UNIVERSITY OF SOUTHAMPTON

FACULTY OF HUMAN AND SOCIAL SCIENCES

Geography and Environment

RADPOP: A New Modelling Framework for Radiation Protection

by

Becky Alexis-Martin

Thesis for the degree of Doctor of Philosophy

September 2016

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF HUMAN AND SOCIAL SCIENCES

Geography and Environment

Thesis for the degree of Doctor of Philosophy

RADPOP: A NEW MODELLING FRAMEWORK FOR RADIATION PROTECTION

Becky Alexis-Martin

Ionising radiation is often useful to our society, and has been implemented for medicine, industry, energy generation and defence. However, nuclear and radiation accidents have the capacity to have a negative impact upon humans and may have a long-lasting legacy due to challenges associated with remediation and the slow decay of radionuclides. It is therefore a priority to ensure that there is adequate emergency preparedness, to prevent and manage any accidental release of ionising radiation to the communities that surround nuclear installations (NI).

The emergency planning process includes desktop studies and exercises which are designed to examine the impact of hypothetical scenarios in real-time. However, greater spatiotemporal realism is required to understand the scale of a hypothetical radiation exposure to specific populations in space and time, to anticipate how the behaviour of the population will affect the outcome of an emergency, and to determine the strategy required for its management. This thesis presents a new modelling framework for radiation protection, called RADPOP. This framework combines spatiotemporal aggregate population density subgroup estimates with radionuclide plume dispersal modelling and agent-based modelling, to begin to understand how changes in spatiotemporal population density can influence the likelihood of exposure. Whilst sophisticated estimates of meteorological and atmospheric dispersal exist, there limited resources for the production of equivalent and contemporary high-resolution spatiotemporal population statistics. There is also no existing modelling framework for radiation protection and emergency preparedness, which implements spatiotemporal population estimates to understand the subsequent movement of an aggregate population, as it seeks shelter during a radiation emergency. This thesis investigates these challenges with focus upon the female population subgroup, as a group which has been identified in the literature as having greater vulnerability during evacuation.

Table of Contents

List of Tables

List of Figures

DECLARATION OF AUTHORSHIP

I, ... [please print name]

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

[title of thesis] ....

....

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Part of this work have been published as: Alexis-Martin, B (2015) The Chernobyl necklace: the psychosocial experiences of female radiation emergency survivors. Belgeo. Revue belge de géographie, (1)

Signed: ....

Date: ....

Acknowledgements

Thanks to my lovely PhD supervisors Dr Sam Cockings and Professor David Martin for giving me the chance to study and for supporting and guiding my work from conception to completion - it has been the most amazing intellectual adventure and I am very lucky to have you both! Thank you to Dr Stephanie Heywood and the amazing team at PHE. Thank you to my kind friends, colleagues and family for your support, you know who you are. Thanks to the South West Academy of Art for allowing me to sit and write for hours on very few cups of coffee.

Source acknowledgements for Figures 1, 2, 6, 7, 41, 44, 45, 46, 52, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66 and 68: OS 1:150,000 Scale Raster [WMS map service], Coverage: Exeter, Ordnance Survey/EDINA supplied service © Crown Copyright 2014. PACE and NAME modelling output and MESUM5 archive weather datasets © Copyright/database rights Met Office and Public Health England 2003-2016, Census Output Area Boundaries and Workplace Zones © Crown copyright 2011.

Abbreviations

A: Atomic weight

ABM: Agent Based Modelling

AFRRI: Armed Forces Radiobiology Research Institute

AWE: Atomic Weapons Establishment

BNFL: British Nuclear Fuels Plc

Bq: Becquerel

CA: Cellular Automata

CBRN: Chemical, Biological, Radiological and Nuclear

CCA: Civil Contingencies Act (2004)

CCS: Civil Contingencies Secretariat

COMAH: Control of Major Accident Hazards Regulations (1999)

DEPZ: Detailed Emergency Planning Zone

DNA: Deoxyribonucleic Acid

DSS: Decision Support System

E&W: England and Wales

EPZ: Emergency Planning Zone

ERL: Emergency Reference Level

EU: European Union

GIS: Geographical Information System

PHE: Public Health England

HMNB: Her Majesty's Naval Base

IAEA: International Atomic Energy Agency

ICRP: International Commission on Radiological Protection

IDW: Inverse Distance Weighting

INES: International Nuclear Event Scale

LRF: Local Resilience Forum

LSOA: Lower Super Output Area

LWR: Light Water Reactor

MAUP: Modifiable Areal Unit Problem

MoD: Ministry of Defence

MYE: Mid-Year Estimate

NAME: Numerical Atmospheric Modelling Environment

NARO: Nuclear Accident Response Organisation

NDA: Nuclear Decommissioning Authority

NI: Nuclear Installation

NII: Nuclear Installations Inspectorate

NIREP: UK Nuclear Industry Road/Rail Emergency Response Plan

NNL: National Nuclear Laboratory

NSD: Nuclear Safety Directorate

OA: Output Area

ONR: Office of Nuclear Regulation

ONS: Office of National Statistics

OS: Ordinance Survey of Great Britain

PACE: Probabilistic Accident Consequence Evaluation

PHE: Public Health England

PITS: Potassium Iodate Tablets

PWR: Pressurised water reactor

RAD: Radiation Absorbed Dose

RCA: Radiation Control Area

REPPIR: (Radiation Emergency Preparedness and Public Information) regulations 2001

RIMNET: Radioactive Incident Monitoring Network

SNI: Sensitive Nuclear Information

Sv: Sievert

THORP: Thermal Oxide Reprocessing Plant, Sellafield

UKAEA: United Kingdom Atomic Energy Authority

UNISDR: United Nations International Strategy for Disaster Reduction

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

Chapter 1: Introduction

1.1 Why is a new modelling framework for radiation emergency planning required?

Since the advent of the nuclear age, ionising radiation has been used for applications as diverse as medical imaging and treatment, energy generation and defence. However, exposure to ionising radiation can cause harm to human health. Radiation accidents occur when ionising radiation is unintentionally released to the environment, and which can result in accidental human exposure. Because of significant risk to health and limited treatment options for radiation exposure, nuclear accidents are high-impact events. Historical radiation incidents of note include Windscale in the UK (1957), Chazhma Bay in Russia (1985), Chernobyl in Ukraine (1986), and Fukushima in Japan (2011).

Radioactivity causes harm to humans through both short-term deterministic and long-term stochastic health effects. Deterministic health effects can occur from exposure to a large radiation dose over a short timescale and can range from vomiting, skin damage, cataracts, bone marrow syndrome to central nervous system death, dependent upon dose amount and severity. Stochastic effects correlate to chronic low dose exposure, which increases the likelihood of long-term health problems including cancer and hereditary diseases due to the impacts of ionising radiation upon human DNA. There is a differential in vulnerability across a population, meaning that certain subgroups, including children and females, are more susceptible to the effects of exposure. The effects of radiation exposure are also cumulative over time. It is therefore important to have an effective emergency response strategy for radiation hazards that minimises exposure to the most vulnerable population subgroups.

To enable emergency management decisions to be made effectively, decision-makers need comprehensive information about both the scale of release and the demographic distribution across the duration of the incident, the latter of which will let them anticipate the whereabouts of vulnerable people. However, whilst accurate models of radiation plume dispersion exist, there have not been equivalent advances in the modelling of spatiotemporal population statistics, limiting the ability to estimate the projected dose to a specific subgroup. Current population modelling approaches are based almost exclusively on residential location data for infrequent time slices, despite the logical and conceptual requirements that daily, weekly and seasonal variation should be considered. Imprecision is inevitably associated with the early stages of a nuclear accident due to incomplete knowledge of population distribution at the time of the emergency, changes in the original dynamic, and the nature of the hazard itself.

There is consequently a need for refinement, and for inclusion of daytime population data representing the proportions of subgroups engaged in activities such as transport, employment, education, recreation and tourism at specific times. The purpose of this research is to explore the changing spatiotemporal dynamics of vulnerability for specific population subgroups, in the context of radiation hazard. This work uses a combination of modelling approaches to describe how female exposure changes in space and time. The first case study combines gender-split Population247 output (Martin et. al. 2015) with spatiotemporal radiation dispersion modelling outputs generated by PACE NAMEIII (Charnock et. al. 2015) for dose estimation, to improve assessment of the health effects of radiation exposure to a usual daytime population. This refines understanding of the spatiotemporal controls upon subgroup vulnerability and the likelihood of immediate deterministic health effects. However, Population247 cannot anticipate the changing whereabouts of vulnerable populations during an emergency, and there is still a need to understand how this dynamic changes due to different behaviours of different population subgroups. Therefore, agent-based modelling is used in the second case study to explore changes in population distribution that occur due to implementation of countermeasures, during the emergency response. The combined framework developed for this thesis is named RADPOP, as it comparatively assesses a specific population's spatiotemporal exposure to radiation.

1.2 Aims and Objectives

The overarching aim of the thesis is to develop and exemplify a new modelling framework for understanding how population distribution changes before and during a radiation emergency scenario.

Aim 1: Review the present literature pertaining to spatiotemporal population modelling, radiation protection, radiation emergencies, and methods of determining radiation exposure.

Aim 2: Investigate the way that gender affects likelihood of exposure during urban radiation emergencies, by constructing and implementing a new spatiotemporal population data library. Spatiotemporal modelling output will be combined with new hypothetical spatiotemporal radiation hazard models to assess exposure.

Aim 3: Assess the challenges of traditional spatiotemporal modelling approaches. Develop a new approach, RADPOP, which enables the spatiotemporal behaviour of populations during radiation emergencies to be more accurately represented.

1.3 Thesis Structure

Chapter 1 summarised the key underpinning research concepts, described the purpose of this work and outlined the thesis structure.

Chapter 2 provides a review of spatiotemporal population modelling. The chapter is divided into four sections that investigate interpolation, spatiotemporal population modelling, temporal GIS and dynamic population modelling approaches. This review cements existing knowledge, while identifying the need for a combined population modelling approach, which is developed in subsequent chapters.

Chapter 3 delivers a review of radiation protection and society. This chapter consists of six sections, that include relevant literature pertaining to technological hazards, humans and radiation, emergency planning and management for radiation hazards, modelling radiation dispersal, modelling populations at risk for emergency planning and management, and modelling populations at risk using agent-based modelling. The conclusion of this review brings together key concepts from Chapter 2 and Chapter 3. An adapted version of Chapter 3 has been published as Alexis-Martin (2015), and has gained media attention from The Guardian newspaper (August 2015). Both the paper abstract and media excerpts have been included in this thesis in Appendix A.

Chapter 4 is a methodology that describes the data and research design used to construct the RADPOP modelling framework for this thesis. This chapter consists of three sections, which reflect the three components of the RADPOP framework. These are Component A: modelling populations in space and time, Component B: Assessing hazard distribution and health effects, and Component C: Understanding changes in population distribution during emergencies. Component A explains the parameters and information needed to construct a gender-split spatiotemporal population model using Population247, Component B describes the process of using the PACE NAMEIII extension to produce spatiotemporal radiation hazard plumes and assess exposure. Component C describes the method behind the new and unique agent-based model developed to fill a research gap identified by this thesis, which uses Population247 output population behavioural characteristics, sheltering protocols and PACE outputs to predict the movement of populations during radiation emergencies.

Chapter 5 is the first of two case studies that explore how population dynamics can be modelled to improve our understanding of exposure during radiation emergencies. This study includes a new 2011 Population247 data library that enables representation of the whereabouts of both males and females. This chapter also includes contaminant plume modelling outputs constructed under the guidance of the Radiation Protection team at PHE. The study investigates some of the hypothetical exposure outcomes to a usual spatiotemporal population, due to a hypothetical radiation emergency in Exeter, UK.

Chapter 6 presents the second case study, which examines how the whereabouts of the female population at the start of a radiation emergency affects the distance and time needed to reach shelter, and likelihood of exposure to a hazard. This is investigated by agent-based modelling. Study 2 builds on the foundations provided by Study 1, implements and therefore demonstrates the usefulness of original modelling outputs, and gives insight into how implementation of timing countermeasures can reduce population exposure.

Chapter 7 discusses the study outcomes, and identifies the highlights and challenges of the RADPOP modelling framework. This chapter also considers approaches for model validation, and the contributions of this thesis to the field of radiation protection.

Chapter 8 concludes with a summary of significant thesis outputs, referring back to the aims and objectives defined in Section 1.2. Achievements and advancements are highlighted, and limitations are summarised. Concepts for further research and development are identified.

A glossary of relevant terminology for radiation protection and population modelling is included at the end of this thesis.

1.4 Novel Contributions

This thesis includes a number of novel contributions to human geography, including:

- Novel and comprehensive reviews of literature pertaining to spatiotemporal population modelling, emergency planning, radiation protection and society.
- The development and inclusion of new male and female population subgroup data libraries for the Population247 spatiotemporal population modelling framework.
- The first implementation of Population247 spatiotemporal modelling approach in the domain of radiation protection.
- The first inclusion of Population247 spatiotemporal modelling outputs for an agent-based modelling approach to understand evacuation.

