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Visualization of Model Results
and Field Observations in
Irregular Coastal Regions.
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Next Steps: *These results will be disseminated to the appropriate persons making the decisions on how best to manage the coastal zone on Lake Ontario.*

Visualization of Model Results and Field Observations in Irregular Coastal Regions

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Accurate simulations of the circulation and transport of material substance in the coastal zones of the Great Lakes are needed to assess the impacts of such shoreline developments as drinking water intakes and sewage outfalls and diversions on water quality. It is almost impossible for the coastal modeller to develop or apply three-dimensional fluid dynamics models without having access to good visualization tools, which are a necessary step before model performance can be evaluated. The visualization package with rendering ability, Iris Explorer, has been used in a study of coastal exchange flow between Hamilton Harbour and Lake Ontario. Three-dimensional irregularly gridded output of coastal models is difficult to handle computationally. Novel extensions of the software written to visualize irregular three-dimensional and time-dependent data either from finite element models or from arrays of field instruments are described. A number of examples are provided which illustrate the benefits of advanced visualization methods and computer animation in interpreting three-dimensional mathematical model output and of the employment of these display tools in validating the models with extensive collections of field data.
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Keywords: visualization; animation; finite element model; irregular data; Hamilton Harbour; Lake Ontario

Introduction

The need for assessing the impacts of development on water quality on the coastal zones of large lakes has led to the formulation of mathematical models and the collection of field data for evaluating their performance. The data sets generated by three-dimensional (3-D) model output and extensive field observations in the coastal zone can be so large and complex that standard presentation software is too cumbersome. It is difficult to examine the underlying physical processes with conventional software. This shortcoming has given rise to 3-D data visualization and animation techniques that facilitate the absorption of information contained in these data sets by the coastal modeller. A commercially available programme Iris Explorer which has been used in the case of irregular regions, does not satisfy all the requirements of the coastal modeller dealing with combinations of vector and scalar data. The purpose of this paper is to describe how this commercially based visualization and animation programme has been extended for the requirements of the coastal zone of a large lake and to

demonstrate how the comparison of model output and field data can be facilitated through animations.

Although many coastal modellers employ advanced data display methods in their studies, the literature on visualization and animation techniques in the coastal zone is scant. Bedford et al. (1990) describe software for animation and visualization of model results and introduced the potentially useful concept of stereographic animations. Yen et al. (1992) provide examples of temperature distributions on various vertical slices through a 3-D model of Lake Erie and some references to early work on visualization and animation of model results of the lake. King et al. (1996) present a useful summary of various display strategies for displaying coastal model output using the Data Explorer visualization software. Rennie and Hamrick (1992) discuss the comparison of field data to data extracted from 3-D models also employing proprietary software. One of the goals of this study is to contribute to the literature on data visualization in coastal zones.

Study description

The study site is located at the western extremity of one of the North American Great Lakes, Lake Ontario, and was chosen on account of concerns for elevated levels of contaminants in the harbour portion

of the study area and to investigate the impact of a proposed diversion of domestic sewage from the harbour to a nearby part of the lake. The exchange of flow and dissolved constituents between the lake and harbour was studied for that time of the year when stratification is absent by means of mathematical models, (Hamblin, 1998). This study also reviewed the theory and available data appropriate for the stratified period and found that the traditional internal hydraulic theory was inadequate to deal with the highly transient conditions experienced in the study area. Stratified exchange flow under unsteady conditions has been investigated in the laboratory by Helfrich (1995) who showed that exchange can be reduced under unsteady conditions. For this reason, a programme of field data collection was mounted and the previous vertically averaged coastal models were extended to three dimensions.

The shoreline configuration and bathymetry of the study area is shown in a 3-D perspective view, looking from south to north, in Figure 1. As it is difficult to show the scale and orientation of a water body in perspective, these are indicated in the plan view of Figure 2. In order to show bathymetry clearly, the vertical co-ordinate was exaggerated a hundredfold. The important features to note are the relatively shallow western extremity of Lake Ontario, the long (828 m), narrow (88 m) and shallow (10 m) ship canal connecting the lake with Hamilton Harbour (area, 21·8 km^2). As well, the locations of an array of field measurements, both attended and unattended are given. The moored field instrumentation included three acoustic Doppler current profilers, five thermistor chains, six water level gages, two current meters, two meteorological stations and an atmospheric radiation station. Area-wide surveys of temperature and salinity were conducted periodically throughout the 45-day study period starting in early July to ensure stratified conditions.

