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A MODEL FOR POLLUTION STUDIES IN THE BALTIC SEA

by Lennart Funkquist and Lars Gidhagen

SMHI SWEDISH METEOROLOGICAL AND HYDROLOGICAL INSTITUTE

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Abstract

A combination of a circulation and a diffusion model has been developed to be used for dispersion studies in the Baltic Sea. As the time scale of interest is from months up to several years a straightforward way to model the dispersion would require the circulation model to be run for a very long time, which would be impractible. Instead a typical meteorological year has been constructed for which the circulation model has been run. The circulation model is three-dimensional, uses six layers in the vertical and has a horizontal resolution of 10 kilometres. The diffusion model is of Monte Carlo type in all three dimensions. So far only passive pollutants have been treated but the model will be extended to include biochemical interaction and sedimentation processes. Results of applications to three outlets are shown.

Key words

Baltic Sea, pollution studies, dispersion model, circulation model, Monte Carlo

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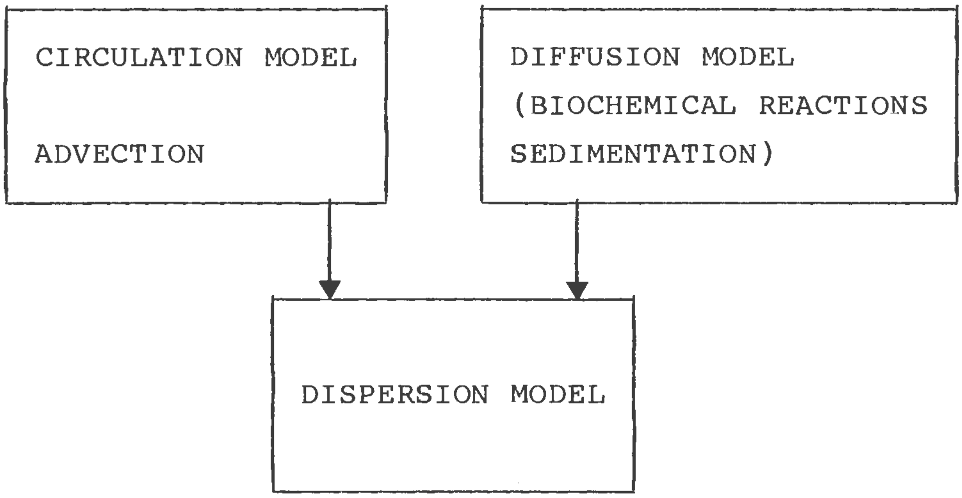
1. INTRODUCTION

Because of their simplicity, box models have long been in use to calculate the spreading of pollutants for longer periods of time (e.g. Bolin, 1971, and Sjöberg et al., 1972).The quality of the results from these models relies on good estimates of the fluxes between the boxes. This demand is difficult to fulfil in complicated basins like the Baltic Sea. There are normally only a few boxes in the horizontal dimension and the models are to a large extent concentrated on vertical exchange. Often a steady state of the circulation is assumed.

However, there is considerable horizontal variability in the sea of both physical parameters like current or temperature and chemical or biological parameters. This fact has been particularly illustrated with the increased use of satellite information. As regards the physical part the horizontal variability shows itself in form of eddies, fronts and meanders. These are particularly evident in satellite IR images, where the isotherm pattern reflects the surface circulation (Gidhagen, 1984).

The temporal variability of the currents is too great to assume a steady state or mean seasonal circulation patterns. It is responsible for a significant dispersion especially in the upper layers. Measurements in the western Baltic Proper (Kielmann et al.,1973 and Francke, 1981) show that current spectra have peaks for periods similar to those of wind spectra, i.e. in the order of days. It has also been shown that the energy of the corresponding current fluctuations is an order of magnitude larger than that of the seasonal mean state, which in turn shows a large variation compared to the yearly mean state.

As a consequence, a realistic modelling of the spatial and temporal variability of the currents becomes very important. Depending on the biological or chemical process of interest both the time and horizontal scales are different compared with the physical part. This suggests that the dispersion model is split up into one submodel describing the physical part and another submodel for the the biochemical reactions.



However, if a Monte Carlo type of diffusion model is used, there are reasons to split the model further by treating the advective and diffusive parts of the transport separately. Firstly it is computationally much easier not to solve the full advection-diffusion equation at every time a new outlet of pollutant tracers is studied, and calculations only have to be performed in those areas where the tracers occur. Secondly it is an accepted way of modelling turbulent motion to cut off the turbulence at a particular frequency and treat the short fluctuations separately. This type of diffusion model also has advantages in connection with biochemical modelling.

By treating the tracers separately there is no possibility to let them have any dynamical influence on the flow. Active tracers like heat should be treated in a different way.

In principle the above-mentioned important effects of both temporal and spatial variability can be included in a box model. Then the resolution and computer demand is approximately the same as for a finite difference or finite element circulation model, which is the alternative to the box model.

The main difference between the two is that in the box model the flow must be prescribed whereas in the circulation model the flow is calculated. The necessity to prescribe the flow limits the utility of box models to water-bodies with uniform flow conditions where only a relatively small number of boxes are needed. An advantage is a highly reduced computer cost. On the other hand only the relatively large-scale features can be handled, and the temporal variability, which in the model is coupled to the size of the boxes, is restricted.

The circulation model, once set up, can easily be adjusted to cover most scales of interest. Small-scale turbulence is accounted for by the diffusion model. The temporal variability is automatically included by the necessarily high time resolution in the circulation model. Therefore, in relation to the object of the present study there are obvious advantages with the circulation model approach.

Usually the time scale in biochemical modelling is several orders of magnitude larger than the time step in the circulation model. Therefore the computed currents have to be averaged by applying some kind of filter. Because of the often high energy peak near the inertial frequency it is important how the averaging is done.

In this introductory discussion we have arrived at a basic idea of how a dispersion model of the Baltic Sea should be constructed. A similar technique has been used for oil drift forcasts (Ambjörn et al., 1981) and also in Lake Vänern (Bork, 1977). The main use of the model will be in connection with dispersion studies on time scales from months to years. The purpose of the present study is to formulate and test such a model for a number of outlets in the Baltic Sea. Details of the meteorological forcing and the circulation model are found in Chapters 2 and 3. The diffusion model is described in Chapter 4, and the linkage between the two submodels is described in Chapter 5. Finally results from three applications are shown in Chapter 6.

2. METEOROLOGICAL FORCING

With the ambition to use an advanced circulation model and to make dispersion studies on time scales of several years one easily gets into difficulties. The computer demand for the circulation model is still too high to run the model in real time for several years. One way to get around this is to construct a typical year that contains the most probable weather events. Most of the time variance should then be contained in this year and the time variance from year to year is regarded as of minor importance compared with the variance within a year.

In choosing the typical year the weather statistics of the last 50 years have been studied. Representative weather events have been sorted out and the different events have been chosen from the years 1978-82 studying daily weather maps. In the selection process special attention has been paid to the wind and the duration of typical events. To cover the relatively changing weather it has been necessary to use 25-30 days, built up from 4-6 events, for each season. The seasonal grouping is done because it is a natural time scale both for the weather and the stratification in the sea.

The circulation model has then been run for every event and the currents have been stored every sixth hour. In the selection of meteorological forcing, attention has also been paid to the order in which the events usually occur. By repeating them in that order it is then possible to obtain a full year. Although it cannot be regarded as a true year it is not entirely artificial and should rather be regarded as a climatological year. As it does not contain all the variability that occurs during a time scale of many years, it should be used with care for such long time scales.

An overview of the meteorological forcing of this climatological year is found in Appendix 3 and 4. A comparison of the wind statistics from the selected periods with corresponding values of a 20 years long period is found in Appendix 2.

The wind strength is in excellent agreement, while the wind direction is more evenly distributed in the statistics for the 20-years period. The reason for this is that each of the selected weather events represents a whole set of events which are of the same type but differ in the exact trajectory of e.g. the cyclone center.

During part of the year some areas in the Baltic Sea are ice-covered. This is not a serious problem for the offshore parts of the Baltic Proper but it should be taken into consideration in connection with dispersion in the Gulf of Bothnia.

3. CIRCULATION MODEL

Modelling of the Baltic Sea started with sea level models, e.g. the two-dimensional barotropic model by Uusitalo (1960). Later both two- and three-dimensional circulation models with different degrees of approximation appeared. The latest and perhaps the most advanced is the model described in Kielmann (1981), where also a recent review of Baltic Sea modelling is provided.

The Kielmann model which has been chosen for the present study is a time dependent and three-dimensional baroclinic model especially developed for the Baltic Sea from Simons model (Simons, 1973). The latter has been verified with great success in both small and large lakes and also in a limited part of the Baltic Sea (Simons, 1978). The horizontal resolution for the present application is 10 km and in the vertical 6 layers have been used, the thickness of which is given in Table 1. The layer depths have been chosen to account both for stratification and the dispersion effect caused by the vertical current shear. The eddy viscosities (see Table 1) are defined for every level and lie well within the range of values observed in the Baltic Sea (see Voipio, 1981). Horizontal eddy viscosity and eddy diffusivity have been set to 100 resp 10 m^2s^{-1}.

Table 1. Vertical eddy viscosity in m^2s^{-1} for different depths. The vertical eddy diffusivity is one hundredth of the viscosity.

Depth (m)	Spring	Summer	Autumn	Winter
5	0.0100	0.0100	0.0100	0.0100
10	0.0050	0.0050	0.0050	0.0050
20	0.0020	0.0010	0.0020	0.0020
40	0.0020	0.0020	0.0020	0.0020
60	0.0005	0.0005	0.0005	0.0005

In the Baltic Sea the circulation is a synthesis of wind-induced and thermohaline circulation, the latter caused by seasonal cooling and warming, inflow of Kattegat water, and river outfall. In this study the emphasis is on the effect of the wind-induced currents. Its importance is readily understood by the fact that the mean wind speed in the Baltic Sea as estimated from Swedish coastal stations is 7 - 8 ms^{-1} at 25 m above sea surface with a dominant direction from SW and W.

An important mechanism besides wind stress is the direct pressure force caused by the heterogeneous air pressure. Autumn cooling and spring heating are simulated on a season to season basis by specifying typical density profiles for each season.

The circulation has been computed for every period that was described in Chapter 2. Each simulation started with no currents and a horizontally uniform stratified density field. Two days of adjustment proved to be enough for the currents to accelerate to a reasonably true level in all layers.

The surface wind stress is computed at every grid point from the geostrophic wind using the same method as in Kielmann, 1981. Originally one uses the six-hourly 150 km pressure fields, which then are interpolated to the 10 km grid in the circulation model. Between the six-hourly wind stress fields linear interpolation is used.

Appendices 7 to 10 show the mean-field of the surface layer for each season. The currents are weak during spring and summer. During autumn and winter there is a dominance of Ekman drift towards east and northeast.

The mean currents for each layer during the whole climatological year are plotted in Appendices 11 to 16. The two upper layers are very similar and dominated by Ekman drift (0.03 - 0.04 ms^{-1}) towards east and northgoing coastal currents (0.05 - 0.10 ms^{-1}). The pure Ekman drift is disturbed by large eddies in some specific regions. Northeast of Bornholm, north of Poland, the Gulf of Gdansk and Gotland and outside the entrance to the Gulf of Finland there are deviations from the Ekman drift. Both the Bothnian Sea and the Bothnian Bay have anticyclonic eddies in the southern and cyclonic eddies in the northern part. In layer 3 to 6 the circulation is governed by topography. The mean currents are weak (< 1 ms^{-1}) in the inner parts of the basin with the exception of the return flow northwestwards from Poland and westwards from the Gulf of Finland. The mean coastal currents are somewhat stronger with maximum values of 4 - 5 ms^{-1}.

4. DIFFUSION MODEL

The diffusive transport of particles created by turbulence on scales smaller than the grid-size (in the horizontal) and the layer depth (in the vertical), is modelled by a Monte Carlo technique. This means that the calculated turbulent part of the particle velocity is related to the eddy diffusivity in a physically correct way.

Horizontal diffusion

The turbulent velocity contribution in the two horizontal directions is taken from a rectangular random distribution with a maximum value of

$$|u'| = |v'| = \sqrt{\frac{6K_h}{\Delta t}}$$

where K_h is the horizontal eddy diffusivity and Δt the time step between each Monte Carlo calculation, (Maier-Reimer, 1975).

The value of $K_h = 10\ m^2s^{-1}$ is in accordance with the result of experiments with dye releases (Kullenberg et al., 1973). The assumption of a constant and isotropic eddy diffusivity is acceptable for most parts of the Baltic, but it is a less satisfying description of the turbulence close to the shore.

Very close to the coast - within a couple of kilometres - the restriction for a particle to cross the coastline in practice implies a diminished turbulent velocity in the direction perpendicular to the coast. This sometimes leads to a gathering of particles close to the coast.

With the value of K_h mentioned above, the turbulent velocity has a maximum of 0.13 ms^{-1} in each component direction. This velocity is of the same order as the advective velocities taken from the circulation model.

Vertical diffusion

The vertical eddy diffusivity is depth dependent. The strongest turbulence is normally found in the uppermost layers, where the wind contributes to the turbulent energy. The exchange over a pycnocline is very limited, leading to a local minimum of the eddy diffusivity.

The varying values of the eddy diffusivity in the vertical cause some difficulties in the Monte Carlo approach. Passive particles have a tendency to gather at the level of the smallest diffusivity.

This problem has temporarily been solved by using a constant eddy diffusivity - the value being representative for the uppermost layers - from the surface to the bottom. Instead of the diffusivity variation, "permeability" coefficients are introduced at the levels of density jumps. The consequence of this approach is that the vertical distribution within each layer is correctly modelled only in the uppermost layers. Between the layers, the "permeability" coefficients can restrict the penetration of particles. The degree of restriction between each layer reflects the local strength of the stratification.

The turbulent contribution to the vertical velocity is modelled by:

$$|w'| = \sqrt{\frac{6K_v}{\Delta t}}$$

The value of the vertical eddy diffusivity K_v depends on the characteristic windspeed for each season:

PERIOD	DEPTH TO FIRST DENSITY DISCONTINUITY (m)	$K_v (m^2 s^{-1})$
spring	60	0.010
summer	20	0.002
fall	40	0.018
winter	60	0.018

This gives turbulent velocities up to 0.0055 ms^{-1}, which is considerably higher than the vertical velocities simulated by the circulation model.

The density discontinuities correspond to those prescribed in the circulation model. The probability of a particle penetrating a pycnocline has been parameterized from the Munk-Anderson formula for quantifying the eddy diffusivity variation (Munk & Anderson, 1948):

$$K_v = A_0(1 + 3.33 \cdot Ri)^{-1.5}$$

where A_0 is a function depending on the wind-forcing and

$$Ri = \frac{g}{\rho} \frac{\Delta\rho \; \Delta z}{(\Delta u)^2}$$

The parenthesis $(1 + 3.33 \cdot Ri)^{-1.5}$ can be interpreted as a measure of the exchange decrease over a pycnocline, suggesting the definition of a "permeability" coefficient:

$$P_L = 1 - (1 + 3.33 \cdot Ri)^{-1.5}$$

The different values of the Richardson number give values of P_L as follows:

	Spring	Summer	Fall	Winter
P_L (5m)	0.0	0.0	0.0	0.0
P_L(10m)	0.0	0.0	0.0	0.0
P_L(20m)	0.0	0.9987	0.0	0.0
P_L(40m)	0.0	0.9983	0.9931	0.0
P_L(60m)	0.9997	0.9997	0.9997	0.9997

5. DISPERSION MODEL

In the dispersion model, particles are released into the Baltic from point sources (periodic or continuous release) or from a homogeneously distributed source (like atmospheric fall-out). The particles are then affected by the advective velocities simulated in the circulation model and by the turbulent velocities calculated in the diffusion model. Both the advective and the turbulent part of the movement are three-dimensional.

In the calculations reported here, the particles are released from a point source at a rate of one particle every third hour. The particles act like passive tracers of the water movement. The calculations in the dispersion model (with a time step of one hour) proceed as follows:

First the particle is horizontally displaced. The advective velocities are given every sixth hour, which means that they are constant during six time steps in the dispersion model. The advective velocity in the nearest gridpoint is used, except close to the coast. By definition the coastline consists of gridpoints with zero velocities, so the particles close to the shore use the nearest gridpoint situated ten kilometres out from the coastline.

The sum of the advective velocity and the turbulent velocity from the Monte Carlo calculation defines the total horizontal movement of the particle during one time step.

Thus:

$$X_t = X_{t-1} + \Delta t(U_{adv} + U_{turb})$$

$$Y_t = Y_{t-1} + \Delta t(V_{adv} + V_{turb})$$

The particles are not allowed to penetrate the coastline, but they are affected by the coast-parallel component. The coastline is defined separately for the six layers.

Thereafter the vertical movement is performed. The nearest gridpoint of vertical advective velocity is looked for, and to that velocity the turbulent part is added. If the particle seems about to penetrate a pycnocline, the "permeability" coefficient gives the probability of this actually happening. The local bottom depth also restricts the vertical movement of the particles. For the vertical deplacement we have:

$$Z_t = Z_{t-1} + \Delta t(W_{adv} + W_{turb})$$

6. APPLICATIONS

The dispersion model has been applied to three different outlets. Each simulation has lasted one year and synoptic spreading patterns will with some exceptions be shown after every season. As earlier pointed out both the temporal and spatial variability have a great effect on the spreading and it is therefore difficult to draw any conclusions as to how the particles have moved between the different synoptic situations. The points of release have been 5 km out from the coastline and at 1 m depth. Although all outlets are close to river outlets, they are not considered in this version of the model. If included, it is probable that the spreading picture close to the rivers would be different.

6.1 Outlet: Umeå (Bothnian Sea)

This simulation started at the beginning of spring and the first picture shows the spreading pattern after summer (Appendices 17 to 18). During spring the particles were effectively mixed from the surface down to the halocline and the large differences between the patterns in Appendix 17 (0 - 5 m) and 18 (20 -40 m) reflect the effect of the summer stratification. The more pronounced vertical variability of the current and the effect of the thermocline on the vertical mixing are clearly demonstrated. In the surface layer some particles have escaped into the Bothnian Bay and there is a marked concentration along the coast southwards from the outlet. The latter is evidently an effect of a combination of wind drift towards the coastline and a smaller horizontal diffusion close to the coast, which was explained earlier in Chapter 4. During autumn there is a general increase of the currents and the upper 40 meters are well-mixed. The result is a rather uniform distribution of particles (Appendix 19) in the Bothnian Bay and the northern part of the Bothnian Sea.

After one year (Appendices 20 to 25) the whole Gulf of Bothnia is covered by particles and some have even spread southwards through the Åland Sea. The patterns in the upper 5 layers do not differ very much and in general there is a lower concentration in the central part of the Bothnian Sea. In synoptic as well as in mean current fields there is a well-defined cyclonic eddy outside the outlet. The effect of this is clearly seen in the comparatively low concentration in that region. Instead it helps to concentrate particles in the gulf south-west of the outlet where the southward transport caused by the eddy often meets a northward-going current.

6.2 Outlet: Gävle (Bothnian Sea)

This simulation also started in the beginning of spring. In the surface layer (Appendix 26) the particles are trapped along the coast both southeastwards and northwards from the outlet. In layer 4 (20 - 40 m) most particles seem to be found along a deeper channel eastward from the outlet (Appendix 27).

The stronger winds in autumn then spread out the particles rather evenly and they have not yet reached the eastern coast (Appendix 28). The winter pictures (Appendices 29 to 34) have, like the Umeå case, an almost clean spot in the centre of the Bothnian Sea. Now the highest concentration is found along the Swedish coast but with no particular area of high concentration. Only one particle is found in the Bothnian Bay while up to 50 particles have entered the Baltic Proper.

6.3 Outlet: Gulf of Gdansk (Baltic Proper)

To illustrate the importance of the summer stratification better this simulation started in the beginning of autumn. There is a surprisingly strong westward transport of particles towards the Swedish coast (see Appendix 35). Looking at the mean (Appendix 11) as well as synoptic current maps the westward transport is explained by the high rate of westgoing currents along the Stolpe Channel. The typical presence of an anti-cyclonic eddy in the Gulf of Gdansk makes many of the surface particles escape out into the open sea at the western part of the gulf. In lower layers (Appendix 36) there is a more effective spreading and the whole southern and south-eastern part of the Baltic Proper has been affected.

During winter (Appendices 37 to 38) the northward transport dominates and the concentration is high all along the Lithuanian coast. The Gulf of Gdansk again gets rather affected during spring (Appendices 39 to 40).

The final pictures show the summer situation (Appendices 41 to 46) when the western regions inside Öland and Gotland also contain particles. However the overall picture shows that most particles in the upper layers are trapped near the coast close to the outlet. Below the thermocline there is a more homogeneous picture and the area of distribution is limited to the southern and eastern part of the Baltic Proper.

7. CONCLUSIONS

The first steps towards a practicable long-time dispersion model of the Baltic are formulated.

The dispersion model is applied to discharges of passive, individual particles at three different coastal localities. The model takes many known effects into account, e.g. the variable wind-forcing in space and time, the existence of meso-scale eddies at certain places after a certain wind-forcing, dispersion created by vertical velocity shears and a variable stratification limiting the vertical exchange. The particle distribution seems to be reasonable and the above-mentioned factors seem to have acted in a realistic way.

Although the model represents a major step forward in dispersion modelling important further developments are still needed. What comes first is to verify the two submodels. The circulation model needs to be verified primarily against current measurements. The diffusion model is very sensitive to the diffusivity parameters which describe the turbulent motion on the scales smaller than 10 kilometres. Current measurements and dye spread experiments in the Baltic can be used to find the optimal values of the diffusivity parameters.

The model is easily applied to the spreading of other substances than passive tracers, making allowance for various physical, chemical and biological processes to enter, e.g. sedimentation and plancton uptake. The circulation model must include the effect of the estuarine circulation if the dispersion model is to be used for time-scales of tens of years and more.

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	Weather type	Days
WINTER (Jan 1 - Mar 31)		
1982 Jan 8-15	W - NW	8
1982 Feb 9-15	SW - S	7
1979 Mar 7-12	S - SE	6
1980 Mar 14-19	E -NE	6
1979 Jan 2-4	N	3
SPRING (Apr 1 - Jun 15)		
1982 Apr 1-5	NW	5
1979 May 12-20	SW	9
1979 May 21-26	SE	6
1978 May 6-13	NE	8
1978 Apr 22-23	variable	2
SUMMER (Jun 16 - Sep 30)		
1978 Aug 8-14	NW & variable	7
1979 Aug 14-19	SE	6
1982 Aug 17-28	SW	12
1979 Jul 5-9	N - NE	3
AUTUMN (Oct 1 - Dec 31)		
1982 Nov 2-7	W - NW	6
1982 Nov 8-18	SW - S	11
1982 Oct 1-10	S - SE	10
1979 Oct 24	variable	1
1978 Dec 23-25	E - NE	3

Selected weather periods which together constitute a climatological year.

