp reed zone areas.

The Altwarp sediment core 236040 was the longest core and had been analysed more thoroughly than the other core samples. The analyses covered not only the water content and grain size, but also geochemical and carbon analyses. The analyses of this core showed a general increase of major elements (Al, Fe, Mg and P), heavy metals (Zn, Cu, Pb, Ni and Li), TIC, N and TC elements with increasing depth (see appendix 8). The peaks were found at depths between 40 and 50 cm except for Co, Cr and Mn which showed a higher concentration at 22.5 cm as well as Ca and K elements which showed a higher concentration at the uppermost core section or at 2.5 cm depth. The general trend of increasing concentration of those elements to the depth is related to the higher proportions of the clay to silt fraction (less than 63 micrometer) as shown in figure 4.15. To remove the effect of this fine grain size, the concentrations of the heavy metals Zn, Cu and Pb were normalised to Li. The normal concentration between Li and other heavy metals is constant. After the normalisation, the peak can be seen at depth 22.5 cm (see figure 4.16.).

The trend of graphic from low, high and then lowering concentrations of anthropogenic heavy metals Zn, Cu and Pb as shown by the geochemical analyses was also observed by Klutentreter (2000) at the core sample taken from the Wielki Zalew (Grosses Haff). In Arkona Basin, north of the lagoon in the Baltic Sea, similar results were also observed by Neumann et al. (1996). The source of the anthropogenic heavy metals in the basin was predicted as from the Oder river via the lagoon to the Baltic Sea. Dating of the core sediment showed a low concentration around the year 1990 and high concentrations around 1940 to 1975 (Neumann et al., 1996). There was no dating applied during the Altwarp core sediment analyses, therefore the precise pollution history is not known. However, from the general knowledge it is known that the industrialisation time began around 1850 and the most severe pollution happenned from 1930 to 1980. Approximately, from the year 1990 onwards a reduction of the pollution happenned due to the measures taken to reduce the pollution load.

The peaks in the Altwarp core might be attributed to the historical high concentrations of anthropogenic heavy metals during the past. The concentrations of Zn, Cu and Pb showed a development from the background conditions which started around 1850 (lower concentrations) to increasing concentrations due to the anthropogenic pollution during the industrialisation time around 1930 to 1980. Then a reduction of pollution occurred during the past three decades (see figure 4.16.).

5.7 The Oder Lagoon suspended particulate matter mass balance estimation

The Oder Lagoon suspended particulate matter mass balance was estimated mainly based on the analyses of the lagoon's suspended particulate matter concentration and wind speed relationship (see figure 4.38.). The dry bulk density of the lagoon's sediment, the volume of the lagoon, the discharge and suspended particulate matter concentration of the Oder river were additional important data for the estimation. Data were taken from previous studies as well as from the wind speed and suspended particulate matter concentration data analyses. According to Leipe et al. (1998), the input load of sediment from the Oder river is approximately 425.000 ton per year in the 80's which is equal to an input of suspended particulate matter of of 25 mg/l.

Beside the input of suspended particulate matter load from the Oder river which is the largest input for the lagoon, a smaller amount of suspended particulate matter load transported to the lagoon from other sources such as from the Uecker river and the adjacent coastal areas. However the amount of these materials is low compared to the input from the Oder river. The amount of the sediment transported from the Uecker river is estimated to be about 2513.64 tons per year which is calculated from the discharge of the river (4.89 m^3/s) and the average suspended particulate matter concentration (16.3 g/m^3). This input load is about 0.6 % of the Oder river suspended particulate matter load. This value is relatively small and the Oder river remains the major source of the suspended particulate matter for the lagoon.

To maintain the depth of the shipping channel that connects the Baltic Sea and the harbour of Szczecin via the Swina river, the channel is dredged every year. The yearly average amount of the dredged material is estimated to be about 298062 tons per year (Minning et al., 2003). If the amount of the sediments from the dredging activities is not taken into account, a balance of input of the suspended particulate matter load from the Oder river and the output via Swina, Dziwna and Peene rivers is reached at a wind speed of 4.3 m/s. This is similar to the average wind speed in the lagoon (4 m/s).

Due to the dredging activities, a wind speed as low as about 0.8 m/s is enough to make the balance of input and output of the sediment. This wind speed is far below the average wind speed in the lagoon (4 m/s). Hence the lagoon is at present acting as an exporting system. If the resuspension activity in the lagoon remains in the same conditions due to the prevailing average wind speed, then the lagoon may lose some of the sediment that is transported to the Baltic Sea. In the long run if the same wind conditions prevail and the dredging activities continue like at present time, the lagoon may become deeper.

6 SUMMARY AND CONCLUSIONS

6.1 Summary

The Oder Lagoon which is located at the border between Germany and Poland is a large lagoon. The lagoon has an area of about 687 km^2, nearly the same as the areas of the country of Singapore which is 682 km² and slightly smaller than Hamburg State in Germany which is 755 km². Although the size is large, the lagoon is shallow with an average water depth of only 3.8 meter. The deepest part is the man-made shipping channel stretching from the south-east to the north-west in the eastern part of the lagoon connecting the city of Szczecin and the Baltic Sea via Swina outlet. The depth of this shipping channel is around 10.8 meter while the natural depth reaches only about 7.7 meter. In this large but shallow lagoon, the hydrodynamics and the sediment resuspension are largely influenced by the prevailing wind.

Based on the daily average wind analyses, the prevailing wind in the lagoon is the south-west wind with a frequency of 25%. The other winds according to their frequencies from higher to lower were south (17.19%), west (16.01%), north-east (11.05%), east (10.55%), south-east (7.79%), north (6.2%) and north-west winds (6.17%). The average wind speed was 4 m/s with a frequency of 49.07% compared to the other wind speeds. Mostly, the winds are relatively calm in which 84.93% of the wind speed were less than 6 m/s. As the wind speed increased the importance of south-west and west winds became more significant. The frequency of south-west and west winds of wind speed stronger than 4 m/s, 6 m/s, 8 m/s were: 37.42% and 23.12%, 47.2% and 28.93%, 54.25% and 35.29% respectively. The wind speed of stronger than 10 m/s were mostly the west and south-west winds with 51.61% and 35.48% respectively. In winter, the average wind speed was the highest (4.72 m/s) compared to other seasons and summer has the lowest average wind speed (3.47 m/s).

Air temperatures in the lagoon area follow the cycle of cold temperatures in winter and warm temperatures in summer seasons with the lowest monthly average temperature of 0.84 °C in January and the highest one of 17.85 °C in August. During the winter time the lagoon water surface may be entirely or partly frozen due to prevailing temperatures of below zero °C. As the temperatures become lower, the effects of wind to the hydrodynamics and the sediment resuspension in the lagoon are reducing.

The surface sediments of the Oder Lagoon mainly consists of sand at the coastal zones to a water depth of about 2.9 meter and silts in the deeper areas. Mussel banks of predominantly *Dreissena polymorpha* are found in some areas like off-coast Mönkebude at water depths of about 3.5 meter. The water content of the sediments are closely related to the sediment types. Sand sediments have a lower water content ranging from 12.52 % to 19.79 %. The silt sediments have a higher water content ranging from 62.36 % to 87.88 %. The average grain size of the silt sediments is between 31 μm and 63 μm (coarse silt) and the sand sediments have an average grain size between 177 µm and 322 µm (fine to medium sand). The sand sediments have D_{50} values between 161 µm and 310 µm and their D_{90} values are between 210 µm and 750 µm. The D_{50} values of the silt sediments are between 28 µm and 57 µm whereas their D_{90} values were between 53 µm and 116 µm.

The core sediments from the reed zones of Mönkebude and Altwarp are predominantly sand with an average grain size between 135 µm and 287 µm (fine to medium sand). Their water content was between 21.16 % and 64.66 %.

The TOC/N ratio of the silt sediments is below 10 except the sediment from the Altwarp Port. They range from 5.61 to 9.25 indicating a phytoplankton origin of the carbon in the sediments. The core sample 236040 showed a range of TOC/N ratio between 5.9 to 21.6 indicating both a phytoplankton and terrestrial origin of the carbon in the sediments.

Along the section from Mönkebude to Kamminke (south-west to north-east in the Kleines Haff), the geogenic and redox elements in the silt sediments showed a relatively higher concentration in the north-eastern section. A slightly higher concentration of anthropogenic heavy metals (Zn, Cu and Pb) was also found in the northern part of the section. The nutrient element's concentration was slightly higher in the central part of the section.

The longest sediment core from Altwarp (sample and locality 236040) revealed the history of anthropogenic pollution in the Oder Lagoon. The general trend of geochemical elements throughout the core section from 2.5 cm to 47.5 cm depth showed an increasing concentrations toward the deeper section. All elements were increasing to the deeper section except Co, Cr , Mn, Ca and K. The water content and percentage of clay to silt fraction also showed this phenomenon. However, the normalisation of heavy metals Zn, Cu and Pb to Li showed the peak to be in the middle of the core section at 22.5 cm depth and lower concentration at the deepest section. The position of this peak may be related to the anthropogenic pollution brought by the Oder river into the lagoon. The deeper part of the core is related to the background conditions with low pollution, then higher pollution occurs during the industrialisation time around 1940 to 1980. The pollution reduction efforts during the past decades have resulted in a decrease of the anthropogenic pollution as shown by the lowering of the heavy metals concentration.

The suspended particulate matter of the Oder Lagoon had an average grain size between 29 µm and 37 µm. The suspended particulate matter concentration at the Mönkebude to Kamminke section in 15 August 2001 were between 13.7 to 23 mg/l with an average concentration of 16.4 mg/l. The amount of organic components was considerably higher compared to the inorganic components (between 73.4% and 97.2% compared to 2.8% and 26.6%). The vertical profile of suspended particulate matter concentrations at 5 meter depth in the central part of the Kleines Haff in 16 August 2001 showed only slightly higher values in the upper part of the water column, from 17 mg/l to 12 mg/l. The organic part consists predominantly of phytoplankton. The five most abundant species were *Planktothrix sp.*, *Anabaena sp.*, *Mycrosistis sp.*, *Anabaenopsis sp.* and *Pseudanabaena /*

Limnothrix sp. Biogenic opal was the most dominant mineral in the Oder Lagoon suspended particulate matter comprising 43.9% to 46%. The suspended particulate matter compositions are influenced by the nearby sediments, i.e. near the coastal areas Quartz is more abundant and the sum of clay minerals which include Chlorite, Kaolinite, Illite, Illite-ML and Smectite are more abundant in the central part of the lagoon in the Kleines Haff. The fluffy layer is formed on the surface of the lagoon's sediments during very calm wind conditions. In this fluffy layer, the sum of the clay minerals was dominant comprising 71.5% of its total composition. During calm and warm weather conditions, anoxic environments at the sediment surface might be formed. This is shown by the absence of Mn-oxides as it was recorded on 14 August 2001.

The Femflow2D hydrodynamic and transport model is a two dimensional model. The simulated flow velocities are averages from the surface down to the bottom of the water bodies. For the Oder Lagoon, the suitable input paramater values used to simulate the lagoon hydrodynamics are a Manning roughness coefficient of 0.015 $m^{-1/3}$, a turbulence exchange coefficient of 0.1 m^2/s, a wind drag force of 3.2×10^{-6}, a Coriolis parameter of 1.174×10^{4}. In order to fit with the real hydrodynamic conditions in the lagoon, the depth of the coastline needs to be set to 0.5 meter. Furthermore, a constant discharge from the Oder river, a constant outflow discharge via Swina river (69% of the Oder discharge), open boundaries at Peene and Dziwna rivers are suggested to be used in the simulations.