Model description

Figure 2 shows a plan view of the mesh used in the 3-D finite element model. It consists of 892 nodal points and 1374 triangular elements. The element size is proportional to the square root of depth in regions away from shore or where more detailed resolution is not needed. In discretizing the 3-D domain, we need only to develop a mesh on the 2-D horizontal plane and then to duplicate it along the vertical. The vertical resolution can be easily changed and model variables can also be approximated either linearly (first order elements) or quadraticly (second order element) over an element. Figure 2 also indicates the observation

stations which were used for model input and the locations of the animations to follow. The cluster of small elements in the lake portion of the study area is the site of a proposed sewage outfall.

The finite element model for hydrodynamics is based on the hydrostatic form of the Navier–Stokes equations with a free surface boundary condition and the model of the transport equations being the advection–diffusion equations for temperature and any other needed variables such as salinity. The model follows generally the approach outlined by Janin et al. (1993). The horizontal diffusion terms have been left out of both models for reasons of economy and since numerical methods usually have sufficient numerical diffusion. Additionally, 3-D advection in both models is treated by the Eulerian–Lagrangian method. Vertical eddy coefficients are prescribed according to the K-ε theory (Svensson, 1978). Principal physical phenomena which affect the flow are included. They are, for instance, the influence of the temperature on the density, the wind stress on the free surface, the heat exchange with the atmosphere and the Coriolis force. Variations of the density due to the temperature are taken into account in the momentum equations via the Boussinesq approximation.

The free surface was calculated in the conventional manner by vertical integration of the hydrodynamic model and then introduced into the 3-D model as the surface pressure gradient. Next, the 3-D velocity and temperature fields are obtained from the 3-D models. Every term in the 3-D models is calculated in the sigma co-ordinate system except for baroclinic term which is been solved in a Cartesian or Z co-ordinate system to reduce errors due to the large bottom slopes in the model domain. Sixteen sigma levels with greater resolution near surface and bottom boundaries were used. Initial conditions were interpolated from the field temperatures measured at the locations shown in Figure 2 and indicated by the pink coloured stations. The boundary conditions on the outer open boundary are driven by the measured free surface and temperature (measured locations are shown in Figure 2 as white coloured points) and interpolated to the boundary mesh points. Due to lack of measured current information on the outer boundary, velocity data output from the model's previous time step was used to calculate the boundary flux line integral. All other boundaries are solid. The model was started on 5 July 1996 with zero velocity and level free surface at all points. All results visualized in this paper are for period from 24 July to 27 July 1996, as this period is sufficiently far from the startup to allow for model spin up. The time step is 15 s and model was run on a dual PPro PC.

Software modifications for visualization of irregularly gridded 3-D data

The visualization software package that was chosen is based on a different approach from more standard graphical presentation software. In Iris Explorer, the data set to be examined is read in by an appropriate routine referred to as the input module which, in the most cases, is the only module written by the user. Then, the data are manipulated by a series of subroutines or modules until the output or rendering routine is reached. The various modules are laid out on the computer desktop and their interconnections displayed. This ensemble is referred to as a map. The unique feature of rendering is that the 3-D object can be viewed readily from any angle or distance so that it easy to find the optimum viewing position for the data in question. The final step is to capture the display of each model output saved for the purposes of later animation. Iris Explorer is powerful visualization software package which can process both regular and irregular gridded data. However, it offers more options for visualizing regular gridded data than for irregular data. This shortcoming directly affects our ability to display certain data especially vector data. Thus, in the ensuing discussion we focus on how to display both vector and scalar data extracted from the 3-D field. The approach followed is to interpolate 3-D data from the nearest mesh points to an arbitrary plane whose position is chosen by the modeller.

Extracting a 2-D data set from an irregular 3-D space. In coastal studies, most data sets are composed of irregular or unstructured grids, for example, non-uniform finite element meshes as is the case in the present study. It is a challenge for visualization software to handle such random meshes. In order to examine the 3-D finite element model output and field measurement data in detail, we need to be able to interpolate any variable defined on a 3-D mesh onto a randomly orientated plane with any desired resolution.

