Journal of Shellfish Research, Vol. 7, No. 2, 241–252, 1988.

SHELLFISH CULTIVATION AND FISHERY BEFORE AND AFTER A MAJOR FLOOD BARRIER CONSTRUCTION PROJECT IN THE SOUTHWESTERN NETHERLANDS

Renger Dijkema
Netherlands Institute for Fishery Investigations
Yerseke, Netherlands

ABSTRACT After a disastrous flood in 1953, a law was passed to close the mouths of all estuaries but one in the Southwest of the Netherlands. The estuaries concerned were planned to become fresh water lakes. Existing bottom culture of the blue mussel (*Mytilus edulis*) and the European flat oyster (*Ostrea edulis*) as well as finfish and shrimp fisheries were to disappear from the area. After a change in national politics and intensive lobbying by nature conservation and fishery organizations, this plan was modified in such a way that a restricted tidal movement would remain possible in the main estuary, the Oosterschelde (Eastern Scheldt). Besides, good ecological conditions in another estuary already shut off from the sea, prompted the decision to conserve this area as a tideless marine lake. These decisions gave new hopes for the aquaculture and fishing industry. Although many of the existing shellfish cultivation plots had to be abandoned, also new possibilities have become apparent, such as the emerging of a natural population of the European flat oyster in stagnant Lake Grevelingen. Besides, new chances for bottom cultivation of mussels and oysters have become apparent in places where tidal current velocities have been reduced. Limits to shellfish culture and fishery can be set by locally too low current velocities and by food limitation due to competition or a reduced import of suspended matter from the North Sea. Phytoplankton production might also become limited as a result of reduced import of nutrients by rivers.

Research is under way to assess new possibilities for aquaculture to predict possible effects of the project on environment and mariculture in the area. Management of aquaculture and fishery is facing the problems of compensating for lost cultivating plots, allotment of new ones and conflicts of interest between different cultures and fisheries.

KEY WORDS: Culture of oysters, mussels, *Ostrea edulis*, *Mytilus edulis*, Bottom cultivation, Flood barrier construction, Fishery management

1. PROLOGUE: A STORM FLOOD AND ITS AFTERMATH, THE DELTA PLAN

The long-standing reputation of the Dutch as land reclaimers and hydraulic engineers is built on a centuries-long series of battles against the sea. Most of these battles were won but, in many cases, it was the defeats which gave the spur to efforts which led to the next victory. In this way, the Low Countries have, in the course of the last centuries, created a protection from floods by means of a girdle of dikes. This dike system, however, had frequently to be repaired when storms or currents had damaged it, or heightened when necessary. Also the need of the population for new farmland prompted, until some years ago, new land reclamations. But there are periods when money is short and local and central governments not able or motivated to do much about the upkeep of the dikes. This was the case during the first half of this century, when successively the first world war, the economic crisis and the second world war had distracted money and attention from the maintenance of this vital defense against the sea. Most of the sea dikes of the country were too low to match the effects of a steadily subsiding soil and rising of the sea level. Also many dikes were in a poor state of repair. Still to the astonishment of many, on the night of the first of February 1953, a fatal combination of spring tide, a force 13 storm and shifting wind direction pushed up the sea water in the southern North Sea. The shifting wind drove the flood high up into the estuaries in the southeast of the Netherlands. Water levels of 3 m above the normal spring flood level were reached. On many places the dikes broke through and a total area of 250,000 ha (600,000 acres) was flooded. Over one thousand eight hundred people died and thousands of head of cattle drowned. This catastrophe prompted the adoption of a law in 1958, aimed at safeguarding the protection of the coastline in the Southwestern Netherlands. The law comprised a scheme called the "Delta Plan", which encompassed the closure of all southern estuaries, except the Westerschelde (Western Scheldt), which is the waterway to the large seaport of Antwerpen. The strategy of the plan was to straighten the coastline, thus decreasing the length of the sea-defense line with 700 km. For instance, a dam in the Oosterschelde with a length of 9 km would replace 245 kms of dike. Besides, the plan aimed at increasing the height of the sea-dikes in such a way that the risk of a storm flooding was brought down to 1 : 4,000.

2. BENEFITS AND DISADVANTAGES OF THE PLAN

The benefits of this plan were obvious: On a national level, security would be guaranteed, for the many islands in the Delta area the plan would also end a centuries-long isolation and lead the way to further development. Opportunities would arise for industrial development in a province which before had been based on agriculture and fishery. Agriculture, in its turn, would benefit from the fresh water which was planned to surround the islands. Salt water intrusion would be stopped in important horticultural and agricultural regions, which would make the production of an

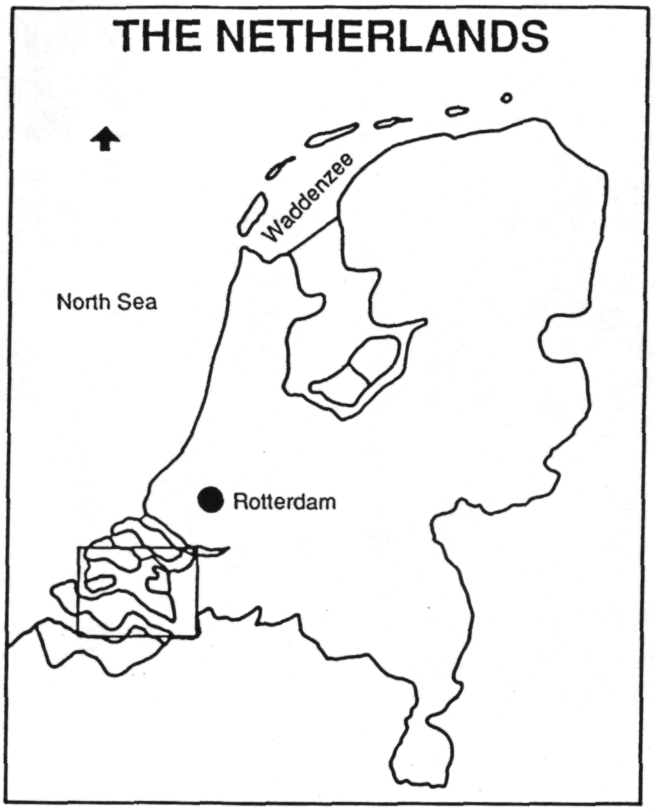

Figure 1. General view of the Netherlands, showing the Delta region and the Waddenzee.

assortment of new crops possible. But it was realised also that there would be disadvantages, notably to fishery and mariculture. A commission was installed to assess the total economic damage to these industries and to the trade and industry branches dependent on them. Even the impact on the national import and export balance was studied. The total damage to all fisheries and aquaculture was, in 1955, estimated 142 millions of Dutch guilders (one guilder is about US$ 0.50). In these days this would mean the relatively modest amount of 619 millions of guilders. Figure 2 shows the locations where mariculture was carried out before the Delta Plan. A series of compensating and mitigating actions were necessary.

