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PACE: A GEOGRAPHIC INFORMATION SYSTEM BASED LEVEL 3 PROBABILISTIC ACCIDENT CONSEQUENCE EVALUATION PROGRAM

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ABSTRACT

In the UK a new program to build nuclear power plants is commencing. In preparation Public Health England has developed a new Level 3 PSA code. The new tool called PACE incorporates advances in scientific understanding made since the last time such analysis was performed in the UK in the early 1990s. It also takes advantage of advances in computer technology including processing power, usability and specifically Geographic Information Systems. This allows PACE to utilize the spatial datasets of demographic, agricultural, economic and environmental attributes that are compiled and maintained nationally and internationally as well as incorporate a sophisticated though computationally intensive atmospheric dispersion model. PACE was implemented in the commercial GIS ArcGIS™; this decision freed the developers to concentrate on the core modeling functionality and data compilation while PACE still benefits from powerful data handling and visualization capabilities, and provides the user with a flexible and modern user interface. PACE estimates public doses, numbers of stochastic and deterministic health effects and economic costs with and without mitigating countermeasures including sheltering, evacuation, stable iodine prophylaxis, relocation, food restriction and clean-up.

Key Words: Level 3 PSA, GIS, Accidents, Health, Economics

1 INTRODUCTION

Currently in the UK there is a potential new program to build nuclear power plants and Public Health England[*] (PHE) has the remit to provide the licensing authorities with advice on the potential health impacts of the new designs, both generically and in more detail for any specific site. The advice includes consideration of both normal operations and emergency conditions. Consideration of emergencies requires a probabilistic approach but the tools for Level 3 Probabilistic Safety Assessment (PSA) were last used in the UK in support of the Public Inquiries into the building of PWRs at Sizewell in Suffolk and Hinkley Point in Somerset in the 1980s and early 1990s.

As preparation for the new build program, HPA reviewed all the available PSA codes and found that there had been no significant development since the early 1990s and that consequently they did not take into account advances in scientific knowledge [1]. The study also noted that

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[*] PHE was formed in April 2013 from the Health Protection Agency (HPA) and other organizations.

since the early 1990s there have been major advances in computer technology including processing power, usability and data visualization capabilities. In addition, increasingly fine resolution electronic spatial datasets of demographic, agricultural, economic and environmental attributes are now compiled and maintained nationally and internationally. With these advances it is possible to perform much more sophisticated assessments on relatively inexpensive computers. As a result of the study a substantial 3-year development program was undertaken to develop a new PSA tool built within a Geographic Information System (GIS).

The new system is called PACE (Probabilistic Accident Consequence Evaluation) and has been used in-house at PHE for more than a year with further development ongoing and a commercial version of the tool scheduled for release in the near future. Although the tool was intended for new build, its development has proved timely for studies of possible accidents at existing facilities undertaken as a consequence of the increased scrutiny of the industry following the Fukushima accident.

2 DESIGN AND IMPLEMENTATION

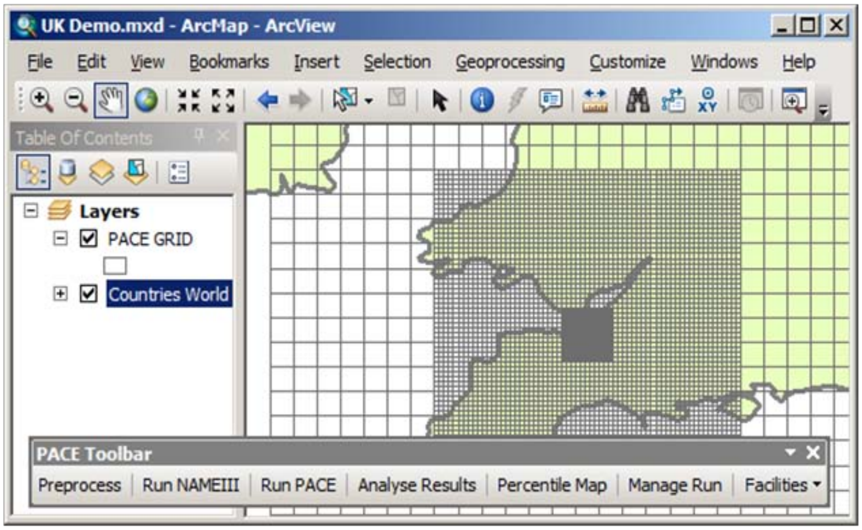


Figure 1 The PACE tool bar within the ArcGIS Desktop Software; A PACE calculation grid has been specified on the underlying map.