Chapter 2: Spatiotemporal Population Modelling

"Everything is related to everything else, but near things are more related than distant things"

1st Law of Geography, Tobler (1970)

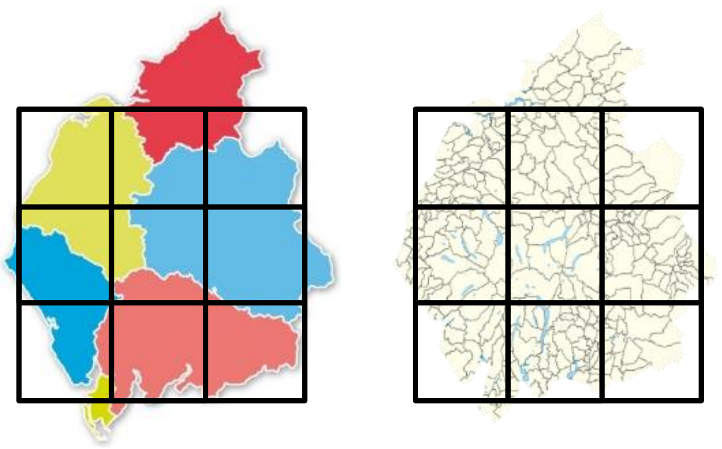
Unless an individual is immobile, there is a strong likelihood that they will undertake certain day-to-day activities in aggregate with others on a cyclical basis, such as travelling to a place of work or education. However, the existing means of representing the geography of daytime population movement are limited. Current approaches are based almost exclusively on residential location data and draw heavily upon census definitions of "resident population", despite the logical and conceptual requirements that daily, weekly and seasonal variation in daytime population distribution should be considered (Martin et al., 2010). The purpose of this chapter is therefore to identify appropriate methods for both modelling cyclical spatiotemporal population distribution, and representing the dynamic changes that occur as a population adapts to the requirements of an emergency scenario.

This chapter addresses the methods required to create high-resolution spatiotemporal gridded maps of usual population distribution. There are many attractions to using gridded representations when it is necessary to integrate data from multiple sources, as the outputs from many environmental models are gridded and it improves the possibility of comparability across data. This chapter begins by exploring the challenges of accurately redistributing population density data from irregular to regular units, and summarising a selection of spatial interpolation approaches. The most relevant approaches are examined in more detail, and the section concludes by identifying the most appropriate methods for this thesis. Time is then introduced and spatiotemporal population modelling approaches are described, including temporal GIS (t-GIS), spatiotemporal interpolation and the Population247 framework. This chapter then considers agent-based modelling (ABM) as a dynamic approach to modelling rapid changes in spatiotemporal population distributions, and concludes by describing a framework for linking Population247 and ABM.

2.1 The Challenges of Modelling Population Data

This section identifies the challenges of accurately representing spatiotemporal population data. It is rare that data of any type are available in a form that is immediately useful and accessible, and population data are no exception. Original spatial units - or source zones - for which residential population data are available, are subject to change over time and are not necessarily directly spatially comparable with source zone data from other provenances, such as workplace or education data. There is therefore a need for a uniform target zone to which all source zones can be transferred, to enable comparison of spatial population phenomena for different activities (Goodchild et al., 1980, Lam, 1983b, Flowerdew et al., 1991, Goodchild et al., 1993, Lam, 1983a). Comparable spatial units are required to assess changes in the type of population activity over time, as one source zone may include several different activities at different times.

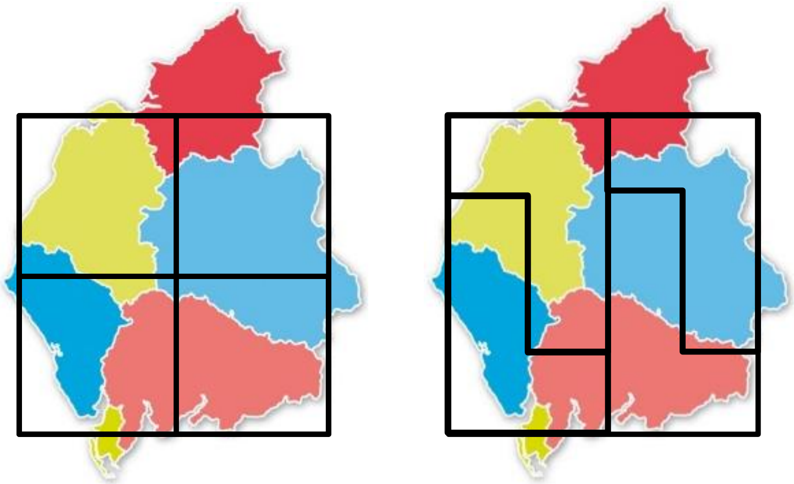
Figure 1 a) shows the difference between irregular source zones and uniform target zones, where source zones are coloured and target zones are outlined in black. To create a robust map of population density, it is necessary to consider approaches that data from multiple aggregate source zones to be distributed from their original different source zones onto one universal regular set of target zones without loss of resolution, and without creating or destroying population volume in the process (Lam, 1983a, Langford and Unwin, 1994a).



a) b)

Figure 1: An example of irregular source zones and uniform target zones, for two different sets of source zones across the same space. The differences between source zone and target zone scale for 1a) and 1b) show how significantly scale can affect the resolution of spatial phenomena (adapted from (Openshaw, 1984)).

It is important to make sure that a uniform target zone is appropriately defined to ensure that spatial phenomena are accurately represented. The effect that zone boundary definition has upon the accuracy of spatial phenomena is known as the Modifiable Areal Unit Problem (MAUP) and is of great significance to spatial and spatiotemporal population modelling. MAUP is a geographical manifestation of the ecological fallacy that demonstrates how scale, or difference in size of a zone; and aggregation, or difference in the shapes of zones of uniform scale, will affect the interpretation of spatial phenomena (Openshaw, 1984, Waller and Gotway, 2004). Figure 1a and 1b show the effect of different source zone scales upon a uniform target zone. The resolution of source zone data will be significantly decreased when it is redistributed to target zones in Figure 1b compared to Figure 1a, where there is less difference between source zone and target zone size. Equally, smaller target zones could increase sampling variance across a dataset (Gregory, 2002). Figure 2 shows how aggregation of identical source zone data to target zones of different shapes can result in different representation of the same original spatial phenomena.



a) b)

Figure 2: The aggregation effect of the Modifiable Areal Unit Problem, where the same source zone spatial phenomena are represented differently within target zone units of the same size but of different shapes (adapted from figures from (Openshaw, 1984)).

Whilst there is no overarching solution, acknowledgement of the challenges MAUP poses is imperative (Flowerdew, 2011). It is important to ensure that target zone size and shape are appropriate to the spatial phenomena being represented, and grids have been recognised as suitable target zones for population phenomena (Green and Flowerdew, 1996). MAUP is also applicable to the transformation of spatial units across units of time, and is known as the modifiable temporal unit problem (MTUP) (Jacquez, 2011). As a consequence of MTUP, analysis that is spatially detailed but temporally coarse is just as likely to impair analysis as that which is temporally detailed but spatially course. To conclude, creating a uniform target zone for multiple different source zones is beneficial for spatiotemporal comparison of disparate data. However, the uniform target zone and method of data redistribution must be selected very carefully to ensure that spatial and temporal resolution is not lost or obscured.

2.2 Interpolating Spatially Distributed Phenomena

This section defines the basic concepts of spatial interpolation and the important features for the construction of a population density surface. Relevant methods for interpolating population data are described and evaluated, and ways of including additional data to improve the accuracy of the interpolation are explored.

Interpolation can be point-based or area-based, where point-based methods use point-to-point interpolation from source zone to target zone, and area-based methods include zone boundaries for the estimation. Spatial interpolation is point-based and uses known spatial data points to estimate the value of an unknown variable at a specific location (Goodchild et al., 1980). This can be applied to transform data from known population data points in source zones to estimated points in target zones of uniform units. This is advantageous for comparison of spatiotemporal data, but also for identification of uninhabited spaces when target zones are smaller than source zones, as areas without population can be estimated as zero by target zones in source zones. Areal weighting interpolation is area-based, and is the simplest method of interpolating population data from source zones to different target zones by calculating the proportion of source zone and target zone overlap, enabling data to be transferred from one zone to another (Goodchild et al., 1993, Flowerdew et al., 1991). Whilst no further data are required, simple weighted redistributions are not usually sufficiently accurate for the representation of population phenomena (Goodchild et al., 1980), particularly at the small area (local) level.

A gridded population map can be converted into a continuous function of a discrete population count, or population density surface, which represents population density more realistically (Alexander and Zahorchak, 1943, Tobler, 1979, Martin, 1989). The accuracy of a population density surface map is controlled by source zone data quality. Original data with errors may become less valid during interpolation to target zones and it is important to use high quality datasets. Control point density is also significant and related to MAUP. Control points are the points in source zones that are used to construct an estimated value at unknown points, and higher density increases the accuracy of the estimation (MacEachren and Davidson, 1987, Martin, 1995). The spatial distribution of data collection points is also relevant, as disparate points may create a less accurate estimation than points that are uniformly distributed. The inherent spatial variability of a population density surface also impacts upon accuracy, whereas a fine mesh of target units will provide more accurate representation of a variable surface (MacEachren and Davidson, 1987, Martin, 1995). The next section summarises existing methods for interpolation of spatial phenomena, and identifies techniques suitable for modelling population density.

2.3 Summary of Interpolation Methods for Modelling Population Density

This thesis explores interpolating population data as a specific spatial phenomenon, and henceforth focus is upon the suitability of applications for a population density modelling approach. Figure 3 identifies the various interpolation methods, which are classified by point or areal approach; global or local extent; and approximate or exact results. Point-based approaches are highlighted in red while areal approaches are highlighted in blue. The figure also contextualises dasymetric interpolation.

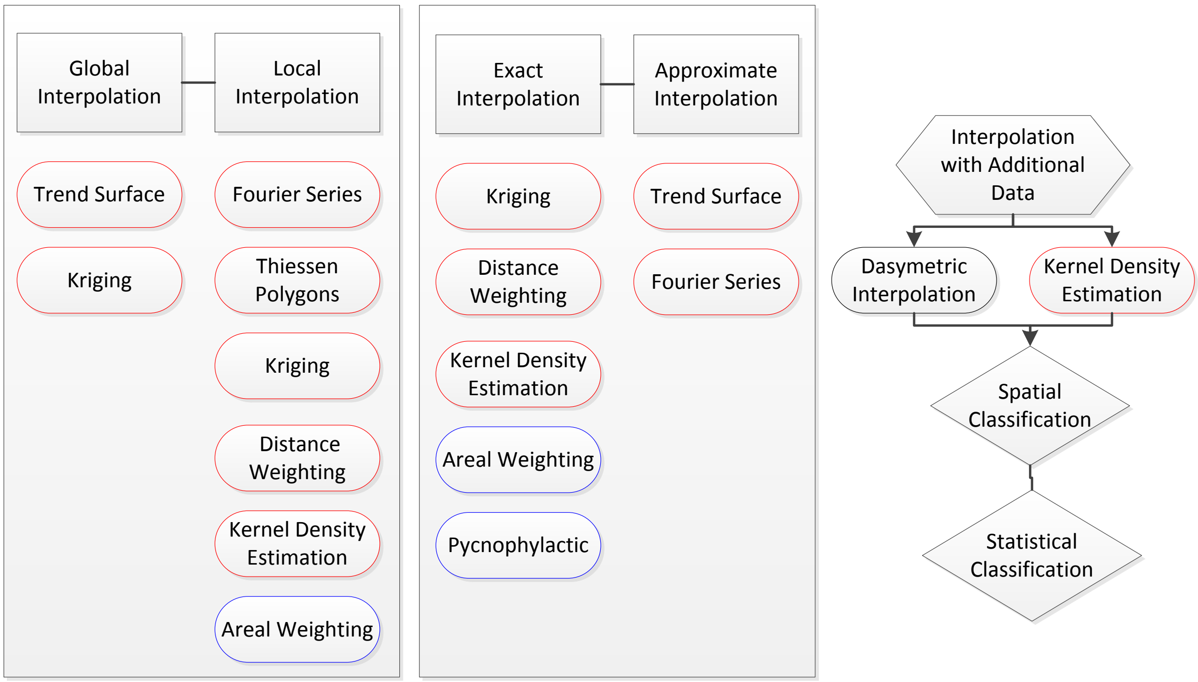


Figure 3: Interpolation methods classified by point or areal approach; global or local extent; and approximate or exact estimation, and dasymetric interpolation approaches for improving population density modelling with spatial and statistical data.

As outlined in the previous section, interpolation can be point-based, using known points across source zones to estimate point distribution in target zones (Lam, 1983a). Alternatively, interpolation approaches can be areal and use data in the specific area of a source zone to estimate the distribution of a population across the area of target zones. Population density is a local phenomenon, whereby proximate populations are more analogous to each other than to populations that are further away (Mitas and Mitasova, 1999). Therefore, a local interpolation approach that applies a function repeatedly to local subsets of spatial data provides a more realistic representation of population distribution (Mitas and Mitasova, 1999). Another requirement of a realistic population density model is that population volume should be preserved, i.e. there should be no loss or gain of data during the interpolation process. Precise methods of interpolation honour known values at data points, and thereby maintain the original population density for the model output; conversely, approximate methods create new values at known data points (Lam, 1983a). Whilst it is possible to model population density without additional information, dasymetric interpolation methods that include spatial and statistical data can refine the population density model by weighting locations differently, in proportion to likelihood of containing a population.

Areal weighting, trend surfaces, Thiessen polygons and Fourier series are not appropriate methods for interpolating population density within the context of this thesis. This section considers the features of area-based pycnophylactic interpolation, point-based inverse-distance weighting, Kriging, and kernel density estimation interpolation approaches.

