Presenting Uncertain Information in Radiological Emergencies

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Management Summary for ADMLC

In a radiological emergency, as indeed with any emergency, there is a great deal of uncertainty, often geographical uncertainty. During any threat and the early phases, there will be a rapidly developing and changing understanding of the nature and impact of the release and its potential spread. Dispersion predictions and consequent public health advice will alter over time to reflect this. Thus there is a need to present information relevant to those making decisions, recognising that knowledge of the situation will inevitably change with time, being sparse and broad in scope to begin with and gradually becoming more detailed. Such changes and refinements in the information picture present challenges in communication. It is difficult to convey uncertainty and risk, and geographic uncertainty is among the hardest to explain. Moreover, recipients of the information may have inaccurate perceptions of what is realistically achievable in the early hours, leading to a loss of confidence in scientific advice as the information picture evolves. Communicating these issues to the public and communities at risk is challenging; but it is at least as challenging to communicate them to the decision makers to support their deliberations on countermeasures and other actions that they might take.

The objectives of this project were:

- to develop improved presentational techniques for representing the uncertainties and lack of knowledge in the early stages of a radiological emergency;
- to build an improved, shared understanding and realistic expectations between decision-makers, scientists and communicators of what will be known in the early phase of a radiological emergency and how this knowledge, *particularly relating to the areas at risk as any plume spreads,* will evolve.

The project focused primarily on communication of uncertainty between analysts at the Met Office, Public Health England (PHE), the Scientific Advisory Group for Emergencies (SAGE) and the UK's national crisis response group (COBR).

As background, the project reviewed published techniques for presenting uncertain information to decision makers during the response to an emergency and the sources of uncertainty in the scientific assessments. The key activities, however, related to three workshops designed to assess how the needs of decision makers would be best met by alternative methods of data presentation. The first workshop, essentially ran an exercise for SAGE and sought to understand the decision makers' needs. A clear finding was that SAGE, and presumably COBR, expected to develop and work with a *reasonable worst case*. The idea of a reasonable worst case is common in emergency planning and more generally in risk assessment, where it is defined as being "designed to exclude theoretically possible scenarios which have so little probability of occurring that planning for them would lead to a disproportionate use of resources". The concept has been taken over, consciously or otherwise, from emergency *planning* into emergency *response* without apparent recognition that the contexts of these two activities is significantly different. The former considers the possibility, remote or otherwise, of some disaster. The latter relates to something that has most definitely happened. While a reasonable worst case – or one might suggest, several reasonable worst cases – are essential in emergency planning to ensure sufficient resilience is built into a system without being excessive, it is far from clear that emergency response should focus almost entirely on a single reasonable worst case. We believe that basing a response on a reasonable worst case is too focused on assessing 'how bad things may get'. Moreover, in this context there may be several possible reasonable worst cases, which are quite qualitatively different in terms of their impact. Our literature review and experience suggests that this poses risks to the quality of decision making. We suggest that a better way forward to present and explore the uncertainty would be to present several scenarios 'spanning' the possibilities. For the present, we do not propose using probability assessments since there would be no time to quantify the key uncertainties. This conclusion was tested and discussed at a second workshop which included many risk and decision analysts of international standing. We also discussed our conclusions with one of the UK's Chief Scientists, who could potentially chair SAGE. We then developed a second exercise for SAGE which presented the uncertainty in the form of four possible scenarios. The third workshop again simulated the workings of SAGE using these four scenarios to describe the accident. The participants also discussed our proposals more generally.

Overall our conclusions suggest that presenting the possible evolution of a radiation accident as several scenarios offers a better way forward than the current process of developing a single reasonable worst case. However, we recognise that this may not fit with the current processes for running SAGE and COBR meetings, since these have been developed not just for radiation accidents, but for all crises that may have regional or national impacts.

More specific recommendations[1] are:

Recommendation 1: *Attention should be given to the effects of promotions and career development within the Civil Service and Government agencies on the expertise that may be available to SAGE during a radiation accident – and presumably other events.*

Recommendation 2: *There are logistical, support and organisational issues which limit how information can be presented to SAGE and COBR. There may be benefit in reviewing whether the need to present a greater range of information e.g. as in the case of JAM, requires some modification of the structure and organisation of the communication and information presentation within SAGE and COBR.*

Recommendation 3: *There may be benefit in exercising SAGE (and other bodies) with more significant accident scenarios than are conventionally used.*

Recommendation 4: *Process briefing documents for chief scientists and participants in SAGE should recognise the importance of bringing 'challenge into the room' to reduce the risk of errors, slips and misinterpretation.*

Recommendation 5: *Standard templates, legends and explanations relating to all maps, plots, tables for both SAGE and COBR should be developed in advance.*

Recommendation 6: *The presentation of observational and modelling data should be implemented with consistency in the use of scales, units, colour, etc. This is particularly true of geographical information, which should be presented using maps that can be easily aligned. Ideally once the source term and meteorology have been set for a scenario the output should be developed and produced automatically by the system providing an agreed set of maps, tables and plots for SAGE without further intervention or collation.*

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[1] Recommendations 1 to 4 relate to the general organisation and processes of SAGE and are not entirely within the remit of our project. These recommendations suggest that to some extent current practices constrain the presentation of uncertainties and the availability of expertise to understand, discuss and address those uncertainties. Recommendations 1 to 4 arise largely because the University of Warwick members of the research team were able to observe the processes within SAGE in a 'disinterested' fashion, but we recognise that inevitably these observations are partial because their 'disinterested' status also means that these observations were made without a full awareness of the history and process that led to current practice.

Recommendations 11 to 13 refer to JAM, a shorthand for the current development of the Joint Agency Modelling procedures and processes to provide timely plots and predictions to SAGE, drawing together the output of several agencies.

Where possible, these should be designed to support discussion of potential countermeasures, rather than simply show contours of dose or deposition.

Recommendation 7: *SAGE should not adopt a probability lexicon to give quantitative meaning to everyday expressions of uncertainty unless and until a common lexicon is adopted and used consistently across all government departments and agencies in their day-to-day activities.*

Recommendation 8: *Discussions with the operators, ONR and other relevant parties should take place to see if it were possible to get some very rough quantitative probabilities relating to the source term in the early stages of the event.*

Recommendation 9: *Timelines relating to the availability of further information in respect of each key uncertainty should be provided to SAGE and COBR.*

Recommendation 10: *SAGE should be provided with 3-5 scenarios which together provide an overview of the range of possible impacts that might result from the accidental release.*

Recommendation 11: *SAGE should look at all scenarios prepared to explain the range of possible impacts. To aid in this, the geographical plots prepared for each scenario should be supplemented by a brief list of the key impacts in tabular or bulleted form. A template for doing this should be prepared. Moreover, the design of any supporting IT systems such as JAM should provide the key tables, though some of the more qualitative comparisons will need to be summarised by hand.*

Recommendation 12: *Procedures and guidance for constructing the 3-5 scenarios to present to SAGE should be developed. These procedures should be developed and exercised in collaboration with the designers and developers of supporting IT systems such as JAM.*

Recommendation 13: *It should be the responsibility of the teams using supporting IT systems, e.g. JAM, to identify and develop the scenarios to present to SAGE. Ideally, if SAGE wish to see a further scenario, it should be possible for a request to be made from within SAGE, the necessary runs made and the results sent back into SAGE.*

Recommendation 14: *Consider an exploration in the longer term of the potential for providing SAGE with probabilities as described at the end of Section 4.5.*

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1 Introduction

1.1 Background

In many emergencies there is a risk of atmospheric spread of contamination: e.g. chemical plant accidents, biological hazard release, CBRN incidents and, as discussed here, an accidental release of radiation at a nuclear plant. Such accidents are inevitably shrouded in many uncertainties, which interact to mean that any predictions of the spread of contamination are far from certain. Decision makers have to decide in the face of this uncertainty what protective measures, if any, to put in place. Not only may such measures be costly in financial terms, including lost production from nearby agricultural and economic activity; but, more importantly, they may themselves also have risks in relation to human safety. It has been estimated, for instance, that the health effects arising from stress and social upheaval relating to the evacuation and relocation of populations after the Chernobyl Accident are of the same order as those arising from the radioactive contamination itself (Havenaar et al., 2003; Rahu, 2003; International Atomic Energy Agency, 2006; Bromet and Havenaar, 2007). Although the long term consequences of the Fukushima Daiichi Disaster will not be known for some years, it is expected that those arising from stress and upheaval will be significantly greater than the radiation-related health impacts (Nomura et al., 2013; IAEA, 2015; Murakami et al., 2015; Blandford and Sagan, 2016; Hasegawa et al., 2016).

Thus decision makers need to balance complex risks in the face of considerable uncertainty. But to do that they need to understand the uncertainties that face them. Here we focus on a seemingly straightforward question: how should experts convey to the national emergency managers the uncertainties related to the geographical spread of atmospherically borne radionuclides after an accident at a nuclear plant?

Such a question, however, is far from straightforward. Firstly, atmospheric dispersion plumes have very similar visual (and mathematical) characteristics to spatio-temporal probability distributions. Hence there is considerable potential for confusion between the two when uncertainty in the spread of a plume is the main concern. Presenting the uncertainty simplistically risks visually enlarging the footprint of the plume, psychologically creating an impression among the decision makers that the potential consequences are far greater than they might be. Secondly, the uncertainties do not simply relate to the transport of radionuclides in wind, there are many uncertainties relating to scale, profile,

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mix of radionuclides, energy, etc. of the release: see section 1.3 below. Thirdly, while in principle all uncertainties might be modelled probabilistically, in the urgency of an incident there may not be the time nor the understanding to do this and gain broad consensus among the experts. Decision makers may need to react in the face of some *deep* uncertainties which cannot be modelled in a simple probabilistic way (Cox, 2012; French, 2014). Fourthly, the plume is not static, thus the uncertainties in the level of contamination at different points and different times need be presented to convey the evolution of the plume fully.

We also note that we need be aware of the risk of placing too much faith in models and any quantitative estimates of uncertainty provided by such models (French and Niculae, 2005). Any model provides some approximation to reality and inevitably leaves some variation and aspects unmodelled; and this is particularly likely to be true in the heat of an emergency when there is little time to confirm the 'fit' of a model and that it is appropriate to the situation. In stepping back from any model output to manage the actual event, emergency managers need to recognise that some unquantifiable modelling error will always be present.

This report relates to the outputs of the project *Review of Best Practice and the Development of Principles for Presenting Uncertain Information in Radiological Emergencies*, funded by the UK Atmospheric Dispersion Liaison Committee (ADMLC). This project focuses on the threat and immediate response phases of a radiological accident at a nuclear plant and considers, firstly, how information on the potential or actual spread of a plume would be presented and discussed within the team of experts advising central government; and, secondly, how their assessments would be conveyed to COBR, i.e. to the national emergency management cell within UK government. While we recognise both that the structure of emergency management locally and nationally may differ and that these structures vary between countries (see, e.g., Carter and French, 2005), the issues that we discuss have a very wide relevance. Nonetheless, our examples and discussion are set in the context of the UK's national emergency management process.

1.2 Radiation Accident Response Management

Before any nuclear plant is licenced for operation, detailed plans and preparations are made to deal with potential emergencies. These are continually revisited, updated and exercised during the normal running of the plant. The exercises involve operators, the 'blue-light' services, regional and often national officials. These exercises should be seen as an education so that those who will be involved in deciding on the most suitable measures to deal with an accident will be sensitive to issues that may arise. In addition to the emergency planning specific to particular sites, much guidance has been developed nationally and by bodies such as the International Commission on Radiation Protection (ICRP), the European Commission (EC), the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD- NEA) and the International Atomic Energy Agency (IAEA).

Typically, radiation accidents are described as evolving through a number of broad phases: threat, immediate response and long term recovery. Decisions during the early phases of the accident will be driven primarily by the imperative to avert dose, i.e. the exposure to radiation. In the later phases, however, issues of reducing stress, socio-economic and environmental impacts are likely to become much more important. No accident ever goes 'as planned'. Indeed, one of the salutary lessons from the Fukushima Daiichi Disaster was that it took a very different form from that at Chernobyl twenty five years earlier, rendering inappropriate many of the models and responses developed since then. Thus, during an accident, emergency managers need continually to assess the actual situation modifying the planned response to be appropriate to the actual circumstances. Moreover, the situation is shrouded in many uncertainties, and these may both increase or fall as the event unfolds.

In the UK, most of the immediate response is handled locally to the plant; but central government's crisis response unit, COBR, would have oversight and if the accident was significant would exert a strong co-ordination role. It also has a role in ensuring that all necessary resources are available for the local and national response.

If the plant operator detects an imminent risk of an accident or an actual release of radiation, a number of actions would be taken. Most obviously, plant officials and engineers would take appropriate engineering actions to avoid or mitigate the risk of a release. Our concern here, though, is with the decisions on off-site countermeasures to protect the public. The local emergency management team would consider whether to take any immediate measures such as:

- warning the public;
- advice to take pre-distributed stable iodine tablets;
- advising the public to shelter;
- evacuating some of the public most at risk.

In the event of a significant actual release of radioactivity, other short and medium term countermeasures may need to be considered: e.g.

- food-bans and decontamination of livestock and agricultural produce;
- decontamination of properties;
- restrictions on activities;
- restrictions on access to the region.

In the long term after a very serious release, it may be necessary to consider permanent relocation of some local inhabitants, establishing an exclusion zone, and changes in agricultural practice, business and economic activity.

Our project is concerned primarily with the threat and immediate response phases and so we shall focus on decisions relating to the issue of iodine tablets, sheltering and evacuation, and preparations needed for urgent food-bans and agricultural countermeasures. In the early phase there is a need to anticipate the ultimate scale of the consequences both to set realistic expectations across government and among the public, as well as to prepare and deploy resources that might be needed in the coming days and weeks. Moreover, we focus on the response to radiation accidents within the UK. The government crisis management teams also have to respond to overseas accidents in order to advise British citizens and interests nearby, but we do not consider that.

Within the UK there are local and national nodes co-ordinating any emergency response. Locally the relevant Chief Constable has full executive authority to respond. He or she is advised by a Scientific and Technical Advisory Cell (STAC) of experts drawn from the operators and various government agencies and regulators. Nationally the crisis management team (COBR) within Cabinet Office is advised by the Scientific Advisory Group for Emergencies (SAGE), which is drawn from the relevant ministries, national agencies and regulators (Cabinet Office, 2012). Figure 1 indicates the communication links between these and other actors, in particular, the teams at the Met Office, Public Health England (PHE), and the Office for Nuclear Regulation (ONR). In any accident with a release of radiation having off-site implications, there are legal requirements to notify international bodies such as the EU and IAEA, as well as neighbouring countries. Also there is a need to consider communications to the media and the public. Our work focuses on the communication between the modellers who provide predictions to SAGE, discussions within SAGE, and communications between SAGE and COBR. This is not to suggest that similar issues do not arise in relation to communication and discussions of uncertainty in the local nodes; rather our project needed a clear focus to make the best use of the resources available to it.

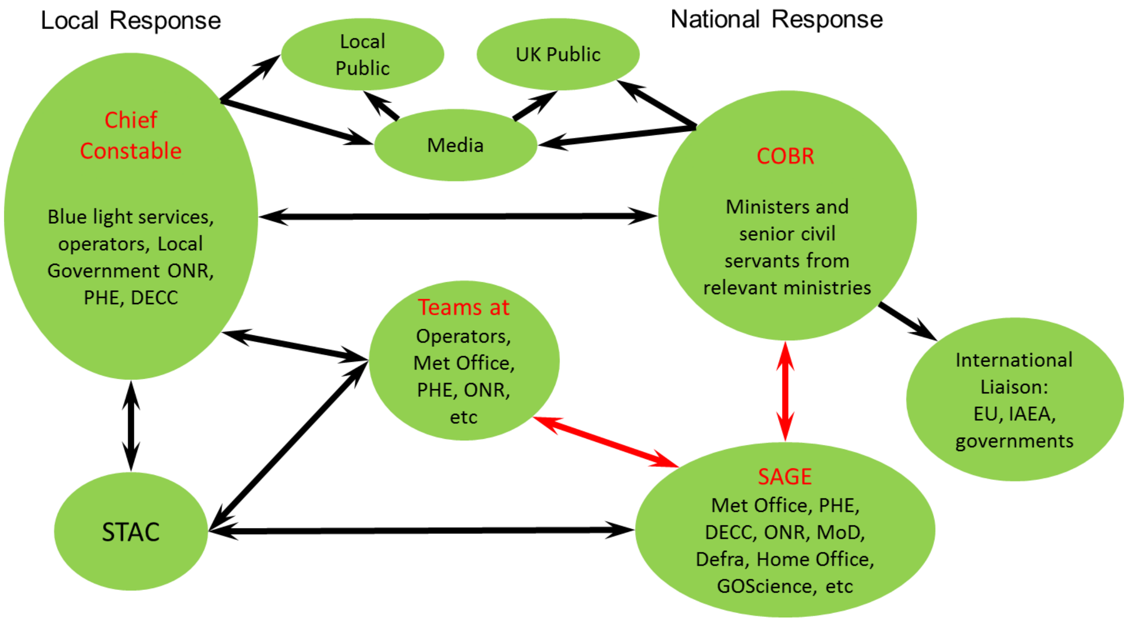

Figure 1: Communications between the different participants to the emergency management process. This report focuses particularly on the communications indicated by red arrows between SAGE and COBR, on one side, and SAGE and modellers, on the other.

In the UK deliberations on the path, strength and consequences of any plume of radioactive contamination is supported by predictions made using complex atmospheric dispersion, deposition, health and agricultural models. Such models and their use are described in, e.g., Benamrane and Boustras (2015), Ehrhardt and Weiss (2000), French et al. (2007) and Jones et al. (2007). The UK uses the Met Office's Numerical Atmospheric-dispersion Modelling Environment (NAME) system (Jones et al., 2007) for predicting atmospheric dispersion and deposition, which feeds into PHE's systems (Charnock et al., 2013) for assessing the likely doses and other impacts. Currently, processes and protocols for interactions between the Met Office, PHE and other departments and agencies are being developed to provide comprehensive evaluations of the possible evolution of a radiation plume, the resulting ground contamination and its potential health and other impacts. Known as the Joint Agency Model (JAM), this project will effectively produce a distributed system and process to provide timely, coherent information to STAC, SAGE and others. Currently, many of its elements exist as usable elements, but there no final date for completion.

1.3 Different Factors contributing to the Uncertainty about the Geographical Spread of Contamination and its health impacts

As we have indicated, there are many factors contributing to the uncertainty in the predictions of the atmospheric dispersion of the radionuclides (French, 2002; Haywood et al., 2010; Havskov Sørensen et al., 2014). Figure 2 and Figure 3 indicate (some of) these and how they influence the final uncertainty in the plume and the ultimate health impacts. Note that these figures simply represent how uncertainties and errors enter the modelling and then propagate through the modelling chain. They are conceptual and should not be read in a chronological manner from left to right. The modelling itself is iterative and complexly so. For example: there are the temporal iterations necessary to make predictions of the effects at a sequence of times to show their spread; there are computational iterations needed to 'solve' the mathematics; and there are iterations in the Monte Carlo simulations used in some of the modules along the model chain.

Imagine then that a reactor has 'tripped' in the sense that 'warning lights are flashing' and it is not working normally.

Uncertainties about factors that affect the physical process of atmospheric dispersion and deposition.

- Will the aberrant conditions in the reactor lead to an off-site release? Or will the reactor be brought back under control?
- If there is a release, will it be into a sound containment building from which the gaseous radionuclides can be vented in a controlled way and particulate radionuclides filtered out of any release?
- If the release is uncontrolled, when will it occur?
- What will be the composition of the release in terms of radionuclides?
- How big will the release be?
- What will be the time profile of the release, including variation in its composition?
- What is the energy of the source term and its effective release height? If there is substantial wind shear, this will affect the direction that the plume takes.
- What will be the weather conditions at the time of the release and during the passage of the plume?
- What monitoring data do we have both on-site and off-site and how accurate are these?
- How much of the particulate release will be deposited at each stage of the passage of the plume? This will be affected by the ground topography and surface roughness and increased by any precipitation.

Uncertainties about factors that relate to the modelling used to forecast dispersion, deposition and consequent impacts

- What models are used to predict the source term? What are the assumptions underlying these?
- What atmospheric dispersion and deposition models are to be used? What are the assumptions underlying these?
- What statistical analysis is used to assimilate monitoring data into the models?
- Where is expert judgement used to set model parameters or similar? How uncertain are these judgements? How well calibrated are the experts?
- What numerical methods are used to approximate the solution of the dispersion and deposition models?
- How good is our GIS data in terms of topography, geology, land use, agricultural production, position of dwellings and local populations?
- What models are used to assess potential agricultural impacts and the potential need for immediate food bans?
- How good is our knowledge of the demography, diet and behaviour in the areas potentially affected?
- What assumptions and models are used to predict any health effects?

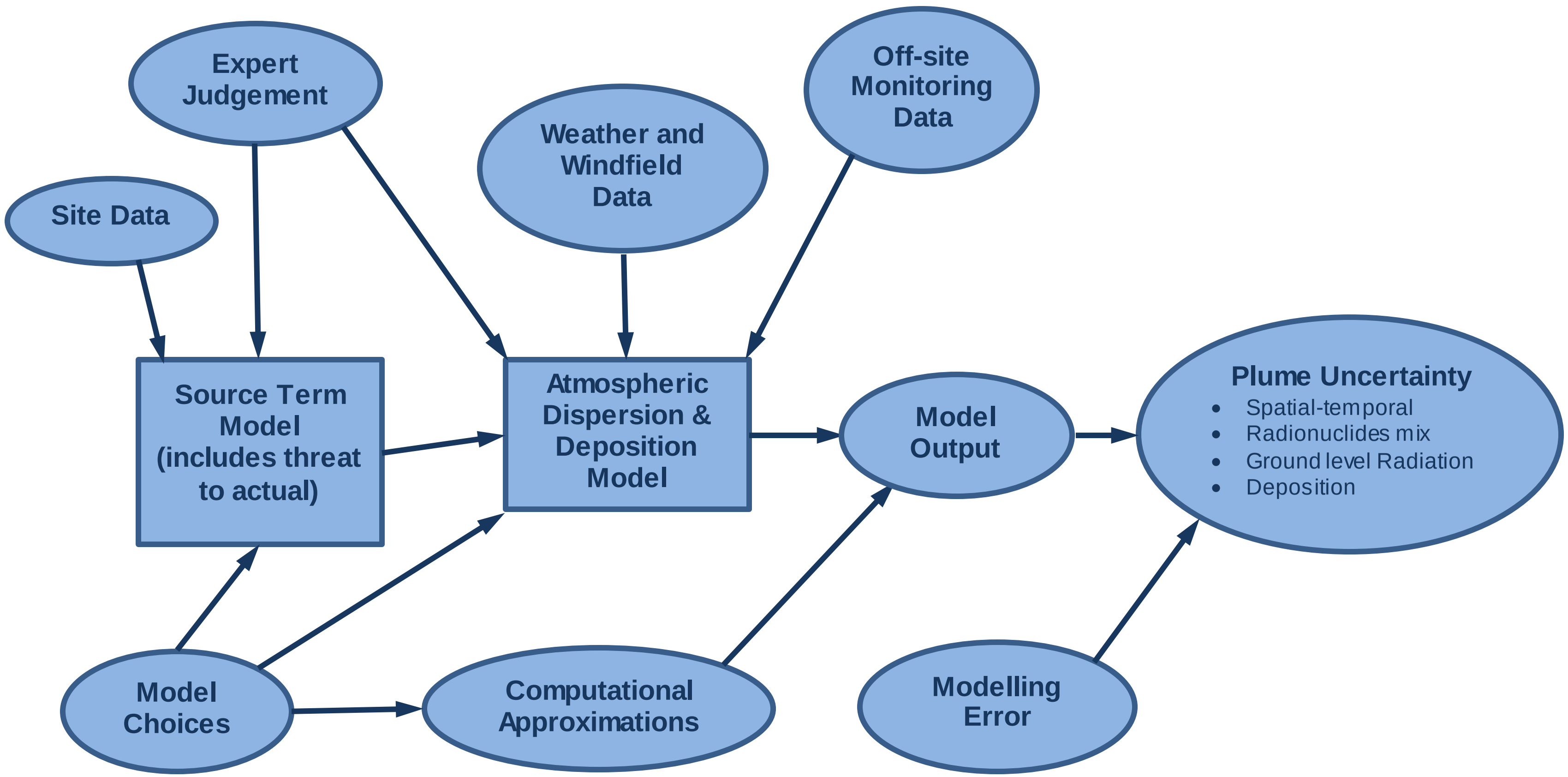

Figure 2: **Factors contributing to the uncertainty in the spread of atmospheric dispersion**

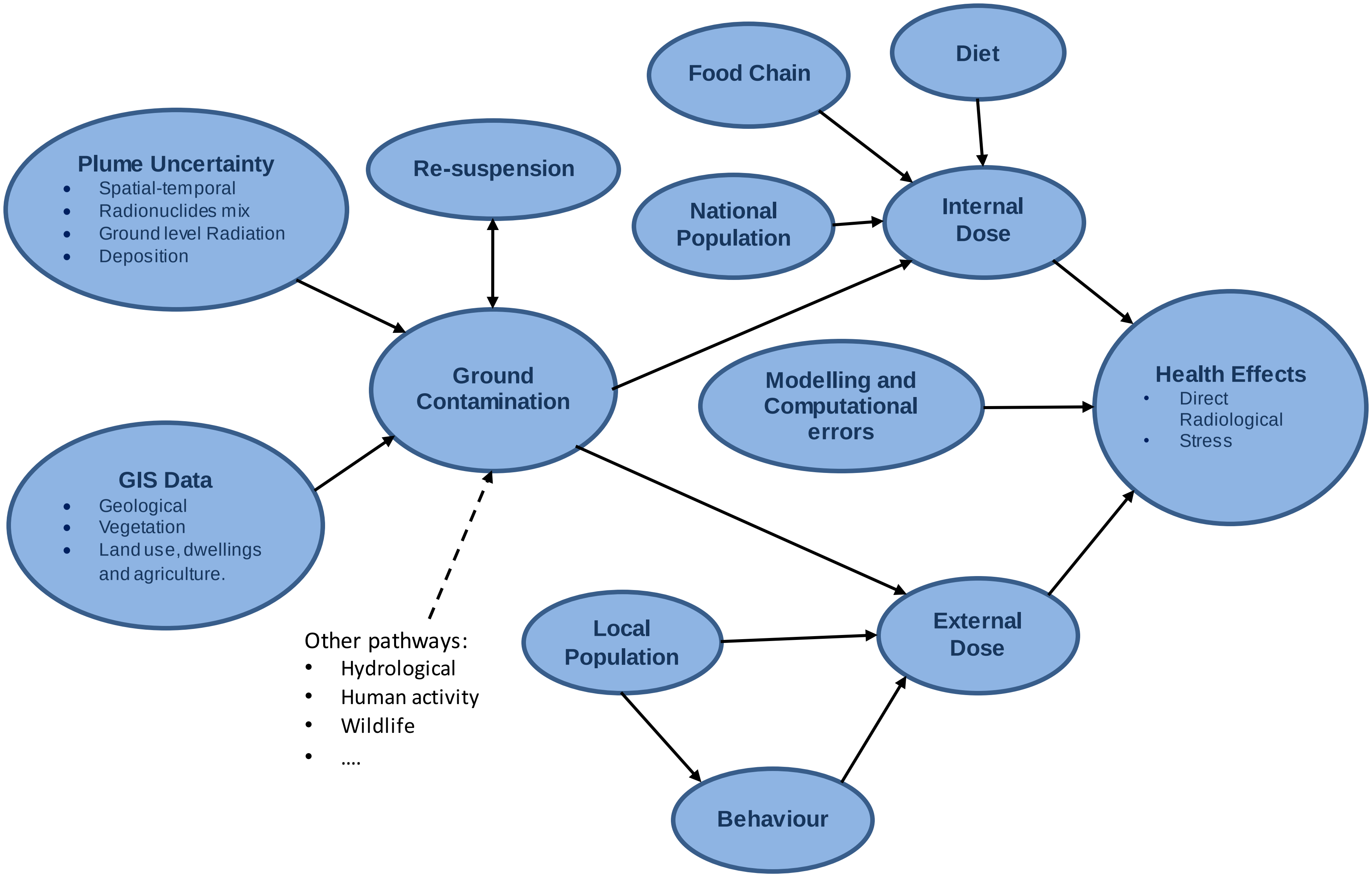

Figure 3: Factors contributing to the uncertainty in the predictions of dose and human health effects

- If several models are used in parallel to predict broadly the same effects, how are any conflicts between their predictions resolved?
- If we could calculate perfectly and had perfect data, how accurate would the models be?

In the first hours, the uncertainty in modelling public health impact assessments is generally dominated by source term uncertainties such as those relating to the release height, timing and scale and, secondly, to meteorological uncertainties, particularly the arrival of any front and precipitation patterns.

The modelling of the processes that lead to health and other impacts involves much simplistic averaging across many sub-groups. Moreover, the *linear hypothesis*, which is used to estimate the health risk to populations exposed to very low levels of radiation over long time periods, is precisely what its name suggests: a hypothesis justified by linear extrapolation from observed effects at much higher doses (Argyris and French, 2016; Blandford and Sagan, 2016). When combined with many conservative assumptions on the average exposure of members of the population, the linear hypothesis may lead to overestimation of the public dose.

SAGE has to balance all these uncertainties in formulating its advice to COBR. Some of these uncertainties may be modelled probabilistically, but for others this may not be possible in the time available in the urgency of an accident. For further discussion, see, e.g., French (1997) and Haywood et al. (2010). In particular, it is extremely unlikely that there will be any quantification of the uncertainties relating to the scale, timing, profile and composition of the source term(s). Even if such composition is conceptually possible (e.g. through the use of a rudimentary belief net such as RODOS-STM, Ehrhardt and Weiss, 2000), such methods are not implemented in the UK. Thus uncertainties will be presented, discussed and analysed in qualitative terms.

The ADMLC project focuses on the *atmospheric* spread of contamination. In the event that some of the radioactivity is spread via hydrological pathways yet more uncertainty would be introduced.

1.4 Communication of Risk and Uncertainty to Decision Makers

There is an enormous body of research on risk perception and communication: for summaries and critiques, see Bennett et al. (2010), Campbell (2011), Fischhoff (2008), Maule (2008), Palenchar and Heath (2007) and Spiegelhalter and Riesch (2011). Building on this there is much guidance, particularly within government circles, on how to communicate and advise sensitively and effectively about risks. In the UK, we note *UK Resilience*: *Communicating Risk* (Cabinet Office, 2011), based upon earlier reports by the Department of Health (1998) and the Interdepartmental Liaison Group on Risk Assessment (1998) and *A Practical Guide to Public Risk Communication* (Risk and Regulation Advisory Council, 2009); Similar documents have been produced by many other governments and international bodies: e.g. (EFSA, 2012), OECD (2002) and US DHHS (2002).

However, although there is this wealth of literature, we note two points relevant to our context. Firstly, the majority of these publications focus on the communication of risk and uncertainty to the public, not to decision makers. While there are many parallels in the conscious and subconscious processes which drive understanding of risk and uncertain information between the unfocused public and the focused emergency manager, they are not identical. Secondly, very little of our knowledge concerns the risk perception and communication of geographical uncertainties and risks. MacEachren et al. (2005) surveyed what little we knew a decade ago and sadly there have been no dramatic advances since[3]. In Section 2.4 below we provide a current survey of the relevant literature.

1.5 Outline of the Report

In the next section we discuss in more, but not exhaustive detail what is known about risk perception and communication. In Section 3 we describe our project and the UK's emergency management structure in a little more detail, particularly in respect of information flows, thus setting the context for our results and analysis. Sections 4 and 5 describe those results and analysis, while Section 6 lists our conclusions and recommendations.

[3] MacEachren (2014) Private communication.

2 Risk Behaviour and Risk Communication Theory: a Literature Review

2.1 Risk and Uncertainty

Risk, *uncertainty* and *probability* are often used almost interchangeably in everyday language. In the professional and scientific literature, there are many definitions, often contradictory and confusing. Many of those confusions stem from differences in philosophical perspectives, some of which are passing out of vogue. We refer to the wider literature for broad discussions of the issues: e.g. Cox (2012), Flage et al. (2014), French (1995; 2013; 2015), Moore (1983), Paté-Cornell (1996), Spiegelhalter and Riesch (2011) and Strand and Oughton (2009). Here we shall adopt the following approach. We recognise two broad forms of uncertainty.

- *Aleatory uncertainty* or *randomness*: such uncertainty relates to natural variation and randomness such as the unpredictability of a throw of a die or local gusts of wind.
- *Epistemological uncertainty*: such uncertainty relates to our lack of knowledge or scientific understanding.

When uncertainty is sufficiently well understood to be modelled quantitatively, we shall assume that it is done so via *probability*. *Risk* will be taken to reflect both the uncertainty of an event and its impact on us. We do not suggest that risk can be quantified as a single entity, but do accept that the uncertainty and the potential impact can be quantified separately. In taking this approach we are entirely compatible with current thinking on formal risk and decision analysis as discussed in, e.g., Bedford and Cooke (2001), French et al. (2009) and Smith (2010).

We should note that formal decision analysis is based on normative models, i.e. models of how we *should* behave. Obviously in emergency management, as in other areas of government decision making, we want to use such sound and defensible approaches to analysis. To apply normative models in practice, we need to recognise and draw upon complementary behavioural studies which have investigated how we *do* decide and behave. Only when we understand actual behaviour, can we communicate and inform decision makers, stakeholders and the public, because they may not hear, think about and react to such analyses in ways that are compatible with the tenets of normative thinking. While there has long been a recognition within decision and risk analysis that actual behaviour may differ from the idealised assumptions within decision models (Edwards, 1954; von Winterfeldt and Edwards, 1986; Morton and Fasolo, 2009), this has not been so much the case across other broad areas of operational research. Currently there is a lot of activity underway to recognise this, see, e.g., Hämäläinen (2015), Hämäläinen et al. (2013), Katsikopoulos and Gigerenzer (2013) and Keller and Katsikopoulos (2015).

A further matter of terminology that is current in many discussions that we shall refer to and draw upon is that of deep uncertainty. This refers to circumstances in which some uncertainties are so deep that it is impossible to agree on probabilities for these. Some writers effectively deny the conceptual existence of probabilities for such events. Knight (1921) was among the first to discuss the issue. Discussion has been reawakened in the past few years with the realisation among many risk and decision analysts that whether or not one might argue in theory that it should be possible to represent *all* uncertainties with quantitative probabilities, in practice there might neither be the time nor agreement among experts to do so (Cox, 2012; French, 2013; French, 2015).

2.2 Risk and Decision Behaviour

Kahneman (2011) introduces two types of thinking: System 1 and System 2. The former, often referred to as 'intuition' or 'gut reaction', involves a superficial analysis/interpretation of the relevant information based on much simpler forms of thinking on the fringes or outside of consciousness. System 1 Thinking guides how we do decide and behave and essentially comprises the 'hard-wired' reactions that are generated in the face of some event and are studied in behavioural decision science. Being 'hard-wired', this form of thinking has been laid down over the generations and hence is not entirely suited to risks and events in modern society. Indeed, System 1 Thinking can lead to some very unwise judgements and behaviours. Before this terminology of System 1 and System 2 Thinking came into common use, System 1 Thinking was usually referred to under the somewhat pejorative heading of 'heuristics and biases', reflecting a view that it was not rational or analytic (see, e.g., Kahneman et al., 1982).

System 2 Thinking is characterised by conscious analytical thought that involves a detailed evaluation of a broad range of information, often based on a rule that is assumed to provide the 'correct' answer or solution. Not all forms of System 2 Thinking are necessarily rational. It is entirely possible unfortunately to enter into some explicit form of analysis that is completely meaningless and ill-directed. However, in our context, formal risk and decision analyses – normative analyses – are examples of System 2 Thinking that have been validated against both careful axiomatic analysis and experience over many years (French and Rios Insua, 2000; Bedford and Cooke, 2001; French et al., 2009; Smith, 2010). The methodologies of risk and decision analyses are designed to help decision makers, experts and stakeholders avoid the pitfalls that may arise from System 1 Thinking and guide them to a shared understanding of the uncertainties and possible impacts.

Whether there is a true dichotomy between System 1 and System 2 or a gradation between subconscious informal and explicit formal thought is moot in behavioural science (Shleifer, 2012), but for our purposes here a simple distinction will serve.

An example of System 1 Thinking is provided by the *Plausibility Effect*, in which people substitute plausibility for probability Tversky and Kahneman (1983). System 1 assumes more plausible outcomes as having a greater chance of happening. Without System 2 actively being engaged in order to rectify this association, incorrect decisions can be made. Given that the members of SAGE and COBR, as well as other participants in the emergency management process are shown simulations of the evolution of the accident and the passage of the plume, those scenarios clearly become plausible to them and so may be seen as more probable than they are. Other heuristics used in System 1 Thinking to assimilate and react to information quickly can also lead to assessments of uncertainty that are generally too high or too low depending on the circumstances.

During the project (see Section 4) the view was expressed to us that experts in general and those in SAGE, in particular, would be less susceptible to the vagaries of System 1 Thinking. Less susceptible, perhaps; but the evidence shows that they are far from immune. Experts' knowledge and their judgements are based on extensive experience of and practice in their field. They understand the past well. Kahneman (2011) suggests that this means experts find it difficult to believe they have limited forecasting ability, because the future may not echo the past as much as they subconsciously assume. It means they will sometimes rely too much on System 1 Thinking, forming quick judgements rather than conducting slower more explicit analyses. Time pressures in emergency management inevitably encourage quick judgement. Tetlock (2005) performed a twenty-year study in which he asked experts of "political and economic trends" to predict whether certain events would happen in the short-term future. He found that the experts performed worse than if they had assigned equal probabilities to the events. Interestingly, the most knowledgeable experts performed worse overall. They were overconfident and made more outrageous predictions. In some instances, experts can be misled by statistics, even when they are supposed to have a full understanding of them. Soyer and Hogarth (2012) conducted an experiment where they showed economists statistical analyses of a simple, well-defined model and then asked them to provide related probabilistic forecasts. Experts who were shown graphical results only were generally able to provide better forecasts than those shown more quantitative output. Moreover, they were liable to ignore information on the fit of the model, inferring the same results even when the reliability of the fit was halved. They also found that the primary factor that influenced the quality of their forecasts was the length of time spent and that there was no relationship to professional rank or frequency of using regression analysis.

Experts can also be misled, especially when they fail to recognise the novelty in a situation; and serious radiation accidents are – fortunately – very rare events and so inevitably novel. Kahneman and Klein (2009) discuss the *naturalistic decision making*[4] approach, which relates intuitive judgements to the recognition of patterns. They observed the intuition of firemen and their ability to make highly effective decisions in any given scenario. The firemen had so many opportunities to practice, as well as fast, high-quality feedback, that they had developed an expert skill, which meant their reliance on intuition never failed them. It is in these recurrent regular scenarios with highly valid cues that such naturalistic decision making is most successful. Kahneman and Klein (2009) view intuition as being derived from a collection of heuristics that are less accurate and prone to natural human biases. In novel scenarios, they describe an expert's intuitive belief as being subject to the 'illusion of validity', where they have an unjustified sense of confidence but no applicable experience on which to base this. Genuine expertise in these environments comes from the ability to recognize the limits of one's own knowledge. Instead of relying on quick intuitive judgements based on System 1 heuristics, experts should pause and analyse, engaging System 2 Thinking. Hence Kahneman and Klein (2009) suggest that experts' confidence in their intuitions is not a reliable guide to their validity and should be questioned, especially in novel uncertain scenarios. Indeed, questioning and challenge are the key to keeping experts (and others) 'within the straight and narrow of System 2 Thinking'. Psychologists and management scientists working on developing sound processes of facilitating meetings which build a shared understanding of issues and then come to a well-founded decision or recommendation have long known that gentle but insistent challenge to all stages of the analysis avoids many of the pitfalls that can occur when System 1 Thinking drifts into the discussion unnoticed (French et al., 2009).

A salutary example of an expert misinterpreting information presented occurred during an exercise based at Hinckley point (MacFarlane and Leigh, 2014). See Figure 4. Despite information that the wind was blowing from the east, an experienced expert interpreted the lines locating the photo at Hinckley Point as outlining the plume, triggering a discussion on whether to evacuate Bristol.