At the start of the development the design requirements were identified and the most significant of these were:

- utilization of electronic spatial datasets of demographic, agricultural, economic and environmental attributes,
- incorporation of a realistic representation of atmospheric dispersion using spatially varying meteorological datasets,
- incorporation of the latest scientific understanding of dose assessment including the mitigating effects of countermeasures such as decontamination,
- incorporation of the latest scientific understanding of the relationship between dose and health effects,
- incorporation of the COCO2 [2] economic consequences of accidents model, and

- development of a commercial product with a modern user interface including the ability for flexible visualization and analysis of the data.

The requirement to handle large datasets and to implement and incorporate new scientific advances and sophisticated models as well as the imperative to be commercial led to the decision to embed the new PSA tool within a commercially available Geographic Information System (GIS). This approach provides powerful data handling and visualization tools as well as a modern interface in which the user can interact with the maps generated while leaving the developers free to concentrate on the functionality, modeling and data. The GIS chosen was ArcGIS™ [3] which has comprehensive functionality built in, but can also be extended and customized using standard programming tools. The PACE software appears as a toolbar within the ArcGIS desktop interface, Fig. 1. ArcGIS is used by many UK Government departments and agencies and its formats for spatial data have become a *de facto* standard.

3 MODELS AND DATA

The PACE tool is not a single model but a synthesis of several models that represent the impacts on and consequences for people and different parts of the environment. Some models are included explicitly such as those for atmospheric dispersion; while others are included implicitly as data files of model generated parameters such as food concentration factors derived from food chain models.

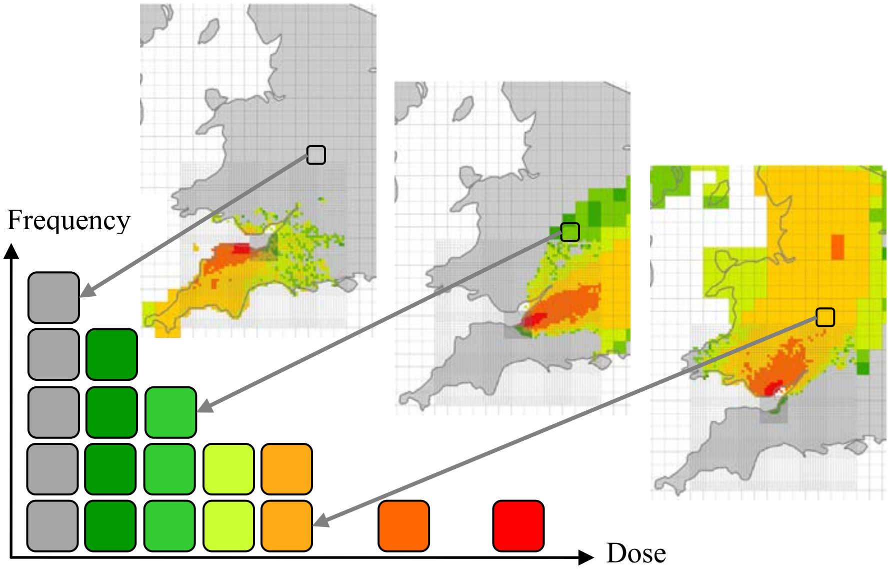


Figure 2 Example plumes predicted using the same hypothetical source term under different meteorological conditions. The values of an endpoint, for example dose, under any particular condition can be extracted to construct an estimate of the probability density function over all meteorological conditions for each grid square.