HOLMÖGADD

Strength (ms^{-1})

	calm	1 - 2	3 - 8	9 - 14	15
Selection	0.9	10.3	61.7	23.5	3.5
1961-80	1.9	11.8	62.1	21.8	3.3

Direction

	calm	NE	E	SE	S	SW	W	NW	N
Selection	0.9	4.5	5.4	6.0	34.7	10.0	13.4	3.0	22.0
1961-80	1.9	11.7	6.0	9.5	18.4	17.3	9.7	11.1	14.3

UNGSKÄR

Strength (ms^{-1})

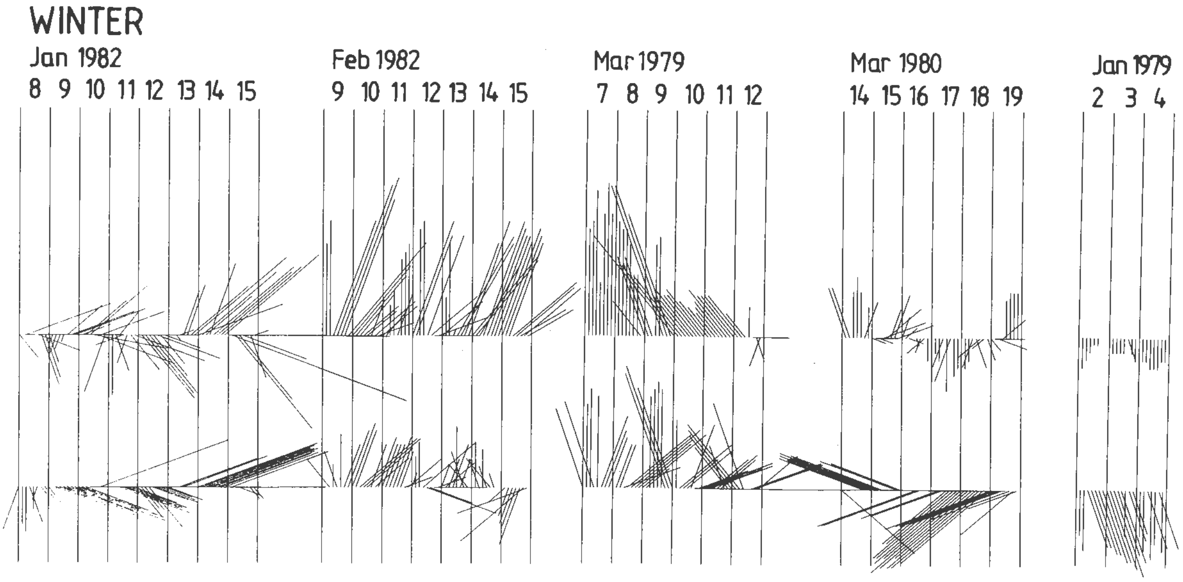
	calm	1 - 2	3 - 8	9 - 14	15
Selection	0.7	5.2	51.7	36.7	5.7
1973-80	1.7	7.6	52.2	32.9	5.6

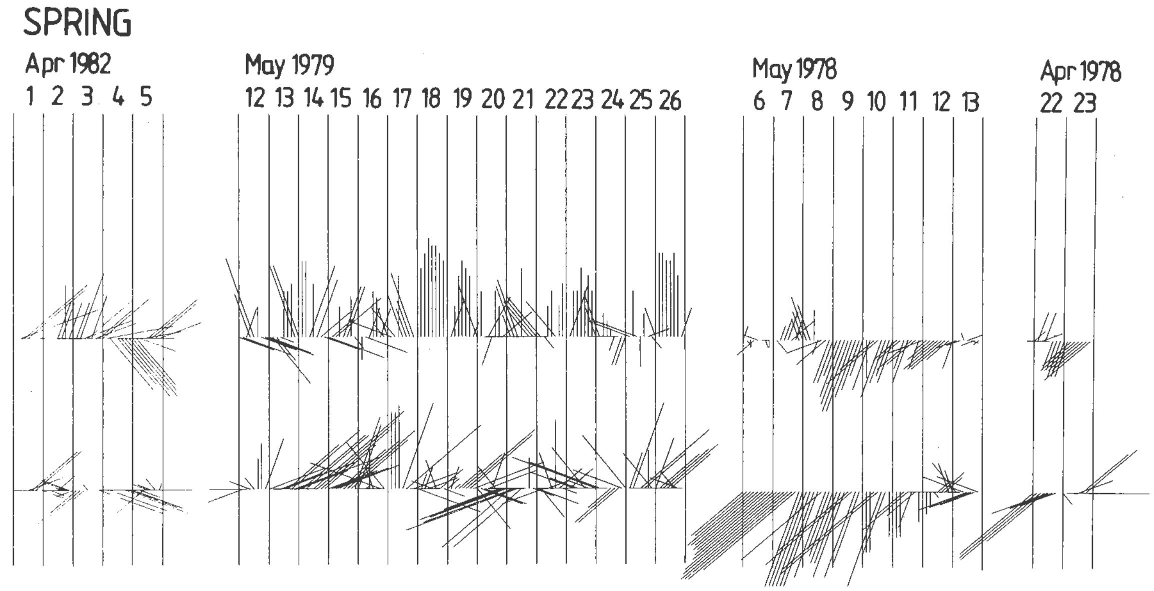
Direction

	calm	NE	E	SE	S	SW	W	NW	N
Selection	0.7	8.1	19.2	4.1	15.8	11.7	27.7	2.6	10.0
1973-80	1.7	14.9	9.4	8.0	8.2	19.9	19.4	10.5	8.0

Comparison between statistics for the climatological year and data from 1961 - 1980 (Holmögadd, representing northern Baltic Sea) and from 1973 - 1980 (Ungskär, representing southern Baltic Sea).

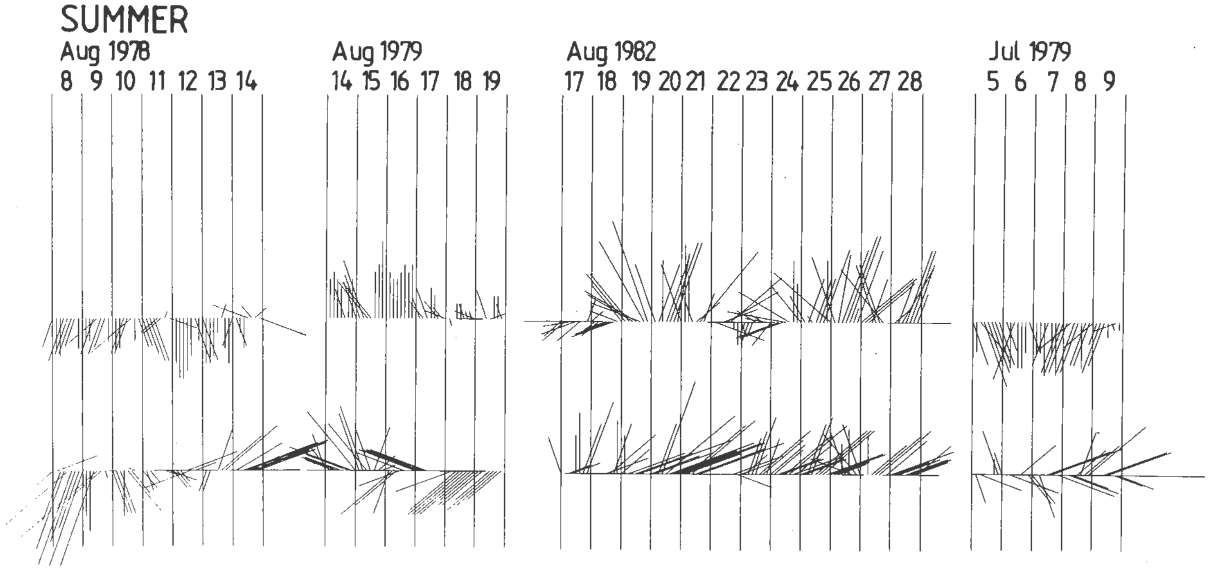
Appendix 3

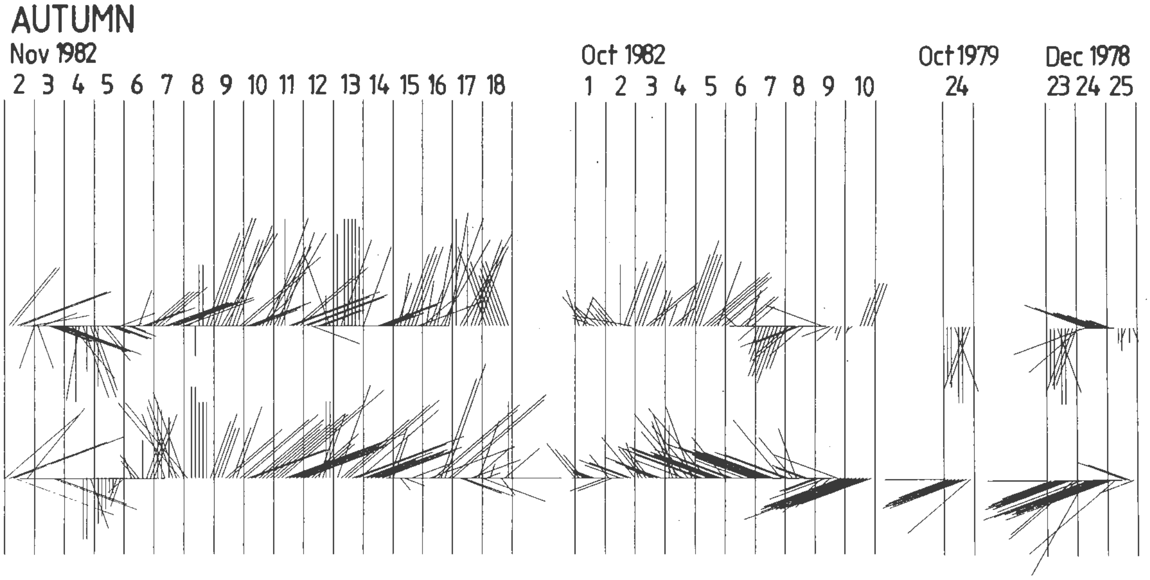




Wind vectors from measurements at Holmögadd (upper series) and Ungskär (lower series) representing northern and southern Baltic Sea respectively. The vectors point in the direction of the wind. Scale: 1 cm = 10 ms^{-1}.

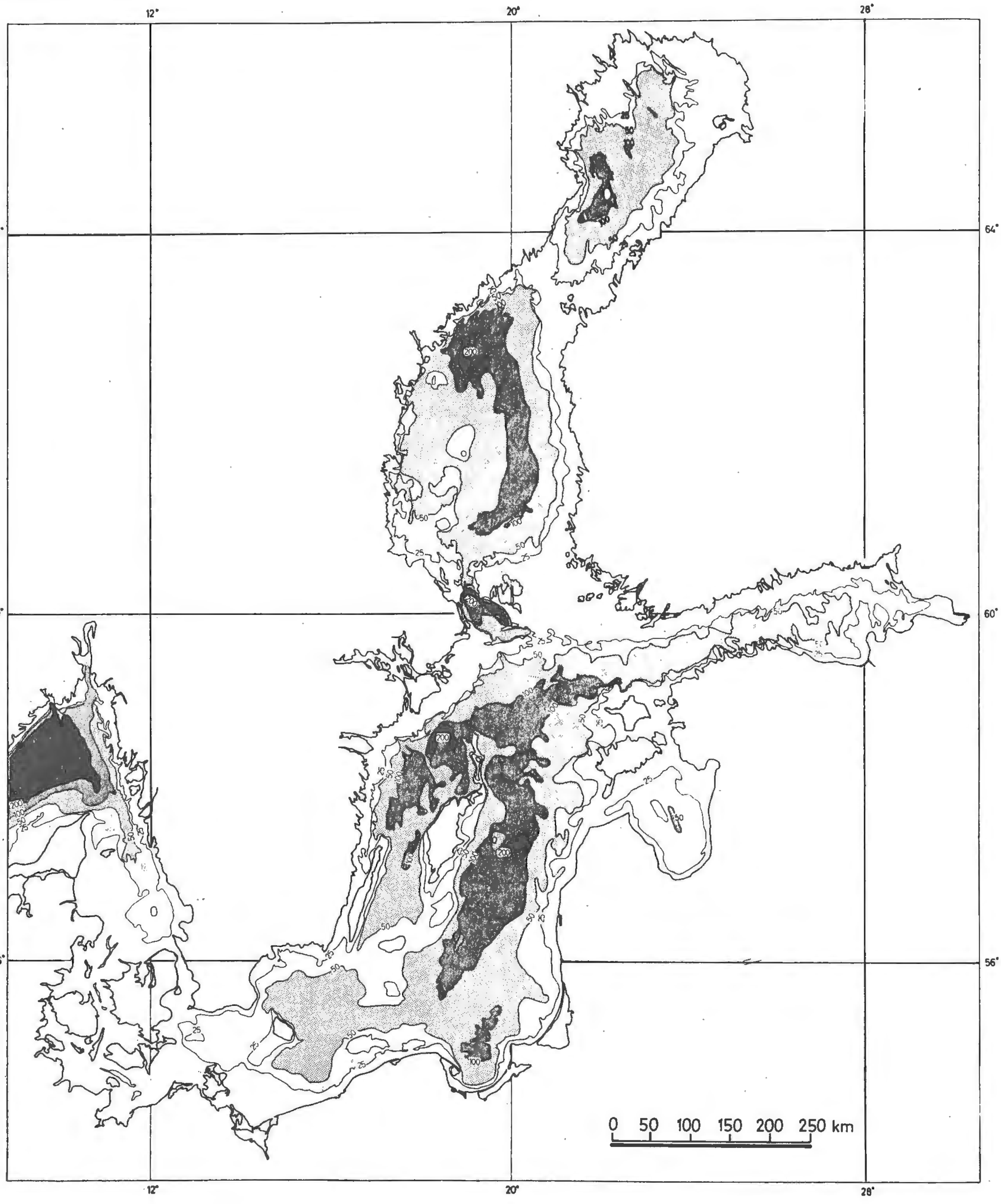
Appendix 4





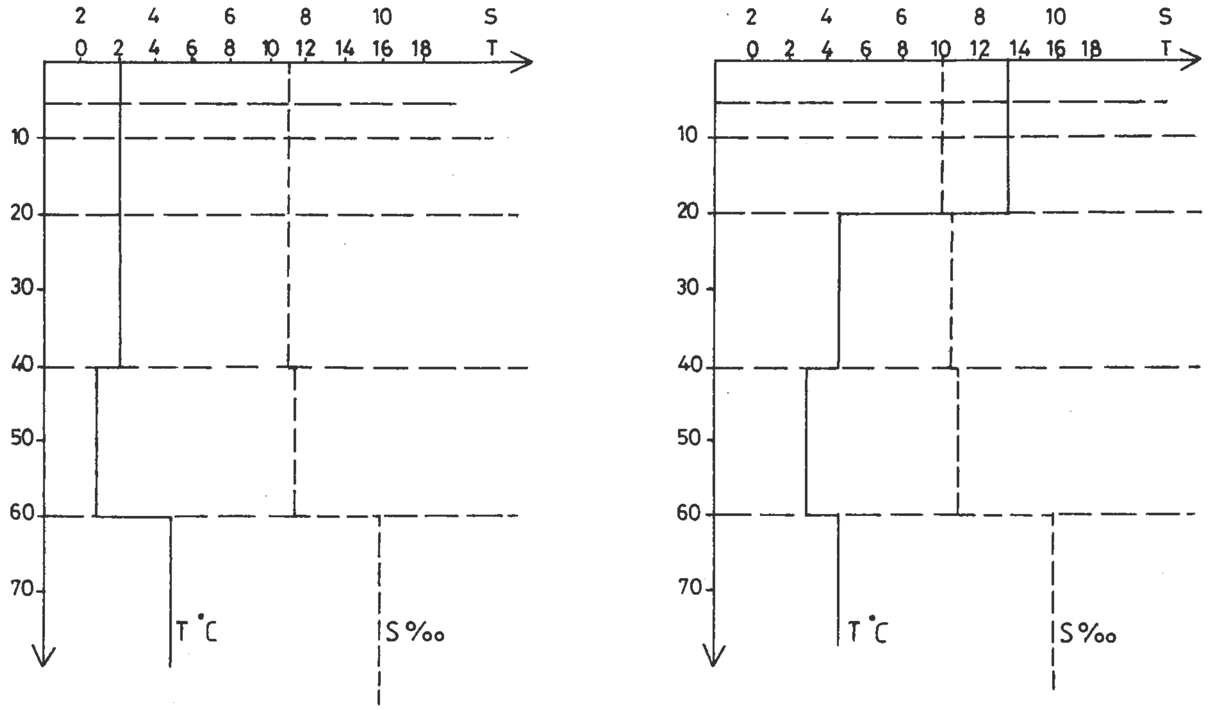
Wind vectors from measurements at Holmögadd (upper series) and Ungskär (lower series) representing northern and southern Baltic Sea respectively. The vectors point in the direction of the wind. Scale: 1 cm = 10 ms^{-1}.

Appendix 5

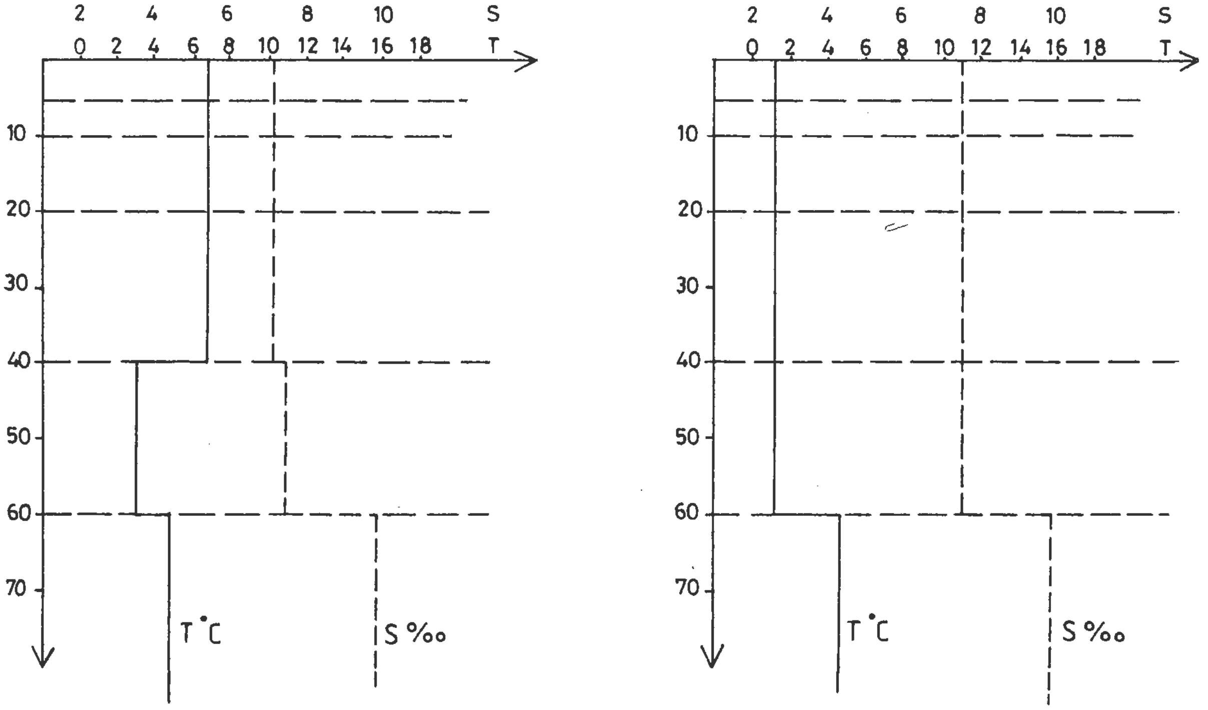


Bathymetric chart of the Baltic. The isobaths of 25, 50, 100 and 200 metres are marked.