Perhaps the leading model of System 1 Thinking is provided by *Prospect Theory* (Kahneman and Tversky, 1979; Levy, 2003; Barberis, 2012). This theory has at its heart a mathematical model, which can be looked at as a sort of perturbation of the expected utility model, a System

[4] Also called *instinctive* or *recognition-primed* decision making (French et al., 2009)

2 model lying at the heart of much of decision and risk theory. We shall not explore Prospect Theory in any detail: there are too many subtleties to do so. But we shall note four general, related and often observed behaviours that it models.

- *Reference-dependence*: the value ascribed to an impact depends on whether it represents a gain or loss relative to the perceived *status quo* and not to some absolute measure of value that is independent of the starting point. In emergency management, this might lead the acceptability of a potential consequence changing over time with changing perceptions of the course of the accident might take.
- *Loss aversion*: related to reference-dependence, this behaviour recognises that people are more sensitive to losses than to commensurate gains, both being interpreted as relative to their perceived *status quo*.

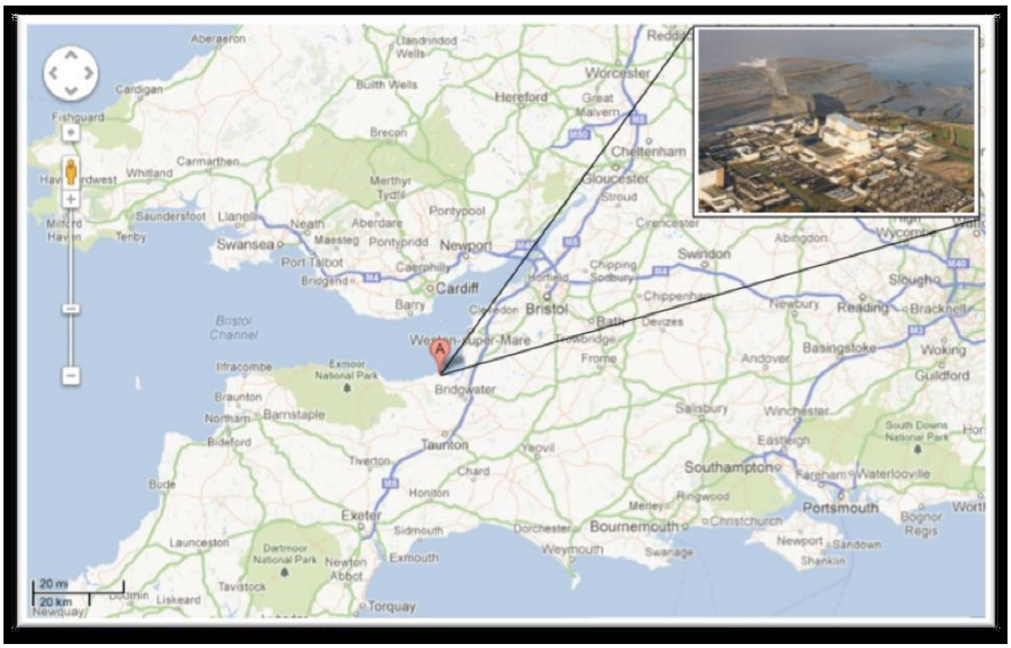

Figure 4: The lines locating the aerial photo of the plant at Hinckley Point were interpreted as the plume by an experienced expert during an exercise

- *Positive* and *Negative Framing*: when presented with a problem framed negatively in terms of losses people are more prone to take risks than when presented with the same problem framed positively in terms of gains.
- *Diminishing sensitivity*: the impact of a change diminishes with the distance from perceived *status quo*, i.e. diminishing marginal values are assigned to positive impacts *and* diminishing marginal losses are assigned to negative impacts.

These all relate to the *status quo* as perceived by decision makers. The word 'perceived' is important, because the framing of the issues can set that perception. Moreover, in an evolving event – an inevitable aspect of emergency management – perceptions of the *status quo* naturally evolve. Hence people's intuitive valuation of a consequence will change. Taken together these points imply the need to be explicit about the *status quo* in a decision and, if we are to help decision makers towards System 2 Thinking, to fix that *status quo* firmly in their minds during the discussion. This is particularly important in discussing how best and worst cases should be brought into any deliberation, because they may reset perceptions of the *status quo*.

There are issues relating to the perception of uncertainty as well as the perception of value. Gigerenzer (2002) categorised how people misunderstand uncertainty under four headings:

- *illusion of certainty*, which occurs because of a predisposition to create certainty from uncertain information;
- *ignorance of risk*, which occurs when people acknowledge the presence of uncertainty, but are unaware of its magnitude;
- *miscommunication of risk*, which derives from an inability to communicate present risks, thereby limiting knowledge of the risks;
- *clouded thinking*, which comes from understanding the risks but not being able to draw conclusions from them.

Gigerenzer attributes these misunderstandings to an innate innumeracy or, in recent terminology, a failure to adopt sound System 2 Thinking. Uncertainty and risk are complex concepts, requiring careful analytic thought if they are to be fully appreciated. These four misunderstandings can be present in poor crisis management. Any lack of transparency between decision-makers and scientific advisors can be attributed to the miscommunication of risk. Emergency managers may be ignorant of the risks, and without knowledge of the exact size of the uncertainty, their decision making will be superficial. Clouded thinking may arise, but is clearly to be avoided – and may be if the managers are guided to use sound System 2 Thinking. Kahneman (2011), in discussing misunderstanding of uncertainty, uses the acronym WYSIATI, meaning 'what you see is all there is', the notion that assumptions are made from incomplete information. The human mind is reluctant to accept ambiguities and instead uses available information to form a coherent impression that is then taken as certain. Kahneman suggests that the above four behaviours used to deal with uncertainty can be explained using this principle.

2.3 Communicating Risks to Decision Makers

The references cited in Section 2.1 point to an extensive literature on risk communication in general. Many academic studies have shown the difficulty in communicating risks. In the case of Chernobyl, it has been shown that poor communication and information provision to the public led to many of the socio-psychological consequences and stress-related health effects in the aftermath of the accident and that these were commensurate with the risks from the radiation itself: e.g. 1996 estimates, made 10 years after the Accident, suggested that morbidity arising from stress in contaminated areas of Belarus affected more than two thirds of the public (Karaoglou et al., 1996; Havenaar et al., 2003; Rahu, 2003; International Atomic Energy Agency, 2006; Bromet and Havenaar, 2007). In the UK, poor handling of many health scares during the 1990s led to a broad range of initiatives across government to improve the way that risks were presented to and discussed with those affected and the public in general (Bennett and Calman, 1999; Bennett et al., 1999). Those initiatives have broadly maintained momentum and the UK government can claim to be at the forefront of practice of public risk communication (Risk and Regulation Advisory Council, 2009; Bennett et al., 2010).

However, while there is now much guidance on how to present risk to stakeholders and the public, there is less guidance on how to communicate risks between different analysts and departments within government and ultimately to the decision makers. An exception is the work of Allen, Mishra and Pearman, who in a series of articles have considered the information needs of decision makers in emergencies and complex situations (Mishra et al., 2011; Mishra et al., 2013; Mishra et al., 2015). The Treasury's Orange Book (2004) is also a useful document setting the context for risk management in Government and organisations, which emphasises the need for clear communication of the risks to decision makers. However, it provides little clear advice on how this might be achieved.

Deitrick and Wentz (2015) provide an interesting contrast of the different needs of scientists and of decision makers in working with visualisations of geographic uncertainty. They recognise that scientists are interested more in the uncertainties that arise from their data, while decision-makers are more interested in the uncertainties about what their policies may achieve. While it is true that in the practice of science, scientists are seldom interested in predicting the consequences of particular actions, they miss the point that the uncertainties in the consequences of a policy are built on and include the scientific uncertainties arising from data and modelling. In our case, the uncertainties facing SAGE and COBR most definitely include those arising from meteorological and plant data as well of those inherent in predicting the dose reductions from various countermeasures.

To focus on our context, there is a lack of guidance on how the different departments and agencies should present their assessments to SAGE and how SAGE should offer its overall advice to COBR. Yet we have noted that the framing of information can affect greatly how it is perceived and dealt with by the listener. For instance, positive and negative framing effects (Kahneman and Tversky, 1974) suggest that decision problems framed in terms of potential benefits tend to make decision makers risk averse, while framing the problem more negatively make them more risk prone. Many studies on the effects of different framing have been extensive and emphatically confirmed the general result. Guidance suggests that the effect can be countered by presenting predictions in ways that emphasise *both* the potential losses and benefits, repeating the information in both frames (Maule, 1989); but, of course, this runs counter to the common imperative in an emergency to be brief and succinct. We may also note, in anticipation of our discussion of 'reasonable worst case analyses' in Section 4.3 below, that current government practice to lean to negatively framed considerations of 'how bad it may get' in an emergency may make the emergency managers more prone to take risks.

Decision analysts have developed many ways of helping decision makers and stakeholders understand and discuss risks during the formulation, analysis and evaluation of complex decisions (see, e.g., Clemen and Reilly, 2004; O'Hagan et al., 2006; French et al., 2009; Montibeller and Winterfeldt, 2015; Argyris and French, 2016). Modern decision analysis addresses the tensions between System 1 and System 2 Thinking and has many ways of countering superficial understandings. But it is a time-consuming process that does not easily fit into the urgency of emergency management. Moreover, it uses quantitative models to articulate and focus discussion. While many complex models are used during a radiation accident to predict the course of a plume, its strength, the likely pattern of deposition and the ultimate health effects, operationally there is, at present, no attempt to quantify the uncertainty and hence the risks. Some directions for research and development in this respect have been suggested and some steps have been taken. However, currently this is perceived as one of the major research needs within the Horizon2020 R&D programme within Europe[5]. A conference[6] between academia and UK government departments in early 2015 also emphasised this research imperative.

One key question in communicating risks to decision makers is whether it is better to use qualitative or quantitative expressions of uncertainty. There is a vast body of research literature which suggests that qualitative expressions can be understood in a variety of ways (see, e.g., Phillips and Wright, 1977; Budescu et al., 1988; Clark, 1990; Teigen and Brun, 1999; Hunink et al., 2001; Theil, 2002; Witteman and Renooij, 2003; Dieckmann et al., 2015). Some of these papers warn that the interpretation of uncertainty expressions are so varied that their use risks significant misunderstandings between decision makers; others are a little more optimistic in that they suggest that, with clear definitions of words such as 'probable' and 'unlikely' in terms of numerical probabilities, qualitative expression can be effective and unambiguous. The *Intergovernmental Panel on Climate Change* (IPCC) has made considerable efforts over several years to use a formalised system, a *probability lexicon*, to express uncertainties qualitatively to inform a range of governmental decision makers and stakeholders (Moss and Schneider, 2000; Intergovernmental Panel on Climate Change Core Writing Team et al., 2010):

Virtually certain	>	99%
Very likely	>	90%
Likely	>	66%
About as likely as not:		33% to 66%
Unlikely	<	33%
Very unlikely	<	10%
Exceptionally unlikely	<	1%

However, ongoing criticism suggests that they may not have been unambiguously successful (Budescu et al., 2009; Harris and Corner, 2011; Cooke, 2015). Moreover, while these attributions of meaning might be applicable to climate change, they may not be useful in other circumstances: e.g. in medicine a 1% chance of side-effects from a drug is not considered "unlikely". Rowe (2010, p18) summarised much evidence and discussion on the effectiveness of probability lexicons as:

> "Research suggests that people have different 'linguistic probability lexicons', meaning that they are likely to interpret specific uncertainty (probability) terms differently from one another. Differences in interpretation of verbal expressions have been found between people from different countries (cultural differences), of different ages, with different numeracy skills (and education level), and even between experts working within domains that frequently deal with uncertainty. Studies of formalized systems for using verbal uncertainty terms (e.g. the IPCC's system) reveal similar problems: there is wide inter-individual variability in interpretation of the terms chosen, and these are inconsistent with guideline definitions."

5 http://www.concert-h2020.eu/~/media/Files/Concert/calls/transnational_2016/02_EJPCONCERT_JTC2016_Preannouncement_VF.pdf?la=en.

6 *Calculating and Communicating Uncertainty*, BIS Conference Centre, London, 27-28 January 2015. http://www.southampton.ac.uk/~ccu2015/index.html.

There is the further issue of agreeing a way of combining statements made using such a lexicon. If the wind direction is likely to veer 30° to the north in two hours and the release is unlikely to be capped in less than three hours, how likely is it that the plume will pass over a particular village? Cooke (2015) provides an eloquent critique of probability lexicons from such a perspective.

Whatever the case, any approach of agreeing a formalised system of quantitative meanings for verbal descriptions of uncertainty is unlikely to be applicable in our context unless it is agreed and adopted across all of UK government and its agencies. Such a system effectively requires that all users are familiar and skilled in its use, instinctively understanding what each word means. For groups such as SAGE and COBR, which are called and formed quickly and with membership and expertise specific to an emergency, there is no time to learn a specific language of uncertainty during the handling of an incident. One could perhaps argue that for 'common' emergencies such as flooding, it might be possible to develop a common understanding of uncertainty terms; but for thankfully rare events such as radiation incidents, no such possibility exists.

In Section 2.1 we introduced the concept of deep uncertainty. This relates to uncertainties for which experts cannot agree on quantitative probabilities. Their disagreement might arise from some deep seated theoretical difference, but in the case of emergency management is far more likely to arise from lack of knowledge and time. For instance, if there is a threat of a failure that would lead to a release of radioactivity, there may be little prior experience to predict any source term, much less the probability that engineering actions will avert any release, nor might there be time to do any calculations relating to the dynamics within the reactor to estimate the source term that way. Several authors have begun discussions on how more qualitative forms of analytic discussion may be combined with more quantitative forms of analysis to address deep uncertainties. In particular, the idea of using multiple scenarios to conduct several parallel quantitative analyses. The combination of scenario planning and decision analysis has been a frequent focus (Wright and Goodwin, 1999; French et al., 2010; Stewart et al., 2010; Williamson and Goldstein, 2012; French, 2015). Several authors have noted the potential of this approach to structure analyses for nuclear emergency management (Carter and French, 2003a; Haywood, 2010; Comes et al., 2013; Comes et al., 2015). However, these references have tended to use more quantitative and probabilistic methods than are not yet computationally feasible in the first few hours of an accident. Moreover, it may not be possible to muster the expert judgements needed to initialise them quickly enough. For the present more qualitative means of exploring scenarios, much more in the classical tradition of scenario planning, may offer the way forward (Schoemaker, 1995; van der Heijden, 1996).

An advantage of considering several scenarios is that doing so brings an implicit challenge to any overconfidence in the accuracy of a model and the consequent danger of 'living too much in the model' (French and Niculae, 2005). Against this, it is important to remember the plausibility effect (Section 2.2 above) and address the potential of the plausibility of a scenario to increase its perceived likelihood.

2.4 Communicating Geographical Risk and Uncertainty

Introductions to discussions of uncertainty and its modelling by probability usually focus on uncertainty about events or, perhaps, propositions. Adding a spatial dimension to the things about which we are uncertain adds several conceptual, technical and psychological complexities. Uncertainty about a single point is not so hard, but uncertainty about a line, boundary or region inevitably brings in issues of probabilistic dependence: properties of points spatially close together are usually correlated. If we learn that a point is inside a region, then our uncertainties about whether points close to it also lie inside the region may be changed. Understanding and modelling spatial probabilistic dependence is hard. Add in a time dimension relating to the evolution and/or movement of a spatial entity and the problem becomes even more complex. Consider, for instance, the dependency structure within a time evolving area which has to maintain connectedness. Notwithstanding this difficulty, statisticians have developed many approaches to modelling and analysing spatial uncertainty and of spatio-temporal processes (Cressie, 1993; Gelfand et al., 2010). In our context, there are many particle and puff models of atmospheric dispersion which are, of course, spatio-temporal stochastic processes of specific natural processes (Jones et al., 2007; Rentai, 2011; Benamrane and Boustras, 2015).

However, once analysis of such models has produced informative answers to questions relating to spatial uncertainty, there has been remarkably little work and less progress on how to communicate the results to non-technical decision makers and others. In some cases, simply plotting pie charts or histograms at different geographical points may be both sufficient and intuitively interpretable: see Figure 5 for an example.

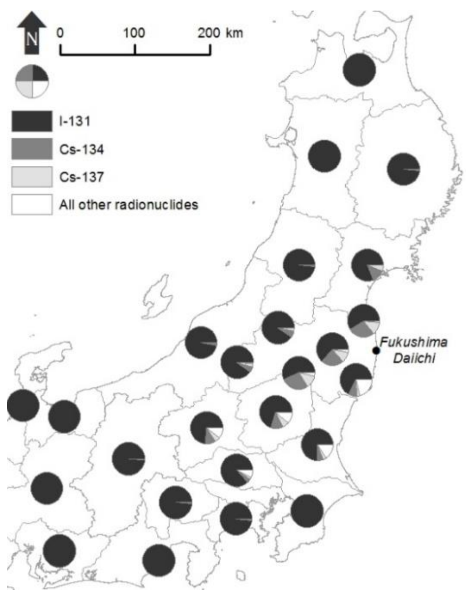

Figure 5: Geographical variability of the contributing radionuclides to the estimated 1st year thyroid dose to an infant (Bedwell et al., 2015)

Roth (2009a; 2009b) has conducted some preliminary work on the interpretation of a range of plots showing geographical variation and uncertainty, obtaining some indications of differences between expert and novice users. Taylor et al. (2015) show a plot of the probability of exceeding current average temperatures at some fixed future time. In the Euporias project[7] they tested a range of plots for their effectiveness in communicating uncertainty relating to climate forecasts. One can imagine a sequence of such plots over a number of years used as a means of demonstrating climate change.

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7 http://www.euporias.eu/Impact-Model-Assessment.

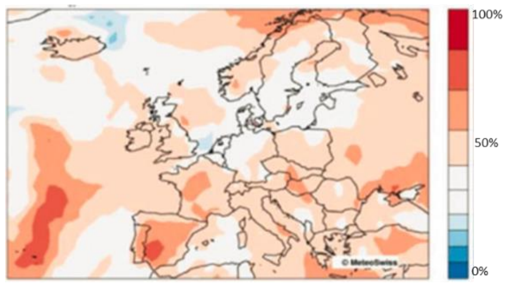


Figure 6: Plot of probability of exceeding current average temperatures at some future time (Taylor et al., 2015)

However, note that Figure 6 shows the probability of exceeding a number at any point at a particular time. There is no locational uncertainty about an evolving system such as a dispersion plume. Atmospheric dispersion plumes have very similar visual (and mathematical) characteristics to spatio-temporal probability distributions. Thus if we try to show the uncertainty in the location of several contours, there is a risk of confusion between the location of the plume and its uncertainty. Presenting the uncertainty simplistically risks visually enlarging the footprint of the plume, psychologically creating an impression among the decision makers that the potential consequences are far greater than they might be. Nonetheless, a sequence of plots similar to Figure 6 might present a way forward, if instead of seeking to plot information about the whole plume, we simply plot the probability of exceeding some quantity such as a proposed intervention level at a particular time.

Within computer graphics and cartography we note the papers of Brodlie et al. (2012), Edsall (2003), Fisher (1999) and Pang (2001), but recognise that they are barely a first step to offering a way forward. Pang (2001) does make one suggestion for displaying uncertain contours: see Figure 7. Uncertainty for variables such as temperature or humidity is coded as gaps in contour lines. The more uncertainty, the larger the gaps. However, a little thought shows that this representation relies again on there being limited positional uncertainty and that the location of higher values of the variables is more certain. For a plume of contamination in moderately changing winds the centreline would be so uncertain that this representation would become 'all gaps'.

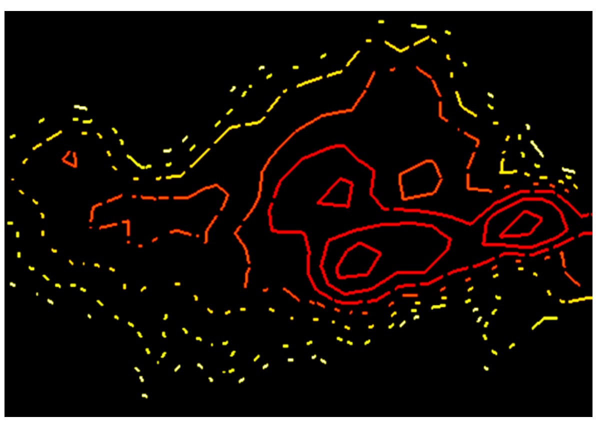


Figure 7: Uncertainty in contours indicated by gaps in contour lines: the greater the uncertainty the longer the gaps (Pang, 2001)

A decade ago, MacEachren et al. (2005) listed many challenges remaining to be addressed in the presentation and communication of geographical uncertainty, including:

- understanding the components of uncertainty and their relationships to domains, users, and information needs;
- understanding how knowledge of information uncertainty influences information analysis, decision making, and decision outcomes;
- understanding how (or whether) uncertainty visualization aids exploratory analysis;
- developing methods for capturing and encoding analysts' or decision makers' uncertainty;
- developing representation methods for depicting multiple kinds of uncertainty;
- developing methods and tools for interacting with uncertainty depictions;
- assessing the usability and utility of uncertainty capture, representation, and interaction methods and tools.

Since their review of the area, little progress has been made and the subject is still perhaps the 'Cinderella' of cartographical research. Jurin et al. (2010) are silent on geographical uncertainty although the topic would seem central to their topic of environmental communication; Gregory et al. (2013) are similarly silent in their discussion of decision making in the environmental arena. Tomaszewski (2014) barely considers the presentation of uncertainty in his recent text on the use of geographical information systems in disaster management, although he does touch on spatial statistics. The concept video (http://precisioninformation.org/.) produced by the Pacific Northwest National Laboratory for the US Department of Homeland Security does indicate some interesting suggestions for exploring, e.g., the implications of different weather scenarios, particularly in terms of wind direction. However, the video and its accompanying report are relatively silent on the general communication of geographical uncertainty (PNNL, 2011).

There are further reasons why the communication of geographical uncertainty is particularly challenging. Firstly, there are many conceptual issues in understanding what we mean by 'uncertainty' in a general sense; the literature referred to in Section 2.1 provides more than sufficient evidence of this. Adding a geographical dimension brings further conceptual complexities. Take one very simple sentence, apparently one that states uncertainty in probabilistic terms with some clarity: "The probability of the radiation plume reaching Warwick this afternoon is 30%." This begs questions about several confounded issues such as:

- What does one mean by 'radiation plume'? Does it mean any detectable radiation above average background or radiation at a level of significance for human health? Does the centreline of the plume have to pass over Warwick?
- What does one mean by 'this afternoon? – beginning to arrive around noon and continuing during the afternoon or arriving before 6.00pm or …?
- What is meant by 'in Warwick? – at a predefined point: or at any point in Market Square; and, if one is thinking of an area rather than a single point, how big does that area have to be?
- Might the 30% not refer to the chance of a particular event happening? Perhaps one is asserting that the plume is virtually certain to pass over Warwick during the afternoon covering about 30% of its area, but one is not quite sure where that area will be.

Defining spatio-temporal events in unambiguous terms is not trivial and, although risk and decision analysts recognise this and can define them in mathematically precise terms, it is far from clear that non-technical decision makers will follow and understand the nuances of their definition, particularly in the urgent circumstances of emergency management.

Geographical uncertainty inevitably means that the points and areas of interest and uncertainties about them will be located on maps; and this brings into play several psychological and cultural issues. Cartography is a long established skill in our society and for several centuries we have striven to produce more and more accurate maps. We are conditioned to expect maps to be precise. Severtson and Myers (2013) remark, “The concrete nature of images, such as maps, may convey more certainty than warranted for modelled information.” We do not represent uncertainty on maps in everyday life. Even the maps used in the media to forecast the vagaries of our weather make no attempt to represent uncertainty. Communication of uncertainty, if attempted, is left to the commentary of the presenter. Thus few people encounter any representation of uncertainty on maps. Meteorologists are clear exceptions in that they regularly look at traces of particles and ensembles to get a feeling of the likely changes in weather patterns; it just that they do not regularly take such representations into their discussions with the users of their forecasts. In the UK the Met Office will, of course, be a key participant in SAGE in preparing advice for COBR. However, the other members of SAGE will be much less familiar with any convention for indicating uncertainty, and their comprehension of any uncertainty representation would require them to learn and understand the convention during a time-pressed meeting. Moreover, one of the guiding principles of developing clear figures and charts in statistics is to focus on at most 3 or 4 ‘messages’ (Chapman and Mahon, 1986; Ehrenberg, 1986). But maps show many hundreds of details. Overlaying any representation of uncertainty on a map risks confusing the user with many extraneous geographical details. But what details are extraneous in the handling of a radiation incident are far from clear *a priori*. Is the name of that village important? Is the location of the regional hospital important? Etc.

One very relevant piece of research relates to the presentation and communication of the predicted paths of hurricanes (Wu et al., 2014). However, it should be noted that there is, in a sense, much greater uncertainty in predicting atmospheric dispersion of a plume from a radiation accident. While the strength of a hurricane and timing of landfall are to some extent uncertain, the main uncertainty relates to the track, particularly in what are by definition such unstable weather conditions. In a radiation accident there are much greater uncertainties about the strength and timing, i.e. the characteristics of the source term, which combined with vertical wind-shear can, perhaps surprisingly, create more uncertain conditions than those for predicting hurricane tracks and impacts. Moreover, the decisions faced by emergency managers in protecting populations in the paths of hurricanes are perhaps a little simpler: short-term ones on where and how to evacuate. Responses to radiation accidents require decisions on balancing short and long term risks in evacuation and sheltering, anticipating food bans, etc. which together may be more complex.

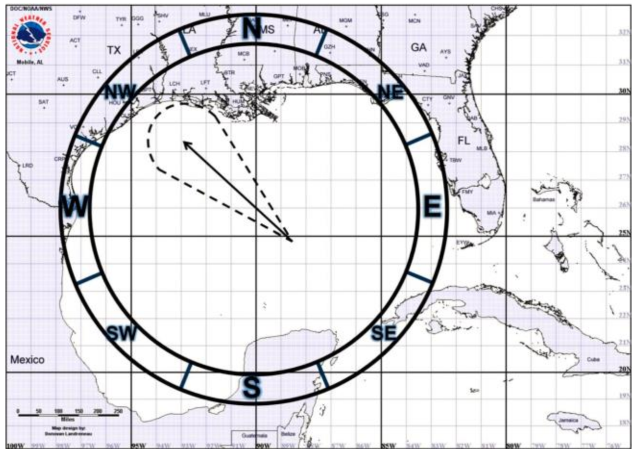


Figure 8: Representation of uncertain hurricane track used by Wu et al. (2014)

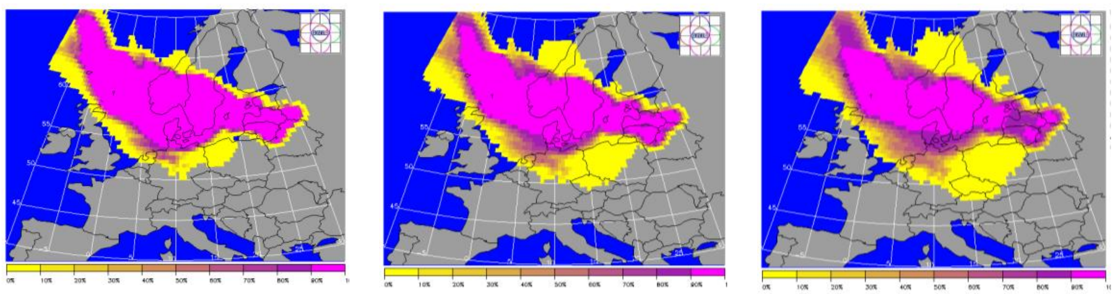
Nonetheless, we note that (Wu et al., 2014, p1037) found:

> "The results of this study provide mixed evidence for people's ability to comprehend probabilistic information about hurricanes. The positive findings are that people seem to be able to understand four fundamental aspects of hurricane track forecasting. First, they understand that a hurricane is most likely to strike the sector toward which the forecast track is pointing and the type of track forecast display appears to make no difference in their understanding of this idea. Second, they understand that a hurricane can change its direction toward the adjacent sectors. Here, too, there appear to be no differences among the three types of track forecast display in their understanding of this idea. Third, they understand that there are nonzero probabilities of the hurricane striking other sectors – although they recognize that the probability of a hurricane reversing its direction is low. Fourth, people are able to use base rate information about hurricane directions when that is the only information available to them.
>
> Nonetheless, there are negative findings as well. Participants' judgments were affected by an irrelevant factor, hurricane intensity, which indicates that major negative consequences might inflate local elected officials' expectations that they will be struck. Moreover, most participants violated the summation property, which might indicate that local elected officials also have inflated expectations that they will be struck by an approaching hurricane. The economic consequences of both of these errors are potentially quite significant."

The positive findings suggest that emergency managers are well able to appreciate and use information on uncertain tracks in their decision making. Though, of course, in our context there is far less base rate information available on the strength of any plume. However, the findings relating to negative consequences may be of much more concern. Violation of the summation property would indicate a tendency to overestimate some probabilities. We have already noted that negative framing issues may be worrisome if too much emphasis is given to reasonable worst cases, i.e. 'how bad things might get'. Here there is further evidence that overemphasis of very bad outcomes can skew emergency manager's judgements. We shall pick this point up further in Section 4.3.

Returning to the point about overlaying uncertainty information on the complexity of a map, note that Wu *et al* used a simplified map under their indication of the hurricane's track. Note also that the hurricane track was much simplified, effectively to a straight line. Atmospheric dispersion plume have much more complex paths, bending with changes in wind direction, and will need more complex displays.

There have been some previous suggestions for displaying uncertainty relating to paths and strengths of plumes in a radiation accident. Carter and French (2003b) suggested plotting the probability of the dose at a point exceeding a particular intervention level: cf. Figure 6. Raskob et al. (2009) and Hiete et al. (2010) made similar suggestions, as in more detail did Haywood (2010). However Carter and French's suggestion had gone one stage further. They recognised that it would be seldom the case that such a probability distribution would be known. So they assumed as a first approximation that the error between the forecast dose and the actual dose would be lognormally distributed. They then plotted the probability for different values of the standard deviation. They suggested asking the meteorologists to suggest several values for the standard deviation in terms of order of the magnitude of the forecast dose: see Figure 9. However, they noted that whether one took a sequence of 0.5,1.0 and 1.5 orders of magnitude or 1.0, 2.0 and 3.0 would be a matter for judgement. They also failed to convince the meteorologists in the ENSEMBLE project (Mikkelsen et al., 2003) that this would be a feasible or valuable way forward and it was not investigated further.



Error ~ 0.5 order of magnitude | Error ~ 1 orders of magnitude | Error ~ 1.5 orders of magnitude

Figure 9: Plot of the probability of exceeding some intervention level if the error in the forecast is 0.5, 1 or 1.5 orders of magnitude (Figure 1, Carter and French, 2003b).

Implicit in Haywood (2010) is the suggestion that one might use computer graphics to repeatedly plot plumes generated by sampling from the probability distributions of the source term and the weather predictions. This 'visual Monte Carlo' would show the decision makers the possible plumes that might arise given the uncertainties in the source term strength, time and duration of release and the uncertain evolution of the weather. It is, of course, an approach that would consume a lot of computer time and a lot of observation time on the part of the decision makers.

3 Context

3.1 The UK's Civil Contingency Act, SAGE and COBR

Different countries organise their national, regional and local emergency structures in different ways with different balances of responsibilities, accountabilities and authorities between local, regional and national centres. Carter and French (2005) describe some of the structures used in Europe as they existed a little over a decade ago, discussing their relative advantages. Some countries have national emergency centres with full time staffing. In the UK the Civil Contingencies Act of 2004 established the current framework for emergency planning and response ranging from local to national level. The Act replaces the civil defence legislation of the previous century. The Act places responsibilities on local authorities, the blue light services, a range of utilities and other organisations to engage in emergency planning and to build local resilience to a wide range of potential emergencies. During an emergency, the local chief constable is given executive authority and responsibility to establish and manage the response. He or she does this with advice from emergency planning officers, the blue light services, local authorities and other relevant utilities and organisations and, if technical advice is needed, from the local STAC. Nationally, the response is co-ordinated by COBR, advised by SAGE. As we have noted in Section 1.2, the focus of the project and this report is on developing and communicating SAGE's advice to COBR in the event of a radiation accident and, specifically, how geographical uncertainty might be assessed and communicated.

Note that the UK system applies to *all* crises with the potential for regional and nation impacts. Thus there will be inevitable compromises inherent in the organisation and processes of SAGE and its interactions with agencies, departments, the local response and, particularly, COBR. The organisation and processes will not be perfect for dealing with a radiation accident nor a national epidemic nor a volcanic ash cloud nor any other potential disaster. Rather the requirement is that they should be flexible enough that they can deal with any national crisis that requires a scientific assessment of the risks.

The Science and Technology Committee (2011a) Report describes the workings of SAGE and COBR during the Swine Flu Pandemic, as well as more generally. More generally, Cabinet Office (2012) publishes guidance on the organisation of SAGE and its accountabilities, authorities and responsibilities.

There are no permanent members of SAGE and COBR. Indeed, COBR is an abbreviation of Cabinet Office Briefing Room. That the national crisis response unit is derived from a location is a reflection, perhaps, of the fact that the UK's emergency response at all levels is organised very contingently. Membership of the teams and groups being largely formed on the day to bring together the relevant skills, knowledge and authorities needed to handle the emergency. This approach has the clear advantage that the *right* expertise should be present; but it also risks the disadvantage that the teams may never have worked together before the incident. True, regular exercises reduces some of the latter risk, although some members might not attend exercises, possibly sending a more junior representative. Moreover, major national exercises are few, maybe 1 or 2 per year, and perhaps for a variety of reasons not as challenging as they might be. This means, for instance, that members of SAGE may not have a common understanding nor, more importantly for us, a common language for uncertainty: see discussion on qualitative expressions of uncertainty in Section 2.3.

One aspect of the operation of SAGE and COBR that constrains the potential ways of communicating geographical uncertainty is the facilities available in their meeting rooms. For security reasons, computer projection is limited to highly secure software such as well tested office products. Thus there is (currently) very limited opportunity for

- using geographical information systems to answer specific queries about local demography, size of schools, hospitals, types of local industry, etc.;
- changing the scale, contour levels and other characteristics of plots 'on the fly';
- displaying the evolution of plumes over time in a simple video;
- interacting with software during the meetings and asking 'what-if' questions;

nor, specifically, for

- using decision support software such as RODOS (French et al., 2000), ARGOS (Hoe et al., 2000) or, indeed, displaying interactively output from the software used within the JAM process currently being developed.

This denies SAGE and COBR some of the advantages of such software discussed in, e.g., French et al. (2000), French et al. (2007) and Benamrane and Boustras (2015). However, the timescales under which SAGE and, particularly, COBR work may mean that such interactive computing is not feasible within their meetings anyway and it may be better used in the 'back-rooms' at the agencies and departments feeding information to these meetings. However inter-operability across those 'back-rooms' equally needs to exist.

3.2 The ADMLC Project

The UK Atmospheric Dispersion Modelling Liaison Committee sponsored this *Review of Best Practice and the Development of Principles for Presenting Uncertain Information in Radiological Emergencies*. The objectives of the underlying project were:

- to develop improved presentational techniques for representing the uncertainties and lack of knowledge in the early stages of a radiological emergency and
- to build an improved, shared understanding and realistic expectations between decision-makers, scientists and communicators of what will be known in the early phase of a radiological emergency and how this knowledge, *particularly relating to the areas at risk as any plume spreads*, will evolve.

It involved a range of activities, including the substantial literature review that underpins Section 2; however, its key elements related to three workshops. The first workshop aimed to understand the current processes of information presentation and discussion within SAGE, as well as their decision making needs. The workshop revolved around a hypothetical scenario based upon previously observed weather dispersion. During the workshop the scenario was presented, stepping through the first few hours of the accident and explaining what would be known at each time, what would not be known, what seemed most likely to happen, and what the radiological and health impacts might be. The scenario contained many features which illustrated the inherent uncertainty in such events. The focus of discussion was on how to advise COBR and senior government on the significance of the uncertainties involved in predicting the course of the plume, the impact of this on health and the likely need to prepare resources to support recovery. Building on the experience of this workshop we developed our proposals for presenting information on the potential geographical spread and impact of a radiation plume during an accident at a nuclear plant. The second workshop involved many world experts on the presentation of scientific and expert advice in high risk contexts. Its aim was to challenge and criticise our proposals for the presentation of uncertainty during a radiological emergency, and to gain advice on how to improve our techniques. The third workshop had similar attendance to the first, but this time focusing on the presentation of information using plots, graphs, and other display techniques proposed by the project to convey the uncertainty, particularly its geographical aspects, and then to reflect on how useful the different approaches are.

One caveat should be noted here: although the project focused in large measure on the provision of information and advice to COBR, it had no direct contact with COBR. Our understanding of their drivers and expectations derived from working with and meetings with those who organised, advised and reported to COBR. Indeed, in some sense we did not have direct contact with SAGE, but only individuals who had or might serve on SAGE in some capacity. Future work might seek to clarify with COBR directly what they perceive as their information needs, what they are trying to manage and get right and, perhaps, what they are trying to avoid getting wrong.

4 First Exploratory Workshop with SAGE and Subsequent Discussions

4.1 Organisation

In September 2014, we ran the first one-day workshop with SAGE; or, to be more precise, a group of experts who might well be called into SAGE during a radiological emergency. Attendees at the workshop were drawn from:

- the Cabinet Office;
- the Department of Energy and Climate Change;
- the Department of the Environment, Food and Rural Affairs (DEFRA);
- the Department of Health (DH);
- the Environment Agency (EA),
- the Food Standards Agency (FSA),
- the Government Office of Science;
- the Home Office;
- the Met Office;
- the Ministry of Defence (MOD);
- the Office of Nuclear Regulation (ONR);
- the Radioactive Incident Monitoring Network (RIMNET); and
- Public Health England (PHE).

As such the workshop simulated the operation of SAGE who would be responsible for providing input to the Government emergency management team COBR. In general, the composition of SAGE is determined on the day according to the specifics of the emergency and who is on call within the ministries and agencies concerned.

We note that the academic members of the project were surprised that several of the key representatives from departments and agencies were relatively inexperienced and brought less expertise to the workshop than they had hoped. Promotions and career development within the Civil Service ‘moves people on’, often to unrelated posts, losing expertise in the departments that they leave, and seemingly does so with growing frequency these days.

In this case, the workshop was structured around an accident at a hypothetical reactor sited at Abbotsbury near Weymouth in the south of the England[8]. We used real geography, demography and a weather sequence that had occurred in the recent past. However, we emphasise that there has never been any nuclear plant there nor is there any suggestion that any nuclear plant would be sited there. Using a hypothetical plant had two clear advantages. First, none of the participants would be biased or advantaged by previous experience of an exercise sited on the plant. Secondly, they would all have to learn about the site and local geography from the maps and other information during the workshop.

A realistic emergency plan was developed for the site with appropriate zones, bands and sectors. This plan specified sheltering and evacuation strategies and advice on taking iodine tablets to be implemented immediately in the event of an offsite release exceeding an action trigger level of 100 $\mu Sv\ h^{-1}$ gamma dose rate at perimeter monitors.

[8] The slides used to present the incident to the workshop are appended in Annex 1

The hypothetical accident was assumed to have begun during the early morning of the workshop. The offsite release exceeded the action trigger level and at 8.00am an offsite emergency was declared. During the workshop, we stepped through the accident in 'real time', providing SAGE with the information and details that would be available to them. To do this we predicted mobile monitoring measurements using the Met Office's atmospheric dispersion/deposition program, NAME, based on actual weather conditions and evolution that had occurred sometime before in the area and a specific source term and profile (~0.2% of inventory) that we had chosen. The dispersion, deposition and dose predictions were produced using NAME and PHE's consequence modelling programmes, using weather forecasts provided by the Met Office. Moreover, the source term and its profile changed over the day to correspond with (hypothetical) changing information from the plant. Predictions of the total release were taken to be ~2% of the Chernobyl inventory initially, but these declined during the day. The simulation recognised that the models take time to configure, run and check. Thus it was assumed that the predictions presented to SAGE at, say, noon would be based on data and weather forecasts available at 10.00am, whereas any mobile monitoring measurements could have been collected as late as 11.30am. In addition, we used RODOS, a nuclear emergency management system which uses comparable but different atmospheric dispersion, deposition and dose modelling programmes, to provide SAGE with predictions that would be available from our near European neighbours. Thus SAGE were provided with measurements and predictions that agreed in general terms, but differed in detail. Such conflicting information almost inevitably is encountered in practice.