The PACE probabilistic approach is simple and straight forward. The input is a source term giving the amount of different radionuclides released in different phases and at different heights; generally the output from a Level 2 PSA. The PACE model is run for a large number of different meteorological sequences sampled to be representative of a dataset of historical meteorological conditions. For each run, doses, health effects, and economic consequence endpoints are estimated with and without mitigating countermeasures. At the end of the analysis each endpoint has a distribution of values in each grid square (Fig. 2) and a distribution of aggregated values over the whole grid from which probabilistic results can be presented.

3.1 Atmospheric dispersion models

PACE incorporates two atmospheric dispersion models. It utilizes a simple Gaussian model such as is found in older Level 3 PSA codes [1] but the full potential of the system is realized when it is run with the UK Met Office Lagrangian particle dispersion model, NAMEIII [4]. NAMEIII uses hourly numerical weather prediction (NWP) data on a 3-dimensional grid and can model dispersion realistically on regional, national and international scales.

One of the implications of using a complex model is that categorizing and assigning probabilities to different weather patterns is no longer feasible. For simple Gaussian models that rely on single site meteorological data it is reasonable to state that, for example, 60% of the time the atmospheric stability can be categorized as a particular category or that wind direction is blowing from 0 to 30 degrees from north. These categories can then be folded into a computationally efficient stratified sampling probabilistic approach. The 4-dimensional NWP data defies such simple categorization and so a more time consuming cyclic sampling approach is required whereby the model is repeatedly run on meteorological data at intervals of a fixed number of hours over several years of data.

When combined with the long running time of complex dispersion models this can mean that a full PACE analysis takes several days to complete. The computational requirements coupled with the storage requirements of the NWP data (which can be of the order of terabytes) underline the fact that this kind of analysis has only recently been practicable on a high end desktop computer.

When using a complex model in a cyclic sampling approach there is a chance of omitting weather conditions that give rise to extreme events. Using several years of NWP data and having a small cycle interval reduces the chance but increases running times and data storage requirements. This problem does not arise with Gaussian formulations using single site data that are amenable to a stratified sampling approach. However, such formulations have difficulty representing some combinations of conditions that would give extreme endpoints. For example, a plume encountering relatively calm conditions and being washed out by heavy rain over a city to produce a hotspot of exposure with a large population. Such hotspots have been a feature of real accidents and it is an advantage of PACE that it can represent them. Work comparing the results of Gaussian and Lagrangian particle models when used probabilistically as in PACE or deterministically as for emergency response is an ongoing area of investigation at PHE [5].

3.2 Built environment and decontamination

One feature that distinguishes PACE from previous Level 3 PSA codes is that it allows the population to be divided among different building types. The current version allows two building types – by default these are brick houses and multistory concrete apartment blocks – but future versions will allow more types to be added; balancing the greater realism that more environments bring with the increased computational requirements and the availability of data to support that capability.

Building types with their different shielding properties, affect not only the dose that the population is exposed to, but also the efficacy and cost of the clean-up operations. The ERMIN model [6] was used to generate location factors and the dose reduction expected following clean-up. However, decision-makers have very wide discretion when deciding on the detailed strategy for clean-up that cannot be contained or fully emulated by PACE. For example, the decision process leading to the strategy could be expected to incorporate public acceptability and other intangible factors as well as more readily quantifiable factors such as a radiological assessment. PACE circumvents the need to specify gradations of options and implementation rules by providing two representative packages of clean-up countermeasures. The packages were analyzed with ERMIN for the two built environments to give dose reduction factors and costs and represent a low intensity, low cost, low disruption option that includes vacuum sweeping roads and grass cutting, and a high intensity, high cost and high disruption option that includes high pressure hosing all paved surfaces, roofs and walls, soil removal, tree pruning and vacuuming interiors. The PACE user may set dose criteria to trigger one or other of these packages within a particular grid square in a particular meteorological sequence.