Appendix 6

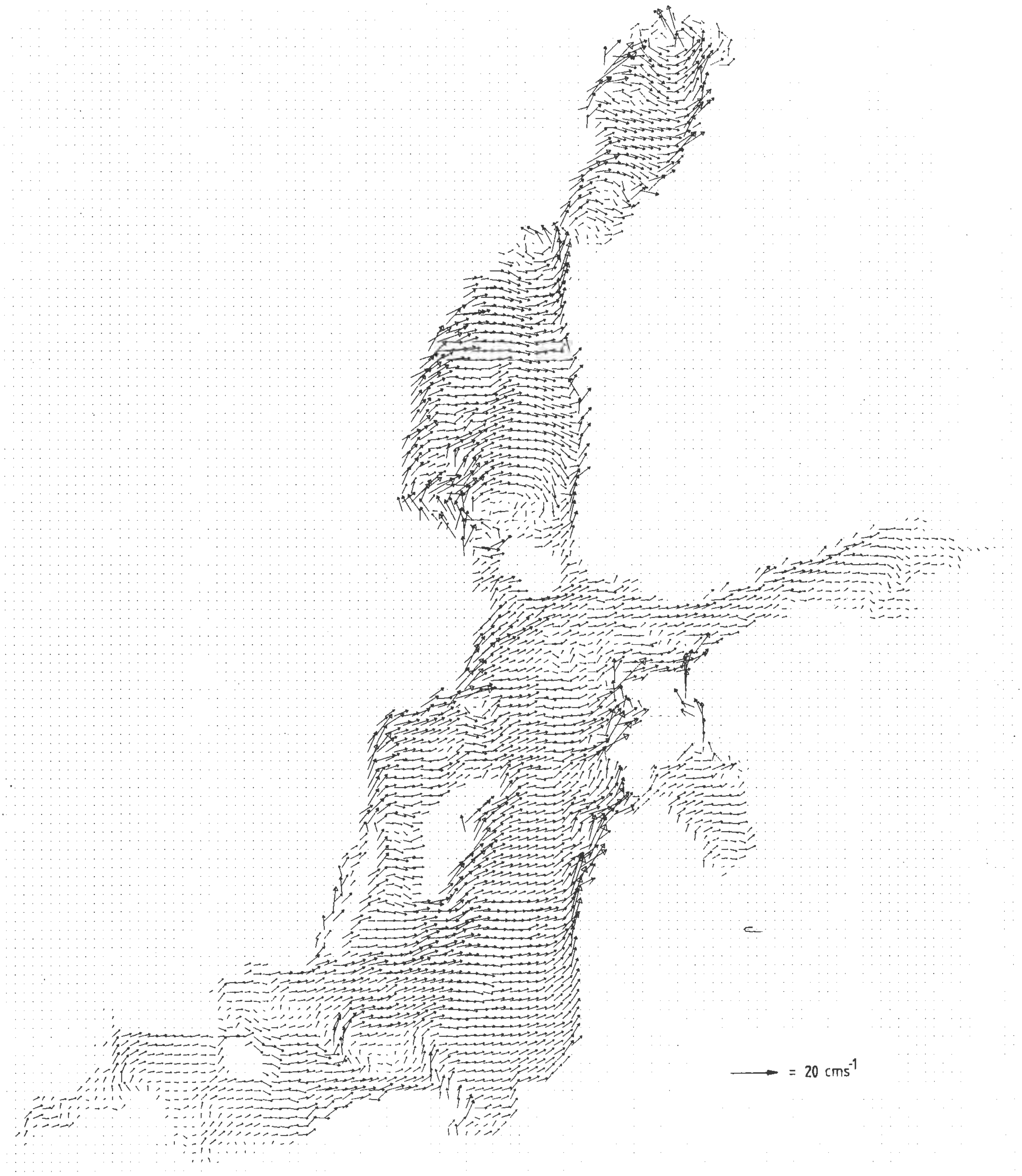

Spring: Apr 1 Jun 15

Summer: Jun 16 - Sep 30


Autumn: Oct 1 - Dec 30

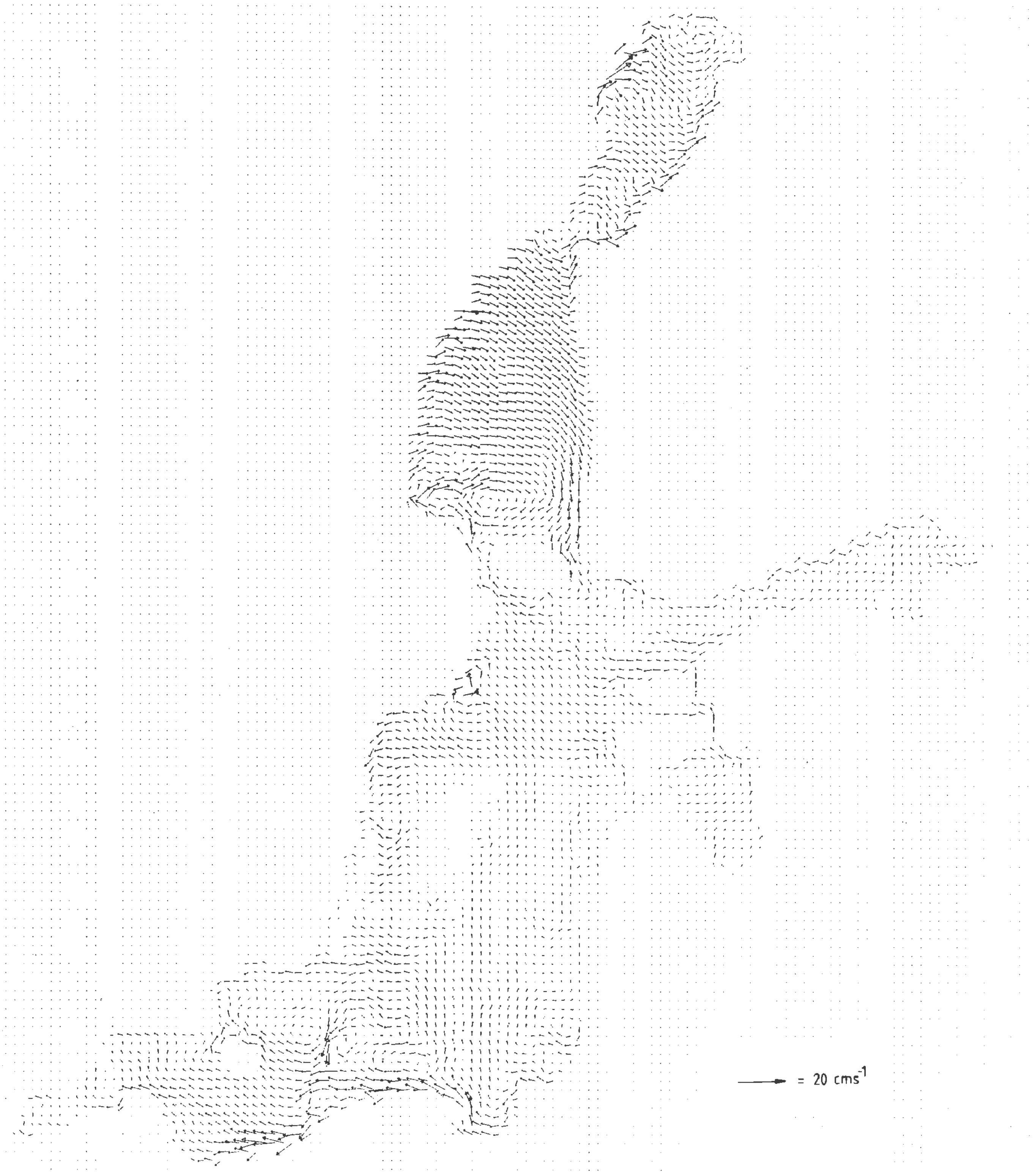
Winter Jan 1 - Mar 31

Temperature and salinity stratification during different seasons (based on typical conditions in the central part of the Baltic Proper.

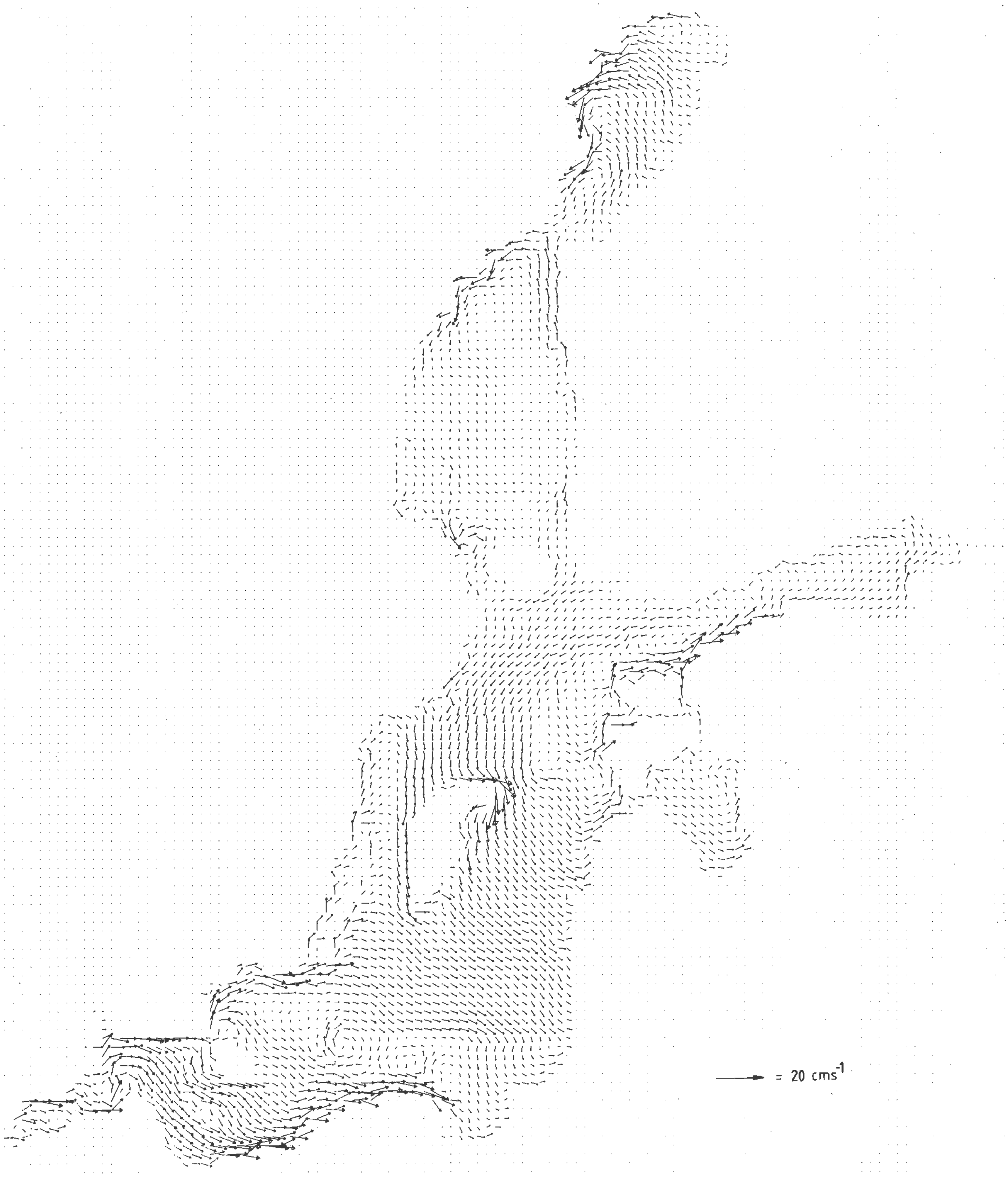


Winter period: computed mean currents for the surface layer (0-5 m).

Appendix 8

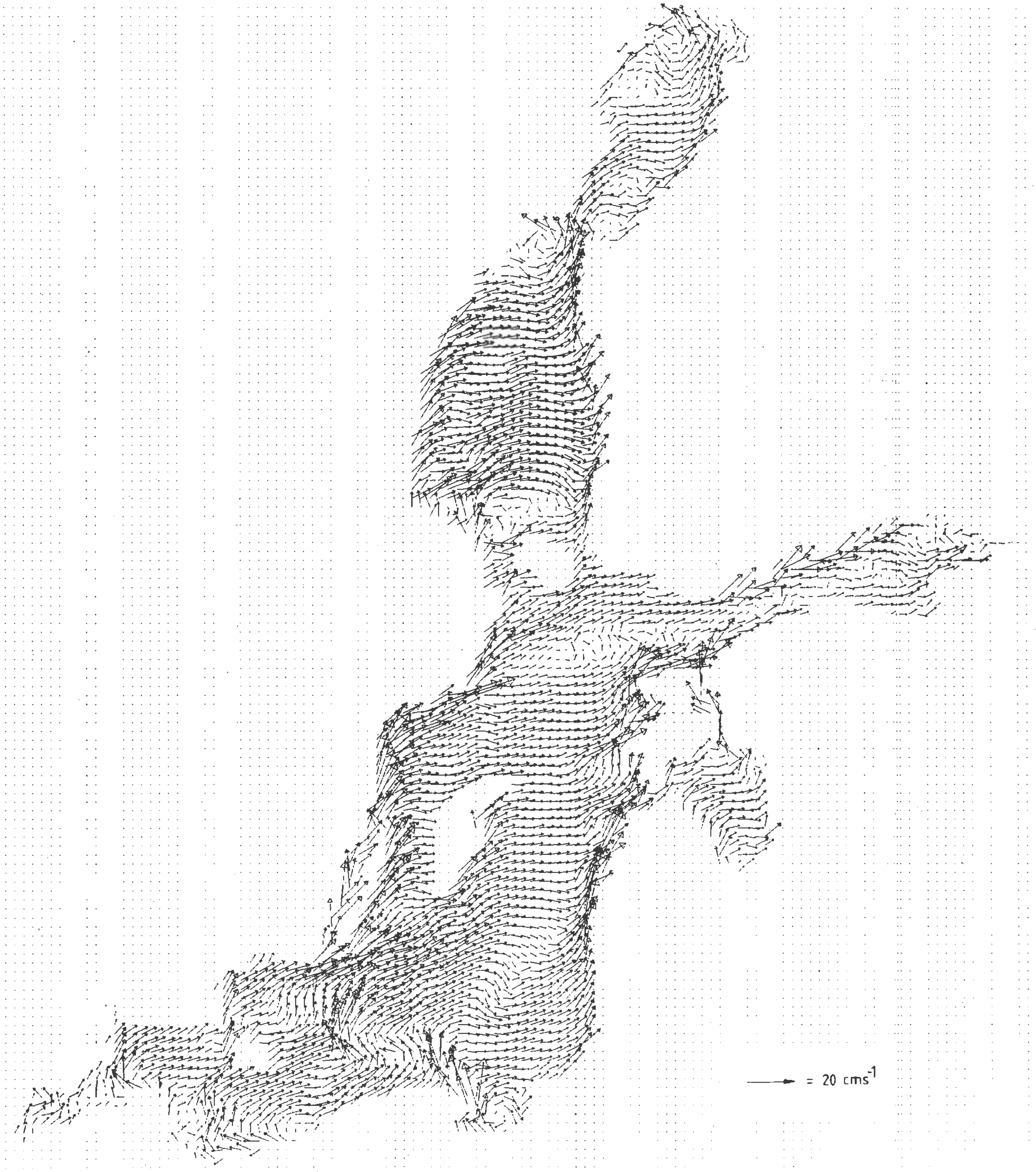


Spring period: computed mean currents for the surface layer (0-5 m).

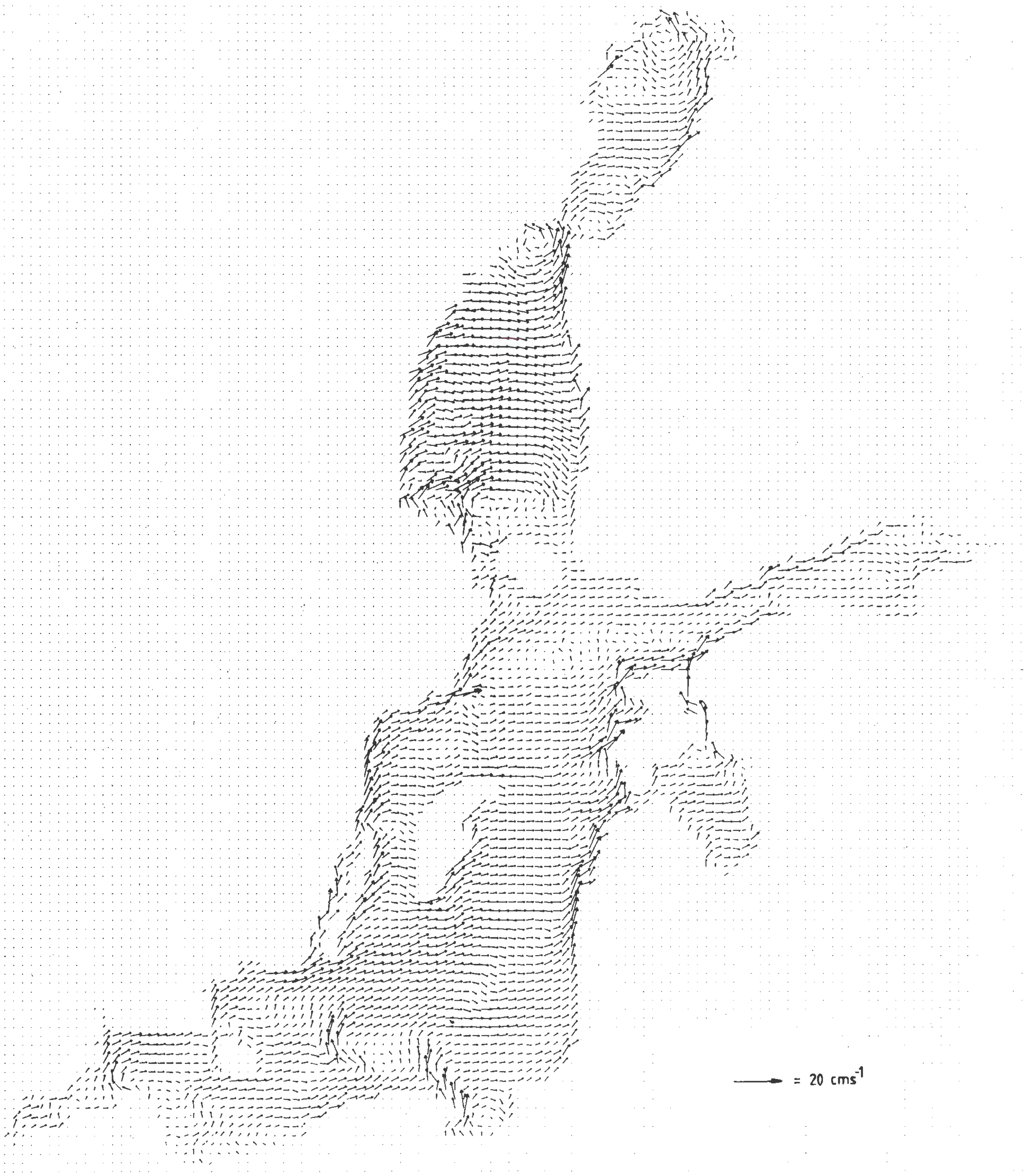


Summer period: computed mean currents for the surface layer (0-5 m).

Appendix 10

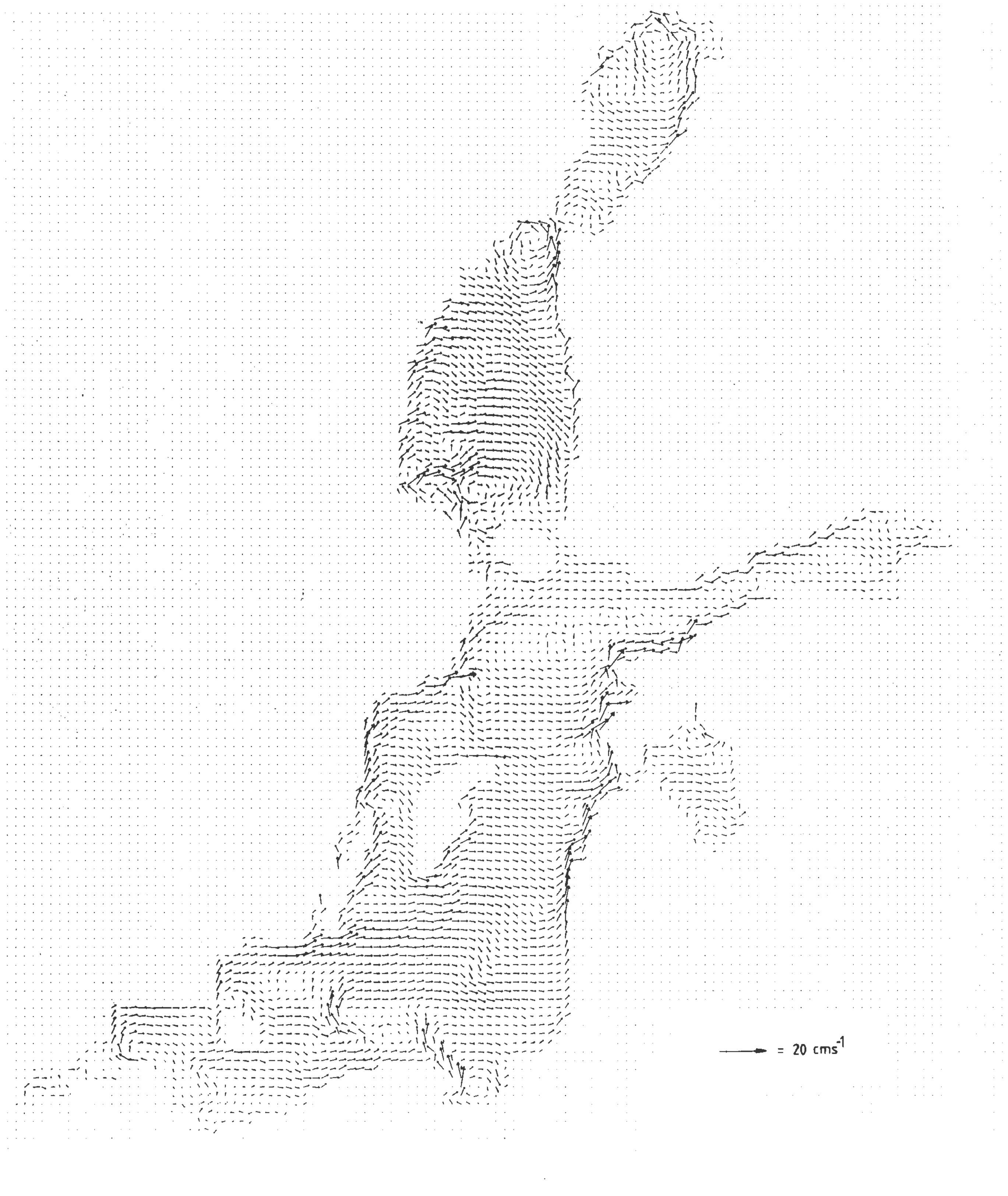


Autumn period: computed mean currents for the surface layer (0-5 m).



Whole year: computed mean currents for the surface layer (0-5 m).

Appendix 12



Whole year: computed mean currents for layer 2 (5-10 m).

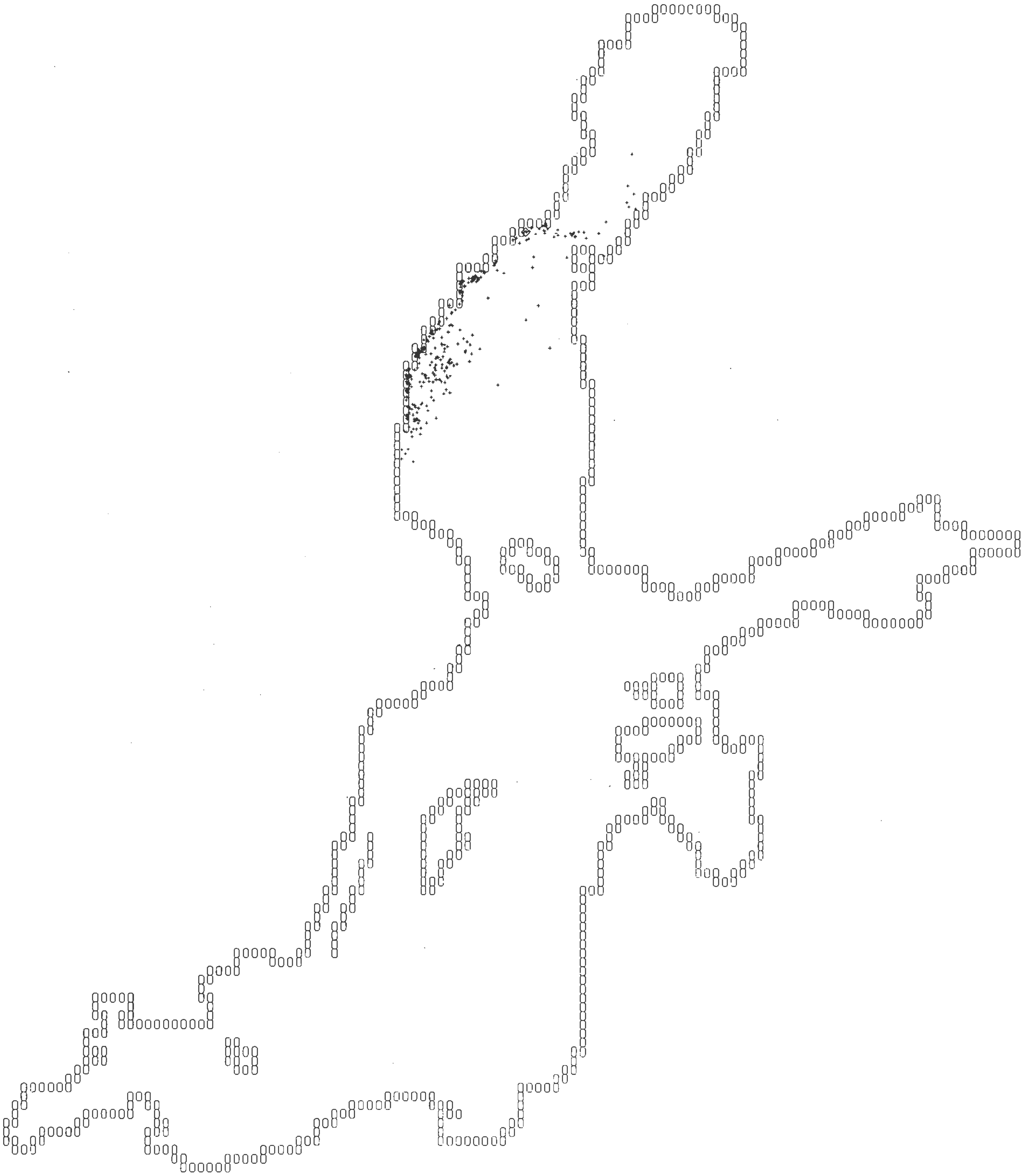
Whole year: computed mean currents for layer 3 (10-20 m).