2.3.1 **Pycnophylactic Interpolation**

Pycnophylactic interpolation is an area-based, two-stage gridded approach for creating a continuous surface over a volume, resulting in a volume-preserving isopycnic map of population density (Tobler, 1979). The approach assumes that spatial attributes will influence each other, that there are no sudden changes at zone boundaries, and that volume must be preserved during the interpolation from source zone to target zone (Tobler, 1979). This approach uses interpolation to transpose estimated points from source zone boundaries to the target zone area of a high resolution grid, producing a smooth surface. To preserve source zone data, it is important for the grid to be of high resolution. Figure 4 shows the stages of pycnophylactic interpolation from a) a blocky histogram of irregular units to b) a grid of regular units, and c) the final smoothed surface (Rase, 2001).

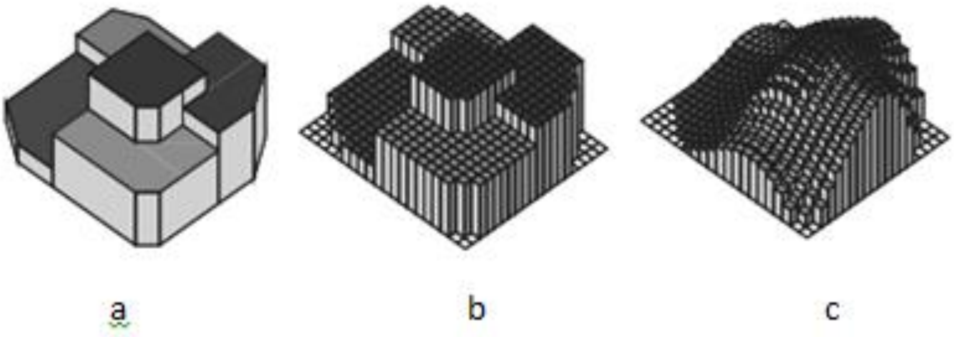


Figure 4: The stages of pycnophylactic interpolation with a) the source zone data represented by a blocky bivariate histogram b) the creation of a grid and c) the smoothed pycnophylactic surface adapted from p. 3 (Rase, 2009).

The Pycnophlactic approach enables the bivariate histogram of original data to be exactly reconstructed from the population density surface by computing the volume underneath, making the process reversible without loss of population (Tobler, 1979). It can be used to interpolate aggregate population data, and has advantages over point-based methods in which source zone boundaries are not included in the interpolation, resulting in loss of volume (Rase, 2009). However, the assertion that population data in one geographical area always proportionally influences data in adjacent areas is not necessarily true for population phenomena.

2.3.2 Distance Weighting

Distance weighting is a simple approach for the redistribution of source zone point population data to gridded target zones, as a weighted average of values available at known points (Shepard, 1968, Lam, 1983a). This approach redistributes a population across a specified radius or “neighbourhood”, where each value within the neighbourhood has decreasing significance with distance from a central point within a source zone, and neighbourhood size is therefore dependent upon a weighting coefficient that is influenced by distance to the prediction location (Mitas and Mitasova, 1999). The method uses data points or centroids within the source zones as local summary points for a more detailed, but unknown population distribution, and is represented by the following equation.

$$\hat{\boldsymbol{P}}_{\boldsymbol{i}} = \sum_{\boldsymbol{j=1}}^{\boldsymbol{c}} \boldsymbol{P_j W_{ij}}$$

Where $\hat{\boldsymbol{P}}_{\boldsymbol{i}}$ is the estimated population at location $\boldsymbol{i}$, $\boldsymbol{P_j}$ is the empirical population recorded at sampled location $\boldsymbol{j}$, $\boldsymbol{c}$ is the total number of sampled locations, and $\boldsymbol{W_{ij}}$ is the unique weighting of location $\boldsymbol{i}$ with respect to point $\boldsymbol{j}$. The value of $\boldsymbol{W}$ controls the region of influence of each of the sampled locations, and as $\boldsymbol{W}$ increases, the region of influence decreases to a lower limit, when it becomes the area which is closer to location $\boldsymbol{i}$ than to any other.

However, inverse distance weighting is only appropriate for point data where each value is individual; it therefore does not require reference to values in an area, as population density does. This approach is affected by uneven data distribution and is susceptible to clustering of input data, which may lead to failure to reproduce significant peaks and troughs across a surface and inaccurate or artificially increased representation of population (Mitas and Mitasova, 1999). If the distance decay parameter can be variable or “adaptive” according to the characteristic spatial patterns of the sampled points in a neighbourhood, then the accuracy of the interpolation can be improved.

2.3.3 **Kriging**

Kriging is a geostatistical technique that is similar to distance weighting interpolation. The general formula for both interpolators is formed as a weighted sum of the data. However, whilst the weight depends solely upon the distance to the prediction location for inverse distance weighting, with Kriging the weights are based not only upon distance between the measured points and prediction location, but also the overall spatial arrangement of the measured points (Kyriakidis, 2004). Kriging is therefore a two-stage process where regression-based estimates are derived, then interpolated by an area-to-point Kriging function (Kyriakidis et al., 2008). However, Kriging is unnecessarily complex and in need of further processes to model populations onto a uniform target zone output, which is essential when modelling population change for different activities over time (Liu et al., 2008). Kriging also presents further challenges in accurately representing population density, as linear estimation techniques cannot demonstrate the non-linear relationships that realistically occur across populations.

2.3.4 **Kernel Density Estimation**

Kernel density estimation is a point-based interpolation method. This approach interpolates populations from high data points, or centroids, to a gridded surface. Kernel density estimation uses a kernel with a potentially adaptive radius of influence to estimate distance between zone centroids and discern the most appropriate area of influence for the interpolation (Bracken and Martin, 1989).

This can be combined with other interpolation approaches to produce a population model that reconstructs populated and unpopulated space (Martin and Bracken, 1991). A two stage approach with an adaptive kernel interpolation including distance-weighing interpolation was developed by

Martin and Bracken. This approach uses population centroids, where each centroid corresponds to a high information point in a source zone unit. The approach systematically redistributes data associated with source zones to gridded target zones by a user-defined kernel width algorithm that assigns weighting to population points according to an adaptive distance decay function (Martin and Bracken, 1991). These data are then interpolated using inverse distance weighting. The adaptive kernel function for kernel density estimation is shown by Figure 5, where the radius of influence is determined by distance d_{ij} between the centre of the kernel zone i and the population data point j; and w_{ij}, the weighting of kernel k with respect to i and j. The process is controlled by an exponent α, which changes the shape of the distance decay curve; and the kernel width k determines the maximum spatial extent for population allocation (Martin, 1989, Martin and Bracken, 1991).

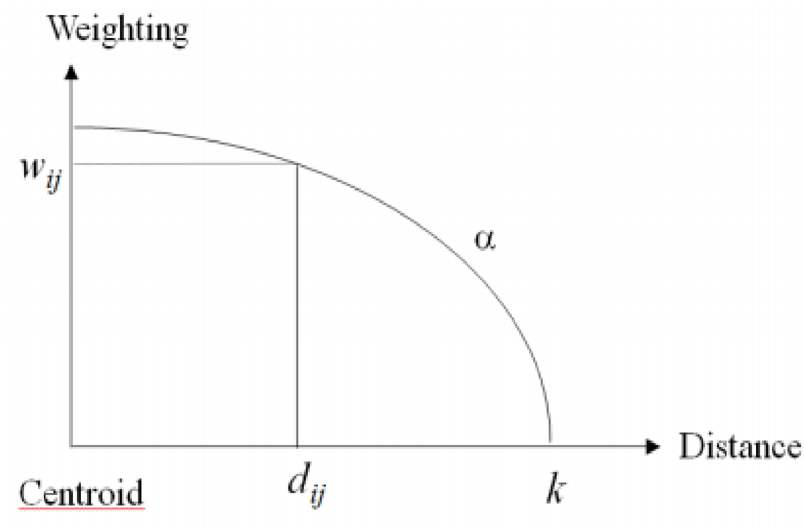


Figure 5: The general form of the adaptive distance-weighting kernel (Bracken and Martin, 1989).

A distance decay function is used to evaluate the likelihood that each target zone in a grid will receive a proportion of the total population of a centroid (Bracken and Martin, 1989). This approach allows the population to be redistributed whilst creating unpopulated grid cells to represent places where there is no population.

The second stage requires application of inverse distance weighting to redistribute the population according to the radii of the adaptive kernels. When population points are clustered, only target grid cells adjacent to population centroids will receive a population count; conversely, where inter-centroid distances are large, values will be dispersed widely across the radius of influence. The kernel estimation is applied across the centroid data, and the adaptive distance decay function is used to evaluate the proportion of the population count associated with that centroid. Target grid cells beyond the radius limit will receive no count values (Bracken and Martin, 1989).

By this method, the redistribution of population count by an adaptive kernel function enables areas of zero population to be mapped (Bracken and Martin, 1989, Martin, 1989).

This approach has been successfully used to compare 1981 and 1991 Census data with different source zone boundary areas, by redistribution onto gridded target zones (Bracken and Martin, 1995). This approach also forms the basis of the Population247 spatiotemporal gridded population density model that is explored in further detail later in the thesis. However, whilst interpolation approaches that include kernel density estimation are useful for transferring data from different source zones to a uniform target zone, the approach does not include spatial features beyond the population datasets that still affect population distribution. This challenge can be solved by including dasymetric classification within the interpolation to constrain the population distribution, and using additional data to assess the likelihood of populations being present within specific grid cells (Bracken and Martin, 1989). The next section describes ways of including ancillary data within the population density model.

2.3.5 **Dasymetric Interpolation**

Dasymetric interpolation enhances the approaches discussed previously by inclusion of additional spatial and geographic data. This can improve the accuracy of the interpolation by weighting locations in proportion to their probability of containing populations. This approach improves the resolution of population density by downscaling available data within zones to finer units by using ancillary datasets (Sleeter and Wood, 2006). Dasymetric interpolation therefore produces a more realistic model of population density where, for instance, environmental and social drivers of population distribution can be included within the model (Mennis, 2003). The simplest approach is binary dasymetric classification, where two classes are used to define distribution using a weighting function of 1 or 0 (Eicher and Brewer, 2001). This approach has been applied to distribute populations across inhabited and uninhabited areas using additional spatial information, shown by Figure 6 (Langford, 2005).

a) b)

Figure 6: A 1:50.000 raster map (a), where a binary dasymetric layer (b) has been applied to highlight residential areas for dasymetric interpolation (p.12, Langford (2005)).

Dasymetric methods have been adapted for use with the multiple spatial classifications of remotely sensed imagery and road network data (Mennis, 2003, Reibel and Bufalino, 2005), and have also been applied to the relationship between the underlying statistical surface and ancillary data classes using regression; the expectation maximisation algorithm; and maximum likelihood estimations (Langford et al., 1991, Goodchild et al., 1993, Mrozinski and Cromley, 1999, Flowerdew et al., 1991). The accuracy of dasymetric classification is dependent upon both the strength of the relationship between source and ancillary data, and the geometry of source, target and ancillary data zones (Sadahiro, 2000, Mennis and Hultgren, 2006). The number of classes can be increased by weighting with ancillary data, such as land classification data shown in 7a (Mennis, 2003, Mennis and Hultgren, 2006).

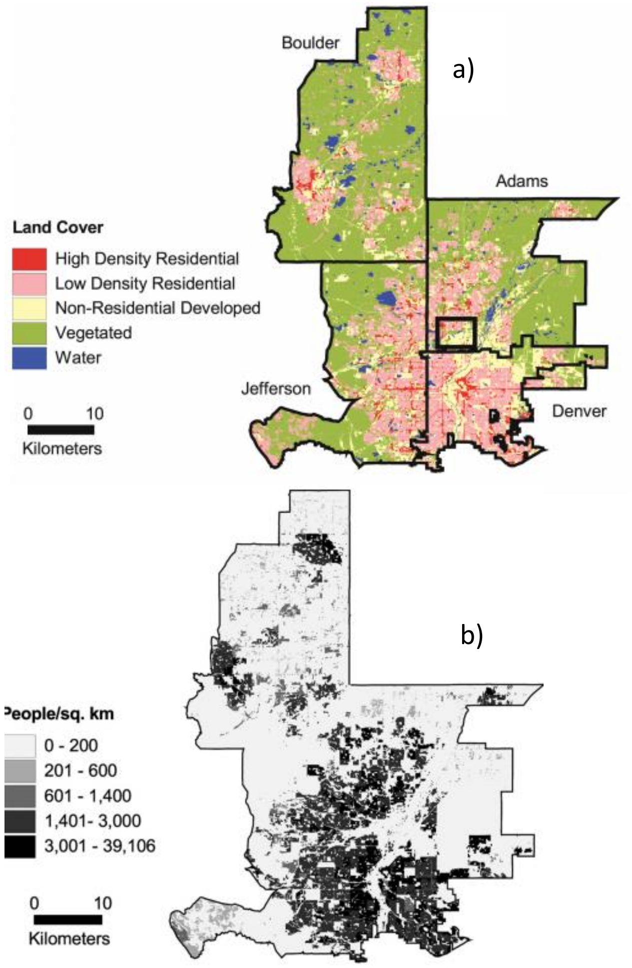


Figure 7: a) Land cover classified dasymetric population map and b) map of total population density produced using percentage land cover sampling pp. 185-187 (Mennis and Hultgren, 2006).