4.2 Findings

The event was run under Chatham House Rules so many details of the event and discussion are confidential to the participants. Thus while we summarise the conclusions from the discussion, there is no attribution of who made particular points nor the organisation that they represented.

4.2.1 *Reasonable Worst Case Analysis*

There was a strong view that COBR (and hence SAGE?) would be more interested in 'How bad it could get?' more than relative likelihoods or quantification of uncertainty. So if we take risk as some compound 'uncertainty⊗impact', then there would be more interest in information that bounds the impact than that bounding the uncertainty. It was felt therefore that a 'reasonable' worst case was needed, but there was much discussion during – and continuing after the exercise – about what was a reasonable worst case and how it should be distinguished from an absolute worst case? One point that should be made here is that, whatever a *reasonable* worst case might be, an *absolute* worst case, particularly during the period that a release is on-going, would inevitably be very significant, covering substantial tracts of land.

Discussion also concerned how a reasonable worst case would evolve as information and data came in. Some suggested that as the accident evolved and predictions of the source term generally reduced, there would be a process of redefining the reasonable worst case or moving towards a prediction. In general, as the event progressed it might be expected that

COBR/SAGE would want to know the 'current situation' and 'best estimate' as well as a reasonable worst case[9].

After the workshop, there was a long interchange of emails continuing the discussion, some asking for a worst case that did provide a bound on the worst that could conceivably happen, whereas others recognised that it might 'get worse' as the event evolved. One participant summarised the former view as:

> "What it has clarified in my mind is that we need to focus on providing two outputs: the best estimate impact and the 'bounding reasonable worst case' impact. The best estimate is self-explanatory and can change in time, both up and down, without causing too much concern. However, your summary would seem to suggest that the reasonable worst case should provide an upper bound to the impact; this means it could be reduced over time, but should not be revised upwards, and most certainly should not turn out to be an underestimate. It sounds as if the presentation of these two estimates will provide decision makers with the communication of uncertainty they perceive they need.
>
> "I suggest you need to test whether this is in fact the case - I admit, it sounds very plausible to me. If this is correct, then the focus of the work of specialists, in the context of communicating uncertainty, needs to be on how to generate bounding reasonable worst case impacts that are never going to be revised upwards, but are also not so conservative as to be useless."

The opposing position was summarised as:

> "A Reasonable Worst Case (RWC) by definition is not the worst case. The concept that this could not be wrong and an unreasonable/unforeseen set of events might unfold does not make sense to me. If we never want to risk underestimating just how bad it could get then we have to go beyond reasonable. … In terms of impact I think the idea of bounding it with 100% certainty has even more problems as the range of factors, pathways and individual impacts (e.g. food, health, ecosystems) means that there is no universal worse case. There may be a dominating impact such as health and that makes it more sensible. However in terms of forecasting potential impact the issues around the weather including precipitation, changes in wind, timing of release with timing in weather mean we cannot tie ourselves to the idea that the impact might change/be better or worse."

From both the discussions in the workshop and the subsequent email discussion, two key questions stood out.

1. How to present information that indicates the uncertainty associated with whatever the scientists manage to produce?

[9] Note that there is potential for confusion in non-scientific communities between 'best estimate' and 'best case'. The former refers to current expectations about what will happen; the latter to the best outcome that might result even though the likelihood of that might be very low. The former derives from statistical terminology relating to producing what might be loosely called a good approximation to what is actually the case; the latter derives from risk analysis terminology relating to the best – in this case, least damaging – outcome that we might expect. Both terms were used within the workshop and later discussions. Care clearly needs to be taken in using them in COBR and other non-scientific contexts.

2. What do the decision makers, i.e. COBR, need to support their decision making, and hence what sort of uncertainty they are actually looking for on whatever information they are given?

The two questions are clearly linked, but solving the latter is a political as much as a technical issue.

4.2.2 *Lack of real information on uncertainties*

Note that *no* slides, plots or indeed verbal presentation of the accident used any quantification of uncertainty. Currently the models and communications do not quantify uncertainty in any formal sense. The Met Office may offer comparisons of likelihood, e.g. being sure of some rain, but uncertain where, but that is all. Uncertainty was handled purely through qualitative discussion of the possibilities.

Nonetheless, participants were often confused by the uncertainty in predictions (not just the geographical part). There were several points made about presenting only 'facts' to COBR. This might, *in extremis*, mean that little useful would be presented for making a decision, because of the lack of clear facts in the early stages of a radiation accident – and forecasting is not fact by definition. Participants, often confusing *reasonable* worst case with the worst case, repeatedly articulated a need to 'bound' the worst case. They also argued that credibility would be undermined by any reasonable worst case that was exceeded by incoming data – a circumstance that is very likely during an incident. It was not fully appreciated that even a very reasonable prediction can turn out to be wrong and that we cannot post-rationalise uncertainty. On the other hand, participants were not given any information that could have helped them get to grips with the geographical uncertainty or the variability in depositions, e.g. different trajectories, different dose predictions etc. Some of the comments indicated that this would have been useful, as would have been the effect of various countermeasures.

Some participants suggested that COBR and ministers might be more willing to live with the uncertainty than SAGE members. If so, they need more information on the possible actions, impacts and associated costs, risks and benefits as opposed to more formal information on the uncertainty? The focus should be on the impact of uncertainty on the advice and decisions rather than the underlying situation. If the recommendations are robust to the uncertainties, i.e. SAGE would advise same actions over all current possibilities, then the uncertainty is not important *per se*. COBR might accept more uncertainty at the start to avoid understating the worst case and having to get more pessimistic as time goes on.

4.2.3 *The possibility of making erroneous judgements*

It was suggested by the facilitator that plotting lower contours might have the psychological effect of suggesting an accident of greater geographical extent. However, there was strong agreement among the participants that SAGE experts would *not* be misled. There was a consensus that experts would handle the information available in a sound way and not make mistakes. These assertions suggest a misplaced confidence if the evidence in the literature is to be taken at face value: see Section 2.2, p17. A short report[10] on the risks of expert overconfidence in their ability to avoid error was produced after the meeting and circulated to ADMLC.

10 This has been slightly extended and incorporated into Section 2.2.

On the specific issue of plotting more contours than were strictly necessary, it was noted that having lower contours on the map allowed the levels to be scaled up quickly in the event of evidence that the release was greater than believed.

4.2.4 *Comparing different maps*

Different GIS software produce maps on different scales and it is hard to compare them by eye, relating points of interest. Indeed, many maps are built by systems which use different algorithms to label places and features. So sometimes a town of interest on one map is not labelled on another. Thus it was difficult to line up and compare different plots. This conclusion had been anticipated during the preparation of the hypothetical event, but was confirmed during the meeting as participants compared information between different maps.

4.2.5 *Maps showing arrival times of the plume*

There was a suggestion that maps predicting time of arrival of the plume could be useful, e.g. time-contours for arrival times of radionuclides; or, perhaps better, maps showing time-contours predicting when certain concentrations or levels of radioactivity would be exceeded. However this was not a majority view and it was felt that simple mental calculations on rough wind speeds would enable questions relating to arrival times of plumes to be answered sufficiently accurately for the purposes of SAGE and COBR.

4.2.6 *Contingency planning for large scale distribution of stable iodine*

Early in the discussion it was recognised that there was a possibility that stable iodine would be needed to be distributed to larger numbers than there were local supplies. Accordingly, a decision was made to move supplies to the region from the national stockpile as a contingency.

4.3 Reasonable Worst Case: A Critique

Possibly the clearest finding from the workshop was that the concept of a reasonable worst case was central to the thinking of the participants playing SAGE – even if there were clear differences in their individual understanding of what this concept actually meant.

The idea of a reasonable worst case is common in emergency planning and more generally in risk assessment. The Scientific and Technology Select Committee (2011a) take as the definition that a reasonable worst-case is "designed to exclude theoretically possible scenarios which have so little probability of occurring that planning for them would lead to a disproportionate use of resources". The National Risk Register of Civil Emergencies (Cabinet Office, 2015) defines the term as: "A 'reasonable worst case' is chosen which represents a challenging manifestation of the scenario after highly implausible scenarios are excluded." The concept has been taken over, consciously or otherwise, from emergency *planning* into emergency *response* without apparent recognition that the contexts of these two activities is significantly different. In the former, one is considering the possibility, remote or otherwise, of some disaster. In the latter, something has most definitely happened. This difference is recognised in radiation protection in that public dose limits for normal living are much lower than the intervention levels recommended for emergency response to a radiation accident.

While a reasonable worst case – or one might suggest, several reasonable worst cases – are essential in emergency planning to ensure sufficient resilience is built into a system without being excessive, it is far from clear that emergency response should focus almost entirely on a single reasonable worst case. Winkler (2015) emphasises the importance of a balanced view of uncertainty in his reflections on the response to Winter Storm Juno which threatened North Eastern United States in January 2015. Our review of risk behaviour in Section 2.3, indicated that focusing on negatively framed outcomes can induce risk prone behaviour and increase the plausibility of such outcomes making them seem more likely. The results of Wu et al. (2014) suggest that this is a very real possibility: see the quotation in Section 2.4. The concept of reference-dependence would see any better consequence as more acceptable if it is considered relative to a worst case than if it is considered relative to previous *status quo*: e.g. "We are only facing 300 likely cancers and it could have been 12,000."

It is interesting that in their response to the Scientific and Technology Select Committee (2011a) *Report on Scientific Advice and Evidence in Emergencies*, the Government said (§53):

> "The Government recognised in its response to the 2009 influenza pandemic and the 2010 volcanic ash episode that the 'reasonable worst case scenario' may not always be the best way to communicate risk to the general public as it can raise unnecessary alarm. During response, communication of the best, most probable and worst case can be a helpful way of communicating uncertainty and the range of possible scenarios." (House of Commons Science and Technology Committee, 2011b)

Yet our experience in Workshop 1 and, indeed, to some extent in Workshop 3 (see Section 5 below) suggests that SAGE would communicate the risks and uncertainties to COBR using a reasonable worst case. It is also clear from the Scientific and Technology Select Committee (2011a) report that the use of a reasonable worst case was central to the handling of the Swine Flu Pandemic and its use may have delayed an appreciation that the flu was actually much less virulent than this suggested. It might be suggested that SAGE and COBR's ways of working have been developed for a much wider range of emergencies than radiation accidents; so reasonable worst case analysis might be a robust approach which is able to provide support for emergency decision making in a wide range of different contexts. But the observations of the Science and Technology Select Committee do not lean in this direction, though they are far from definitive.

A further criticism of focusing on a single reasonable worst case is that there may be many different negative impacts that could arise and some may not be visible in a single reasonable worst case. Clearly health impacts are bad and mitigating them is important: that is what the discussion revolved around in the first workshop. But what about agricultural impacts? Being based upon much lower intervention levels, food bans can be much more extensive than the areas recommended for sheltering and evacuation. Food bans can also be long lasting: witness sheep farming in Cumbria after Chernobyl. There are also scenarios in which an economic activity can be placed at risk from short term evacuation. For instance, oil refineries cannot just be shut down. They take 24 hours or so to power down, otherwise irreparable damage may be done. If such impacts do not show up in the single reasonable worst case because they occur with a different plume direction, then SAGE and COBR will not fully appreciate 'how bad it might get' and so not put in place the necessary resources and contingency plans.

Finally we note that the advice and assessments from SAGE are sought by COBR in relation to what should be *done*: their purpose is to support decision making. It is far from clear that describing a reasonable worst case is the most helpful form of information for this. The focus of a reasonable worst case is simply on what might happen. It does not offer an analysis of what might happen if different actions are taken. Suppose a reasonable worst case is used as a basis for evacuating a small town that might be exposed to moderate doses. However, the timing of the release, its strength and the weather that actually occur are such that a smaller village is exposed to much higher (though not deterministic) doses. Getting the evacuation plans wrong in this way not only results in exposures to significant dose, but may also lose public confidence in the response more generally, with a consequent loss of compliance with subsequent countermeasures and increases in stress that bring health effects of their own (note the remarks and references in Section 1.1). This might lead to a worse outcome than that taken as the reasonable worst case; and, moreover, an outcome that would have been avoidable.

4.4 Possible ways forward

The first thing that was apparent when thinking about how the communication of uncertainty within SAGE discussions and in their report and advice to COBR was that currently it is impractical to consider presenting uncertainties as probabilities on maps. There are several reasons for this:

- Neither NAME nor PHE's systems produce probabilistic assessments in their current operational use, nor is it likely in the near future that they could do within computational times commensurate with emergency response.
- Even if NAME and PHE's systems could produce probabilistic assessments in reasonable time, they would need as input the probabilities of the different possible source terms which would be very difficult to obtain. Indeed, one may argue that the uncertainty on the source term is deep (see Section 2.1), with little data available and a likely lack of consensus among the available experts, who in any case would be focused on actions to bring the plant under control.
- Were probabilistic assessments available, the lack of interactive computing within the rooms used by SAGE and COBR would greatly limit what could be displayed and communicated.

Thus we quickly settled on more qualitative ways of communicating and discussing the uncertainties. Three directions for development were identified:

- *Verbal descriptors*. One possibility would be to develop a formalised lexicon of probability terms along the lines of the IPCC scale (see page 22). As noted earlier, for this to work within the context of SAGE and COBR the scale would need be adopted across UK government and its agencies so that all participants were completely familiar and used to working with the same interpretation of each verbal descriptor.
- *Present a range of scenarios*. Scenario analysis is used throughout business and government to develop strategic thinking (Schoemaker, 1995; van der Heijden, 1996). The most basic forms of scenario analysis develop a series of maybe 4 or 5 scenarios that are 'interesting' in some sense and may be used as backdrops for strategic conversations. How 'interesting' is defined is moot. There are many possibilities. Here one might consider 'the best we can hope for', the 'most likely outcome' and the 'reasonable worst case'; or, picking up on our remarks above, two or three reasonable worst cases reflecting qualitatively different impacts. The details of such scenarios would be fleshed out using different NAME and PHE's systems runs.
- *Expert Assessments of the Uncertainty*. We might consider asking the experts in SAGE – particularly those from ONR and the Met Office – to draw together their understanding

from the various qualitative reports and discussion within SAGE to give quantitative probabilities for scenarios[11] such as those mentioned above.

We discounted the use of verbal descriptors fairly quickly because of doubts about their consistent use (see discussion in Section 2.3). Moreover, any steps in that direction would require authority from levels above ADMLC and thus would not help ADMLC improve their current practices within the short term. Thus our thinking developed along the lines of presenting several scenarios and possibly eliciting some quantitative probabilities from the experts within SAGE.

4.5 Proposal for Presenting Several Scenarios to SAGE

Scenario analysis has a history going back several decades (Hughes, 2009). In its most basic form, it develops a series of maybe 4 or 5 scenarios that are 'interesting'. In our context ‘interesting’ relates to different resolutions of uncertainty: e.g.

- best and worst cases of some form – useful for bounding possibilities;
- a likely case – useful for maintaining a balanced perspective;
- an assumption that a particular event happens or does not – useful if a key event is unpredictable and shrouded in deep uncertainty.

Note that only a handful of scenarios are developed. Part of this is because in qualitative scenario analysis, each scenario is debated and explored at length and there is not time to do more; certainly not within the context of emergency management. But there is also the issue of cognitive capacity in that decision makers often cannot absorb and balance out the implications of many scenarios. Miller (1956) warns that human information processing capacity is limited to a handful of things.

Note also that scenario planning insists neither that the scenarios are mutually exclusive nor span/partition the future. Thus assigning meaningful probabilities to scenarios is non-trivial and requires careful explication of the underlying events.

In the more technical use of scenarios such as SAGE's, the scenarios may be developed constructively by focusing on the key uncertainties (Schoemaker, 1993; Mahmoud et al., 2009). In our case, the key uncertainties relate to (Haywood et al., 2010):

- the source term including release profile, release composition, and release height;
- weather including windfield, precipitation, and the arrival of any front.

The first step is to discretise the possibilities: see Figure 10. The tree on the left suggests how different possible weather systems might be generated: will or will not a front arrive; how might the windfield evolve; will or will it not rain? Obviously, one might consider not whether a front will arrive, but what time it will, generating more than two possibilities. Other eventualities may be split into more or less possibilities. What matters is that developing such a tree helps set up a set of different weather systems that are candidates for consideration in the analysis. Similarly, the possibilities for the source term (the tree at the top of the figure) are partitioned according to its time profile, its composition and its effective release height.

[11] Strictly a set of scenarios do not form a partition of the future, so assessing probabilities is not straightforward. We give a much more operational meaning to this below.

However, we do emphasise that this is indicative of how the various possibilities might be developed. Other splittings might well be considered. It would depend on the circumstances.

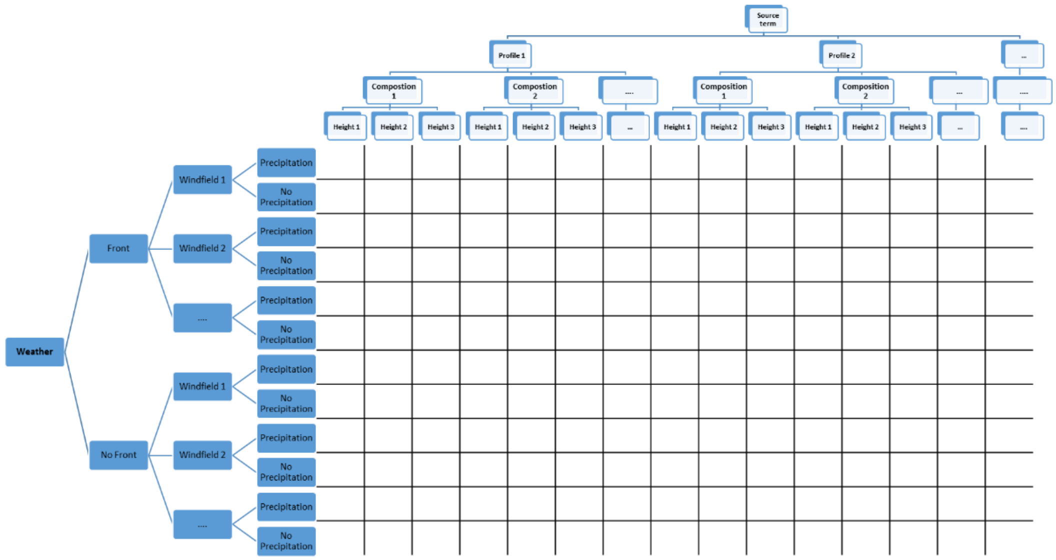


Figure 10: Generating scenarios to consider during a radiation accident (1)
Note: the trees are Illustrative only and different breakdowns of the uncertainty would be used in any specific case

The leaf nodes of the weather and source term trees label the rows and columns of the table in Figure 10. Each element in the table defines a scenario. Note that at this stage we have partitioned the future in mutually exclusive scenarios which span all possible futures. Thus conceptually it is possible to assign probabilities[12], although as we have indicated above, this would be practically impossible given the time and information available.

Even with the simplest set of possibilities on the components of the source term and weather, there would be too many scenarios to generate, much less discuss within SAGE. Thus the next step is to select a few 'interesting' source terms and a few 'interesting' weather systems, but that would still leave many scenarios to consider: e.g. if we selected four weather systems plus four source terms, we would have 16 scenarios to consider: e.g. those shaded in Figure 11.

Note that the shaded scenarios no longer partition the future so assigning probabilities would leave a large proportion of the probability mass unassigned.

But it is clear that selecting a few 'interesting' weather systems and source terms independently will generate too many scenarios to explore and understand in the time available. Instead it is better to select interesting scenarios, i.e. elements in the table, directly. We might simply consider, say, five scenarios, see Figure 12:

- A 'bad' worst case, if not the absolute worst case (WC)

12 Strictly, we need to recognise that the discretisation of continuous variables in forming the weather and source term trees means that we are approximating the probabilities; but that process is well understood within decision and risk analysis (Høyland and Wallace, 2001).

- Two more reasonable worst cases (RWC1, RWC2)
- A 'likely' case (LC)
- A 'best' case (BC)

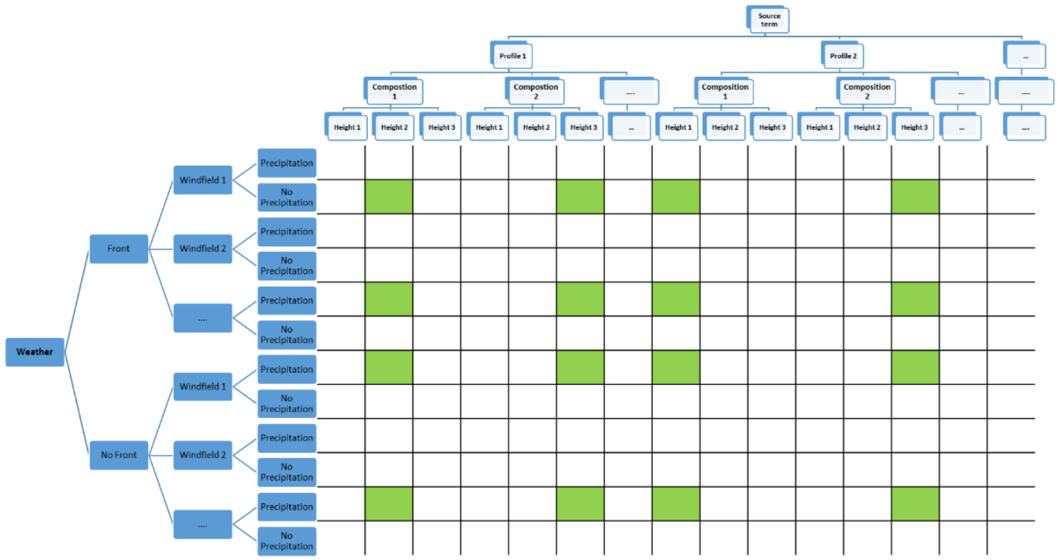


Figure 11: Generating scenarios to consider during a radiation accident (2)

Even developing just five such scenarios will not be an easy task, requiring much skill and judgement, though it is a skill that can be rehearsed and developed through exercising. Note also that this choice of five scenarios emphasises worst cases so that the downside expectations are bounded, but still includes a best and likely case to emphasise that it might well not be as bad as a worst case.

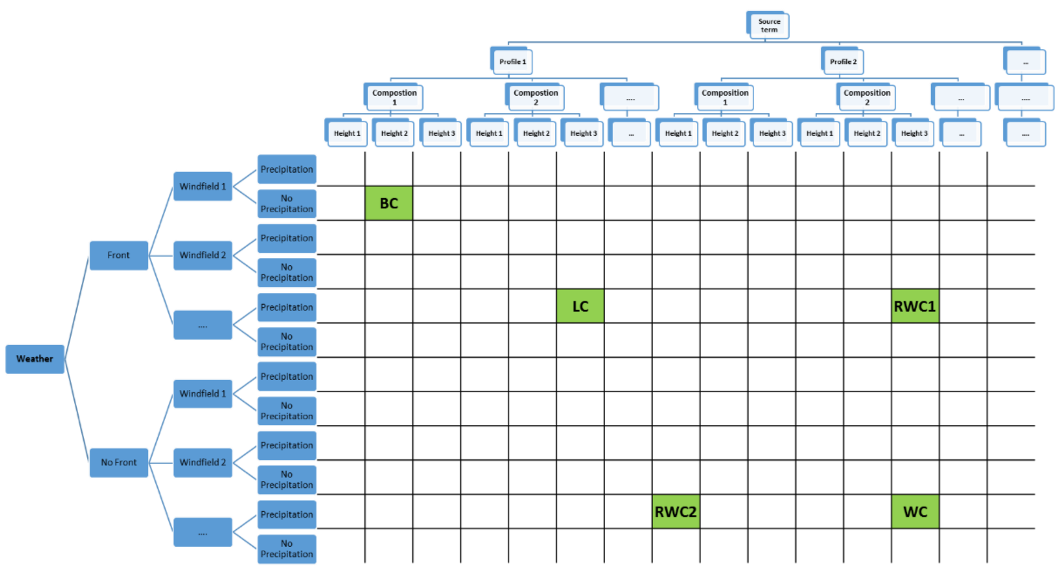


Figure 12: Generating scenarios to consider during a radiation accident (3)

Assigning probabilities to these five scenarios is now clearly only allocating a small fraction of the probability mass: i.e. it is much more probable that something else will happen. Since we developed the qualitative presentation of uncertainty to SAGE for the third workshop in terms of the scenarios alone, this was not a problem for us. However, we now indicate how the relevant probabilities might be defined.

What we might do is ask experts, either teams involving ONR and the Met Office or SAGE itself, to assign rough probabilities to broad events whose outcomes are similar to these events. By 'outcome', we mean the health, agricultural and other consequences that arise from the contamination. By 'similar to' we mean the overall impact of these consequences is roughly the same. Thus we might ask the experts to consider the following four events, which might with careful interpretation be considered a partition (see Figure 13):

- *Event 1*: the outcome is broadly similar to that shown in the BC scenario, though the details including the precise geographical area affected may be different (shaded yellow).
- *Event 2*: the outcome is broadly similar to that shown in the LC scenario, though the details including the precise geographical area affected may be different (shaded green).
- *Event 3*: the outcome is broadly similar to those shown in the RWC1 and RWC2 scenarios, though the details including the precise geographical area affected may be different (shaded blue).
- *Event 4*: the outcome is broadly similar to that shown in the WC scenario, though the details including the precise geographical area affected may be different (shaded red).

In simpler terms, one might take plots and details relating to the 5 scenarios into COBR and say something like:

> "Roughly our judgement is that there is a probability of a% that the outcome could be as good or better than BC, a probability of b% that the outcome will be comparable with LC, a probability of c% that it could get as bad as RWC1 and RWC1 or something similar, and a probability of d% that it would get as bad as WC."

Clearly $a+b+c+d = 1$ in this case; and one would expect $(c+d)$ to be very much less than $(a+b)$. If one could in some way assign probabilities to all possible source terms and all possible weather systems (i.e. to the rows and columns) and if one could allocate every possible scenario in the matrix to one of the four events one might be able to calculate the four probabilities using something like the figure above, but this approach would – as we have been arguing – take too long relative to the timescales of emergency management. But it might be possible to elicit very rough probabilities to provide an expression of the judged balance of the risks to inform the decision making. For instance, a teleconference between the Met Office, the operators, ONR and perhaps PHE could discuss the risks and generate rough probabilities to take into SAGE. This could take place in parallel to the development of the various plots and dose assessments needed by SAGE. If not done in advance of the SAGE meeting, such probabilities might be developed during discussion within SAGE to help inform COBR.

But, as will become clear, we did not seriously explore either of these possibilities in the project.

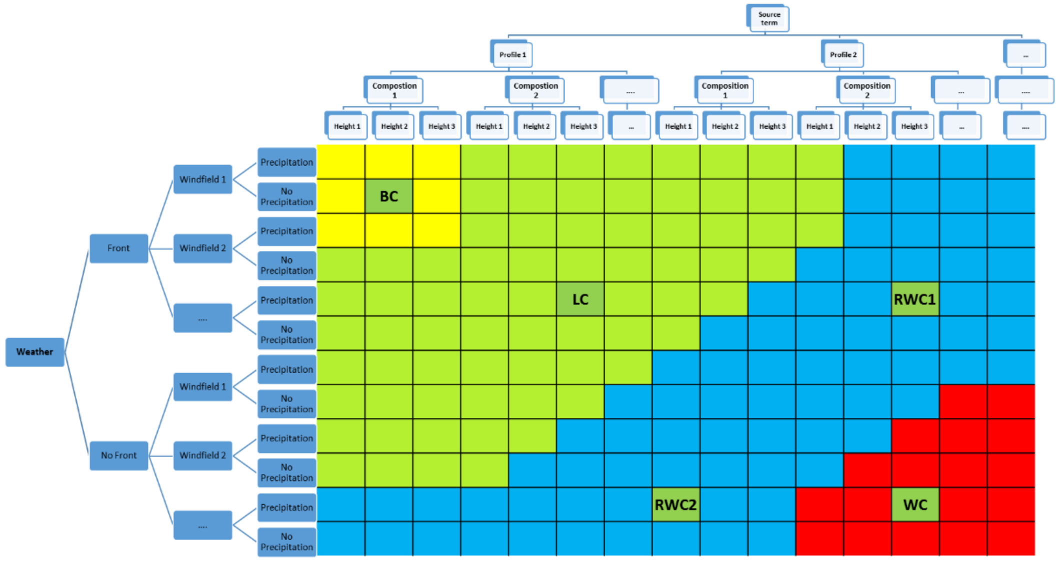


Figure 13: Possible way of reintroducing probabilities into the analysis

4.6 Workshop 2: External Critique

To test our developing ideas we took them to a meeting of the COST action IS1304[13]: *Expert Judgment Network – Bridging the Gap Between Scientific Uncertainty and Evidence-Based Decision Making*. This took place in mid April 2015. This action brings together many of the leading risk and decision analysts from across Europe who are concerned with the structured elicitation and use of expert judgement. We ran two plenary sessions at the Action's meeting to draw in their advice on our progress.

The opening afternoon was spent on a general discussion of geographical uncertainty and the difficulty in communicating it. The following morning, we ran through the hypothetical accident developed for and used in the first workshop. This generated a lot of discussion as the participants came up to speed. We then discussed the suggestion to use scenarios given above in Section 4.5. Many points repeated those developed and discussed during the first workshop. Noteworthy points were:

- Should dose be presented as a population weighted value on the maps? Dose relates to increased individual risk.
- Mapping - how much does different detail matter or is it just there for general referencing?
- Qualitative decision trees have proved useful in laying out contingencies to decision makers. Might they be developed and used here?
- Where would expert judgement fit in? If quantified uncertainties are used, would they all be based on expert judgement or could some come from models?

13 http://www.cost.eu/COST_Actions/isch/IS1304, http://expertsinuncertainty.net/.

- Are maps the best way to present the information that COBR needs? Might 'FN' curves be (more) useful: i.e. a rough plot of the number of people exposed above a certain dose versus the likelihood that they are?
- There is a need to focus on what is important for the decisions to be made. If the same decision would be made however some uncertainty was resolved, then there is no need to display and discuss that uncertainty.
- Should uncertainties be expressed on what might happen or what might need be done: e.g.,
    - 'There is a 10% probability of values exceeding' or
    - 'There is a 10% probability of the need to evacuate'
- It might help to show the matrix (Figure 12) used to develop the scenarios to SAGE and perhaps COBR: i.e. attempt to show how the scenarios are built up and how individual scenarios relate.
- Most relevant scenarios are dependent on the end point that is of interest. So how do we answer everyone's questions?

The most important observation for this project was, perhaps, that no one suggested ways forward that we had not considered, at least partially; nor were we referred to any significant previous projects or references that we had not seen.

4.7 Discussion with Prof Robin Grimes

In May, we met with Professor Robin Grimes, the Chief Scientist at the Foreign and Commonwealth Office. Professor Grimes was part of the SAGE group that provided official advice on the 2011 Fukushima disaster, and is a leading academic in the UK nuclear research community. He is a likely candidate to chair SAGE in the event of an actual radiation accident.

We learnt of some recent changes to the working of SAGE and COBR:

- STAC now have direct links to SAGE and COBR through their respective Chairs. This has many advantages, but it also means that STAC may provide data and observations directly to COBR, which are more up to date than those that SAGE have seen.
- An operator's representative will now be present in SAGE to observe proceedings and provide information when asked.

He felt that the idea of providing several scenarios to SAGE was sound, and similarly scenarios could be provided to COBR, but he felt that there would be time to present at most three in SAGE's report and advice to COBR, perhaps a good case, a likely case and a reasonable worst case. The timescales in managing an event would, he suggested make eliciting probabilities impossible.

4.8 Development of materials for the Third Workshop

In planning the third workshop and how we would present and encourage discussion of uncertainties, we came to the conclusion that it was impractical to present or elicit probabilities. The time pressures in a real event would simply be too great; and would also be too great in the third workshop itself. Furthermore, exploring the use of probabilities might well lose the sympathy of the participants, since they would know that any greater quantification than at present would be impossible to implement. It seemed more important to us to help develop better forms of qualitative argument and to encourage SAGE to move towards a more balanced perspective than a focus on a reasonable worst case. Thus we decided to use several qualitative scenarios to help present different possible evolutions of a radiation accident to SAGE.

In developing the hypothetical event, we also wished to include the risk of a substantial impact other than the direct risks to human health. We wanted to emphasise that the use of a single worst case might miss such a risk.

In this case, the workshop was structured around an accident at a hypothetical reactor sited at Pagham Harbour on Selsey Bill in West Sussex. As in the first workshop, the accident at the hypothetical reactor was set in real geography, used real demography, land use, etc. and a weather sequence that had occurred in the recent past, though we changed its timing slightly, but well within the bounds of realism. We emphasise that there has never been any nuclear plant there nor is there any suggestion that any nuclear plant would be sited there. Again, note that by using a hypothetical plant we ensured that, first, none of the participants would be biased or advantaged by previous experience of an exercise sited on the plant and, secondly, they would need to learn about the site and local geography from the maps and other information during the workshop. We assumed that a realistic emergency plan had been developed for the site with appropriate zones, bands and sectors, and was implemented fully and successfully by the local response.

In order to test the idea of using scenarios, we developed a description of a two stage accident: an initial moderate release (approximately 1×10^{14} Bq of iodine-131 over 1 hour), with a risk of a much more significant one that could be a large release (approximately 4×10^{14} Bq of caesium-137 and 1×10^{16} Bq of iodine-131 over 2 hours) or very large release ($4 \times$ the large release: 2×10^{15} Bq of caesium-137 and 4×10^{16} Bq of iodine-131 over 2 hours). Moreover, the weather conditions included the likely arrival of a front with consequent change of wind direction around the time of this possible second release. The discussion in the workshop would take place after the moderate release, but before any larger release had occurred. The scale of the large releases is such that very significant proportions of UK agriculture stretching from West Sussex up into East Anglia could be subject to food bans lasting a month or so.

We used the Met Office's NAME and PHE's Probabilistic Accident Consequence Evaluation software (PACE) to develop the scenarios. PACE is a probabilistic accident consequence modelling tool, built within a geographic information system (Charnock et al., 2013). Having modelled and investigated a number of scenarios, we selected four of these to present to the participants of the workshop (N.b. we maintained the number of the scenarios we had used in the development to emphasise that the Met Office and PHE would have looked at more than the four scenarios before reporting to SAGE):

Scenario 1. The moderate release at 11.00am only.

Scenario 3. The moderate release at 11.00 followed by a large release starting at 14.00 and ending at 16.00 with steady weather conditions and the delayed arrival of the front after that. The magnitude of the large release is approximately 4×10^{14} Bq of caesium-137 and 1×10^{16} Bq of iodine-131 over 2 hours.

Scenario 5. The moderate release at 11.00 followed by a large release starting at 14.00 and ending at 16.00 with a change in weather conditions following the arrival of the front. The magnitude of the large release is approximately 4×10^{14} Bq of caesium-137 and 1×10^{16} Bq of iodine-131 over 2 hours.

Scenario 6. The moderate release at 11.00 followed by a *very large* release starting at 14.00 and ending at 16.00 with steady weather conditions and the delayed arrival of the front after that. The magnitude of the very large release is approximately 2×10^{15} Bq of caesium-137 and 4×10^{16} Bq of iodine-131 over 2 hours (four times greater than the “large” release).

Discussions in SAGE would take place at noon, with a requirement to report to COBR at 13.00. The materials presenting the 4 scenarios to the workshop are appended at Annex 2.

5 The Third Workshop

5.1 Organisation

We ran the third one-day workshop in London in November 2015. Again we sought attendance from those who might be members of SAGE during the response to a radiation accident. We were fortunate that Professor Robin Grimes attended and chaired SAGE during the exercise as a Chief Scientist. We invited all those who had attended the first workshop, but several had changed roles and others who had taken over their responsibilities were invited. On the day, three invitees were unable to attend because they were required to deal with flooding incidents, leaving thirteen attendees who could role play SAGE. Of these five had not attended the first workshop. The following departments and agencies were represented:

- the Cabinet Office;
- the Department of Energy and Climate Change;
- the Department of Health (DH);
- the Environment Agency (EA),
- the Food Standards Agency (FSA),
- the Foreign and Commonwealth Office
- the Government Office of Science;
- the Met Office;
- the Ministry of Defence (MOD);
- the Office of Nuclear Regulation (ONR);
- the Radioactive Incident Monitoring Network (RIMNET);
- Public Health England (PHE).

In addition to the research team, a number of observers were also invited to the workshop.

5.2 Structure of Workshop

After a welcome and introductions, the workshop was broadly organised into the following sequence of activities.

- Presentation of the hypothetical incident via scenarios 1, 3, 5 and 6 (see Annex 2). At this point we did not allow discussion, although questions of clarification were allowed.
- Immediately after the presentation of the hypothetical incident, we issued an individual questionnaire (see Annex 3) to all participants who had not been involved in developing the event. The aim was to elicit their initial understandings and perceptions of the key issues, capturing each participant's rough mental model (Granger Morgan et al., 2002) of the situation.
- The Players, chaired by the Professor Robin Grimes, then discussed the situation under the same time pressures as SAGE would. They had to prepare analysis and recommendations to take into SAGE exactly 1 hour from the start of their SAGE meeting, which effectively limited their discussion to 45-50 minutes. No further information would be available to them during this time.
- The workshop then moved away from the discussion of the hypothetical incident and its handling *per se* and discussed the format (4 scenarios) in which information about the event and, particularly, the uncertainty was given to SAGE. Was this more useful than the

current practice of presenting essentially one reasonable worst case? Note: this discussion did not focus on their recommendations and advice to COBR. This discussion was structured using post-its. Each participant was issued with several post-its and asked to note on each any topic, issue or concern reflecting on the morning's discussion, the issues within the exercise/event and the way that we presented the scenarios. These were stuck on a white-board and then sorted into groups of related ideas during the discussion.

- Discussion and advice to the ADMLC Research Team on the lessons and conclusions that they should include in their final project report.
- A second individual questionnaire (see Annex 4) to elicit how the Players' views and perspectives had changed over the day, what advice and suggestions they had for the project.

5.3 Findings

Organisationally the workshop worked well. The hypothetical accident gave the participants cause for thought, making them reflect deeply on how to address the uncertainties, more so than in the first workshop. There are asides to this effect in the questionnaire responses, and many participants said this as they were leaving at the end of the day. With hindsight, we should have included someone to role play the operator's observer in SAGE. In responding to the first questionnaire, 8 participants felt that they needed more information on the potential source term. Given that the scale, timing and character of the source term is a key uncertainty in managing the response to a radiation accident, this is not surprising. But here it may also be a reflection that we provided very little detail of the form of the accident at the plant and thus any engineering insight on how the accident might progress. Someone role playing the operator's observer at SAGE could have input information on the progression of the accident and attempts to seal the leak and shut down the reactor. Some simulation of the link with STAC might also have been advisable. However, the participants accepted these lacks of realism and it does not seem to have affected our general findings.

Unlike the first workshop run in September 2014, the mini-exercise here allowed SAGE to run broadly as it would on the day. It was chaired by a chief scientist and in no way facilitated by the research team. Its workings were formal and kept broadly to a sequential agenda. Given that the Government Office for Science (GO-Science) is currently working on documents to emphasise the key questions that chief scientists and SAGE need address in such situations, such formality of working is likely to be the case in a real event – and is probably the most efficient way of developing advice within the short time limits faced by SAGE.

1. The most relevant observation is that presenting 4 possible scenarios did broaden the discussion within SAGE over that in the first workshop in which a single reasonable worst case was presented. Formal and informal comments from participants at both confirm that. However, scenarios 3 and 5 were relatively quickly eliminated from discussion, and scenario 6 quickly became a reasonable worst case. This happened despite the presentation having made clear that it had not been produced as a 'bounding case' and despite a protest that the Met Office and PHE had not developed it as such. It seems that the need to think and work with a reasonable worst case is embedded deep in the psyche of the running of SAGE and COBR. One reason for this, articulated both during the workshop and elsewhere, is that COBR's role is to ensure that resources are ready should the accident become very bad. Whatever the case, the majority of the discussion

focused on Scenario 6 and assumed that, if the accident were limited to the scale of Scenario 1, the local emergency plan would be broadly sufficient. If the need to identify a single reasonable worst case remains central to the operation of SAGE, then this has implications for how scenarios are generated and selected for presentation to SAGE.