Appendix 14

Whole year: computed mean currents for layer 4 (20-40 m).

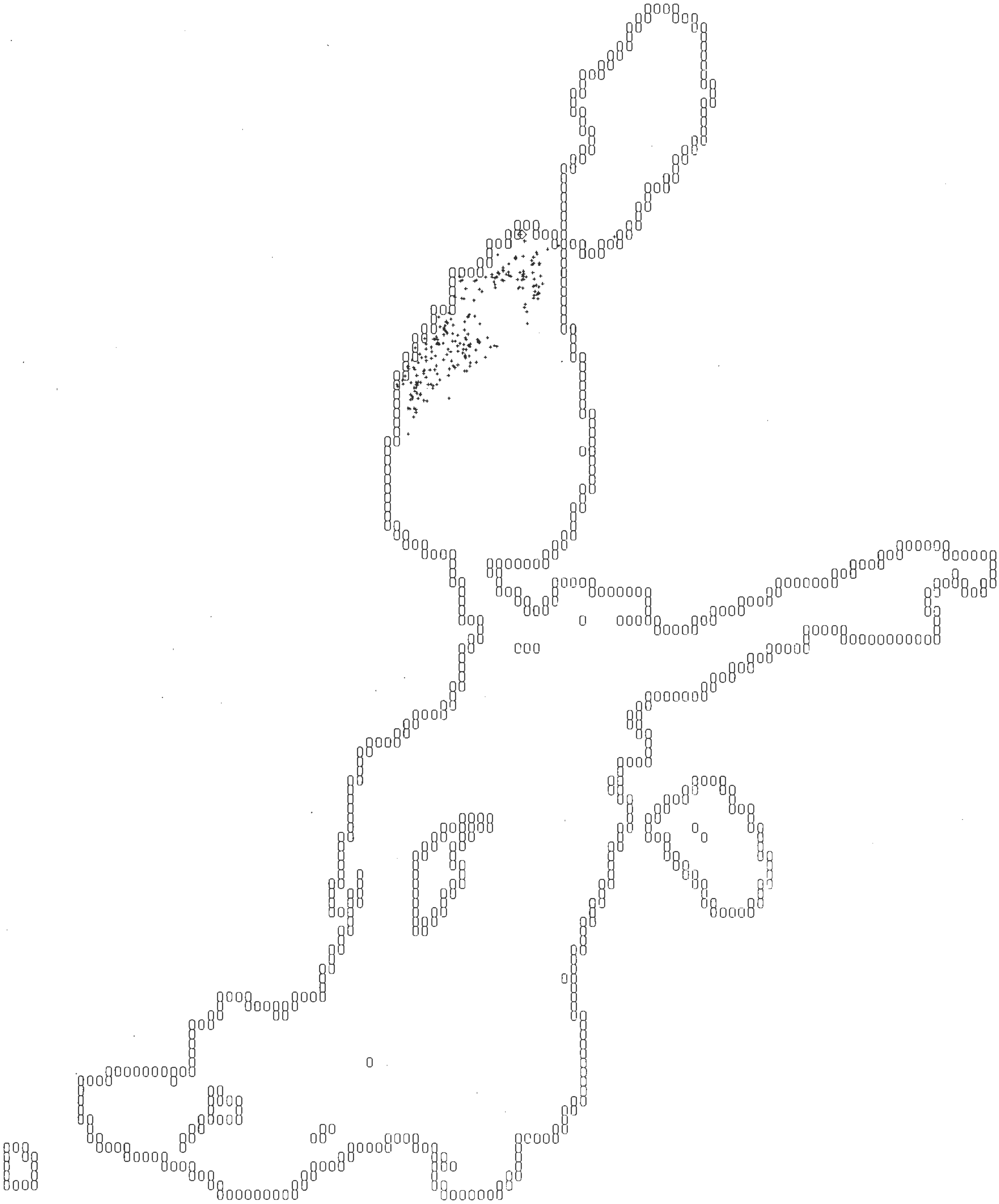
Whole year: computed mean currents for layer 5 (40-60 m).

Whole year: computed mean currents for layer 6 (60 m to bottom).

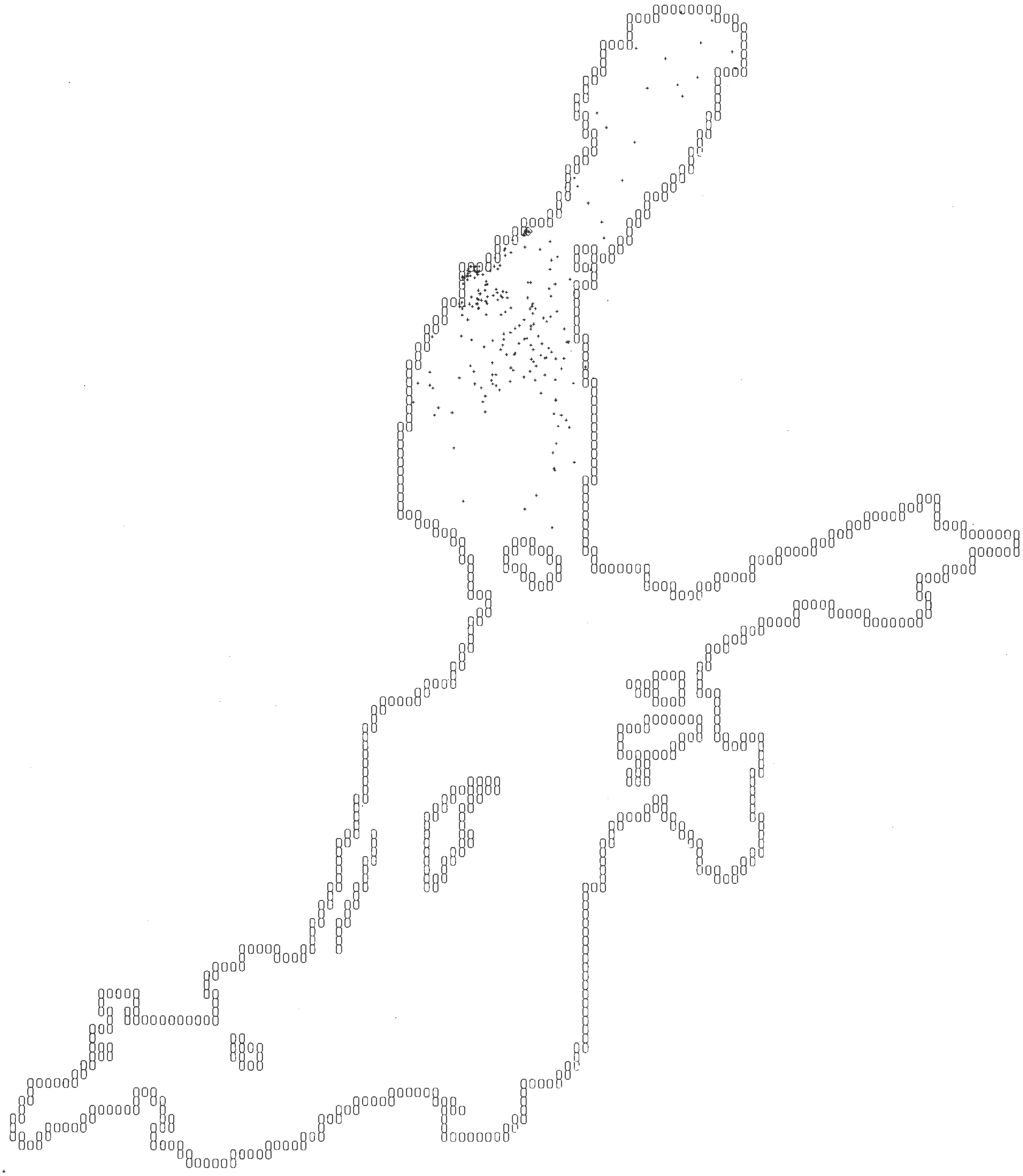


Outlet: Umeå. Particle distribution in layer 1 (0-5 m) after summer, 20 % of total number.

Appendix 18

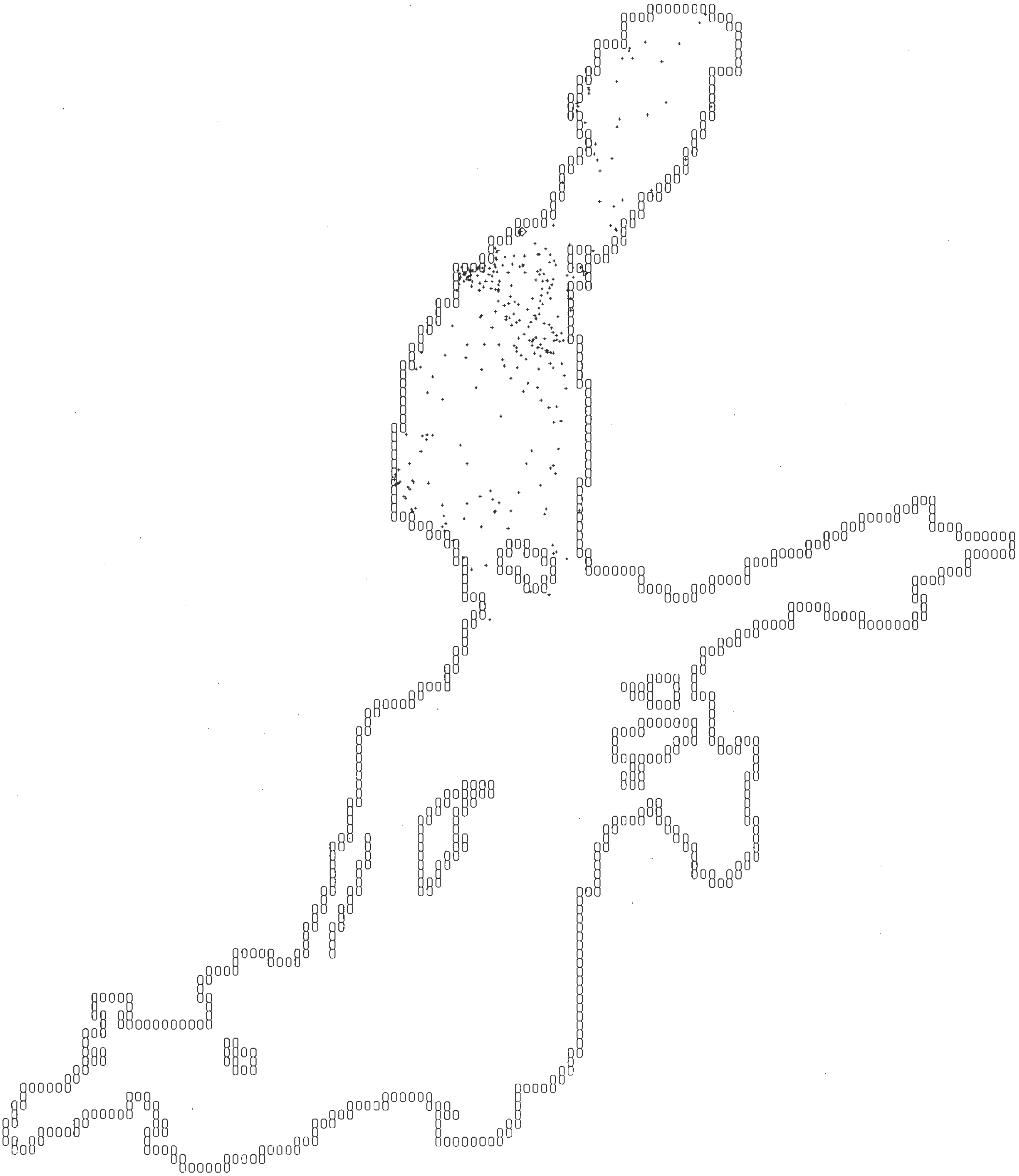


Outlet: Umeå. Particle distribution in layer 4 (20-40 m) after summer, 15 % of total number.

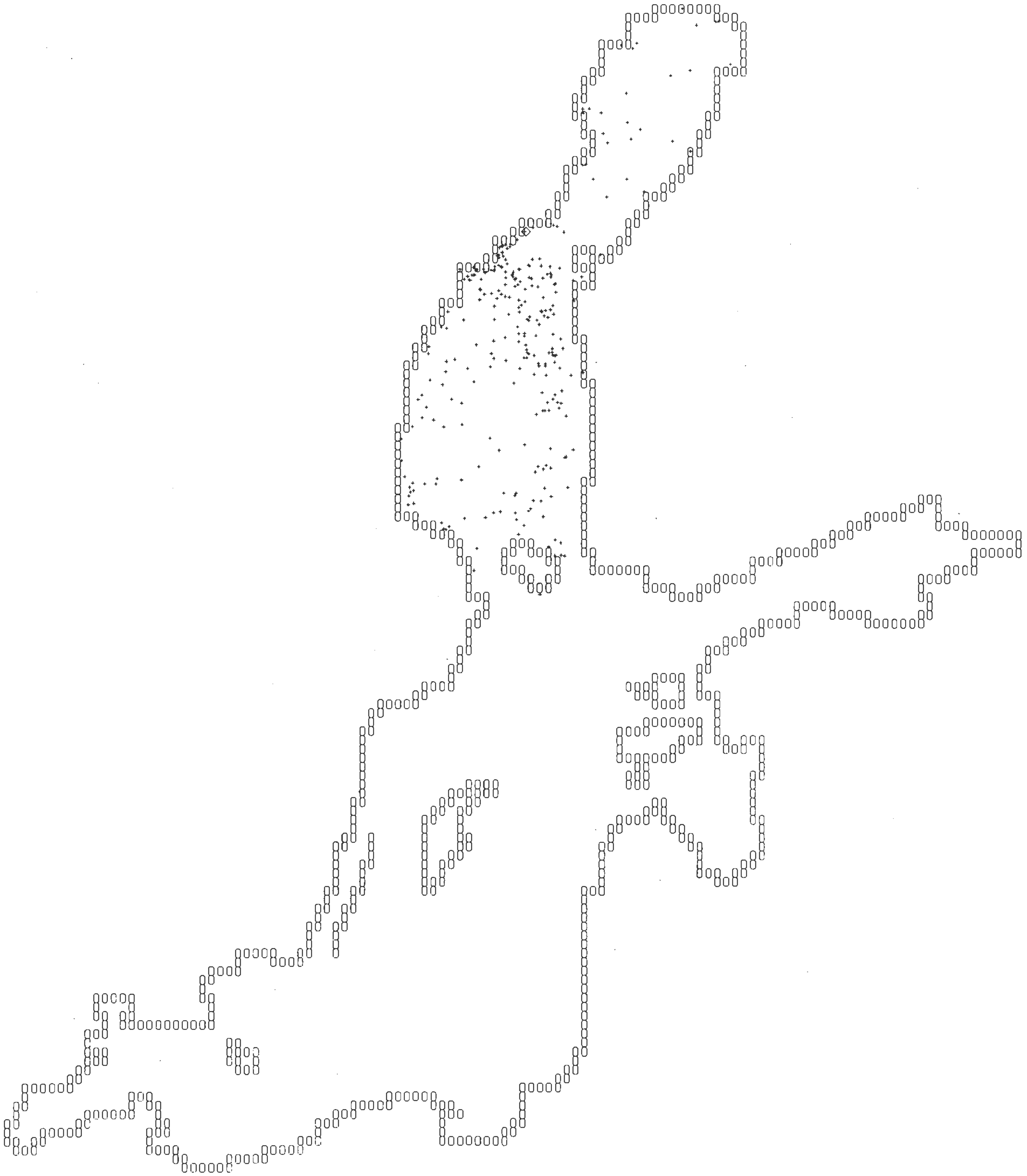


Outlet: Umeå. Particle distribution in layer 1 (0-5 m) after autumn, 10 % of total number.

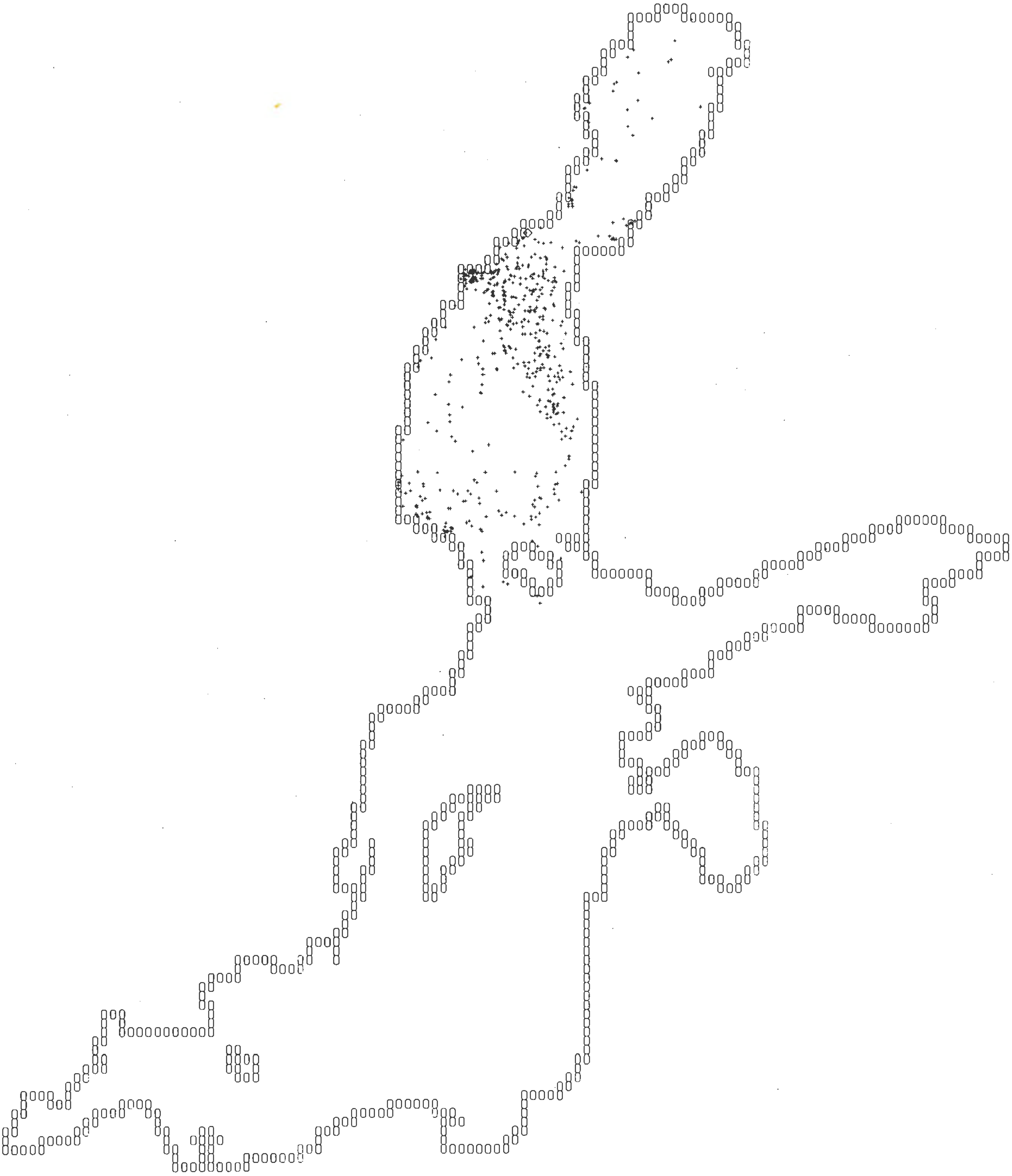
Appendix 20



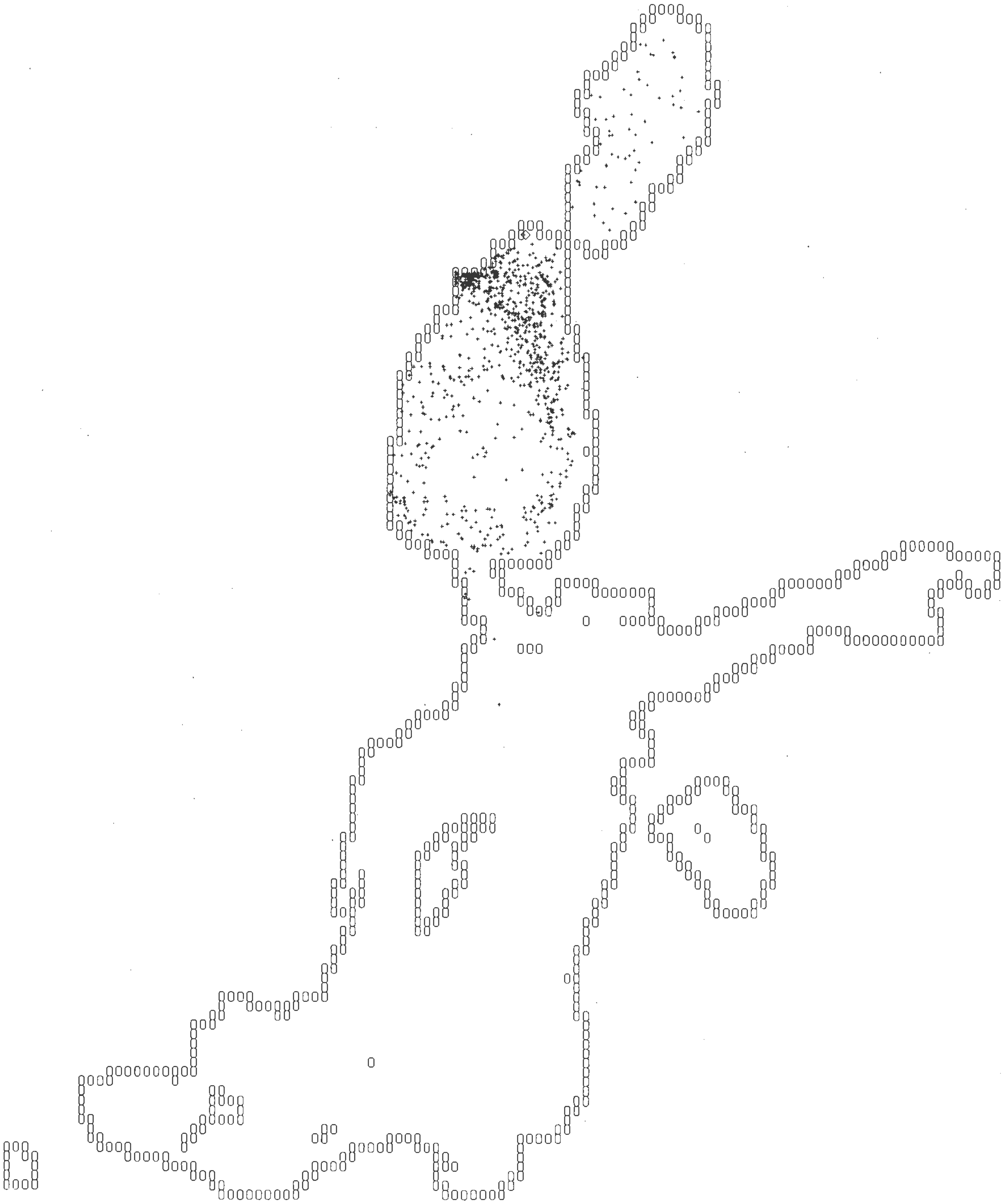
Outlet: Umeå. Particle distribution in layer 1 (0-5 m) after winter, 10 % of total number.



