Author(s): Li, Yang.
Article Title: Control of spatial discretisation in coastal oil spill modelling
Year of publication: 2007
Citation: Li, Y. (2007) 'Control of spatial discretisation in coastal oil spill modelling' International Journal of Applied Earth Observation and Geoinformation 9 (4) 392-402
Link to published version: http://dx.doi.org/10.1016/j.jag.2007.02.003
DOI: 10.1016/j.jag.2007.02.003

Control of Spatial Discretisation in Coastal Oil Spill Modelling

YANG LI
Centre for Geo-Information Studies,
University of East London, Longbridge Road, Dagenham, Essex RM8 2AS, UK;
e-mail y.li@uel.ac.uk

Abstract. Spatial discretisation plays an important role in many numerical environmental models. This paper studies the control of spatial discretisation in coastal oil spill modelling with a view to assure the quality of modelling outputs for given spatial data inputs. Spatial data analysis techniques are effective for investigating and improving the spatial discretisation in different phases of the modelling. Proposed methods are implemented and tested with experimental models. A new "automatic search" method based on GIS zone design principles is shown to significantly improve discretisation of bathymetric data and hydrodynamic modelling outputs. The concepts and methods developed in the study are expected to have general relevance for a range of applications in numerical environmental modelling.

Keywords: zone design, discretisation, spatial data quality, coastal oil spill modelling

1. Introduction

Spatial discretisation is one effective means of spatial data modelling. Data aggregation or division over space for social or economic modelling has attracted much attention in GIS research (e.g. Longley *et al.*, 1998; Openshaw & Abrahart, 2000). Zone design issues are being studied comprehensively and related techniques have been successfully applied (Martin *et al.*, 2001; Marine, 2003; Flowerdew *et al.,* 2004). One significant outcome is that data structures are well established for social and economic modelling. For example, reporting of British census data conforms to a standard hierarchical structure (i.e. output area, super output area, ward and district) with attached metadata. A range of social and economic studies (such as health, education, crime and development) can then share the same census data as well as the benefit of relevant zone design technology.

For environmental problems, the impact of environmental change also has a spatial dimension. In most environmental simulation modelling, the numerical computation or manipulation has to work with discretised spatial data rather than continuous data or point survey data. Spatial discretisation has therefore been widely used for numerical environmental modelling (e.g. Goodchild *et al.*, 1996; NCGIA, 2000; Brimicombe, 2003).

Through spatial discretisation, a tessellation for numerical modelling is established to regroup spatial data to match specific criteria. From this perspective, the discretisation in numerical environmental modelling should also be regarded as a zone design issue. Environmental models show more diversity and complexity in data structures and computation. Modelling could be very different for water quality, air quality, soil pollution, flooding, landslide, soil degradation and so on. Consequently, there are a range of different spatial discretisation procedures in environmental modelling (Castro *et al.*, 2001; Pinder 2002; Strutwolf & Britz**,** 2003). It raises a number of interesting issues as well as demand for proper study.

In coastal oil spill modelling, spatial discretisation is the basis for numerical computation and simulation. Discretisation is used to construct the modelling mesh for Finite Element or Finite Differential computation in hydrodynamic modelling. It will also generate the modelling grid for trajectory and fate simulations. Current *de facto* industry procedures for such discretisations are pragmatic. However in many cases, they lack quality control and depend on the modeller's experience. With spatial analysis techniques, this paper studies the control of spatial discretisation in coastal oil spill modelling with a view to assuring the quality of modelling outputs for given spatial data inputs. The study aims to be generally applicable for different coastal oil spill models regardless to their modelling details. It also expects such quality control would be easily implemented without spatial data quality expertise.

