The integration of trajectory models and analysis into spill response information systems

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ABSTRACT

The spill response community is engaged in a technological rush towards computer-based, information-synthesis systems. Typically, they are modeled after many successful "incident command" or "command and control" systems that rely on micro- or mini-computer technology that is friendly and graphically oriented. Virtually all of these systems offer spill trajectory modeling components. What is typically lacking in this modeling output is any reliable way to estimate the uncertainty. This means that advice derived from the models is of questionable value, and when integrated into a complex response plan, the propagation of errors could seriously compromise the usefulness of results.

It is shown that no single trajectory model run can provide the necessary information to respond in an optimal, "minimum regret" strategy. However, a well-defined series of model runs used as the basis for trajectory analysis can provide the required information. A discussion of options suggests that the adoption of a minimum standard analysis procedure would significantly improve the ability of integrated response systems to use the predictions of oil distributions.

INTRODUCTION

The use of computer procedures to solve the mass balance distribution equation for oil (equation 1) that is introduced into the environment is generally referred to as "trajectory modeling", or oil "spill trajectory modeling".

$$\frac{\partial c}{\partial t} = -(\bar{V} \bullet \nabla)c + \nabla(k\nabla c) + S(\bar{r},t) \qquad (1)$$

Basically, this equation says that the time rate of change of oil concentration at any location is due to changes caused by currents moving it around, diffusion spreading it out, and sources (spills) that add pollutant at some place and time or sinks (cleanup and weathering) that remove it from consideration. There are a number of available models that have been developed to solve this problem and a recent review is given by Yapa (in press). In addition, a discussion of physical processes and modeling/analysis procedures is given by Galt (1994). For the subject matter that is considered in this paper, it is useful to note that all three of the right-hand side terms are based on model or algorithmic formulations that are independent of this equation and thus enter into the problem in the form of external parameters. These include such formidable tasks as representing the ocean current patterns, upper ocean dynamic mixing processes, and the complex weathering of the oil itself. To complicate the problem even more, all of these processes depend on an accurate forecast of geophysical forcing which includes the weather. These external parameterizations are typically carried out with other models (usually stacked several deep) of variable accuracy and, despite the sensitivity of the final model outcome to certain types of errors (Galt, 1994), there is usually no indication in the trajectory model results that indicate uncertainty. Under these conditions, if the responder is to get any of the uncertainty estimates they must come in the form of a briefing from the trajectory analyst, assuming that he or she actually knew the weaknesses of the external components. Clearly models that are presented as a turn-key, or "black box" are going to be difficult to utilize with confidence at the response level.

What is obvious to the spill response community, but less commonly understood generally, is that the distribution of oil, in and of itself, is not of real concern. The future oil distribution is only useful as data in a stream of information where typically it is necessary to weave together facts, forecasts, and analyses in the context of available response options. It is often useful to think of technical support for spill response as corresponding to developing the answers to a series of questions:

What got spilled?
Where will it go?
Who will it hit?
How can it hurt?
So what?

First, it must be understood what the problem is in terms of the pollutant that got spilled into the environment. Next, it is important to try and estimate where it will go and what it will be like when it gets there. The distribution information developed by answering this second question needs to be passed on as input to determine the resources at risk, which basically defines who would be exposed to the oil. The next question relates to how the various resources will be affected by the presence of given amounts of oil. It is this complexity of data to which the responders must actually respond. The various threats must be categorized within the context of available resources and realistic time constraints. Context is critical in using any of the information that is developed throughout this chain of investigation. A great deal of experience gained in artificial intelligence research and in the use of expert systems has shown that information fragments that are taken out of context are likely to be misleading and hard to use reliably (Haugeland, 1985), (Nilsson, 1980). A particularly difficult aspect of using data out of context is that it is next to impossible to evaluate the potential for error propagation. The ultimate user of the information cannot tell how undocumented errors at some stage in the analysis may bias the complex decision logic that is required in solving response problems that depend on technical information spanning many specialties.