Oyster culture, which was practised exclusively in the Delta waters, would disappear. As no alternative locations existed, the entire industry, about 100 companies among which 15 large ones, would have to be compensated, which would cost 40 millions of guilders. In 1962–1963, an extraordinarily cold winter destroyed most of the cultivation installations and decimated the stock of cultivated oysters. Although the closure of the Oosterschelde was not due yet, the government decided to anticipate the compensation of the oyster industry, as re-building of the industry for such a short period had little sense. All but 10 of the 100 oyster farmers were bought out and terminated their activities. The ten that remained, which had also other means of existence and hence were less dependent on oyster culture alone, were indemnised as well. They were allowed to remain in business as long as this was still possible, but had no right to claim any damages. The other ninety, whose sole occupation was oyster farming, found other professions or retired. This development gave rise to the establishment of a number of mushroom and poultry farms in the neighbourhood of the township of Yerseke, the center of the shellfish industry in Zeeland, situated in the southeastern part of the Oosterschelde (figure. 1) Mussel cultivation, as far as carried out in the Delta area, would have to disappear and be moved to the Waddenzee in the North of the country, where new cultivation grounds should have to be sought. More than half of the mussel cultivation was already being practised in that area. For reasons of risk-spreading, most mussel farmers rented plots in the more sheltered southern estuaries as well as in the productive, but exposed and hence risky Waddenzee. This meant that for most of them the change was not too drastic, but that the risk of storm and ice damage in winter would increase. The first mussel culturists to lose their plots in the Delta region were those from the Zandkreek and the Grevelingen. (figure 3). Many of them could be allotted plots in other areas, others stopped mussel farming and took to other professions like fishing eels with fyke nets, which fishery was expected to be profitable in the future fresh lakes. Another aspect was the trade and processing of mussels. The entire Dutch mussel production, including that from the Waddenzee, (about 100,000 tons per year) is processed and packed in and around Yerseke. A vital stage in mussel processing is the purification or "rewatering", a compulsory re-laying period of minimally 10 days in quiet, clear and bacteriologically pure seawater within the tidal range. This stage is necessary to eliminate dead and crushed mussels, to enable the mussels to dispose of sand and silt and to give them the shelf life and sanitary quality which is required for export. The only location where these requirements can be met is situated close to Yerseke in the Oosterschelde. Rewatering in the Waddenzee is impossible because of a high turbidity of the water and a limited tidal range. An installation would have to be designed to do this artifically. The Netherlands Institute for Fishery Investigations was given the assignment to develop this process in a pilot-plant and to make a blueprint for a definitive installation, big enough to process the entire Dutch mussel production. To this end the Mussel Experimental Station of the Netherlands Institute for Fishery Investigations was built in 1969 on the Waddenzee island of Texel. This was in operation until 1979, when the laboratory was moved back to the Delta region and was established in Yerseke. Also the inshore fishermen would lose their fishing grounds and jobs or would have to accept lower incomes due to the Delta Plan. Likewise would the fish traders and exporters, as most of the catches were destined to foreign markets like Belgium, France or Germany. This trade comprised a variety of species like shrimps, lobsters (locally captured or imported

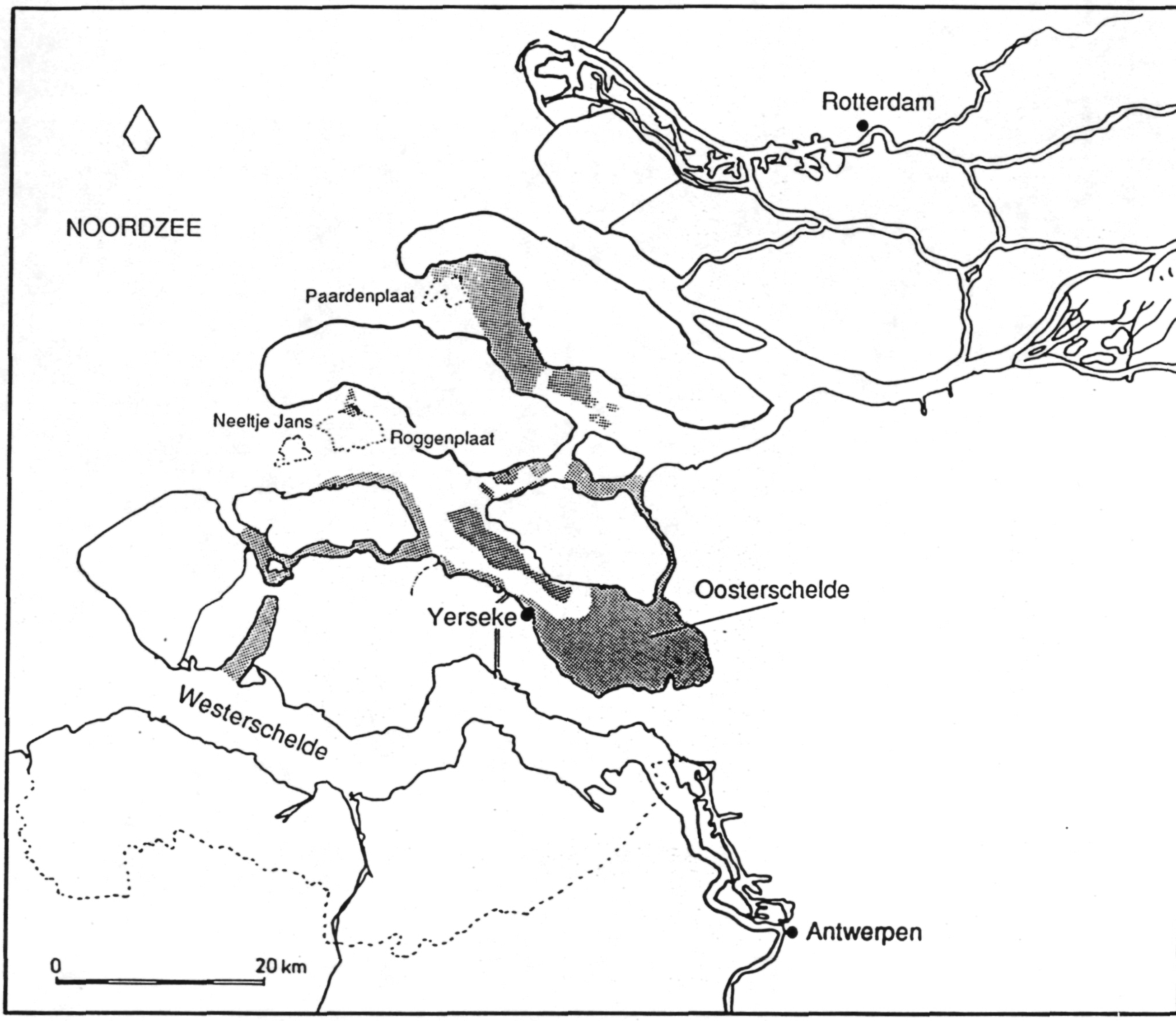

Figure 2. The areas in the Delta region (hatched) where mussels and oysters were cultivated before the start of the Delta plan in 1963.

