# CHAPTER 74

## HYDRAULIC SURVEY AND MODEL INVESTIGATION OF THE INNER RANA FJORD

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## SYNOPSIS

The characteristic feature of the water masses in a fjord is their stratification. This stratification and its annual cycle are explained in terms of the physiography of the fjord regions. The glacial origin of these regions is outlined in order to expose the sediment sources and the present sediment regime.

A case study of a fjord in Northern Norway is reported. The results of a field survey comprising measurements of tidal and river flows are given. The measurements revealed that the tidal flow had a steady component giving a horizontal circulation in the fjord, in addition to the vertical circulation associated with the diffusion of salt water upwards into the surface layer.

The reduced scale model of the lower river and the Inner Fjord was built to avoid adverse affects of a constriction of the river mouth. The model also showed that a small jetty would turn the turbid surface jet away from the incoming tidal current towards the outbound current caused by the horizontal circulation, thereby relieving the harbour area of some of its present sediment supply.

## FJORD PHYSIOGRAPHY

### TOPOGRAPHY

The fjord type of estuary is studied primarily in Norway, where there is a large number of them, and in Canada, where they are also numerous on the Pacific Coast. The outstanding feature of the water masses in a fjord is their pronounced stratification. This is a consequence of the characteristic topography both below and above the water surface (fig. 1).

First, the water body has a large depth to width ratio, which facilitates layering, so the mixing due to tidal flows becomes small.

Secondly, and probably more important, the mixing due to

wind waves and currents is checked by the generally short fetches due to the small width and often winding course of the fjord.

Finally, although the topography may funnel the wind to very high local velocities, the overall effect of the steep and irregular land forms is a thickening of the air boundary layer and a reduction of wind speeds compared to those prevailing on a coastal plain.

These three topographical effects, together with the characteristic hydrology of fjord regions, seem to explain the observations of both Canadian and Norwegian oceanographers. It is apparent that the fjords are more strongly stratified than any other bodies of water. (3), (4), (5).

## HYDROLOGY

The prevailing westerly winds are pushing moist air masses from the North Atlantic against the Norwegian Coast. Most of the resulting orographic precipitation reaches the fjords at their heads. However, the winter precipitation is snow, which accumulates in the mountains until the spring. The hydrograph of fresh water inflow to the fjord therefore shows an annual cycle with low inflow during the winter, a spring flood and a relatively high summer inflow. (fig. 3).

There is a corresponding annual cycle for the stratification of the fjord. During the winter, when the fresh water inflow is low, the density gradients are relatively weak. During the summer, when the fresh water inflow is large, very strong stratifications develop.

This trend due to the seasonal distribution of runoff is enhanced by the seasonal distribution of storms and high winds. The mixing due to wind stresses at the free surface is most intense in the winter and least in the summer.

Both these trends become more important at higher latitudes. Our northern fjords sometimes develop almost homogeneous surface layers down to 50 - 100 m in the cold and stormy winter season.

## SEDIMENTS

The geologic history of the fjord countries is one of gradual changes. Their formation by glaciers was a very slow carving process, and a very thorough one: It was a clean sweep which left only marginal deposits within the fjord area.

During the glacial regression successive cross sections of the newly formed fjord became ending points for the glacifluvial transport. However, in most places the glaciers regressed rather fast and left only traces of sediments.

It was only after the ice front had retreated beyond the head of the fjord that a more permanent pattern of deposition could again be established. Between the glacier and the sea a river now formed, and at its mouth a delta. However, the normal process of delta formation has been influenced by the regression of the sea. As the weight of the ice is gradually diminishing, the compressed mantle of the earth gradually springs back. The land rise due to the mantle elasticity has more than compensated for the rise in sea level due to the melted ice. The net effect has been the emergence of the sea bottom to considerable heights - a marine border of 50 to 200 m is common over most of Scandinavia. The consequent choking of the river mouth has disturbed the normal delta process and encouraged the formation of gorge - like cuts through the emerged terraces by single channels. These river channels end in relatively young and therefore small deltas.

Glacial deposits contain sufficient quantities of coarse material to facilitate the formation of a cover layer that stops the erosion. Non-glacial rivers flowing across glacial deposits therefore are clean until they reach the marine border. Below this border the river may pick up a sediment load and deliver it to the fjord. - Glacial rivers, on the other hand, have from their origin a sediment load, which may increase or decrease below the marine border.

The marine terraces are eroded not only by rivers, but frequently also by wave action on exposed slopes. In most fjords the emerged marine terraces are the only sediment sources of any importance.

The quick settling at the river mouth and the convergence of sediments on the same area due to opposing undercurrents are the chief factors determining the initial distribution of sediments. The sediments deposit on the usually steep and long rear slope of the fjord basin, often with a loose structure.

A characteristic feature of these slopes is that their contour lines are irregular and often concave towards the basin. This is in contrast to the normal delta, which has regular and usually convex contours. The reason for this peculiar topography is that the fjord slopes fail, so their upper contours look like a succession of crescents and cusps.

The redistribution of sediments through slope failures is a major reason why one seldom finds long fjord deltas. The sediments are transported to the deep fjord, but the mode of transport is largely unknown. Observations by Holtedahl (2) in the

Hardanger Fjord have demonstrated beyond doubt that turbidity currents have been active.