The result of combining multiple land cover classes to redistribute population is a dasymetric map that shows a percentage of population for different environmental and social land-classification, as shown in Figure b. It is evident that Figure 7b shows a number of similarities to the land cover classification map in Figure 7a, as population have been redistributed by both areal interpolation and land cover. This method can be further adapted to adjust population for other demographic variables. For example, within urban areas containing industrial sites and parkland, dasymetric interpolation can be used to produce estimations of population density that are more realistic, and are often higher than original estimates as the population is actually existing within other spaces (Langford and Unwin, 1994b). Dasymetric methods have been applied to other interpolation methods to improve socioeconomic analysis, and are therefore a valuable component of the population modelling approach and Population247.

To summarise, this section on spatial modelling has introduced the concept of interpolation for transferring population data from source zones to target zones, and has considered ways that population density surface realism can be enhanced by using dasymetric mapping. An adaptive kernel-based interpolation with dasymetric classification is the most appropriate approach for realistically modelling population distribution, and this forms a significant component of Population247. The next section describes spatiotemporal population modelling and explains the Population247 approach.

2.3.6 Spatiotemporal Population Modelling

Spatial population density modelling can only provide a single temporal snapshot of population distribution, whereas a spatiotemporal approach can create a more realistic model of population change over time (Worboys, 1994). Temporal geography originated as a way to describe the behaviour and movement of people within time for the assessment of the impacts of past, present, and future events upon humans (Pred, 1977, Hägerstrand, 1985).

Time cannot be measured tangibly like space, but is perceived via the effects of change. It is part of a measuring system used to sequence events of any type across the past, present and future, to compare their durations and intervals, and to quantify rates of change (Elias and Jephcott, 1992). For the purposes of time-geography, time can be linear or cyclical. Linear time is unidirectional and represents progress across a fixed past, to the present and into an undefined future (Worboys and Duckham, 1995). Conversely, cyclical or looping time is associated with periodic patterns and is used to represent recurrent events such as days or weeks (Ulam and von Neumann, 1947). Cyclical time is therefore useful for the representation of recurrent activities in the context of a linear timescale. Time density describes the way time is divided; it can be continuous and without divisions, or discrete with specific units such as minutes or seconds (Van Benthem, 1983). Population activity is subject to trends, changes and events across a temporal scale, where periodicity defines the time intervals across a time series to reflect specific changes (Langran and Chrisman, 1988). Periodicity can be at any scale such as hourly, weekly or annually, or it can be applied to compare the same time parameter across months or years (Worboys, 1994). It is also possible to have time invariant properties that are constant over time (Renolen, 1999).

Temporal data differs from other types due to a dichotomy between temporal state and event, where state is considered to hold over an extent of time, and event delimits state and is considered to be instantaneous (Renolen, 1999). The semantics of time can be distinguished in three ways. It can be an additional parameter and applied as a control argument, whilst its effects upon variables are investigated; it can be a property of existing data fields by temporal tables or attributes; or it can be included as an additional dimension (Langran, 1989, Worboys, 1994).

The three approaches that are relevant to spatiotemporal population modelling are space-time geography, temporal GIS (t-GIS), and spatiotemporal interpolation. Each of these is explored in more detail in this chapter. Space-time geography is a way of understanding the pathways of an individual through time that pre-dates - but relates to - t-GIS and spatiotemporal interpolation (Pred, 1977). The next section describes Hagerstrand's original space-time geography for describing population movement in space and time (Hägerstrand, 1985).

2.3.7 Hagerstrand's space-time geography

Cartographic time distils the characteristics of time that are essential for representing spatiotemporiality in the most pragmatic and generic fashion (Langran, 1992). Hagerstrand's space-time geography is an early approach to modelling spatiotemporiality. It is a way of tracing the pathways of individuals through space and time, to identify interactions and trajectories by creating a cube that represents the relationship between times, locations, and activities in space. The approach theorises that a space-time path can show how an individual navigates through the spatiotemporal environment, where the physical area around an individual is reduced to a two-dimensional plain upon which their location and destination are represented by zero dimensional points (Pred, 1977, Hagerstrand, 1982). Figure 8 shows the principles of the space-time cube for mapping an individual's day of activities. In this instance, the person travels from home to work then returns home, before going to a restaurant. The three different locations are represented by poles, time is represented by the y axis, and the journey between locations through time is depicted by red lines that connect the locations in space and time; in each case, the gradient of a line informs travel speed (Hägerstrand, 1975, Hagerstrand, 1982).

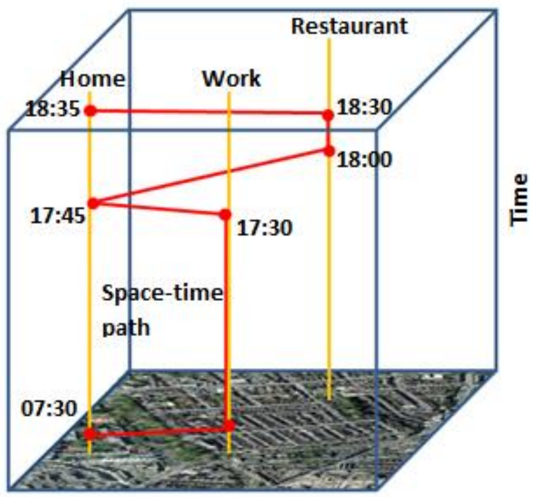


Figure 8: The principles of Hagerstrand's space-time cube, adapted from Kraak (2003).

Hagerstrand's space-time cube can be used to model multiple interactions, such as the pathways of individuals to a meeting place. Whilst the approach offers perceptive insights into the trajectories of an individual in space and time, it is limited; modelling a significant number of individuals in this way would become extremely complex. There are also topological limitations to the description of states, events, objects and mutations, as the approach can only represent known changes of state and event, and is mechanically restricted to past and present interactions. Parallels exist between this method and agent-based modelling - which is discussed later in this chapter - as both can be used to show the local interactions of individuals in an environment. However, Hagerstrand's space-time cube has neither the flexibility, nor the predictive and large-scale capacity of agent-based modelling (Neutens et al., 2008).

2.4 Temporal GIS

Temporal GIS (t-GIS) reinterprets the time-cube approach developed by Hagerstrand to represent dynamic phenomena across space and time. Within non-temporal GIS, the phenomena are representative of the information that was available at the time the map was created. A single non-temporal GIS may be "a-temporal" and include multiple sources of information from undetermined times, or may represent a cartographic time as a snapshot that is analogous to real world time. The semantics of time have been distinguished within t-GIS in three ways.

The concept of a time snapshot created the field of t-GIS for population modelling, when snapshots with discrete temporal boundaries - known as time slices - were combined to assess change in population distribution over time (Langran, 1992). Figure 9 shows how time slices can be used to represent the subdivisions of a whole, where *x* and *y* show the spatial dimension, *t* is the temporal dimension, and temporal units that share a boundary can be considered to be contiguous neighbours in time.

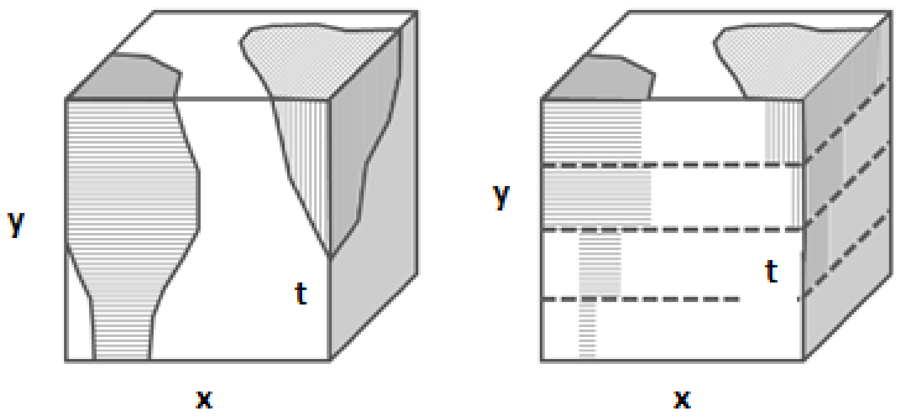


Figure 9: Discrete boundaries between time slices stored in a cartographic representation, adapted from Langran (1992).

The sequential snapshot t-GIS approach builds upon the concept of snapshots in time within GIS. It is a feature-oriented technique that uses a sequence of slices to capture linear change through time (Langran, 1992, Armstrong, 1988, Hunter and Williamson, 1990). This approach implements timestamps, which are a series of characters or encoded information within each temporal layer, to identify when an event occurred (Langran, 1992). The entire geographical object can be timestamped but this only provides limited expression of the temporal properties of the object. Alternately, time and space can be fused together by this approach, allowing an expression of temporal variability with a much finer resolution.

Whilst the snapshot approach provides insight into simple spatial, temporal and spatiotemporal questions, it can only describe what exists at a single point in space for valid time (Snodgrass, 1992). The approach only shows space plus time and is not continuous or cyclical; as a result, interactions between populations, space and time are not realistically represented. Additionally, a new snapshot is required for each time slice, requiring duplication of all unchanged data regardless of the magnitude of change (Langran, 1992, Yuan, 1996). The snapshot approach can be improved on using composites of spatial and temporal data within the snapshot model. Space-time composites store a spatial component in a snapshot model, whilst thematic attributes are stored in a temporal database (Langran, 1992). This approach treats time as another dimension of space and applies separate attribute structures. Figure 10 shows a space-time composite of population, where density of population for urban or rural is differentiated by shade.

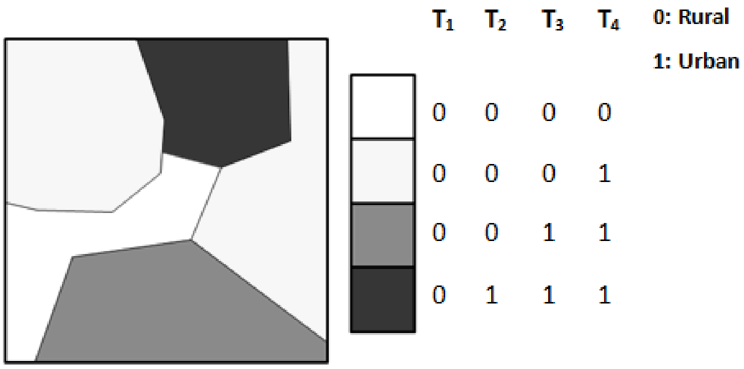


Figure 10: An example of a space-time composite model layer for urban and non-urban populations (adapted from Langran and Chrisman (1988) p. 12)

The composite approach has difficulty facilitating queries of spatio-temporal behaviour and relationships, which are important for modelling populations in space and time (Langran, 1992). Both spatial objects and attribute tables have to be reorganised to accommodate change of geometrical and topological relationship within the approach, which means that the model is not very accommodating of the changes in scale and unit that are necessary for modelling population dynamics. The approach is also vulnerable to fragmentation over time, (Saalfeld, 1991).

The composite snapshot approach can be improved upon by creating objects of time for a GIS database, where temporal objects are used to define types of temporal event or change that affect characteristics of a model. The temporal object approach envisages that population density states have duration and are represented by time intervals, where each object mutation is an event that produces a new object version and model state (Langran, 1992). Therefore, the principle of the object-oriented approach is that any entity, independent of complexity and structure may be represented by exactly one “object” of data (Dittrich, 1986).

The object-oriented approach encapsulates an entity and its history into one single object. It enables geographical and non-geographical objects to be modelled with temporal and non-temporal objects, in a uniform way, through their specific interactions (Renolen, 1999). This approach is more resilient to changes of unit and scale than other approaches, which is relevant to spatiotemporal population modelling if combined with interpolation of different source zones (Worboys, 1992, Peuquet and Wentz, 1994, Renolen, 1999). However, this approach only represents sudden change for a specific time structure due to the discrete nature of the space-time atoms, and therefore cannot realistically portray the transition, process or motion activities of a population.

The previous approaches have represented spatiotemporal data as states across a GIS raster, which inhibits the features of a specific phenomenon being easily traced through time. However, event-oriented t-GIS approaches are vector-based and represent data as events rather than states, enabling the history of an event to represented (Langran, 1992). This approach is similar to the snapshot composite approach, as it portrays changes of a single theme at predefined locations by grouping timestamped layers to show observations of a single event in a temporal sequence. However, the approach stores changes in relation to a previous state, rather than in a snapshot of a previous instance (Peuquet and Duan, 1995, Yuan, 1996).

The event-oriented t-GIS approaches record events in temporal order, where each event is associated with a list of all changes that occurred since the last update of an event (Peuquet and Wentz, 1994). An event may represent either an abrupt change, or a gradual development over time considered significant enough to register change. Changes are stored as differences from the previous version to avoid data redundancy (Pelekis et al., 2004). Event-oriented modelling has the advantage that the state of each object can be obtained for any time, by computation from an initial state and then summation of all previous events that have been applied to the object (Renolen, 1999). Explicit information about what happened to objects is stored in a database that enables both forward and backward tracing of events. Figure 11 shows the elements and structure of an event-oriented spatiotemporal data model (ESTDM) for event-oriented t-GIS

(Peuquet and Duan, 1995). The base map shows an initial snapshot of a single phenomenon for a specific space. A header file contains information about the thematic domain, with a pointer to a base map and pointers to the first and last event lists, where each event is time-stamped and associated with a list of event components to indicate where changes have occurred. Each event component shows changes to a predefined location at a specific point in time (Peuquet and Duan, 1995).