The basic structure of coastal oil spill modelling will now be briefly introduced; a more detailed presentation can be found in Li *et al.* (2000). Coastal oil spill modelling is normally regarded as a model system which comprises of a series of sub-models. Although models are scalable for various applications, the basic sub-models are usually: hydrodynamic sub-model, trajectory sub-model and fate sub-models. There are a range of coastal oil spill models using different numerical computation techniques. The principles of some spatial data operations are however similar and play an essential role in the modelling. The hydrodynamic computation is carried over the discretised space with bathymetric and tidal data to simulate the coastal tidal current, sometimes also the mean current. The trajectory simulation, using the output from the hydrodynamic computation, is usually run on a different discretised grid for modelling the transportation and diffusion of spilled oil. And the fate simulations also rely on the discretised grid for shore-line absorption, spread, evaporation and so on. Figure 1 shows the general structure for coastal oil spill modelling in which all inputs, outputs and modelling processes are in fact on different spatial discretisations. Only major inputs, outputs and sub-models are displayed here (based on Foreman, 1990; Garcia-Martinez & Brebbia, 1998; Mira Digital, 2001; White, 2005). In coastal oil spill models, various modelling processes and factors will inevitably increase the complexity of analyses as well as the generality of the conclusions.

[*Figure 1 about here*]

This paper describes two sets of experiments on different aspects of discretisation for coastal oil spill modelling. The first (the preliminary study) considers the effect of grid size on coastal oil spill trajectory sub-modelling and is largely a qualitative analysis of the outputs that nevertheless highlights the importance of appropriate control of the discretisation. The second (the quantitative study) is a more complex set of experiments which tests a new method of discretisation for Finite Element computation in hydrodynamic sub-modelling against the *de facto* industry standard approach.

2. Preliminary study for controlling spatial discretisation in trajectory sub-modelling

Although the coastal oil spill model is a complex system of multiple sub-models with multiple inputs, a user's attention is usually focused on the final outputs which are used to support the response operation, planning or assessment. Thus many data quality problems are often only noticed for the first time from the final outputs. In this paper, it is also relatively easy to introduce the idea of data quality control of discretisation from the perspective of final outputs. The trajectory simulation is one such output and has an important role in decision-making and other tangible results. This study therefore begins with the discretisation in trajectory sub-modelling.

Within this sub-model, the water area where an oil spill scenario is to be simulated is usually spatially discretised into a grid mesh where each grid cell is a small square. The spilled oil is normally represented by discrete droplets. The number of oil droplets is then assigned as one attribute of the grid cell where an equivalent amount of spilled oil is to be released into the environment. Through spatial discretisation, the oil spill process can then be modelled numerically (see, for example, Garcia-Martinez & Brebbia, 1998). Figure 2 illustrates an oil spill grid for numerical trajectory simulation. The oil droplets can move across the water cells in response to currents, get stuck on the shoreline cells, be stopped by land cells, be lost due to weathering processes or leaving the study area by moving across the outer sea boundary.

[*Figure 2 about here*]

The spatial discretisation in the trajectory sub-modelling is affected by various factors such as the scale of oil spill accidents, the area of water under study, the speed of currents, the time step of computation, the geographic features and so on. Although calibration may be undertaken sometimes, the size of grid cell is normally determined subjectively by experience. This paper suggests the use of sensitivity analysis (Saltelli *et al*., 2000) for determining the appropriate cell size with the consideration of oil spill behaviour. Sensitivity analysis could efficiently explore the relation between model output and parameter setting without going to the details of modelling process. It should be helpful for controlling spatial discretisation in trajectory modelling which involve too many factors and too many elements. In the experiment, the cell size is set at different levels and trajectory simulations are run on these grids. In order to preserve experimental simplicity, it has been assumed that all of the oil generated in the spill entered the trajectory model instantaneously at the beginning of the run and at one location. This location is marked by a cross in Figure 2. From progressive experimentation, it can be found that for this case the trajectory simulation is sensitive to cell sizes in the range of 100m to 400m (Figures 3 to 5.