In Iris Explorer, there are a number of modules for manipulating the 3-D data defined on irregular grids, Unfortunately, the most suitable one, ' SlicePyr ', can only extract one scalar variable from a 3-D irregular data set and furthermore, does not have any means of adjusting either the horizontal or vertical resolution of the extracted variable. For example, the coastal modeller would normally have temperature, salinity and three components of velocity but would be able to display only one of these variables with the supplied software. The coastal modeller would like to be able to display any combination of up to four variables at once. It would be useful to be able to expand the resolution in order to improve the appearance of the

display. This is especially important in the vertical where coastal models often have much poorer resolution than in the horizontal directions. The following will briefly explain how we have adapted Iris Explorer to handle irregularly gridded data.

The Lattice and Pyramid data types are created by Iris Explorer to handle regularly and irregularly gridded data respectively. For the Pyramid data structure, the relation between the different layers of data required to build a pyramidal structure is defined. In finite element data for example, the element grid can be considered as a collection of vertices (points), edges (line), faces (polygons), elements (3-D cells), objects (collections of 3-D elements), assemblies (collections of objects), and so on. These can be fitted together to make an object from faces, bounded by edges, which are in turn delimited by vertices (Silicon Graphics, 1993).

A processing module, ' OrthSlicePyr ', was constructed by choosing the above mentioned pyramidal data type. This module must not only read in the data to be visualized that include the variables at each nodal point, but also nodal locations and the nodal connection list for edges, faces and elements. As well, it has to input a 4×4 transformation matrix which contains information on the rotation and translation of the desired plane of visualization with respect to the co-ordinate system of the 3-D data set. This transformation matrix is computed by the Iris Explorer module, ' TransformGen '. A 3-D object such as a coastal model mesh, is constructed from the above input data. By adjusting the rotation and translation control panels of the module ' TransformGen ', any desired viewing plane can be chosen. The information which characterizes the chosen plane is represented as a 4×4 matrix. In turn, this matrix is sent to the ' OrthSlicePyr ' module. The ' TransformGen ' module does not extract any 2-D data from the 3-D data set, it provides only the rotation and translation information for other module's use. Rotation is always about the origin and translation is post-multiplied onto the rotation matrix, i.e. translation is applied after rotation.

The next step is to find the location of the 2-D viewing plane which should orthogonalize one of the co-ordinate axes. Due to the fact that Iris Explorer constructs the pyramidal data type in a different way in horizontal direction from the vertical direction, the method of finding the intersecting plane is also different. To interpolate data onto the XY-plane (display plane is perpendicular to Z-axis), all that is needed is to find those nodes bracketing the intersecting surface and then to interpolate the variable values at these nodes into the intersecting plane. It is a little more difficult in the case when the chosen plane is vertical (with an orientation perpendicular to the X or

Figure 7 is the same as Figure 6 except without the front spotlight. One of the features of Iris Explorer is that it can emphasize obscured features by the illumination option. The appearance of Figure 6 is much improved over Figure 7. For example, the warmer surface water under conditions similar to those in Figure 4 is evident in Figure 6 exiting from the ship canal flows alongshore in a southerly direction. It is easier to see that currents at depth are much weaker in the lake than in eastern part of the harbour where the exchange flow dominates. The four slices probably provide too much information to be absorbed in an animated display. In the next section model results will be examined on the plane passing through the ship canal.

Animations

Animation 1 shows modelled temperatures and profiles of three dimensional flow at selected positions along a vertical plane passing through the ship canal from the outer boundary to the inner shoreline of the harbour (see Figure 2). Each frame is stepped by 30 min of prototype time. Note that the plane has been rotated in a counterclockwise direction so that the view is to the north-west. For further reference, the major horizontal flow vector of the current scale glyph is directed to the east. The wind speed vector is represented by an single arrow at the top and centre is scaled such that a wind speed of the same size as the current glyph (30 cm s^{-1}) is 6 m s^{-1}.