## EFFECTS OF FRESH WATER STORAGE

The human activities around a fjord are adjusted to the seasonal variations of the stratification in much the same way that they are adjusted to the local climate. - Some features are cherished, as the opportunity for recreational swimming. With the stable summer stratification, it takes only a few days of sunshine and warm weather to heat the surface layers to quite comfortable temperatures. - Of great economic importance is the weak winter stratification because it reduces the ice formation. Therefore, navigation is not seriously hampered in normal years, except in particularly well sheltered waters.

However, in certain of our fjords the natural stratification is disturbed by extensive hydro-electric developments. The construction of artificial storage reservoirs for power production interferes with the natural inflow of fresh water to most of our fjords. The purpose of the artificial storage is to make the runoff hydrograph conform more to the power load curve. In a northern climate this means holding back summer flows in order to increase the winter discharge. Fig. 3 shows the changes that are planned of the hydrograph for fresh water inflow to the Inner Rana Fjord. The winter flows are to be increased two or three times.

Any increase of the winter inflow will increase the ice hazard in a fjord. Experience from Sørfjorden, the southern branch of the Rana Fjord, shows that such inflows as are expected for the Inner Rana Fjord, may well create a sufficiently stable surface layer to facilitate the formation of a permanent ice cover.

Ice troubles are only the most obvious, adverse result of manipulations with the fresh water hydrograph. In the author's opinion other effects are likely to receive attention in the future, especially the biological consequences of the changed environment. Work in this area has only recently been taken up by our marine biologists.

The economic benefits of the storage are generally overwhelming and outweigh by far the adverse effects. - With intelligent operating schedules flood peaks are cut back, so sediment loads and flood damage are reduced. However, the reservoirs pay for themselves primarily in terms of the inexpensive hydro power, which is so vital for the national economy.

## FIELD OBSERVATIONS

The field observations that form the substance of this paper, were made in the Inner Rana Fjord in 1964. This fjord (fig. 1) is located just south of the Arctic Circle and displays many of the characteristics of a typical fjord described in the preceding section.

The fjord extends about 60 km from the coast line and about 80 km from the ocean. Its width varies between 1 and 4 km and its maximum depth between 300 and 530 m. The mouth is wide open, not choked by a sill as is the case with most fjords. - The surrounding mountains rise steeply to an altitude of 600 to 1000 m within a few km from the sea.

At the fjord head the Rana River discharges an annual average of 180 $m^3/s$. Other rivers contribute another 20% to the inner basin.

Two kilometers from the fjord the river drops over its last fall, Sjøfossen, which provides an absolute barrier for the salt water intrusion. During river flows less than 100 $m^3/s$ the salt water reaches this barrier. For higher flows the salt water wedge is stopped farther downstream, and for flows exceeding 1000 $m^3/s$ the salt water is pushed entirely out of the river (fig. 2).

The lower river reach is incapable of mixing fresh and sea water to any great extent, so surface salinities seldom exceed 5 o/oo at the river mouth. As a rule the fjord is covered by a blanket of brackish water, increasing both in thickness and salinity with distance from the river mouth.

This further mixing is by wind stresses at the free surface and by tidal currents. Because of the large depth to width ratio tidal currents are not very effective, so most of the mixing is by wind waves and currents.

## HYDRAULIC SURVEY

The surface flow pattern was readily obtained by means of dye streaks photographed from the air. (We learned the technique from dr. Per Bruun, who used it in Florida). Dye cakes, weighing about 500 grammes and consisting of a mixture of Rhodamin B and a wax, were suspended in anchored buoys. The dye labeled the water passing near the cakes, and the wax inhibited diffusion. Even in a rough river flow with velocities exceeding 1 m/s, 500 m long streak lines were visible on the air photos. On fig. 4 the dye cake positions are indicated by circles, and the dye streaks drawn

with heavy lines.

Velocities were measured with propeller meters. We used two Ekman instruments and two recording instruments of a new design (Ruud-Føyn-Beyer). Like other propeller meters these instruments have a limiting velocity of a few cm/s, which was rarely exceeded at lower depths than 10 m. The measurements were continued throughout one tidal cycle at each station. We had 15 stations, shown on fig. 5, and since we kept one instrument at a reference station all the time, the entire observation period was 6 days. During this time the river flow increased from 350 to 440 $m^3/s$ and the tidal range from 1.5 to 2.8 m. The resulting flow picture is therefore not a synoptic one.

Within the surface jet the flow directions at each station do not change much during the tidal period, although the velocities vary considerably. In the river mouth, where a critical two-layer flow occurs, the maximum velocity 1.3 m/s was observed at station 8. In front of the Toranes pier, 1.5 km from the river mouth, the maximum velocity still was 0,9 m/s (station 12).

The vertical distribution of velocities within the surface jet seems to be influenced by the varying surface slope, as shown on fig. 6. The measurements also suggest a change towards a triangular velocity profile with distance from the river mouth.

At 3 m depth the flow pattern was essentially the reverse of that at the surface. There was a net flow towards the river mouth at most stations. This flow forms the compensation current that maintains the salt water wedge in the river.

At 6 m depth there was also a net inflow along the east land. The outflow must be either by vertical upwelling or as an outbound current along the opposite land. At 10 m depth the flow pattern was essentially the same as for 6 m, but the velocities were less. At larger depths than 10 m velocities seldom reached the detectable minimum.

Examples of the flow observations are shown as polar velocity diagrams on fig. 7 for depths 0.3 and 6 m, respectively.