The goal of many decision support systems that are under development is to electronically string together all of the information developed by various technical team members so that responders can have instant access to synthesized data and possibly "expert recommendations". For this to be successful, the technical teams that supply the component pieces of information must provide a broader range of data so that uncertainty and context can be passed along and factored into the information synthesis process. The remainder of this paper will consider how trajectory modeling and analysis procedures can be used in decision support systems.

MODEL UNCERTAINTY AND MINIMUM REGRET RESPONSE STRATEGY

Given all the pieces and components that go into trajectory analysis, the ultimate usefulness of the information will depend on how relevant the advice that is generated is to the actual response. It is clear that more than just trajectory models, oceanography and meteorology are required for successful trajectory analysis support. In addition, it is very important to understand operations in an environment that is initially data sparse, and driven by truly phenomenal pressures to respond immediately. Fragments of information that are available may have high uncertainty and any projections into the future, with regard to forecasted environmental conditions or the arrival of needed response equipment will also be uncertain. In trying to understand how to best apply the information that is available to develop productive spill response actions and at the same time not be misled by the possible inaccuracies it is relevant to consider some options that are derived from studies of game theory (Dresher, 1961), (Operations Analysis Study Group, 1977). In any particular game where chance plays a part, the player can take all of the information available and try and respond to achieve a "maximum win". This would provide the best chance of maximizing the return relative to their investment. An alternate, and generally different, game strategy is more appropriate if the player is protecting very high-value resources. In this case the player would attempt to "minimize regret" rather then "maximize win".

In spill response, the inherent uncertainties in understanding the spill situation and its potential to unfold into the future suggest that trajectory analysis should be aimed at supporting a "minimum regret" rather than a "maximum win" strategy. To put this into context a "maximum win" strategy would be one where the very best estimates of winds, currents, and initial distribution of pollutants were collected and the resulting forecast would be taken as "the" threat that needs to be responded to. This is where a trajectory model, or analyst, would "give it their best shot" and come up with a most probable scenario. This is, in fact, what most oil spill modelers and builders of automated decision support systems seem to think they want. A "minimum regret" strategy, on the other hand, would use whatever analysis techniques are available to investigate the sensitivity of various estimates of errors in the input data and explore the implications of alternate, plausible scenarios in the geophysical forcing functions. For example, what would be the significance of an atmospheric frontal passage arriving six hours before the forecasted time of arrival? Or, if the coastal current is known to reverse this time of year what would be the consequences of such a reversal on the planned response options? Clearly, to carry out this type of analysis, the modeler must have some understanding about the capabilities of the models and, in addition, must know what the models cannot provide. This is obviously a more difficult task, but once done, it can develop briefing material that can provide response organizations with a "best guess" and at the same time cover alternate possibilities that might present a significant threat. The major difference between these approaches is that the second one can identify less likely, but extremely dangerous or expensive, scenarios that may require the development of alternate protection strategies.

ALTERNATE MODEL USE PROCEDURES

The next problem to consider is how to use trajectory modeling techniques to develop the information sets that are needed to support a "minimum regret" trajectory analysis for use in an integrated spill response information system. At the core of any trajectory modeling procedures is a series of computational algorithms or numerical look-ups into databases. Trajectory models must be able to handle variable scale resolution because most significant spills start off small, or localized, in space and become large. To handle this numerically, all major spill models have gone to a mixed Eulerian/Lagrangian formulation where the oil is represented as a number of particles embedded in a series of vector fields that represent the advective processes due to winds and currents. Each of these particles represents some amount of oil and can have associated with it attributes that describe its age, type, weathering state, and beached status. This type of formulation has proven extremely powerful and is free from the numerical dispersion that would be a problem from small sources in a purely Eulerian formulation. There are some limiting facets of this approach. The first is that, as the particles move and spread, the spacing between them may become large and for any particular area, the oil may be represented by a small number of particles. Such distributions are clearly patchy and interpretation may be difficult. A second difficulty of representing oil distributions as clusters of particles is that oil density data is not directly available. In order for trajectory routines to provide quality graphical data for use in an integrated response system, the presentations must be compact, in the sense that the information density must be high and compressed into a limited display. One of the clear lessons from years of experience at trying to present trajectory analysis results is that, if the information takes a number of pages, some of those will become separated. Usually, the graphics are saved, the caveats are discarded, and the remainder is easily misinterpreted with potentially disappointing results.