[*Figure 3 about here*]

[*Figure 4 about here*]

[*Figure 5 about here*]

Consider the results depicted in terms of the oil spill behaviour. The simulated trajectory on the 400m grid in Figure 5(a) has become a linear streak and in Figure 5(c) has broken up into a number of widely separated portions, both of which do not accord with the observed reality of oil slick behaviour (Mira Digital, 2001). The 400m discretisation is therefore considered to be too large and hides finer transportation and diffusion processes. It is also noticeable that the area of oil spill trajectory on the 400m grid is larger than those simulated using the smaller grid sizes. This is not simply because the area of 400m grid cell is bigger; larger grid cells have a tendency to exaggerate the movement of transportation in whole grid increments when the actual distance travelled may be just over half the size of any cell. For the same reason, the trajectory will move relatively faster and touch the shoreline earlier. Thus the use of a discretisation that is too large will mislead decision-makers formulating a response. Again, the simulated trajectory on a 100m grid (Figure 3) doesn't accord well with the observed distribution of oil density in a slick which should be higher at the centre of the slick and gradually decrease to the edge of the slick. There also seems to be insufficient dispersion in Figure 3(a) – the slick remains too compact. On the other hand, inspection of Figure 3(b) shows that the slick has become finely scatted rather than remaining as a coherent slick of oil. Again, this is not normal observed oil spill behaviour. The reason for these problems arising with the 100m grid is because cell is too small and thus has a tendency to amplify the diffusivity.. In the other words, the oil droplets may move across the grid due to very small turbulences from flow and wind speed. The trajectory on the 200m grid in Figure 4 has less of the defaults attributed to the other two: the slick is not scatted and maintains reasonable shape, the density distribution also reflects the observed spreading behaviour of oil slicks. On balance then, the 200m grid is regarded as an appropriate grid size *in this specific case* for simulating the trajectory of the oil spill.

The above experiment shows that this simple sensitivity test is effective for controlling the spatial discretisation in trajectory sub-modelling. For the same trajectory model, the appropriate size of grid cell may need to be varied according to geographic location (shape of bathymetry and shore line, tidal conditions) or oil spill scenario. Such tests should often be undertaken to assure the quality of model output. The suggested method is obviously practical for such purposes. Of course, this preliminary study relies heavily on qualitative analysis and professional judgement but is sufficient for illustrating the necessity for such analyses of discretisation in environmental modelling. More quantitative analyses can be planned and carried using more complex designs of sensitivity analysis.

3. Quantitative study for controlling spatial discretisation in hydrodynamic sub-modelling

For a model system such as coastal oil spill modelling, systematic analysis is required for quality effects on cascaded intermediate outputs within the model system and their consequent effects on subsequent sub-models. The hydrodynamic sub-model is essential for any coastal oil spill model and, as it is the first stage of modelling, can have important knock-on impacts on the sub-models that follow. The hydrodynamic sub-model is also more complex than the other sub-models and is therefore methodologically more challenging. This next section of the paper presents a quantitative study for controlling the data quality of spatial discretisation in hydrodynamic sub-modelling.

For the experimental model in this paper, the tidal current simulation is output as four elements: eastward amplitude (Ua), eastward phase-lag (Ug), northward amplitude (Va), northward phase-lag (Vg). The tidal current can then be represented in the following formula:

$$
\begin{aligned}
U(x, t) &= Ua \cos(\omega t - Ug) \\
V(x, t) &= Va \cos(\omega t - Vg) \qquad (1)
\end{aligned}
$$

where U(x,t) is the eastward velocity, V(x,t) is the northward velocity, x is the location, t is the time, ω is the angular frequency.

3.1. Discretisation methods

For numerical computation in hydrodynamic modelling, the bathymetric data should be discretised into a group of spatial elements. The spatial elements are usually triangular for Finite Element method or grid for Finite Differential method (Foreman, 1990). The size of each element varies over space following the Courant criterion. In hydrodynamic modelling, the Courant criterion will assure the stability and accuracy of numerical computation. It couples the size of spatial element and the time step of numerical computation as follows (Molkenthin, 1996):