## COMMENTS

As the net inflow along the east land was much larger than the outflow in the surface layer, there must be a net outflow along the opposite land. Clear indications of this flow were obtained at station 14 and at station 15, 2 km from the river mouth.

The vertical circulation, with an undercurrent directed upstream within the salt water wedge and with outflow in the surface

layer, is well known from most estuaries - in fact it is so common that it is called the estuarine circulation.

The horizontal circulation that our measurements in the Rana Fjord revealed, is probably no less common, although it is perhaps less obvious and not so easily detectable. It is well known that inertial and frictional forces in an oscillating flow do create streaming, i.e. a steady flow component. In contrast to the periodic tidal flow, the induced steady flow is independent of the distance x from the open sea. The streaming velocities will of course depend on the cross sections of flow and are therefore functions of x.

An undercurrent may greatly influence the trajectories of particles settling out of suspension in a flowing surface layer. - The average size of such particles will decrease in the direction of surface flow. If the undercurrent is opposed to the surface jet, the particle trajectories will converge on a relatively small area of deposition near the river mouth. - If there is no undercurrent, the area of deposition will equal that of the sediment carrying surface jet. - If the undercurrent is parallel to the jet, the trajectories will diverge, and the area of deposition will be large compared to that of the turbid surface jet.

The sedimentation pattern in the Rana Fjord agrees well with the general picture just presented. Large deposits are found primarily in that part of the basin where the observed undercurrent would be expected to concentrate the settling sediment load. This is precicely in the harbour area, between the Toranes pier and the river mouth. Maintenance dredging will therefore be required for the navigation channels across the shallow sea bottom.

The undercurrent caused by the vertical circulation can only transport settling particles towards the river mouth. There are numerous examples of the transporting capacity of the undercurrent associated with the vertical circulation. We have a fresh case in point from the Rana River, where tailings from an ore dressing plant, released in the fjord through a submerged waste pipe line, have been recovered in the lower river reach.

However, the more important effect of the vertical circulation is not on the areal distribution of the sediments, but on their grain size distribution. The vertical circulation acts as a filter on sediment particles, holding back the extreme sizes and passing the medium ones only. - First, as long as the salt water wedge is maintained within the river, the river flow is forced to drop its bed load at the wedge toe. Thus the coarser fractions of the load are removed. - Second, the vertical circulation changes the electrically neutral river water into an electrolyte, which permits the suspended clay and silt particles to flocculate. The flocs that are formed, have fall velocities several orders of magnitude higher than the individual clay particles. In this way the

finer fractions of the sediment load are removed.

The Rana River provides a particularly good example of the latter mechanism. The glacial tributary Røvassåga flows through a 50 m deep lake, Langvatn, (fig. 1), which is always muddy due to suspended clay particles. When the same clay suspension is discharged into the fjord, it flocculates and disappears from the surface layer after a relatively short travel.

## SEDIMENT SOURCES

No systematic measurements have been made of the sediment load in the Rana River. However, the river physiography allows one to infer that the bed load must be negligible, whereas the suspended load is appreciable - at any rate compared to other Norwegian rivers.

About 1½ km upstream of the river mouth there is a deep pool, which would presumably act as a bed load trap. Coarse material delivered to the fjord by the river would have to be eroded in its lower reach, but there is no indication of serious erosion.

On the other hand, the Rana River receives part of its water from the glacier Svartisen (fig. 1). This glacier still carries on the same carving process that once shaped the Rana fjord itself, and the ice front is still no more than about 30 km from the head of the fjord.

During the summer the silt-laden tributary fed by the melting glacier is seen to mix slowly with the clean main stem of the river downstream of their confluence, eventually to make the entire flow opaque with a characteristic greenish grey colour.

At its mouth the river shoots across the fjord as an easily visible surface jet, forming large eddies on either side. The turbidity in these surface eddies is much less than in the jet.

While the river only supplies finer sediments, wave action supplies coarser material by an interesting process: The 30 m high terrace Mjølaodden is exposed to waves from south west (fig. 4) undercutting its slope. Normally such undercutting would lead to the development of a berm that would check and eventually stop the erosion. In this case the berm never has become fully effective, because where wave action subsides on the submarine slope, slumping takes over as a transporting mechanism. The bottom contours on fig. 8 and 9 demonstrate this clearly.

Another conspicuous topographical feature is the spit which is shaped by the combined action of currents and waves. Some of the terrace material surely must have taken the detour

along or across the spit and into the river channel, only to be flushed out through the river mouth. Tailings dumped on the beach during occasional breakdowns of the previously mentioned waste pipe line are observed to follow this path.

The Rana Fjord also provides a fresh example of the redistribution of sediments by slope failures. Fig. 8 shows contours and a cross section along the waste pipe line of the ore dressing plant. Between 1963 and 1965 a surcharge of some 6 m was deposited on the shallow submarine plain. The soundings made last summer revealed that a huge, 50 m deep bowl had been formed by slumping during the last year. We do not know whether there has been one large slide or many smaller ones. It may be argued that since nobody has noticed any anomalies in the fjord, the slumping must have proceeded gradually. But there is really little evidence for the assumption that large submarine slides must necessarily cause surface disturbances.

The last sounding was made the 22 June 1966. Six days later the attempt to salvage a section of the waste pipe line that had been torn off by a ship anchor, was frustrated by renewed slumping that removed the pipe altogether. The rim was moved 65 m closer to the shore by this last known slide, but neither surface waves nor increased turbidity has been reported.