When most people think of trajectory modeling they assume that the modeling activity will forecast the future distribution of the oil based on its initial or present distribution. In this sense, the models are used in much the same way as a standard weather forecast model. In this mode of operation, the distribution of Lagrangian particles of oil represents actual oil density and the number of particles per unit area represent a measure of the local oil concentration $\left(kg / m^2\right)$.

Another mode of running trajectory models is to use statistical distributions of geophysical forcing and parametric inputs. In this case, it is usual for each Lagrangian particle to be subject to a statistically different realization of the forcing. Each of the particles can be thought of as the centroid of an independent spill. In this way, the future distribution of an ensemble of spills can be represented. Although this mode of trajectory modeling will result in a scatter of Lagrangian particles that may appear very much like an example of a forecast, the interpretation is quite different. In this case, the distribution is not related to oil concentration, but rather to the probability that any spill will result in oil moving into a unit area. The obvious advantage of using models in statistical mode is that some information can be developed about expected variability and it is possible to explore potential situation spaces. There are a variety of different statistical distributions that could be used in this mode. One more or less standard choice would formulate the runs with climatological representations of the environmental data, using the model output to span potential scenarios for contingency planning or an extended outlook forecast. Another possibility would be to use forecasted environmental data with statistical variations representing the uncertainty in the forecasts or the models algorithmic processes. In this case, the model output would give a statistical representation of the model uncertainty or an expected error bound on the forecast. This would be equivalent to using Monte Carlo techniques to carry out sensitivity analysis on the components of the trajectory analysis and, as such, is critical to formulating "minimum regret" trajectory response information.

A third mode of model formulation is to focus attention on a particular high-value resource or target area. In this case, the modeling question turns out to be: "Where could oil come from such that it will arrive at the high value target?" There are two different but statistically equivalent ways of formulating this problem. The first, which is referred to as receptor mode modeling (Gilbert, 1983), initiates a spill at the receptor site and runs all the advective and time-dependent processes in reverse. The oil is seen to spread in reverse time and after the process is repeated for a statistical ensemble of particles, the results are presented in the form of a joint-probability distribution (threat map) and a time-of-travel map. This technique is an extremely useful planning tool in that it defines where reconnaissance should be carried out to determine whether there is a threat and how long responders would have to get ready if a threat developed. A statistically equivalent formulation has been used by the US. Minerals Management Service (Smith et. al., 1982) which uses a predefined oil source point and then determines the forward-in-time, statistical probability of various target, or receptor sites being hit. If the receptor mode analysis is summed over all receptor sites and the forward model is summed over all source sites the statistical results should be the same.

THIESSEN ANALYSIS OF LAGRANGIAN PARTICLE DISTRIBUTIONS

The use of Lagrangian particles to represent oil distributions is computationally useful and numerically stable. This technique has found its way into virtually all of the commonly used oil trajectory models. This means that the direct output from these models will represent the oil distribution as something that appears like a swarm of bees. This format results in a useful graphic that gives a general idea of the extent and approximate density of the oil, but does not give the user a real quantitative feeling for the distribution. In cases such as investigating the impact of oil on sensitive coastal resources, estimates of actual oil concentration are desirable.

There are several ways to go from a Lagrangian point distribution to a Eulerian density distribution (Diggle, 1983) and many models provide for some mechanism to do this as part of a post-processor step that displays the data. The simplest way to do this is to divide the domain into cells and count the number of particles in each cell, then present the results as a rastor map. This is a very fast routine but has the weakness that it becomes patchy around the fringes and answers will depend, to some extent, on cell size.