$$\Delta t < \Delta x \,/\, (|u| + \sqrt{gH}\,) \tag{2}$$

where Δx is the element size, Δt is the time step of computation, $|u|$ is a global fixed constant for the water body being modelled, g is the acceleration of gravity and H is the water depth at the location of relevant element. A too large a time step will cause instability and thus generate inaccurate or misleading results. On the other hand, a too small time step will adversely increase the time for long term simulation; oil spill modelling over relatively large areas would then be intractable with such computational effort. The output of (2) is a series of zones that meet the criterion. In the case of Finite Element method, a Delaunay triangular mesh will be constructed using the central points of each zone and numerical computation will be carried out on this *modelling mesh*. Following this principle, the spatial discretisation for hydrodynamic modelling with Finite Element method can been established. The computational time step in the Finite Element method is fixed for the whole study area and thus from (2) the size of each discretised spatial element should be in direct proportion to the square root of water depth where each spatial element is located. From the point view of spatial data analysis, such a spatial discretisation is in fact the development of a zonal system, in which smaller zones are in shallow water near the shoreline and larger zones are in deep water far away from the shoreline. Could GIS-based zone design techniques be employed to improve the quality of discretisation and hence the quality of modelling?

The function of zone area to water depth is derived from the Courant criterion with which zone design procedure is implemented. Two zone design methods have been tested. One is the *de facto* industry standard (Figure 6(a)) which expands each zone through a “spiral search” around an initial point (Seaconsult, 1998). Thus a first zone will be developed to match the Courant criterion and then second zone will be created next to the first one. The zone system will grow by repeating such expansion until no room is left for creating any more zones that match the Courant criterion. In the process of "spiral search", zones created later may have contorted shapes due to the constraint from previously created zones. The geometric centroid of these irregular shapes (used subsequently to form the triangular modelling mesh) may not be able to well represent their zones and hence may not satisfy the Courant criterion. Some zones have to be abandoned if they can't match the Courant criterion, which then leaves gaps in the study area. However, for Finite Element computation to be effective, the triangular modelling mesh generated from the centroids of these zones must cover the whole study area. Thus the "spiral search" method is both theoretically unsatisfactory as a tessellation and could easily impact the quality of numerical computation, although adjustments to the zones are sometimes carried subjectively by the modeller based on experience.

The second method (Figure 6 (b)) is new and is proposed by this study. It is enhanced from existing ideas of spatial zone design (Openshaw & Rao 1995; Openshaw 1996, 1998) and can be defined as an "automatic search" method. The "automatic search" method firstly expands each zone as a circle around the initial point. If some of these initial zones can't match the Courant criterion or have no room to be expanded, they will be left temporally. In a second stage, each zone is further modified with the Courant criterion. The modification includes enlarging the zones, shrinking the zones or loosening the criteria. The initial zone can be enlarged as a circle or can grab the uncovered space next to it. The modified zones can also give up the grabbed space to the zones around it. If there are still uncovered space after all these efforts, the criteria could be loosened and the modification would be carried on. The modification process is repeated until the whole study area is covered. This new method is designed to produce a complete and relatively regular zone system, which would then lead to a triangular modelling mesh for matching the Courant criterion and a sounder basis for numerical hydrodynamic modelling.

[*Figure 6 about here*]

3.2. Experiments and analyses

Two experiments have been designed for comparing the "spiral search" and "automatic search" methods. Synthetic bathymetric data are employed for excising control over the systematic testing and to provide a baseline to test the affects of spatial discretisation (i.e. the zone system). Also, for experimentation, the synthetic data could be made to provide a greater range of challenges than might be presented in a real data set. The reference currents (or the "true" currents) for error analysis of the outputs are derived from bathymetric sampling at high resolution which can automatically match the Courant criterion and cover every topographic detail. Of course, such a high resolution approach is computationally very time-consuming and would not normally be used in coastal oil spill modelling but can be usefully used here to derive the reference currents for the experiments. In order to focus on the affect of these two discritisation methods, simplified synthetic data are input. The study area is designed as a square or a rectangle. The shoreline and open boundary therefore are all straight while the tidal data are uniformly distributed along the open boundary. Through such simplification, fewer uncertainties would be introduced from initial inputs to the results of experiments.