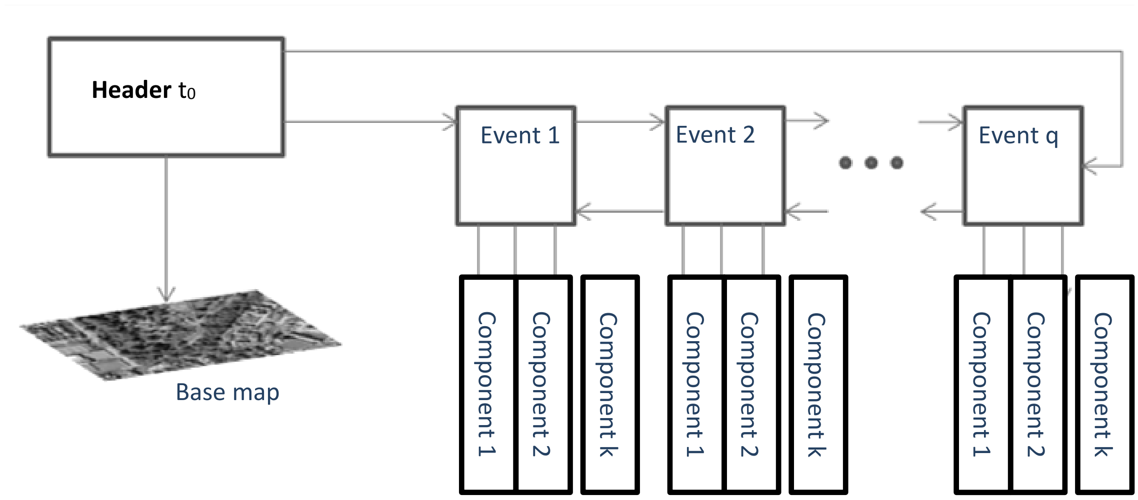


Figure 11: The elements and structure of an event-oriented spatiotemporal data model, adapted from p. 15 Peuquet and Duan (1995).

In Figure 11, *m* is the base map at the beginning of model time, *t* represents time, *k* represents any additional components for each event, and *q* represents time after the event. The ESTDM is capable of efficiently supporting both spatial and temporal queries, however transformation of ESTDM to a vector based system requires substantial redesign of event components.

The previous approaches show how spatial objects, temporal objects and events have been linked within t-GIS to provide insight into changes in phenomena over time. However, whilst much work has been done within t-GIS to develop relevant ontologies and data structures (Langran, 1992, Peuquet and Duan, 1995, Yuan, 2002), there has been little overall advance with regard to the integration of mainstream data sources or the specific modelling required to estimate time-specific population distributions (Martin et al., 2015). Therefore, none of these approaches have the capacity to represent the semantic objects of themes, entities or processes – such as groups or types of people – that are relevant to the spatiotemporal representation of population phenomena. The next section reviews the three-domain t-GIS approach for modelling spatiotemporal population distribution. The three domain approach departs from the static map metaphor and integrates temporal, semantic and spatial objects to provide the most realistic representation of populations in space and time.

2.4.1 The Three Domain t-GIS Approach

The three domain approach is the most relevant to modelling populations in space and time, as it enables the spatiotemporal context of specific population activities to be realistically represented. This approach adds attributes to space and time to create three subsystems of “what”, “where” and “when” to a t-GIS (Peuquet, 2002). Figure 12 shows how the semantic, temporal and spatial object domains are strongly interrelated and based upon objects, places and processes in the context of a spatiotemporal population model.

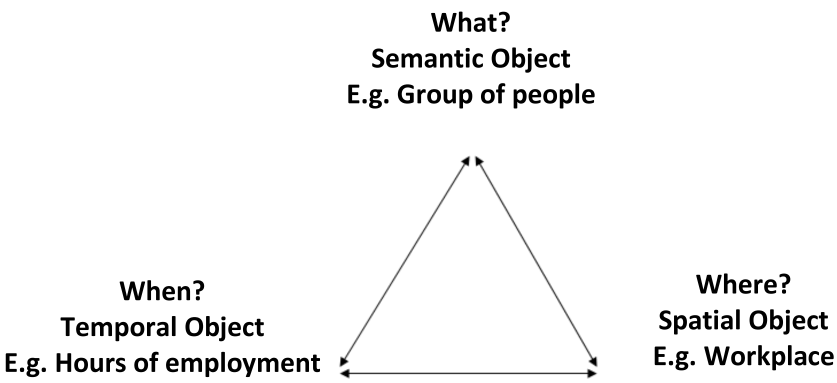
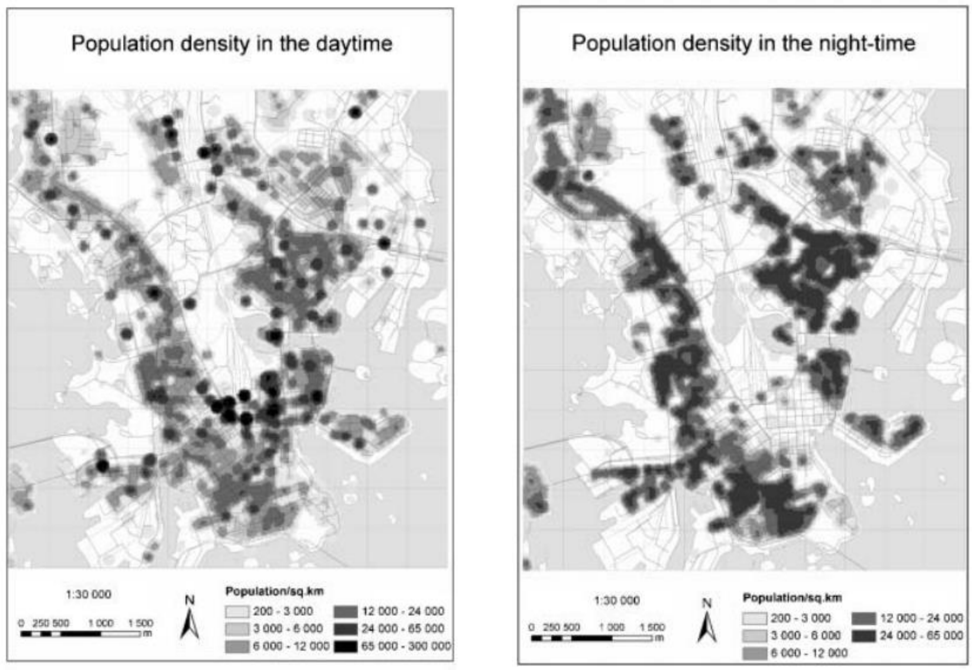


Figure 12: The three domain approach to t-GIS for the context of the spatiotemporal population model, adapted from p. 203 (Peuquet, 2002).

Within this structure, object links may be one of three types: (1) pointers that associate objects of different domains with spatiotemporal facts (2) mathematical functions that indicate spatiotemporal behaviours, and (3) models that predict trends or processes in space and time (Yuan, 1999). This model is relevant, as it enables populations to be placed to specific activities at the appropriate times. For instance, with appropriate data availability, night-shift healthcare workers can be placed in hospitals for the duration of a night shift. This greatly enhances the capacity for modelling different population demographics when compared to previous t-GIS methods.

The three-domain method presented by Peuquet and Wentz (1994) has been applied by Ahola *et al.* as a component of a population modelling approach for representing change over time of model worker flows in Helsinki, Finland. Here, spatial, semantic and temporal data are treated as three separate but linked domains to describe the behaviour of a population (Ahola et al., 2007). The three-domain approach is combined with a moving kernel density interpolation, and overlaid with background data such as water areas and roads, to identify hotspots of population density at specific places during the day time or night time (Ahola et al., 2007). Fourteen different time periods including “week morning” and “Saturday evening” have been modelled for ten different population subgroups with this approach (Ahola et al., 2007). Figure 13. shows an example of the output for population differences at a) day time 9am to 3pm and b) night time 12pm to 6 am population densities.



a) b)

Figure 13: Population density modelling for a) day time and b) night time for the Helsinki model pp 950 (Ahola et al., 2007)

This approach uses building data to classify areas based upon use, as a spatial reference for population distribution including schools, hospitals and leisure facilities. This spatial data is combined with semantic data for specific population groups, including schoolchildren and shoppers to place populations to the appropriate space and time for their activity (Ahola et al., 2007). This approach offers a more detailed perspective upon population change across time than other approaches, due to having fourteen temporal subdivisions. However, most of the values used to associate proportions of populations to different activities are based upon expert knowledge instead of definitive empirical data (Martin et al., 2015). The three-domain approach therefore provides an accurate representation of change in population distribution. It also forms a significant component of the underlying concepts of the Population247 model, which is introduced in the next section.

2.4.2 **Population247**

Population247 is a framework for the estimation of spatiotemporal population distribution. It combines the three-domain approach with adaptive kernel density estimation and dasymetric interpolation, resulting in a volume-preserving and adaptable spatiotemporal population subgroup gridded surface model (Martin et al., 2009, Martin et al., 2015). Population247 is implemented by the SurfaceBuilder247 application, the manual of which can be viewed at the Population247 homepage.

Within Population247, a gridded spatial framework is used to create stable boundaries over time and to facilitate integration with other sources of spatial data (Smith, 2013). Whilst previous spatiotemporal population modelling approaches have been limited by spatial or temporal resolution, Population247 can provide high resolution temporal and spatial estimates of population distribution, therefore improving tolerance to MAUP and MTUP (Martin et al., 2015). Population247 consists of two systems: a data system and an analysis system. Within the data system is a three-domain model, as shown in Figure 14, where domains are spatial, temporal, and attribute-based. This is equivalent to the semantic domain in Peuquet's three-domain model.

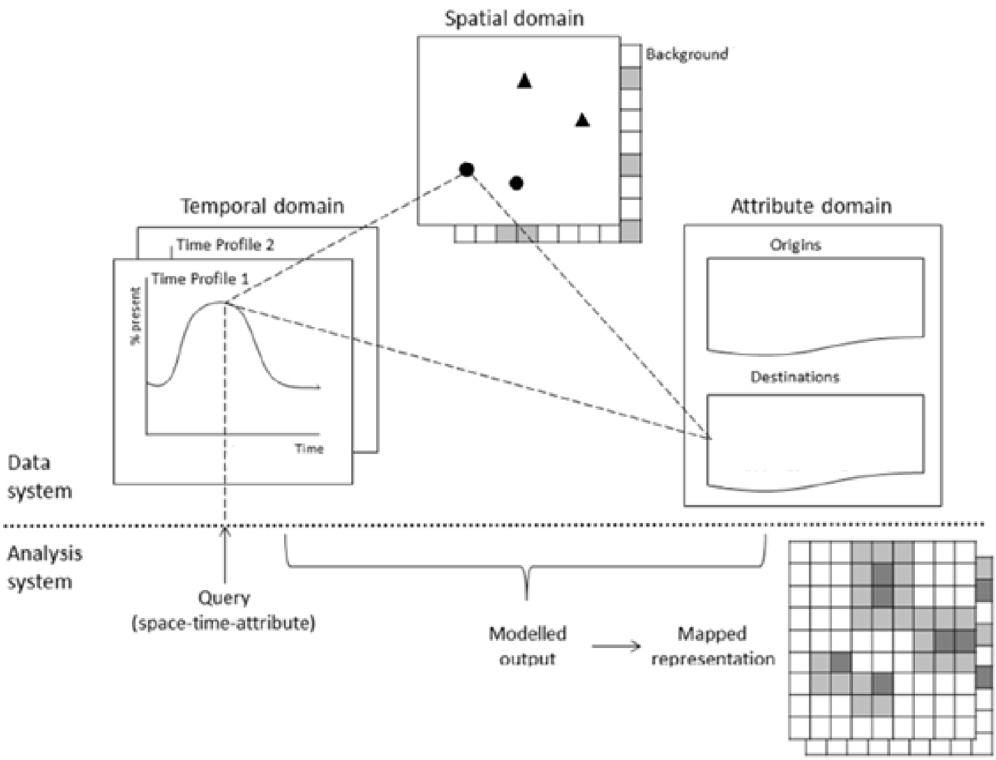


Figure 14: The data system and analysis system of Population247. The data system has a three-domain structure showing the temporal, spatial and attribute domains (Martin et al., 2015)

The spatial domain consists of two types of spatial object referred to as spatial containers, for origin populations and destination populations (Martin et al., 2015). For a region to be modelled, the sum of the origin containers represents the entire residential population, plus or minus any known population flows into or out of the region, to preserve volume. The destination containers represent additional locations with non-resident populations for specific activities. These containers reflect the maximum number of individuals at that destination at any one time, where each destination container has one or more time profiles and assorted catchments representing the area from which origin populations can be taken to participate in activities (Martin et al., 2015). The total population can be reallocated between spatial containers but cannot be lost or gained.

There is also an in-transit population that exists between origin and destination containers, which is modelled for the spatial domain as a second layer, forming a component of background space. This features transport links that carry populations between origins and destinations, but can also include land-use classification for places that cannot include populations, such as open water (Martin et al., 2015). Spatial containers can be allocated time profiles, where the time profile is the second domain of the approach, and describes the population present, as a proportion of its total capacity over time; therefore any number of specific and continuous time profiles can be used to describe the working day. The third domain of the system is the attribute domain, which describes the attributes of the spatial containers, including the division of population into subgroups that share an activity (Martin et al., 2015). Subgroups can be identified as mobile or immobile, where activity is restricted to the origin location. Spatiotemporal analysis is the second system within the approach, and is used to estimate population distribution across the intersection of spatial, temporal and attribute domains (Martin et al., 2015). These intersections identify the population subgroups present for each container for a specified time. Spatial analysis is used to redistribute populations from origin to destination containers by a weighted allocation to the nearest distance bands, to accommodate overlapping catchment areas and preserve total population volume.