2. Many of the reflections in the questionnaires suggested the need for numerical probabilities or some form of quantitative likelihood to be attached to the scenarios or events within them. Yet on the two occasions that probabilities did occur within the discussion there was some confusion as to their meaning and to the research team observing the discussion it seemed that a misinterpretation was promulgated through much of the discussion. Specifically, an assessment was made early in the meeting that *if a second release occurred*, it was 50-50 whether this would be a large or very large release. Note that those are conditional probabilities. Later it was stated that the probability of a second release was about 10%, meaning that the probability of a very large release was about 5%. Yet for much of the discussion there was an impression that this probability was much higher. Indeed, towards the end of the discussion, a participant noted this. That comment did stimulate some reflection on the effect of this misinterpretation and it was concluded that since they had focused on a bounding case the probability was irrelevant and their advice would be unaffected. Another argument for using a reasonable worst case? But the real point to make here is that probability calculus is not easy, particularly in the case of conditionality; and here we have an example of experts being confused to some extent.

3. Whatever the case about quantitative probabilities, many made comments on the need for a standardised language – a probability lexicon – to discuss the qualitative likelihood of events. Nonetheless, it was notable in the discussion after lunch that there was not really a clear common understanding of 'credible' and some question of whether COBR would have the same understanding of the word.

4. Similar remarks were made about the need for standardisation in other areas. It appears that MOD use different integration periods for dose in their emergency planning than other departments and from the 2 day integration period used to produce the dose plots for this exercise. It was also remarked that common formats are needed for maps and geographical information across *all* emergency management: flooding, radiation, whatever.

5. The need for more information on time was remarked on in both the questionnaires and during the discussions. Most particularly, there was a need for a timeline showing when different information might be expected to be available and different uncertainties resolved. Some remarked that showing the evolution of the plume over time would be helpful in indicating how long the response had to implement measures at different places. Similarly, timelines of the accumulation of dose would show the relative risks of evacuating before and after plume passage.

6. In terms of potential impact the discussion focused almost entirely on (direct) health effects. Consequences for agriculture were hardly discussed despite the information offered in the (verbal) presentation of the scenarios that preliminary modelling just completed suggested that very significant proportions of the country's dairy and arable production could be affected. In discussion, it was made clear that COBR, particularly in the early stages of an incident were *only* concerned with human health. As people were leaving one of the research team asked two participants about how they would

treat a situation where they had two scenarios with similar likelihoods: one with a localised health impact (e.g. a small area such as a village); and another where there was a huge possible economic impact (e.g. a container port being unusable). The answer was that government would only focus on the health impact scenario in the early phase as they had to be seen to be protecting health. Other impacts would be regarded as less important.

7. Although there was far from a clear view, there was a majority who felt that SAGE should deal with the details of uncertainties and give COBR clear, uncomplicated messages with only broad statements of the key uncertainties and a timeline for their resolution.

8. In terms of presenting the scenarios, it was clear that in addition to maps there was a need for numerical tables summarising such things as the numbers of people exposed to different levels of dose, numbers evacuated, etc.

9. Many participants reflected on the need to develop, in advance of any incident, standard templates, summaries and legends, not just to facilitate and standardise the presentation of information, but also to prompt the collection of relevant data. Specifically, in terms of the scenarios, there should have been short descriptive summaries of their assumptions and the consequences that they entail.

10. Interestingly, though perhaps not relevant to the ADMLC project, as in the first workshop there was a decision to begin mobilising the national stable iodine stocks and move supplies to the accident area as a contingency measure.

6 Conclusions and Recommendations

6.1 General Remarks on the Context of the Research

Any discussion of how uncertainty – or anything else for that matter – should be analysed and communicated needs to pay attention to the context in which this occurs, particularly how the conclusions of that discussion will be used. Here, as we emphasised in Section 1.2, our focus is on how SAGE should be informed of the uncertainties relating to the evolution of a radiation accident in its early hours, how SAGE should deliberate on those uncertainties in formulating its advice to COBR, and how it should then communicate the uncertain context of its advice to COBR. There are several key points that need be noted.

- During the early hours of an accident, there is much that is or could be unknown: see Section 1.3. Currently, few, if any, of these uncertainties are quantified, partly from the lack of (implemented) methodologies to do so, but mainly because of the urgency of the situation and the need for those with the expertise and information to focus on bringing the plant under control and implementing the emergency plans.
- While local emergency management address the immediate response, the roles of SAGE and COBR are to take a slightly longer term view of the event and put into place those resources that might be needed in the coming hours and days.
- SAGE and COBR have formal ways of working. They are committees established by the Civil Contingencies Act and set within the formal governance structures of the UK. This was particularly evident during the third workshop.
- The current development of JAM and the improved synthesis of information that it will bring provides an opportunity to consider how information including the uncertainties will be provided to SAGE.

While not entirely within the remit of our project, we begin in Section 6.2 with more general recommendations relating to the general organisation and processes of SAGE. These recommendations suggest that to some extent current practices constrain the presentation of uncertainties and the availability of expertise to understand, discuss and address those uncertainties. Recommendations 1 to 4 arise largely because the University of Warwick members of the research team were able to observe the processes within SAGE in a 'disinterested' fashion, but inevitably these observations are partial because their 'disinterested' status also means that they are made without a full awareness of the history and process that led to current practice. Sections 6.3 and 6.4 provide discussion, observations and recommendations that more clearly address the objectives of the project.

6.2 Organisational and Logistical Issues

In recruiting participants for the first workshop, we discovered that several 'experts', who we invited and who would be candidates for membership of SAGE during a real accident, were very new to their posts and had little experience related to radiation accidents. For the third workshop which took place only 14 months later, we made a similar observation, finding that several of the participants at the first workshop had been promoted or moved on to other unrelated posts. This represents a major issue for the effectiveness of SAGE during an actual accident. If our experience is a guide, it is possible that 25%-40% of the experts sent by agencies and ministries may be inexperienced and may not have attended any major exercise. Participants at workshops 1 and 3 also commented on this; as have several members of

ADMLC[14]. This potential presence of inexperience and consequent reduced expertise in the specifics of responding to a radiation accident is a significant constraint on the discussions within SAGE in relation to understanding and addressing the uncertainties, particularly since much of the uncertainty is currently unquantified.

> *Recommendation 1:* Attention should be given to the effects of promotions and career development within the Civil Service and Government agencies on the expertise that may be available to SAGE during a radiation accident – and presumably other events.

In running the project, we learnt of a number of factors that limit the format and quality of the information presented to SAGE and COBR. For instance, for security reasons the software available in the meeting rooms is limited to well-tested office products (word processing, spreadsheet and presentation software). Nor is it easy to link to systems run remotely at the Met Office or PHE. This means that emergency management systems[15] such as JAM cannot be run in the room to answer such questions as:

- What is the integrated dose likely at that hospital?
- What would happen if the release continued for 3 or 4 hours longer than expected?
- How many people will need to shelter in the area for which this countermeasure is planned?

Moreover, there is no possibility of running a video sequence showing the evolution of the plume within a given scenario over time nor to 'jitter' plumes to indicate uncertainty.

Materials to be presented to SAGE will come from a variety of sources: word documents, PowerPoint slides, emails and, possibly, telephone messages. Drawing these together into a *coherent* set of materials with common use of terminology, units, formats, etc. for SAGE and then summarising them for COBR is a significant challenge. The advent of guidance notes and key questions for the Chief Scientist and SAGE during a radiation accident will reduce this challenge, and the development of formal reporting templates (if not already underway) could significantly reduce the risk of poor information capture and communication and that of failure to take into account some piece of information. We also noted that the SAGE secretariat is provided by GO-Science and thus may not be immediately located at the SAGE meeting room. At best, this risks delays in production of copies of notes through unfamiliarity with the local facilities; at worst, they may limit the form of the notes and materials that can be produced by SAGE for COBR.

Information system scientists would address these problems by developing an *executive information system* which would pull together information from multiple sources, automatically using common scales, axes and so on for graphs and plots and producing the required tables to compare different scenarios, etc. Results would be conveyed through an interactive *dashboard* (French et al., 2009; Jashapara, 2011). However, as noted, such systems are not currently available within the security cordon around SAGE and COBR.

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14 Wider knowledge management issues relating to the loss of expertise through promotions and the career structure of the Civil Service have also been reported by the BBC; See http://www.bbc.com/news/business-35821782.

15 For a survey of the functionality of such systems see (French et al, 2007)

We recognise that such logistical, support, organisational and security constraints may be in place for the best of reasons in terms of the overall security and support of UK Government in all forms of crisis, but we also note that they are constraints that affect the implementation of best practice in emergency management within the narrow perspective of the precise emergency faced, here a civil radiation accident.

> *Recommendation 2: There are logistical, support and organisational issues which limit how information can be presented to SAGE and COBR. There may be benefit in reviewing whether the need to present a greater range of information e.g. as in the case of JAM, requires some modification of the structure and organisation of the communication and information presentation within SAGE and COBR.*

It has often been remarked that no accident ever goes as 'planned'. The academic members of our team were quite surprised to discover that most UK national exercises only rehearse response to design-basis accidents. Moreover, those that do go beyond this may not do so in full detail or for times beyond the first day, or even part day. In any case, it is not clear that there are sufficient exercises to ensure that all potential members of SAGE will experience a sufficient range of potential accidents to understand fully their potential impacts. Our exercises went substantially beyond design-basis, though nowhere near the scale of the Chernobyl or Fukushima Daiichi disasters. Several participants at the workshops said that they found this useful in that it stretched their thinking more than in more restrained – and, therefore, very probably more realistic – exercises. For instance, in both of the project's exercises there was a realisation that the need for stable iodine might exceed its availability locally and hence, as a contingency, it would be worth moving supplies to the area from the national stockpile (Sections 4.2.6 and 5.3).

> *Recommendation 3: There may be benefit in exercising SAGE (and other bodies) with more significant accident scenarios than are conventionally used.*

In Section 2.2 we noted that experts are not immune from making slips and errors in interpreting or analysing information. In the third workshop, it was apparent some participants misinterpreted probabilities conditional on the occurrence of a second release as unconditional probabilities at least for part of their deliberations. We also noted that facilitators of problem solving workshops use gentle but insistent challenging questions and interventions to counter such misinterpretations (French et al., 2009). However, while emergency management is undoubtedly a problem solving context, the stress and pressures of time mean the carefully-paced, reflective, iterative processes that take place in such workshops are too slow to be incorporated into the workings of SAGE. Nonetheless, deliberations within SAGE can and should incorporate as much challenge as possible. They do incorporate much challenge; we saw much in the workshops. Scientists invariably question the evidence and reasoning behind their colleagues' statements. However, it is important that guidance documents for chief scientists recognise this and encourage as much challenge as can be achieved in the time available.

> *Recommendation 4: Process briefing documents for chief scientists and participants in SAGE should recognise the importance of bringing 'challenge into the room' to reduce the risk of errors, slips and misinterpretation.*

6.3 Presenting Uncertainty and other Information to SAGE and thence to COBR

A common observation made in all three workshops and indeed in our preparations for them was that departments, agencies and, particularly, software output used different conventions, units, map scales, colours and symbols, etc. for reporting consequences. For instance, in the first workshop it was difficult to align maps to show different aspects of the release and its management; in the third workshop there was confusion over the integration period used for calculating dose. The urgency of any emergency means that there is no time to explain notation, the choice of units, integration periods, re-plot maps to common scales, develop legends and explanations of graphs, etc. While achieving full standardisation across all departments and agencies would require significant resources, not least in negotiating agreements, it should be possible to reduce the risk of confusion within SAGE and subsequently COBR by developing templates for capturing the information, along with standardised explanation of the terms for both bodies. Input templates would have the additional advantage of acting as an *aide memoire* of the minimum information that each body would be expecting to receive.

> *Recommendation 5: Standard templates, legends and explanations relating to all maps, plots, tables for both SAGE and COBR should be developed in advance.*

Moreover, the advent of JAM provides an opportunity for all geographical plots to be provided for SAGE and COBR from a common source, allowing consistent use of scale, colour, etc. JAM could also produce automatically all the maps, plots and tables that would be needed by SAGE. Reflecting on our observations at all the workshops and the remarks made at the second one particularly, plots that contour emergency reference levels and thus are focused on potential actions and countermeasures may be more helpful than simple maps of dose or deposition. Several authors identified in our literature review also emphasised the need for action-oriented plots (Carter and French, 2003b; Haywood, 2010; Comes et al., 2013; Comes et al., 2015).

> *Recommendation 6: The presentation of observational and modelling data should be implemented with consistency in the use of scales, units, colour, etc. This is particularly true of geographical information, which should be presented using maps that can be easily aligned. Ideally once the source term and meteorology have been set for a scenario the output should be developed and produced automatically by the system providing an agreed set of maps, tables and plots for SAGE without further intervention or collation. Where possible, these should be designed to support discussion of potential countermeasures, rather than simply show contours of dose or deposition.*

Initially we believed the project's focus would be on communicating geographical uncertainty, or more precisely, communicating spatio-temporal uncertainty about the spread of an atmospheric plume of radioactive contamination and the consequent uncertain predictions of dose maps; and indeed much of our focus has been on understanding the likely spread. However, we rapidly understood that many of the key uncertainties that are discussed within SAGE relate to non-geographical events and parameters, in particular the source term. Moreover, current practice does not seem to use a formal way for addressing these uncertainties. Probabilities are not offered to SAGE. As noted in Section 1.3 and elsewhere, the two sets of key uncertainties relate to the weather and the source term. Although many atmospheric dispersion models are essentially stochastic (NAME certainly is), the output currently prepared for SAGE and COBR is deterministic, depicting a single plume. In the case of the source term, the emphasis seems to be on describing the physical situation, the fault(s) and the engineering actions being taken, along with best guesses of when the release might be capped, and its scale and evolution until then. Members of SAGE along with the rest of the emergency management process have to internalise this information to form their own assessment of the uncertainty.

It was suggested to us in the first and third workshop and at other points that a probability lexicon might provide a way of communicating and discussing uncertainties, particularly in the early phase when the situation is very uncertain and information sparse. However, we are very concerned that unless members of SAGE are fully familiar with a standardised use of the same lexicon and use it regularly in their daily lives, this would be very likely to cause more confusion and miscommunication than it resolves: see Section 2.3. Thus we strongly believe that any steps in this direction should be taken only after such an approach has been fully adopted across government.

> *Recommendation 7: SAGE should not adopt a probability lexicon to give quantitative meaning to everyday expressions of uncertainty unless and until a common lexicon is adopted and used consistently across all government departments and agencies in their day-to-day activities.*

It is possible that we are being too defeatist in thinking that it is impossible to get some quantitative probabilities for some of the key early uncertainties. Might the operators, ONR or some others be prepared to give some very rough probabilities? The operators were not at all involved in this project and ONR was only peripherally involved as workshop attendees. Of course, anyone who argues that a probability lexicon could be implemented is also arguing implicitly that it is possible to give rough probabilities, because that is what a lexicon is based on. To develop a range of 3-5 scenarios, as we recommend below, it would be sufficient to have some rough indication on the balance of probabilities between small and large releases, its duration and roughly what radionuclides might be present. So this would be worth exploring. It might also be the case that SAGE is able to work with quantitative probabilities, recognising the limits of their accuracy at this stage; but that it would unwise to pass such rough numbers onto COBR.

> *Recommendation 8: Discussions with the operators, ONR and other relevant parties should take place to see if it were possible to get some very rough quantitative probabilities relating to the source term in the early stages of the event.*

A key point made in both the first and third workshop relates to the importance of setting clear expectations of when further information will come in and uncertainties be resolved or at least reduced. Members of COBR and to a lesser extent some members of SAGE may have inaccurate perceptions of what is realistically achievable in the early hours, leading to a loss of confidence in scientific advice as the information picture evolves. Thus the initial report to SAGE and that subsequently provided to COBR should provide a timeline for information flows. Ideally, a template for this should be prepared in advance during emergency planning; but it is likely that this can only be an *outline* template that will need additions, deletions and possibly some restructuring during the event, because the few radiation accidents to date have all involved unique happenings in their evolution. However, the ambition must be to note when further information relating to each key uncertainty is likely to be available and to plot these on a rough timeline.

Recommendation 9: Timelines relating to the availability of further information in respect of each key uncertainty should be provided to SAGE and COBR.

6.4 Discussion of Uncertainty within SAGE and Reasonable Worst Case.

In Section 4.3 we argued that focusing on a reasonable worst case might lead to flawed thinking and an overemphasis of the risks of significant escalation. Moreover, we have noted that a reasonable worst case describes what might happen if nothing is done, but it does not offer the basis to discriminate between different possible strategies. It is not focused on supporting decision making. However, it is clear that the use of a reasonable worst case is embedded in the processes used by COBR. That does not mean that it need be embedded to the exclusion of all other possibilities from discussions within SAGE. It is important that SAGE prepare balanced advice for COBR which reflects reasonable expectations of the evolution of the accident, as well as giving guidance on what resources might need to be put in place if that evolution is at the worse end of the spectrum. If public confidence is to be maintained, it is important that the authorities are seen to be anticipating and mitigating the possible course of the accident, *including that which actually occurs*. Moreover, even if COBR's attention in the very early phase is focused on short term risks to human health from direct exposures, some indication of potential longer term health risks, e.g. from food and water, and the scale of the countermeasures needed should also be given. Given that politicians need to be seen to have a comprehensive view of the potential consequences of the accident if public trust is to be maintained, SAGE should briefly consider whether any specific significant long term economic or environmental impacts might occur and include brief mention in their report to COBR.

We believe that this can best be achieved through the use of multiple scenarios, perhaps 3-5. These should include a likely case to set reasonable expectations, 1 to 3 reasonable worst cases and a best case to provide a counter to the pessimism of the latter. We do recognise that the need to ensure that resources are prepared does mean that there has to be a bias towards reasonable worst cases, perhaps including a particularly bad one. Discussions in the second and third workshops confirmed us in the belief that this approach would be much better at supporting a more balanced deliberation within SAGE, while still enabling SAGE to provide the form of advice that COBR require. We were, in truth, somewhat disappointed and concerned that in the third workshop, those playing SAGE in the exercise relatively quickly discounted scenarios 3 and 5 to focus on scenario 6 as a reasonable worst case, but supplemented by some discussion of scenario 1 as the best that might happen. However, it was the first time that the group had encountered an exercise in which they were given information in this form and their reflections in the later discussion and responses to the second questionnaire indicate that presenting 4 scenarios did help them achieve a more balanced, broader view than they had in previous exercises. Moreover, the protocol for running SAGE could be modified to discourage such a rapid discounting of some scenarios. Overall, we are convinced of the need to consider several scenarios. Current processes and timescales would probably limit the number to 3-5 scenarios, although we can imagine circumstances in which even 5 would not fully scope the possibilities.

Recommendation 10: SAGE should be provided with 3-5 scenarios which together provide an overview of the range of possible impacts that might result from the accidental release.

Our presentation of the scenarios and the consequences of the accident were essentially based on maps in the third workshop. Several participants suggested that it would have been helpful to provide tabular summary information to compare the potential impacts of the different scenarios. Doing so would also have the benefit that it might have been more difficult to discount scenarios 3 and 5 so quickly, if the numbers of people affected and other consequences were summarised alongside those of scenarios 1 and 6. Much of this information can be tabulated automatically by JAM, though some more qualitative comparisons will need be judgementally based and summarised by hand.

Recommendation 11: SAGE should look at all scenarios prepared to explain the range of possible impacts. To aid in this, the geographical plots prepared for each scenario should be supplemented by a brief list of the key impacts in tabular or bulleted form. A template for doing this should be prepared. Moreover, the design of any supporting IT systems such as JAM should provide the key tables, though some of the more qualitative comparisons will need to be summarised by hand.

There is a question of how scenarios might be developed. Our discussion in Section 4.5 suggested a constructive way of developing scenarios. It would be nice to suggest that we used this approach to construct the scenarios used in the third workshop. But that is not the case. Rather we developed the storyboard for the hypothetical accident at the same time as the scenarios so that the scenarios would show different possible consequences to the participants. Indeed, the choice of Pagham as the site for the hypothetical reactor was made at the same time. To develop scenarios for a real event would be difficult. However, there are some factors relating to real sites that would help. Firstly, local risk registers relating both to the plant itself and also to other key facilities and population centres should contain pointers to local features which might have implications for the seriousness of different possible plume paths. Moreover, the emergency planners at the site could enhance their risk register the next time they revise it to identify potential consequences of an accidental release that are specific to the plant. Secondly, if the operators and/or ONR can be persuaded to provide some indication of the relative likelihoods of various source terms (Recommendation 9:) then this will help select which columns in Figure 10 are particularly relevant. Similarly the Met Office should be able to give some advice on the selection of interesting and likely rows in Figure 10. Even though there will be huge pressures of time, it is important to recognise that the procedure for developing scenarios is likely to be iterative rather than linear and to involve selection from rather more scenarios that the 3-5 to be presented to SAGE. In preparing materials for the third workshop the 4 scenarios used were selected from 6 or 7 that had been investigated. Once JAM is developed and commissioned, it should be possible to generate scenarios relatively quickly (especially with the continued performance increases in computing); and the production of comparative tables (Recommendation 11:) should help in the selection of 3-5. We may also notice that at present in developing just one reasonable worse case, difficult choices have to be made in selecting just one source term and one meteorology to develop and present.

Nonetheless, we recognise the need to develop procedures and guidance to produce the scenarios for SAGE, beyond the pointers given here. Obviously this work will need to be undertaken in collaboration with the developers of JAM, since that system will be used to generate the maps, plots, tables and other output for the scenarios. Thus:

Recommendation 12: Procedures and guidance for constructing the 3-5 scenarios to present to SAGE should be developed. These procedures should be developed and *exercised in collaboration with the designers and developers of supporting IT systems such as JAM.*

This begs the question of who holds the responsibility for developing the scenarios and presumably for developing the procedures and guidance for doing so. JAM has still to be fully developed and introduced into the national and local emergency management systems and processes. The group running JAM will presumably become a further node in Figure 1, conceptually at least. It may well be that JAM is run at PHE or the Met Office with other agencies collaborating through a video conference in a virtual meeting. It would seem sensible for that group to take responsibility for developing and selecting scenarios for SAGE.

Many approaches to problem solving would suggest that the problem owners, in this case SAGE, should also be involved in the development of the scenarios in order to explore their concerns. Given the urgency of this context, that is clearly not practical. Nonetheless, if it becomes clear during the SAGE meeting that a further possible scenario should be examined, it should be possible for that scenario to be generated.

Recommendation 13: It should be the responsibility of the teams using supporting IT systems, e.g. JAM, to identify and develop the scenarios to present to SAGE. Ideally, if SAGE wish to see a further scenario, it should be possible for a request to be made from within SAGE, the necessary runs made and the results sent back into SAGE.

Our closing remarks in Section 4.5 suggested that 4 events could be constructed for which probabilities might be judged: see Figure 13 and the surrounding discussion. There was not capacity in this project to explore that idea to any depth. But, given the wish expressed by several participants in the third workshop for some rough probabilistic assessment of the risks, there may be merit in exploring this suggestion further. Almost certainly such a development would require the use of structured expert judgement.

Recommendation 14: Consider an exploration in the longer term of the potential for providing SAGE with probabilities as described at the end of Section 4.5.

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16 https://admlc.wordpress.com/

17 http://expertsinuncertainty.net/, http://www.cost.eu/COST_Actions/isch/IS1304.

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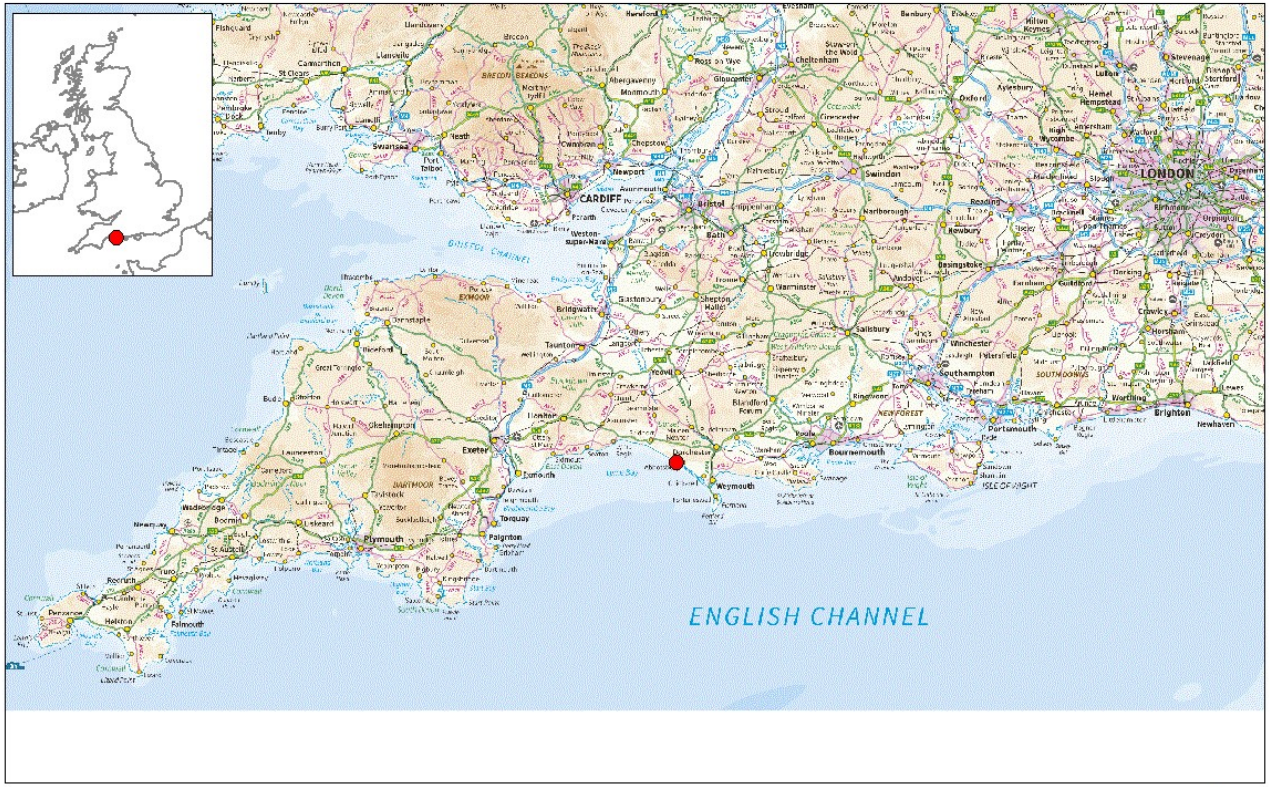
Annex 1: The hypothetical accident used at the first workshop

Background Information

Location


LONDON
CARDIFF
Bristol
Bath
Swansea
Newport
Exeter
Plymouth
Bournemouth
Southampton
Weymouth
Torquay
Salisbury
Brighton
Portsmouth
Taunton
Yeovil
Swindon
Oxford
Gloucester
Cheltenham
EXMOOR
DARTMOOR
BRECON BEACONS
NEW FOREST
ISLE OF WIGHT
BRISTOL CHANNEL
ENGLISH CHANNEL


50
25
0
50 Kilometres
N
W
E
S

Location


Cardiff Airport
Barry
Penarth
Weston-super-Mare
Nailsea
Keynsham
Bath
Corsham
Melksham
North Wessex Downs
Hungerford
Banwell
Blagdon
Cheddar
Mendip Hills
Radstock
Bradford-on-Avon
Trowbridge
Devizes
Pewsey
Burbage
Upavon
Ludgershall
Andover
Burnham-on-Sea
Bridgwater Bay
Wells
Frome
Westbury
Warminster
Salisbury Plain
Amesbury
Glastonbury
Shepton Mallet
Street
Bridgwater
Quantock Hills
Williton
Othery
Bruton
Mere
Wilton
Salisbury
Stockbridge
King's Somborne
Dulverton
Taunton
Wellington
Langport
Ilchester
Wincanton
Gillingham
Templecombe
Cranborne Chase & West Wiltshire Downs
Shaftesbury
Romsey
Stalbridge
Sixpenny Handley
Sherborne
Yeovil
Ilminster
Blackdown Hills
Tiverton
Cullompton
Crewkerne
Sturminster Newton
Fordingbridge
Totton
Verwood
Ringwood
Chard
Beaminster
Blandford Forum
Wimborne Minster
Hythe
NEW FOREST
Crediton
Honiton
Axminster
Ferndown
Lymington
Dorset
Maiden Newton
Puddletown
Bere Regis
Bridport
Poole
Exeter
Ottery St Mary
Lyme Regis
Seaton
Dorchester
Wareham
Christchurch
Bournemouth
Sidmouth
East Devon
Abbotsbury
Wool
Poole Bay
The Needles
Yarmouth
Exmouth
Lyme Bay
Isle of Purbeck
Corfe Castle
Swanage
Isle of Wight
Bovey Tracey
Chickerell
Weymouth
Dawlish
Teignmouth
Babbacombe Bay
Fortuneswell
Portland
St Aldhelm's or St Alban's Head
Newton Abbot
Torquay
Portland Bill
R Exe
R Parrett
R Frome
R Stour
R Avon
R Test
R Dart
M5
M27
A30
A35
A37
A303
A354
20
10
0
20 Kilometres
N
E
S
W

Location

LYME BAY
South West Coast Path
Chesil Beach
England Coast Path
WEYMOUTH to
Guernsey 2 hrs
Jersey 3 hrs
St Malo 5 hrs
DORCHESTER
WEYMOUTH
BRIDPORT
AXMINSTER
BEAMINSTER
LYME REGIS
PORTLAND
FORTUNESWELL
Abbotsbury
Chickerell
Puddletown
Maiden Newton
Portland Harbour
7.5 3.75 0 7.5 Kilometres
N E S W
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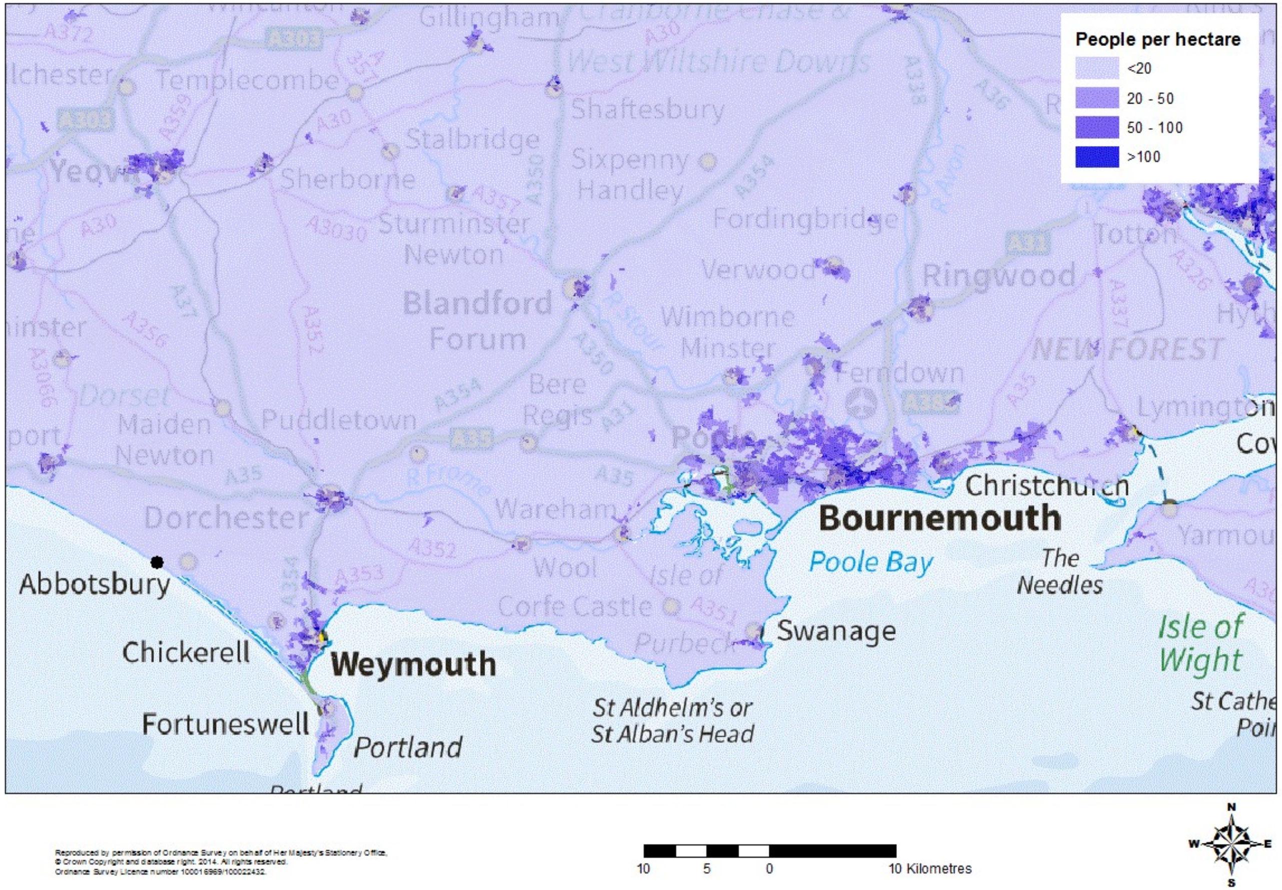
Nearby locations

Town/city	Distance from release (km)	Town/city	Distance from release (km)
Dorchester	15	Torquay	67
Weymouth	15	Exeter	63
Yeovil	32	Salisbury	75
Blandford Forum	40	Bristol	90
Honiton	42	Southampton	92
Poole	48	Cowes	94
Taunton	52	Cardiff	100
Bournemouth	55	Portsmouth	110
Exmouth	55	Plymouth	112
		London	200

Abbotsbury nuclear power station – population density

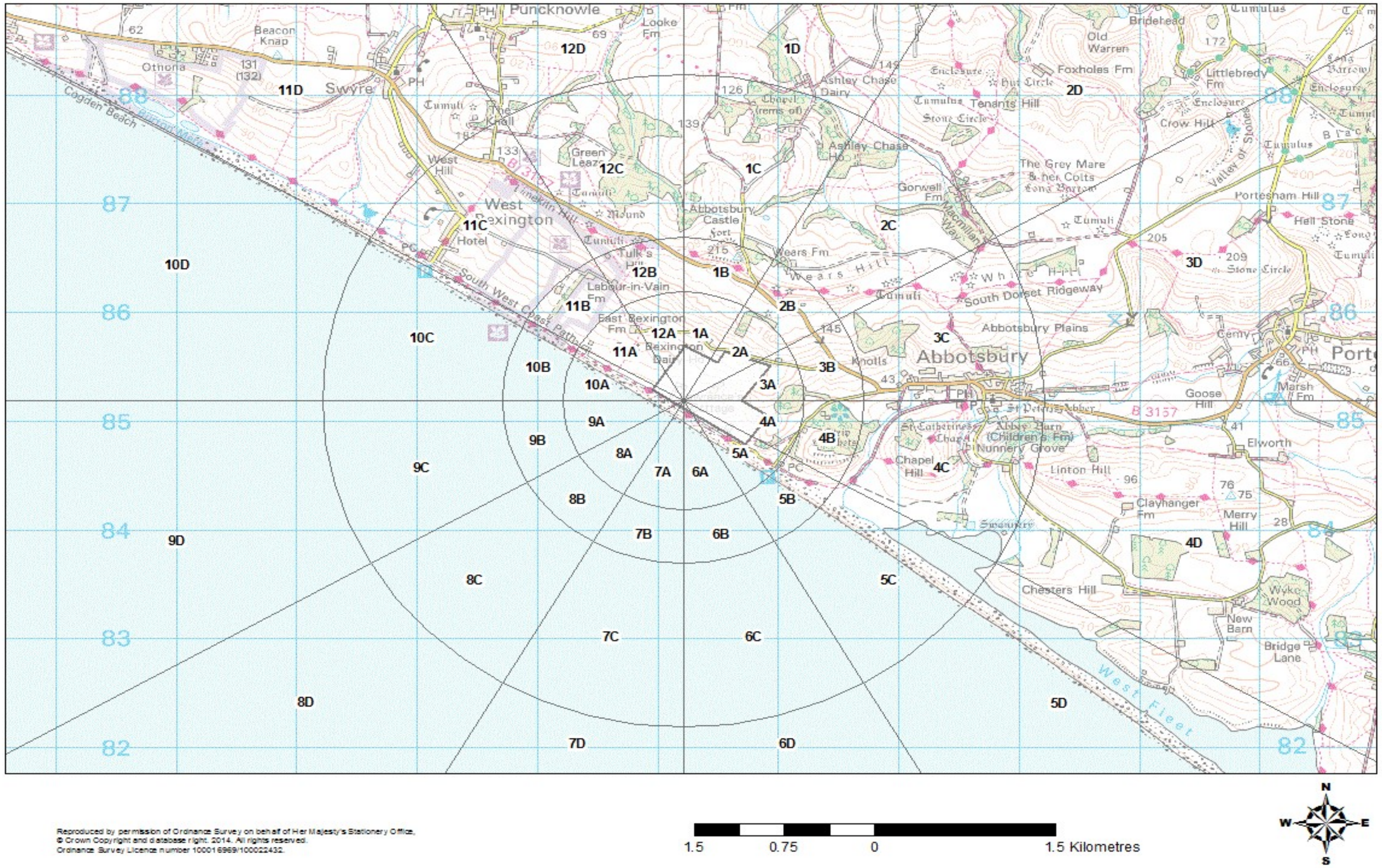


Abbotsbury nuclear power station – population characteristics

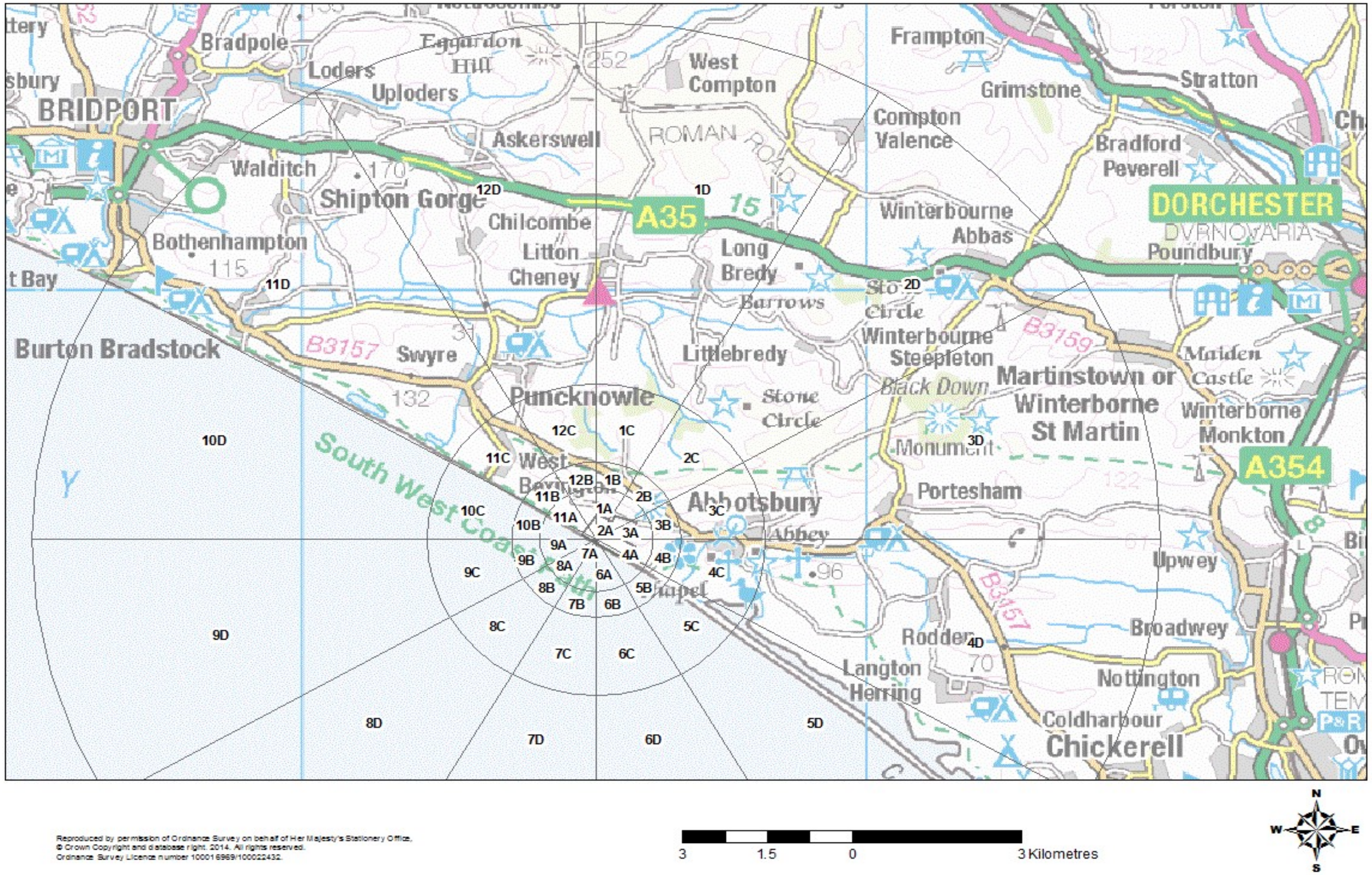
Zone	Residents	Weekday
Abbotsbury	468	194
West Bexington	175	93
<3km	714	318
<10km	6453	
<20km	141684	
Dorchester	23924	
Weymouth and Portland	78212	
Portland	14159	

Regional Description – key locations

Site Emergency Plan – Zones



Site Emergency Plan – Zones



Population: Sectors A & B

Sector A	Segment	Population Day	Population Night
	1	2	5
	2	0	0
	3	0	0
	4	0	0
	5	5	12
	11	3	7
	12	1	2

Sector B	Segment	Population Day	Population Night
	1	0	0
	2	2	5
	3	0	0
	4	0	0
	5	0	0
	11	5	9
	12	1	2

Population: Sectors A & B

Sector C	Segment	Population Day	Population Night
	1	5	12
	2	3	7
	3	177	426
	4	16	40
	5	0	0
	11	100	188
	12	1	2

Sector D	Segment	Population Day	Population Night
	1	240	613
	2	291	708
	3	402	906
	4	252	605
	5	28	62
	11	932	1776
	12	510	1058

Site Emergency Plan – Action triggers

- Certain specified plant conditions and monitoring results (on-site & off-site) typically trigger a site's emergency plan.
- The simple and hypothetical plan for Abbotsbury nuclear power station includes a monitoring result trigger level of 100 $\mu Sv\ h^{-1}$ (total gamma).
- If this is triggered, the site operator will:
  - Inform the local police, fire service, ambulance service, local authority, and national authorities.
  - Advise all residents in bands A and B to take pre-distributed **stable iodine tablets.**
  - Advise the local police to **evacuate** all residents in bands A and B.
  - Advise all residents in some or all sectors in band C to **shelter**.