and stored in in- or outdoor ponds), crabs, periwinkles, whelks and even starfish, which by that time were used for soil improvement in agriculture. Another problem would arise for the North Sea fishermen from the township of Veere. The closure of the sea-arm to that harbour was due in 1961, which meant that the fishermen were obliged to have their ships removed by that time. Some decades earlier, the same had happened with the nearby port of Arnemuiden, from which many fishermen had moved to Veere. For the second time they had to change the registration numbers on the bows of their ships, when a new harbour was created for them in the village of Colijnsplaat at the Oosterschelde. This time it would also mean a provisional removal, as the Oosterschelde was scheduled to be closed off by 1978 and no shiplock was foreseen in the dam. This migration of fishermen and their families created a new aspect: a fishermen's community within the hitherto exclusively agricultural village of Colijnsplaat. Fishery research had demonstrated that the estuaries of the Delta region, with their large areas of sandflats and shoals, form the nursery area where a part of the commercial fish and shrimp stocks pass their first years of life before they migrate to the deeper waters where they are captured. As the fish species concerned: shrimps, plaice, dab and common sole, make out a substantial part of the catches of the coastal fishing fleet, elimination of these nursery zones would have a direct negative impact on fishery. Furthermore, the rocky bottom, created by the stones used for reinforcement of the underwater part of the dike-slopes, makes a suitable environment for many species which normally do not occur at the sandy and muddy coasts between Dover Strait and Norway. Also the relatively high water temperatures in the inland part of the Oosterschelde during summer (up to 24 degrees C) make reproduction possible for a number of species the occurrence of which would otherwise be restricted to warmer waters south of Dover Strait. Also evidence was supplied that the Delta region has a vital importance as a foraging area for thousands of migrating and wintering birds, whose safe arrival in their areas of destination often depends on foraging possibilities during the voyage. The vast intertidal area (a tidal range of about 3.5 m) offered unique feeding grounds for more than 400,000 wading birds, geese and ducks simultaneously. This makes the Delta area second in importance among the European areas for migrating birds. It has also been the main argument to grant the area the official international status as "wetland". Elimination of the tidal zone and creation of fresh water lakes would cause problems for bird populations, breeding in a number of countries.

3. GROWING OPPOSITION AND TURN-AROUND

The first decade after the disaster, most of the attention was understandably aimed at safety aspects. Gradually, a number of persons became aware that the price to be paid for safety would be higher than the costs alone of the plan sketched above. Initially one, later more members of parliament opposed the chosen solution. As said, the arguments for this opposition came in first instance from the fishing and aquaculture industry. Only in a later stage, more attention was paid to the damage, done to the natural environment of the Delta region. This was mainly due to the fact that a public awareness of the importance of nature conservation was just starting to grow by that time. The recent loss of a number of areas of great natural value in behalf of public safety and industrial development and the awareness that the Grevelingen and the Veerse Meer were already lost as tidal areas, gave rise to a growing opposition against closure of the Oosterschelde. Opponents were convinced that the promise of safety, done to the populace of the affected provinces had precluded a proper weighing of arguments in the discussion about whether the Oosterschelde had to remain a tidal water or not. The arguments in favour of nature conservation, fishery and aquaculture had not received, they argued, the attention they deserved. They advocated heightening of the dikes around the Oosterschelde, thus leaving the tidal movement undisturbed. This alternative was contested by representatives of agriculture, water authorities and some conservative politicians, who either wanted fresh water, or just did not want to change the original plans, saying that the alternative was irrealistic. The opponents to closure demanded the installation of an independent commission, comprising experts of all disciplines concerned, which should give advice to the government about which alternative should have to be chosen. In the final stage of the battle, some sixteen national associations of fishermen, aquaculturists and nature conservationists took action, first all on their own, later unitedly. Scientific articles about the natural values of the estuary and the detrimental effects of closure were written, conferences were held about the nature and fishery function of the estuary and all over the province the slogan "Oosterschelde open!" was chalked down in huge characters. Many of the actions were private, others were financed by the industry. The most important aim was, of course, to persuade as many members of parliament as possible, because only in parliament the Delta Plan, which had become law, could be modified. Finally, after many actions and much lobbying, parliament decided, in 1974, to install an independent commission, which should bring out an advice about what to do with the Oosterschelde. This was just in time. The other sea arms had been closed off already, and the preparations for the closure of the Oosterschelde were already in full swing. Six months later, the commission chose the alternative in which the Oosterschelde would be closed with a permeable dam. The tidal flow through that dam had, according to the Commission, to be sufficient to conserve the tidal character of the Oosterschelde and to leave the marine aquatic environment intact, so that the natural value, the fishery and aquaculture should not be affected. To guarantee a sufficient salinity and water quality, two secondary dams would have to be made, in addition to the barrier in the mouth of the Oosterschelde. Primary in this advice stood the interest of nature conservation, the interests of fishery and agriculture came second. Least in importance was considered the interest of recreation, which was becoming an important source of income in many parts of the province, but also was considered as a threat for nature and shellfish cultures. In 1976, Government adopted the advice of the commission and as soon as possible preparations were started for the construction of the permeable dam. As completion of this dam was only expected after at least eight years, all dikes had to be heightened to provide sufficient safety during the period of construction. This can be considered as a concession, made to those politicians who clung to the promise of safety, done to the population and did not want to delay the closure. This turn-around in Government policy was considered a major victory, especially for nature conservationists. That it was possible to change this new law was mainly due to the fact that in the meantime the socialist party had obtained a majority in government, which resulted in an increased awareness of the necessity of nature conservation. Additionally, the financial barriers (the solution chosen would cost 1.6 billions of guilders more than total closure) were taken away mainly thanks to the discovery of huge reserves of natural gas, which substantially alleviated the national financial position. The total costs of the project were then estimated 5 billions of guilders. The final costs appeared to have been 7.8 billions, mainly due to inflation. It is generally acknowledged now, that otherwise the Oosterschelde would have been closed. How narrow the escape was, is illustrated by the fact that the name chosen for the planned fresh-water Oosterschelde: "Zeeuwse Meer" (Lake Zeeland) can nowadays still be found on certain maps.

4. THE FINAL SHAPE OF THE DELTA PROJECT

Construction of a barrier in the mouth of Oosterschelde would inevitably bring about a reduction of the tidal flow and of the tidal range inthe estuary. If this reduction should be too large, problems would arise for the natural environment as well as for fisheries and aquaculture. The commission has realised this, and formulated the requirements for the future tidal range. A technical commission formulated three alternative sizes for the aperture in the Storm Surge Barrier, as it was named, in the Oosterschelde. Finally, an aperture of 14,000 m2 was chosen, which would cause a reduction of the tidal current by 25% and of the tidal volume by 35%. The tidal volume, the mass of water, changed each tide, was to be 1,600 million cubic meters. The tidal range at the location of the mussel rewatering plots off Yerseke would decrease from 3.5 m to 2.7 m, considered sufficient for the mussel cutters to navigate and to fish on the plots. The rate of tidal flushing of the estuary would, if a greater reduction of the aperture should be chosen, be insufficient to maintain a good salinity in the estuary. Figure 3 shows the situation after completion of the Delta project.

The "Compartmentating Dams"

Two secundary dams: the Oesterdam in the southeast of the Oosterschelde and the Philipsdam in its northern branch (figure 3), served three purposes: In the first place they had to decrease the tidal volume and thus to alleviate the current speeds in the barrier. Second, they had to conduct the fresh water, coming from several rivers to the Westerchelde, because otherwise the salinity exigencies for the Oosterschelde, set by the tolerance limits of oysters and lobsters, would not be met. In the third place, the dams were to protect a tide-free waterway between the ports of Antwerpen and Rotterdam, a result of an earlier agreement between the Dutch and Belgian governments. In all dams shiplocks were planned. In the Philipsdam, where the locking of ships would cause intrusion of fresh water into the Oosterschelde and that of salt water in the future fresh water lake, an ingenious system was made to keep fresh and salt water separated during the operation of locking up or down the ships. This system is based on the floating of fresh water on top of sea water.