3.3 Dose, countermeasures and health effects

In each grid square PACE estimates doses to individuals. The pathways included are internal exposure from inhalation of radioactivity in the plume, external exposure to radiation from activity in the plume, external exposure to material deposited on skin and clothes, external exposure to radiation from activity deposited in the environment and internal exposure from inhalation of resuspended radioactive material. In addition PACE calculates the collective dose from the consumption of food produced in each grid square assuming all the food is eaten by someone somewhere. Food activity concentrations for a unit deposit are pre-calculated using the FARMLAND model [7]

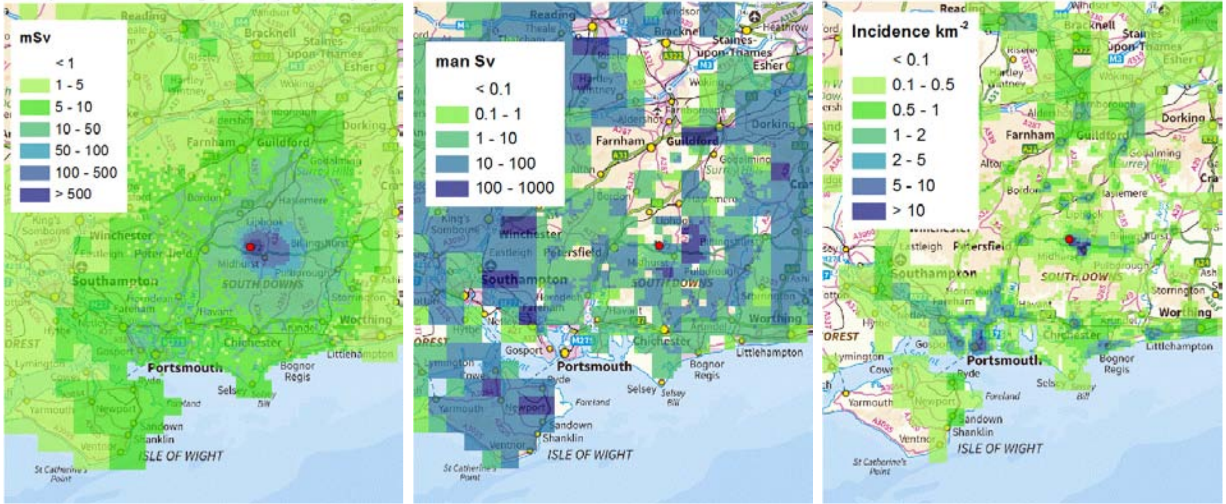
PACE estimates stochastic and deterministic health effects. The default risk factors for cancers and hereditary effects are taken from ICRP [8] and the default deterministic risk function parameters for deterministic effects are from NRPB [9].

Doses and health effects can be mitigated with countermeasures. PACE allows the user to set dose criteria to trigger evacuation, sheltering and stable iodine prophylaxis, and activity concentration criteria for food restrictions. The user sets dose criteria for relocation and PACE calculates how long relocation will be required. As discussed previously the PACE user sets dose criteria for clean-up; clean-up will reduce long term doses and may reduce the duration of relocation.

Fig. 3 gives some graphic examples of PACE output and illustrates the influence of the underlying spatial datasets on which PACE relies for a hypothetical accident and location.