In the first experiment, a simple concave seabed (Figure 7) is discretised. Figure 8 shows the zone systems generated by these two methods. With the "automatic search" method, the shape of each zone is more regular and there are no gaps in study area. It means the geometric centroid can well represent each zone and the zone system can cover the whole study area. The triangular mesh from such a zone system matches the Courant criterion better and therefore decreases the error contribution to current simulation. In contrast, many gaps and contorted shapes can be seen from the result of "spiral search" method. The hydrodynamic model has then been run on the triangular meshes derived using both methods. Errors propagated from the two zone systems have then been analysed. For simplifying the experiment, only *Vg* (i.e. northward phase-lag for tidal current simulation) is set as the sensitive element. Statistical results in Table 1 show that the errors from the new "automatic search" method are less than "spiral search" method. The errors for other elements of tidal current simulation are very small and can be ignored in this experiment. T-test is also carried out for the difference of residual errors in *Vg* for the two methods. There is a significant difference between the two methods at $p < 0.05$.

[*Figure 7 about here*]

[*Figure 8 about here*]

[*Table 1 about here*]

More complex bathymetric data is inputted in the second experiment for further testing. This seabed combines the convex and concave forms as well as a channel and a ridge (Figure 9). Although the bathymetric input is more complex than the previous experiment, similar results can be seen in the zone systems created by spatial discretisation. Figure 10(a) shows the zone system form the "spiral search" method which has more contorted zones and gaps. There are relatively less contorted zones and no gaps for zone system from the new "automatic search" method in Figure 10(b). Error analysis has also been carried out and the results are given in Table 2. In this experiment, *Ug* and *Vg* (i.e. eastward and northward phase-lag) are sensitive to spatial discretisation while the other elements of tidal current simulation are very small and can be ignored. For both *Ug* and *Vg*, the mean values of errors are small and similar, however the standard deviations of errors are relative bigger from the "spiral search" method. As with the first experiment, T-test show that there is a significant difference between the two methods at $p < 0.05$.

[*Figure 9 about here*]

[*Figure 10 about here*]

[*Table 2 about here*]

From the above two experiments, the proposed "automatic search" method did improve the zone systems for bathymetric data in hydrodynamic modelling. The quality of model output is therefore improved. For both simple and complex bathymetric inputs, the consistent results demonstrate that it is feasible to control the spatial discretisation through zone design technology. Although the proposed method can be developed further and more experiments might be needed to further study its effectiveness, the prospects and benefits are good for spatial data analysis and zone design in spatial discretisation for hydrodynamic sub-modelling.

4. Conclusions

Spatial discretisation is critical for coastal oil spill modelling. It in fact provides the basis for numerical computation and spatial data handling in different phases of the modelling. Control of spatial discretisation would assure the reliability of simulations, improve the quality of model outputs and subsequent decision-making. This paper has shown that spatial data analysis techniques are effective for controlling the spatial discretisation in coastal oil spill modelling. Initial methods have been developed for investigating and improving the spatial discretisation with the experimental models, which can be easily implemented by modellers without spatial data quality expertise. Qualitative and quantitative analyses are both helpful to explore the spatial discretisation in different cases. Further study is planned which will focus on the spatial discretisation in different phases of coastal oil spill modelling. For example, in hydrodynamic sub-modelling, the proposed methods of zone design could be further improved with the consideration of data quality improvement and experiments could be designed for a more comprehensive test. Also, in order to deal with the diversity of fate sub-modelling, major weather processes should be investigated systematically in terms of their sensitivity to spatial discretisation. There are many issues of discretisation in coastal oil-spill modelling that still need to be investigated and properly understood, issues which the industry continues to take for granted.

In a broad sense, control of spatial discretisation is also essential for a wide range of environmental models. Spatial discretisation based on triangle or grid is typical for model performance, particularly for the dynamic and distributed models. Analyses in this paper mainly focus on the relevant spatial inputs and operations on them rather then the details of computation in specific modelling. The concepts and methods developed in the study are therefore expected to have general relevance for a range of applications in numerical environmental modelling.