The Haringvliet

The former estuary of the river Meuse, the Haringvliet, in the north of the Delta area, was closed off with a storm barrier in 1968. Apart from providing safety, the dam holds the salt tongue in the estuary in check, thus protecting a very important horticultural area. The resulting fresh water lake now knows a profitable fishery, mainly on eels.

Lake Veere (Veerse Meer)

This was the easiest and for this reason the first sea arm to be closed off in the project, in 1961. The water in this lake is brackish due to freshwater discharges from the surrounding farmland. The mean salinity is about 15–20 parts per thousand. Several mussel and oyster plots had to disappear after the closure of this lake. The aquatic flora and fauna have impoverished considerably, and only a thriving eel fishery is now practised on the lake. Water authorities consider raising the salinity by flushing with water from the sea or the Oosterschelde. This would create new opportunities, at least for oyster culture.

The Zoommeer

This fresh water lake, or rather a string of lakes and waterways, is left between the mainland and the secondary dams in the east of the Delta region. It came into existence when in April 1987 the Philipsdam, as last compartmentating dam, was closed. To speed up the freshening process and avoid a cumbersome period with brackish water, stratification and mass mortalities during the ensuing summer, it was decided to flush the lake with water from the northern rivers. Due to the presence of some small rivers and the salt/freshwater separation system in the shiplocks, the lake will eventually become totally fresh. The first results of eel fishery appear favourable, spontaneous colonisation with other fresh water fishes like roach, perch and pike-perch has started. The consequences of this part of the project for oyster cultivation are not as favourable, the fresh lake now covers a number of former oyster growing plots.

5. THE SURPRISE OF LAKE GREVELINGEN

In 1964 the Grevelingen estuary had been closed at the landward side with a dam. In May 1971, a second dam was completed, which meant that the estuary had become a lake, still filled with sea water. The intention was to leave the lake in that state until fresh water would be available in the adjacent sea arm. All cultivation of mussels and oysters had been stopped and the salt water lake was considered lost, doomed to become a brackish, stagnant and stratificated pool. This feeling was strengthened by the mortality among bottom organisms immediately following the closure.

Apparently the sudden ceasing of tidal movement had caused an ecological change to which many of these organisms were not adapted. In the following years, however, aquatic flora and fauna revived, although not without considerable changes in composition. Particularly those species were favoured which reproduce with large numbers of pelagic larvae, which no longer were dispersed into the open sea and diluted by tidal currents. A series of excessively abundant year classes of such species followed. First came an explosion of the blue mussel (*Mytilus edulis*) in the period 1974–1980. In 1980 the stock of mussels was assessed at 22,000 tons fresh weight. The shells of mussels which had died during a period of stratification gave rise to a birth explosion of the European flat oyster (*Ostrea edulis* L) by offering substrate for settlement. In the meantime,

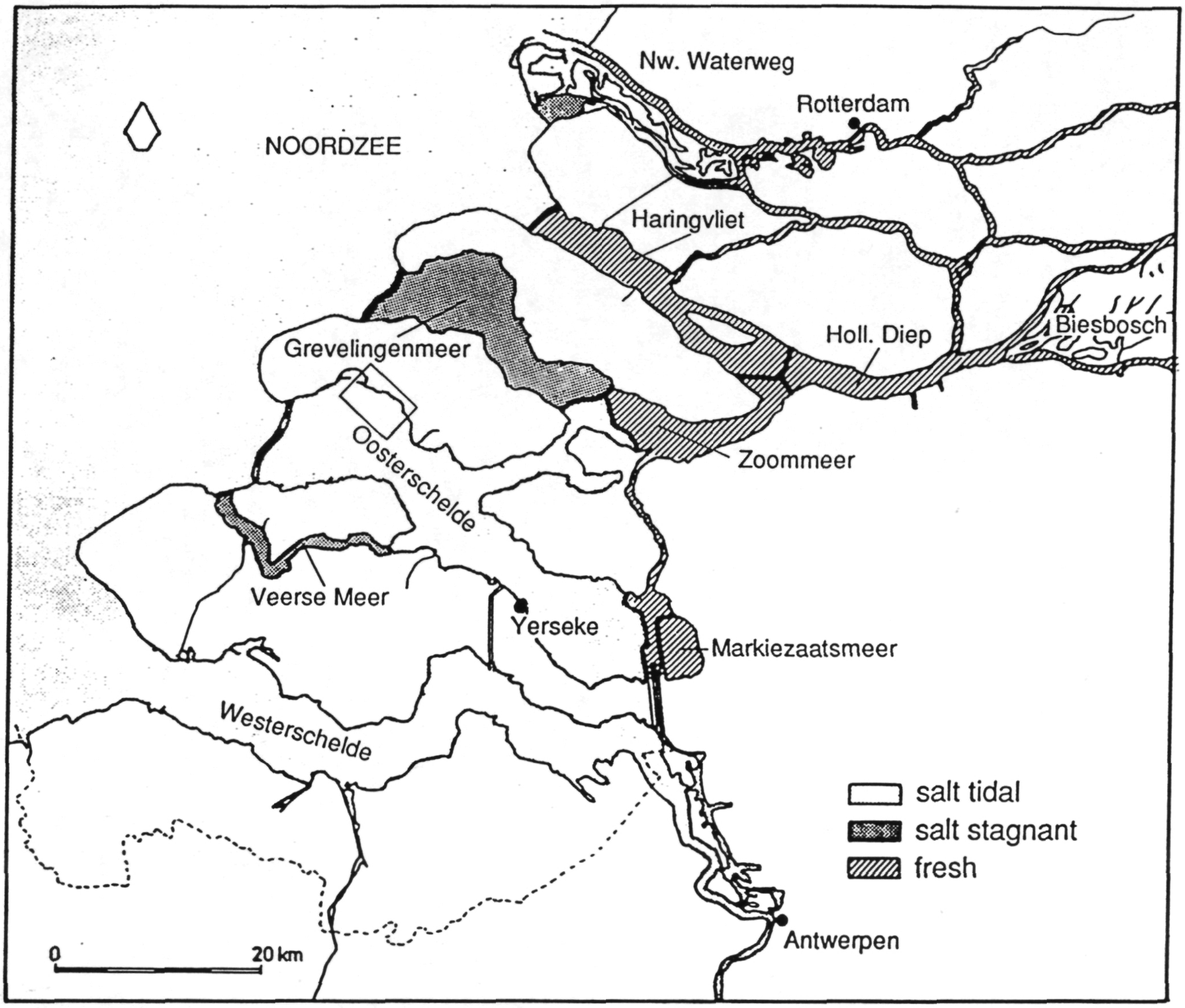

Figure 3. The Delta region in 1987 with –numbered– the different closure dams: 1: Zandkreekdam, 2: Veerse Gat dam, 3: Grevelingendam, 4: Volkerakdam, 5: Haringvliet Barrier, 6: Brouwersdam, 7: Oosterschelde Storm Surge Barrier, 8: Philipsdam, 9: Oesterdam. Different salinities and tidal regimes are indicated. The water in the Veerse Meer is brackish (vide text). The framed area in the Oosterschelde is the area, meant in fig. 6.