An alternate approach is to partition the point distribution domain into Thiessen polygons (Green and Sibson, 1978). The basic idea is to partition the plane into a space-filling set of polygons, such that each polygon is the locus of points that are nearest neighbors to a particular Lagrangian particle. This results in a "turtle back" pattern, where the sides of polygons are made up of lines that are the perpendicular bisectors of the lines' connection points (Figure 1a). The area of the Thiessen polygon that surrounds a particle represents the part of the plane closer to that point than any other and can be thought of as the area belonging to that point. Dividing the mass of the oil represented by the Lagrangian particle by the area of the Thiessen polygon gives an Eulerian density value $\left(kg / m^2\right)$. The second step in the Thiessen analysis is to create a bound for the cluster of Lagrangian points. This is simply an ordered set of points that surrounds the remaining points in the cluster (Figure 1b). The third step in the analysis is to develop a Delaunay triangular mesh where the Lagrangian points become the vertices of a set of space-filling triangles (Figure 1c). Finally, taking the Eulerian density data as "z-values", the triangular mesh can be used to develop a geodesic dome fit to density and this can be contoured (Figure 1d).

Thiessen analysis of Lagrangian point data has the advantage that it provides resolution that is based on the actual size of the distribution and follows the pollutant as it moves and spreads through the domain. It is computationally more difficult than a grid/rastor system, but coded as an a $N^{3/2}$ routine, it can run on a few thousand points, in a few tens of seconds. This is well within practical limits. It should once again be remembered that when any scheme is used to calculate Eulerian density data from Lagrangian particle distributions, the result will represent something entirely different, depending on whether the model is being run as a forecast, or in a statistical mode.

PROPOSED TRAJECTORY ANALYSIS STANDARD

Spill response personnel are required to make decisions based on complex, sparse information sets. The resources that must be protected are often valuable. Under these conditions a "minimum regret" strategy should be used as part of the decision logic. It also seems likely that decision support systems will continue to advance and are likely to become standard tools in the response arsenal. The question then becomes: How can trajectory modeling results be analyzed and packaged into these systems so that the information content provides enough guidance for useful decisions to be made? During major spills, response models are usually run and rerun multiple times, in forecast, statistical, and receptor modes. Statistical exploration of possible scenarios may represent hundreds of individual model runs. It is obvious that all of this information should not clutter up the decision support system and that it should be synthesized into a more compact form. On the other hand, uncertainty and the span of statistically realistic variability in the geophysical forcing must be represented so that less probable, but dangerous or expensive, threats can be identified. With this much as guidance we can consider what a minimum set trajectory analysis components should include.

By what could be considered unanimous request, any trajectory analysis support should include a most probable forecast. Everyone wants and needs to know where the spill is likely to go. There are a numerous ways to present the forecasted distribution and NOAA/HAZMAT has been experimenting with a variety of forms. Based on techniques that were originally presented by the Alaska Department of Natural Resources (1993), a map with both the Lagrangian point distribution and contoured Eulerian density values has been developed (Figure 2a). Based on observational experience the contour values should correspond to visual recognition levels that are typically on a multiplicative scale and vary throughout the duration of the spill. Experimental values that appear useful are 1%, 4%, and 16% of the maximum predicted values. These more or less correspond to what a trained observer would call light, medium, and heavy concentration areas. This particular map product is just model output and, by the standards that are discussed above, does not represent any trajectory analysis. If this was all that was included in the decision support system it would be potentially misleading and certainly could not support "minimum regret" response planning.