## MODEL INVESTIGATION

A model was built at the River and Harbour Research Laboratory of the lower river and the inner fjord, to a horizontal scale 1:200 and a vertical scale 1:50 (fig. 9). The purpose of the model was to find ways of constricting the river mouth without adverse effects on navigability and sedimentation within the harbour area. The constriction is part of a scheme to mix artificially the river flow with sea water. This mixing is intended to allow higher winter discharges without increasing the ice hazard. The only practicable way to do this is by stimulating the vertical circulation so as to maintain high winter salinities within a sufficiently thick surface layer.

At least in principle a forced vertical circulation may be accomplished in several ways. The decision to release air bubbles from a perforated pipe in order to raise a vertical current of sea water was based on economic considerations after full scale tests had demonstrated the feasibility of the method. (1). However, the economy of the design hinges crucially on the constriction of the wide and shallow river mouth.

The model was verified by reproducing the observed flow pattern in the surface layer. The natural vertical circulation

was fairly well reproduced without any special efforts. Reproduction of the horizontal circulation was not attempted, and the model was terminated by a horizontal floor at elevation - 25.

The river mouth has a characteristic left bend. The left bank is a sand spit, while the right bank is solid rock. - A jetty extending along the spit would not increase the highest velocities at falling tide, because during this stage there is no net flow across the spit. The desired short jetty from Åneset does choke the river mouth somewhat. - Nevertheless, it proved possible to reduce quite considerably the surface width of the river mouth without affecting the surface jet significantly.

However, our field observations of the undercurrent made us look for a solution that represented a positive improvement, instead of one that just preserved the not too happy status quo.

The model demonstrated that by constructing a second jetty from the right bank, upstream of the mixing site, the river flow could be turned about 25 degrees to the right (fig. 10). This jet may be directed away from the area with a strong, opposing undercurrent, and thus relieve the harbour area of some of its present sediment supply. More of the river sediments than before will then settle through either stagnant water or an outbound undercurrent and be deposited in the deep fjord, where storage is virtually unlimited.

The verdict of the port authorities on the navigational aspects of the suggested change of the surface flow pattern was that it mattered little one way or the other. Moreover, since their dredging costs are not too much of a burden, they were not inclined to invest in a scheme that would seem to offer only a partial improvement.

Although the benefit-cost ratio in this particular case apparently was too low for the surface flow pattern to be changed, this may not always be so. At any rate it would seem worth while to consider such changes whenever there is a horizontal circulation in the settling basin.

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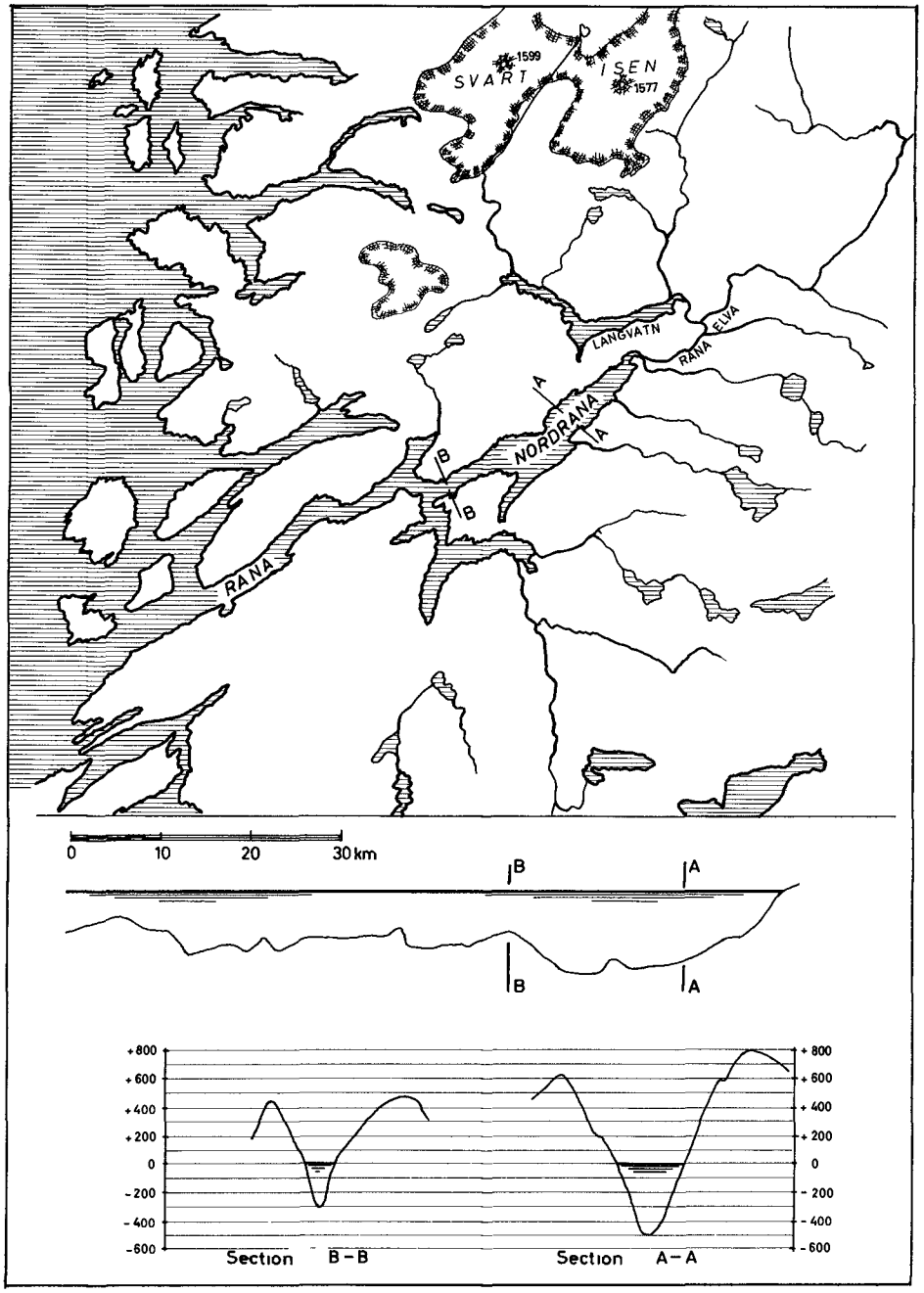