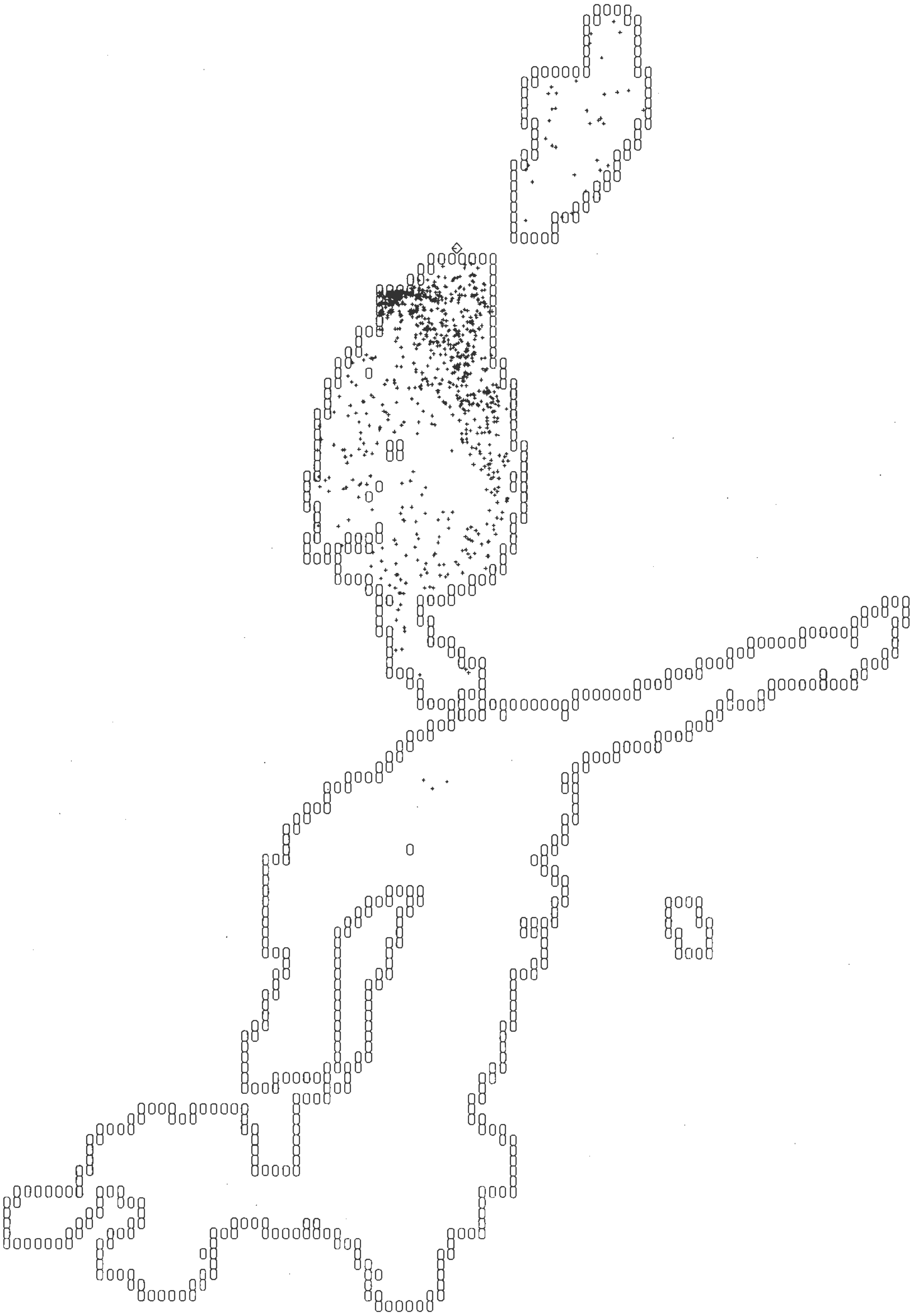
Outlet: Umeå. Particle distribution in layer 2 (5-10 m) after winter, 9 % of total number.



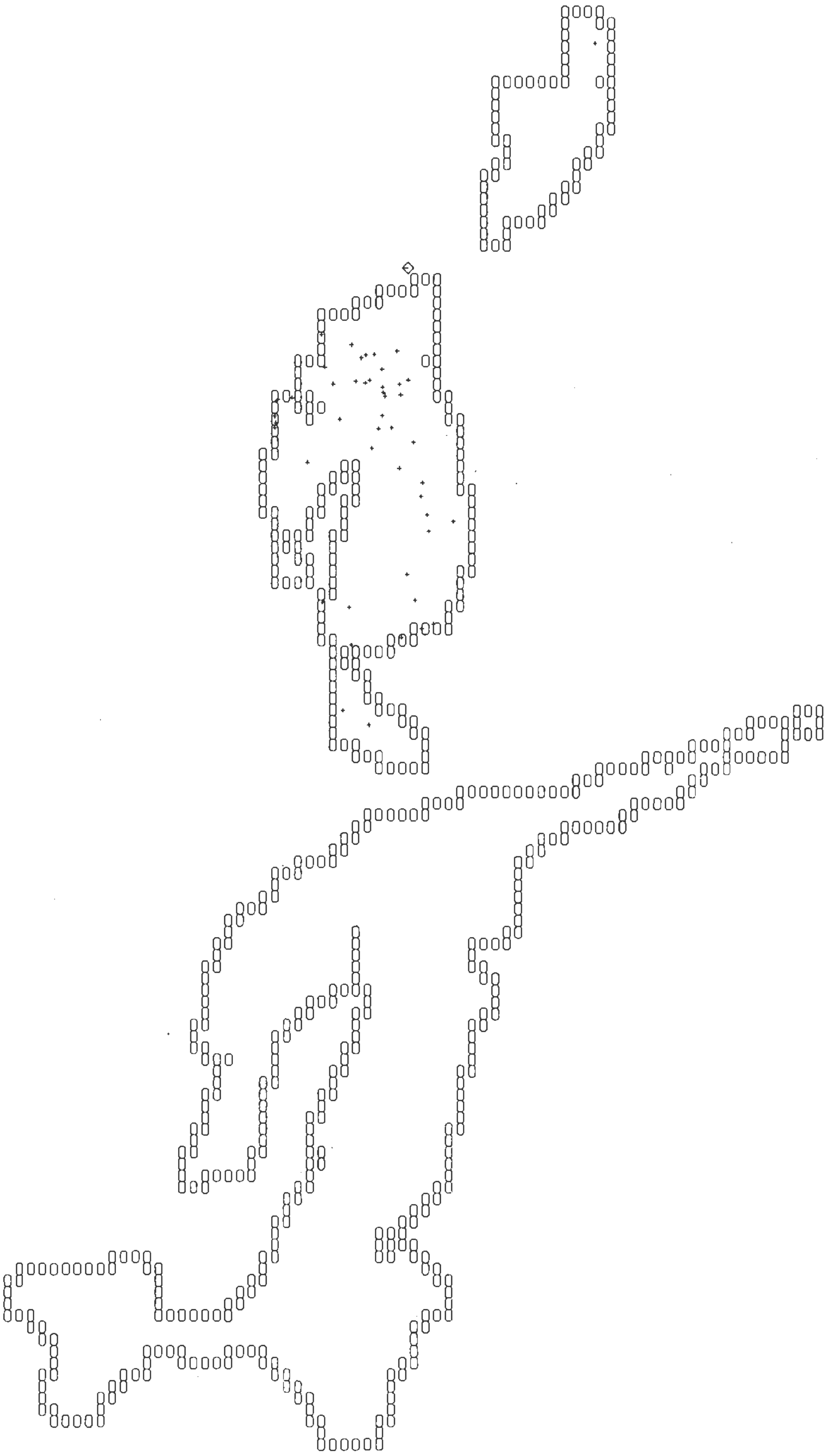
Outlet: Umeå. Particle distribution in layer 3 (10-20 m) after winter, 18 % of total number.



Outlet: Umeå. Particle distribution in layer 4 (20-40 m) after winter, 32 % of total number.

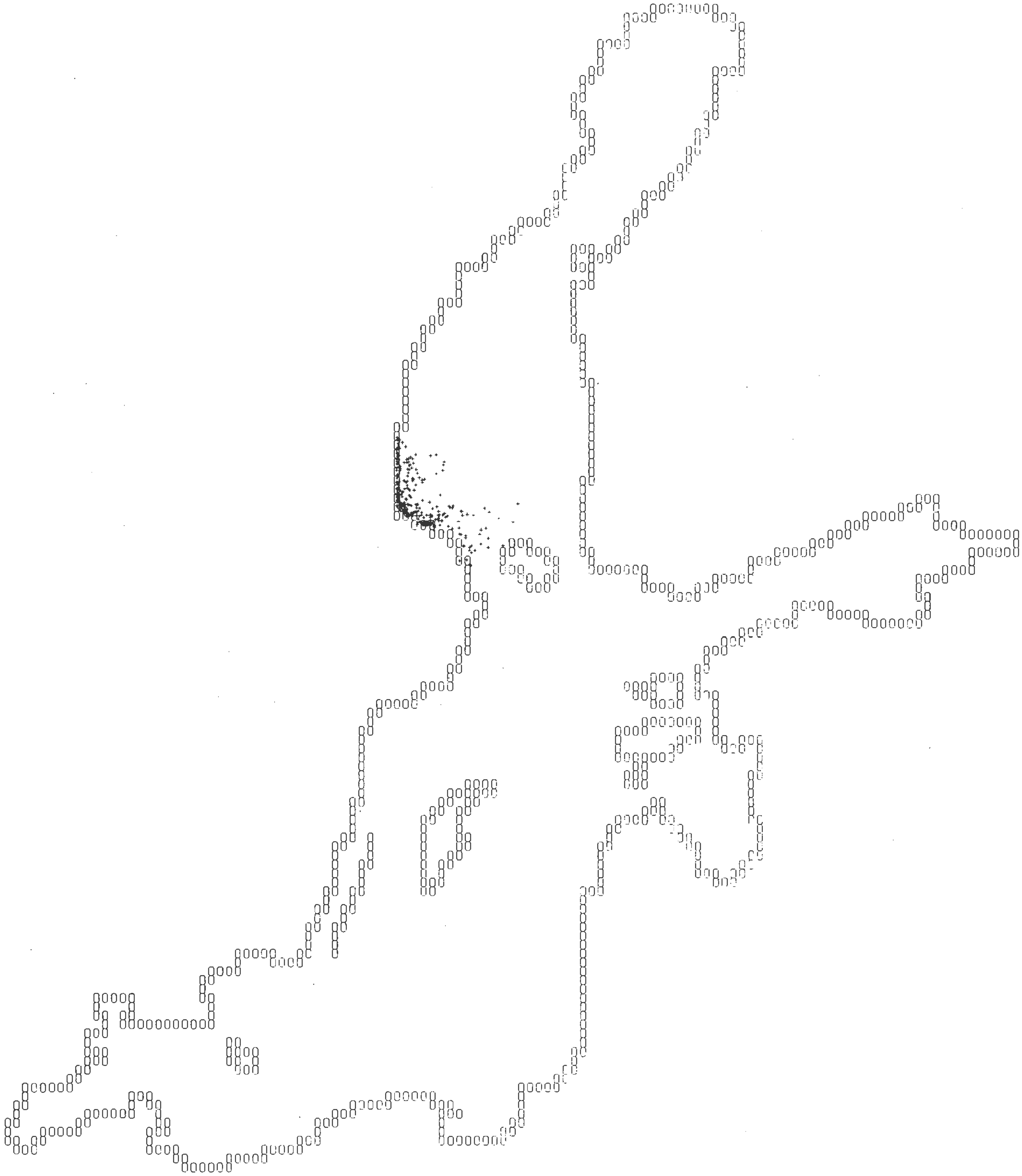


Outlet: Umeå. Particle distribution in layer 5 (40-60 m) after winter, 29 % of total number.

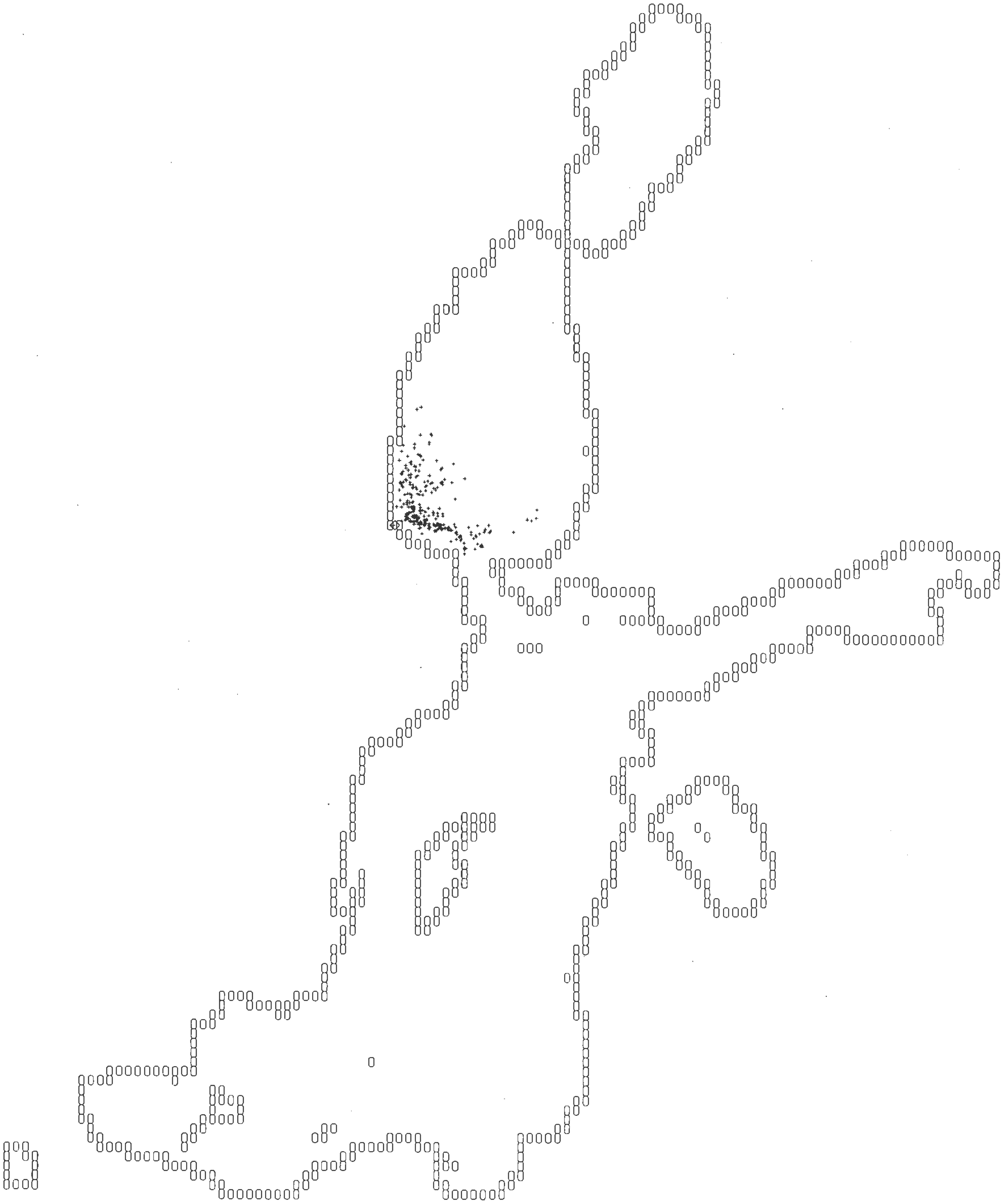


Outlet: Umeå. Particle distribution in layer 6 (60 m to bottom) after winter, 2 % of total number.

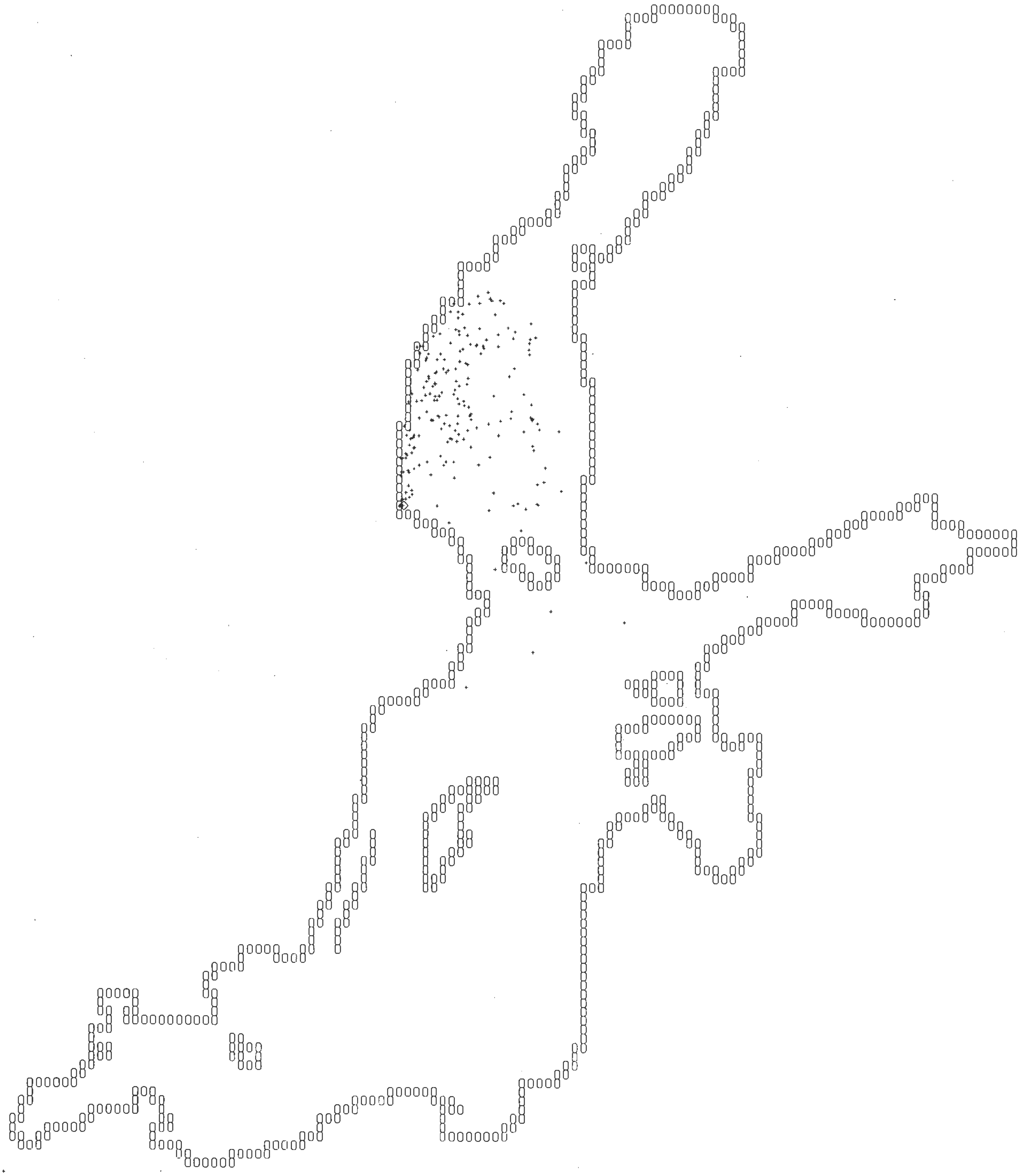
Appendix 26



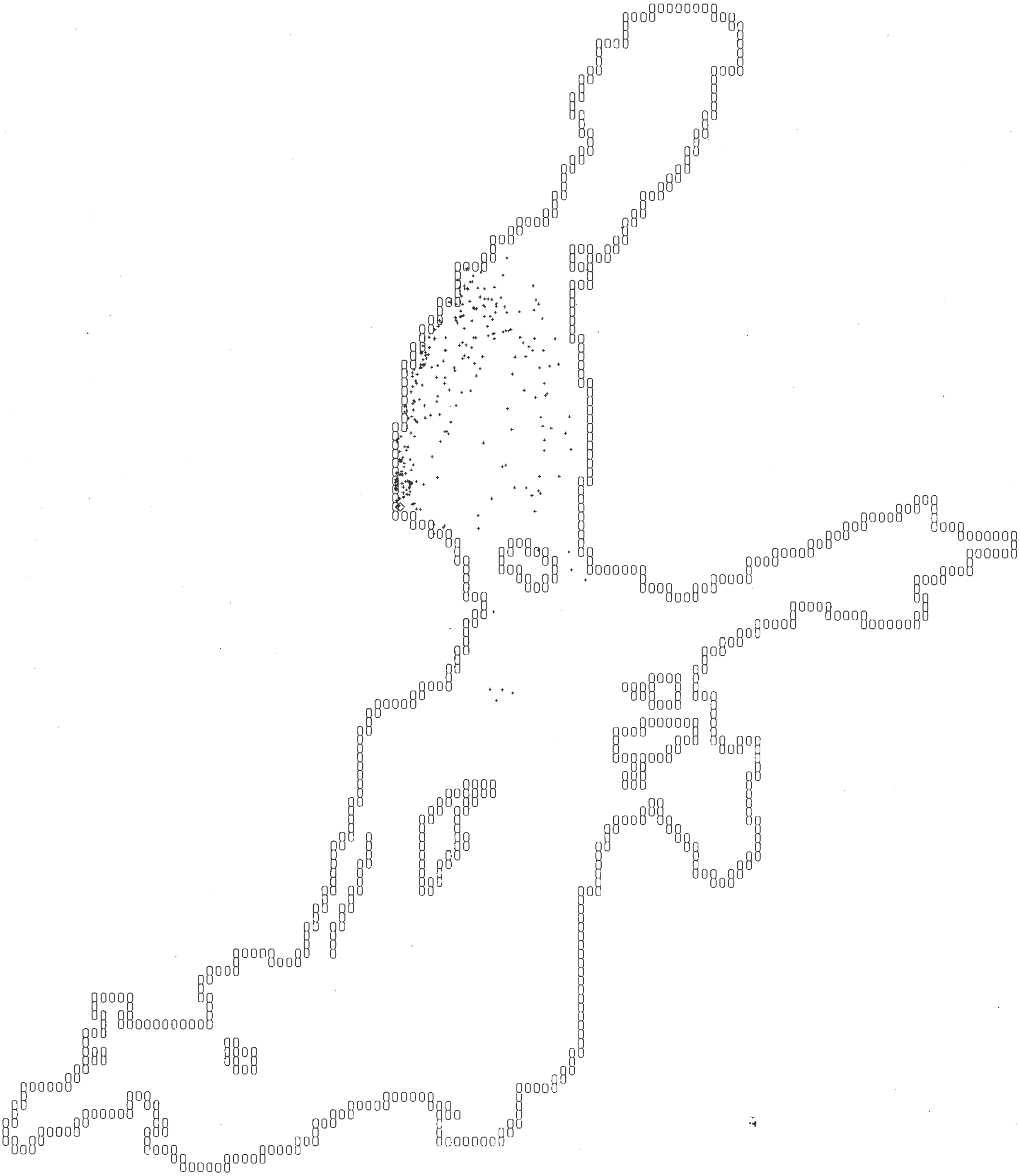
Outlet: Gävle. Particle distribution in layer 1 (0-5 m) after summer, 22 % of total number.