The second component in the minimum trajectory analysis package for decision support must provide some estimate of the uncertainty that surrounds the forecast. To develop this the standard trajectory models need to be reconfigured to run Monte Carlo variability on all of the input parameters that correspond to their expected uncertainty. For example, if the current patterns are expected to be correct to within 30% in their speed, then a corresponding variability should be statistically applied to their values. Likewise, uncertainty in weather forecasts such as wind speed, direction, and time of arrival of frontal passages should also be statistically represented. A statistical run of the model in this configuration will present a probabilistic distribution that spans the expected variability of geophysical situation space relative to the reliability of the particular model, and the particular forecasted conditions (Figure 2b). The output from this model needs to be combined with the presentation from the forecast model run. One option would be to contour the probability distribution and present this as a separate map. Considering the necessity to synthesize information and resist the tendency to create separate pages of error analysis data, an alternate presentation would be to simply overlay the bound of the statistical run over the previously calculated forecast map display. This now gives us a single graphic product that presents the best estimate of where the oil will be at some future time and the bound of potential errors. That is: 1) Here is where we think it will be, and 2) here is how likely we are to be wrong.

For any significant spill, the demand for future estimates of where the pollutant will be are certain to extend beyond the time periods when reliable forecast information is available. What is needed is an extended outlook to give a statistical indication of where future threats may develop. This requires something that is approximated by a forward version of the receptor mode formulation. In particular, the statistical model that was used to develop the error bound for the forecast can be extended in time. The Monte Carlo statistics that initially represented uncertainty in the forecast, or parametric, model input data must smoothly transition to standard climatological values as model times extend beyond forecast time scales. The output from these extended model runs would be a simple sum of the number of Lagrangian particles that hit high-value resource areas. This translates directly into a qualitative measure of the probability of receptor sites being impacted at the extended model times. The actual graphic output would be in the form of shaded receptor areas that have percent probability of future threat printed within or next to them (Figure 2c). In most cases, this output could be overlaid on the same map that has been used for the forecast and error analysis presentation.

Figure 2d represents a single-page trajectory analysis presentation that includes the best-guess forecast, an error bound that indicates potential alternate scenarios that should be considered if they represent dangerous possibilities, and an extended outlook of the potential threat to high-value receptor sites. The data to develop this information can be obtained by two correctly configured trajectory runs. The first is a standard forecast, which all response-oriented oil spill trajectory models are designed to do. The second model run requires a statistical representation that requires some non-standard Monte Carlo procedures, but is well within the capabilities of most presently used models. Simple forecast model runs must have the additional analysis support that is required for them to be safely and productively included into response activities.

The NOAA Hazardous Materials Response and Assessment Division has adopted this combination of model runs and analysis as a proposed minimum trajectory analysis standard that can support spill response decision support systems. At present, standard package output is being consumer-tested for drills and the development of planning scenarios. Studies are on going to maximize the information content for color, black and white, and telefax versions of the minimum standard trajectory analysis products. Digital standards for the presentation and distribution of these maps in standard GIS formats is being investigated in cooperation with states that are developing integrated map-based systems.

To forward simple trajectory modeling forecasts into command and control information systems, without the additional analysis that supports "minimum regret" decision-making, is very likely to lead to poor response choices. A simple trajectory model is not enough. The analysis is required. It is critical that trajectory information be passed on in the context of its reliability with the necessary controls to guarantee its usefulness. This crucial need suggests that a minimum trajectory analysis standard should be defined and required in integrated, spill-response information systems.