Emergency Reference Levels (ERLs)

Countermeasure	Body or organ dose	Averted dose (mSv)	
		Lower	Upper
Sheltering	Whole body	3	30
Evacuation	Whole body	30	300
Stable iodine	Thyroid	30	300

The Scenario

Early morning

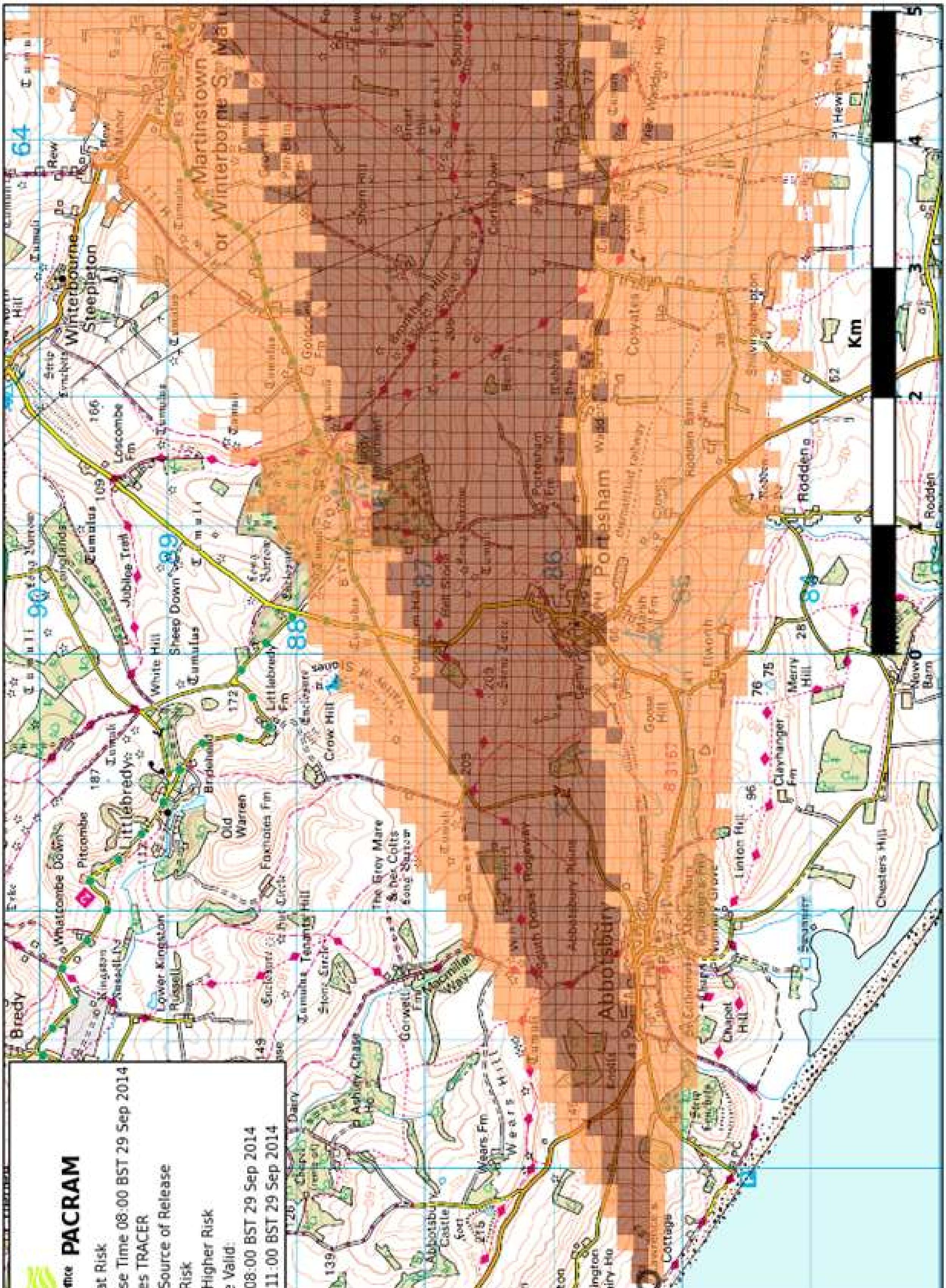
- The site declares an offsite nuclear emergency at 8:00.
- The on-site emergency plan has been activated.
- The site weather monitor indicates the wind is blowing towards the East.
- Met Office issue a PACRAM at 8:25am; this shows wind <u>from</u> 250-260º (plume going towards Dorchester).

- *[Note: the PACRAM is for a unit release, the concentrations are not at this stage indicative of severity, just relative concentrations.]*

Early morning

- Some site-fence monitor measurements exceed the site's trigger level of 100 µSv h^{-1} (total gamma) so the prescribed actions in the off-site plan are activated:

    - All residents out to 1.5 km are advised by an automated ring-round to take pre-distributed stable iodine tablets.
    - The local police are asked to evacuate all residents out to 1.5 km.
    - All residents between 1.5km to 3 km in sectors C1 – C6 (0° - 180°) are advised by an automated ring-round to shelter .



Met Office
PACRAM
Area at Risk
Release Time 08:00 BST 29 Sep 2014
Species TRACER
Source of Release
Risk
Higher Risk
Plume Valid:
Start 08:00 BST 29 Sep 2014
End 11:00 BST 29 Sep 2014
Abbotsbury
Portesham
Martinstown or Winterbourne St Martin
Winterbourne Steepleton
Littlebredy
Coryates
Rodden
Km
0
1
2
3
4
5

Early morning – Issues and Decisions

- Key thoughts at this stage?
- What information would be requested most urgently?
- What decisions (if any) would be made?
- What consideration is given to uncertainty at this time?

Early morning – Issues and Decisions

- Key thoughts at this stage?
- What information would be requested most urgently?
- What decisions (if any) would be made?
- What consideration is given to uncertainty at this time?

- What briefing would be given to COBR members?

Mid/Late morning

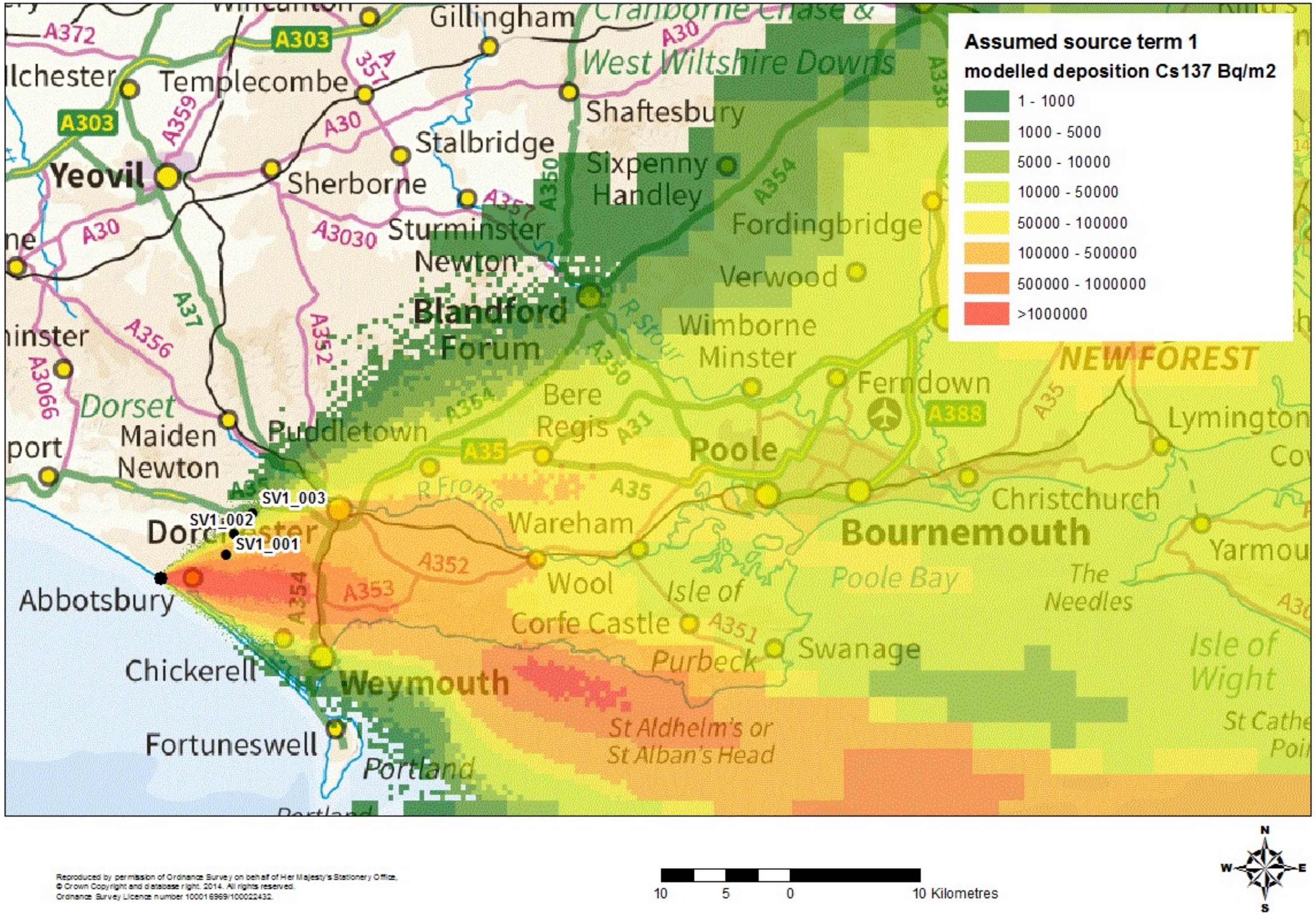
- Site operators report that the damage is serious.
- An early sitting of COBR requests a reasonable worst case scenario, for the national picture.
- A reasonable worst case source term is proposed (2% of inventory of key radionuclides, notably iodines and caesiums), with an estimated 6 hour release starting at 8:00am.
- District survey vehicles start to report measurements in the first few km, these confirm significant radioactivity present in the area east of the site.
- The measurements suggest that evacuation needs to be extended to 4km and that sheltering and stable iodine should be extended to 10km, in sectors C2 – C5 (30° - 150°), and plans to undertake this are activated locally.

Mid/Late morning

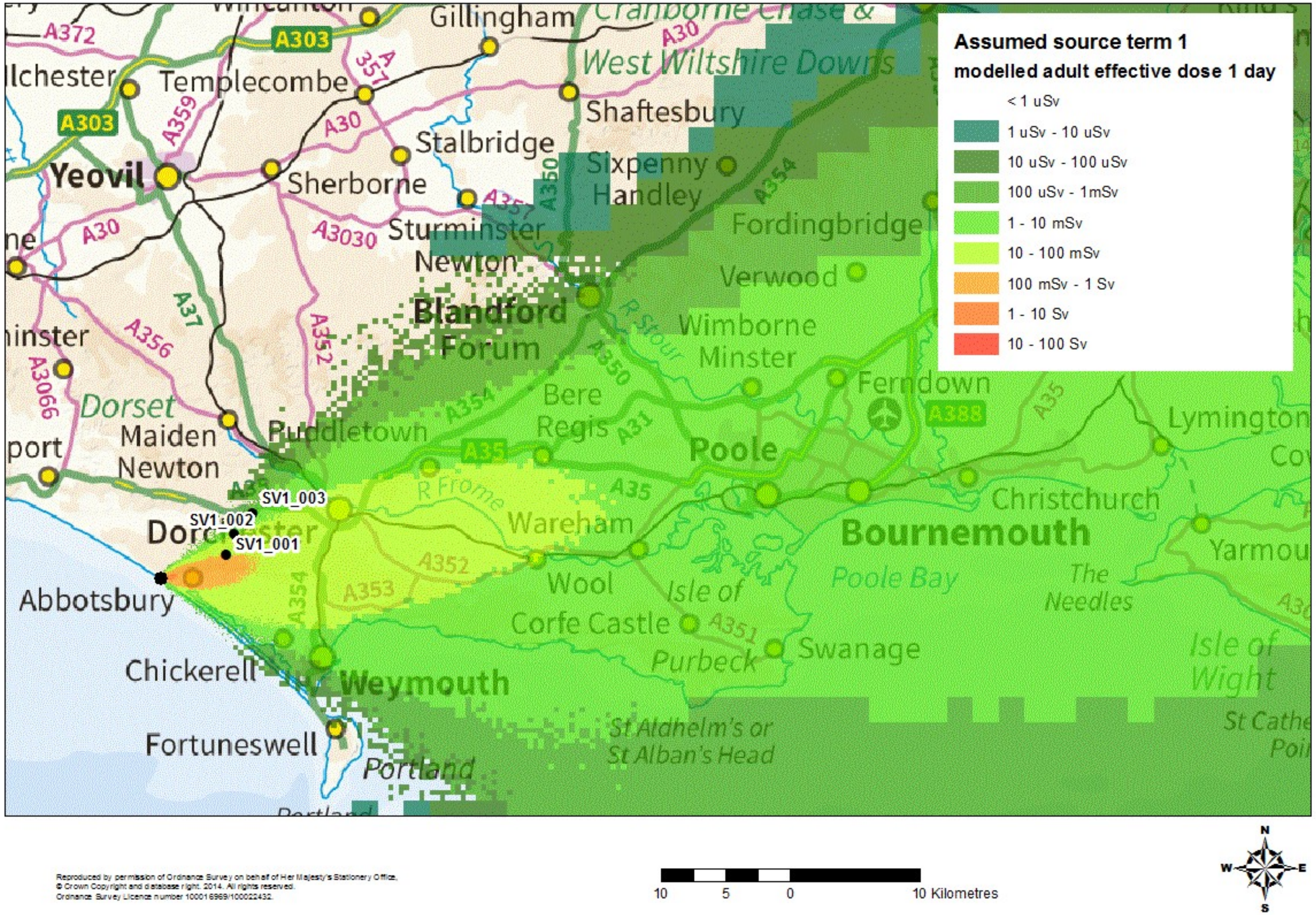
- Met Office predict that the weather will be steady for the morning, however there may be rain middle-afternoon and at this time the wind is expected to veer to be from about 290-300º

- On the basis of the precautionary source term and the dispersion predictions the following deposition and dose contour maps are generated:

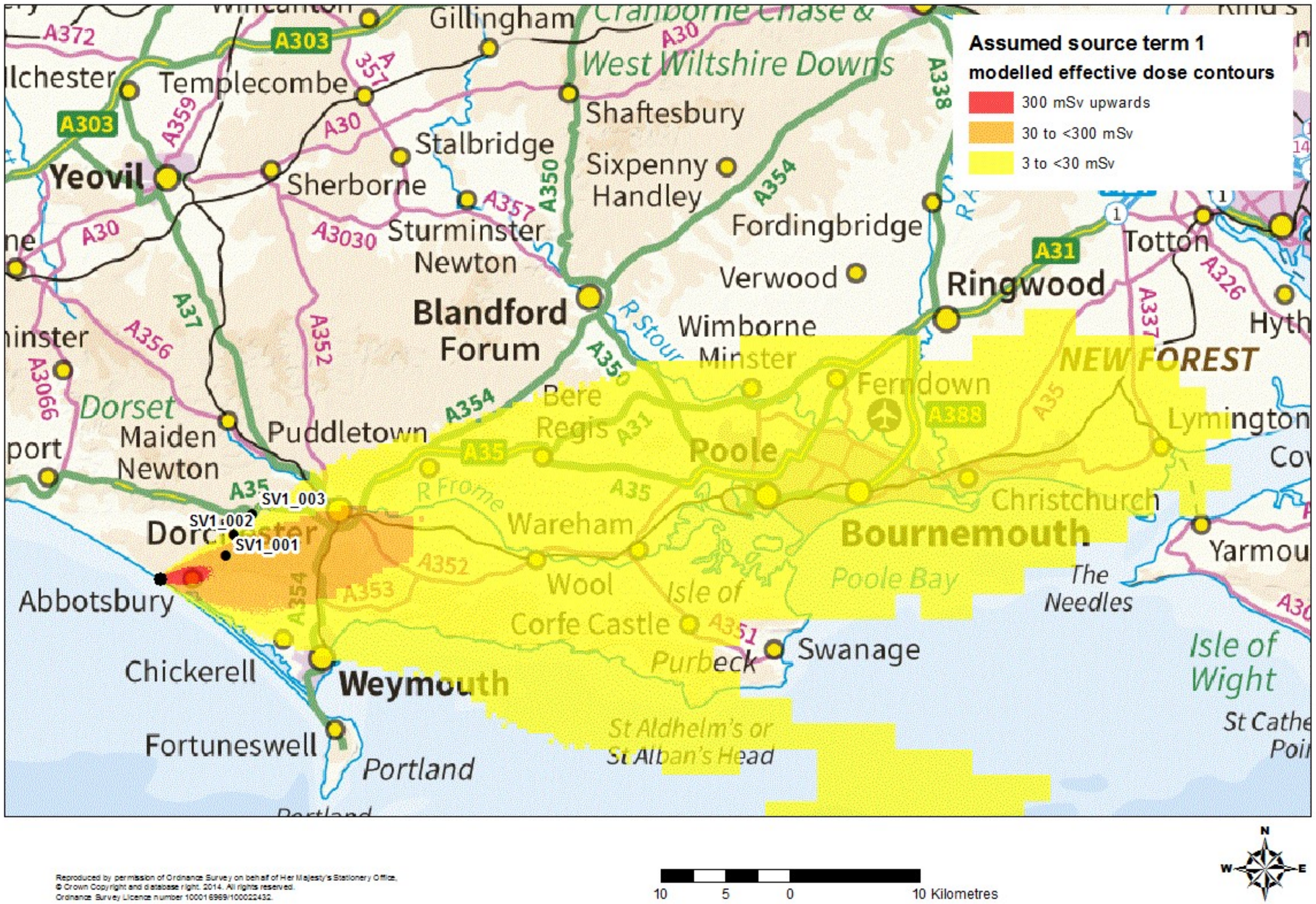
Modelled deposition map and measurement locations



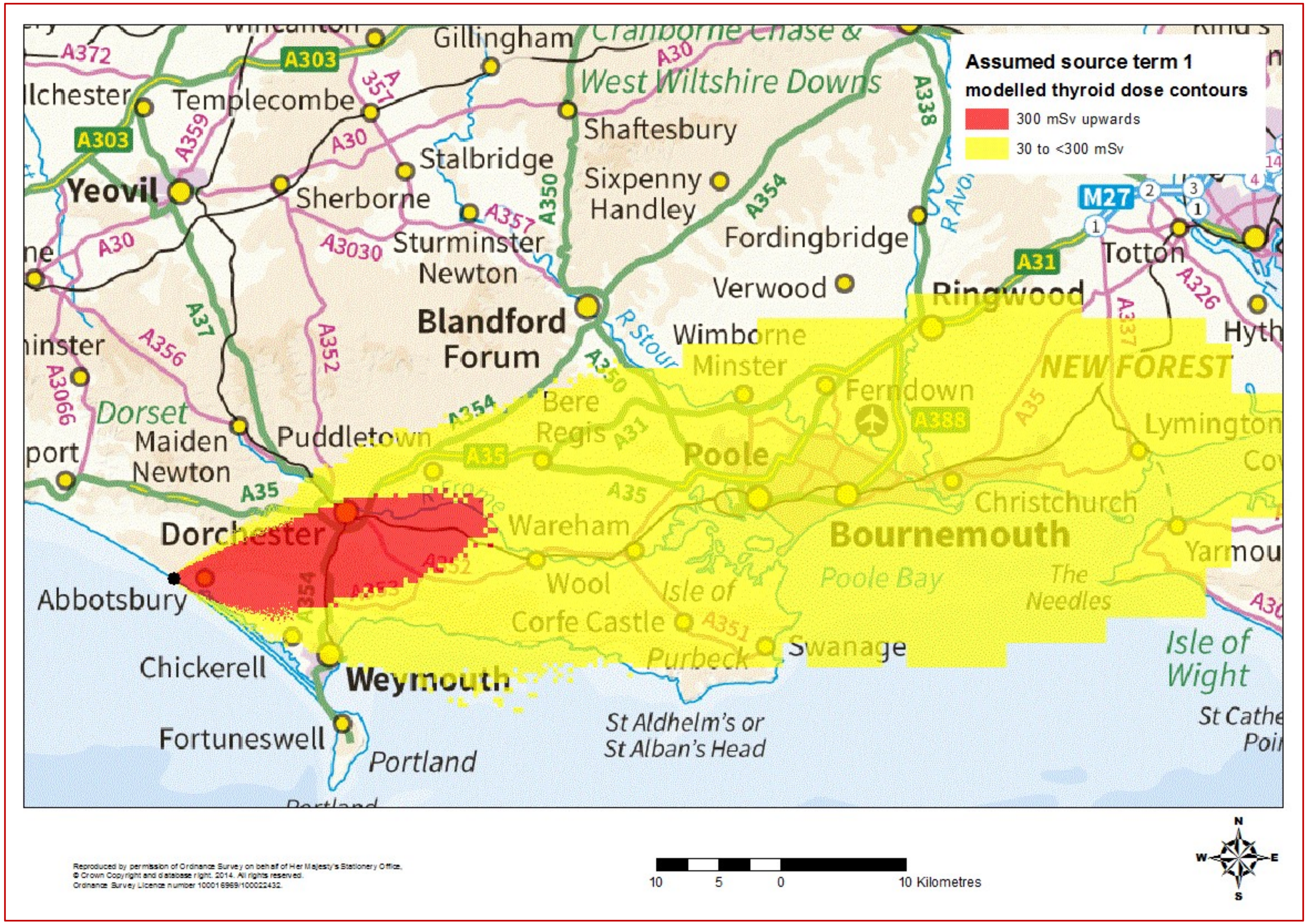
Modelled doses (1st day) and measurement locations



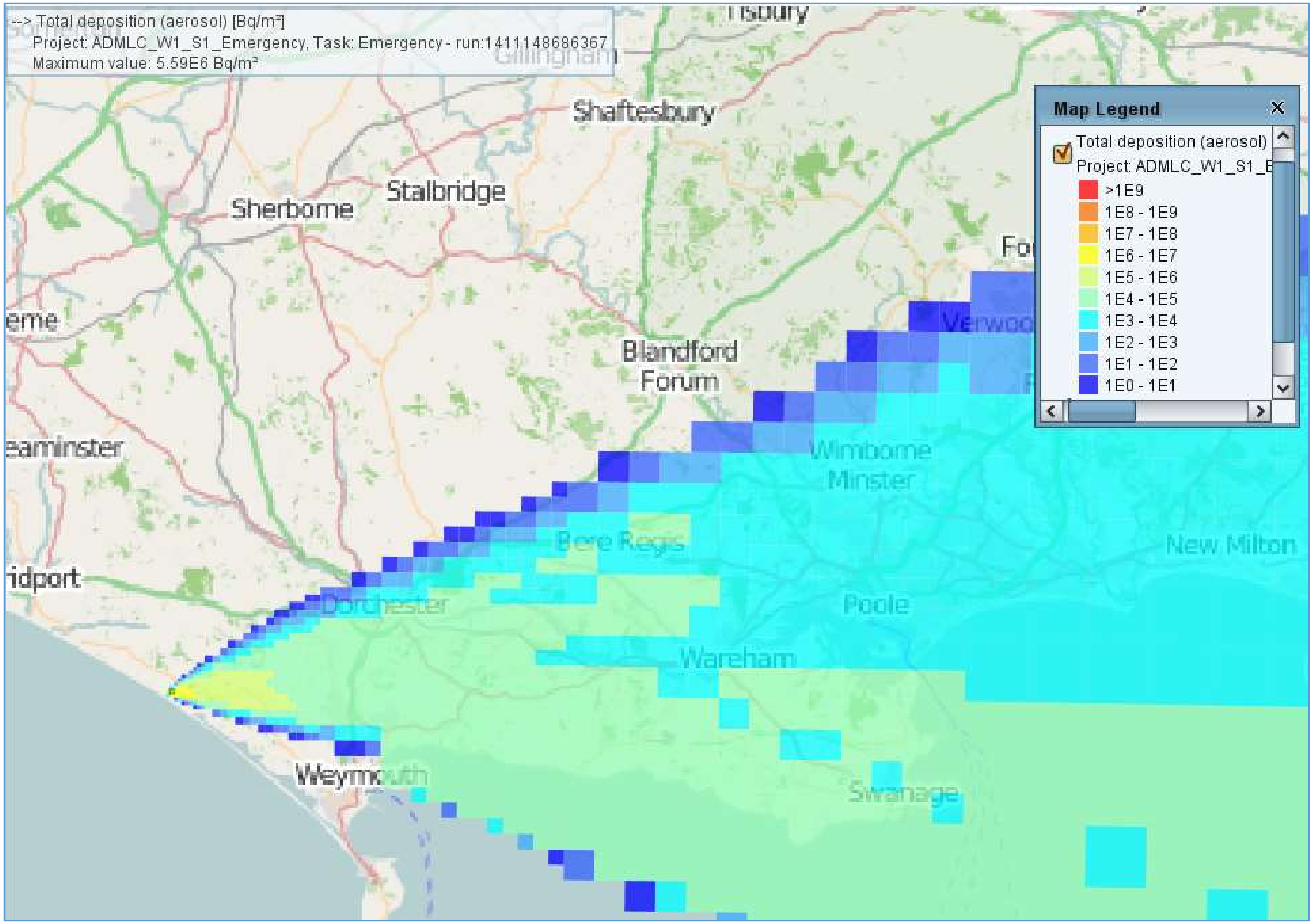
Effective dose contours (modelled)



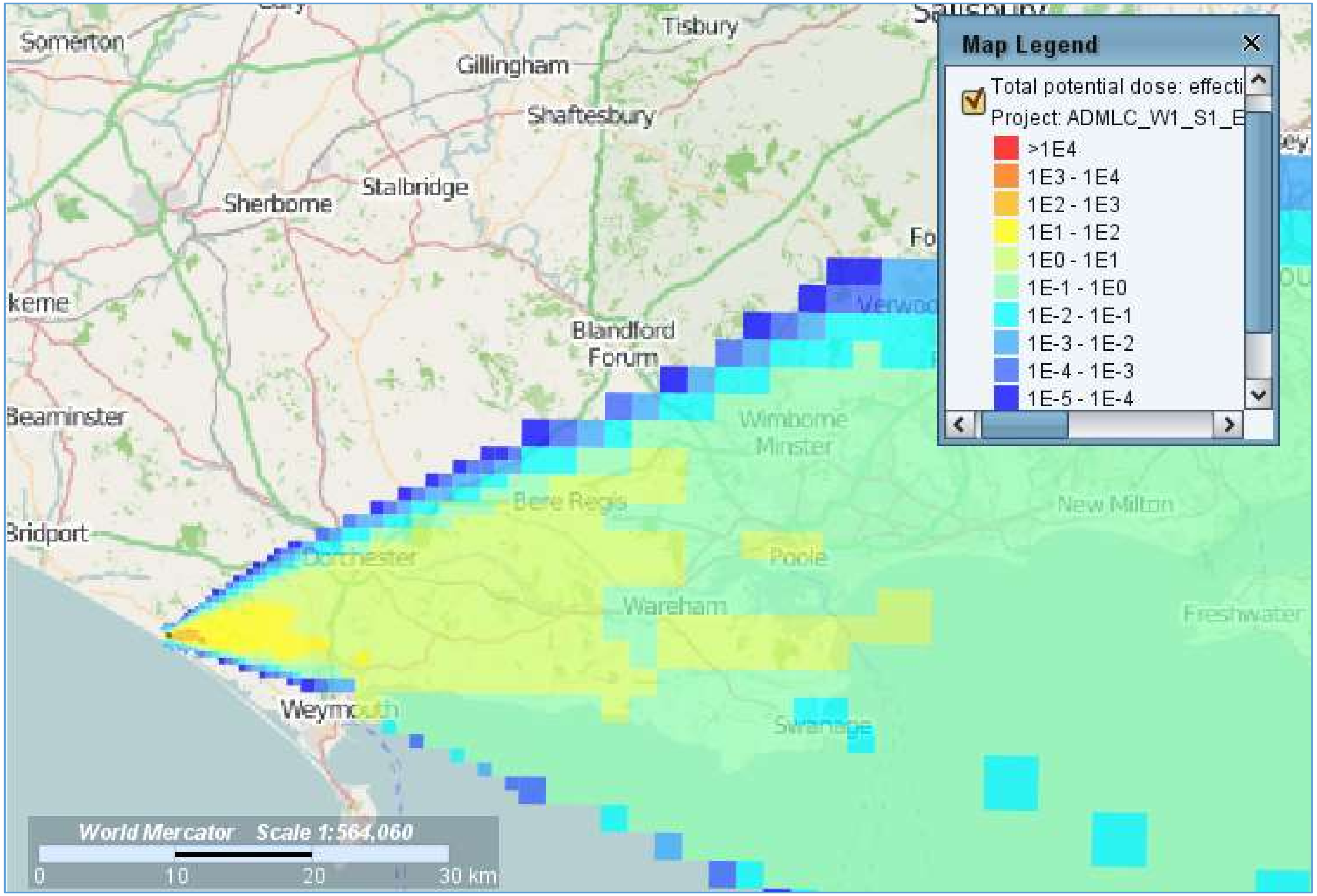
Thyroid dose contours (modelled)



Prediction from Europe: deposition (modelled) - RIMPUFF



Prediction from Europe: doses (modelled) – RIMPUFF



Mid/Late morning – Issues and Decisions

- Key thoughts at this stage?
- What information is required?
- What decisions would be made?
- What consideration is given to uncertainty at this time?

Early afternoon

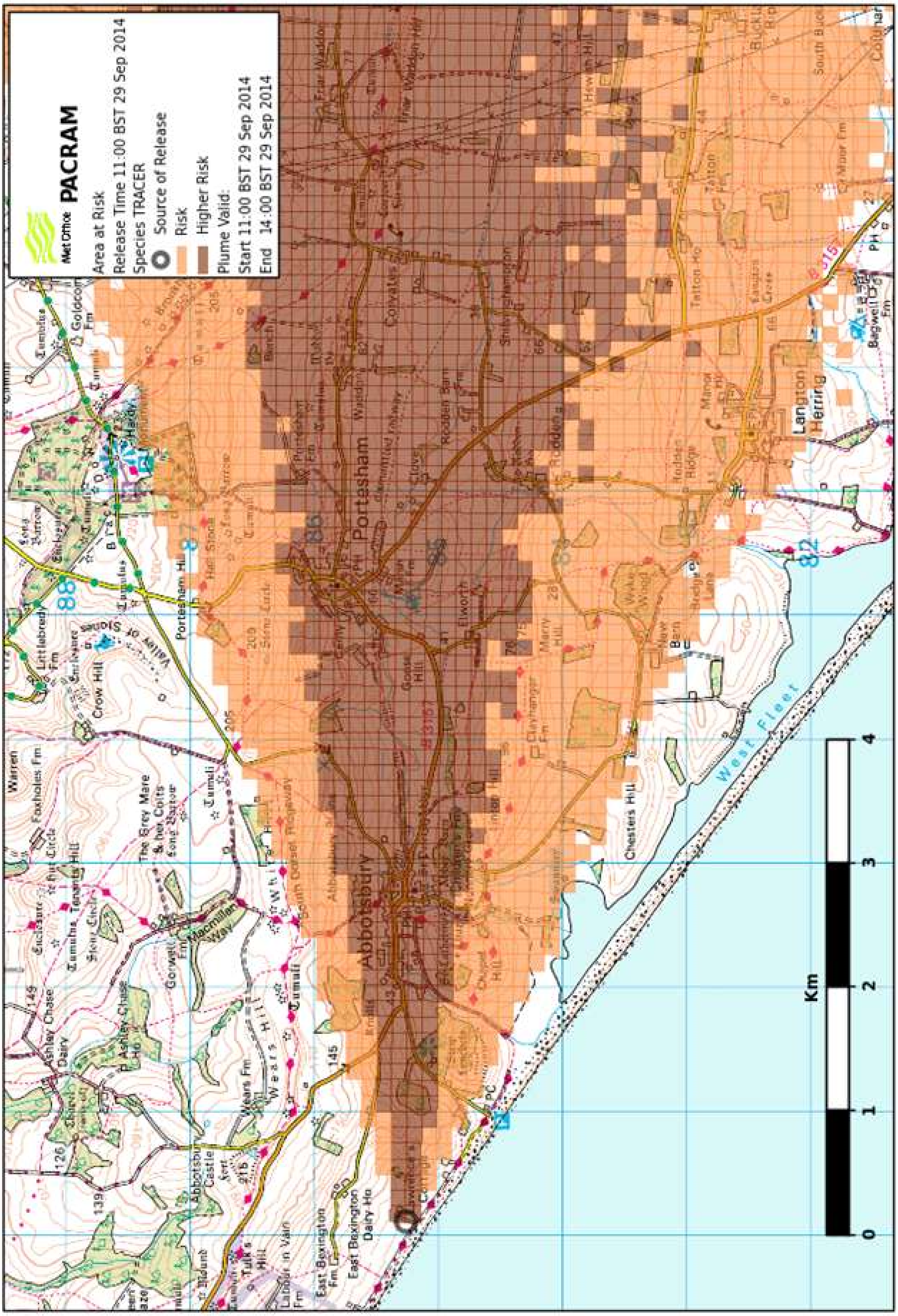
- More information & off-site monitoring measurements result in a reduction of the reasonable worst case source term estimate – still thought to be precautionary – to 1% of inventory of key radionuclides, notably iodines and caesiums, with an estimated release duration remaining at 6hrs from an 8:00am start.
- District survey vehicles report more measurements in the first 10 km, these continue to confirm significant radioactivity present in the area east of the site.
- The measurements suggest that evacuation and sheltering/stable iodine in current areas - 4km and 10km respectively in sectors C2 – C5 (30º - 150º) – remain adequate.

Early afternoon

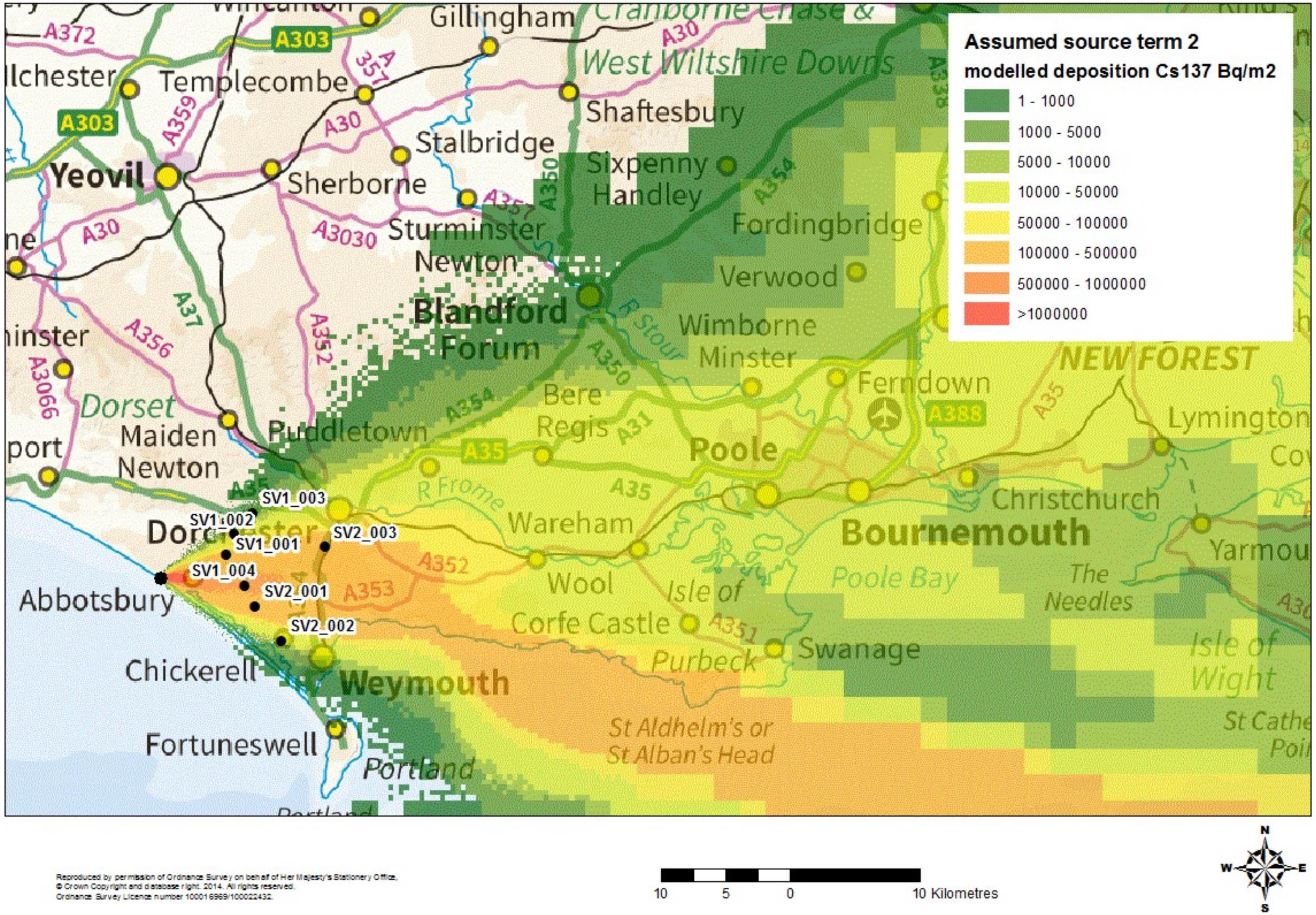
- The weather estimates remain unchanged (a wind direction shift is still anticipated middle-afternoon, together with likely rainfall).