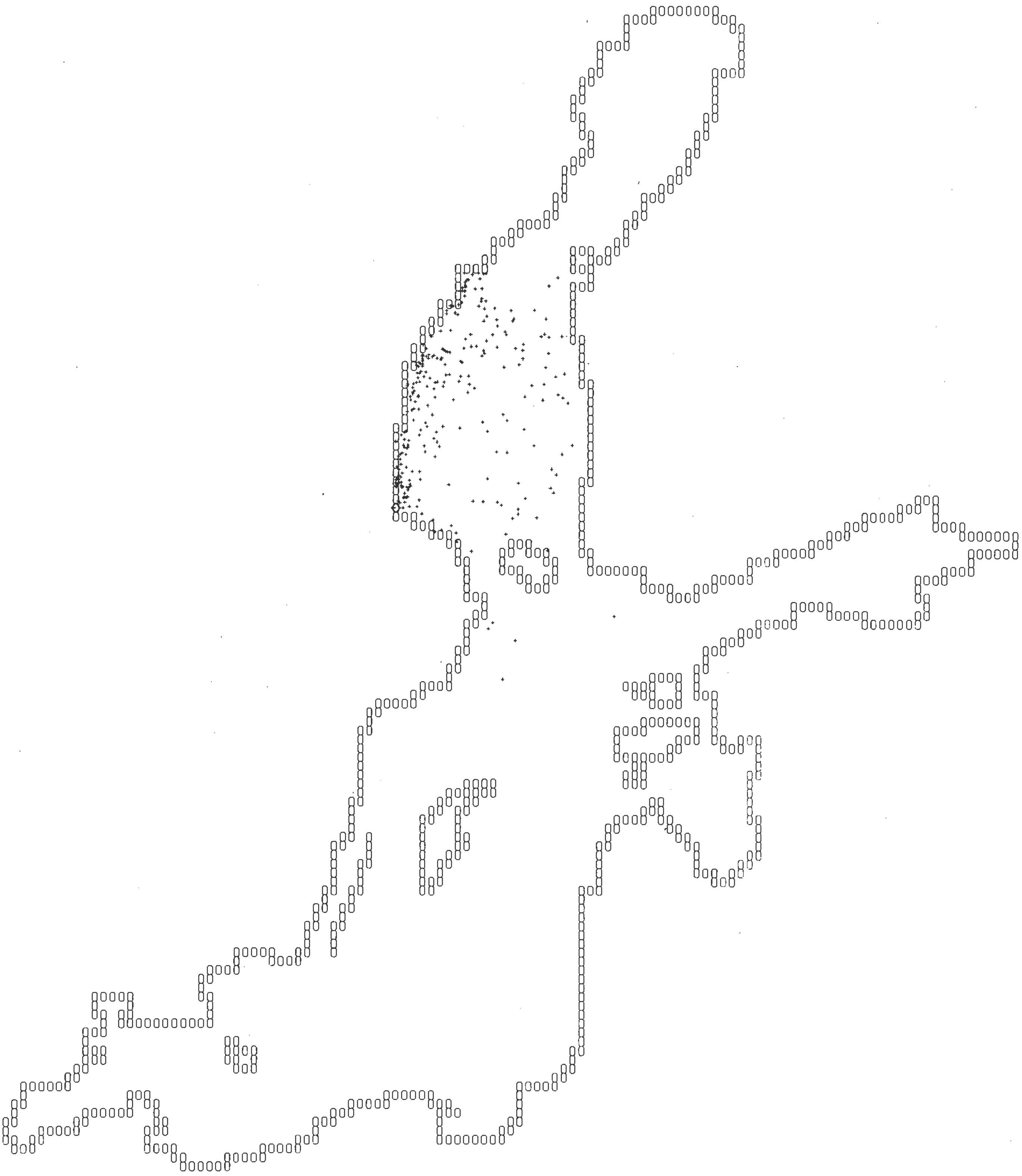
Outlet: Gävle. Particle distribution in layer 4 (20-40 m) after summer, 17 % of total number.



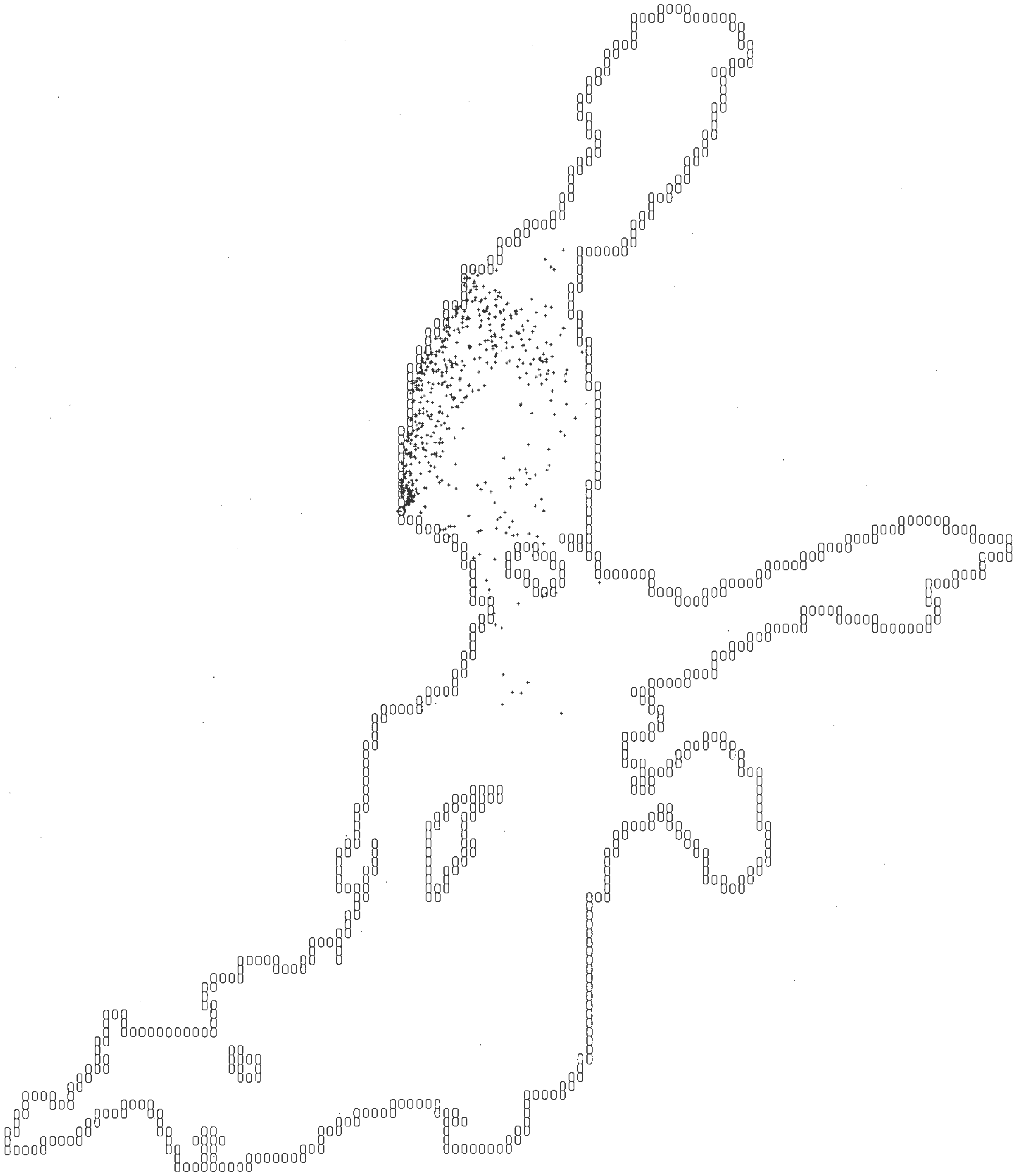
Outlet: Gävle. Particle distribution in layer 1 (0-5 m) after autumn, 9 % of total number.



Outlet: Gävle. Particle distribution in layer 1 (0-5 m) after winter, 9 % of total number.

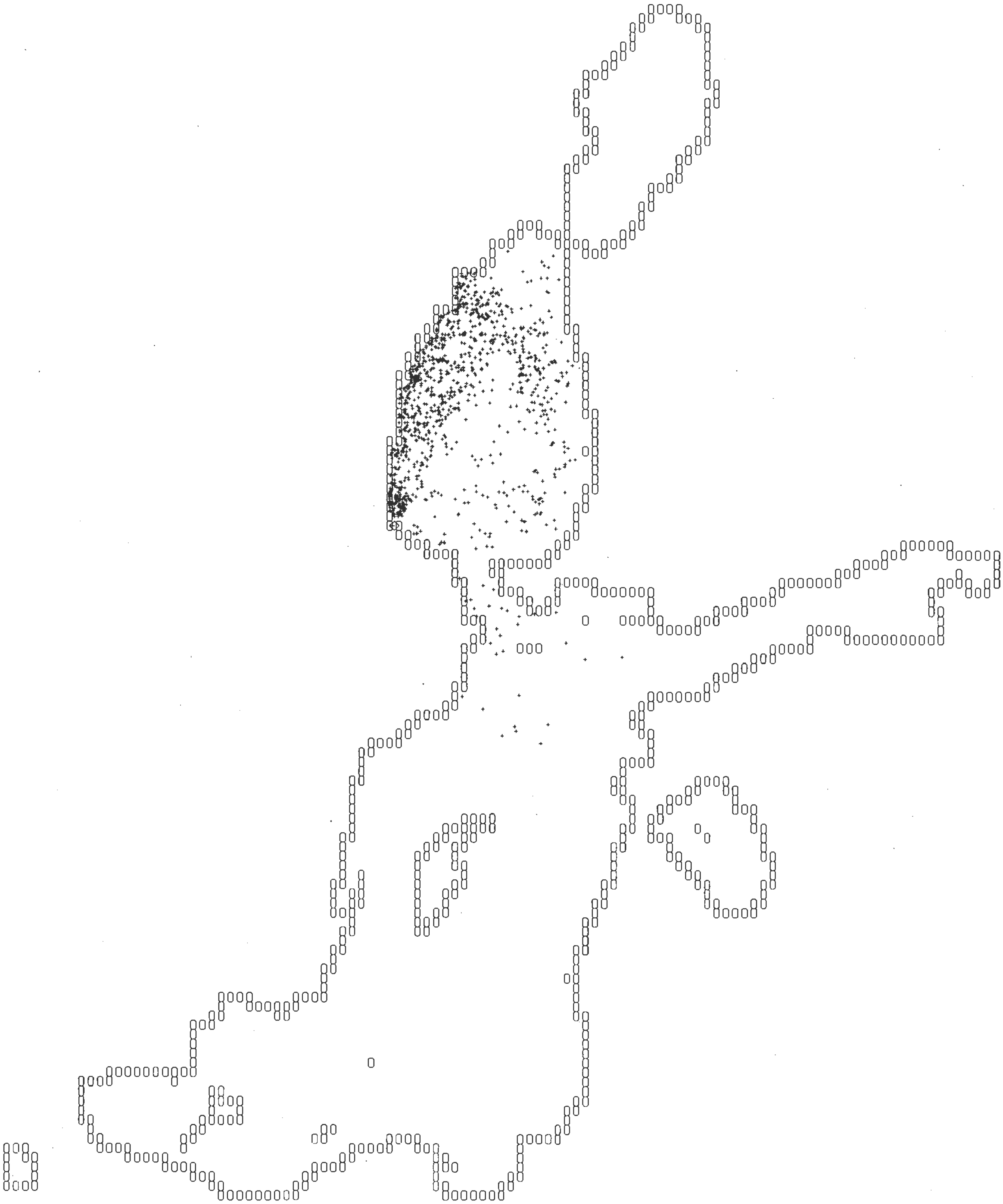


Outlet: Gävle. Particle distribution in layer 2 (5-10 m) after winter, 9 % of total number.

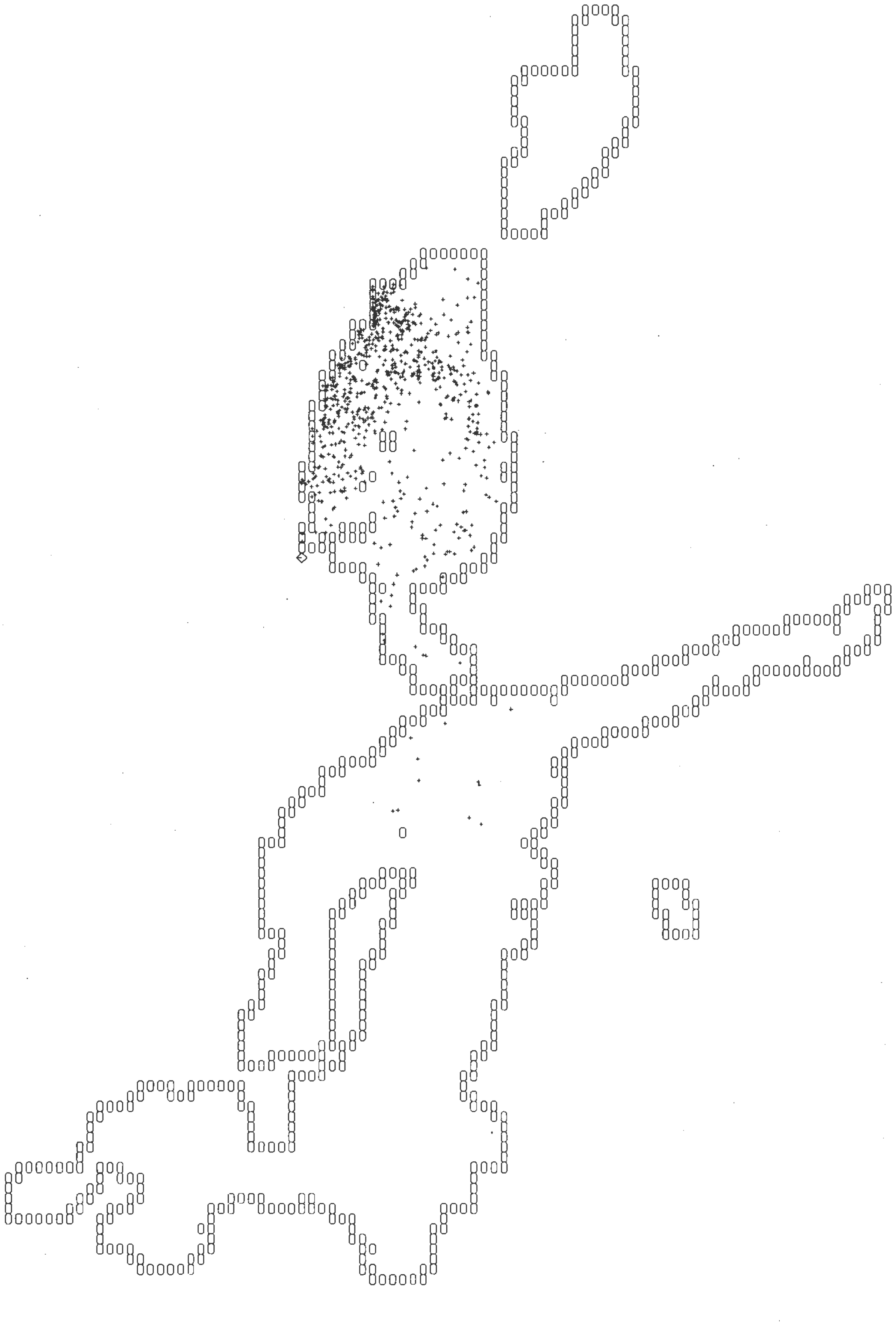


Outlet: Gävle. Particle distribution in layer 3 (10-20 m) after winter, 19 % of total number.

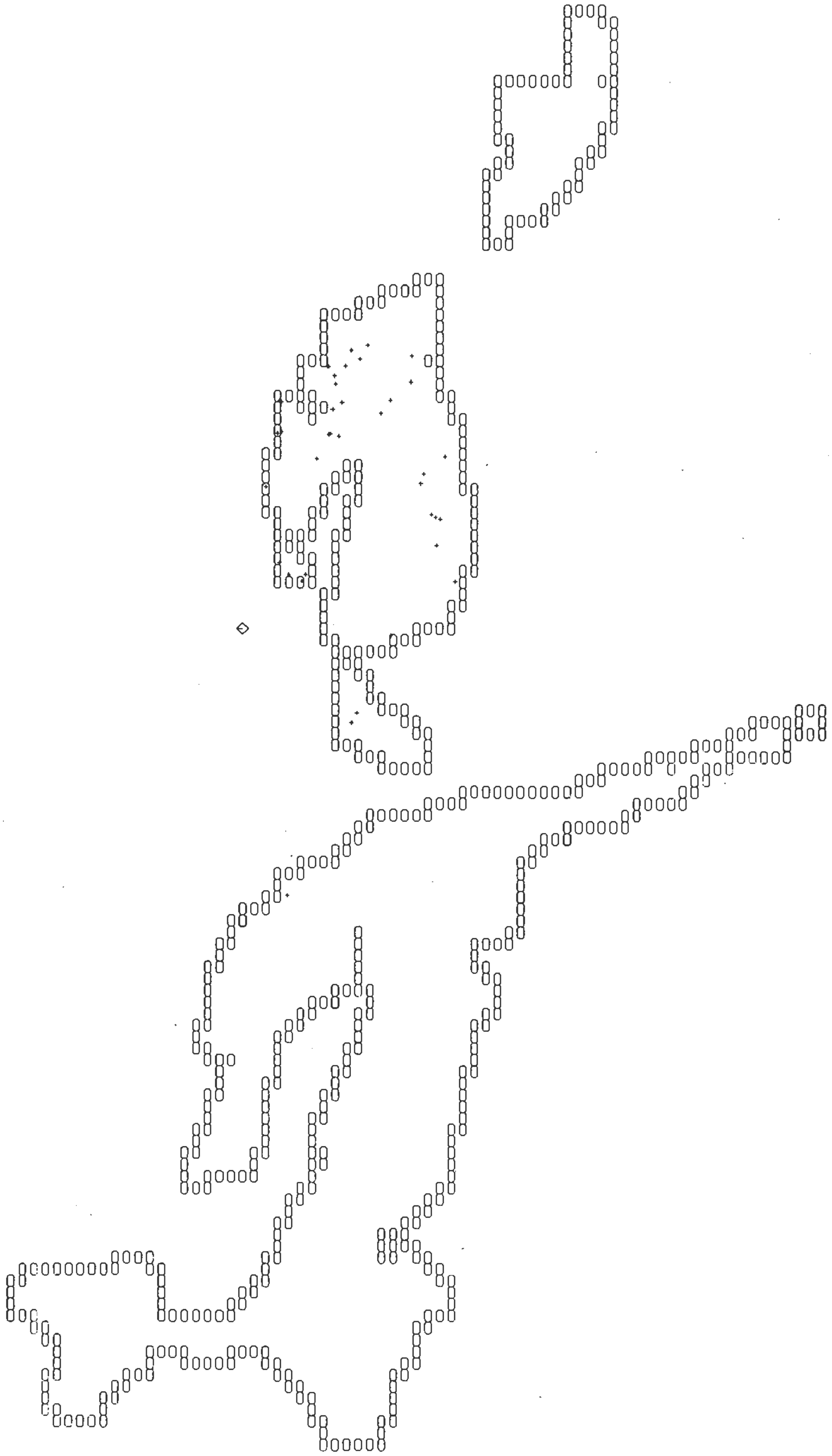
Appendix 32



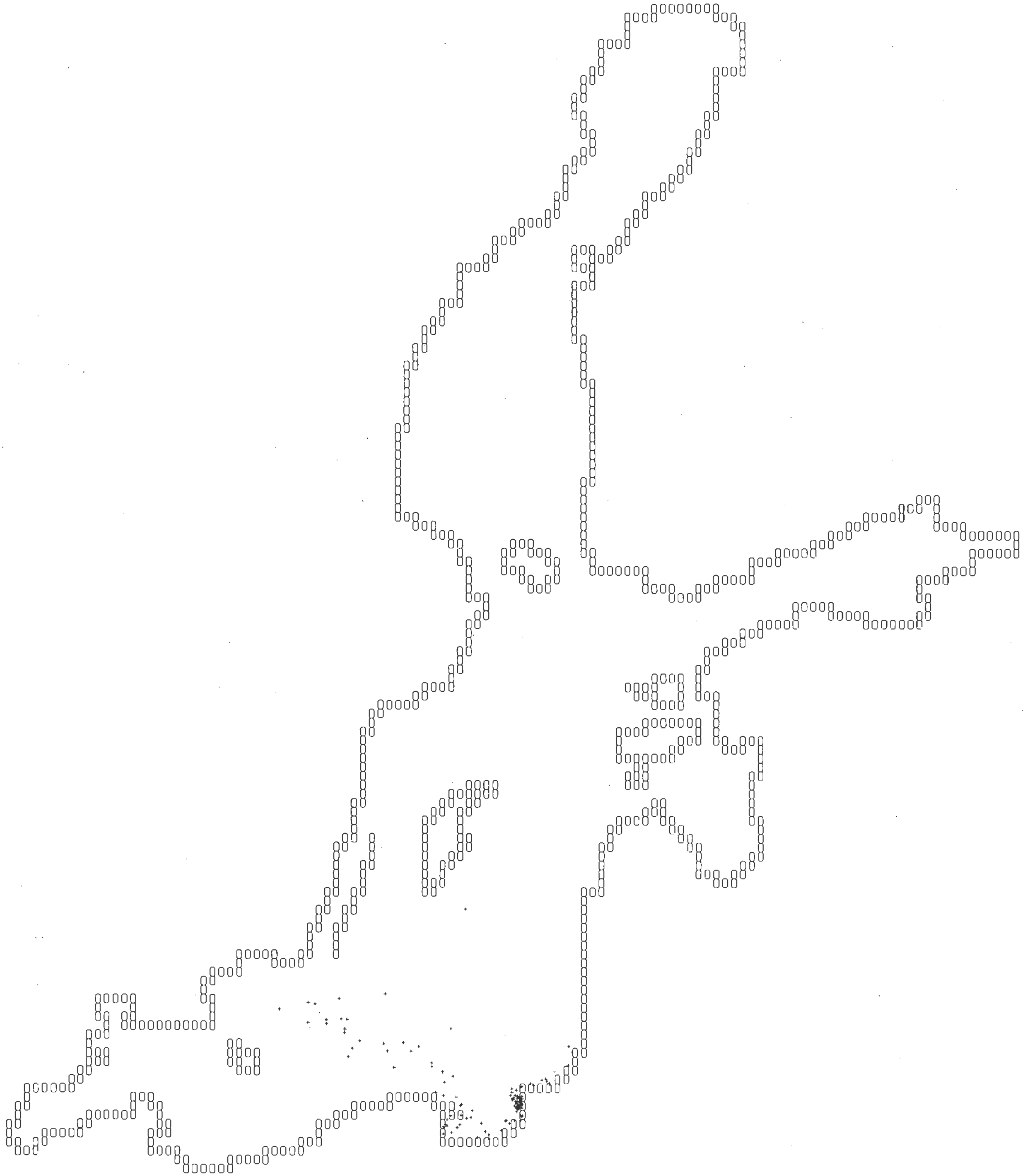
Outlet: Gävle. Particle distribution in layer 4 (20-40 m) after winter, 36 % of total number.