Large thermal gradients are evident both in the vertical and in the horizontal directions. Horizontal gradients drive a densimetric exchange between the lake and the harbour with cooler lake water intruding into and displacing the deeper layers of the harbour. These intrusions maintain the pronounced vertical stratification found in the harbour. At the surface the warmer harbour water flows out into the lake raising the nearshore surface temperatures there.

The flow vectors show that bidirectional two-layer exchange occurs most of the time but that this circulation is disrupted from time to time by episodes of unidirectional flow in the channel connecting the two water bodies. The currents in the harbour and lake appear to respond rapidly to changes in the wind stress especially at the surface. Not surprisingly in a counterclockwise rotating co-ordinate system, these wind driven surface currents are directed to the right of the wind stress, particularly in the lake. Again, the rapid fluctuations in the flow vectors show how dynamic the system is.

Simulated and observed water levels at the north-eastern end of the ship canal are presented in the panel in the lower left portion of the frame. Water levels are also found to fluctuate. As well, close inspection of the surface reveals a black line which is the zero elevation surface line and may be used as a reference point for water level changes along the cross section.

In the above animation it may be noted that flows are represented by thin white arrows instead of the 3-D vectors used in the snapshots. Because velocities vary so much from frame to frame and the velocity display scale factor should not be changed during an animation, if the three-dimensional vectors were shown, the temperature information in many frames would be totally obscured by the velocity vectors. Using a black background reduces the size of animation file.

Animation 2 compares the temperatures observed at three thermistor chains along the ship canal, each consisting of nine temperature loggers with the modelled temperature output of Animation 1 but in much more detail. The animation time step is also 30 min. The modelled output is interpolated to the thermistor locations. Again, the view is to the north-west with the lake on the right and harbour on the left. While there is reasonable correspondence between the model and observations with three layers, a surface mixed layer, a thermocline region and a bottom layer, in general, the modelled thermocline layer is somewhat thinner than the observed. Both panels demonstrate a persistent tilt of the isothermal surfaces upwards towards the lake, in agreement with hydraulic theory. Oddly, the observations appear to be more variable in time with the tilt breaking down episodically while the tilt is more stable in the model. The reason for this difference is not known but it could be that the model is slightly overdamped despite the neglect of horizontal friction or vertical advection could be too weak in the model.

Discussion and conclusions

Due to the relatively severe restrictions on the file size, it is possible to present only a few short animations of limited resolution herein. The field of view and the colour definition of these examples is much poorer than on the CRT display available to the modeller. Despite these limitations we hope that the usefulness of animation and visualization techniques in handling the massive data sets collected in coastal observational and modelling studies has been demonstrated. Unfortunately, publishing limitations do not permit a demonstration of 2-D particle tracking methods. As Iris Explorer lacks the capability of

Y-axes), for example, when the plane is parallel to the XZ-plane. We must first find out all those elements that the cutting plane intersects. From the nodal connection list, those nodal connections passing through the cutting face can be found and their linear equations established. By substituting the Y-value of cutting plane into those linear equations, the X,Y and Z co-ordinates of all intersecting points with the cutting plane can be calculated. Linear interpolation was used to interpolate all co-ordinates and variables. In order to control the horizontal and vertical resolution of any variable displayed the distance between the two most widely separated points in the horizontal and vertical directions must be found.

Other modules developed. In Iris Explorer, the module 'WriteMovie' can be used to write the 3-D image in the previously discussed render window into an animation file. The problem with this module, as far as it has been experienced by the authors, is that it does not release the memory properly, so that when the image data set is too big either because the render window is too large or too many image sequences have been written into the animation file, the random access memory will be filled up and consequently, the whole map will be frozen. This problem was solved by writing an image capture module based on very simple screen capture commands. One point that ought to be kept in mind is that in order to synchronize the capture module with the render window care must be taken to capture the latest updated image in the render window and not a previous image.

Another module which had to be written for animation purposes displays a clock and date for every image frame. This module can input date and time information at any location in the render window, and can start from any arbitrary time and advance at any desired time interval. All modules we developed are written in the C language, however, Iris Explorer also allows use of the Fortran language.

It is noteworthy that Iris Explorer also permits visualization of flow fields by particle tracking. King *et al.* (1996) state that this is a particularly powerful method of conveying flow results to non specialists. Although we have successfully created animations using particle tracing publishing limitations do not permit the inclusion of an example in this paper.