References

Brimicombe, A.J., 2003. *GIS, Environmental Modelling and Engineering*. Taylor & Francis, London.

Castro, M., Macias, J. & Pares, C., 2001. An incomplete LU-based family of preconditioners for numerical resolution of a shallow water system using a duality method – applications. *Applied mathematics letters*, 32(5): 651-656.

Flowerdew, R., Feng, Z. & Manley, D., 2004. Constructing data zones for Scottish neighbourhood statistics. *Proceeding of the GISRUK 12th Annual Conference*. University of East Anglia, pp. 277-279.

Foreman, M.G.G. & Walters, R.A., 1990. A Finite-element tidal model for the Southwest coast of Vancouver Island. *Atmosphere-Ocean*, 28(3): 261-287.

Garcia-Martinez R. & Brebbia C.A., 1998. *Oil and Hydrocarbon Spills: Modelling, Analysis and Control*. Computational Mechanics Publications, Southampton.

Goodchild, M.F., Stayaert, L.T., Parks, B.O., Johnson, C., Maidment, D., Crane, M. & Glendinning, S., 1996. *GIS and Environmen/tal Modeling: Progress and Research Issues*. Wiley.

Li, Y., Brimicombe, A.J. & Ralphs, M.P., 2000. Spatial data quality and sensitivity analysis in GIS and environmental modelling: the case of coastal oil spills. *Computers, Environment and Urban Systems*, 24: 95-108.

Longley, P.A., Brooks, S.M., McDonnell, R. & MacMillan, B., 1998. *Geocomputation: A Primer*. Wiley, Chichester.

Mira Digital, 2001, *International Oil Spill Conference: Global Strategies for prevention, preparedness, response, and restoration.* Tampa, Florida.

Martin, D., 2003. Extending the automated zoning procedure to reconcile incompatible zoning systems. *International Journal of Geographical Information Science*, 17(2): 181-196.

Martin, D., Nolan, A. & Tranmer, M., 2001. The application of zone design methodology in the 2001 UK census. *Environmental and Planning A*, 33: 1949-1962.

Molkenthin, F., 1996. Impact of grid modeling on physical results. In: Ferrante, A.J. & Brebbia, C.A. (Editors), *Coastal environment: environmental problems in coastal regions*. Computational Mechanics publications, Southampton, pp. 295-304.

NCGIA, 2000. *Proceedings Fourth International Conference/Workshop on Integrating GIS and Environmental Modeling* (Banff: NCGIA). *www.colorado.edu/research/cires/banff* as viewed on January 2001.

Openshaw, S., 1996. Developing GIS relevant zone based spatial analysis methods. *www.geog.leeds.ac.uk/staff/m.blake/zdes/re-engin.htm.*

Openshaw, S., 1998. Building automated geographical analysis and explanation machines. In: Longley, P.A., Brooks, S. M., Mcdonnell R. & Macmillan B. (Editors) *Geocomputation: A Primer*. Wiley, Chichester, pp. 95-115.

Openshaw, S. & Abrahart, R.J., 2000. *GeoComputation*. Taylor & Francis, London.

Openshaw, S. & Rao, L., 1995. Re-engineering 1991 census geography. *Environment & Planning A,* 27: 425-426.

Pinder, G. F., 2002. *Groundwater modelling*. John Wiley & Sons, New York.

Saltelli, A., Chan, K. & Scott, E.M. (Editors), 2000. *Sensitivity Analysis*. John Wiley & Sons Ltd, Chichester.

Seaconsult, 1998. Spillsim Oil Spill Response System. Unpublished report, Seaconsult. Vancouver, Canada.

Strutwolf, J. & Britz, D., 2003. High-order spatial discretisations in electrochemical digital simulations. Part 4. Discretisation on an arbitrarily spaced grid. *Computational Biology and Chemistry*, 27(3): 327-337.

White, D., 2005. What happens to oil spills?. *Geoscientist*, 15(5): 4-11.