The average transport conditions are well reflected by the Femflow2D model despite the measurements which showed the water column to be divided into layers with different velocity and direction. The spatial resolution of the model grid is sufficient to show the important eddies and flows. The wind sheltering effects are visible in the lagoon and the sheltered areas depend on the wind speed and direction. Therefore a spatially variable wind field is needed to perform reliable flows in the coastal areas. A detailed knowledge of the wind field and grid size are needed when studying the flows in the coastal areas. Large and small scale eddies are visible at all wind directions and more eddies occur when the south-west wind prevails.

The rate of water mass exchange between the Kleines Haff and the Wielki Zalew depend on the wind speed and wind direction. According to the wind direction, the intensivity of the water mass exchange from high to low are as follows: west, north-west, south-east, east, north, south-west, south and north-east winds. The average water mass exchange between the Kleines Haff and the Wielki Zalew was 506 m^3/s. This is equal to about 140% of the Oder river discharge into the lagoon which is 359 m^3/s. Theoretical water mass exchange time of the Kleines Haff is 43 days.The effect of the wind speed is increasing the amount of water exchange between these two large parts of the lagoon. As the wind speed increases from 4 m/s to 10 m/s the rate of the water mass exchange increases by about 2.5 times.

Despite its limitations, the particle tracking module of the Femflow2D is a very useful tool to investigate the transport of water masses or particles moving with the water in the lagoon. The wind speed and direction play a major role on the transport pathways. Under the average wind speed of 4 m/s and a wind direction of 223°, 62% of the water or particles from the Oder river enter into the western part and 35 % to the eastern part of the Wielki Zalew respectively. As the wind speed become stronger more water masses or particles are transported to the western part of the Wielki Zalew. At wind speed of 10 m/s and a wind direction of 248° (the average wind direction for this wind speed in the ten year period of 1991 to 2000), 96 % of the water masses or particles were transported to the western part of the Maly Zalew. None is transported to the eastern part of the Maly Zalew, the rest of 4 % remains near the Oder river mouth areas. The transport of water masses or suspended particulate matter entering the lagoon from the Oder river affected by the wind speed and direction too. Northerly and north-easterly winds favour a direct transport of the Oder river water mass to the Baltic Sea via Swina. During westerly and north-westerly winds, the water from the Oder River is transported into the western part of the lagoon (Kleines Haff). Under south and south-west wind conditions, the water from the river is transported to both parts of the lagoon. A transport of water mainly to eastern part of the lagoon is observed under south and south-west winds conditions.

The particle tracking module of the Femflow2D model can be further applied to study the anthropogenic heavy metals brought by the Oder river from the hinterland into the lagoon. Most of the heavy metal particles which are mainly bound to suspended particulate matter are deposited in the western side of the Wielki Zalew (Grosses Haff). High concentrations compared to any other areas in the lagoon were found there. This is in accordance with the particle tracking analyses. Furthermore, the higher the wind speed the much more particles are transported to this area. The reason why high amounts of anthropogenic heavy metals are concentrated in this area rather than being further transported to the other parts of the lagoon is because of the eddies in this area. Large and small scale eddies in this area act as traps for those heavy metal particles. Although most of the heavy metal particles were trapped, during strong wind events some of them can be transported as far as to the reed zone in Altwarp (for example in the core sample 236040 area) and deposited in this relatively calm area.

The suspended particulate matter concentration of the Oder Lagoon is closely related to the wind speed (Pearson correlation $R^2 = 0.91$) and the relationship can be written as $y = 5.1x + 3.2$ (y is suspended particulate matter concentration in mg/l and x is wind speed in m/s). From the correlation graphic it can be estimated that the critical wind speed for resuspension of the sediment is about 5 m/s to 6 m/s. Similarly, the transmission values measured and monitored by the GKSS Oder buoys can be converted into suspended particulate matter concentration values in mg/l by a regression relationship of $y = -21.34 \ln(x) + 101.78$ (y is transmission in % and x is suspended particulate matter concentration in mg/l).

The SSC module in the Femflow2D model can be used for simulating the dynamics of SSC in the Oder Lagoon quite reliably particularly for the short simulation period of 24 hours. To simulate the dynamics of suspended particulate matter in the Oder Lagoon, the same input parameter values that have been applied in the flow simulations are used. Additionally input parameters for SSC block are needed. The model shows a good correlation when the physical properties of fluffy materials are entered in the parameters. The input parameter values suitable for both the short and long period of simulation are 28 µm and 53 µm for D_{50} and D_{90} grain size, the settling velocity of 3.3 x 10^{-4} m/s, the power of erosion of 3, the critical erosion and deposition shear stresses of 0.02 N/m^2 and 0.015 N/m^2. Unlike the flow simulations, the turbulence exchange coefficient appropriate for suspended particulate matter simulation is 0.8 m^2/s. For the long simulation period of up to 7 days, a material constant of 2.72 x 10^{-3} g/m^2/s, the constant critical erosion shear stress of 0.015 N/m^2 and critical deposition shear stresses of 0.005 N/m^2 are the appropiate values. Integration time steps of the simulation of 10 seconds as well as the timestep of 30 seconds for sediment transport are suggested. For the short simulation period of 24 hours, the material constant of 0.55 g/m^2/s needs to be applied. Spatially variable critical erosion shear stress is required for the short simulation period. The distribution of erosion shear stress values follows more or less the spatial distribution of sediments in the lagoon. In the coastal areas which are occupied by sand sediments the value of 0.12 N/m^2 are prescribed whereas in the deeper areas 0.013 N/m^2 is a suitable value. The critical deposition shear stress appropiate for the short simulation period is 0.01 N/m^2.

The average concentration of suspended particulate matter input from the Oder river to the lagoon is about 25 mg/l. This is equal to about 425000 tons of sediment that is transported yearly from the Oder river to the lagoon. This suspended particulate matter input is the main sediment load for the Oder Lagoon. Based on the wind speed and suspended particulate matter correlation, the function of the Oder Lagoon in terms of a suspended particulate matter mass balance can be predicted. At wind speeds of 4.3 m/s the lagoon is a balanced system in which the input load to the lagoon is the same as the output load out of the lagoon. At wind speeds below 4.3 m/s the lagoon acts as a trap for the suspended particulate matter and at wind speeds above 4.3 m/s the lagoon exports sediment. In the lagoon, dredging activities along the shipping channel are going on. About 300000 tons of sediment are dredged every year (Minning et al., 2003). If the dredging activities are taken into account then a lower wind speed of 0.8 m/s is enough to bring the lagoon into the balance. This wind speed is below the average wind speed prevailing in the Oder Lagoon which is 4 m/s. Therefore, the lagoon is acting as an exporting sediment system rather than a trapping system at present.

6.2 Conclusions

- The Oder Lagoon is a large (about 687 km^2) and shallow (average depth of 3.8 meter) water body. In this large but shallow water body, the prevailing wind as well as the lagoon morphometry largely influence the hydrodynamics and the sediment resuspension.

- In the winter time when the temperature drops to below zero degree Celcius, the lagoon may be partly or entirely covered with ice. During this time the influence of wind on the hydrodynamics and sediment resuspension of the lagoon is minimum.

- The hydrodynamics of the Oder Lagoon can be simulated by the Femflow2D hydrodynamic and transport model quite reliably. The measurements fit well with the simulated flow field in the lagoon. The wind sheltering effects are visible in the lagoon and the sheltered areas depend on the wind speed and direction.

- Under all wind directions, which are predominated by the south, south-west and west winds, large and small eddy flows develop in the lagoon. These eddies act as important traps for the suspended particulate matter transported in the lagoon.

- The rate of water mass exchange between the Kleines Haff and the Wielki Zalew depends on the wind direction and the wind speed. The exchange of water mass between those two large parts of the lagoon occurs most intensively under west wind conditions and least intensively under nort-east wind conditions. The water mass exchange between the Kleines Haff and the Wielki Zalew is occurring intensively with an average discharge of 506 m^3/s. This is equal to about 140 % of the Oder river discharge which is 359 m^3/s that is used in the calculation. Theoretical water mass exchange time of the Kleines Haff is 43 days. As the wind speed increases the water mass exchange is increasing. The water mass exchange increases by about 2.5 times if the wind speed increases from 4 m/s to 10 m/s.

- At the Oder river mouth area in the Wielki Zalew or Grosses Haff (eastern part of the lagoon) the eddies are trapping the suspended particulate matter brought by the Oder river from the hinterland. High concentrations of anthropogenic heavy metal elements (Zn, Cu and Pb) can be observed in this area as the result of sedimentation in the long term period.

- The wind speed is highly correlated with the suspended particulate matter concentration in the Oder Lagoon ($y = 5.1x + 3.2$, $R^2 = 0.91$). Critical wind speeds for the sediment resuspension are estimated to be about 5 m/s to 6 m/s.

- The Oder Lagoon is characterised by the resuspension of mobile fluffy organic rich materials and the dynamics of the suspended particulate matter of the lagoon. Particularly during strong wind events it can be simulated quite reliably by the Femflow2D hydrodynamic and transport model.

- On the basis of suspended particulate matter and wind speed correlation, the Oder Lagoon can be described in two different ways:
  a. In the natural conditions, the lagoon is a balanced system at wind speeds of 4.3 m/s. The input of suspended particulate matter load to the lagoon is the same as the output load because the suspended particulate matter concentration input from the

Oder river is the same as the suspended particulate matter concentration in the lagoon (25 mg/l).

b. If the dredging activities are taken into account (about 300000 ton per year), the lagoon can be described as a material exporting system or material losing system.

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Appendix 1-A. Wind chart of monthly wind directions period 1991 – 2000 at Ueckermünde Weather Station.