Advantages of Population247 include extensibility, which allows more detailed spatial, temporal or semantic data to be incorporated into a subdivision of existing elements. The system can include real-world complexity at building level. For instance, a school may be occupied by local schoolchildren in day, then adults from wider area attending education at evening, and be unoccupied at night (Martin et al., 2015). Population247 cannot estimate complex flows to non-nearest facilities, and is limited by its ability to only model usual cyclical population distributions. However, dynamic modelling can reflect population change during unusual circumstances such as emergencies.

2.5 Dynamic Spatiotemporal Population Modelling

The previous approaches have the capacity to show distribution of populations in space and time based upon known spatial, temporal and semantic data; they do not, however, deal with the dynamics of population movement. This section outlines approaches for modelling changes in population dynamics, to demonstrate how distribution changes in the short-term when disruptions to usual cycles of movement occur. Combining the previous approaches with simulation techniques – including cellular automata (CA) and agent based modelling (ABM) – enables integration of a broad array of data sources across a dynamic framework, which can realistically reflect spatiotemporal change (Longley et al., 2005, Crooks et al., 2008, Peuquet, 2005).

CA is an approach that evokes a set of rules to update the state of a regular raster of cells, with a finite number of states for each cell and rules that determine how the cell state transitions through time (Wolfram, 1984, Maguire et al., 2005). CA have been used to simulate urban dynamics, urban development and population expansion over time (Batty et al., 1999, Wu and Martin, 2002, Dietzel et al., 2005, Benenson et al., 2006, Torrens, 2006). However, CA are too simple to accurately represent subpopulation dynamics.

ABM shares characteristics with CA, but can model population and environment separately, with spatially mobile agents that can be associated with different spaces, times and groups (Batty et al., 2012). This approach provides a quantitative, theoretical and mechanistic way to explain and predict population behaviour and organisation (Bonabeau, 2002). It is a more powerful approach than CA, and consists of a virtual environment where multiple individual entities – or agents – interact to display the overall properties of a system (Bonabeau, 2002). The combined effect of this interaction creates significantly more complex behaviour than the constituent parts alone; larger patterns generated by small-scale interactions are known as emergent behaviour (Castle and Crooks, 2006).

A key component of ABM is the agent, a partially autonomous entity that can be distinguished from its environment by its spatial, temporal or functional attributes. However, it should be noted that the agent concept is intended as a tool to analyse a system, rather than an absolute classification of either “agent” or “non-agent” (Castle and Crooks, 2006). Agent relationships can be specified in a number of ways. They can be linked spatially and temporally to other agents or entities in a system. Agents also have a temporal domain, since behaviour can be scheduled to take place synchronously, where each agent performs actions at a specific interval; or asynchronously, where agent actions are scheduled by the actions of other agents (Castle and Crooks 2006). To be autonomous, agents must to be able to act, interact, and engage in tasks in a spatial environment without direct external control, where the spatial environment may be discrete, continuous or characterised by networks (Janssen, 2005, Castiglione, 2006). The basic structure of a spatiotemporal ABM is detailed in Figure 15, where the agents interact in an environment, using cues from other agents and the environment itself to determine what action is taken (Macal and North, 2010).

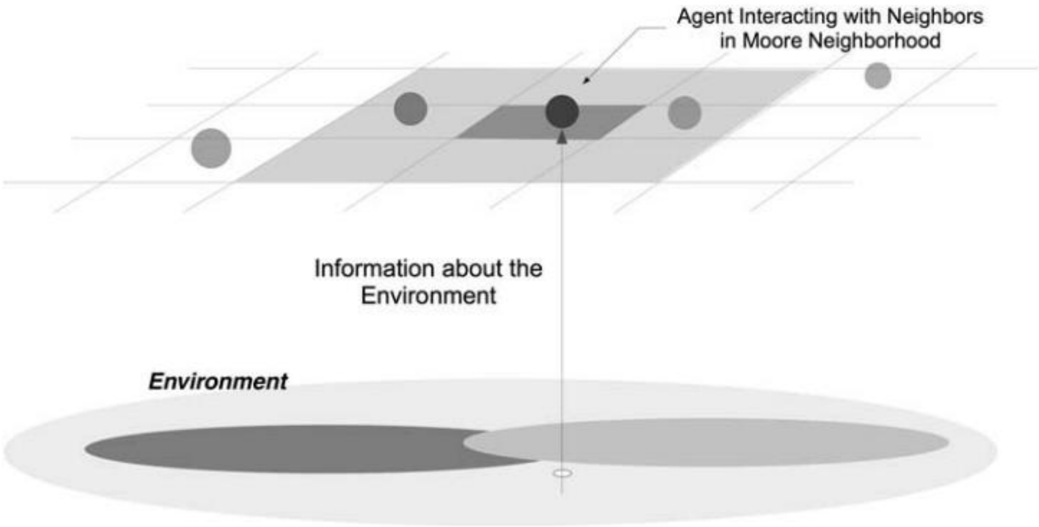


Figure 15: The structure of a typical agent based model p. 152 (Macal and North, 2010)

It is important to note that temporal resolution is as significant as spatial resolution for ABM, as it defines the length of each time increment and the sequence of time steps. However, both spatial and temporal resolution will affect any relationship between the real-world process and the model (Castle and Crooks, 2006). A good ABM requires a plausible initial scenario that applies specific values to parameters according to hypotheses in need of validation. After this configuration, the simulation can be executed across a time-series of regular “steps” such as minutes, hours or days. The agents will then evaluate the situation, plan executable actions, and influence and interact with each other and the controlled environment across the time series, to produce results that will hopefully answer the proposed hypotheses (Wittek and Rubio-Campillo, 2012). There are a number of different programming systems in existence that are suitable for geospatial ABM, across a number of open source, shareware/freeware and proprietary platforms including SWARM, MASON, Repast, Netlogo and Obeus (Castle and Crooks, 2006). Even a simple ABM can exhibit complex behaviour patterns and provide valuable information about the dynamics of the real-world system that it emulates (Bonabeau, 2002). There have been five topologies applied to ABM, including CA, Euclidian spaces, networks, GIS and spatial modelling, as shown by Figure 16 (Macal and North, 2010). The focus of this thesis is upon geospatial representation of population, and therefore GIS is the most appropriate system.

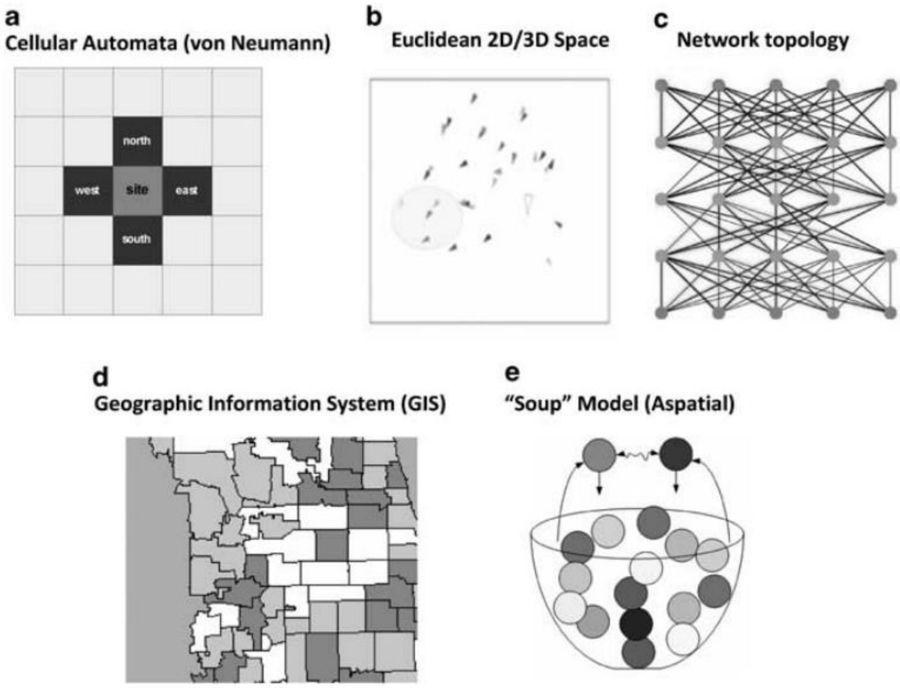


Figure 16: Topologies for agent relationships and social interaction p. 155 Macal and North (2010)

Benefits of ABM include the ability to combine qualitative behavioural information and quantative data, transcending linear notions of cause and effect (Chattoe-Brown, 2013, Lopez-Fernandez and Molina-Azorin, 2011, Caruth, 2013). It is also more natural to describe how populations move across the complex infrastructure of a city over time than it is to come up with equations to govern the complex dynamics of population behaviour (Castle and Crooks, 2006, Bonabeau, 2002). ABM has been applied to model populations across a range of environments, from micro-simulation of student populations (Wu et al., 2008), to the evacuation of crowds from buildings (Zheng et al., 2009), and the social dynamics of terrorist groups (Backus and Glass, 2006).

In the case of this thesis, there is prior knowledge of population distribution at specific snapshots in time, but the dynamics of the population between snapshots is unknown (Martin et al., 2009). Geospatial ABM enables the periods between these snapshots to be investigated. ABM has to be built at the right level of description for each phenomenon, and must have the appropriate level of detail to serve its purpose. It can be challenging to ascertain the correct level of complexity; this can result in models that are excessively complex, or those that over-simplify the phenomena to be investigated (Couclelis, 2002). However, the interpretation and use of ABM by the social sciences can be challenged, and existing models have been described as ad-hoc (Chattoe-Brown, 2013). The lack of standardised protocols for communication of model structure makes cross-comparison difficult (Zvoleff and An, 2013, Grimm et al., 2010, Grimm et al., 2005). ABM is therefore only as useful as the purpose for which it was constructed (Grimm et al., 2005). To conclude, ABM is an important approach for modelling dynamic population distribution and it has applications to this thesis for improving understanding of population distribution at high resolution, and for understanding the processes and behaviours that inform population movement during unusual events.

2.6 Chapter Conclusions

The chapter has explained the use of Population247 spatiotemporal population modelling and agent-based modelling as tools appropriate for exploring cyclical and dynamic population distribution in space and time. This chapter reviewed the challenges associated with the representation of spatial phenomena, and explored interpolation approaches and methods for modelling populations in space and time using t-GIS. Finally, the chapter described agent-based modelling for assessment of unusual population dynamics.

It has been identified that any spatial approach for modelling population density must be volume-preserving and manage the Modifiable Areal Unit Problem (MAUP) (Openshaw, 1984). Interpolation methods were summarised; pycnophylactic interpolation, distance weighting, Kriging and kernel density estimation were reviewed in greater detail; and kernel density estimation was identified as the most appropriate method in the present context due to its adaptive capacity. The use of ancillary data for the interpolation was explored and identified as useful for improving the accuracy of the interpolation. Time in spatial modelling was discussed and t-GIS methods were reviewed. The three-domain model – which includes semantic, spatial and temporal objects – was considered to be the most appropriate type for modelling spatiotemporal populations, as population subgroups and specifically timed activities can be included. This approach was demonstrated by a case study of Ahola *et. al.* (2007), which showed that spatiotemporal population distribution can be modelled effectively with the three domain model. The Population247 approach was then described; this approach forms a major component of the thesis, and is based on an adaptive kernel based interpolation approach. The origins and functions of agent based modelling for dynamic population change were then described.

The next chapter explores hazard, risk, and vulnerability, and the interactions between populations and radiation hazards. It identifies the most vulnerable population groups, and introduces the concept of emergency planning and management. Finally, it reviews approaches for modelling populations at risk of exposure to radiation hazards, as well as approaches for understanding the health effects of radiation.

Chapter 3: Radiation Protection and Society

"Disasters of the future may or may not be bigger or worse, but they are likely to require more sophistication in response and recovery." (Rubin, 1998)

This chapter introduces technological hazard, risk and vulnerability in the context of emergency planning for radiation emergencies. More vulnerable population groups are described and the impacts of radiation upon health are explored. Emergency planning procedures for radiation hazards are described. The historical accounts of two significant nuclear accidents, Chernobyl and Chazhma Bay, are examined to understand the human impact of radiation emergencies; and existing models for describing population and hazard distribution in space and time are evaluated for suitability to nuclear accident scenarios. The chapter concludes with an overview of the importance of new systems for modelling populations at risk. A condensed version of this chapter has been published in BELGEO within Appendix A (Alexis-Martin, 2015).

3.1 Technological Hazard, Risk and Vulnerability

This section explores and defines technological hazard, risk and vulnerability. Technological hazard is also known as man-made hazard, and includes scenarios such as industrial pollution, chemical spills, toxic waste, transport accidents, factory explosions and nuclear accidents (Sapir, 1993, Hohenemser et al., 1983). A hazard is any dangerous phenomenon, substance or condition that has the potential to cause loss of life, injury, property damage, loss of livelihood and services, social and economic disruption or environmental damage (UNISDR, 2009, IAEA, 2007). Whilst natural hazards occur due to natural processes, technological hazard arises due to any human activity that creates a likelihood of risk, through conditions of human negligence or error (Pidgeon and O'Leary, 2000, Slovic, 2000). Usually, little or no warning precedes technological hazard accidents, and victims may not experience the health effects of exposure until many years later.