large yearclasses of the starfish *Asterias rubens L* and the shore crab (*Carcinus maenas*) occurred during the period 1981–1984. Between 1982 and 1985 meadows of the tunicate species *Cionia intestinalis* and *Ascidiella aspersa* covered particularly the deeper ranges of the lake and affected oyster culture by acting as competitors for space on spat collectors. Also the Netted Dog Whelk (*Nassarius reticulatus L*) occurred, especially during the last years, in densities, unknown from "normal" estuarine waters. It is supposed that the fluctuations in numbers of most organisms are stabilising somewhat during the last few years. A cause for such a stabilisation is, however, difficult to give. The flat oyster, on the other hand, showed a gradual increase in numbers, which started in 1975 and levelled off around 1985. This oyster stock originated from a small number of oysters, left over after the oyster farmers had fished clean their plots in 1964, when all aquaculture operations in the estuary ceased. These oysters had survived the very cold winter of 1962–1963, when water temperatures of minus 1.5 degree Celsius prevailed during several months in the ice-covered lake. They must have caused the rapid development of the oyster population, which was triggered by favourable water temperatures during the warm summer of 1976. The population kept on growing during the years to follow. After this oyster population was discovered, our institute embarked on an extensive program, to follow the development and distribution of the population and to obtain a view on settlement and development of the spat. Soon it appeared that Lake Grevelingen has outstanding qualities as breeding area for the flat oyster. Thanks to the absence of tidal exchange, water temperatures rise rapidly in June, and temperatures above 20 degrees Centigrade prevail during several weeks almost every year. Concentrations of oyster larvae of over 20,000 larvae per cubic meter are regularly found with 2,000–4,000 as an average. Spatfall on mussel shells in the lake appeared to be profuse in most years, 20–30 spat on a mussel shell are no exception in the first week after settlement. Mortality of the newly-settled spat, however, is high. In June of the next year not more than 5–10% of the settled spat survived (Dijkema c.s., 1985) (Figure 4). This, however, appears to be sufficient to sustain the oyster population in the lake and to allow a yearly catch of 2–3 millions of wild oysters. Besides, some 10–12 millions of oysters were cultivated on an area of about 150 ha of cultivation plots. This area has been enlarged in 1987 until 380 ha. Plans to use the seed oyster production of Lake Grevelingen to repopulate the cultivation plots in the Oosterschelde, which had been in disuse since 1963, were frustrated by a new disaster: the outbreak of the oyster disease *Bonamia*, introduced from France in 1980, which made a total ban on oyster cultivation in the Oosterschelde necessary. This ban was only partially lifted in 1987, as still traces of *Bonamia* are being found in the area. This event made Lake Grevelingen the cork on which the Dutch oyster industry has been floating until this moment. Deprived of their plots in the Oosterschelde, the oyster growers and exporters could only serve the market with oysters from Lake Grevelingen. Fortunately, the decimation of the flat oyster stocks in Europe's most important producing countries: France and England and later also Ireland, have caused oyster prices to rise sharply, which slightly mitigates the low production. As the oyster disease has more or less been overcome, the Ministry of Agriculture and Fisheries has decided to create conditions for a rapid re-population of the derelict oyster

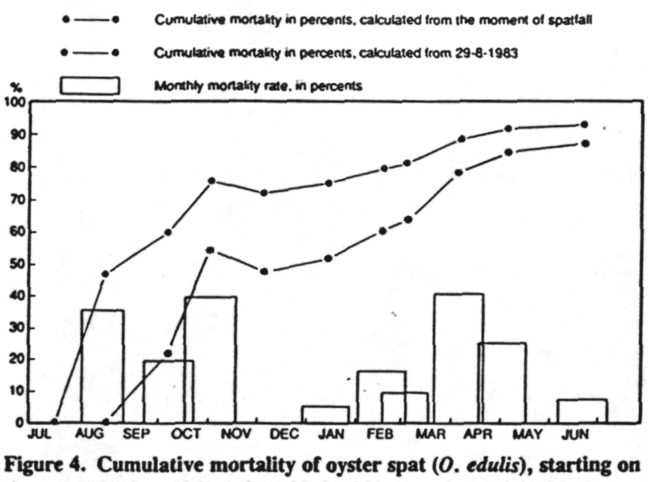

Figure 4. Cumulative mortality of oyster spat (*O. edulis*), starting on the moment of spatfall and on 29–8–1983 (line chart). The histogram represents the monthly mortality rate of the spat during its first year of life. The spat has settled on mussel shell cultch on a plot on the bottom of Lake Grevelingen, period July 1983–June 1984 (Dijkema c.s., 1985).

plots in the Oosterschelde. The basic aim is to use Lake Grevelingen for seed oyster production because of its favourable conditions for settlement, using the Oosterschelde plots (1,700 ha) for final fattening. This is because the ecological conditions in the Oosterschelde: higher current speeds and lower temperatures in summer, are more favourable for fattening. Probably due to the low current velocities in the lake, the shells of the oysters are thin, and can crumble when the oysters are opened. Another shell problem in the Shell Disease (*Ostracoblabe implexa*), which can cause considerable shell damage and mortality after warm summers. For this reason final fattening in the Oosterschelde, with a lower infection rate with shell disease, is preferred. This year an extension has been made of the cultivation and spat collecting plots in the lake from 150 to 500 ha. A possibility has been created for all practising Dutch oyster growers to lease plots, instead of the limited group that was allowed to carry out the first trials in the lake jointly. This means that from now on each farmer can operate individually. A basic goal of the spat-collecting function of Lake Grevelingen is also to make imports of foreign seed oysters unnecessary, thus minimising the risk of introduction of new diseases like *Bonamia*. A last, and important aspect is also that centuries of imports of seed oysters from southern, warmer countries like France and the Mediterranean had caused the native Dutch oysters to lose their original winter-hardiness. The oysters which had started the population in Lake Grevelingen had undergone a selection during the cold winter of 1962–1963 and appeared to have regained the original winter-hardiness of the native Dutch oyster. This is able to endure temperatures as low as the freezing point of sea-water without mortality, while imported southern oysters must be harvested before winter and must be stored in basins with heated water during frost spells. The water authorities still clung to the original plans that Lake Grevelingen should be converted into a fresh water lake as soon as the adjacent sea arm should contain fresh. This point of view was also defended by representatives from agriculture organisations, who considered it as a promise that they should get fresh water for irrigation. The good water quality and rich flora and fauna in the lake and its important role for the Dutch oyster industry, however, made that the original plans were reconsidered. Not earlier than in 1986 the decision was made to conserve Lake Grevelingen as a salt water lake. An ideal salinity in the lake was, in the meantime, safeguarded by the construction of a sluice and a siphon in the opposite closure dikes, making flushing of the lake with sea water possible. As said, these developments and management decisions have been of vital importance for our oyster industry. They can be considered to have saved not only the Dutch share in the European market of flat oysters, but they have also made possible the conservation of the native Dutch flat oyster as a genetic strain, which would otherwise have been lost.