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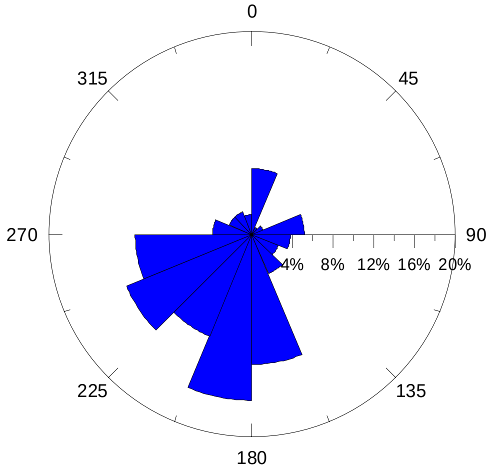

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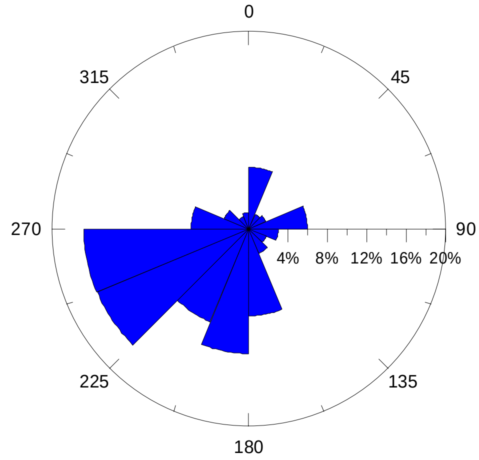

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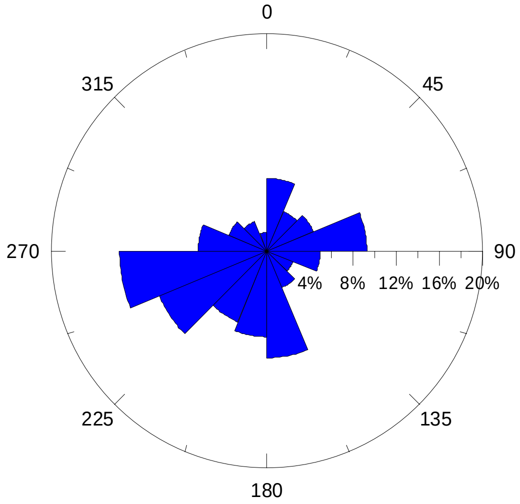

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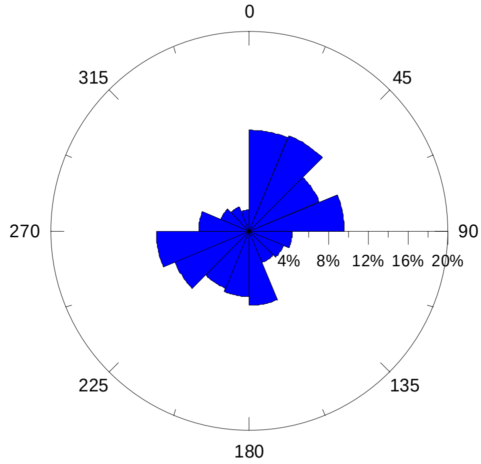

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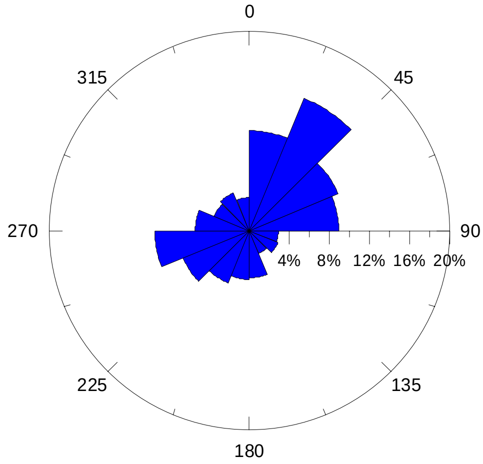

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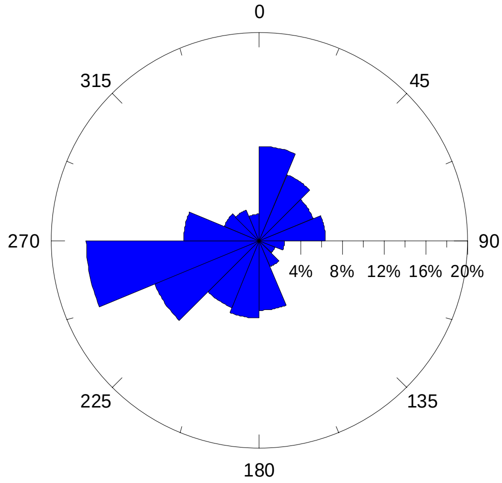

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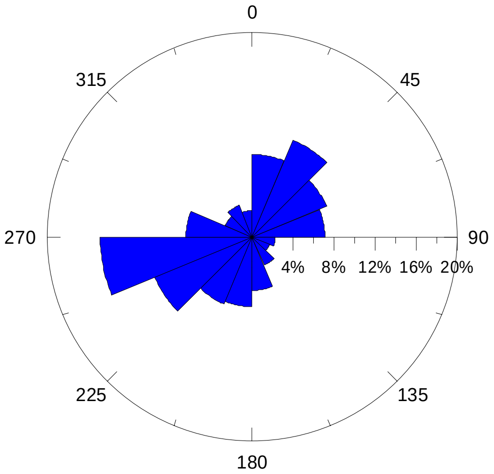

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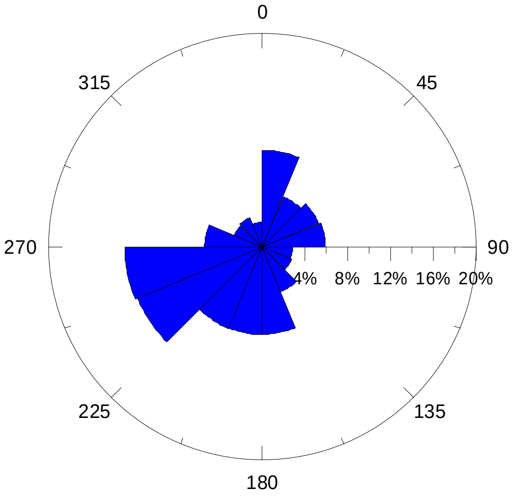

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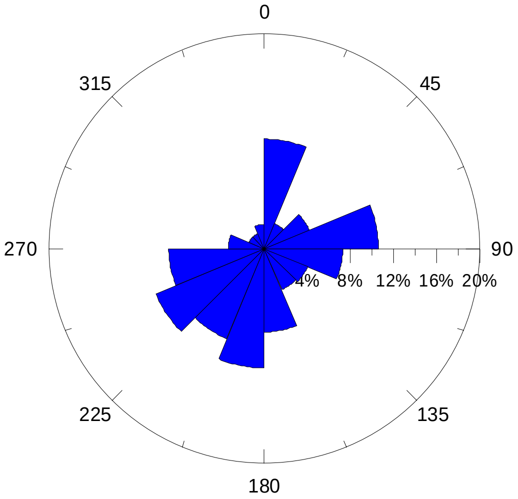

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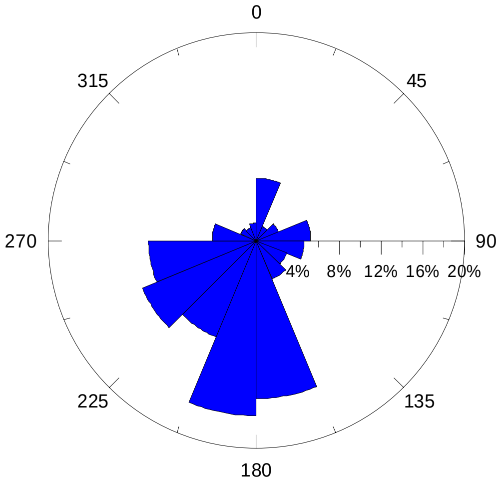

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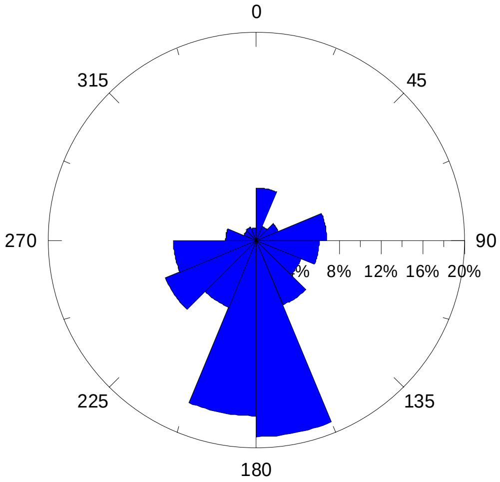

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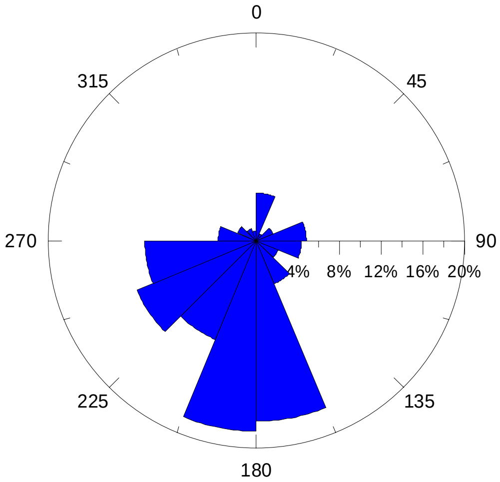
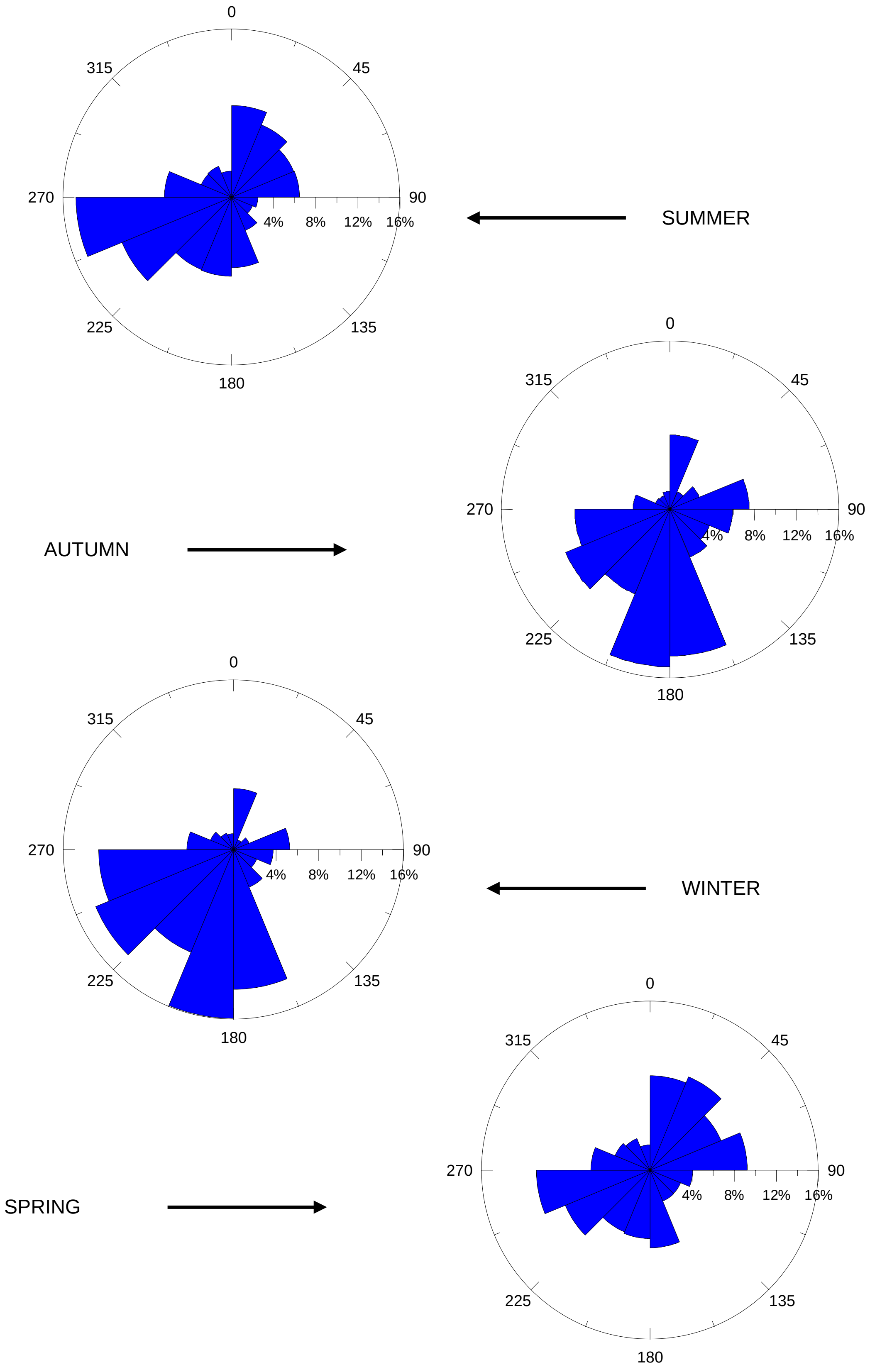


Appendix 1-B. Wind chart of seasonally wind directions period 1991 – 2000 at Ueckermünde Weather Station.