A radiation hazard is the accidental or intentional uncontrolled release, dispersal, emission or spread of radioactive material (Barnett et al., 2006). Exposure to radiation hazard occurs as a consequence of the release of radioactive material from a nuclear installation to the environment, and the release is usually characterised by a cloud-like plume of radioactive aerosols and particulate matter. The major hazards to populations in the vicinity of a radiation plume are from exposure to the body, inhalation of radioactive gases and radionuclides and ingestion of radionuclides (WHO, 2012b). Figure 17 outlines and contextualises some of the most significant international nuclear accident hazards by International Radiological and Nuclear Event Scale (INES), which ranks nuclear accidents according to severity (IAEA, 2014). The scale is designed so that the severity of an event is approximately ten times greater for each increase of INES level (IAEA, 2014).

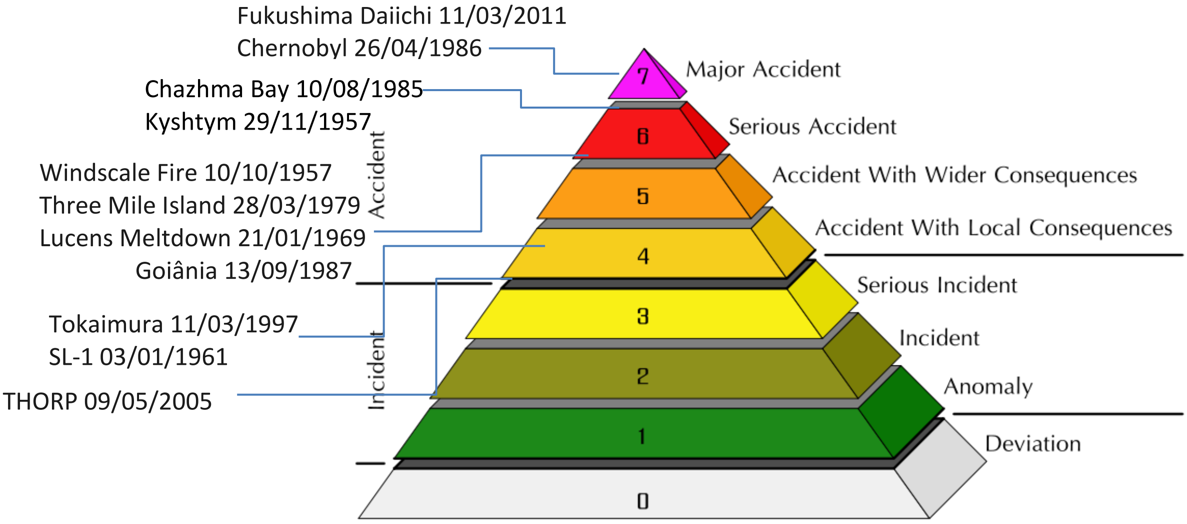


Figure 17: IAEA International Radiological and Nuclear Event Scale (INES) with specific incidents annotated for context (IAEA, 2014).

A number of significant radiation accident hazards including Chernobyl, Three Mile Island and Chazhma Bay are subsequently referenced to by this thesis for the purpose of context.

Radiation hazards are infrequent but have serious and long-term impacts upon exposed population. The likelihood of a radiation hazard occurring is described as risk. Radiation hazard risk management is consequently a very high priority for the UK (Government, 2010). For this thesis, risk is the specific likelihood that a population will be exposed to loss or damage as a consequence of any unintended technological event or accident, including but not limited to operating errors, equipment failure and other mishaps (IAEA, 2007, UN, 2013). Whilst the inevitability of radiation hazards is debated, it is impossible to entirely remove risk. Therefore, risk is managed by ensuring that systems are in place to reduce the likelihood of exposure to hazard (Wisner, 2004). Emergency planning and management form a component of risk reduction by identifying, mitigating and managing hazard and risk.

Vulnerability defines the adaptive capacity and susceptibility to harm of an individual or population due to exposure to stress associated with change (Wisner, 2004, Adger, 2006). As a result of having a reduced adaptive capacity, more vulnerable individuals and populations are more likely to experience loss and other difficulties as a consequence of having decreased adaptive capacity, during exposure to a hazard. The social, cultural and physical differences across a population, including age, gender and health status, can contribute to or alleviate vulnerability (Wisner and Luce, 1993, Wisner, 2004, Bolin, 2007). However, vulnerability is not consistent through time. During the course of an emergency, the adaptive capacity of a population may change over time due to movement or immobility, injury, resource availability, or the cumulative health impacts of a chemical, biological or radiation hazard (CCS, 2008).

Hazard, vulnerability and risk are interlinked, and Figure 18 demonstrates their relationship in the context of a radiation accident hazard example (Cova, 1999, Alexander, 2002). For this scenario, a hazard arises due to the release of radioactive material from a nuclear power station. The surrounding population is vulnerable to the health effects of radiation exposure, which puts individuals without the adaptive capacity to shelter or evacuate at risk of adverse effects.

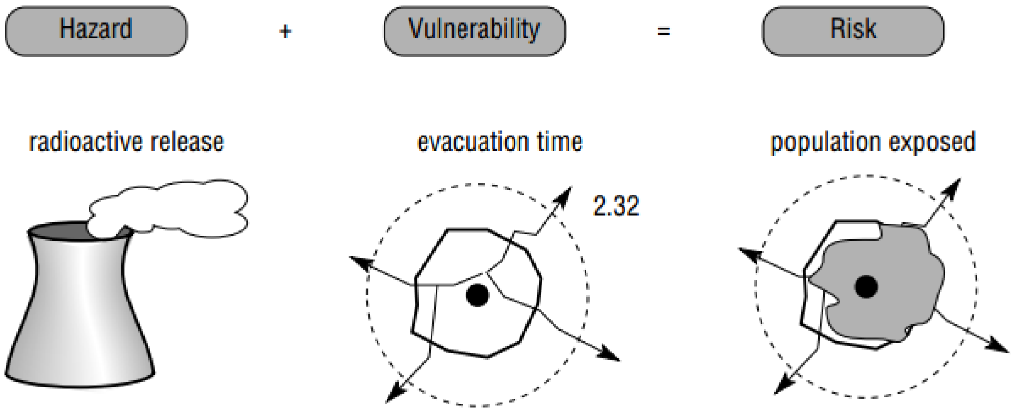


Figure 18: Hazard, vulnerability and risk of a nuclear accident p. 851 (Cova, 1999).

The vulnerability of the population in Figure 18 could be decreased by having a plan for nuclear emergencies that includes methods for informing the public, contingencies for transport infrastructure, and strategies for evacuation. However, it is still challenging to locate more vulnerable population subgroups during emergencies. The next section considers why some subgroups are more vulnerable than others.

3.1.1 **Vulnerable Population Subgroups**

Demography and vulnerability are closely linked. The last section described how vulnerability creates barriers to adaptive capacity. These barriers can include age, physical and mental health, disability, culture, ethnicity, religion, language, citizenship, geography, and socioeconomic status (Ford, 2008, Bolin, 2007). More vulnerable population subgroups engage in different activities across different locations to those who are less vulnerable, which can compromise adaptive behaviours such as self-help and resource accessibility during an emergency. This section discusses how poverty, migration, ethnicity, age and gender can have an impact on vulnerability.

There is a relationship between economic capital and humans, whereby poorer people have fewer choices during an emergency (Yodmani and Center, 2001). Impoverished population subgroups have decreased access to resources, and are more likely to live in less robust housing with fewer relocation opportunities (Donner and Rodríguez, 2008, Tobin and Whiteford, 2001). Populations who are more likely to be economically disadvantaged include certain migrants and ethnic minority groups, older people and women (Bolin, 2007). Relocation has a significant impact upon vulnerability by potentially decreasing an individual or population's economic, social and cultural influence (Slovic, 2000, Hunter, 2005, Donner and Rodríguez, 2008). Relocation and ethnicity can also affect perception and awareness of risk due to cultural and language barriers.

Age is another important determinant of vulnerability (Yaukey et al., 2001, Cutter et al., 2003). Older people are more vulnerable because they are more likely to experience psychological symptoms, be injured or to die during an emergency; possibly due to existing comorbidities that increase the likely need for medical care (Wisner, 1998, Mayhorn, 2005). Older people are also more vulnerable due to difficulties in accessing warning-and-informing information, and challenges around the identification of their location, to provide assistance or evacuation (Cahalan and Renne, 2007, Mayhorn, 2005). Children are more vulnerable – and at greater risk of injury and poor health – due to dependence upon others for livelihood, decision making and emotional support (Peek, 2008, Hoffman, 2008, UNICEF, 2011).

Gender refers to the different roles and characteristics of women and men, which vary by culture, ethnic identity, race, class and age (Eade and Williams, 1995). The influence of gender may be reduced during emergency, and women have been shown to be active responders (Tobin and Whiteford, 2001, Enarson, 1998, Wisner and Luce, 1993). However, women are more vulnerable to physical and psychological harm, injury, fatality, domestic violence, and increased domestic labour during emergencies; and there is a lack of specialist support for women (Finucane et al., 2000, Wisner, 2004, Wiest, 1998, Enarson, 2000, Bonanno et al., 2007). Gender also intersects with other population characteristics to shape overall vulnerability. For example, an elderly, disabled woman might be more vulnerable than a younger, able-bodied woman.

The next section explores why humans are vulnerable to the health effects of ionising radiation, and describes the short-term and long-term effects of exposure.

3.2 Humans and Radiation

This section examines vulnerability to radiation exposure from a physiological perspective, and explains the health effects of radiation exposure. The population subgroups that are more vulnerable to radiation exposure are identified, and current strategies for treatment of radiation exposure are described. Ionising radiation is the excess energy released and emitted by spontaneous disintegration of atoms. It can travel in the form of electromagnetic waves or particles, known as alpha particles, beta particles and gamma waves (WHO, 2012b). Table 1 describes the physical characteristics of alpha (α), beta (β) and gamma (ϒ) radiation, as well as their potential impact upon on humans. Whilst external α radiation has no effect, internal exposure to α and β radiation can damage cell structure and DNA for as long as particles are present and undecayed; whereas damage from ϒ radiation ceases when the source is removed.

Radiation type	Properties
Alpha particle (α)	An alpha particle is a high-mass, low speed, positively charged particle consisting of two protons and two neutrons (^{4}He). Alpha particles are ejected during alpha decay of a heavy radioactive element (IAEA, 2007). Alpha particles have insufficient energy to penetrate skin. Internal exposure is hazardous due to high relative biological effectiveness upon live cells and DNA (WHO, 2012b).
Beta particle (β)	Beta decay occurs when an electron (β^-) or a positron (β^+) beta particle is emitted from the nucleus of a radioactive atom. Beta particles are high energy and high speed particles (IAEA, 2007). Travel further than alpha, can cause radiation burns to exposed skin and are also an internal exposure hazard.
Gamma ray (ϒ)	Gamma rays are energetic photons emitted by excited nuclei during their transition to lower energy levels after beta decay. Gamma rays lose energy slowly and are the most penetrating type of radiation. Several inches of dense material such as lead, is needed to prevent exposure. Gamma rays can pass through the human body and damage tissue and DNA by ionisation (EPA, 2012).

Table 1: The physical properties of gamma waves, alpha particles and beta particles (IAEA, 2007, WHO, 2012b, EPA, 2012).

Unstable elements that disintegrate and dissipate excess energy by emission of ionising radiation are known as radionuclides. Radionuclide type is identified by the energy and type of radiation emitted and by half-life, which is the amount of time required for exponential decay of nuclei to half of its original value (WHO, 2012b). Some naturally occurring radionuclides include isotopes of uranium, thorium, potassium, and decay products such as radium and radon (WHO, 2012b). Manufactured radionuclides include tritium (3H), 60Co, 33P, 35S and 137Cs, 226Ra, although there are others. Standard units are used in this thesis to quantify radiation and radiation dose, and their function and meaning are explained in Table 2 (IAEA, 2007).

Quantity **SI unit**	**Radioactivity** (Bq) **Becquerel (Bq)**	**Absorbed dose** (D_T) **Gray (Gy)**	**Equivalent dose** (H_T) **Sievert (Sv)**	**Effective dose** (E) **Sievert (Sv)**	**Collective dose** (S) **Man Sievert (MSv)**
Derivation	1 Bq = 1 s^{-1}	1 Gy = 1 Jkg^{-1}	1 Sv = 1 Jkg^{-1}	1 Sv = 1 Jkg^{-1}	1 Sv = 1 Jkg^{-1}
Definition	SI derived unit of radioactivity. The activity of a quantity of radioactive material in which one nucleus decays, or disintegrates, per second. E.g.: 0.0169g of K-40 produces 4400 disintegrations per second, or 4.4 kBq of activity.	SI derived unit of ionizing radiation dose. A measure of absorbed dose, defined as the absorption of one joule of radiation energy by one kilogram of matter. Gy is a physical quantity that does not consider biological context and is independent of target material.	SI derived unit of ionizing radiation dose Biological effect of the deposit of a joule of radiation energy in a kg of tissue, for body uniformly irradiated by radiation type R with weighting factor W_R. NB: For ϒ rays, Gy is the same when expressed as Sv; but for α particles, 1 Gy is equivalent to 20 Sv, because of a radiation weighting factor that reflects increased risk.	Biological effect on tissue type T having a weighting factor of W_T. Tissue weighting factor W_T ranges from W_{T1} for whole body irradiation to W_{T2}, W_{T3} etc. for partial irradiation, where the effective dose = summation of effective doses to those parts irradiated. Complete irradiation is if the whole body is irradiated uniformly, where the weightings W_T summate to 1. Total effective dose = equivalent dose	The sum of all individual effective doses from time of release of radiation, until population is removed from source or source ceases to be present. Used to estimate total health effects of radiation release to an exposed population. 1 micro Sievert (µSv) = 1.0 × 10^{-6} Sieverts

Table 2: Explanation of standard units for radioactivity and radiation dose (IAEA, 2007).