3.4 Economics

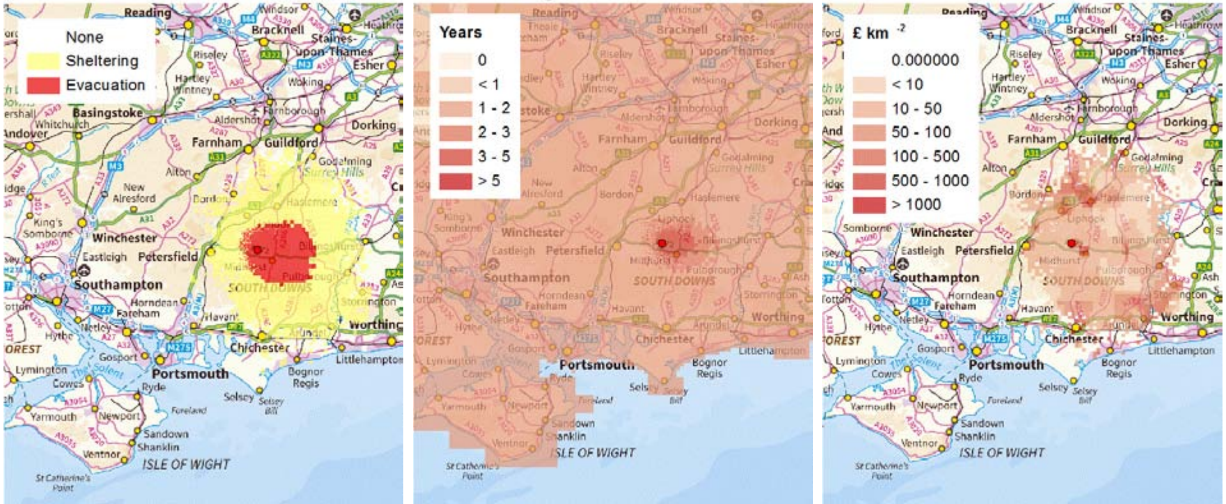
A nuclear accident will produce dislocations in the local, and potentially in the national, economy as the lives of people and the functioning of local businesses are disrupted. It may also cause a real or perceived deterioration of the local environment and incur additional health costs. PACE uses the COCO-2 model [2] to estimate these economic costs in each of several categories as they arise for each realization of an accident sampled from the available meteorological conditions evaluated at each grid square. It provides estimates of the national loss from the disruption of people's lives through evacuation and relocation, the disruption of business, restrictions placed on agriculture, the cost of radiation induced health effects, the cost of countermeasures put in place to reduce the consequences of the accident and the economic losses from reduced tourism to the region primarily affected.



(a) Individual Effective Dose (Sum of non-ingestion pathways)

(b) Collective Committed Effective Dose from Milk Ingestion

(c) Expected Solid Cancer Incidence (excluding ingestion dose)



(d) Requirement for sheltering or evacuation

(e) Duration of Restriction for Marketing of Milk

(f) Indirect Costs of Lost Tourism

Figure 3. Typical PACE output for a hypothetical accident and location. The maps show one meteorological sequence with a plume in fairly calm conditions with a slight eastward drift. Map (a) is a prediction of the individual dose summed over all pathways except ingestion and the shape of the plume is obvious. Map (b) is a prediction of the collective dose from consumption of the milk produced in each grid square. The plume is less obvious as high doses are concentrated on grid squares with high milk production and this result is also sensitive to grid square size. Map (c) is the expected numbers of solid cancers with countermeasures applied excluding ingestion dose; as expected incidence is highest at population centers. Map (d) shows the areas where criteria for sheltering and evacuation are exceeded. Map (e) is the predicted duration of restriction on milk production. Map (f) shows the predicted indirect costs of lost tourism. This includes the disruptive effects of countermeasures and as expected the highest costs for this meteorological sequence are in the picturesque villages of the South Downs.