Appendix 2-A. Water content of surface sediment samples.

Station	North	East	Date	Core slice	Note	Weight (fresh) g	Weight (dry) g	Weight (container) g	Weight H_2O, %	Weight (sample) g
236060	53°44.40	14°16.40	10/05/2001	2 , A - B same sample	Altwarp Port					
236060	53°44.40	14°16.40	10/05/2001	A	Altwarp Port	566.58	215.33	58.94	69.19	156.39
236060	53°44.40	14°16.40	10/05/2001	B	Altwarp Port	543.25	295.48	59.04	51.17	236.44
					Average				**60.18**	
236070	53°44.25	14°16.30	10/05/2001	2 , A - B same sample	Altwarp Bay I					
236070	53°44.25	14°16.30	10/05/2001	A	Altwarp Bay I	341.89	91.56	58.76	88.42	32.8
236070	53°44.25	14°16.30	10/05/2001	B	Altwarp Bay I	437.37	106.65	58.76	87.35	47.89
					Average				**87.88**	
236080	53°44.00	14°16.40	10/05/2001	2 , A - B same sample	Altwarp Bay II					
236080	53°44.00	14°16.40	10/05/2001	A	Altwarp Bay II	539.21	164.24	58.36	77.98	105.88
236080	53°44.00	14°16.40	10/05/2001	B	Altwarp Bay II	495.37	138.9	58.8	81.65	80.1
					Average				**79.82**	
236090	53°46.37	13°58.60	09/05/2001	A (top), 10 cm	Mönkebude-east	506.57	408.08	10.77	19.86	397.31
236090	53°46.37	13°58.60	09/05/2001	B (bottom), 10 cm	Mönkebude-east	506.34	408.67	10.76	19.71	397.91
					Average				**19.79**	
236100	53°46.37	13°58.50	09/05/2001	A (top), 10 cm	Mönkebude-central	216.95	180.57	10.74	17.64	169.83
236100	53°46.37	13°58.50	09/05/2001	B (bottom), 10 cm	Mönkebude-central	198.13	161.07	10.73	19.78	150.34
					Average				**18.71**	
236110	53°46.40	13°58.45	09/05/2001	A (top), 10 cm	Mönkebude-west	489.55	397.47	10.75	19.23	386.72
236110	53°46.40	13°58.45	09/05/2001	B (bottom), 10 cm	Mönkebude-west	504.26	405.95	10.75	19.92	395.2
					Average				**19.58**	

Appendix 2-B. Water content of core sediment samples.

Station	North	East	Date	Core length	Core slice	Note	Weight (fresh) g	Weight (dry) g	Weight (container) g	Weight H_2O, %	Weight (sample) g
236020	53°46.35	13°59.00	09/05/2001	35 cm (total)	5 cm n=7	Mönkebude I					
236020	53°46.35	13°59.00	09/05/2001	2.5	1	Mönkebude I	493.13	350.38	11.13	29.62	339.25
236020	53°46.35	13°59.00	09/05/2001	7.5	2	Mönkebude I	476.28	328.95	11.12	31.67	317.83
236020	53°46.35	13°59.00	09/05/2001	12.5	3	Mönkebude I	536.1	394.17	58.2	29.70	335.97
236020	53°46.35	13°59.00	09/05/2001	17.5	4	Mönkebude I	576.45	430.64	58.68	28.16	371.96
236020	53°46.35	13°59.00	09/05/2001	22.5	5	Mönkebude I	599.25	449.99	58.55	27.60	391.44
236020	53°46.35	13°59.00	09/05/2001	27.5	6	Mönkebude I	506.5	376.57	58.54	29.00	318.03
236020	53°46.35	13°59.00	09/05/2001	32.5	7	Mönkebude I	519.63	392.6	58.32	27.54	334.28

Station	North	East	Date	Core length	Core slice	Note	Weight (fresh) g	Weight (dry) g	Weight (container) g	Weight H_2O, %	Weight (sample) g
236030	53°45.00	14°16.10	10/05/2001	23 cm	5 cm n=5	Altwarp I					
236030	53°45.00	14°16.10	10/05/2001	2.5	1	Altwarp I	374.66	243.54	11.09	36.06	232.45
236030	53°45.00	14°16.10	10/05/2001	7.5	2	Altwarp I	506.72	379.84	11.20	25.61	368.64
236030	53°45.00	14°16.10	10/05/2001	12.5	3	Altwarp I	617.02	468.18	11.17	24.57	457.01
236030	53°45.00	14°16.10	10/05/2001	17.5	4	Altwarp I	559.3	421.13	11.19	25.21	409.94
236030	53°45.00	14°16.10	10/05/2001	22.5	5	Altwarp I	555.21	440.05	11.08	21.16	428.97

Appendix 2-B. Water content of core sediment samples.

Station	**North**	**East**	**Date**	**Core length**	**Core slice**	**Note**	**Weight** (fresh) g	**Weight** (dry) g	**Weight** (container) g	**Weight** H_2O, %	**Weight** (sample) g
236040	53°45.00	14°.16.10	10/05/2001	50 cm	5 cm n=11	Altwarp II					
236040	53°45.00	14°.16.10	10/05/2001	2.5	1	Altwarp II	568.99	362.03	11.08	37.10	350.95
236040	53°45.00	14°.16.10	10/05/2001	7.5	2	Altwarp II	657.03	484.43	11.09	26.72	473.34
236040	53°45.00	14°.16.10	10/05/2001	12.5	3	Altwarp II	570.53	438.91	11.19	23.53	427.72
236040	53°45.00	14°.16.10	10/05/2001	17.5	4	Altwarp II	543.96	420.43	11.13	23.18	409.3
236040	53°45.00	14°.16.10	10/05/2001	22.5	5	Altwarp II	538.5	411.79	11.12	24.03	400.67
236040	53°45.00	14°.16.10	10/05/2001	27.5	6	Altwarp II	691.27	528.49	11.16	23.93	517.33
236040	53°45.00	14°.16.10	10/05/2001	32.5	7	Altwarp II	519.15	365.66	11.27	30.22	354.39
236040	53°45.00	14°.16.10	10/05/2001	37.5	8	Altwarp II	368.87	172.95	11.11	54.76	161.84
236040	53°45.00	14°.16.10	10/05/2001	42.5	9	Altwarp II	355.39	132.8	11.12	64.66	121.68
236040	53°45.00	14°.16.10	10/05/2001	47.5	10	Altwarp II	478.52	266.86	11.13	45.29	255.73

Station	**North**	**East**	**Date**	**Core length**	**Core slice**	**Note**	**Weight** (fresh) g	**Weight** (dry) g	**Weight** (container) g	**Weight** H_2O, %	**Weight** (sample) g
236050	53°45.00	14°.16.10	10/05/2001	45 cm	5 cm n=9	Altwarp III					
236050	53°45.00	14°.16.10	10/05/2001	2.5	1	Altwarp III	496.62	355.1	11.14	29.15	343.96
236050	53°45.00	14°.16.10	10/05/2001	7.5	2	Altwarp III	569.09	437.22	11.07	23.63	426.15
236050	53°45.00	14°.16.10	10/05/2001	12.5	3	Altwarp III	623.56	485.76	11.17	22.50	474.59
236050	53°45.00	14°.16.10	10/05/2001	17.5	4	Altwarp III	623.81	472.93	11.13	24.63	461.8
236050	53°45.00	14°.16.10	10/05/2001	22.5	5	Altwarp III	624.79	482.55	11.14	23.18	471.41
236050	53°45.00	14°.16.10	10/05/2001	27.5	6	Altwarp III	562.42	445.41	11.31	21.23	434.1
236050	53°45.00	14°.16.10	10/05/2001	32.5	7	Altwarp III	526.84	416.01	11.17	21.49	404.84
236050	53°45.00	14°.16.10	10/05/2001	37.5	8	Altwarp III	507.09	347.77	11.22	32.13	336.55
236050	53°45.00	14°.16.10	10/05/2001	42.5	9	Altwarp III	557.14	253.51	11.22	55.62	242.29

Appendix 3. Geochemical Analyses of sediment samples.

Sample	Al %	Ca %	Co ppm	Cr ppm	Cu ppm	Fe %	K %	Li ppm	Mg %	Mn ppm	Ni ppm	P ppm	Pb ppm	Zn ppm	N %	TOC %	TIC %	CaCO3 %	TS %
237280	0.75	0.73	6	29	11	0.87	0.37	3	0.07	526	4	226	2	45	0.06	5.24	1.35	13.07	1.69
237290	1.41	0.53	7	47	9	1.07	0.77	4	0.12	520	3	267	11	36	0.01	0.04	0.30	3.82	0.20
237300	3.1	7.36	14	57	54	3.75	1	24	0.61	2139	31	1157	88	566	1.34	8.38	1.78	33.21	5.05
237310	2.8	10.06	13	61	65	3.34	0.89	21	0.59	2639	34	1887	110	727	1.79	10.04	2.35	44.69	3.60
237320	2.29	12.72	10	39	44	2.84	0.76	17	0.49	1995	24	1305	65	462	1	7.08	3.69	62.50	4.14
237270	3.19	7.83	14	58	55	3.67	1.01	24	0.61	1976	32	959	100	636	1.32	8.17	2.29	38.63	5.84
237260	2.97	7.79	14	64	74	3.44	1	23	0.63	3102	36	2397	113	804	1.65	10.99	1.80	34.49	3.14
237250	4.91	1.98	18	67	44	5.75	1.44	39	0.79	1560	34	707	80	298	1.07	7.25	0.49	9.02	10.02
237240	4.54	3.17	16	68	48	5.52	1.35	35	0.74	1689	33	926	90	324	1.14	7.38	0.80	14.56	8.64
237230	2.92	9.21	14	58	72	3.47	0.99	21	0.59	2051	36	1307	121	856	1.28	9.78	2.09	40.42	3.78
237220	1.23	0.55	12	41	14	1.04	0.55	2	0.17	531	3	369	1	34	0.01	0.48	0.29	3.77	0.38
237210	1.24	0.56	13	39	6	1.15	0.6	2	0.16	542	3	378	10	30	0.01	0.14	0.00	1.40	0.19
237200	1.32	0.27	4	16	6	0.39	0.85	3	0.07	138	1	153	9	16	0.01	0.31	0.00	0.68	0.19

Sample	Al %	Ni ppm	Fe %	Cr ppm	Mg %	Mn ppm	Ca %	P ppm	Zn ppm	Cu ppm	Pb ppm	Li ppm	Co ppm	K %
236060 A	8.09	47	3.82	55	1.55	323	1.47	1009	137	42	21	64	18	2.53
236070 A	3	48	3.56	73	0.52	1618	8.25	1225	666	74	133	21	15	0.83
236070 B	2.81	45	3.4	56	0.47	1432	7.93	1079	645	67	117	38	13	0.77
Average	2.905	47	3.48	64.5	0.495	1525	8.09	1152	655.5	70.5	125	29.5	14	0.8
236080 A	2.53	20	2.25	36	0.34	624	6.37	529	163	31	39	15	8	0.95
236080 B	2.16	16	1.84	31	0.29	602	8.13	571	156	24	39	11	6	0.88
Average	2.345	18	2.045	33.5	0.315	613	7.25	550	159.5	27.5	39	13	7	0.915

Appendix 4. TIC, TC, N and TOC of the surface sediment samples.