Fig. 1. Map of the Rana region and cross sections of the Rana Fjord.

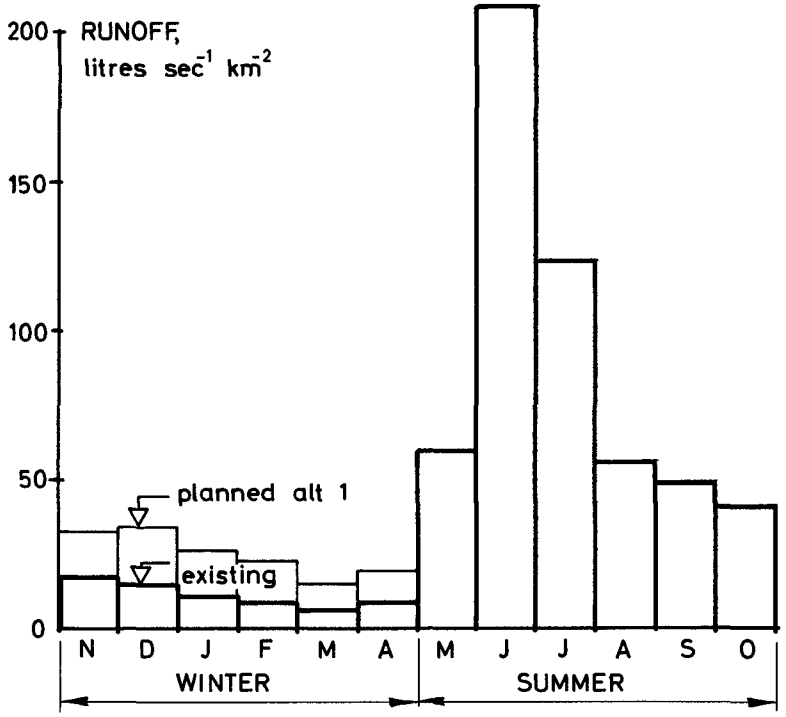



Fig. 2. Longitudinal section of the lower Rana River.

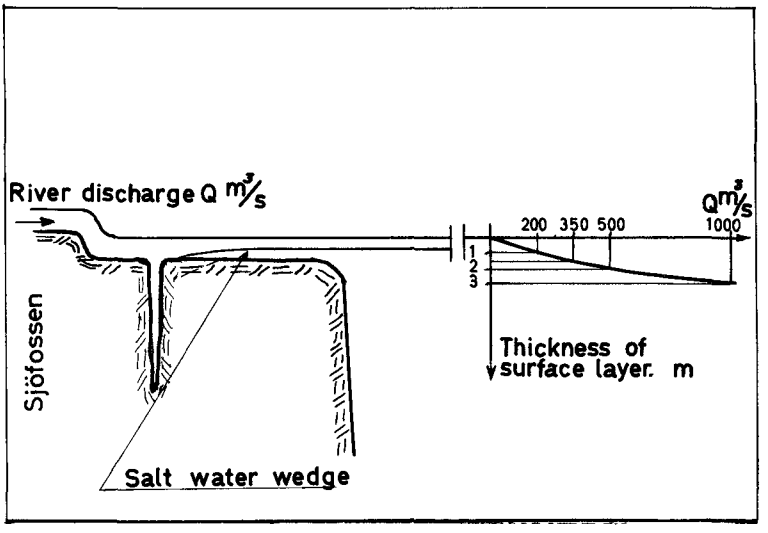



Fig. 3. Runoff hydrograph for the Rana River.

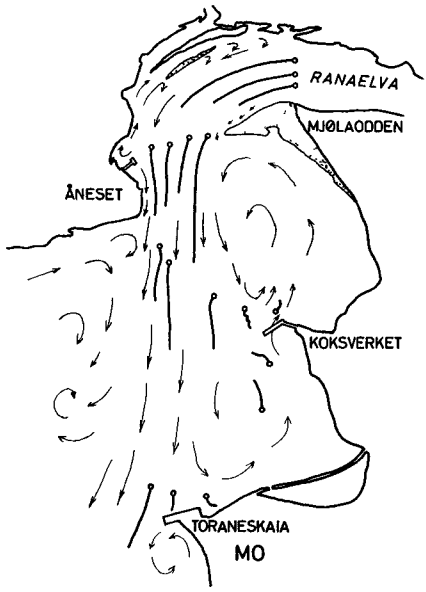



Fig. 4. Surface currents made visible by dye streaks.