6. CONSEQUENCES FOR FISHERY AND AQUACULTURE, RESEARCH AND THE RESULTING PROGNOSES

Despite all precautions, taken during the design of the Oosterschelde barrier and the secundary dams, the compromise between safety and nature conservation could not guarantee freedom from negative effects on nature and aquaculture. One of these was the risk of an increase of sedimentation on mussel rewatering plots off Yerseke, as a result of reduced current velocities. When this should happen, alternative occasions for mussel re-watering should have to be sought. Another question, very relevant to coastal as well as fisheries management, was whether the estuary would be capable in future to nourish as many organisms as it had done before. It was thought possible that the halved supply of nutrients would result in a decrease of primary production of phytoplankton and eventually in a shortage of food for filter feeders. Also the import of food particles from the North Sea could decrease. This could result in a reduction of the carrying capacity of the estuary. This question was imminent because the mussel cultivating industry was putting pressure on government to rent more plots to them, while number one priority in management of the estuary was the conservation of natural values. These interests could easily become conflicting when food supply in the estuary would be limiting for either the cultivated mussels or for wild organisms. Competition for food could then result in an undesired impoverishment of flora and fauna. Finally it was feared that the nursery function of the Oosterschelde for commercially valuable fish species would suffer from the reduced tidal volume. The amounts of planktonic fish larvae, carried in with the flood current could, it was feared, decline. The intertidal nursery area would be reduced by 20–30% by the decrease of the tidal amplitude.

Research

Negative impact on fishery and aquaculture except for the, already indemnified, oyster industry, could entail claims for damages brought out by the industry to the Government. An extensive research program was set up, first to study the original situation (which actually did not longer exist), second to make a prognosis for the changes to come. As far as the natural environment was concerned, these studies were carried out by the Ministry of Public Works and Waterways, responsible for the Delta Plan. Research in the field of fisheries and aquaculture was carried out by or in close cooperation with our institute.

Mussel Rewatering

The first priority for the management was a prognosis of the future sedimentation rate on the rewatering plots for mussels. Such a kind of research requires numerous sampling campaigns during an entire tidal cycle with up to six ships simultaneously. Thousands of water-samples have to be analyzed in the laboratory and a multiple of this number of data, has to be processed. By combining the results of current and flow measurements and data about concentrations of suspended matter in the water with data about the accumulation of silt on beds of mussels, we arrived to the conclusion that the current velocities, expected to prevail on the rewatering location would just be sufficient to prevent accumulation of silt on the plots. This was much to the relief of the mussel traders, who exploit these plots, because otherwise they would have had to look for other locations. That the tolerable limit of the current velocity was almost reached appeared, however, in 1986 when the gates of the barrier had to be closed partially to ease construction works. During that period serious siltation occurred, inflicting damage to the mussel traders. Large amounts of silt had to be washed from between the mussels, mortality took place and the quality of the mussels was affected. Now the works have been finished and the definitive tidal regime is prevailing, siltation and mortality have ceased.

Carrying Capacity

The carrying capacity of the estuary for both wild and cultivated stocks of filter-feeding organisms appeared to be a very complex matter to investigate. We have, in first instance, limited our efforts to the availability of food for suspension feeders, notably mussels and cockles, (*Cerastoderma edule* L), as these groups are by far dominant in biomass and essential as food for migrating and wintering birds. This meant in the first place that an assessment had to be made of the biomass of these organisms and that their rate of food consumption had to be established. On the other hand, we wanted to know the quantity of available food in the water and its expected changes after completion of the Storm Surge Barrier. The first and most basic question, however, was: What is the food of filter feeders, what is its composition and what is the nutritive value of its components? It was discovered that particulate organic matter (POM) could be subdivided into a fraction which could be readily digested (70% or less) and a very stable one (30% or more). Also is was discovered that bacteria and small flagellates, although important in numbers, only had a very limited share in the cell volume biomass of potential food for filter feeders (Smaal c.s., 1986). Phytoplankton can constitute up to 20% (in weight) of POM in summer. An important food component for the filter feeders in the mouth of the estuary appeared to be relatively large phytoplankton organisms, imported from the North Sea by the tidal currents. This extra ration could be held partly responsible for the fact that the growth rate of mussels and cockles is high in the mouth of the estuary and declines along its length axis in upstream direction. (Van Stralen, 1988) Also it is felt, although not demonstrated, that this growth rate gradient finds its origin in food depletion, due to grazing by the filter feeders in the estuary. Research to elucidate this problem is still in progress.

7. EFFECTS OF CURRENT SPEED REDUCTION

The Lower Limit

More than any other form of mollusc cultivation, bottom culture is dependent on the tidal currents. The velocity of the currents above a culture plot leaves a certain tolerable range, within which bottom culture is possible. In mussel cultivation in the Oosterschelde, the lower limit for bottom culture is set by the total consumption of oxygen on and above the bottom on the cultivation plot. Four major oxygen consumers are active on a mussel plot: In the first place the mussels, second all other benthic organisms, in the third place the aerobic heterotrophic bacteria in the upper layers of the sediment and in the "benthic boundary layer". Another modest but important consumer of oxygen is hydrogen sulphide, produced by sulphate-reducing bacteria in the sediment. This highly toxic product diffuses up to the sediment surface and is normally oxydized in the top centimeters of the sediment. In sandy, well oxygenated bottoms, oxygen penetrates quite deeply, while hydrogen sulphide stays down. If, however, the sediment is muddy, the current velocity low and consequently the top layer of the sediment poorly aerated, hydrogen sulphide lingers just below the bottom surface and can reach the water phase and the mussels as soon as oxygen level is too low. In that case mortality can occur, not by anoxia, as is often thought, but by hydrogen sulphide poisoning. This can happen when current velocities are low and when the concentration of decomposing, oxygen-consuming organic matter in the water of the "benthic boundary layer" is higher than normal. In the Oosterschelde this has occurred when an algal bloom had died off and decomposed. A critical lower limit for current velocity is hard to give. When the organic matter content of bottom and water are low and the biomass of cultivated shellfish is not too high, e.g. lower than 3–5 kg fresh weight on a square meter, a current speed of some cm/s, or even a temporary current standstill around slack tide can easily be sustained. Such conditions are, to our experience, not favourable for a good mussel production but can be tolerated for instance on plots with small mussels. In contrast with the slow growth of adult mussels in Lake Grevelingen, where current speed ranges between nil and 20 cm/s, growth rate as well as meat yield of the native oyster *O. edulis* reaches high values. Apparently *O. edulis* is doing much better under low current conditions.

The Upper Limit

The upper limit of the sustainable current velocity range is set by purely mechanical and perhaps by trophic factors: Molluscs living on the substrate, like mussels or oysters, can lose their footing when current and/or waves exert an excessive stress on them. Also filter-feeding becomes less efficient at high current speeds, which mostly are linked to a high silt or sand load of the water. Also molluscs can be buried under shifting sediment, when current speed is very high. This burying can cause immediate death through suffocation, but also growth can be impaired due to loss of energy, when the animals have to clear their gills or have to dig out too frequently. We have tried to establish these upper current speed limits by measuring current velocities during two months on a number of locations: where mussel culture is profitable, where it is marginal and where it is impossible due to excessive current velocities. The results of this comparison are given in figure 5, which shows how frequently a certain current velocity is exceeded on a particular location. Mussel culture appears to be marginally possible on plots where a current velocity of 60 cm/s, measured 40 cm above the bottom, is exceeded during 5% of the time or more during an average tide. We consider this as the critical value, above which mussel culture is too risky to be commercially feasible (Steyaert, 1986). Most profitable mussel culture can generally be expected at current velocities in the range of 50–60 cm/s. Bottom composition is also an important factor for the grip mussels can have on their substrate. Older cultivation grounds, containing a fair amount of shell debris and a certain fraction of mud, appear to offer a better foothold for mussels than new plots with pure and mobile sand. Often, a period of initiation is required before new plots in high current areas become reliable.