Sampling date: 15 August 2001

Sample	TIC %	TC %	TOC %	N %	TOC/N Ratio
237300	1.778	10.16	8.382	1.34	6.26
237310	2.346	12.39	10.044	1.79	5.61
237320	3.686	10.77	7.084	1	7.08
237270	2.287	10.46	8.173	1.32	6.19
237260	1.803	12.79	10.987	1.65	6.66
237250	0.489	7.74	7.251	1.07	6.78
237240	0.796	8.18	7.384	1.14	6.48
237230	2.088	11.87	9.782	1.28	7.64

Sampling date: 10 May 2001

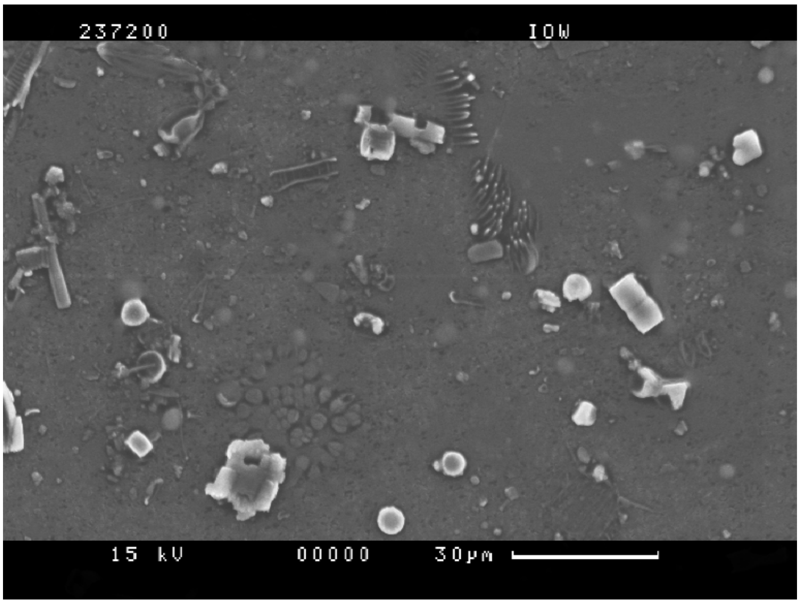
Sample Name	N %	TC %	TIC %	TOC %	C/N Ratio	TOC/N Ratio
236060_A	0.17	1.960	0.0548	1.9052	11.53	11.21
236060_B	0.1	1.080	0.0494	1.0306	10.80	10.31
236070_A	1.52	15.770	2.3054	13.4646	10.38	8.86
236070_B	1.47	15.380	2.2913	13.0887	10.46	8.90
236080_A	0.49	6.230	1.6332	4.5968	12.71	9.38
236080_B	0.52	7.150	2.4060	4.7440	13.75	9.12
Mean						
236060	0.135	1.520	0.0521	1.4679	11.16	10.87
236070	1.495	15.575	2.2984	13.2767	10.42	8.88
236080	0.505	6.690	2.0196	4.6704	13.23	9.25

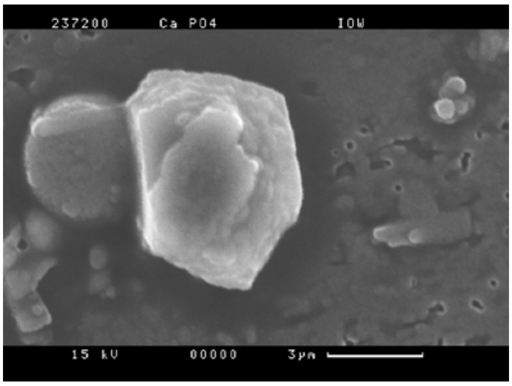
Appendix 5. Suspended particulate matter concentration measurements.

Water Sample (ml)	**North**	**East**	**Filter Number**	**Dry Weight** (filter only) gram	**Dry Weight** (filter + ssc) gram	**SPM Weight** gram	**SPM** mg/l	**Weight burned** gram	**Inorganic** gram	**Inorganic** mg/l	**Inorganic** %	**Organic** gram	**Organic** mg/l	**Organic** %
Sampling date: 15 August 2001														
237200	53°51.893	14°09.374	16	0.03667	0.03829	0.00162	16.2	0.03710	0.00043	4.3	26.60	0.00119	11.9	73.40
237210	53°51.735	14°08.930	13	0.03688	0.03837	0.00149	14.9	0.03704	0.00016	1.6	10.13	0.00133	13.3	89.87
237210	53°51.735	14°08.930	21	0.03733	0.03877	0.00144	14.4	0.03759	0.00026	2.6	16.99	0.00118	11.8	83.01
237210	53°51.735	14°08.930	22	0.03659	0.03803	0.00144	14.4	0.03686	0.00027	2.7	17.65	0.00117	11.7	82.35
237220	53°51.715	14°08.878	15	0.03672	0.03809	0.00137	13.7	0.03700	0.00028	2.8	20.49	0.00109	10.9	79.51
237240	53°49.475	14°06.108	14	0.03697	0.03841	0.00144	14.4	0.03719	0.00022	2.2	15.31	0.00122	12.2	84.69
237250	53°49.303	14°05.031	19	0.03577	0.03750	0.00173	17.3	0.03609	0.00032	3.2	18.53	0.00141	14.1	81.47
237260	53°49.192	14°04.525	18	0.03593	0.03751	0.00158	15.8	0.03631	0.00038	3.8	24.10	0.00120	12.0	75.90
237270	53°49.024	14°03.978	20	0.03700	0.03855	0.00155	15.5	0.03718	0.00018	1.8	11.64	0.00137	13.7	88.36
237280	53°47.141	13°58.090	4	0.03646	0.03858	0.00212	21.2	0.03698	0.00052	5.2	24.57	0.00160	16.0	75.43
237281	53°47.278	13°58.793	8	0.03689	0.03848	0.00159	15.9	0.03718	0.00029	2.9	18.28	0.00130	13.0	81.72
237281	53°47.278	13°58.793	9	0.03682	0.03841	0.00159	15.9	0.03710	0.00028	2.8	17.65	0.00131	13.1	82.35
237282	53°47.503	13°59.367	10	0.03621	0.03792	0.00171	17.1	0.03649	0.00028	2.8	16.41	0.00143	14.3	83.59
237290	53°47.683	14°00.035	11	0.03601	0.03771	0.00170	17.0	0.03627	0.00026	2.6	15.32	0.00144	14.4	84.68
237291	53°47.917	14°00.653	12	0.03588	0.03737	0.00149	14.9	0.03596	0.00008	0.8	5.38	0.00141	14.1	94.62
237300	53°48.216	14°01.565	7	0.03695	0.03864	0.00169	16.9	0.03716	0.00021	2.1	12.45	0.00148	14.8	87.55
237310	53°48.370	14°02.330	5	0.03646	0.03876	0.00230	23.0	0.03685	0.00039	3.9	16.98	0.00191	19.1	83.02
237320	53°48.597	14°03.077	6	0.03746	0.03925	0.00179	17.9	0.03751	0.00005	0.5	2.80	0.00174	17.4	97.20
Sampling date: 16 August 2001														
237240, at 1m	53°49.489	14°06.133	41	0.03602	0.03767	0.00165	16.5	0.03629	0.00027	2.7	16.40	0.00138	13.8	83.60
237240, at 1m	53°49.489	14°06.133	42	0.03598	0.03760	0.00162	16.2	0.03630	0.00032	3.2	19.79	0.00130	13.0	80.21
237240, at 1m	53°49.489	14°06.133	43	0.03603	0.03779	0.00176	17.6	0.03634	0.00031	3.1	17.65	0.00145	14.5	82.35
237240, at 4 m	53°49.489	14°06.133	44	0.03697	0.03841	0.00144	14.4	0.03720	0.00023	2.3	16.01	0.00121	12.1	83.99
237240, at 4 m	53°49.489	14°06.133	45	0.03611	0.03756	0.00145	14.5	0.03634	0.00023	2.3	15.90	0.00122	12.2	84.10
237240, at 4 m	53°49.489	14°06.133	46	0.03679	0.03816	0.00137	13.7	0.03710	0.00031	3.1	22.68	0.00106	10.6	77.32
237240 at 4.9 m	53°49.489	14°06.133	47	0.03642	0.03761	0.00119	11.9	0.03689	0.00047	4.7	39.61	0.00072	7.2	60.39
			51	0.03558	0.03568	0.00010								
			53	0.03657	0.03663	0.00006					*corrections:*	0.00009		
			25	0.03686	0.03698	0.00012								

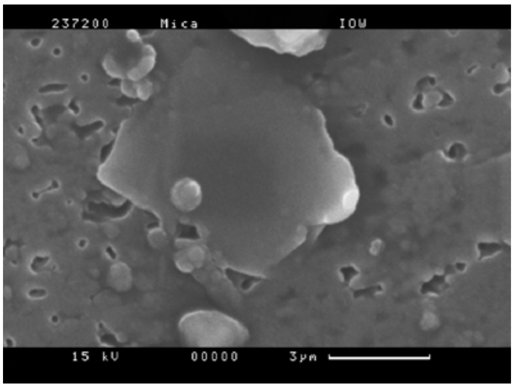
Average SPM = **16.4 mg/l** SPM - organic = **73.4% - 97,2% or 10.9 - 19.1 mg/l** SPM - inorganic = **2.8% - 26.6% or 0.5 - 5.2 mg/l**

Appendix 6-A. Scanning electron microscope pictures of the Odra Lagoon suspended particulate matter, sample 237200.