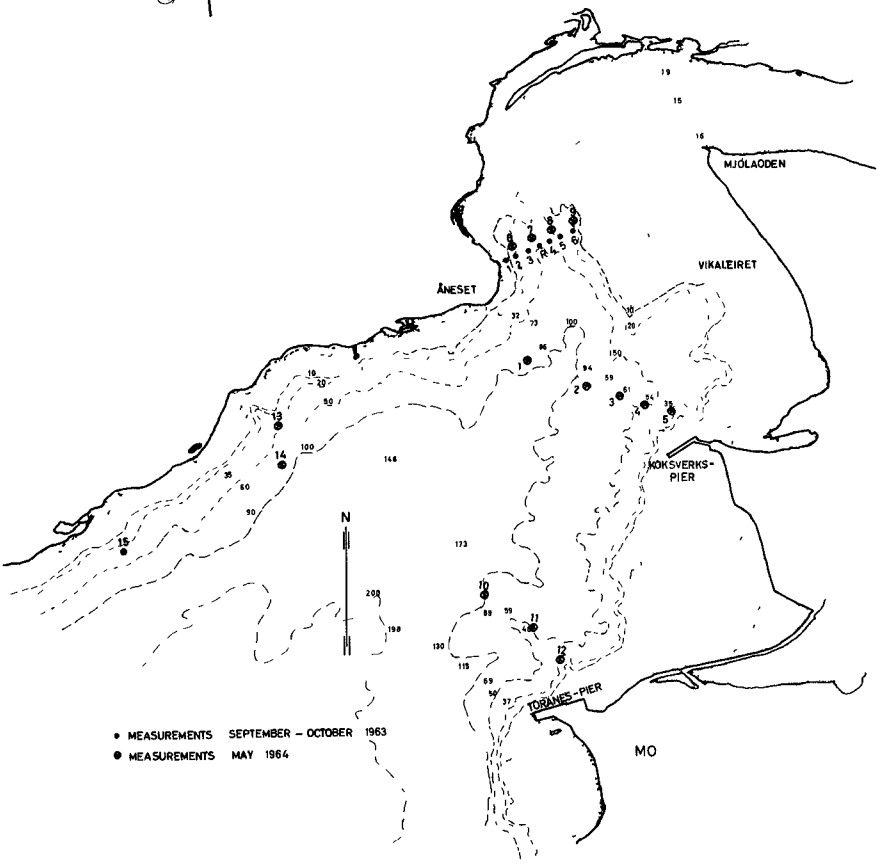
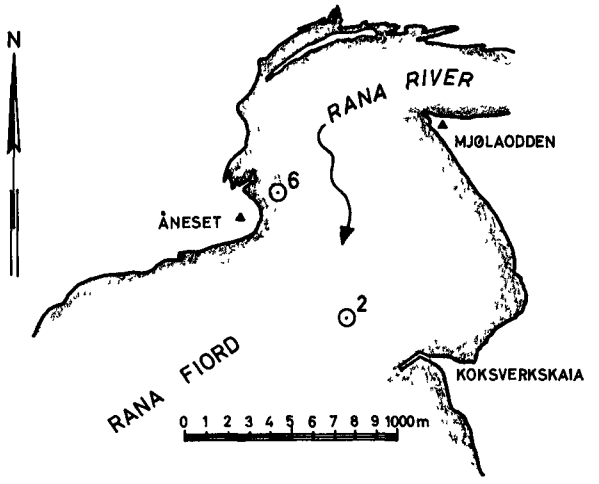
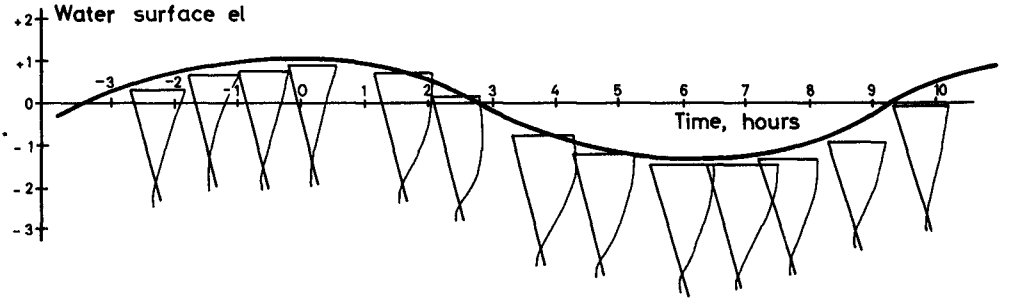
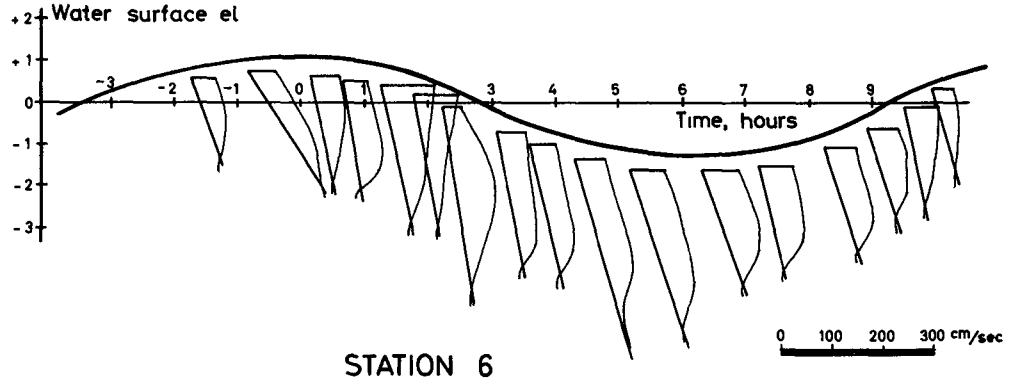



Fig. 5. Observation stations and bottom contours.