- Met Office issue a new PACRAM at 11:00; this covers the period 12:00 to 14:00.

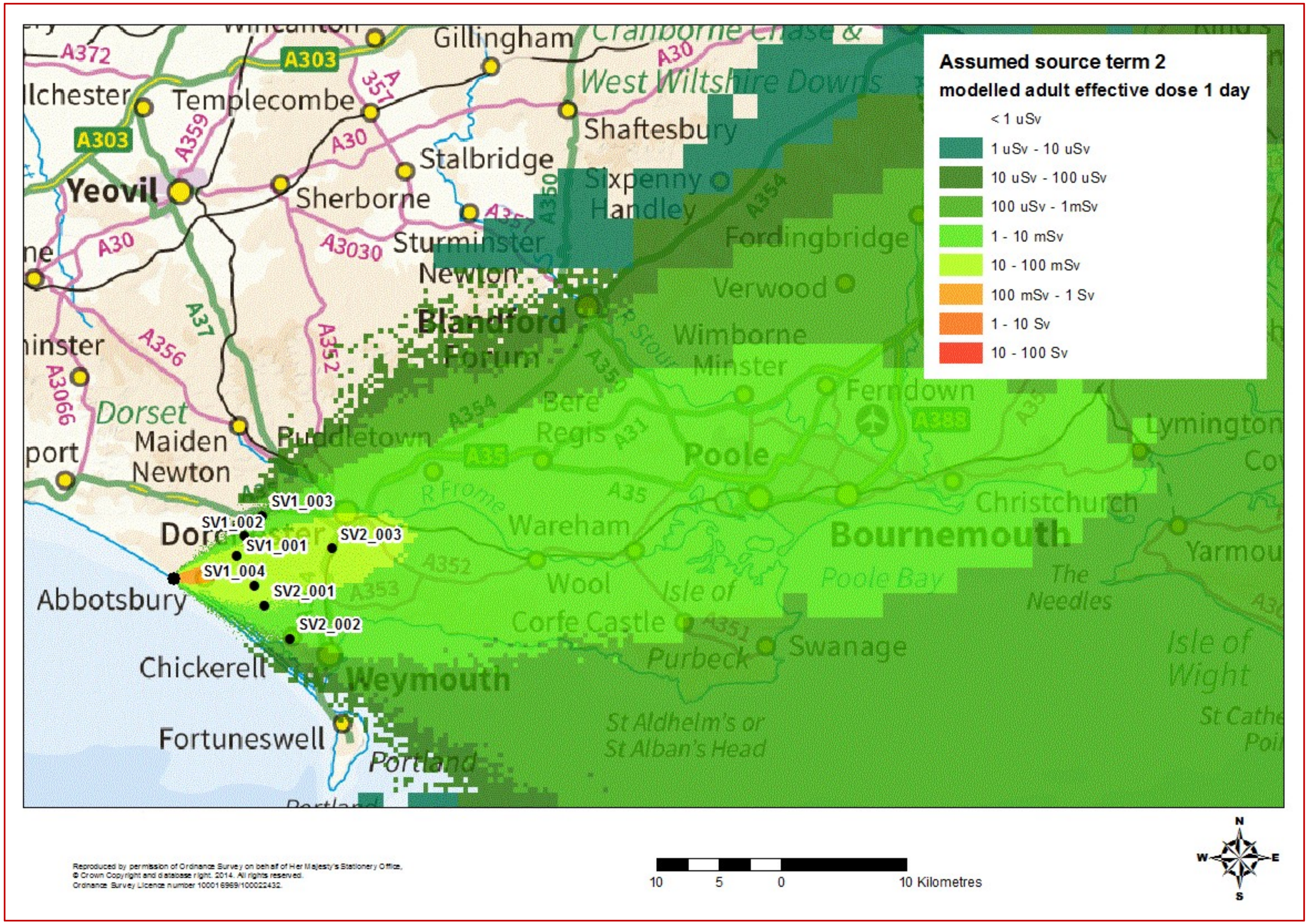
- On the basis of the new estimated source term and the dispersion predictions, the following deposition and dose contour maps are predicted:


Met Office PACRAM
Area at Risk
Release Time 11:00 BST 29 Sep 2014
Species TRACER
Source of Release
Risk
Higher Risk
Plume Valid:
Start 11:00 BST 29 Sep 2014
End 14:00 BST 29 Sep 2014
Km
0
1
2
3
4
Abbotsbury
Portesham
Langton Herring
West Fleet
Chesters Hill
Portesham Hill
Corton Hill
Rodden

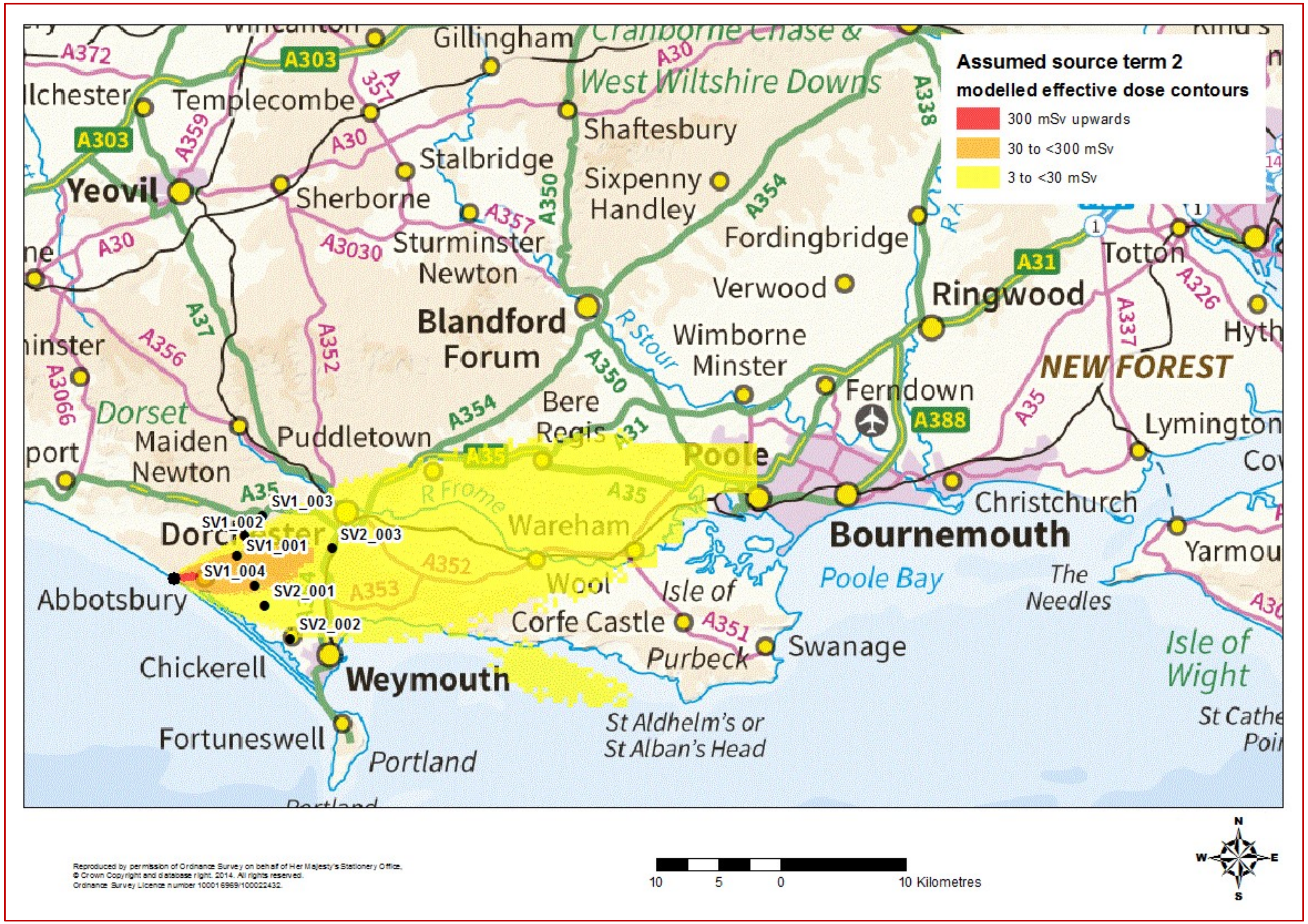
Modelled deposition map and measurement locations



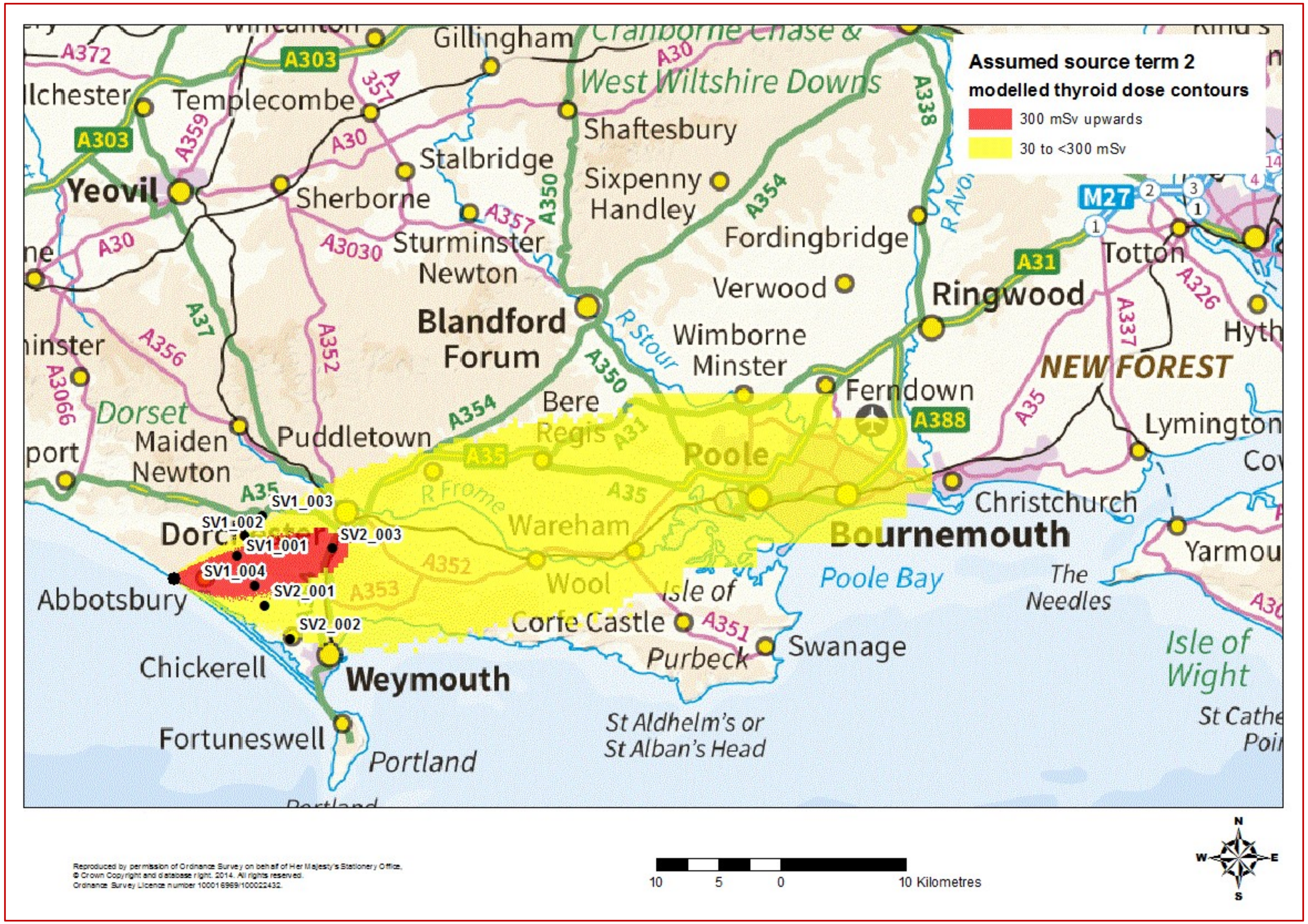
Modelled doses (1st day) and measurement locations



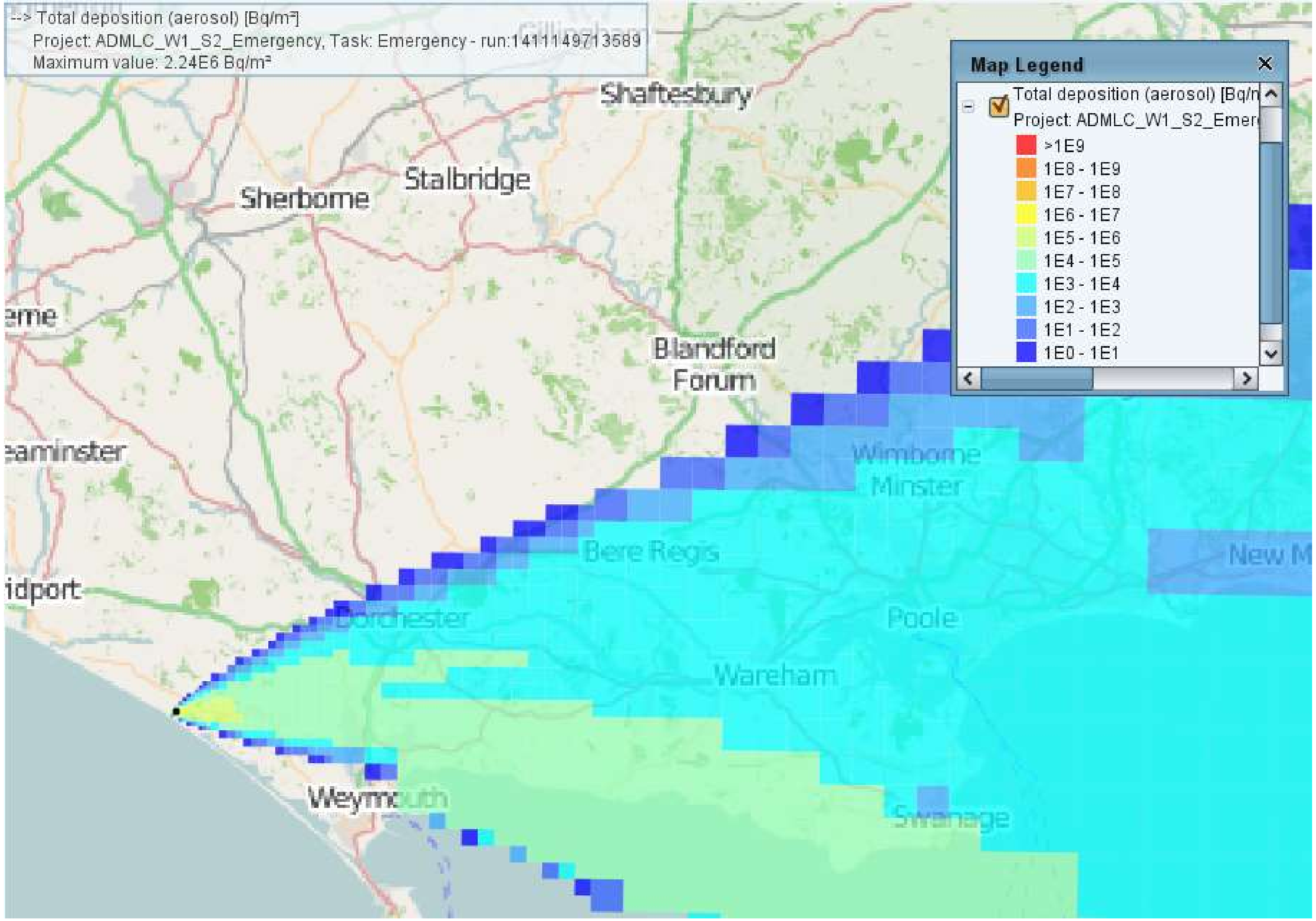
Effective dose contours (modelled)



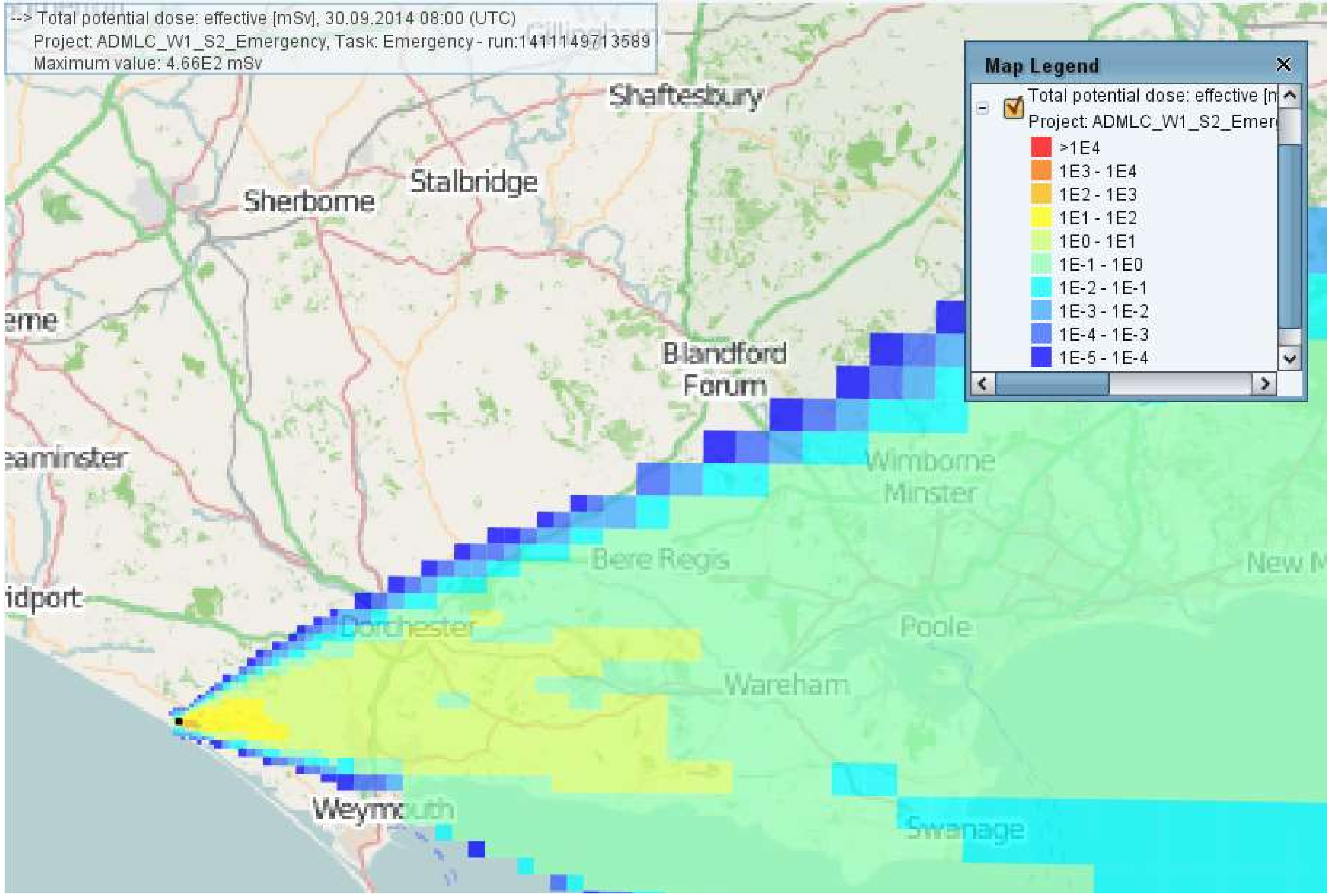
Thyroid dose contours (modelled)



Prediction from Europe: deposition (modelled) - RIMPUFF



Prediction from Europe: doses (modelled) – RIMPUFF



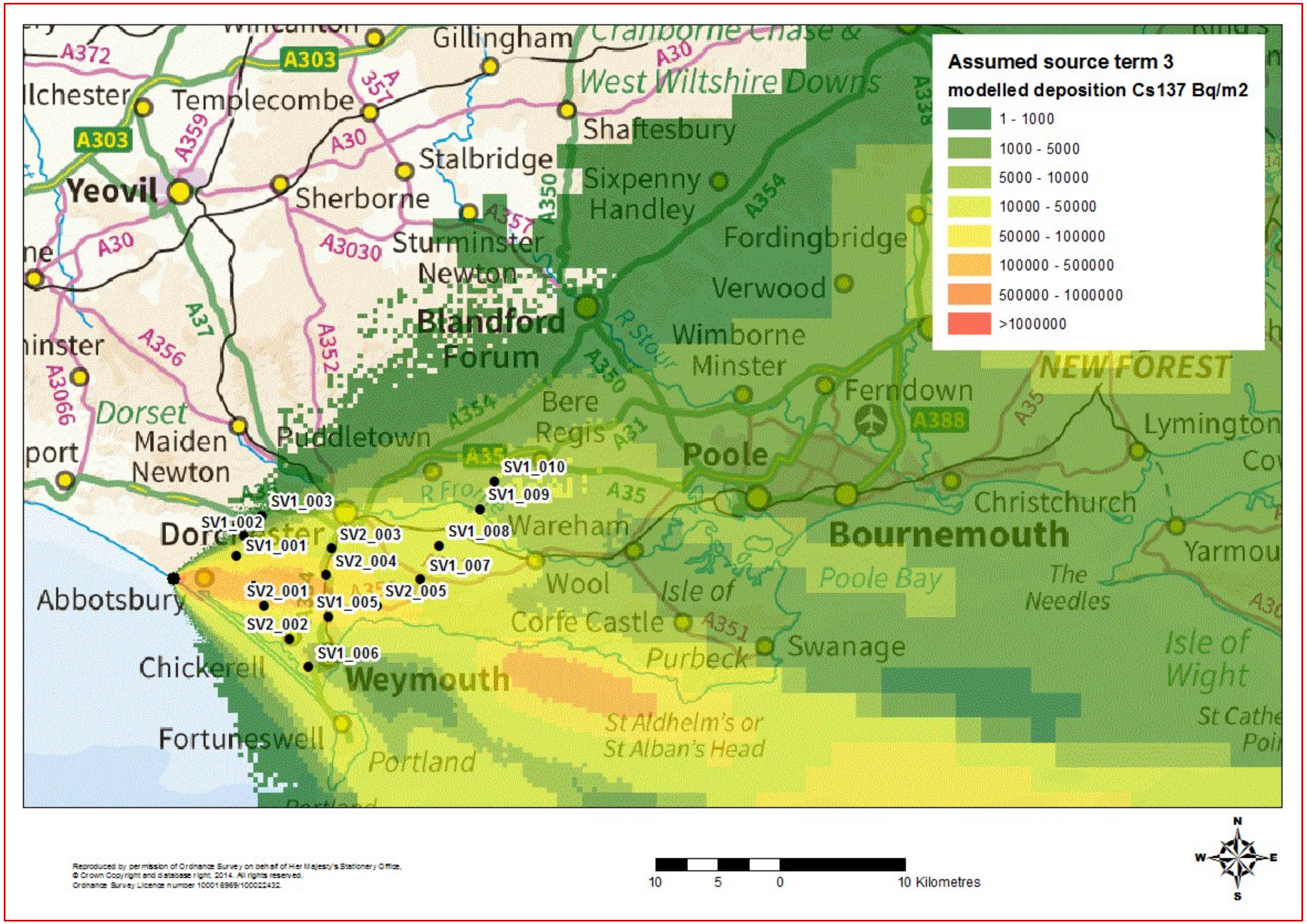
Early afternoon – Issues and Decisions

- Key thoughts at this stage?
- What information is required?
- What decisions would be made?
- What consideration is given to uncertainty at this time?

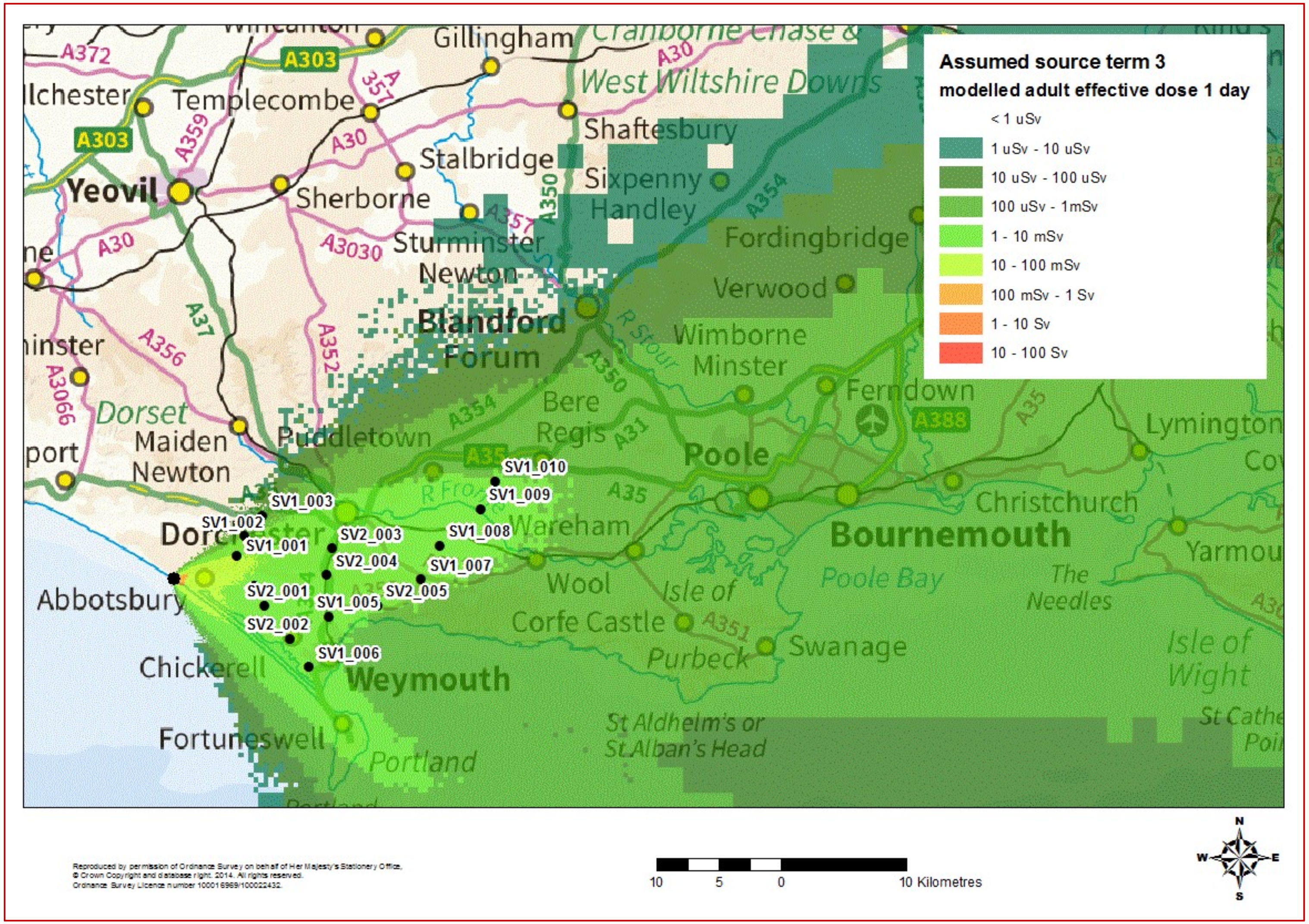
Mid afternoon

- More information & off-site monitoring measurements result in a reduction of the source term estimate – still thought to be precautionary – to 0.5% of inventory of key radionuclides, notably iodines and caesiums.
- However the estimate of release duration is extended to 10hrs from 8:00am. A front has come in bringing changeable weather and some of the plume is now predicted to head towards Weymouth.
- District survey vehicles report more measurements in the first 20 km, these continue to confirm significant radioactivity present in the area east of the site and also suggest that evacuation and sheltering/stable iodine in current areas – 4km and 10km respectively in sectors C2 – C5 (30° - 150°) – remain adequate.

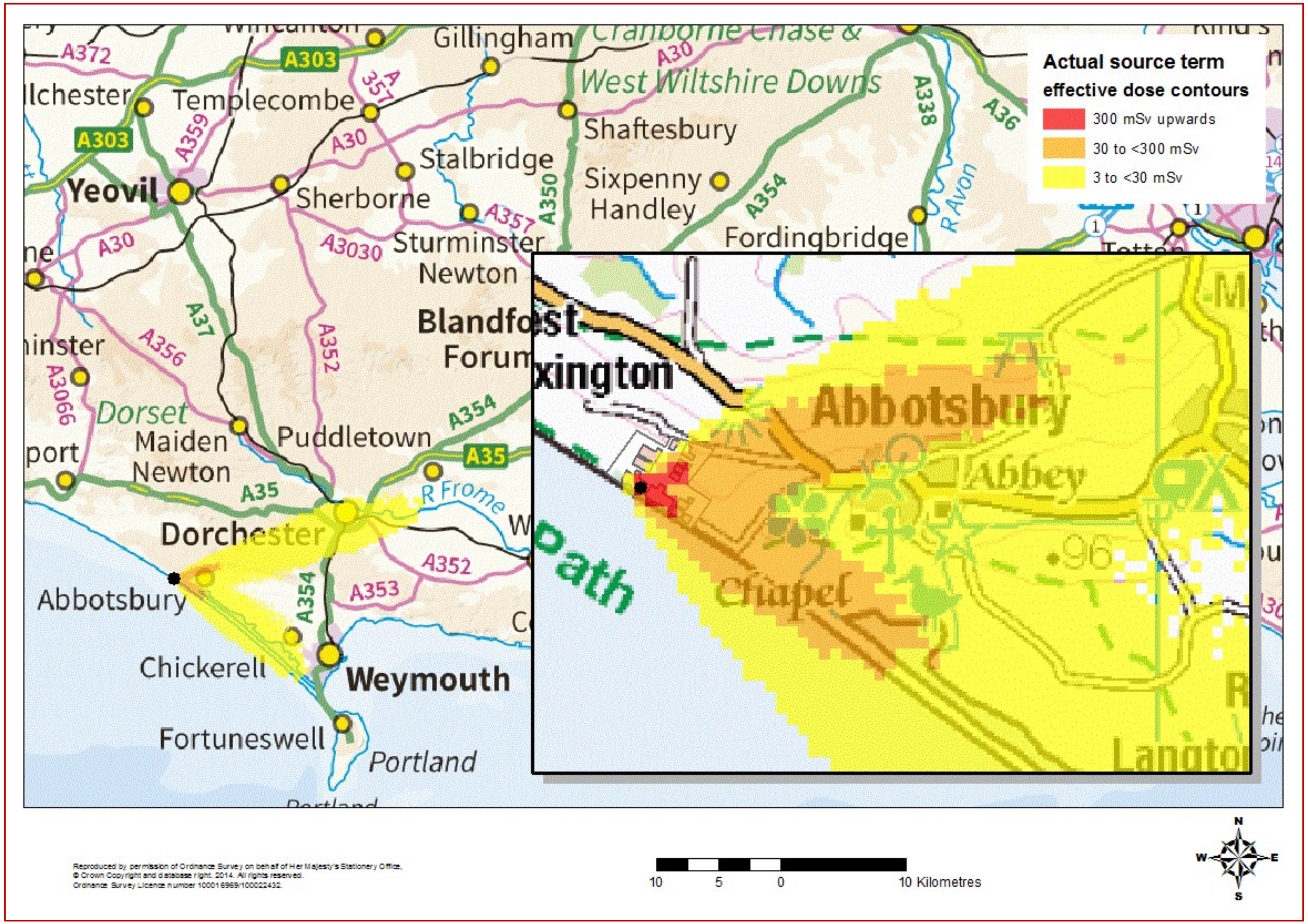
Modelled deposition map and measurement locations



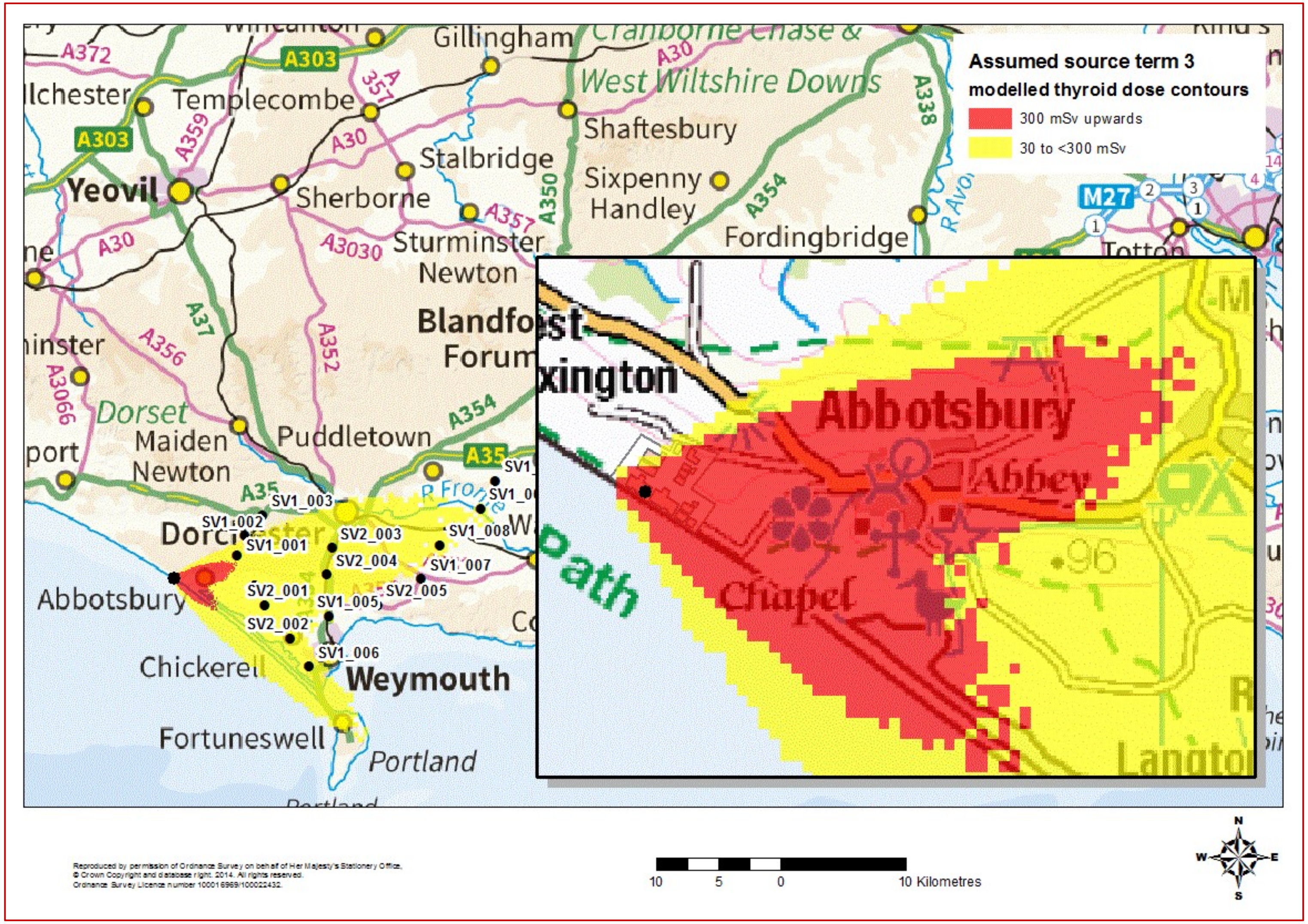
Modelled doses (1st day) and measurement locations



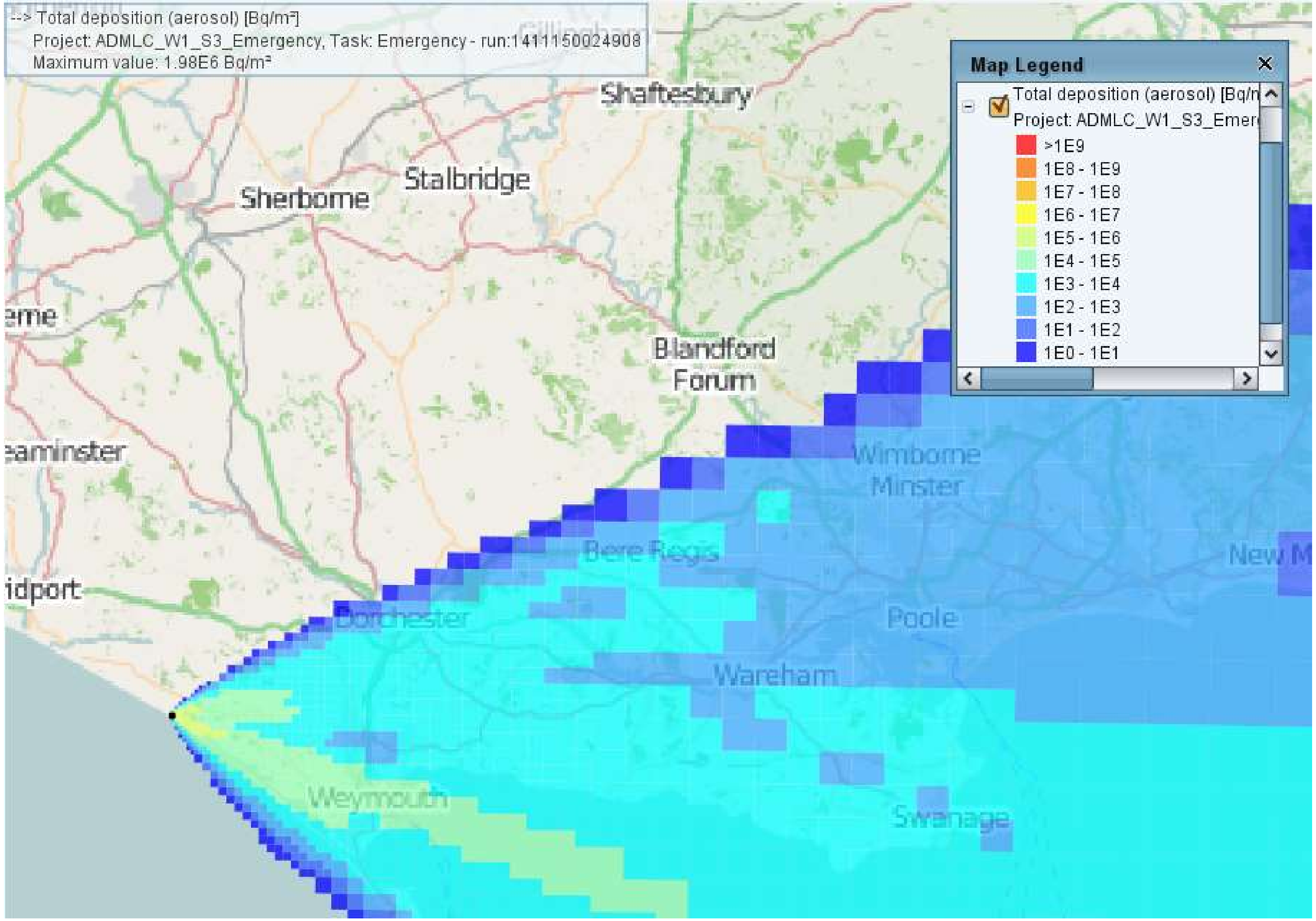
Effective dose contours (modelled)