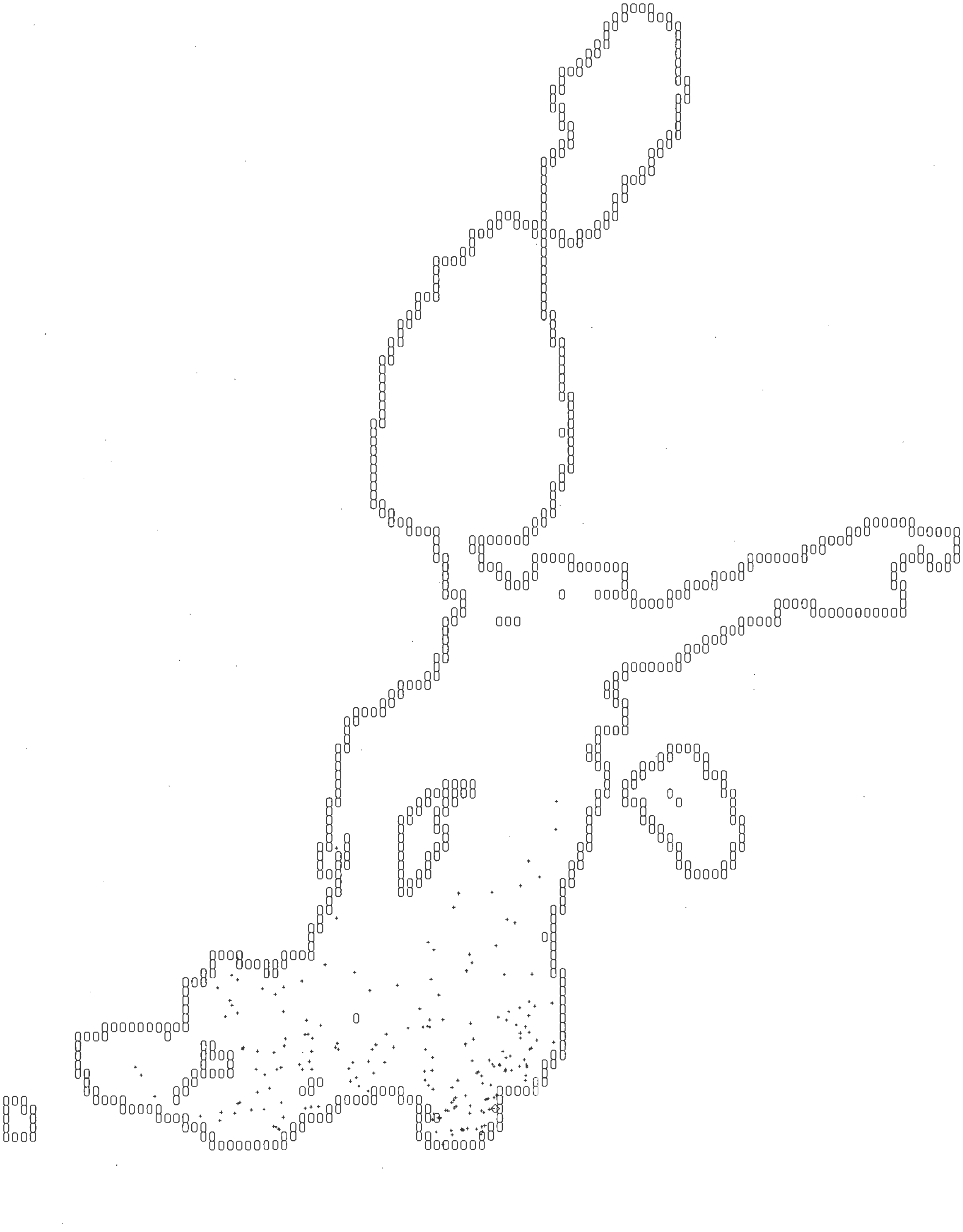
Outlet: Gävle. Particle distribution in layer 5 (40-60 m) after winter, 25 % of total number.



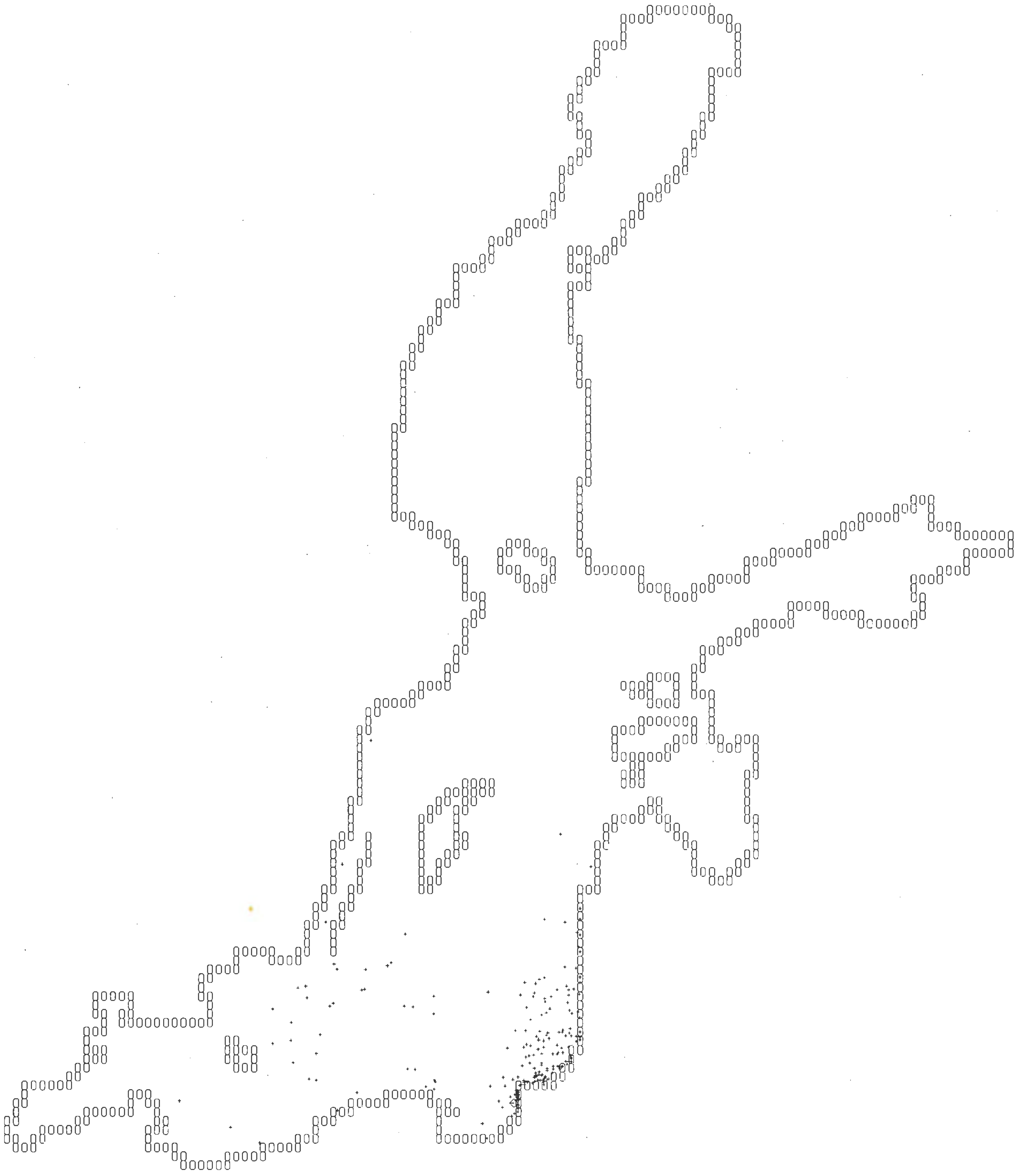
Outlet: Gävle. Particle distribution in layer 6 (60 m to bottom) after winter, 1 % of total number.



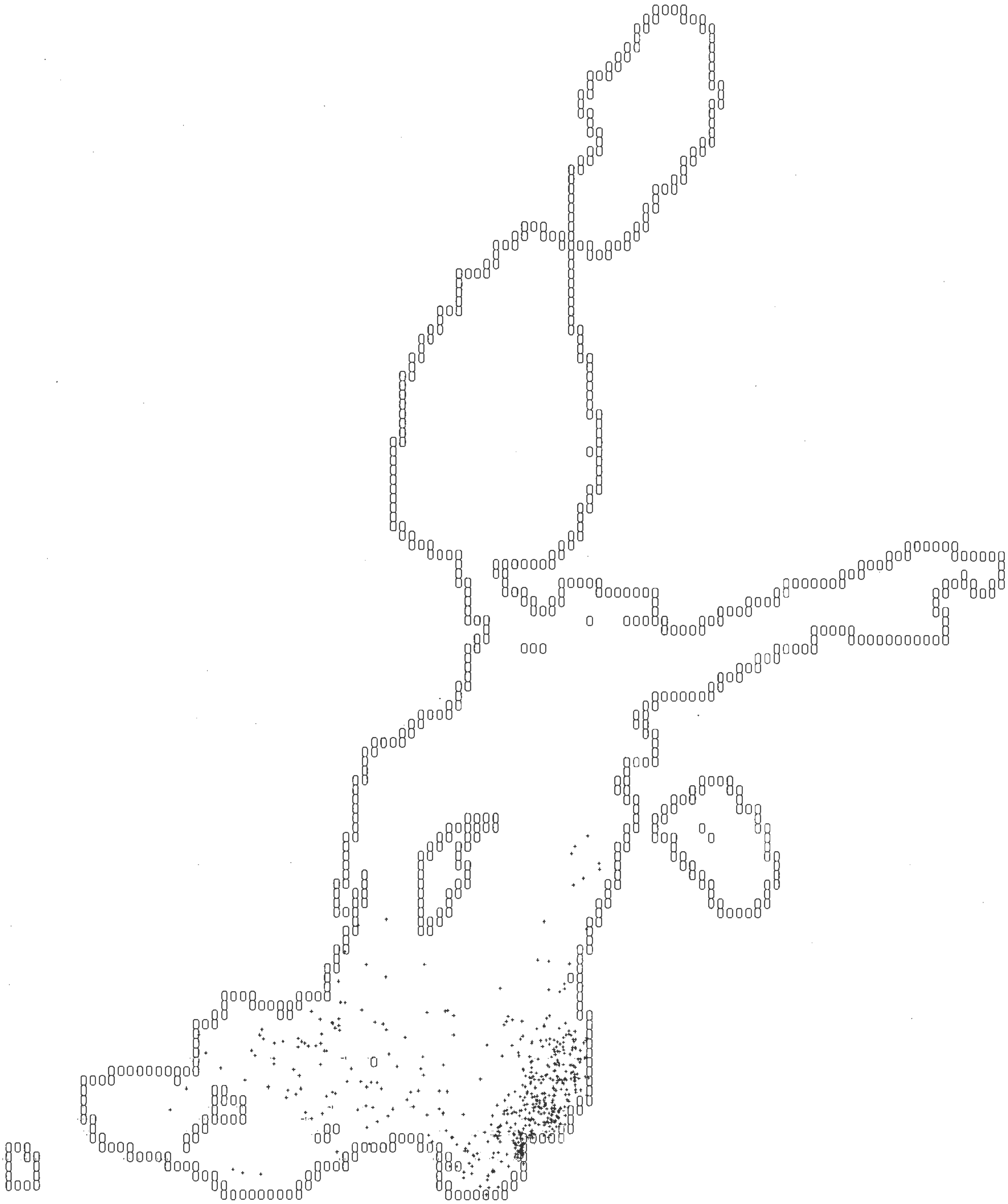
Outlet: Gulf of Gdansk. Particle distribution in layer 1 (0-5 m) after autumn, 15 % of total number.



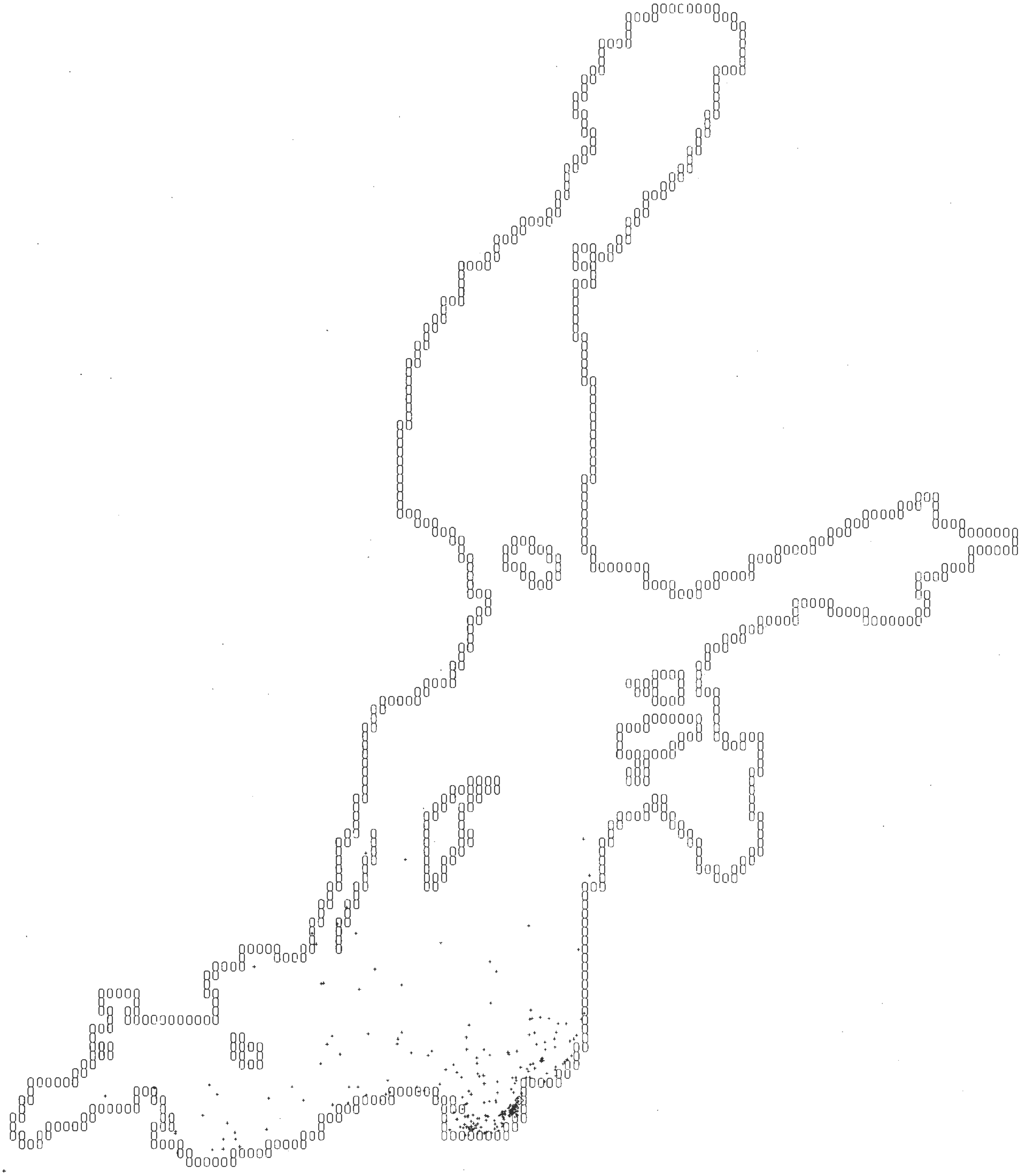
Outlet: Gulf of Gdansk. Particle distribution in layer 4 (20-40 m) after autumn, 27 % of total number.



Outlet: Gulf of Gdansk. Particle distribution in layer 1 (0-5 m) after winter, 14 % of total number.

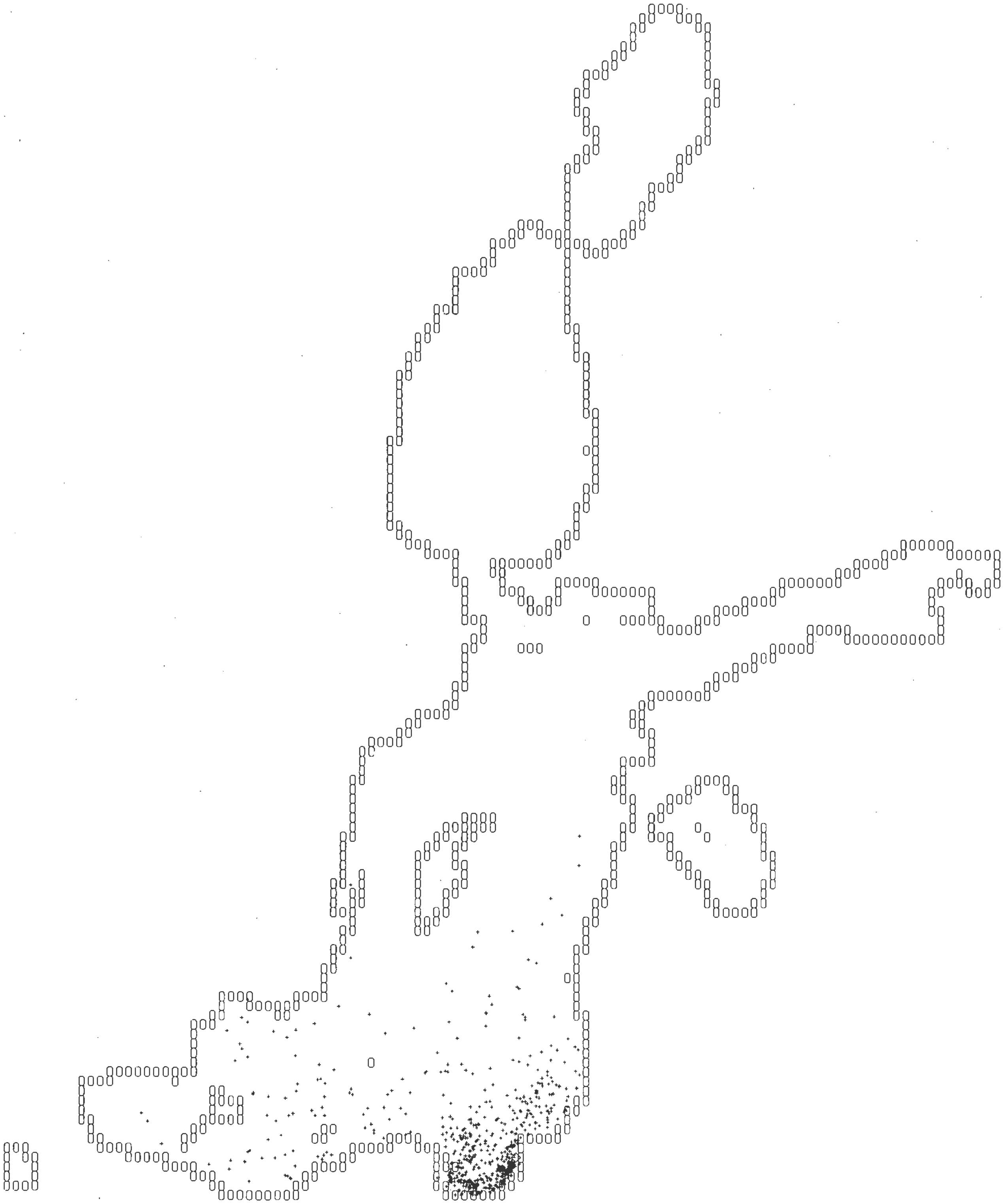


Outlet: Gulf of Gdansk. Particle distribution in layer 4 (20-40 m) after winter, 34 % of total number.