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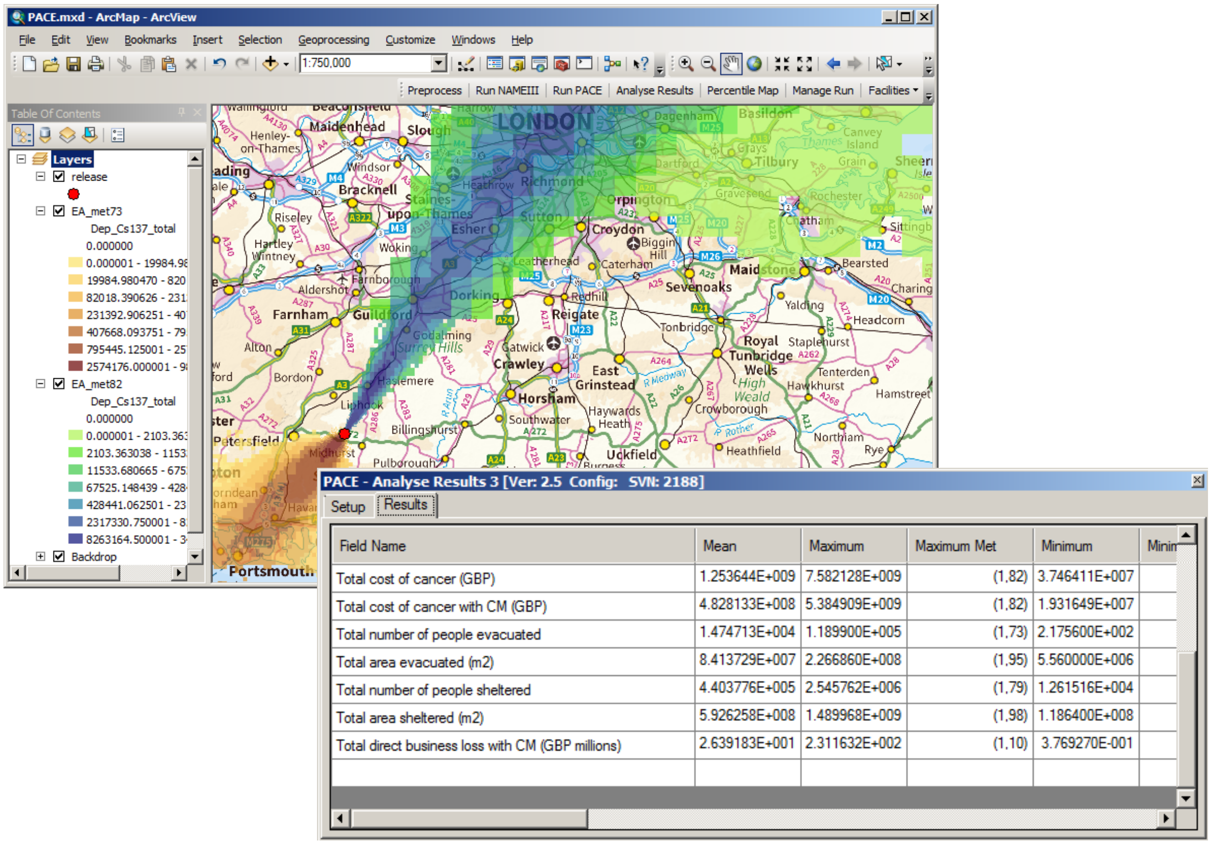
The model makes use of site-specific information within a generic framework and employs Input-Output techniques to represent the effect of lost production in an affected region. This includes estimates of the direct and indirect national loss to the manufacturing, services (including tourism) and agricultural production sectors and in addition, specific tourism losses at a regional level. The opportunity has also been taken to ensure that COCO-2 is able to use the more extensive information on countermeasures that has become available with the publication of the UK Recovery Handbook [10] and importantly to consider a 'willingness to pay / quality of life' based valuation of health effects. During the development of COCO-2 comprehensive and wide ranging spatial datasets of the required input parameters were compiled for the UK and these have subsequently been incorporated into PACE.

4 AGGREGATION, ANALYSIS AND VISUALIZATION

All PACE endpoints are stored as standard ArcGIS spatial datasets and so they can be analyzed and visualized with the many toolsets available in ArcGIS. In addition PACE provides two custom tools.



Field Name	Mean	Maximum	Maximum Met	Minimum	Minin
Total cost of cancer (GBP)	1.253644E+009	7.582128E+009	(1,82)	3.746411E+007	
Total cost of cancer with CM (GBP)	4.828133E+008	5.384909E+009	(1,82)	1.931649E+007	
Total number of people evacuated	1.474713E+004	1.189900E+005	(1,73)	2.175600E+002	
Total area evacuated (m2)	8.413729E+007	2.266860E+008	(1,95)	5.560000E+006	
Total number of people sheltered	4.403776E+005	2.545762E+006	(1,79)	1.261516E+004	
Total area sheltered (m2)	5.926258E+008	1.489968E+009	(1,98)	1.186400E+008	
Total direct business loss with CM (GBP millions)	2.639183E+001	2.311632E+002	(1,10)	3.769270E-001	