STATION 2




STATION 6

Fig. 6. Velocity profiles in the surface layer.

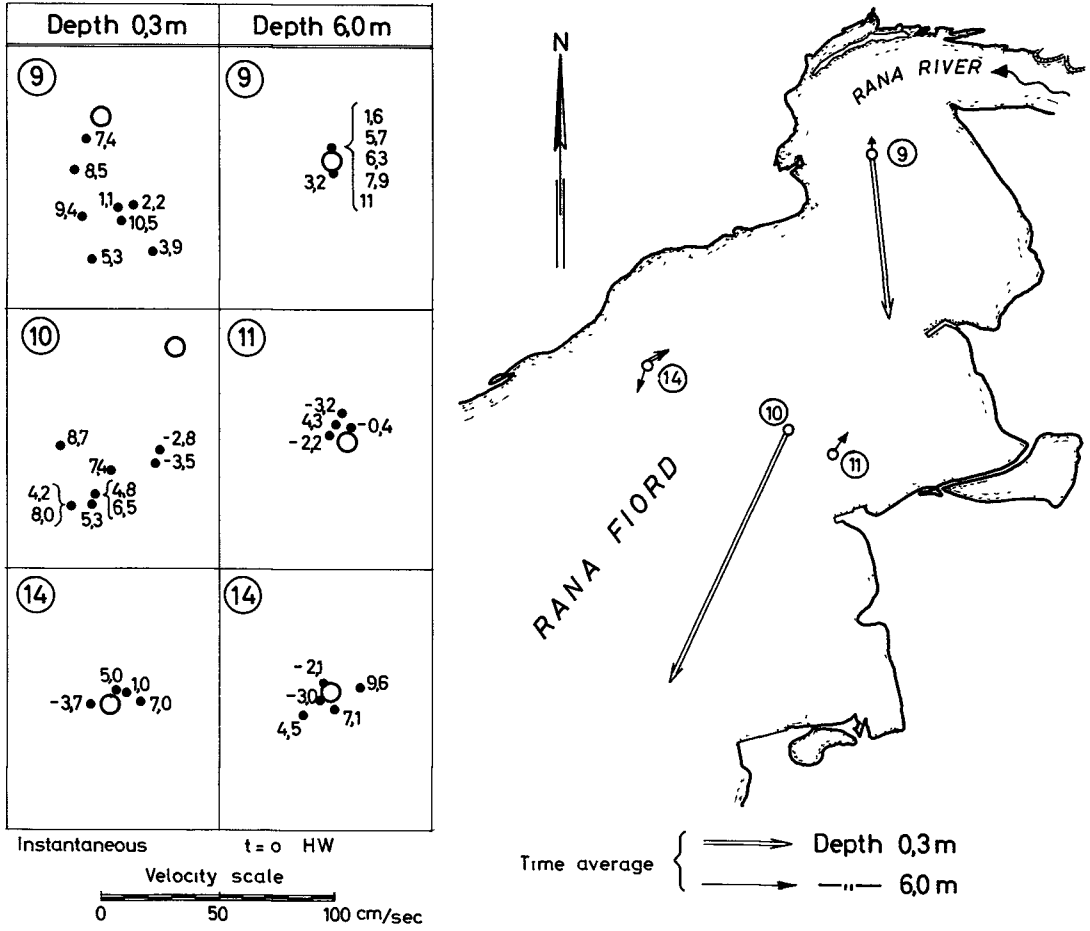



Fig. 7. Instantaneous and average velocity vectors over one tidal period.

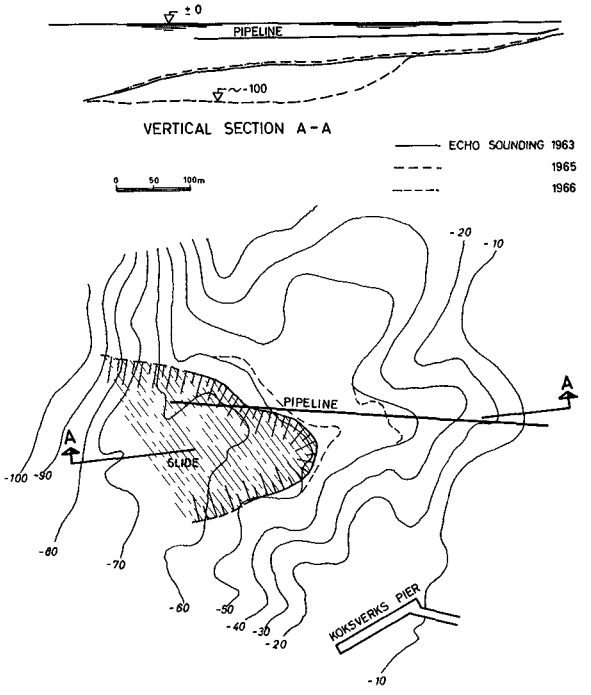



Fig. 8. Surcharge and failure of submarine slope.