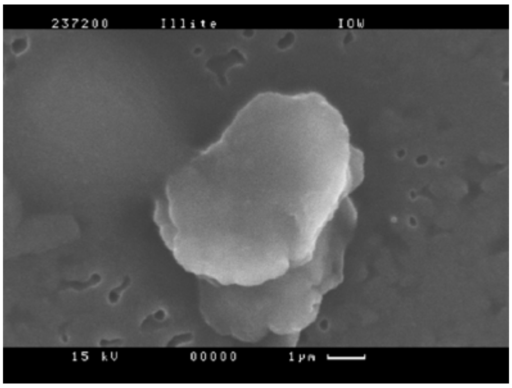




$CaPO_4$



Mica



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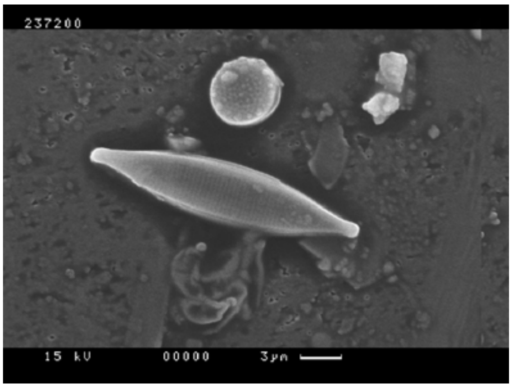
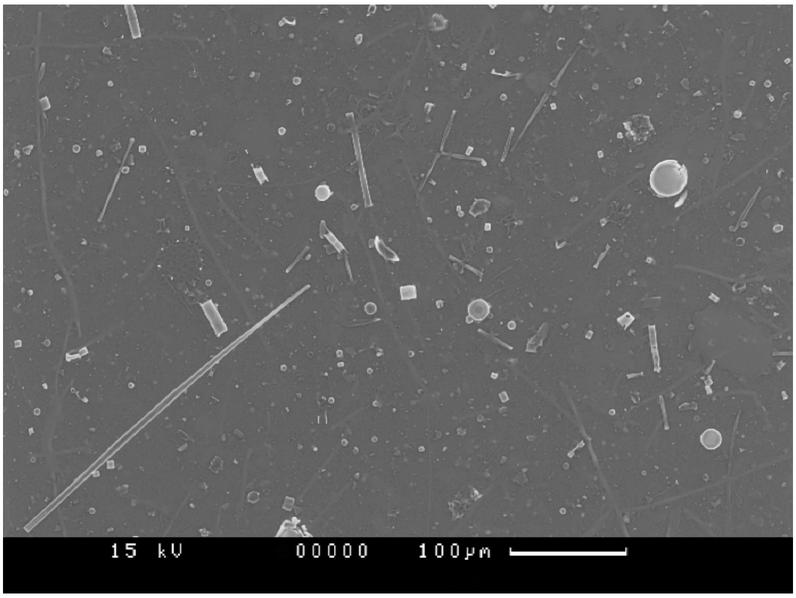
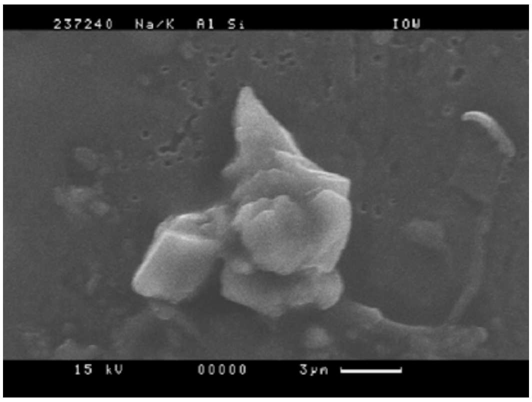


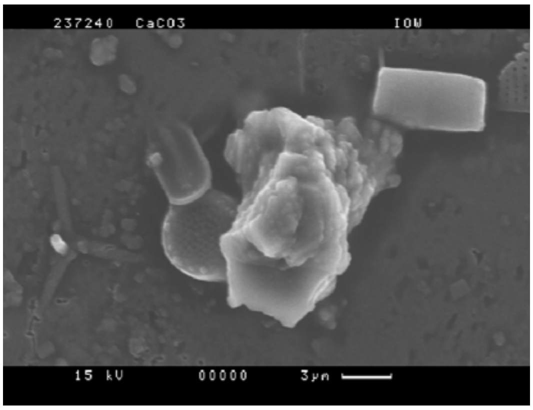
Organic materials

Appendix 6-B. Scanning electron microscope pictures of the Odra Lagoon suspended particulate matter, sample 237240.

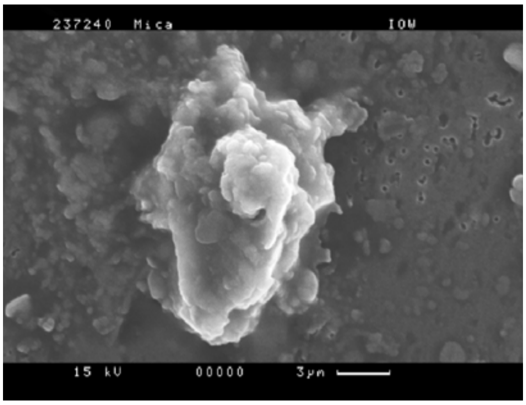




K-Feldspar (Orthoclase)

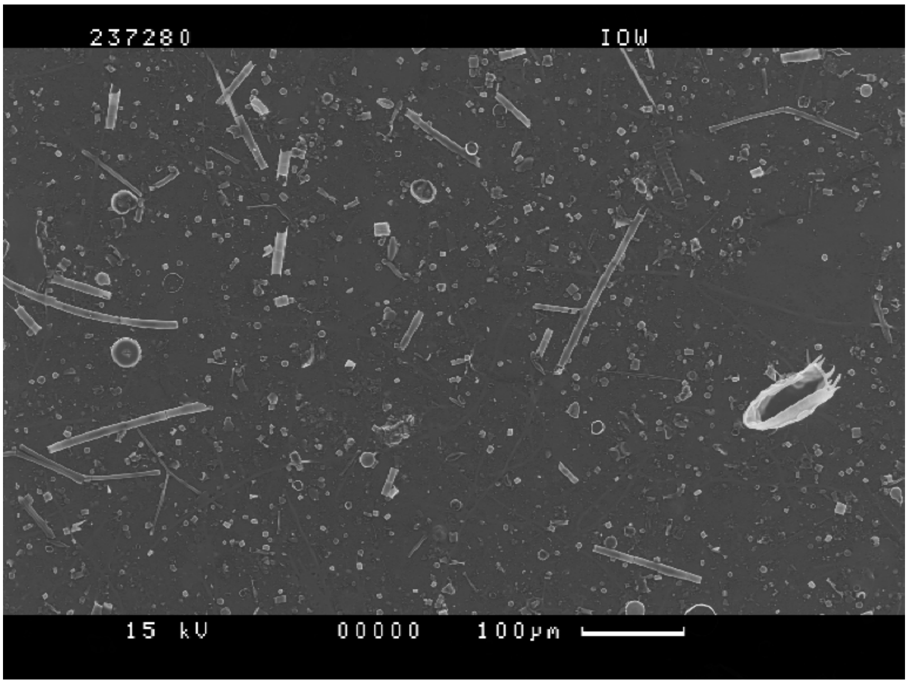


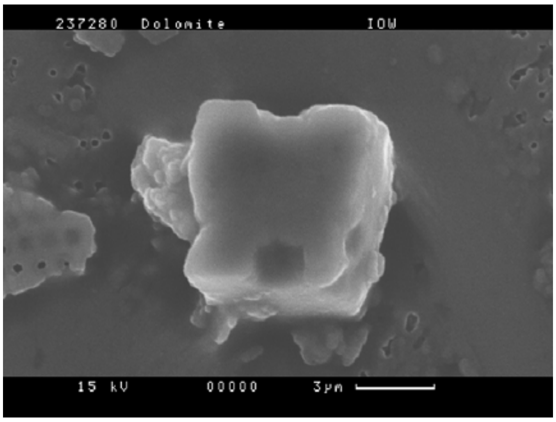
Calcite



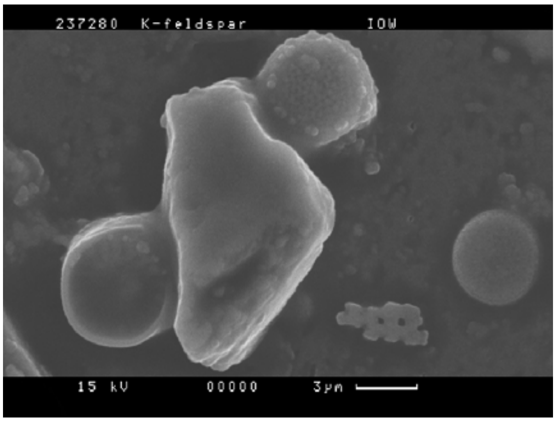
Mica

Appendix 6-C. Scanning electron microscope pictures of the Odra Lagoon suspended particulate matter, sample 237280.





Dolomite

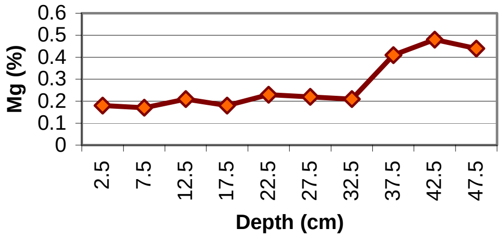


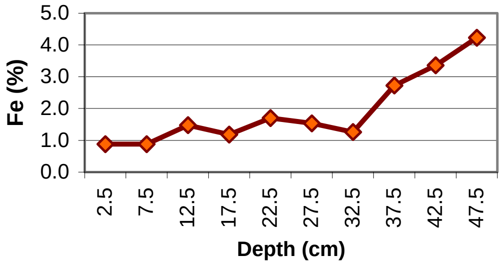
K-Feldspar (Orthoclase)

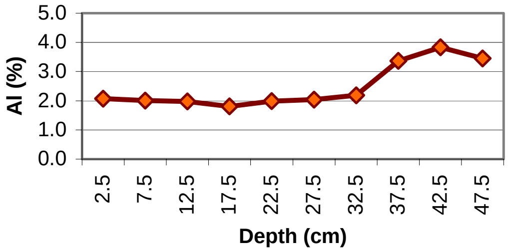
Appendix 7. Phytoplankton and biomass analyses of water sample 237240.

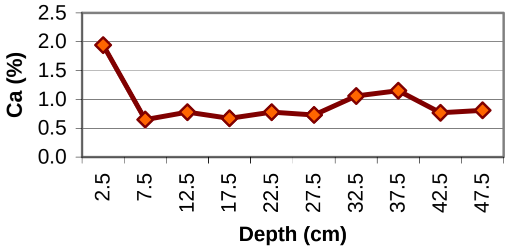
```
Sample number 237240   Sampling date 14.08.01

Sample size (ml/l)... :  250                Analysed by    Susanne Busch
List of depths (m)... : 1                   Date counted   15.02.02
Mixed sample vol (ml) :                     Sedim. volume       3
Preservative ........ : LUGOL+AA            Sedim. time      24
Amount of Preservative:                     Chamber diam.   26.00
Sampler ............. : Ruttner             Microscope     Axiovert100 Ocular 10/20 Ax
Comment ............. :Die Probe ist nicht vollständig gezählt (das würde wohl mindestens 2 Tage dauern). Die häufigsten Arten sind erfaát.
Part counted with 20x:  2 Streifen    COEFF=5507
Part counted with 40x:  1 Streifen    COEFF=21957
Code       Species                              Units Coeff   Units/l   ww mg/m3    ægC/m3
 101010060 Aphanocapsa sp. 25 Zell.zu 1æ          284 21957   6235788      81.1      6236
 101080080 Woronichinia sp. 16Z. 3x2 æ             34 21957    746538      74.7      8212
 101090010 Snowella sp. 16 Z. 2.8 æ                12 21957    263484      49.0      5270
 101100060 Merismopedia tenuissima 4-Zell(1,5æ   1183 21957  25975131     181.8     25975
 101120000 Microcystis sp. 25 Zellen 4æm       2  128  5507    704896     599.2     66260
 102020000 Anabaena sp.                           131  5507    721417    1442.8    155105
 102030020 Anabaenopsis sp. Zelle! 7x6æ           183 21957   4018131     522.4     56254
 102040070 Aphanizomenon sp. 100æ x4æm              4  5507     22028      27.5      3040
 102070060 Planktolyngbya sp. 1 æm(und Filamente) 194 21957   4259658     340.8     38337
 102090010 Planktothrix sp. 3-4 æm breit       1  243 11014   2676402    2569.3    281022
 102090270 Pseudanabaena/Limnothrix 2æm: 100æ      54 21957   1185678     373.5     41499
 201040000 Cryptomonas sp.18æm lang                 1 21957     21957      16.7      1844
 802100000 Chaetoceros sp. 9(AA)x5(PA)æ        1    1 21957     21957       5.5       417
 802100000 Chaetoceros sp. 12(AA)x10(PA        3    2 21957     43914      37.3      2196
 802140000 Centric diatomae 30æm               4    9  5507     49563     346.9     14026
 802220090 Aulacoseira granulata v.granulata        4  5507     22028      37.4      2093
 803150010 Diatoma elongatum 45x3æm            1   18 21957    395226     134.4     13833
 803270000 Nitzschia sp. 3x70 æm               3    3  5507     16521       4.6       463
1202120090 Coelastrum sphaericum (Zelle12æm)        8  5507     44056      39.7      4362
1202390000 Oocystis sp. 8x4æm                  2    2  5507     11014       0.8        88
1202400030 Pediastrum boryanum Zelle 8x8æ      1   24  5507    132168      66.1      7269
1202400080 Pediastrum duplex Zelle12x12æ           16  5507     88112     149.8     16477
1202440100 Scenedesmus sp. Zelle 9x4 æm        2  131 21957   2876367     345.2     37393
1204030000 Closterium sp. 300x8æm              3    1  5507      5507      49.6      5452
1204040000 Cosmarium sp.                            3  5507     16521      20.7      2313
     Class                Units         Units/l   ww mg/m3    ægC/m3
     CYANOPHYCEAE          2450        46809151    6262.0    687209
     CRYPTOPHYCEAE            1           21957      16.7      1844
     DIAPTOMOPHYCEAE         37          549209     566.2     33027
     CHLOROPHYCEAE          185         3173745     671.7     73353
     TOTAL AUTOTROPHS      2673        50554062    7516.6    795434
     Total density units/l: 50554062
     Total units counted:    2673
```