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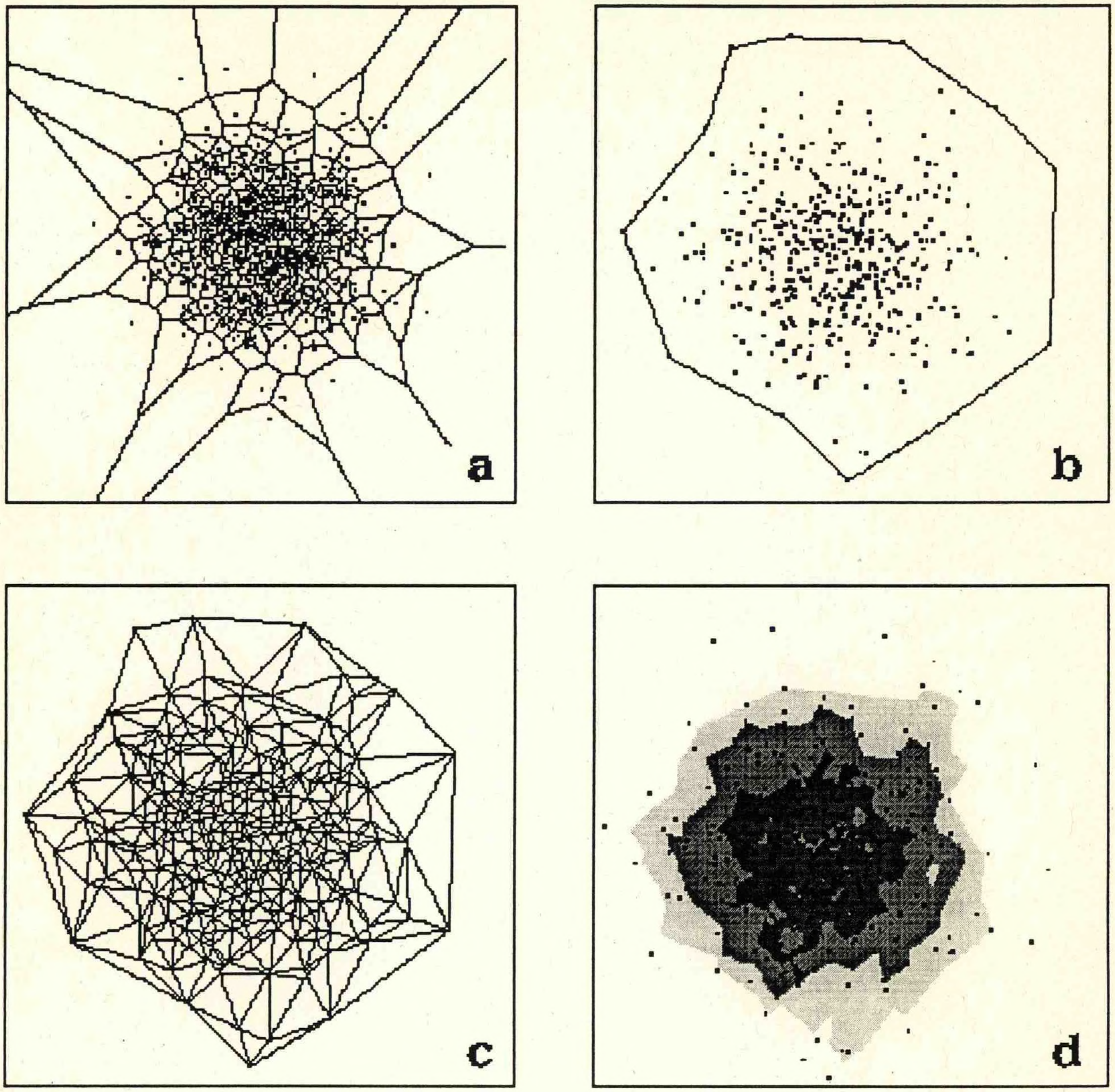
FIGURE CAPTIONS

Figure 1 - (a) Lagrangian particle distribution with Thiessen polygons, (b) boundary of Lagrangian particle distribution, (c) Delaunay triangle mesh with Lagrangian particle distribution as vertices, and (d) Eulerian contours of Lagrangian point density data