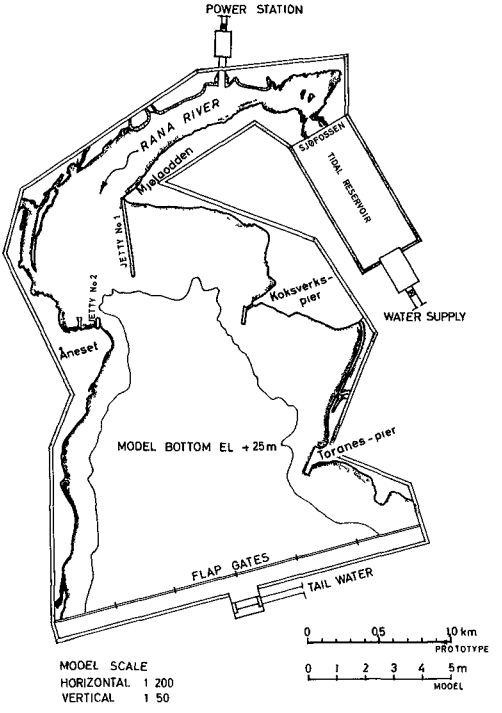



Fig. 9. Model plan.

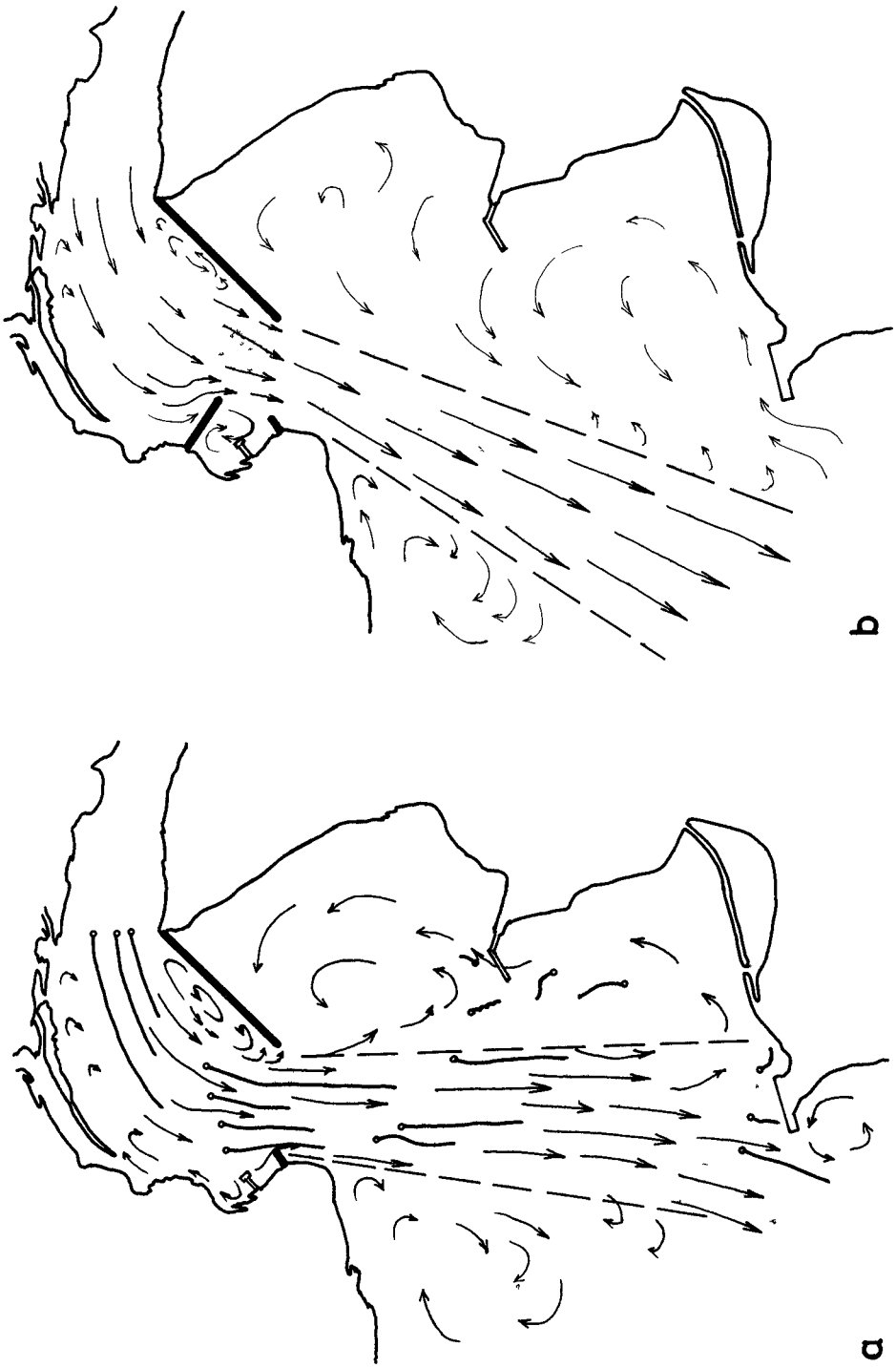



Fig. 10. Surface flow pattern observed in the model. a: With 2 jetties.
b: With 3 jetties.