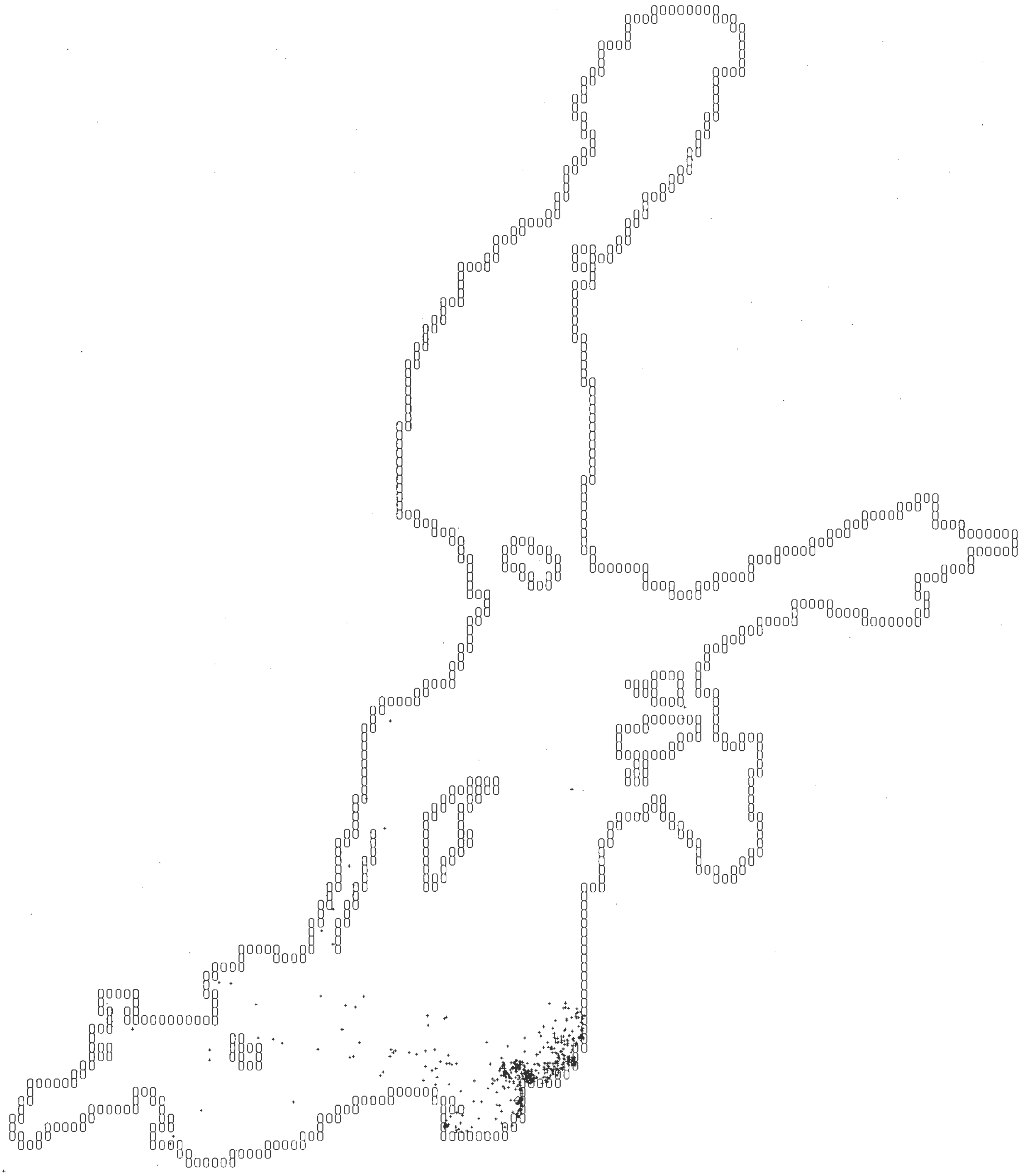


Outlet: Gulf of Gdansk. Particle distribution in layer 1 (0-5 m) after spring, 12 % of total number.

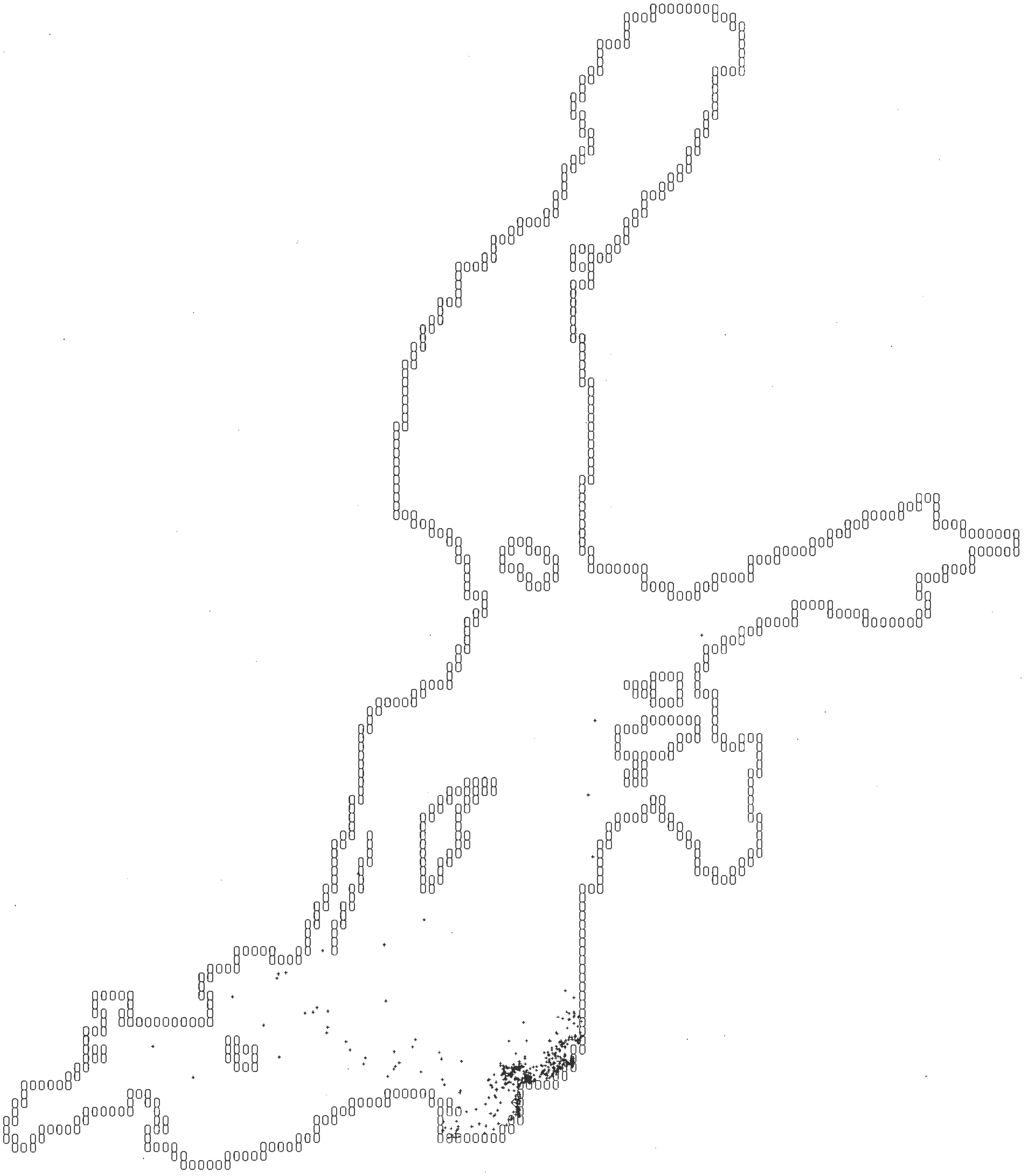
Appendix 40



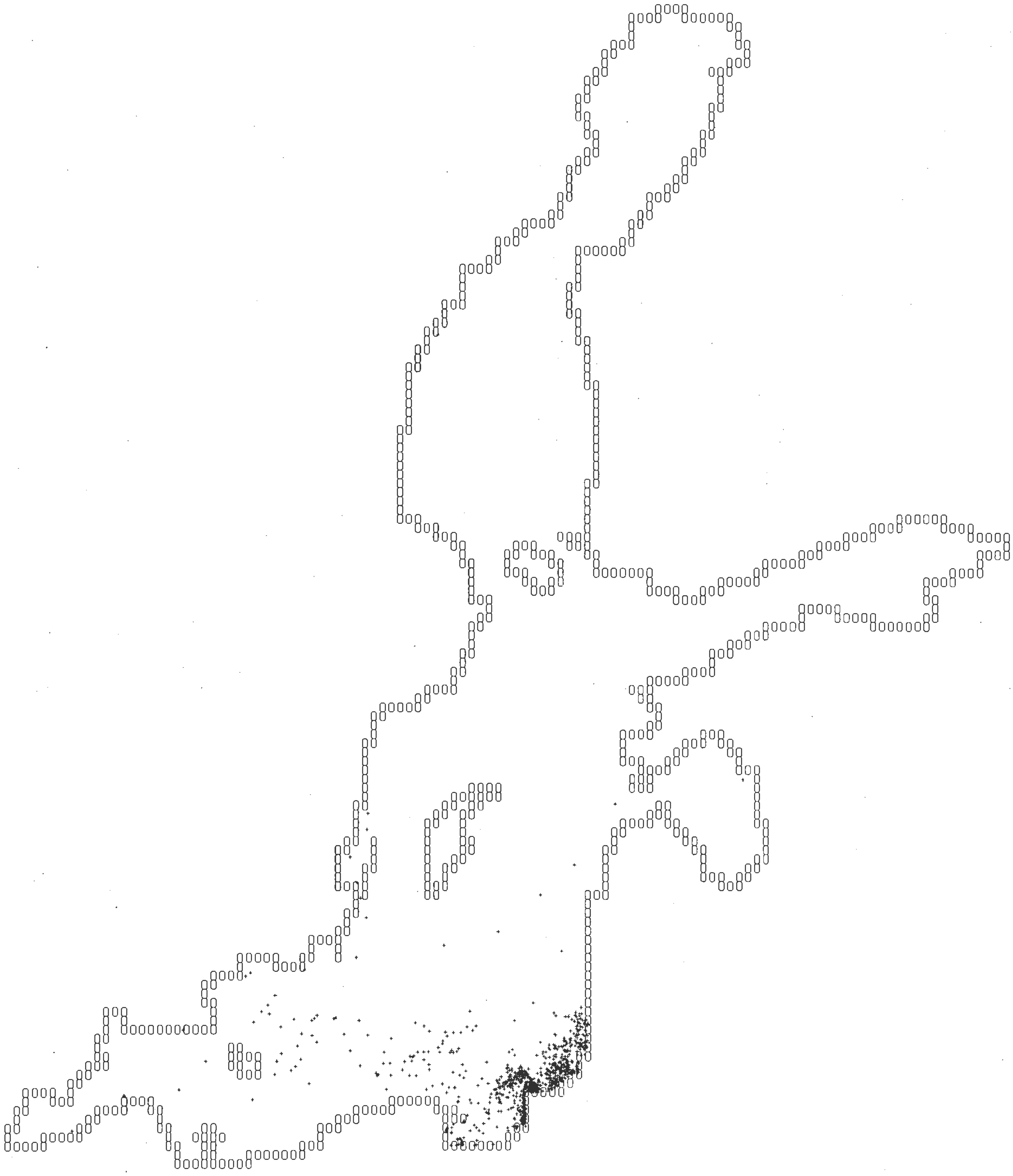
Outlet: Gulf of Gdansk. Particle distribution in layer 4 (20-40 m) after spring, 31 % of total number.



Outlet: Gulf of Gdansk. Particle distribution in layer 1 (0-5 m) after summer, 17 % of total number.

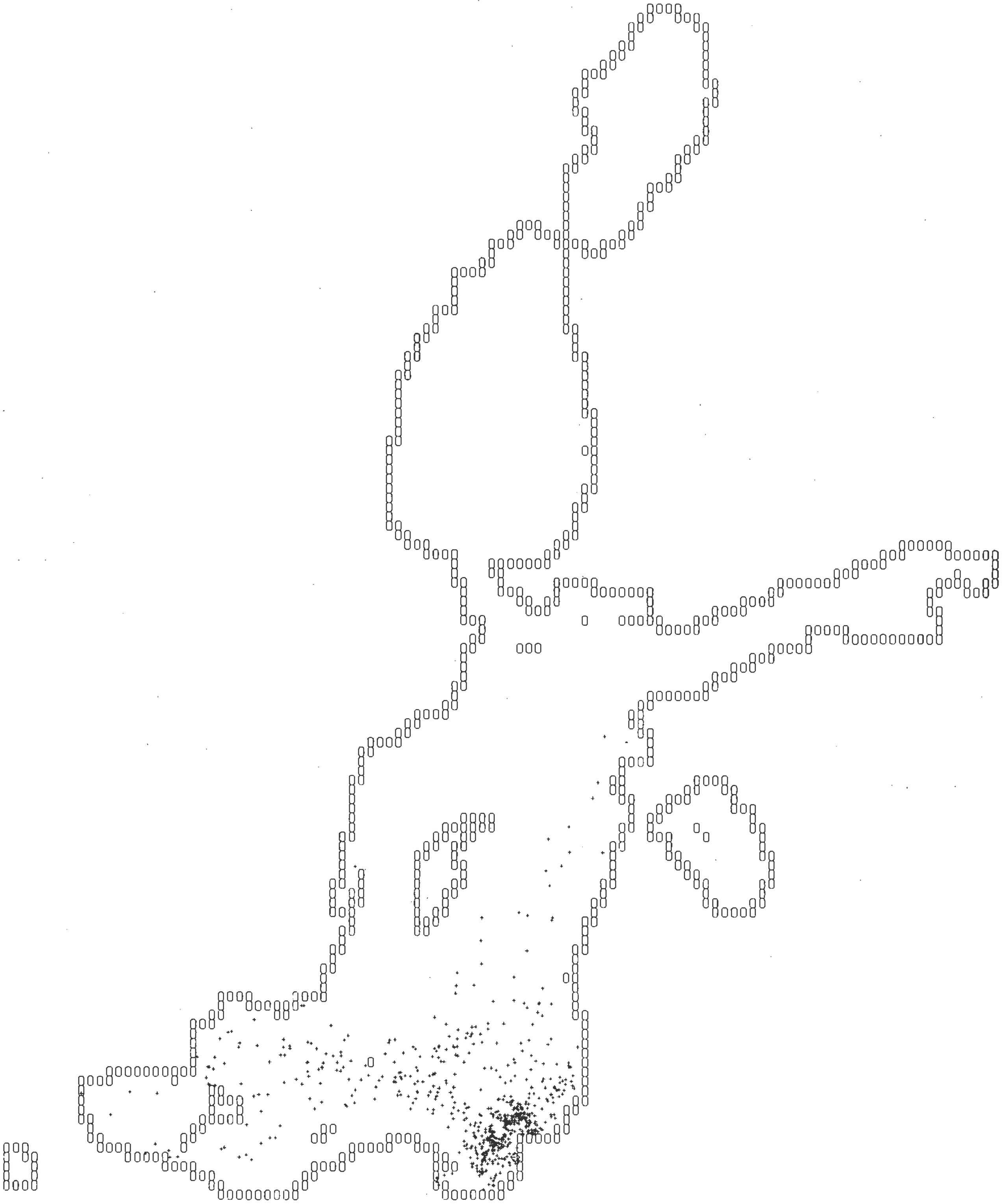


Outlet: Gulf of Gdansk. Particle distribution in layer 2 (5-10 m) after summer, 16 % of total number.

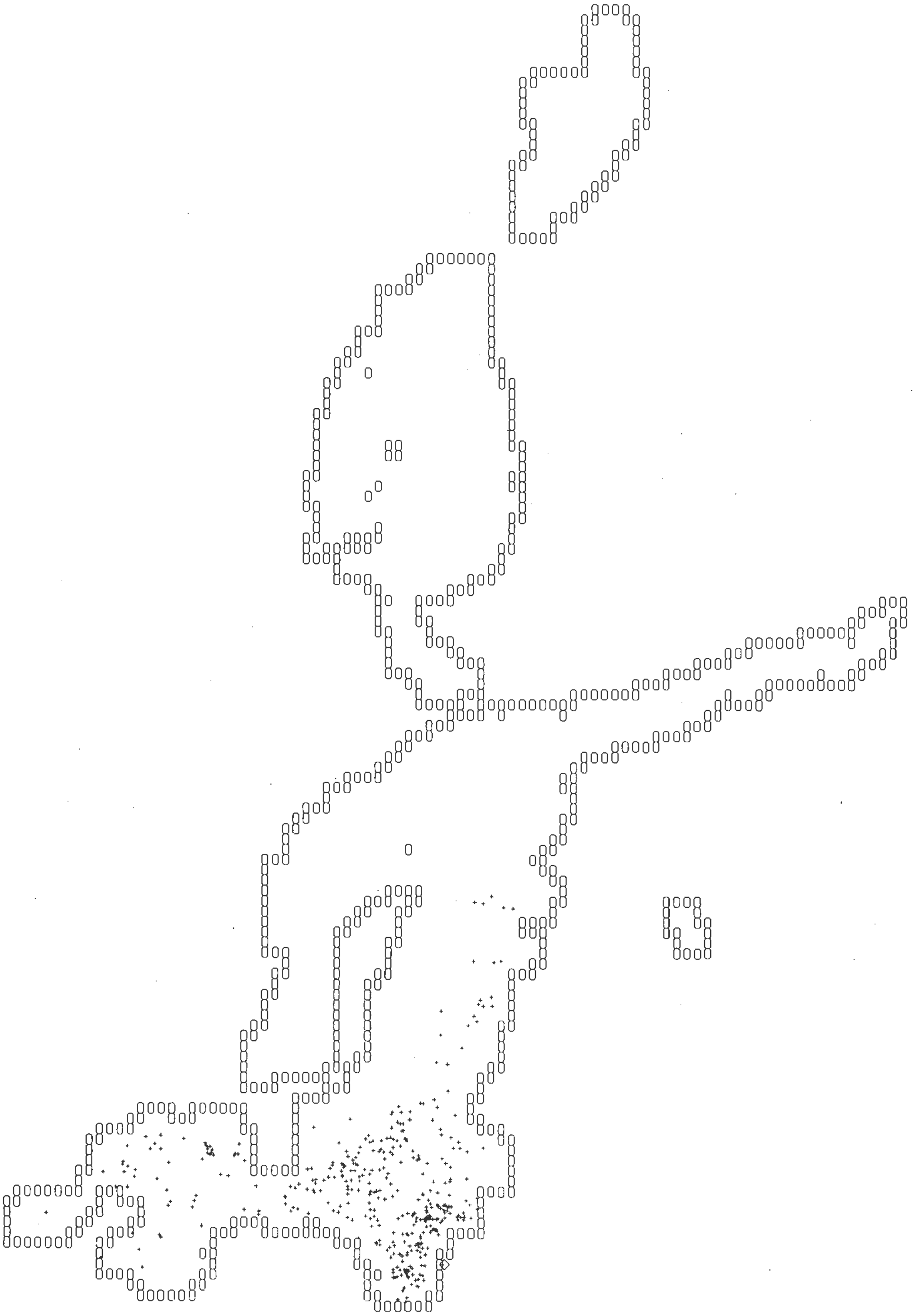


Outlet: Gulf of Gdansk. Particle distribution in layer 3 (10-20 m) after summer, 32 % of total number.

Appendix 44

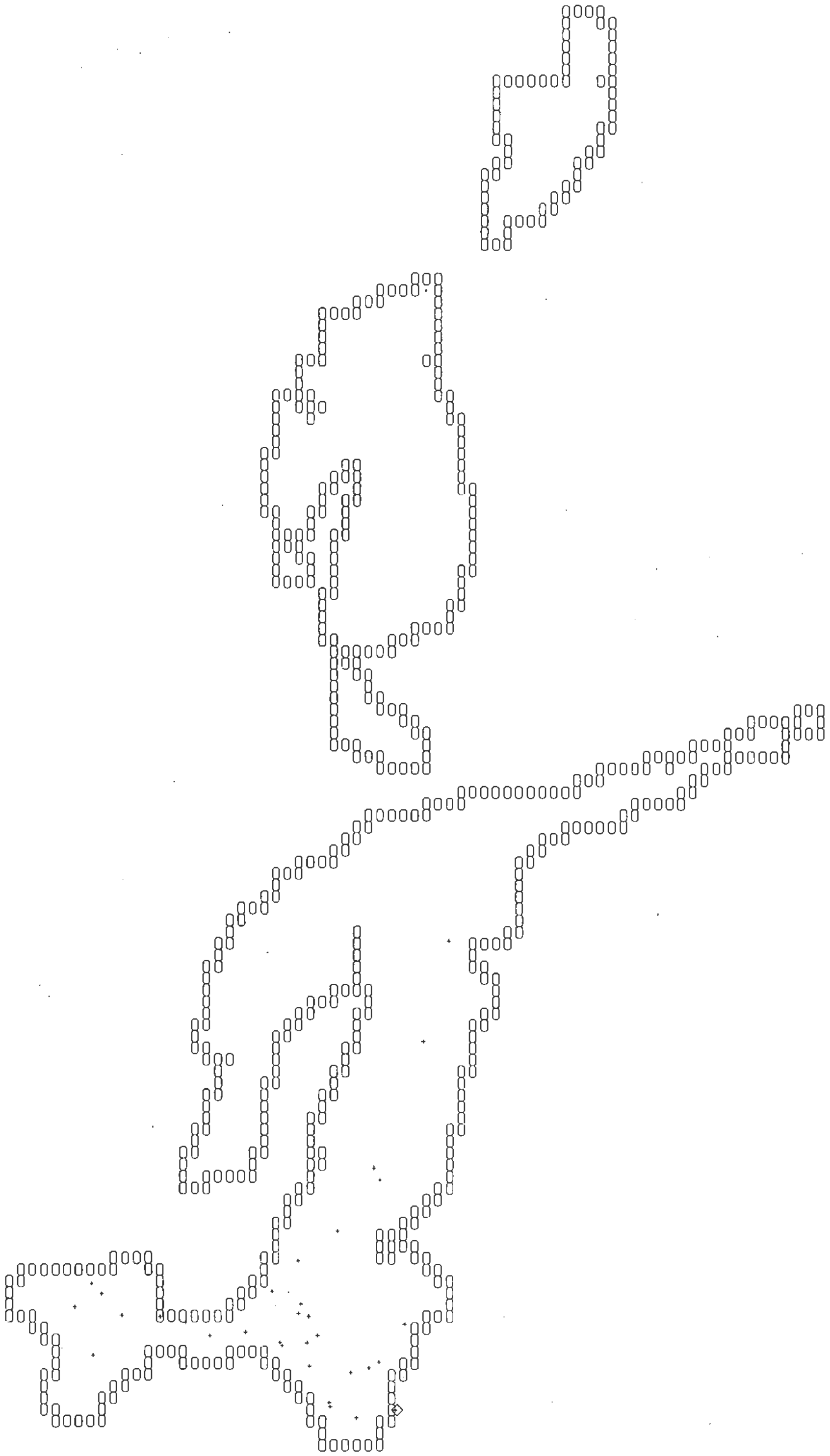


Outlet: Gulf of Gdansk. Particle distribution in layer 4 20-40 m) after summer, 21 % of total number.



Outlet: Gulf of Gdansk. Particle distribution in layer 5 (40-60 m) after summer, 13 % of total number.

Appendix 46



Outlet: Gulf of Gdansk. Particle distribution in layer 6 (60 m to bottom) after summer, 1 % of total number.

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