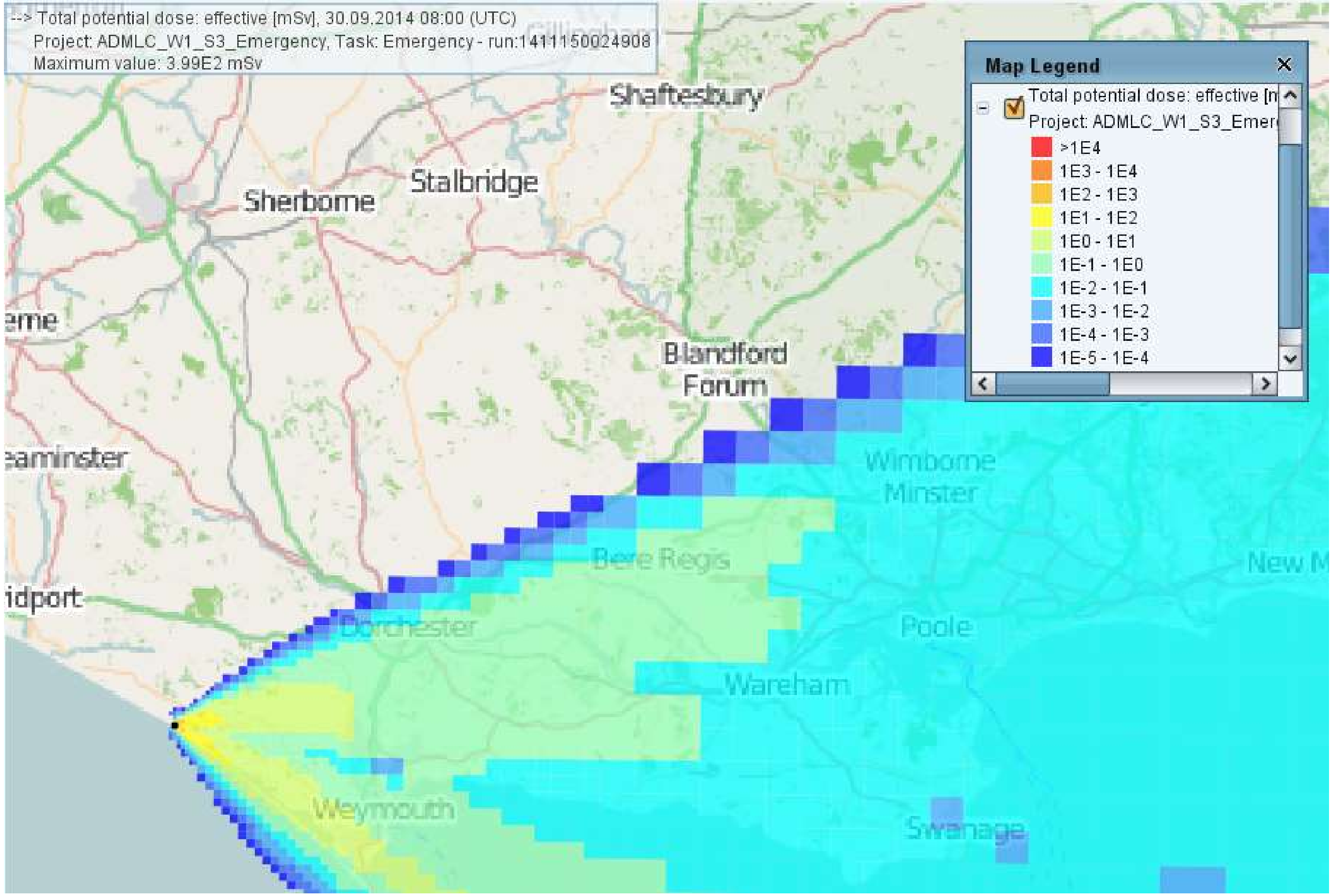
Thyroid dose contours (modelled)



Prediction from Europe: deposition (modelled) - RIMPUFF



Prediction from Europe: doses (modelled) – RIMPUFF



Mid afternoon – Issues and Decisions

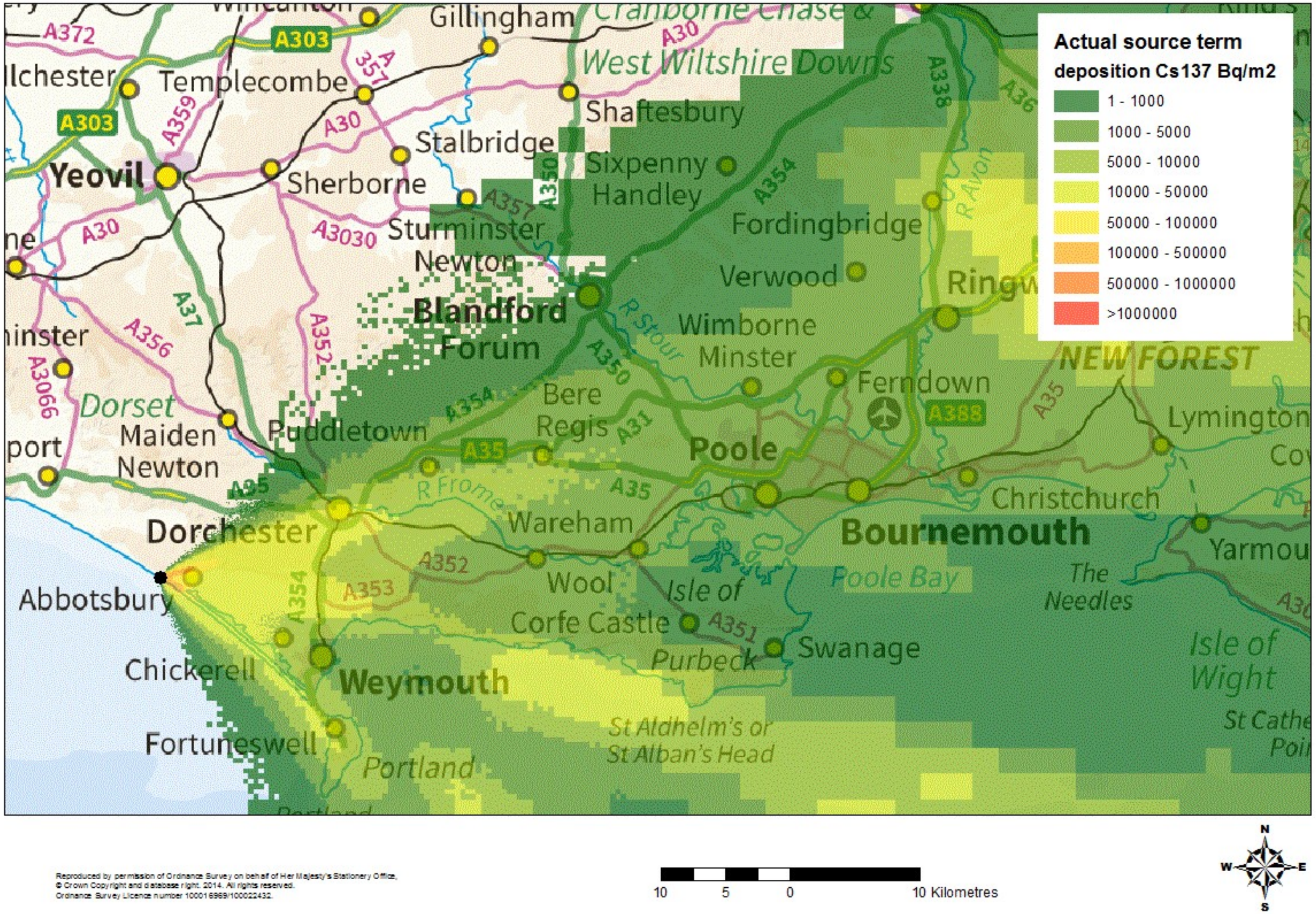
- Key thoughts at this stage?
- What information is required?
- What decisions would be made?
- What consideration is given to uncertainty at this time?

What "actually" happened?

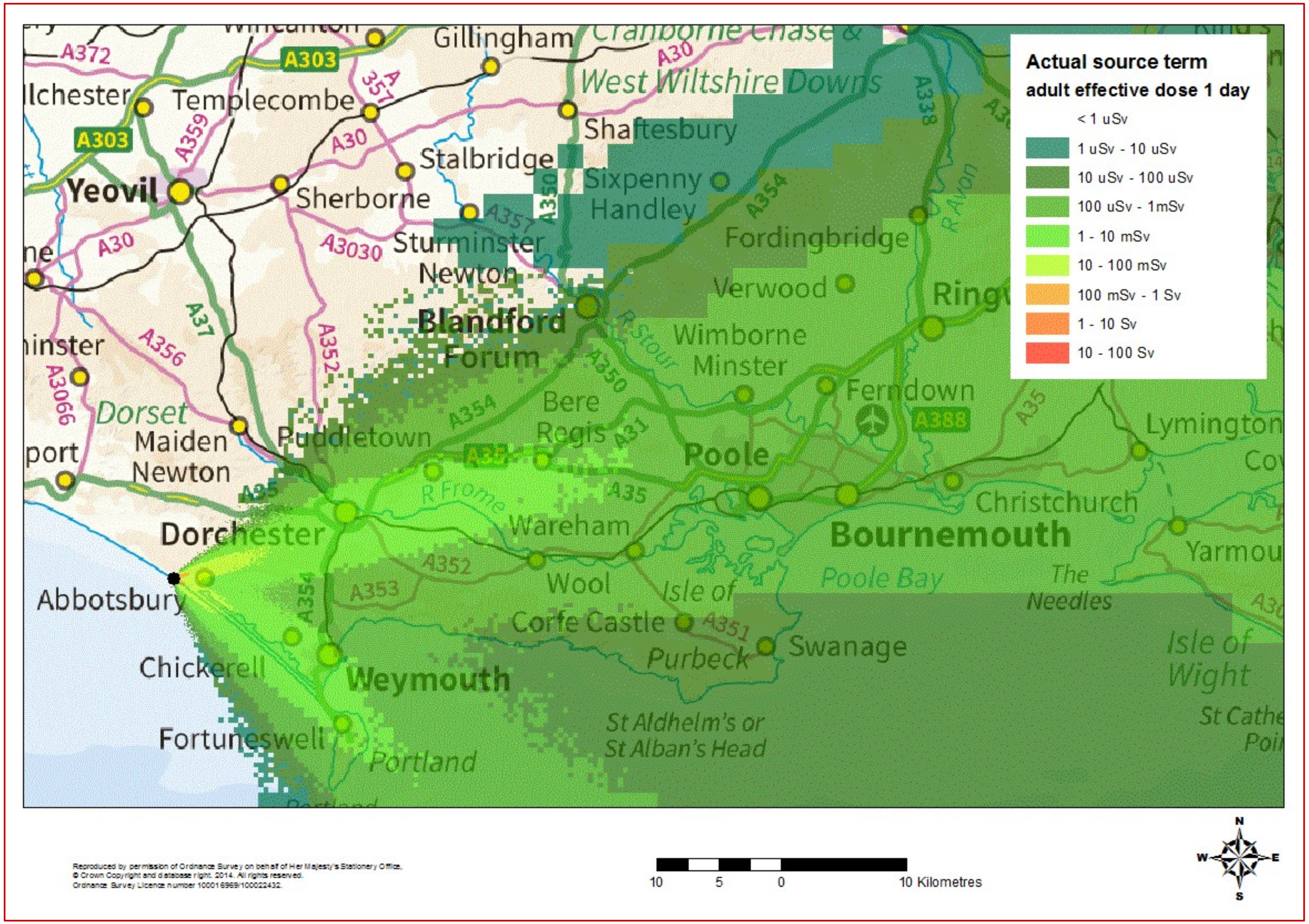
- Actual release was approximately 0.2% of inventory of key radionuclides.
- It continued over 11 hours and the weather front arrived 1 hour earlier than was predicted in the morning, at around 1.00-2.00 pm.
- The release was not uniform but had the characteristics below:

hour	Release (of 0.2%)
1	All noble gases and 40% of other radionuclides
2,3,4,5	10% of other radionuclides
6	30% of other radionuclides
7,8,9,10,11	20% of other radionuclides

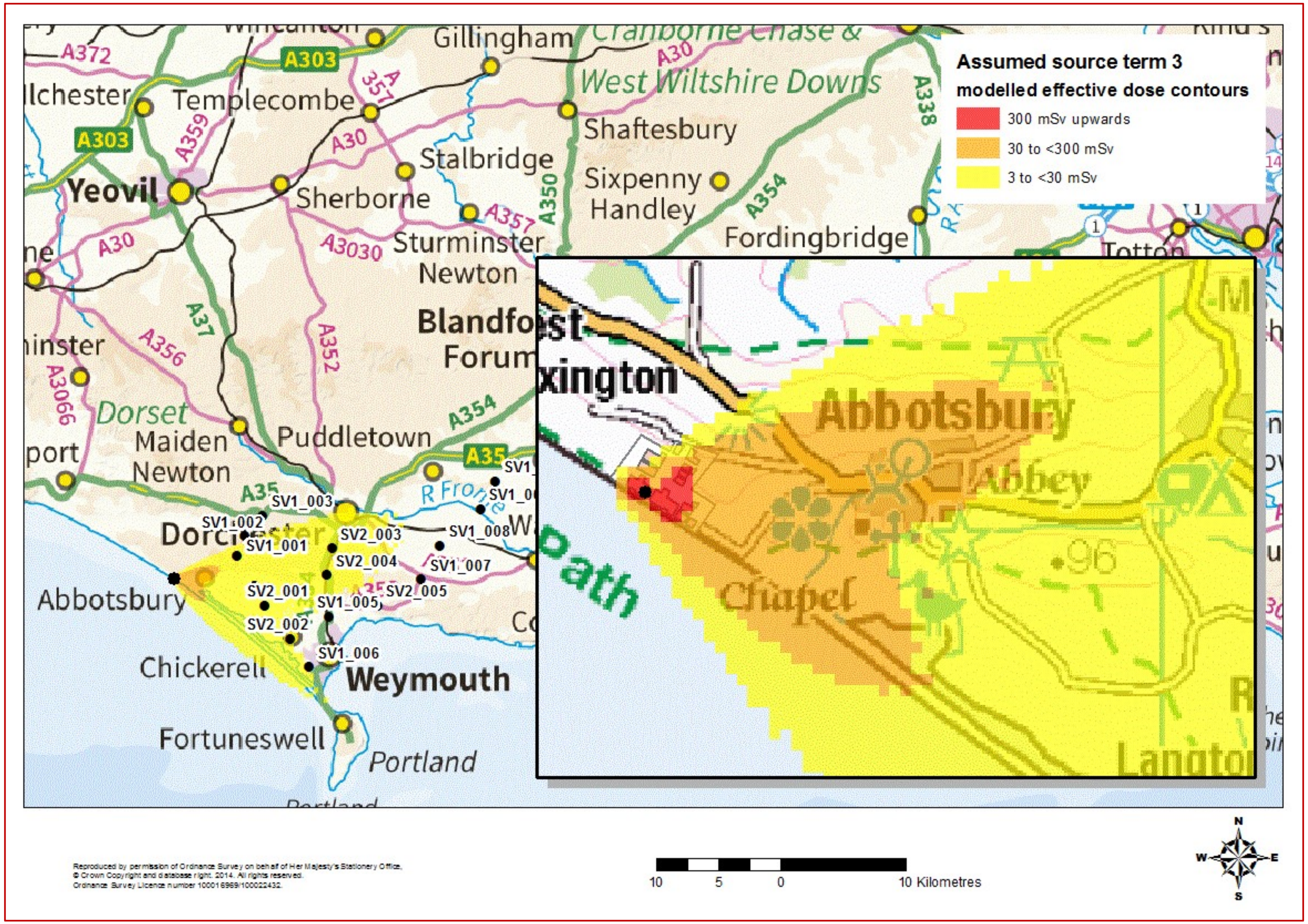
Final total measured deposition of Cs-137 (modelled)



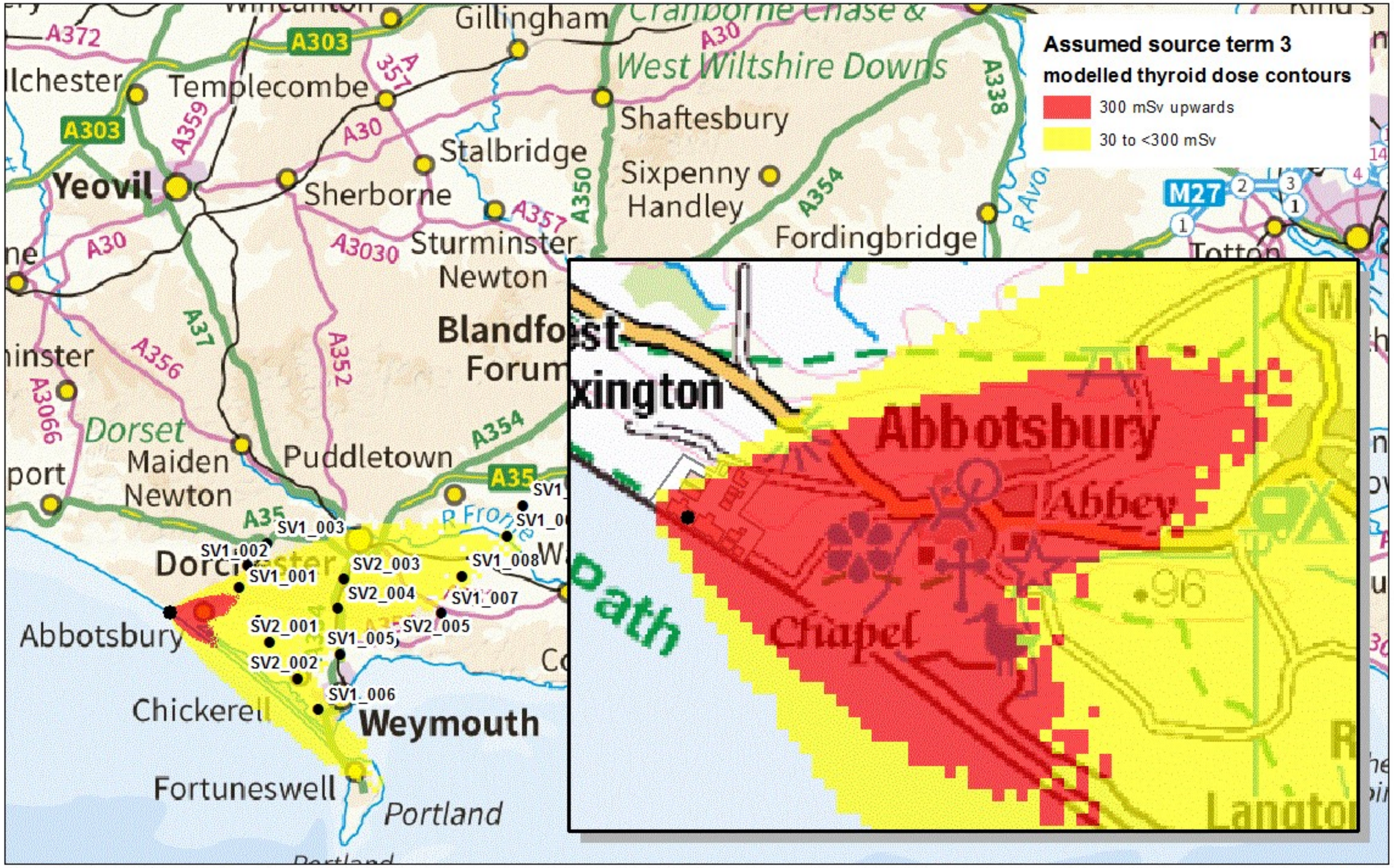
Final doses (modelled) in 1st day



Effective dose contours (modelled)



Thyroid dose contours (modelled)



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Annex 2: The hypothetical accident used at the third workshop

Background Information

Pagham Nuclear Power Station

- Pagham Nuclear Power Plant is located on the West Sussex coast
  - East of Havant
  - South of Chichester
  - South-west of Bognor Regis.
- To the north of Pagham Nuclear Power Plant is an area of predominantly agricultural land.

Hypothetical Reactor Location: Selsey Bill

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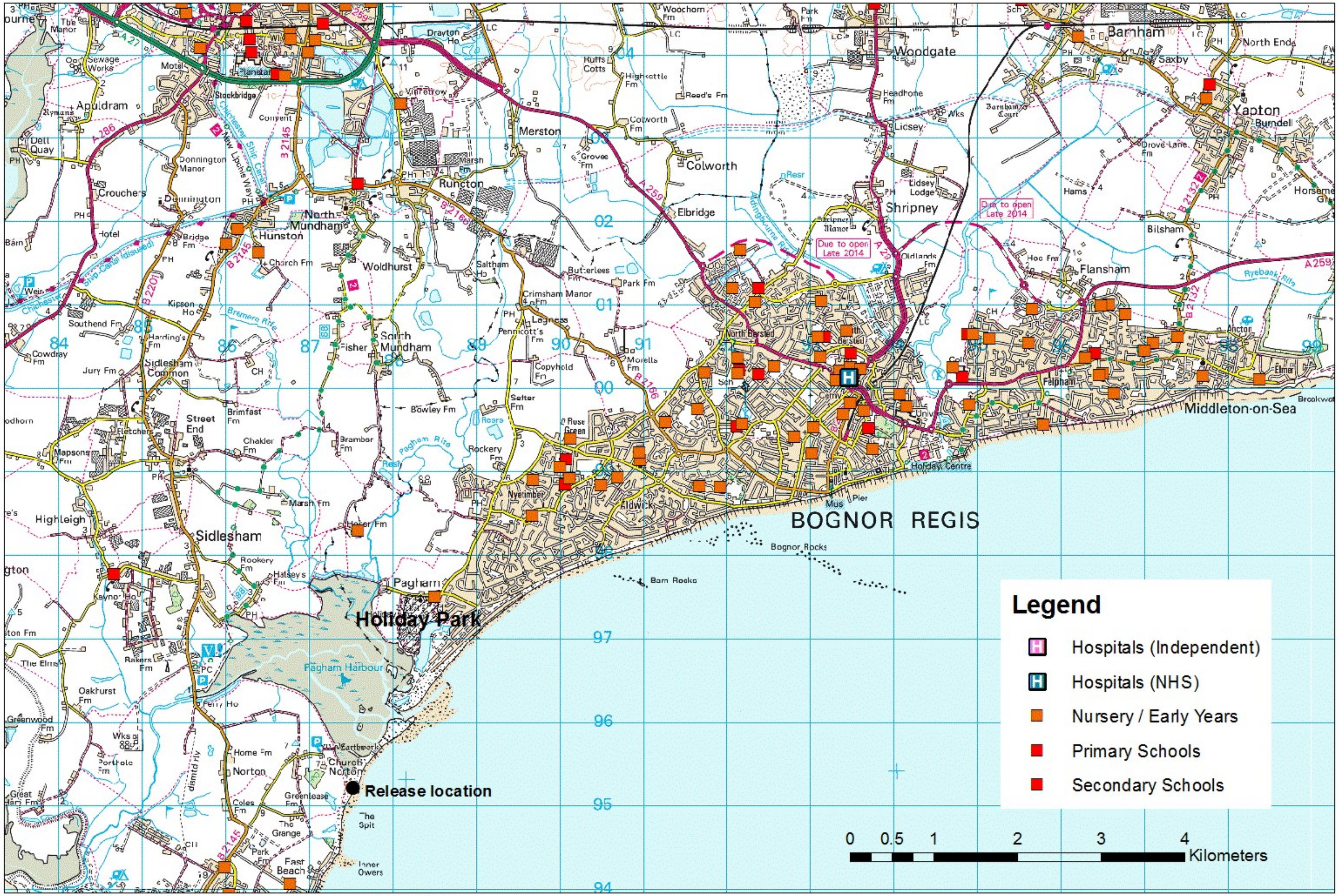
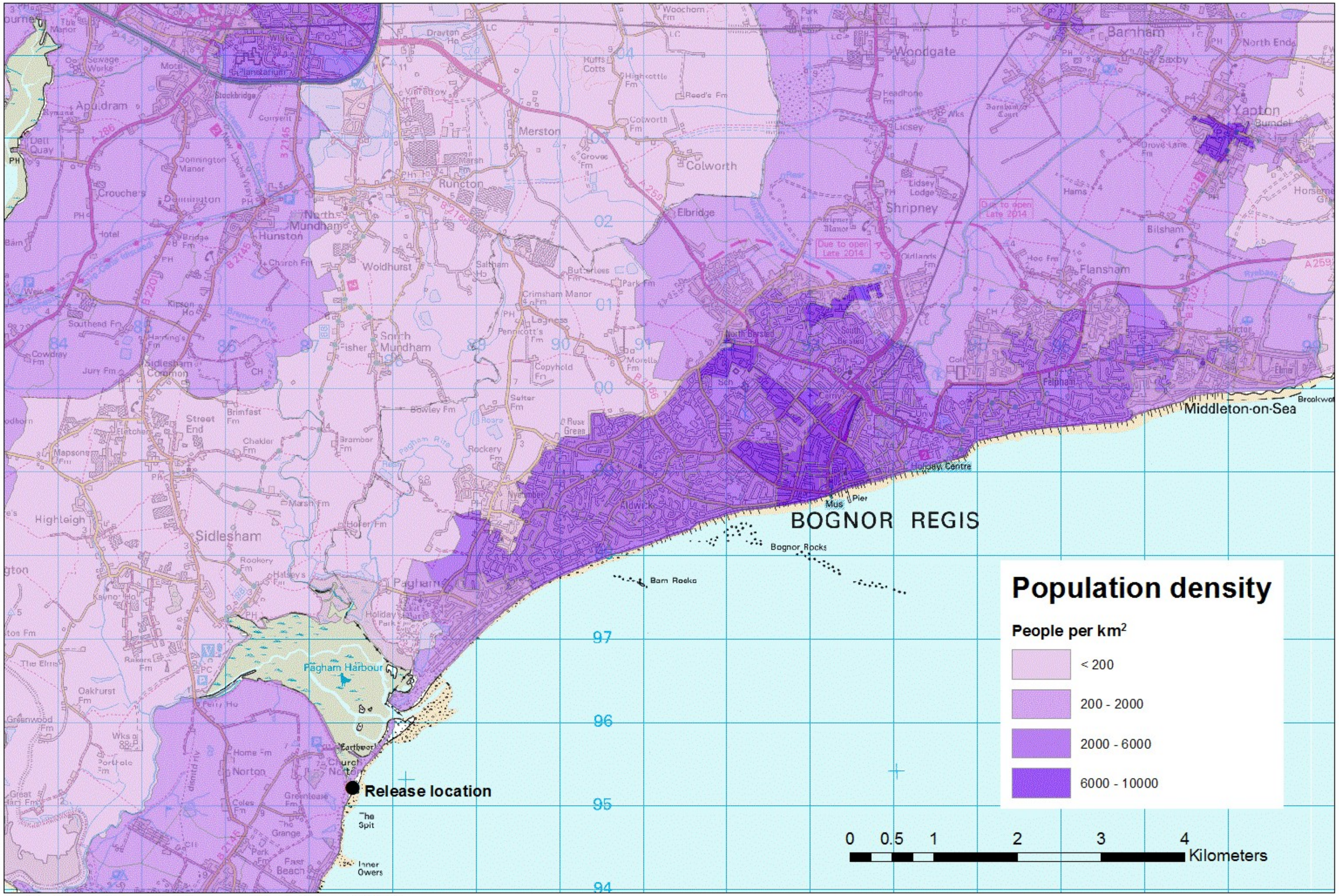
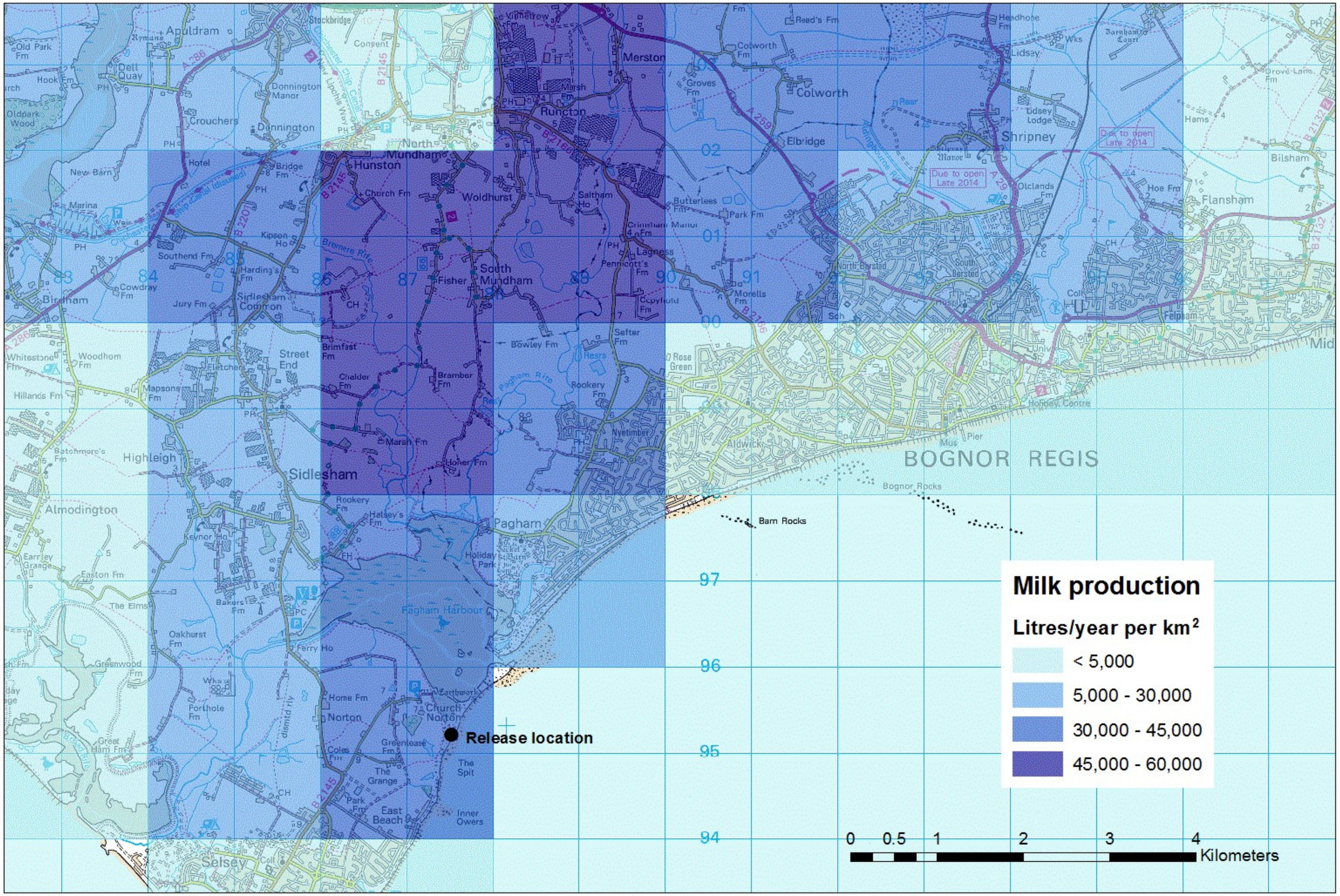
Key Locations



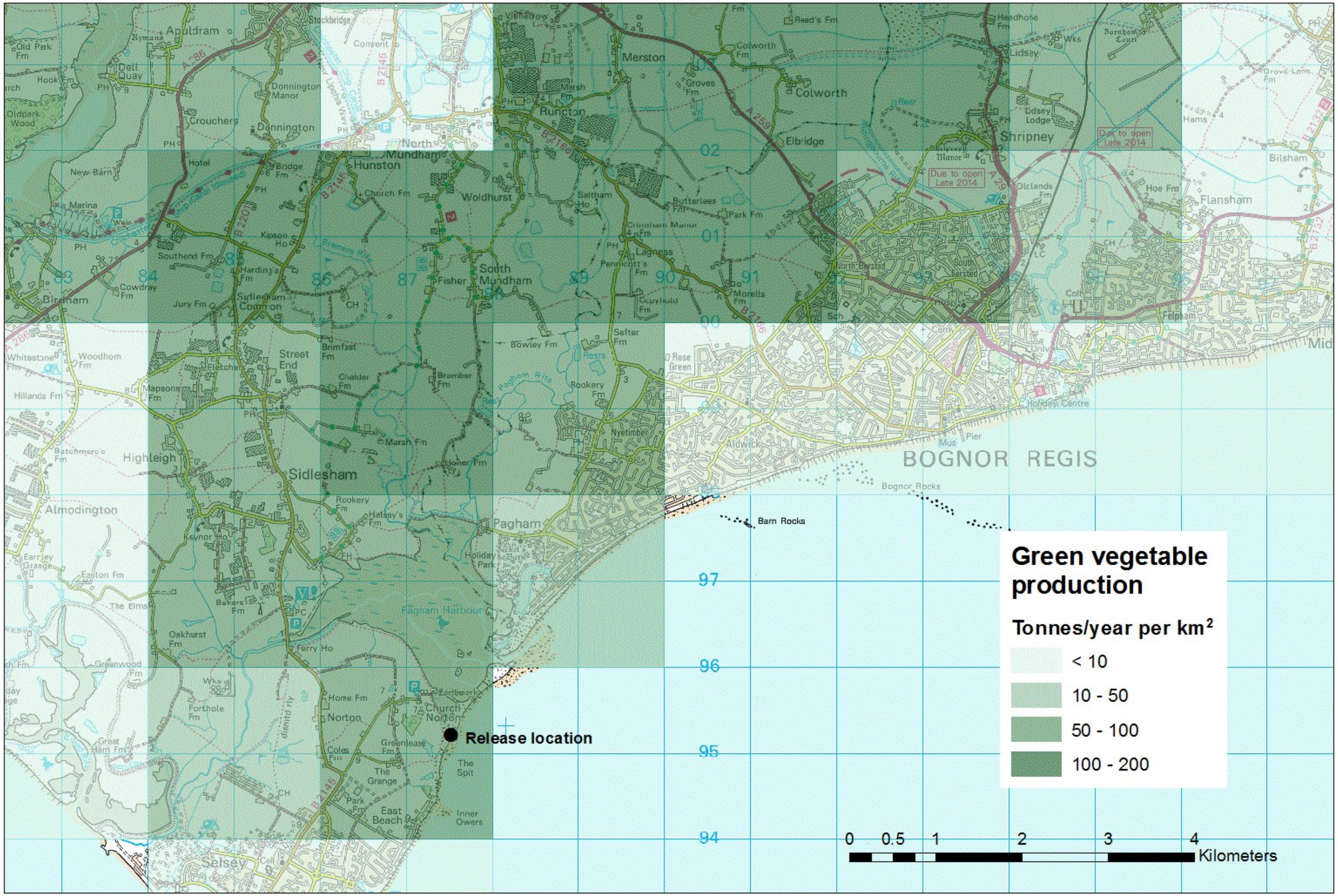
Population Density



Milk Production



Green Vegetable Production



Site Emergency Plan

Pagham Nuclear Power Station emergency plan:

- Specified plant conditions and monitoring results (on-site & off-site) trigger its emergency plan.
- The usual ‘dartboard’ (bands and sectors) around the plant is used to define specific actions.
- If the plan is triggered, the site operator will:
  - Inform the local police, fire service, ambulance service, local authority, and national authorities.
  - Advise all residents in the two inner bands to take pre-distributed **stable iodine tablets.**
  - Advise the local police to **evacuate** all residents in the two inner bands.
  - Advise all residents in some or all sectors in the third band to **shelter**.

The Accident

Please note that we will take questions of clarification *only* while we describe the accident.

We ask you *not* to discuss the accident for the time being.

Friday August 14th 2015

- It is the school summer holidays.
- There is a Folk Festival at Pagham Holiday Park.
- There are bird-watchers at Pagham Harbour Nature Reserve. There are a number of brave souls on the beach at Bognor Regis. And there are both fishing boats and leisure boats off the coast.

09:30 – the nuclear power plant at Pagham reports an engineering fault which has the potential to become more serious.

10:00 – it is clear that immediate engineering actions are not going to rectify the problem quickly and the nuclear power plant takes the decision to inform government of the potential for the situation to escalate. The Met Office and PHE are informed and begin a range of preliminary modelling runs, so that they are ready if it does become an emergency.

Friday August 14th 2015

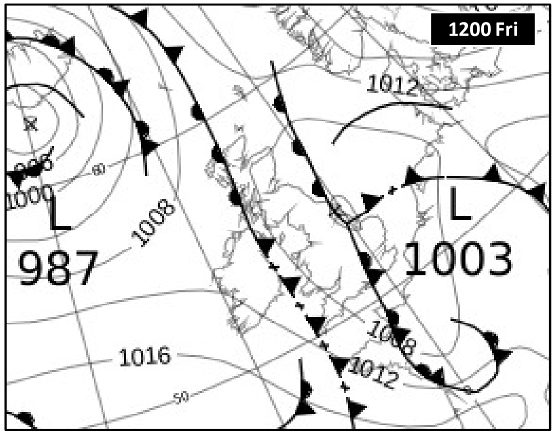
11.00 – a moderate release of radionuclides is detected and the full local emergency plan is followed with local evacuation, uptake of iodine and sheltering begun in the planned areas. No problems are encountered in achieving this.

- The Met Office and PHE begin full modelling.
- Potential escalation of the issue means that a larger release is thought possible, starting between 13:00 and 14:00.
- To complicate matters a front will pass through around this time potentially causing a rapid change in wind direction

Weather Forecast for South East England

- **Headline:** A windy and cloudy day with rain.
- **Today:** A windy, cloudy start for all with a wet start in the west of the region. Rain will spread across to the east of the region by late evening. Continuing to feel cooler than average. Maximum temperature 19C.

- **Tonight:** Staying mostly cloudy with rain becoming light and patchy. Winds will ease overnight. Minimum temperature 13C
- **Saturday:** Saturday will be a mostly cloudy day with some bright spells in the west. It will remain dry but cool for the time of year.



Local forecast for Selsey Bill/Pagham

provided by EMARC/Met Office representative on SAGE at 12:00

Weather in Selsey Bill/Pagham is currently cloudy and dry with wind blowing from the south (south-south-west). The rain, forecast for the region, is expected to reach Selsey Bill/Pagham between 13:00 and 14:00. At the same time the wind direction will change so that the wind blows initially from the south west and later from the west. There is some uncertainty in the timing of the arrival of the rain and change in wind direction.

Modelling results

At 12.00, modelling results are available for a number of likely scenarios. Maps have been produced for what are considered to be the bounding scenarios (labelled 1, 3, 5 and 6). All results include the moderate release starting at 11.00, magnitude of approximately 1 x 10^{14} Bq of iodine-131 over one hour.

1 The moderate release at 11.00 only.

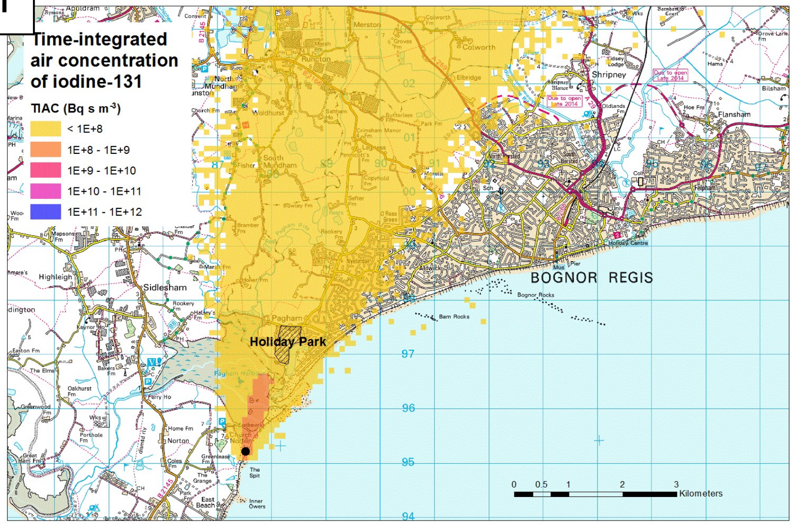
3 The moderate release at 11.00 followed by a large release starting at 14.00 and ending at 16.00 with stable weather conditions. The magnitude of the large release is approximately 4 x 10^{14} Bq of caesium-137 and 1 x 10^{16} Bq of iodine-131 over 2 hours.

5 The moderate release at 11.00 followed by a large release starting at 14.00 and ending at 16.00 with a change in weather conditions following the arrival of the front. The magnitude of the large release is approximately 4 x 10^{14} Bq of caesium-137 and 1 x 10^{16} Bq of iodine-131 over 2 hours.

6 The moderate release at 11.00 followed by a *very large* release starting at 14.00 and ending at 16.00 with stable weather conditions. The magnitude of the very large release is approximately 2 x 10^{15} Bq of caesium-137 and 4 x 10^{16} Bq of iodine-131 over 2 hours (four times greater than the “large” release).