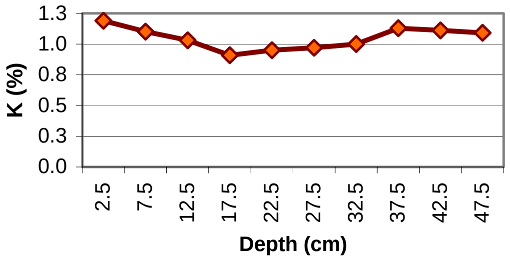
Appendix 8. Geochemical analyses of core sample 236040.

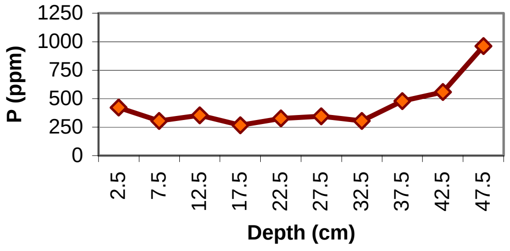


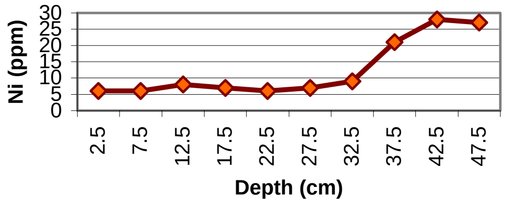


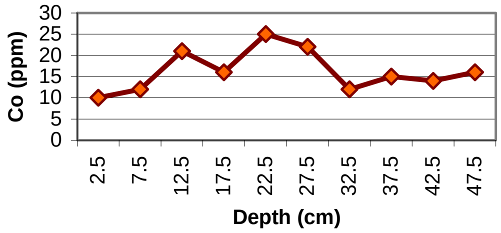


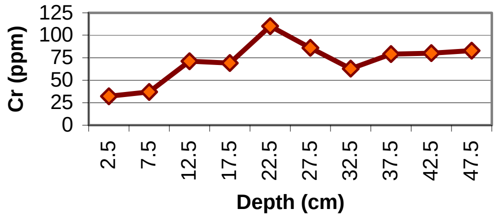


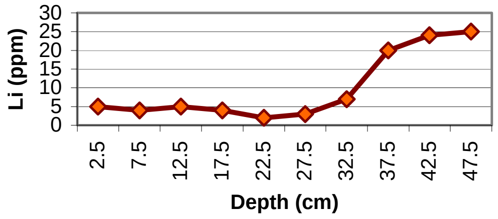


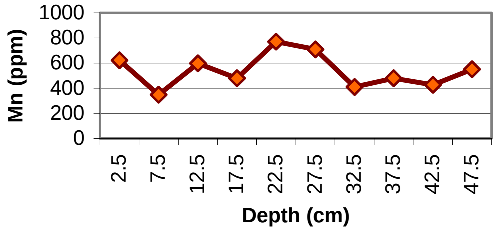






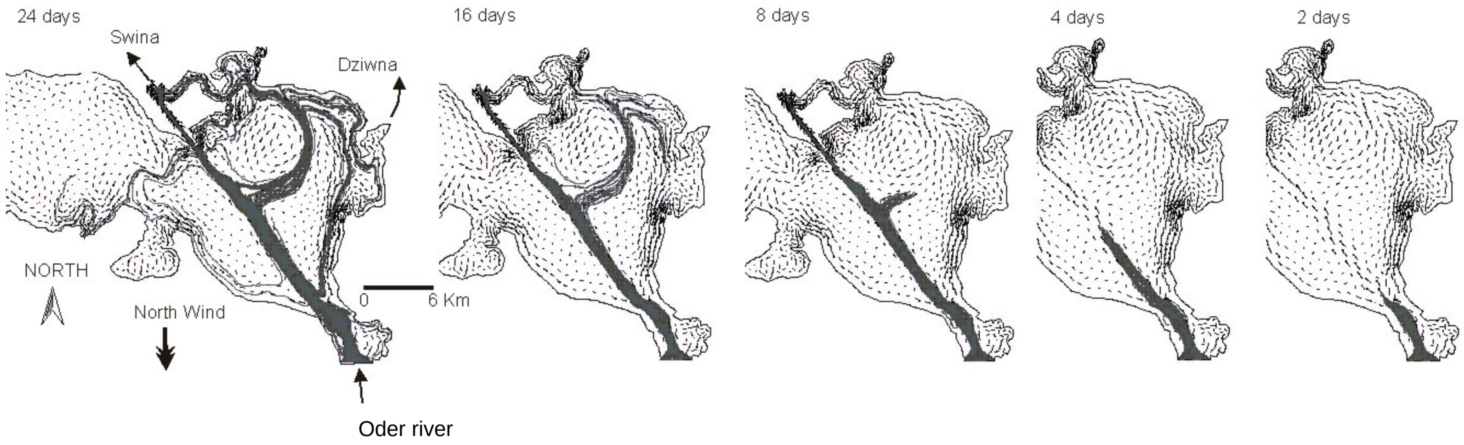




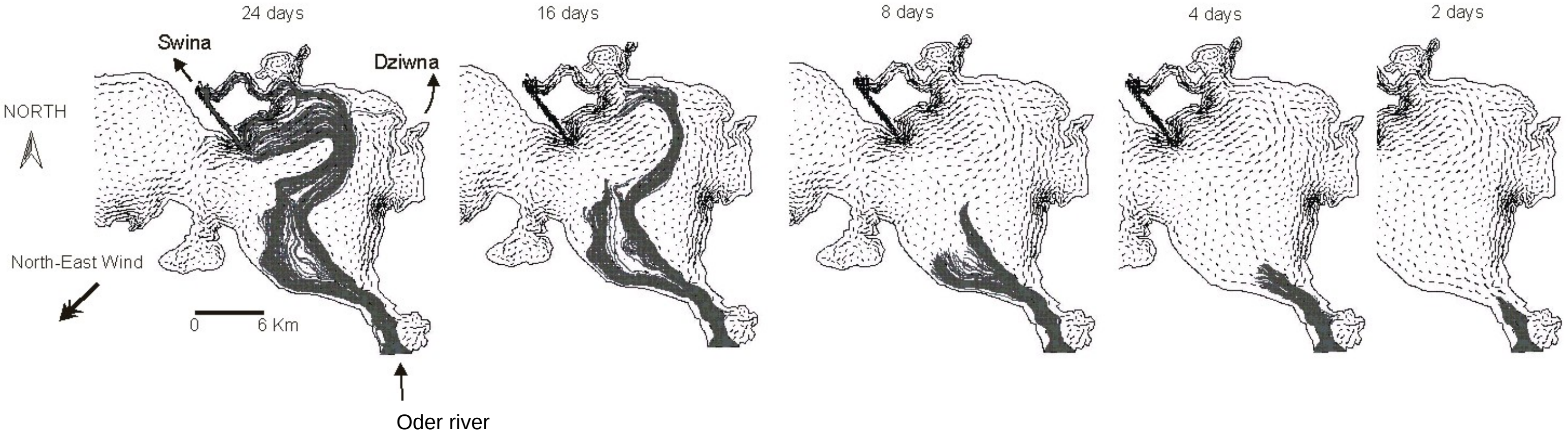


Appendix 9. Trajectories of particles entering from the Oder river to the lagoon under north, north-east, east, south-east, south, south-west, west and north-west winds.