Figure 2 - (a) best estimate "forecast" of a future oil distribution shown as Lagrangian particles and contoured Eulerian density values, (b) bound on a statistical distribution of spill scenarios generated using the variability associated with the uncertainty in the forecast, (c) statistical counts in high-value target areas for an extended-outlook statistical analysis as in -b, and (d) composite trajectory analysis including the forecast, uncertainty or potential error analysis, and the probability of threats developing for high-value resources over an extended forecast period.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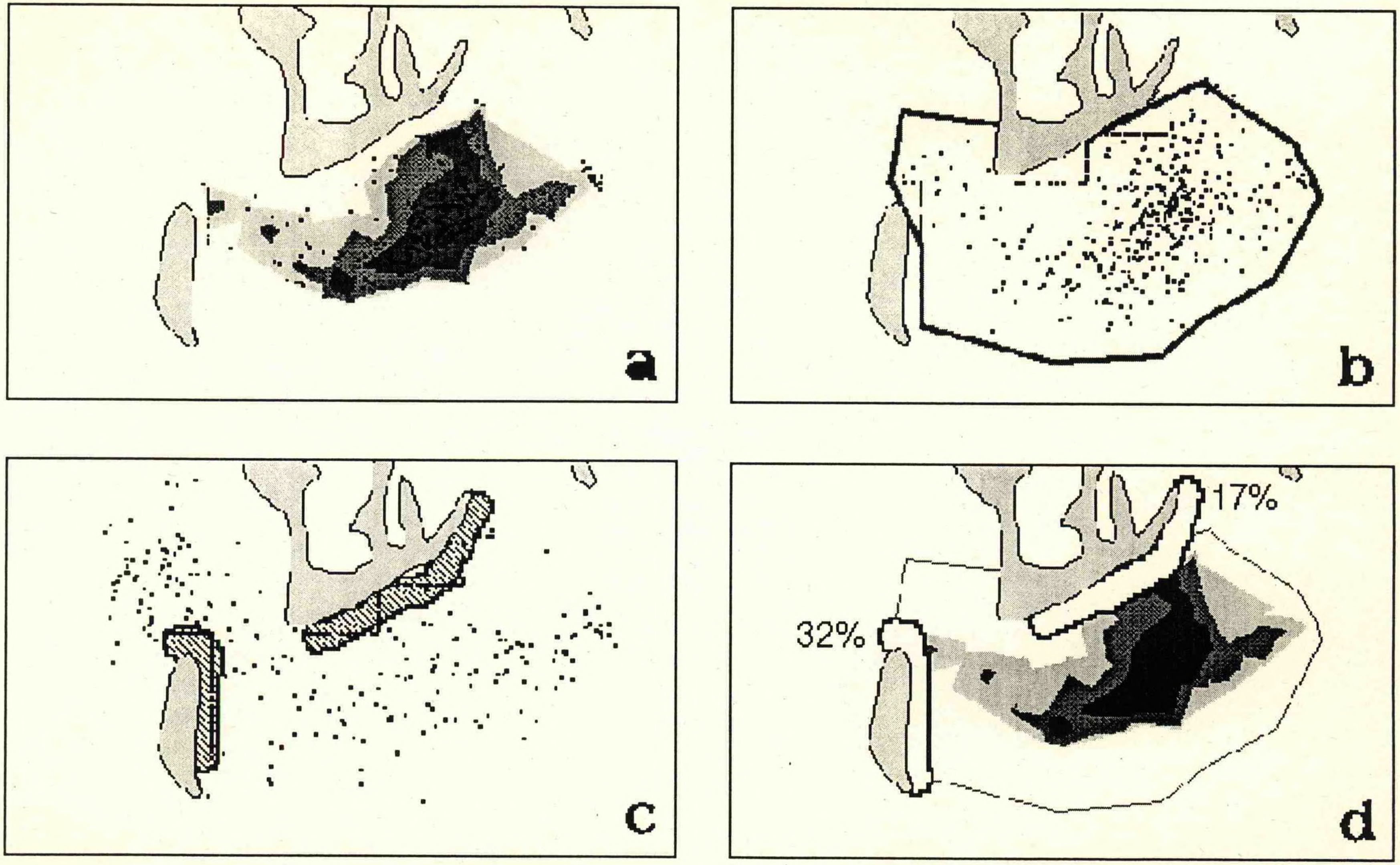
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