Atmospheric dispersion of radioactive material

1



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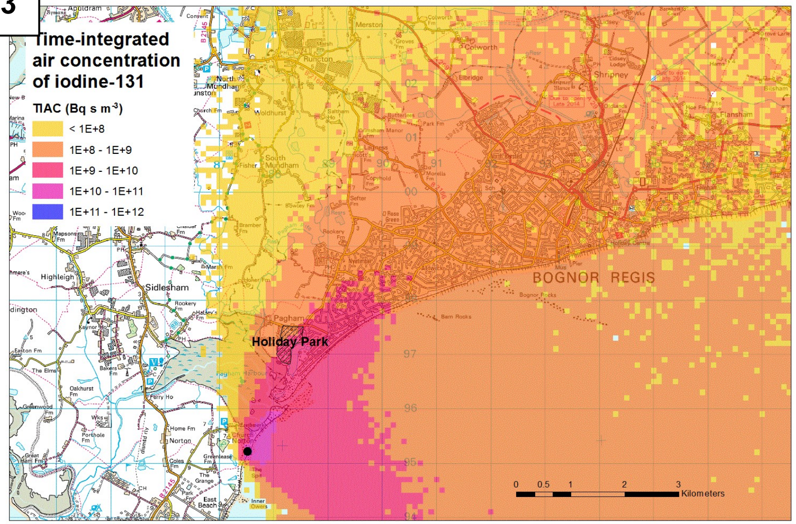

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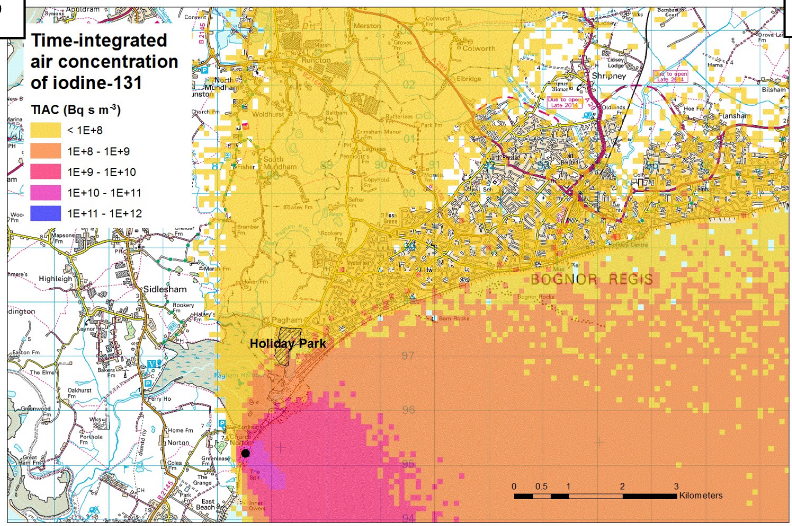

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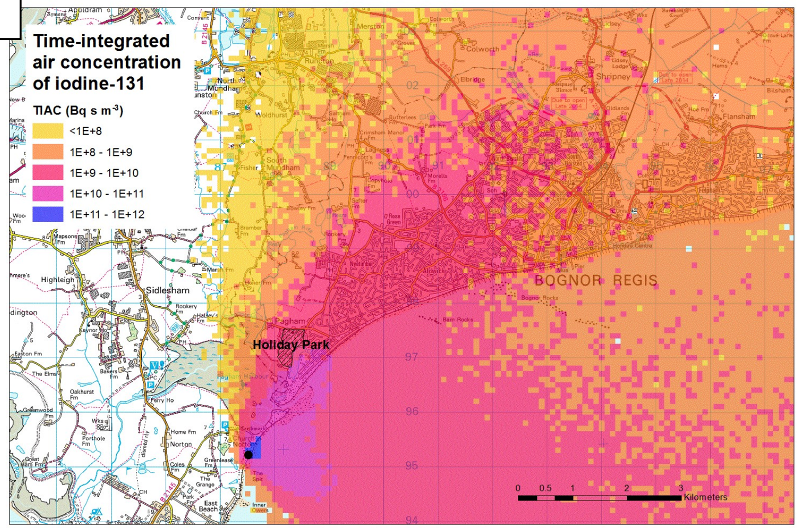

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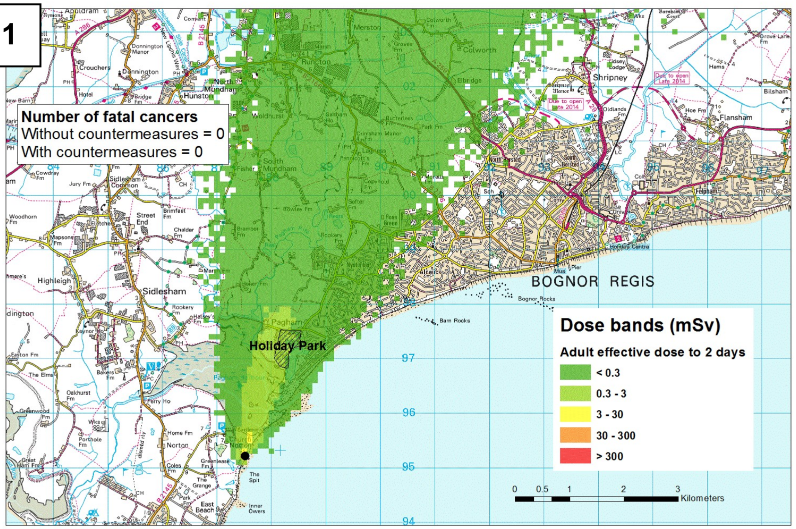
Dose bands (effective dose)

1



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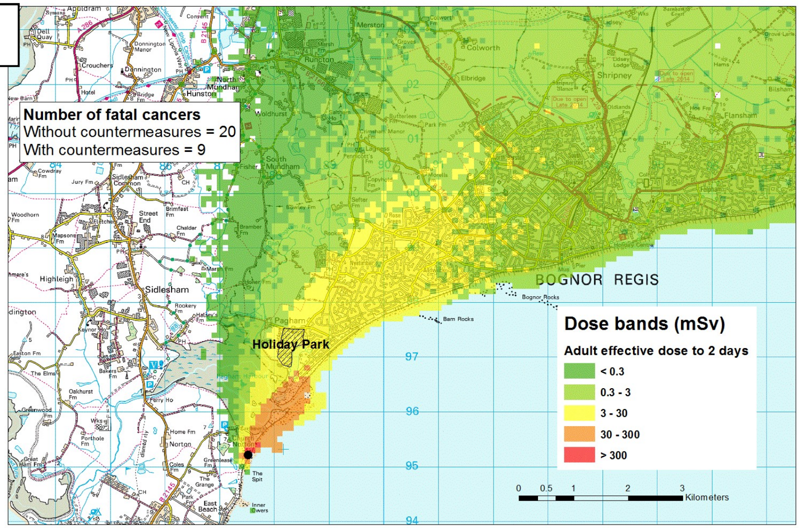

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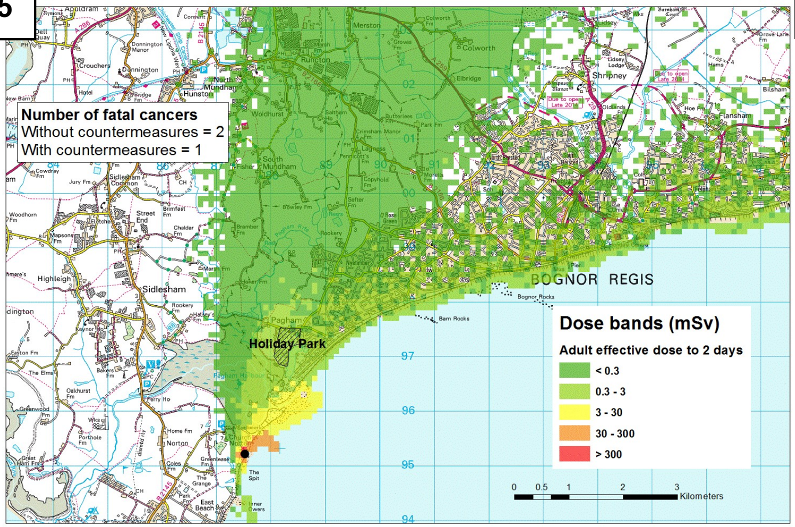

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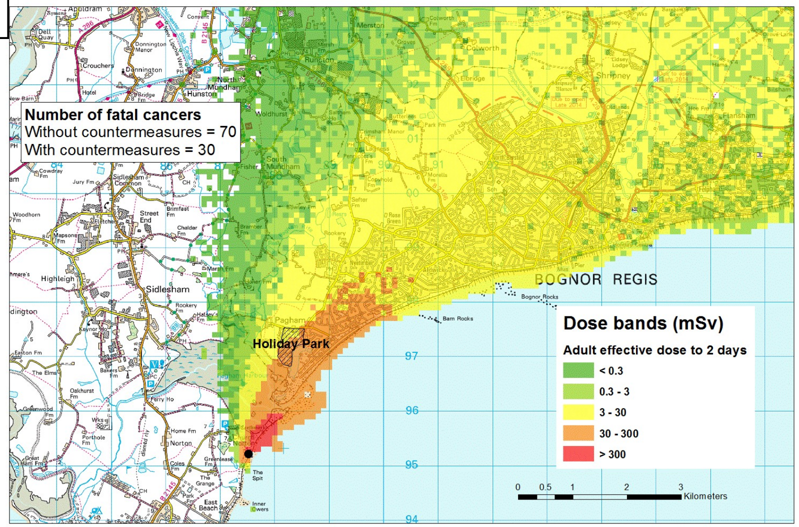

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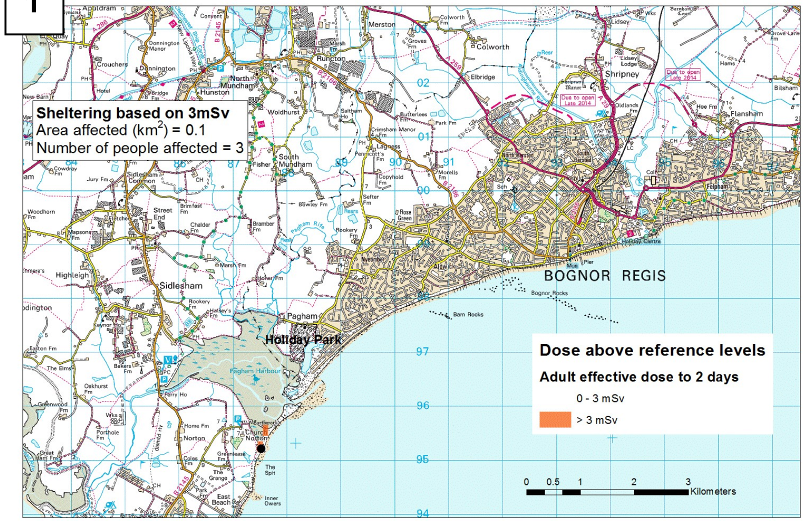
Effective dose > 3 mSv
(lower ERL for sheltering)

1



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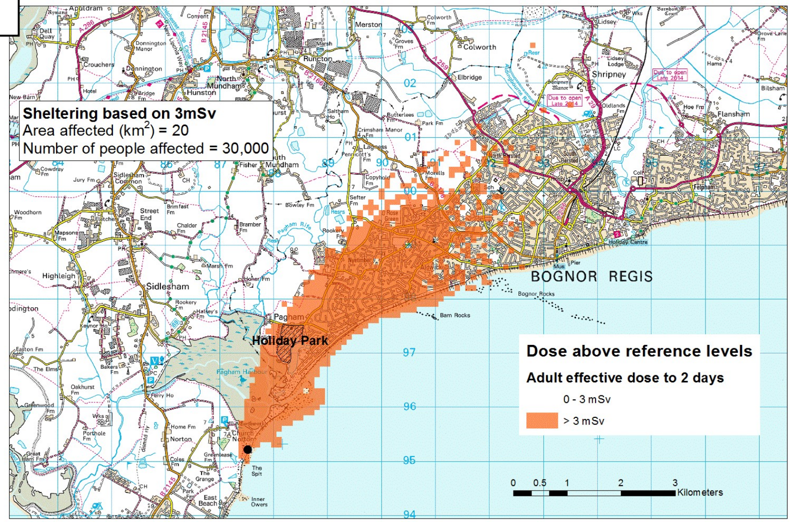

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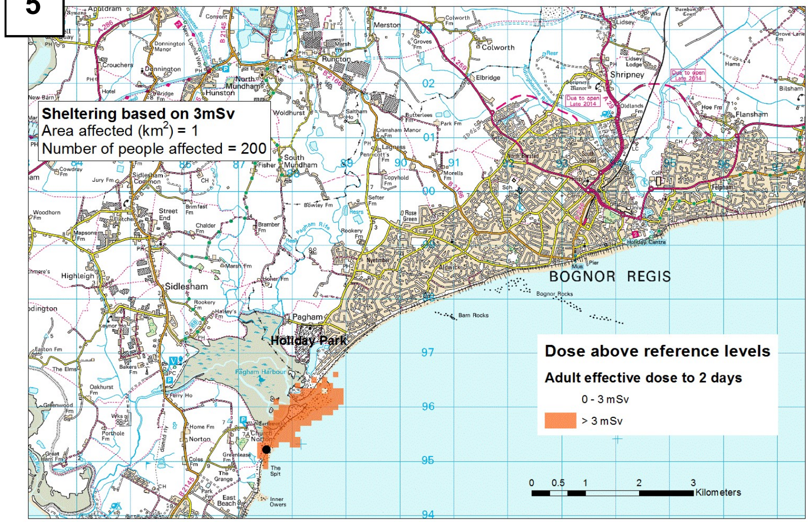

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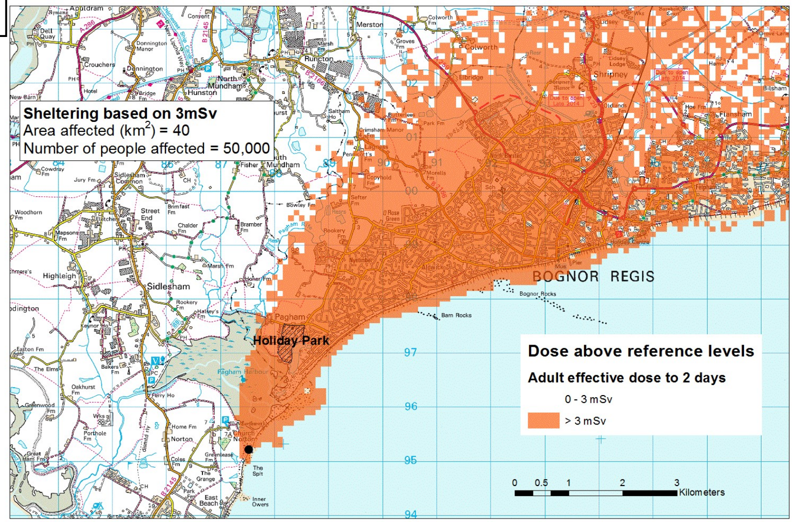
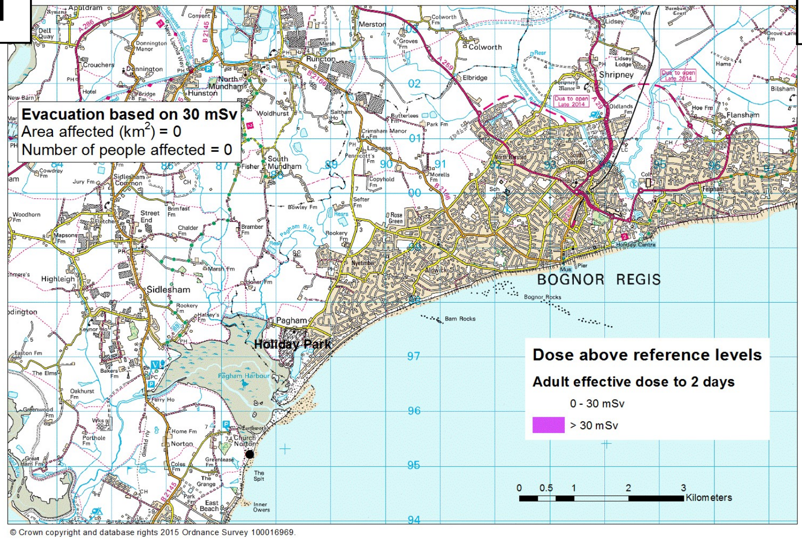


Effective dose > 30 mSv
(lower ERL for evacuation)

1



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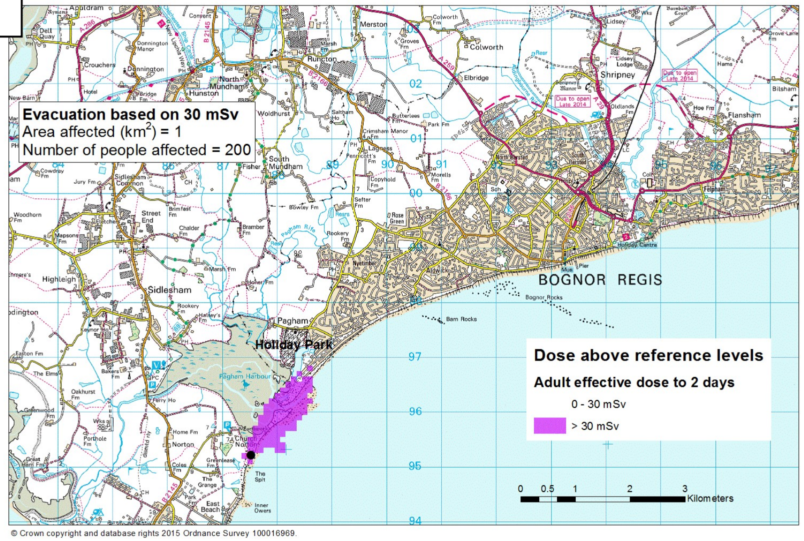

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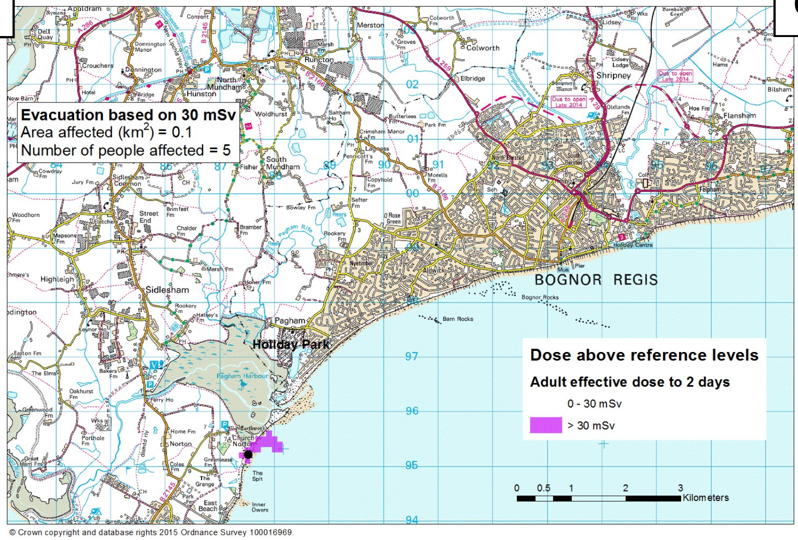

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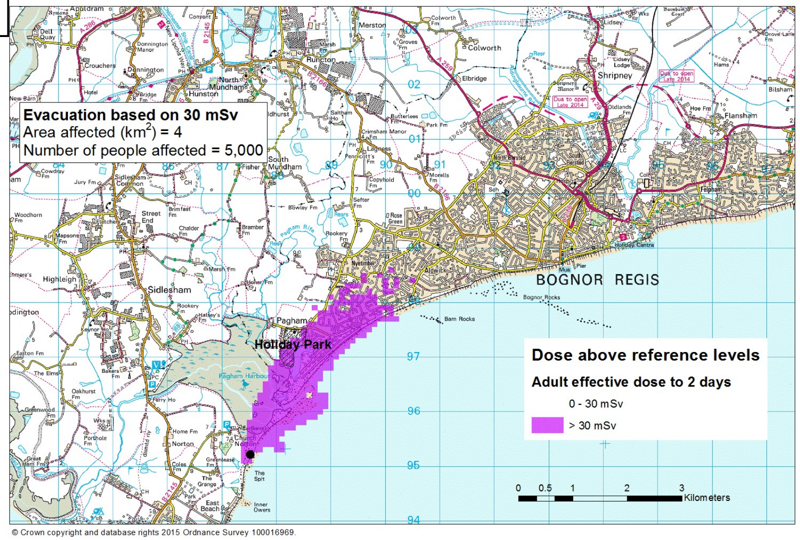
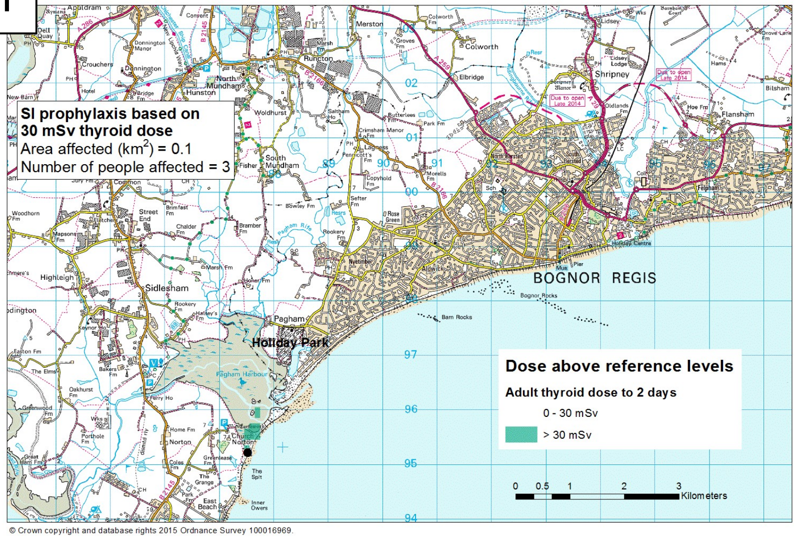


Thyroid dose from iodine-131 > 30 mSv
(lower ERL for stable iodine (SI))

1



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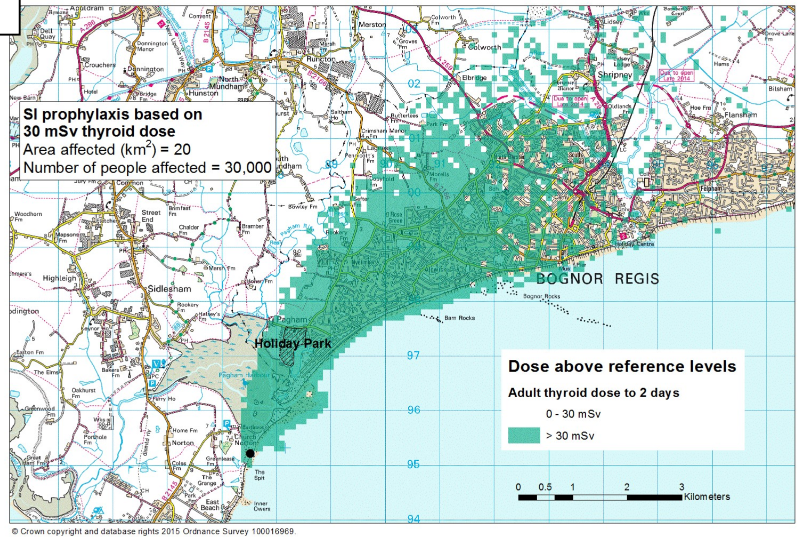

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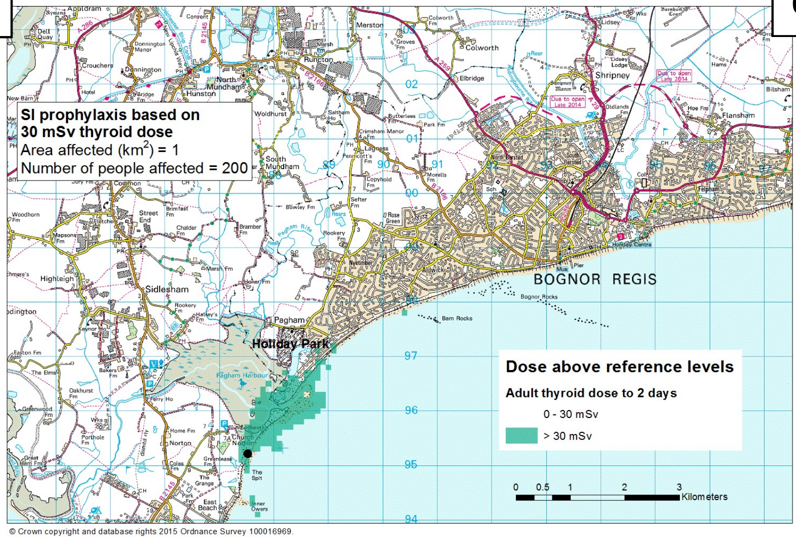

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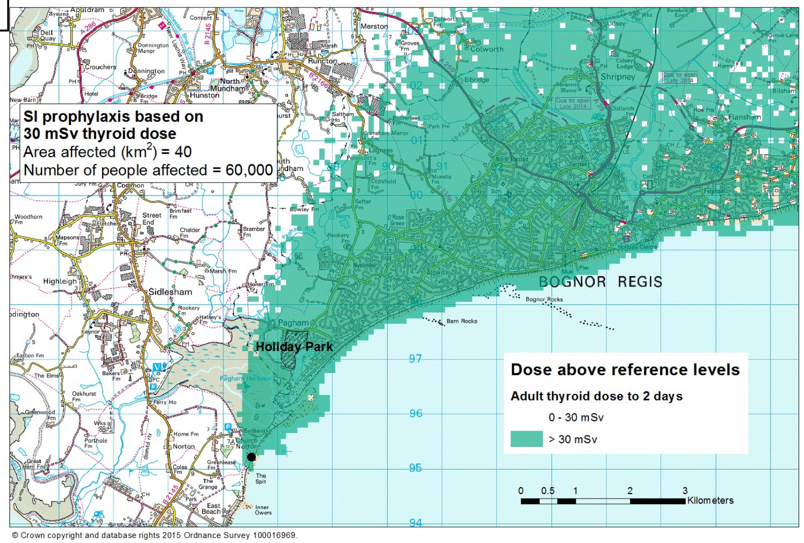
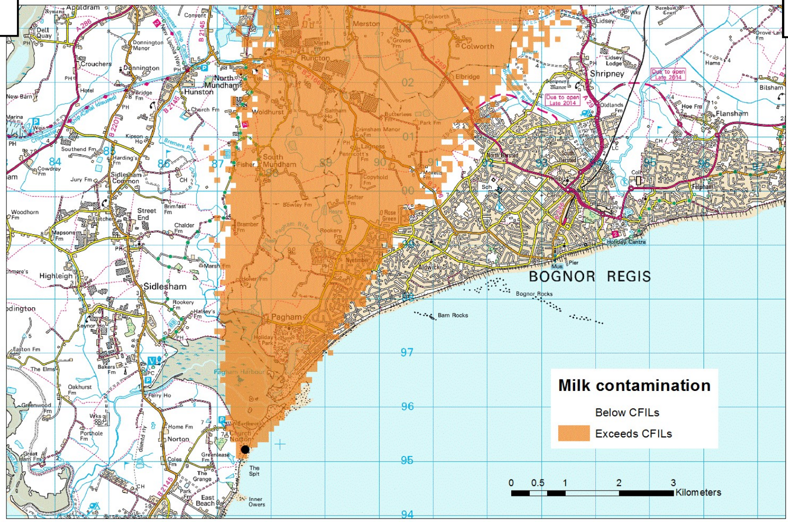


Milk restrictions

1



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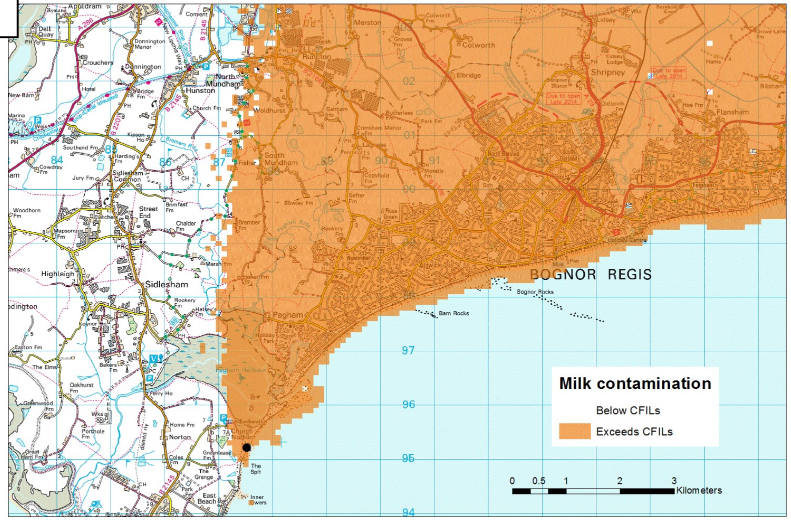

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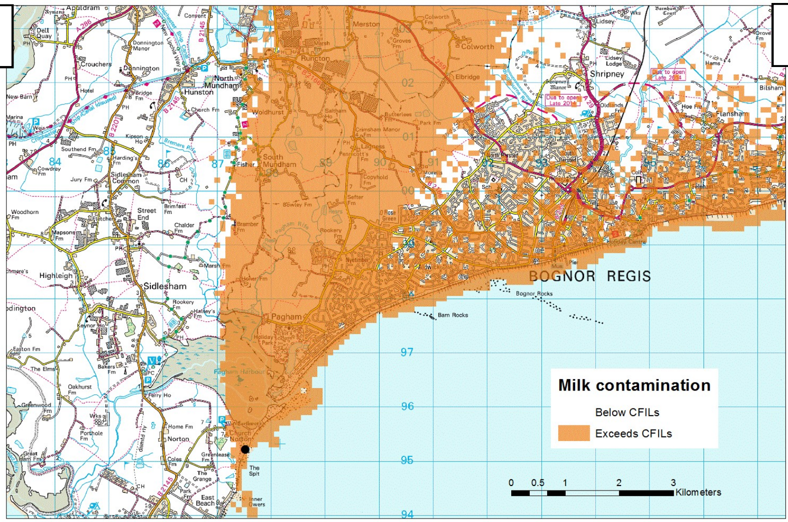

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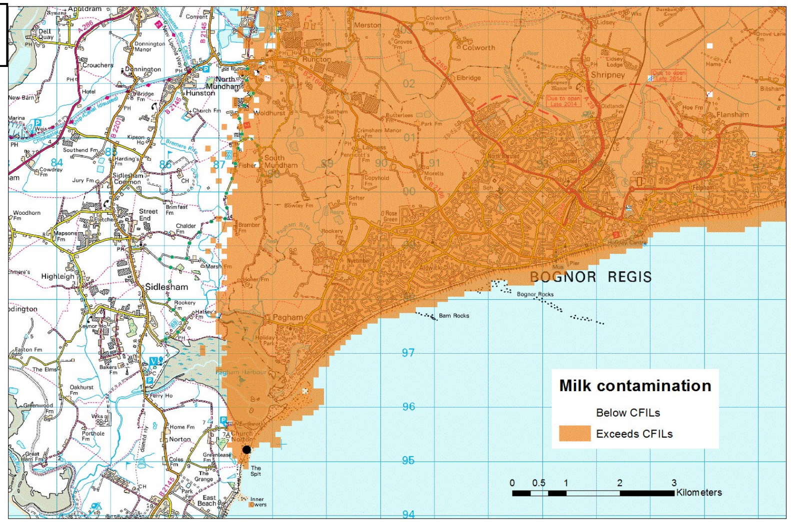

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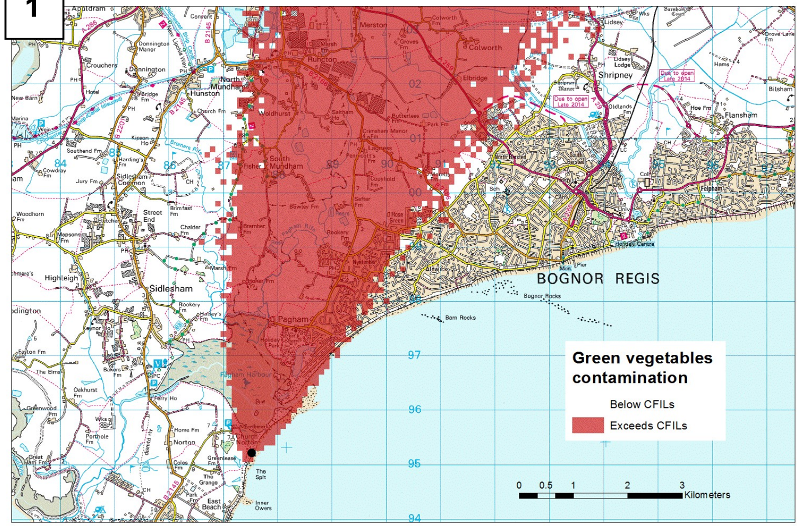
Green Veg restrictions

1



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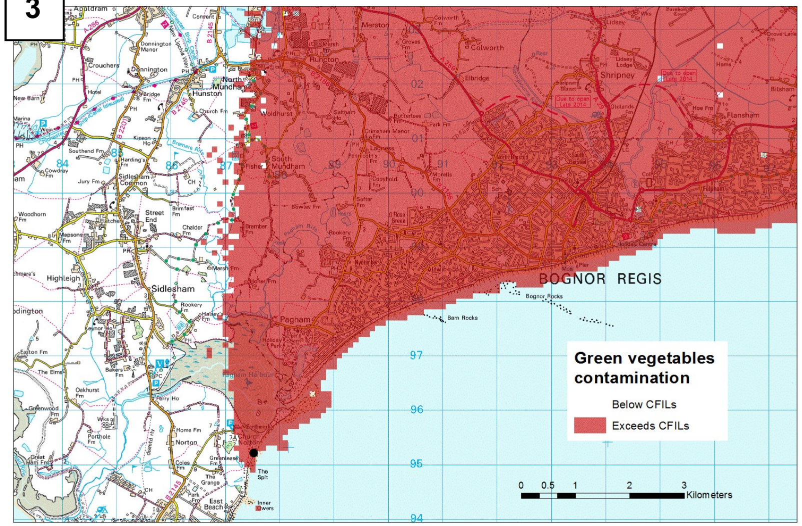

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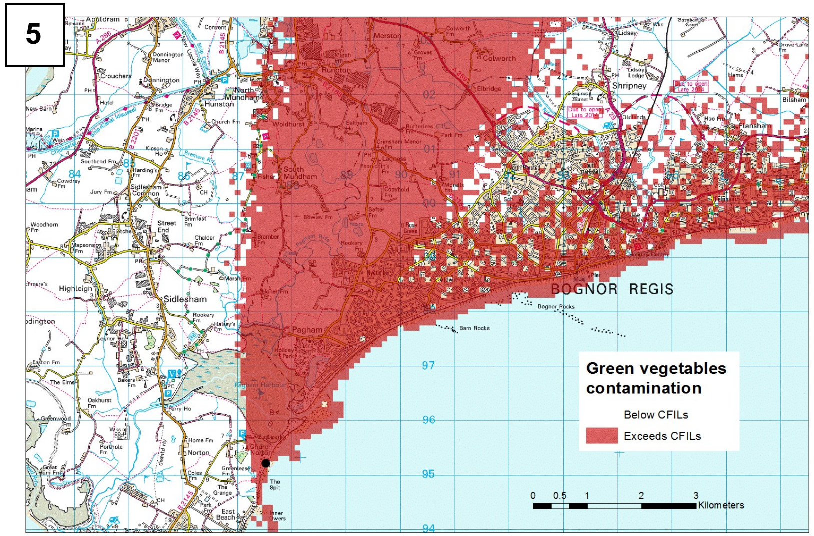

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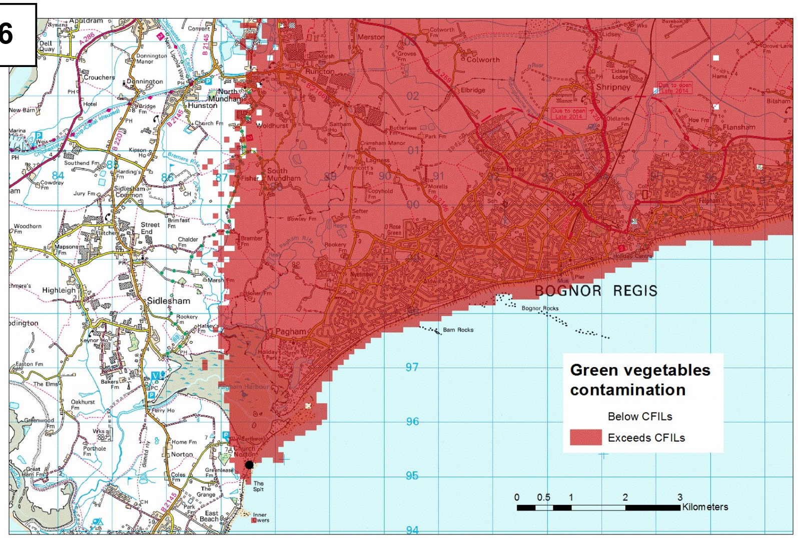

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Annex 3: First questionnaire used at the third workshop

Name*:

Affiliation/Organisation*:

**Confidentiality*: We are running the workshop under Chatham House Rules. Your attendance at the meeting may be reported but no statement will be attributed to you directly nor your affiliation/ organisation in any public report. All files relating to this questionnaire will be anonymised. That said we do ask that you give your name and affiliation above so that (i) we may relate the questionnaire responses to other issues in the day and (ii) we may contact you after the event if there is a need for some clarification.

Before beginning the general discussion we want to capture your individual first impressions of what is happening in the scenario, what you think the key issues are and what the advice to COBR might include. There are *three* questions, for which we want you to imagine that you are a member of SAGE and in one hour's time the Chief Scientist has to go into COBR with advice and recommendations.

Question 1. We have just presented you with details of an accident and several ways in which it might evolve over the next few hours. We want to understand your first thoughts on this in your role as a member of SAGE needing to advise COBR: what are your key concerns; what are the key issues; and so on? Please write these below in any form that you find easiest, e.g. a few questions, bullet points, plain text, a mindmap or cognitive network of interconnected ideas.

Question 2
What further information would you seek during the next hour's discussion before advice needs to be given to COBR? You need recognise that some of this information may be available from other members of SAGE, some you may be able to ring/email out for, but some may not be available until after SAGE has to give its initial advice to COBR.

Question 3
At this stage what are your thoughts about the advice that should be given to COBR? Obviously this may change or be qualified in the discussion to come before that advice is given; here we are interested in capturing your *first* thoughts.

Annex 4: Second questionnaire used at the third workshop

Name*:

Affiliation/Organisation*:

**Confidentiality*: We are running the workshop under Chatham House Rules. Your attendance at the meeting may be reported but no statement will be attributed to you directly nor your affiliation/ organisation in any public report. All files relating to this questionnaire will be anonymised. That said we do ask that you give your name and affiliation above so that (i) we may relate the questionnaire responses to other issues in the day and (ii) we may contact you after the event if there is a need for some clarification.

Thank you for attending the workshop today. Before leaving we would like you to complete a second questionnaire. This is *not* the usual end of workshop questionnaire about the quality of the venue, food and presentations, but a serious part of our research today. We want to understand how your views might have changed during the day, whether the presentation of several scenarios helped you appreciate the inherent uncertainties and the range of possible consequences, and so on. We also want your individual advice on what the project's recommendations should be to ADMLC, and thence into the running of SAGE.

Question 1: Looking back at the role playing discussion 'as SAGE' before lunch, did your views change in any significant way? Did information or arguments offered by others change your initial assessment of the situation? Were there any key learning points for you?

Question 2: Do you feel that the inherent uncertainties in the situation were well communicated? Have you any suggestions for communicating them better? Would any other tables, diagrams, maps, figures, etc. have helped? Feel free to sketch any such below.

Question 3: Overall do you feel that the advice and recommendations to COBR were appropriate given the level of uncertainty and possible evolution of the accident? Would you have personally added to, qualified or retracted any of the advice and recommendations?

Question 4: Finally, the project has to make recommendations to ADMLC on how the uncertainties relating to plume spread and the consequent contamination and consequences should be communicated to and discussed within SAGE, and thence offered to COBR. Have you any advice for us on what those recommendations should be? Feel free to criticise anything that we have offered today, and to do so as harshly and destructively as you wish. We have hard skins and truly wish to get to a set of sensible recommendations for the improvement of current processes.