Results

Snapshots

The following are some examples in either snapshot or animation format, which illustrate how visualization can help the modeller to understand model output, diagnosis model behaviour and to gain insight into complex natural phenomena.

For verification purposes, there is a need to compare model output with time series of field data at selected horizontal positions. A 2-D image with time on the X-axis and depth on the Z-axis may be the most suitable way to display this kind of data as shown in Figure 3. The colour represents the direction and amplitude of velocity over the measurement depth range from 1 to 9 m. Positive currents flow out of the harbour and negative into the harbour. From this display, it can be seen that both model output and observations show that the outflow is at the surface and inflow at bottom for the most time. This is expected since the main wind force for the surface flow is in the direction from harbour to lake and the bottom force, the baroclinic term, is in the opposite direction due to cooler (denser) bottom water temperatures at the Lake Ontario side tending to flow under the warmer (lighter) harbour water. Occasionally, when the wind force opposes with baroclinic forcing or it predominates over the whole water column, the stratification disappears temporarily which can also be seen in Figure 3. Compared to the observations, the model output tends to have stronger bottom currents, a thinner thermocline and a thicker lower layer. In the future it is hoped to be able to improve the model by increasing bottom friction or by adjusting the vertical eddy velocity.

Currents and temperatures at the surface are displayed in Figure 4 for north-west winds. Surface current strengthens in the downwind direction and reaches much higher speeds than at the 10 m depth shown in Figure 5. Outflows from the harbour to the lake maintain warmer surface temperatures to the south of the ship canal.

As might be expected, Figure 5 shows the corresponding inflow of cold water from the lake into the eastern part of the harbour at a depth of 10 m and how, as might be expected it maintains the stratification there under the action of north-west winds. Interestingly, there is a suggestion of upwelling along the north-western shoreline and anticyclonic circulation at this depth in the lake. As mentioned before the model does not include horizontal diffusion terms, so cold water at the bottom indicates that advection in both models is treated reasonably well.

Figure 6 depicts multiple slices of the 3-D model output which is used to illustrate that we can have any number of unevenly spaced slices by using module 'OrthSlicePry'. Since it is almost impossible to display information in full 3-D, it is useful to use the multislice approach to search for key information.

displaying a transparent object, displaying particle tracing in 3-D is difficult.

A useful feature of the software is that it has the option of highlighting certain features that the modeller may wish to examine by using the light function.

We have shown that combining temperature (density) and flow information in one display is helpful to the modeller in establishing whether the solution obeys the physical principles on which it is based. The next step once the solution is found to be credible physically is to compare it critically to field observations. Similarly, animation and visualization methods are invaluable for the purpose of facilitating the formulation of model improvements. Now that the visualization tools are available we intend to undertake these improvements as the subject of a future study which should bring the agreement between observations and model results closer than in the initial stage reported herein.

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FIGURE 1. Perspective view of the study area, bathymetry and locations of observations. The pink symbols are the boat survey locations. The black (interior) and white (boundary) symbols represent various unattended instruments.
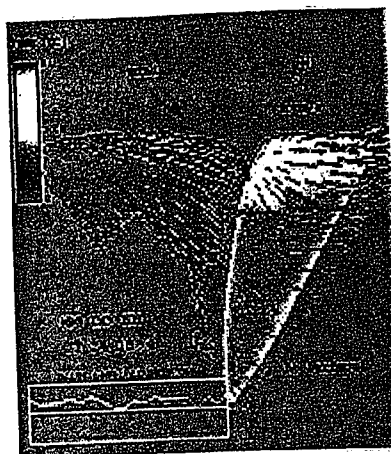

FIGURE 4. Horizontal distribution of modelled currents and temperatures at the surface at 08:24h, 24 July 1996. Current vectors are shown for interior locations only.
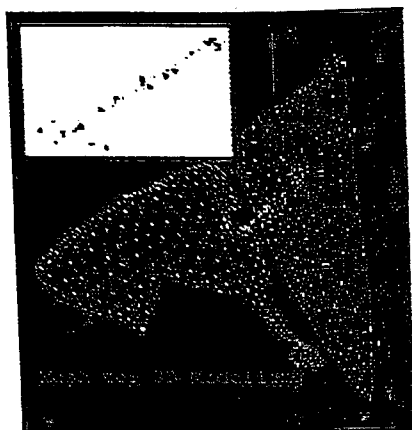