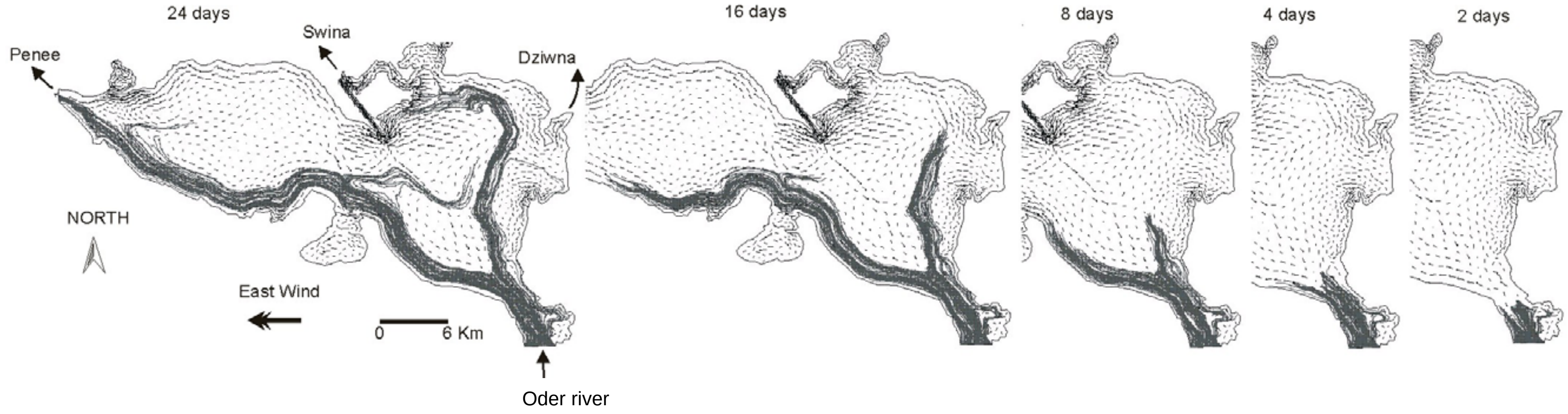
NORTH WIND, Average Wind Speed 4 m/s



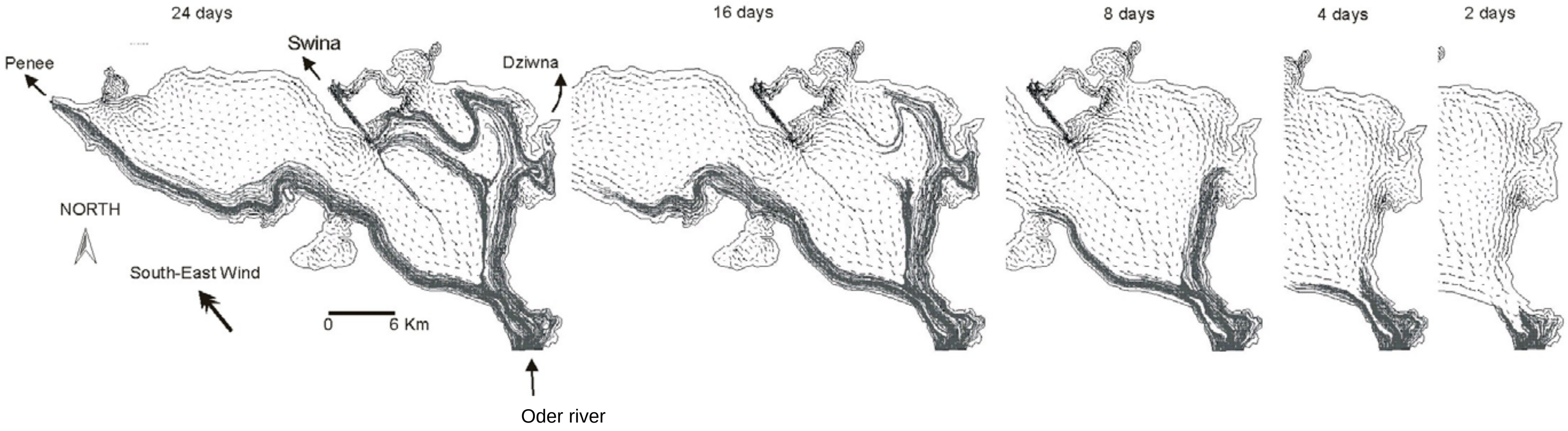
NORTH-EAST WIND, Average Wind Speed 4 m/s



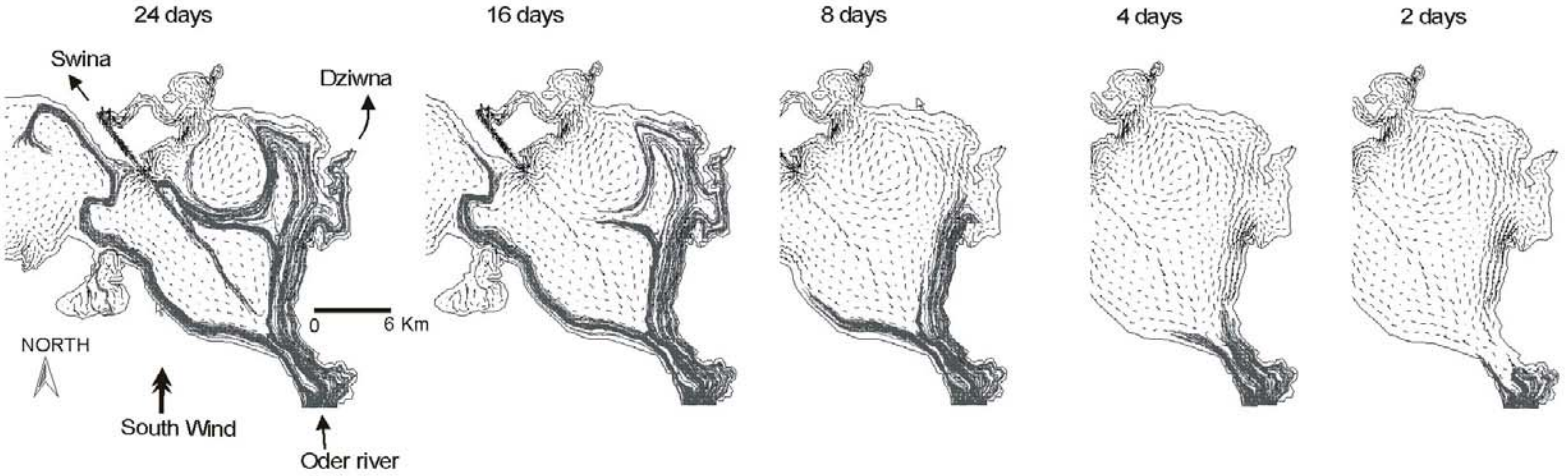
EAST WIND, Average Wind Speed 4 m/s



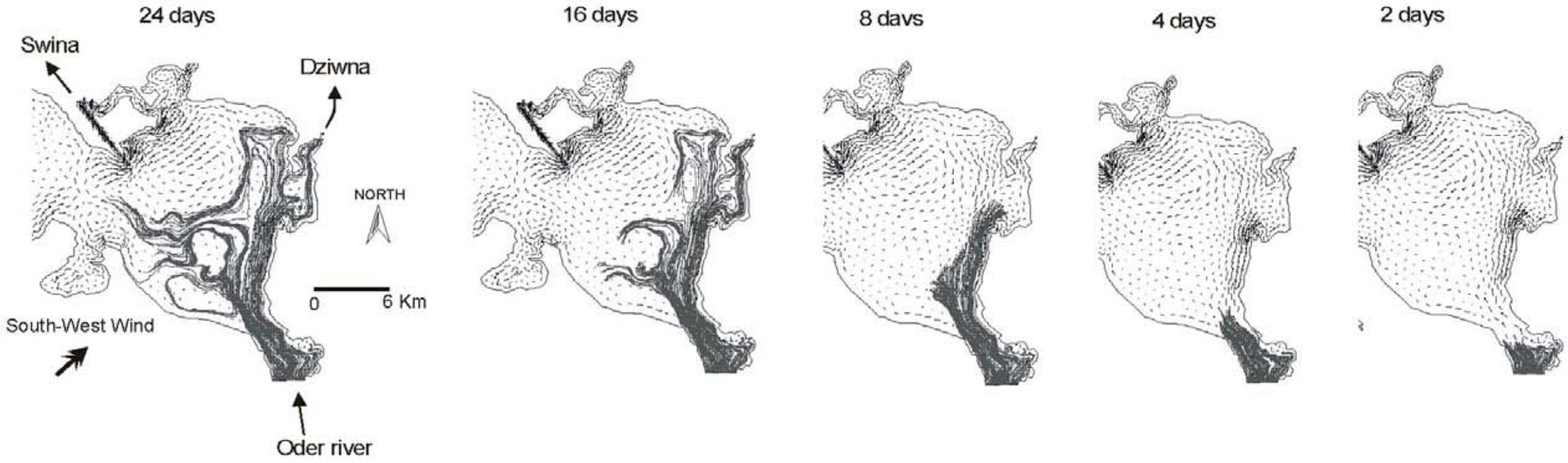
SOUTH-EAST WIND, Average Wind Speed 4 m/s



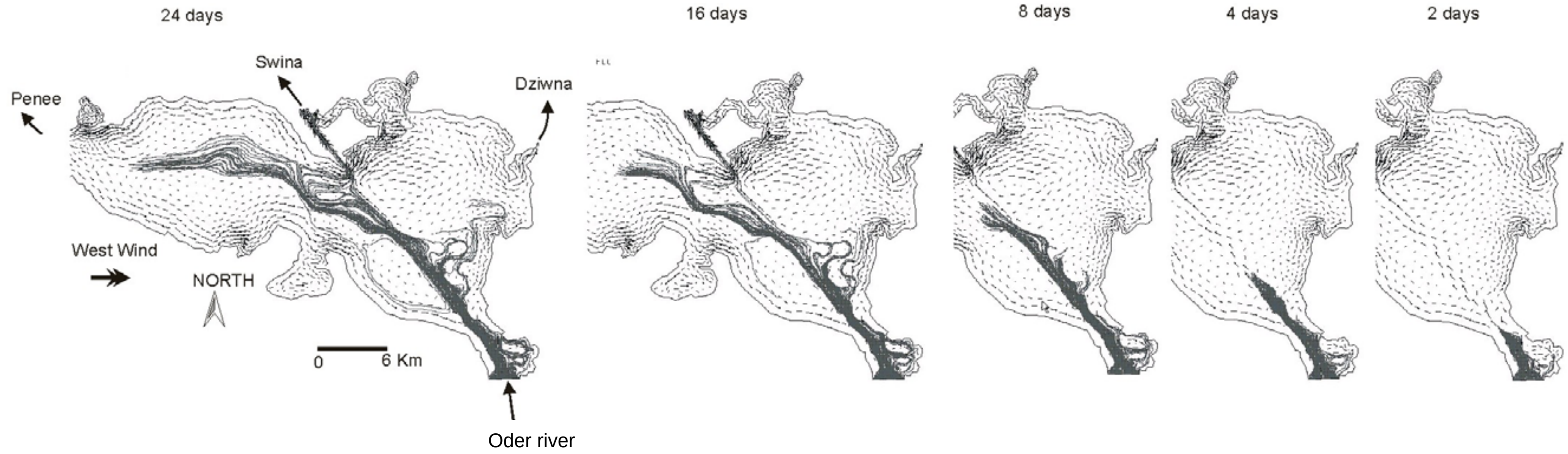
SOUTH WIND, Average Wind Speed 4 m/s



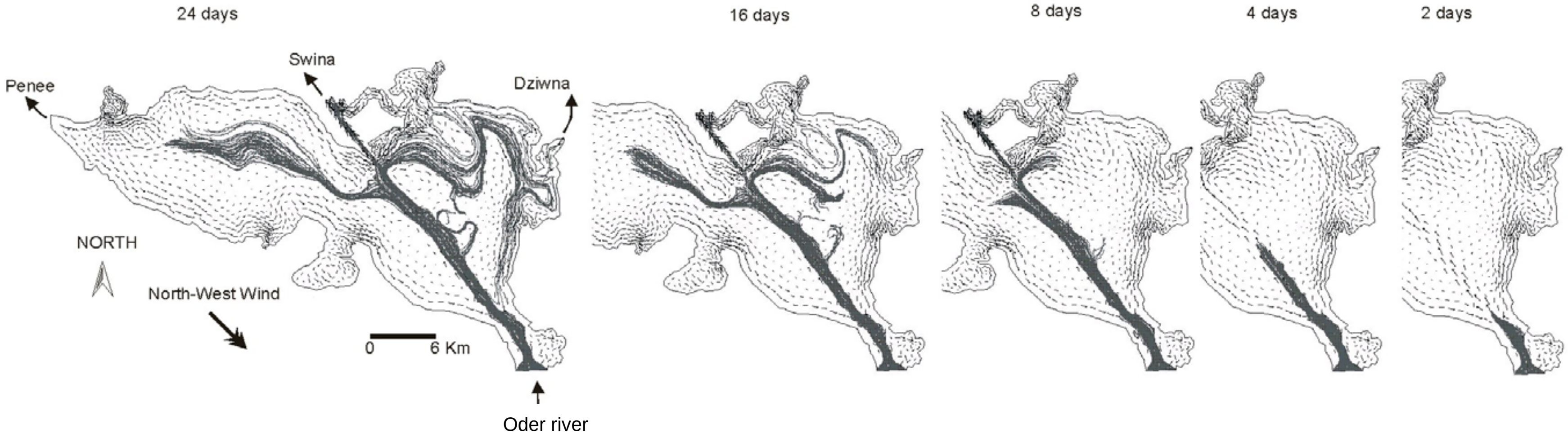
SOUTH-WEST WIND, Average Wind Speed 4 m/s



WEST WIND, Average Wind Speed 4 m/s



NORTH-WEST WIND, Average Wind Speed 4 m/s



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