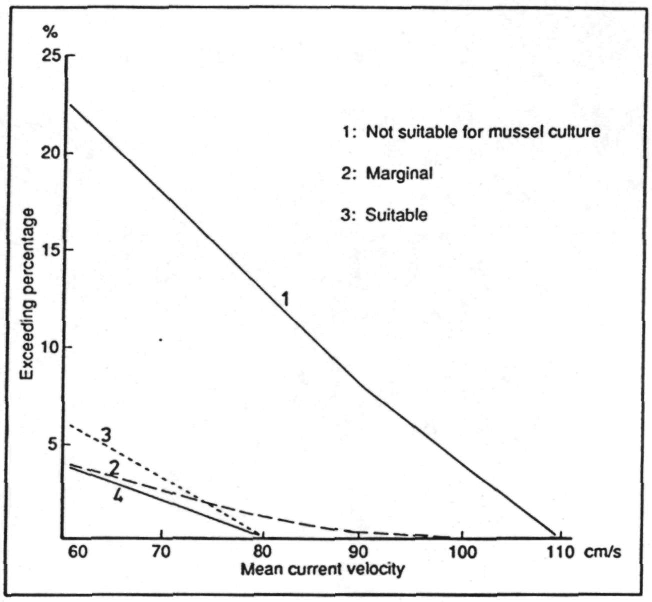

Figure 5. Exceeding percentages of maximal tidal current velocities on cultivation plots with different suitability for mussel culture. On the suitable grounds a speed of 80 cm/s is exceeded in about 4% of the cases. A reliable culture is only possible at speeds lower than 60 cm/s (Steyaert, 1986).

8. FISHERY AND AQUACULTURE IN THE OOSTERSCHELDE IN THE FINAL SITUATION

The construction engineers of the Delta project managed to keep their schedule better than the environmental researchers who had to make the prognoses for nature, fishery and aquaculture: On the twenty-ninth of April 1987, the second of the two secondary dams was closed, which meant that the final shape of the Delta works was reached. Apart from some adaptation of the morphology of the estuary to the new hydraulic conditions, which may take more than 10 years, tidal movement and currents reached their definitive pattern. Already in the course of the works, it became clear that many of the design calculations for the Storm Surge Barrier had been carried out with a certain safety margin in favour of a larger aperture. Final measurements after completion of the works demonstrated that the volume of water flowing through the barrier each tide was larger than had been anticipated. This resulted in a mean tidal range of 3.20 m off Yerseke, instead of the 2.70 m originally deemed acceptable for the conservation of the environment. As the original tidal range had been 3.50 m, the final reduction of the tide appeared minimal: less than 10%. No wonder that mussel growers reported that they could hardly see any difference with the original situation on most of the cultivation plots. Only in one of the three tidal channels through the barrier, current velocities stayed below the original values. In two consecutive years, in the month of May, growth reduction and even mortality occurred on certain plots and the mussel growers complained. We assume the cause of this phenomenon to be the combination of a local decrease of the current speed with increased levels of organic matter in the water just after the yearly returning bloom of the flagellate *Phaeocystis pouchettii* in May. Probably oxygen depletion by the decomposing organic matter has caused anoxia and intoxication by hydrogen sulphide. This was confirmed by the presence of black, smelling mud. The mortality must have been increased by the usual post-spawning mortality of the mussels in that month. Further research will have to show whether this effect is lasting or not. Among the existing cultivation plots on the map of the Oosterschelde, covering some 3,000 ha, more than 30% are not utilized. After the start of the project, the succesive closing of the sea-arms caused a gradual increase of the sea-level and the current velocities in the area. This caused that a number of mussel plots had to be abandoned because either the mussels were swept away, or suffocated in "living sand". This caused that their productivity passed the limit of economic viability. The expected decrease of current velocities on a number of locations revived the interest of both fishery inspectors and mussel farmers in a number of plots which had been abandoned in the past decades. Site selection for bottom cultivation has hitherto been done by rather primitive means, based on the experience and intuition of professionals. No exact approach existed of the question whether or not a certain area is suitable for mussel cultivation. We, scientists think to have other means at our disposal for predicting possibilities for mussel cultivation that probing in the bottom with a boat-hook or spitting into the water to tell the current velocity. Although we may not dispose of generations of practical experience and green fingers, we have gathered the results of many months of continuous current measurements, and are able to fit these together and to make a mathematical model which can predict the current speed on any moment and on any location in the Oosterschelde at intervals of 100 m. The model outcomes were combined with the results of measurements with "Flachsee" type current meters on a selection of plots where mussel culture was profitable, just profitable or marginal. It appeared that at maximum flood current speeds higher than 60 cm/s at mid-depth no feasible mussel culture is possible, whereas in the range between 50 cm/s and 60 cm/s the risk for the mussels to be swept away is acceptable. (Van Stralen, 1988). At lower speeds mussel culture is possible, but too low current speeds entail, as has been exposed before, other risks. This operation yielded a set of current-charts on which the areas could be indicated where the current speed limit of 60 cm/s or of 50 cm/s at mid-depth will be exceeded during an average tide. The area where 60 cm/s will be exceeded will decrease considerably, whereas the area between 50 cm/s and 60 cm/s is expected to increase in comparison with the original situation. This is represented in figure 6 for an important mussel growing area, framed out in figure 3.

B. ASPECTS OF FISHERY AND AQUACULTURE MANAGEMENT

Fishery and aquaculture management in the Netherlands, carried out by the Ministry of Agriculture and Fisheries, has been confronted with various problems since the beginning of the Delta Plan. In the first place there was the problem of indemnification of the oyster industry. As we have seen, ten out of one hundred firms continued oyster farming. As soon as in 1976 it had become clear that the Oosterschelde would stay open, a number of other professionals, often the sons of former oyster growers, expressed the wish to re-start oyster farming and claimed a number of the cultivating plots which now were leased by the ten firms mentioned before. These, understandably, refused to give them back. This affair caused bitter discontent, resulting in the existence, now, of three separate associations of oyster growers and exporters. Another strong winter, followed by the outbreak of the oyster disease *Bonamia ostreae* postponed the solution of this problem. Instead, the battlefield moved to Lake Grevelingen, where, in 1977, the ten oyster firms had started their spat collecting project, had started growing marketable oysters, as well as a fishery for wild oysters. The success of this project did not stay unnoticed for long. In the first place there were the former mussel and oyster growers of the estuary. A number of the growers had opted for compensating plots in the Waddenzee, others had been granted eel fishing rights in Lake Grevelingen. These eel fishermen saw their former colleagues, even from a competing fishing-village, harvesting oysters in the lake where they were only allowed to fish