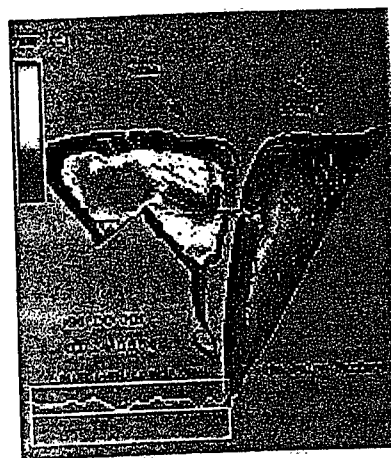FIGURE 2. Finite element mesh and locations of the animations. The coloured symbols are the same as in Figure 1.

FIGURE 5. Same as Figure 4 but at 10 m depth.
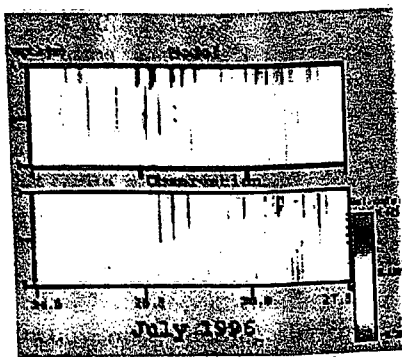
FIGURE 3. Comparison of modelled (upper panel) and observed (lower panel) current profiles at a location on the centreline of the ship canal from 24 to 27 July 1996. Positive currents flow out of the harbour and negative into the harbour. Isotachs are indicated by the colour bar.
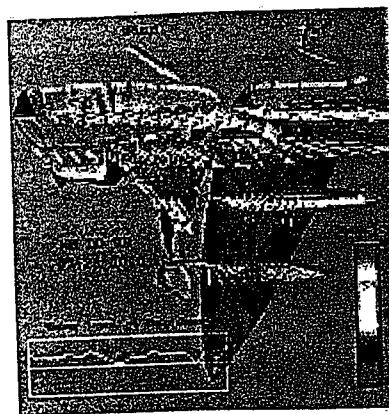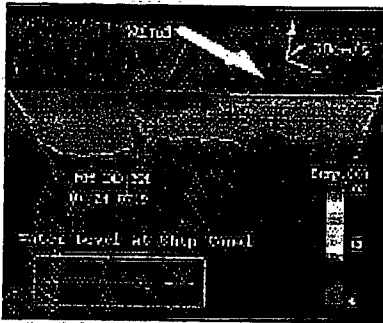

FIGURE 6. A multislice plot of modelled currents (vectors) and temperatures (colour contours) at 08:54h, 24 July 1996 with illumination.

FIGURE 7. Same as Figure 6 but with illumination turned off.

ANIMATION 1. Modelled 3-D current profiles and temperatures along the vertical plane marked A-A' in Figure 2. The wind speed vector at the top centre is 6 m s^{-1} when the same size as the x-axis of the current glyph. The curves in the lower box represent water levels, green, observations and white, modelled. The vertical scale is from -10 to $+10$ cm and the horizontal is time up to the past five days.
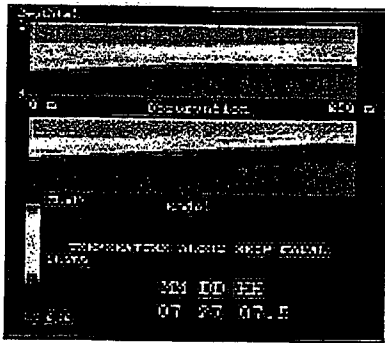
ANIMATION 2. Observed temperature section along ship canal (upper panel) and modelled temperature section (lower panel) along the vertical plane marked B-B' in Figure 2. The harbour is on the left and the lake on the right.

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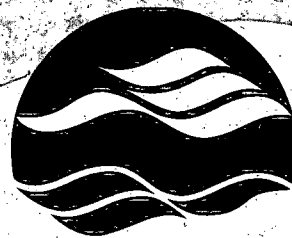
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