Figure 4. The PACE user interface showing the tabulation of aggregated results for a hypothetical accident and location. In this example the maximum total cost of cancers occurs with meteorological sequence 82, source term 1 but meteorological sequence 73, source term 1 gives the most people requiring evacuation. When the total deposition for both sequences is visualized using different color schemes it is clear that they produce plumes going in very different directions and impinging on different population centers.

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There is a simple tool that aggregates PACE results in a tabular format over all grid-squares and meteorological sequences and over a number of different source terms with associated probabilities. For example, it will sum up all solid cancer fatalities in each sequence and provide the user with statistical results such as maximum, minimum and estimates of percentiles. It also allows the user to identify the meteorological sequences that give the maximum and minimum and enables the user to drill down into those sequences to ascertain why they are at the extremes of the distribution, Fig. 4.

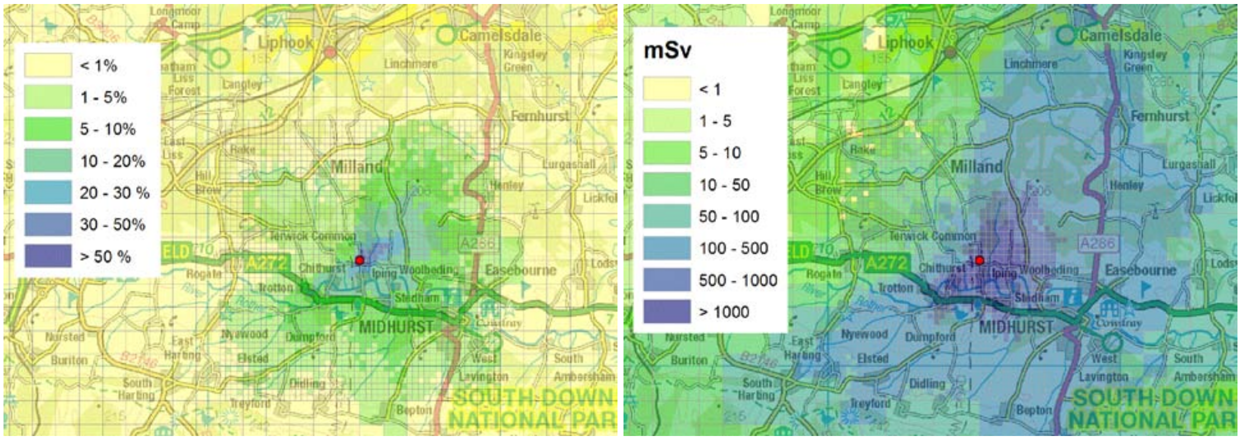

Figure 5. Visualization of PACE results for a hypothetical accident and location. The left hand map illustrates estimated probabilities of exceeding a 300mSv effective dose threshold at each grid square. On the right are the 95th percentile dose values; meaning 95% of the sequences predicted doses at or less than the grid-square value and only 5% exceed it

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The second tool exploits the powerful visualization functionality of ArcGIS to display the aggregated results as maps. Taking individual total dose as an example; for each grid square the tool can simply count of the number of met sequences that exceed a user defined threshold dose or estimate the probability of that threshold dose being exceeded. Alternatively it can estimate the dose value of a user defined percentile value, e.g. 95% of the time met sequences indicate a level of dose below this value, Fig. 5.

5 CONCLUSIONS

PACE has been used in-house for a number of tasks and development is ongoing with a commercial version scheduled to be available in the near future. The decision to use commercial GIS as a framework has meant that the developers are free to concentrate on functionality, modeling and data compilation, which is substantial given the range of models included, while PACE still benefits from powerful data handling and visualization capabilities, and provides the user with a flexible and modern user interface.

6 ACKNOWLEDGMENTS

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