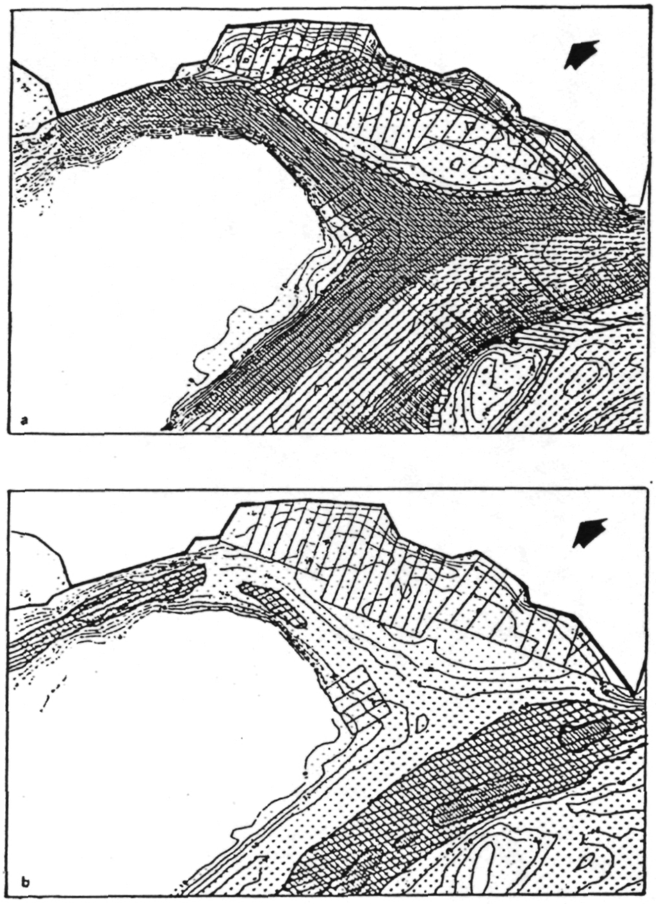

Figure 6. Current charts of the section of the Oosterschelde, framed in figure 3. The lined areas are plots for mussel culture. Fig. 6-a shows the original situation, fig. 6-b the situation after completion of the dams. The finely hatched area (in 6-a not filled) has current speeds over 60 cm/s, the coarsely hatched area has velocities between 50 and 60 cm/s. In the remainder of the channels in fig. 6-b current speeds are less than 50 cm/s. Scale 1: 50,000 (Van Stralen, 1988).

eels. They wanted their share of the newly discovered bounties of what they considered "their" fishing grounds. They argued that their catches did not meet the expectations and that they also wanted to lease concessions for spat collecting and oyster growing. The oyster farmers did not wish to allow anyone to participate in their project and, again, bitter quarrels followed. Both parties hired lawyers, who further sharpened the argument. The affair was made even more complicated because Lake Grevelingen was officially considered an inland lake. As never before oysters had been cultivated in an inland lake, the Inland Fishery Board, responsible for the issuing of fishing rights, now faced a problem it was not at all familiar with. Finally, it managed to untangle the Gordian knot and the compromise was found that the eel fishermen could rent a number of plots, on condition that they should sell their entire crop to the oyster farmers. In 1985, the Ministry considered the experimental project to be concluded and drew up a plan in which the culture area in the lake was to be increased gradually to 500 ha, and plots were issued to all practising oyster farmers. This meant that in total about fifteen firms could start producing oysters in the lake. In contrast with the first project, which had been carried out on a collective basis, individual firms had to lease plots. Again the established firms, this time in close harmony with the eel fishermen, opposed with all possible means the admission of other firms. Only in 1987 the judge ordered allotment of plots to all fifteen oyster firms. Since the start of the Delta Project, some hundreds of hectares of mussel cultivation plots in Lake Veere, in Lake Grevelingen and in the Oosterschelde had disappeared (figure 2). For most of them compensating culture ground was found, mostly in the Waddenzee, where now an area of about 6,000 ha is in lease. A further extension of the mussel cultivating area in the Waddenzee is restricted by the shrimp fishing industry in that area. Unfortunately both the shrimp fishermen and mussel growers prefer the same areas. The shrimp fishermen already saw an increasing portion of their fishing grounds occupied by mussel plots, on which they are not allowed to fish with their trawlnets. At this moment, all suitable grounds are occupied and there is little scope for amplification of the mussel growing area. Another factor is that nature conservationists are looking to mussel culture with more critical eyes than before. Possible depletion of food for other filter feeding organisms by the mussels on the cultivation plots and the fear for alterations of the natural environment around mussel plots, has made nature conservation authorities first want to know if the mussel growing has a negative impact on the environment before any new concessions are allowed. As has been exposed above, the reduction of the current velocities in the Oosterschelde is expected to make mussel culture possible on a number of places where before current velocities had prevented this. Whether or not this potential cultivating ground will actually be destined for the mussel growing industry will mainly depend on the outcome of the investigations into the carrying capacity of the Oosterschelde. Management of shellfish cultivation and fisheries is, in these days, not longer a matter of the fishery authorities alone. Following a modern trend, in the Netherlands on this moment three ministries are responsible for environmental management. As bottom culture of mussels is often carried out in areas of outstanding natural interest, all human activities in these areas, even if they look as environment-friendly as mussel cultivation, are watched with a critical eye. It seems that at last this industry, which has been able to proceed and to flourish practically undisturbed since its birth in 1870, will finally be subjected to the restrictions and regulations of modern society.

LITERATURE CITED

Duursma, E. K. ed. The Dutch delta, a compromise between environment and technology in the struggle against the sea. *Natuur en techniek, Maastricht*, 1982.

Dijkema, R. 1984. Assessment of size, distribution and composition of a newly-developed stock of the European flat oyster (*Ostrea edulis* L) in a stagnant salt water lake in the SW Netherlands. *Int. Council for Exploration of the Sea*, C.M. 1983, K:14.

Dijkema, R., C. S. Vroonland & J. Bol. 1985. Growth and mortality in the first year of spat of the European Flat Oyster (*Ostrea edulis* L.) on commercial plots in marine Lake Grevelingen (SW Netherlands). *International Council for Exploration of the Sea* C.M. 1985, K:15.

Knoester, M. 1984. Introduction to the Delta case studies. *Wat. Sci. Techn*. Vol 16, pp 1–9.

Lambeck R. H. D. 1982. Colonisation and distribution of *Nassarius reticulatus* (Mollusca, prosobrancha) in the newly created saline lake Grevelingen, SW Netherlands. *Neth. J. Sea Res*. 16:67–79.

Misdorp, R., L. H. M. Kohsiek, F. H. I. M. Steyaert & R. Dijkema. 1984. Environmental consequences of a large scale coastal engineering project on aspects of mussel culture in the Eastern Scheldt. *Wat. Sci. Techn*. Vol 16, pp 95–105.

Nienhuis, P. H. 1978. Lake Grevelinge: a case study of ecosystem changes in a closed estuary. *Hydrobiol. Bull*. 12, 346–259.

Saeys, H. L. F. & H. J. M. Baptist. 1980. Coastal engineering an European wintering wetland birds. *Biological Conservation* 17:1 63–83.

Smaal, A. C., J. Verhagen, J. Coosen & H. Haas. 1986. Interactions between seston quantity and quality and benthic suspension feeders in the Oosterschelde, Netherlands. *Ophelia*, 26, 385–399.

Steyaert, F. H. I. M. 1986. Stormvloedkering in de monding van de Oosterschelde, een nieuwe ontwikkeling voor de Zeeuwse mosselcultuur? *Aquaforum*, (1), 3 (In Dutch).

Stralen Van Straien, M. R. 1988. Het functioneren van mosselpercelen in de Oosterschelde. Report of the projectgroep "MOKWE", Tidal waters department & Netherlands Institute for Fishery Investigations, Yerseke. (In Dutch.)