Every population is exposed to levels of naturally occurring radiation. However, there are other sources that contribute to background radiation dosage, which occur due to medicine, occupational exposure, consumer products, radioactive fallout, and waste disposal (HPA, 2005). The approximate dose of background radiation per individual in the UK is 2700 µSv per year. Whilst background radiation poses no discernible risk to health, the release of greater amounts of radiation can have health effects.

The next section considers the effects of exposure above background level to humans and describes symptoms of exposure, the relationship between received dose and exposure time, and the difference between deterministic and stochastic symptoms.

3.2.1 **The Health Effects of Radiation Exposure**

The effects of radiation exposure are controlled by route, type and quantity of radiation, timescale, and tissue sensitivity (Beir, 1990, Mettler and Upton, 1995, NRC, 2005). Internal exposure occurs when a radionuclide or gamma radiation enters the body, and contamination ceases when the radionuclide is eliminated or when the gamma source is removed (Bloom, 1947, Mettler and Upton, 1995, WHO, 2012b). External exposure occurs when radionuclides are deposited upon the skin or clothes, and this type of contamination can be removed by washing (WHO, 2012b). Radionuclides with significant impacts upon human health are iodine and caesium, due to their toxicity and the ease of absorption by the body (HPA, 2005).

Radiation can have deterministic and stochastic effects upon human health (Mettler and Upton, 1995). Deterministic effects are rapid, and caused by immediate cell damage to the structure or function of tissue and organs (WHO, 2012b). These effects begin at doses above a threshold of 100 mSv and include skin redness, nausea, hair loss, cataracts, and sterility; acute radiation syndrome (ARS) occurs at doses of greater than 1000 mSv (NRC, 2005). Higher doses affect cell death mechanisms and make long-term effects more likely.

		Highly survivable		Survivable to lethal		Lethal	
	ARS severity	Mild		Severe	Very severe	Lethal	
	Dose (Gy)	0-1	1-2	2-6	6-8	8-30	>30
Immediate symptoms	Vomiting: Onset time: Duration:		5-50% 3-6 hrs. < 24 hrs.	50-100% 1-6 hrs. < 24 hrs.	75-100% < 2 hrs. < 48 hrs.	98-100% < 1 hrs. < 48 hrs.	100% < 1 hrs. < 48 hrs.
	Lymphocyte count (cells/mm^3):		<1400 at 4 days	<1400 at 48 hours	<1000 at 24 hours	<800 at 24 hours	
Delayed symptoms	Onset time:		>2 weeks	2 days- 2 weeks		0-2 days	
	Critical:		None	4-6 weeks		5-14 days	1-48 hours
Fatality:		0%	0%	0-80%	80-100%	98-100%	
Time to death:				3-12 weeks		1-2 weeks	1-2 days

Table 3: The deterministic effects of Acute Radiation Syndrome (ARS) in healthy adults, adapted from AFRRI (2011).

Table 3 shows some relevant symptoms of acute radiation sickness for healthy adults. Doses of < 0.15 Gy do not produce observable health effects, but the effects become progressively more severe as the dose increases (Borden, 2012). Symptom onset is rapid at higher doses, and healthcare has an important effect upon outcome. Figure 19 shows the relationship between radiation dose, likelihood of fatality, and time to death from deterministic effects of radiation exposure. Percentage fatality by dose is plotted in blue, and time to death by dose is plotted in red. The graph shows that the risk of death is negligible at doses below 2 Gy, increases uniformly until approximately 6 Gy. Likelihood of death increases above 8 Gy, and progression to death thereafter is much more rapid (AFRRI, 2011).

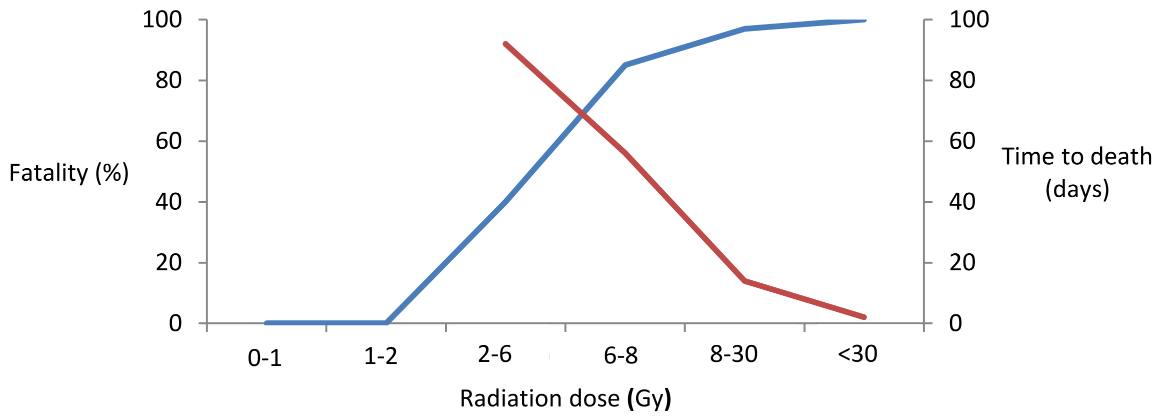


Figure 19: Relationship between dose, % fatality and time of death, adapted from AFRRI (2011).

Stochastic or long-term effects occur when cells are modified by ionising radiation, which creates changes that persist in daughter cells, oocytes and sperm cells. Stochastic effects have long-term implications including cancer, and have a latency time of 20–30 years for solid body tumours and 7–10 years for leukaemia (Mettler Jr and Voelz, 2002). An increase in dose does not increase the severity of stochastic effects, but instead increases likelihood of effects (ATSDR, 1999). Studies of occupational and accidental exposure have shown there is an increased likelihood of stochastic effects at exposure doses above 100 mSv (Thompson et al., 1994, WHO, 2012b, Cullings, 2014).

Human radiosensitivity is controlled by cell proliferation rate, number of future cell divisions and degree of functional difference between cell types. Radiosensitivity is therefore controlled by age, sex and pregnancy, all of which affect cell division (Borden, 2012). Rapidly dividing cells such as those found in children, young adults and foetal nerve cells are more sensitive; whereas tissues that undergo little cell division are more resistant (ATSDR, 1999). Effective dose is used to estimate the impact of radiation across the body by calculating the weighted average of an equivalent dose to different tissues in the body, where weighting factors are applied to reflect different sensitivities and describe individual dose (IAEA, 2007). The next section explains why females and children are more sensitive to the effects of radiation exposure.

3.2.2 The Effects of Radiation Exposure upon Children and Females

Differences between gender and age characteristics of different population subgroups can determine the effects of exposure to radiation. Studies of therapeutic exposure, atomic bomb survivors and nuclear accidents have provided insight into the physical effects of radiation upon children and females, and have demonstrated that these subgroups are more vulnerable.

Children are more vulnerable to deterministic and stochastic effects because their bodies have a smaller mass to surface area; more rapid mitosis; more effective contaminant absorption through the skin; and a longer remaining lifespan for DNA damage to have detrimental effects (Fucic et al., 2008, Mobbs et al., 2010, Baverstock, 1992). Following Chernobyl, the stochastic consequences of childhood exposure to ionising radiation are increased risk of leukaemia, thyroid and breast cancer (Etzel and Balk, 1998). Leukaemia risk is greatest for those exposed before five years of age and is non-linear, being initially higher, but beginning to decrease after ten years following exposure (WHO, 2012a). Risk of thyroid cancer has increased in children under five and those with iodine deficiency (WHO, 2012b). A linear association has been identified between dose and risk of developing thyroid cancer, for children exposed before nineteen (Cullings, 2014). Breast cancer incidence is elevated in women who were exposed to high levels of radiation during childhood, and in female atomic bomb survivors to menopausal age (Etzel and Balk, 1998). Atomic bomb survivors showed a significant increased risk during childhood, (Boice, 1990, Etzel and Balk, 1998, Cullings, 2014). This suggests that children should be prioritised to prevent childhood radiation exposure resulting in adulthood health effects.

Whilst radiation exposure produces similar deterministic symptoms, women are more likely to experience stochastic effects (Boice Jr, 2014). Female body and organ size is often smaller than that of males, and more rapid cell growth of tissues within the reproductive system and breast impacts upon risk of cancer (Boice, 1990, Stabin, 1997, Boice, 2005, Cardis et al., 2005). Women also have an Elevated Excess Relative risk (ERR) compared to men, of cancer of the thyroid, lung, breast, ovaries and some solid body tumours (Jacob et al., 1999, Cardis et al., 2007, Barcellos-Hoff, 2013, Hatch, 2014). Atomic bomb survivors studies show that ERR coefficients at 1 Gy for incidence of solid cancers is 1.6 times greater for women, with excess relative risk of 0.35/Gy for men and 0.58/Gy for women (Preston et al., 2003, Preston et al., 2007, Schonfeld et al., 2013). There is also an increased risk of arteriosclerosis and cardiovascular disease due to radiation exposure in women (Borghini et al., 2013). Fertility, pregnancy and nursing can also be affected. Suppression of ovulation is observed at doses of 1.5 Gy. The estimated dose for permanent female sterility is 3.5 Gy (Mettler and Upton, 1995). Radiation can cause foetus defects and malformations (ATSDR, 1999, Hatch, 2014). Nagasaki and Hiroshima studies show that foetal exposure of 0.12 to 0.23 Gy at 8 to 15 weeks gestation is associated with mental retardation (Etzel and Balk, 1998). Women are also at risk of passing contamination on to children by breast feeding (WHO, 2012b, Hatch, 2014). Table 4 combines evidence to provide an overview of stochastic risks to women and children.

Organ or System	BEIR VII Phase 2 conclusions about deterministic cancer risk (NRC, 2005)
Mammary	Absolute risk of breast cancer from exposure to ionizing radiation is greater for women. Women irradiated at 20 years of age are at higher risk than those irradiated later. No evidence to suggest radiogenic breast cancer will appear during the first 10 years after exposure. Peak incidence occurs 15 to 20 years after exposure.
Lung	Absolute risk of lung cancer from exposure to ionizing radiation is similar for both males and females.
Gastrointestinal (stomach and digestive system)	The incidence of stomach cancers increases with increased exposure to ionizing radiation. Females are at greater risk of developing cancers than are males. The relative risk for developing cancer is higher for those exposed when 30 years of age or younger. The baseline risk for digestive cancers increases with age; most of the excess cancers occur after middle age.
Thyroid	Susceptibility to radiation-induced thyroid cancer is greater in childhood. For those exposed before puberty, the tumours do not appear until after sexual maturation. The risk is greatest for children exposed during the first 5 years of life. Females are 2–3 times more susceptible than males to radiogenic (and spontaneous) thyroid cancer
Brain/central nervous system	Increases in tumour incidence have been reported when subjects irradiated during childhood at doses less than 1–2 Gy.
Urinary tract	Women < 55 years old at the time of exposure are at greater risk than older women, with this risk increasing with time after exposure. However, gender appears to have little effect on the incidence of bladder cancer mortality.
Salivary gland	The incidence of salivary gland tumours was increased in the Japanese A-bomb survivors, patients treated with x rays to the head and neck during childhood, and women treated with 131I (radioactive iodine) when middle-aged.

Table 4: Summary of child and female-specific increased stochastic risks after exposure to ionising radiation. Adapted from p. 158 ATSDR (1999), (NRC, 2005).

Both men and women experience mental health problems following radiation exposure, however women are at greater risk of poor mental health and are more likely to experience post-traumatic stress disorder (PTSD), generalized anxiety disorder (GAD), sleep disorders, depression and anxiety (Bonanno et al., 2007, Bonanno et al., 2011, Bromet and Havenaar, 2007, Bromet, 2014). Analysis of data from nuclear accidents has resulted in identification of elevated risk amongst mothers with young children and older women, potentially due to concern for children and family, increased domestic workload and impact upon usual social networks (Bromet, 2014). To conclude, radiation exposure affects both physical and mental health and has long-term impacts, especially for females. It is therefore important to ensure that processes are in place to protect people from radiation. The next section considers the medical methods of treating radiation exposure.

3.2.3 **Treating Exposure to Radiation**

The complex medical knowledge involved in treating and managing patients with symptoms of radiation exposure is beyond the remit of this thesis. However, it is important to explain preventative medicine for the management of asymptomatic patients, as it forms part of the radiation emergency planning and management process. The medications most commonly used for treatment of radiation exposure are potassium iodate tablets (PITs), Prussian blue, Diethyenetriamine pentacetate (DTPA) and Granulocyte colony-stimulating factor (G-CSF).

Potassium iodate tablets (PITs) are used to block the absorption of radioactive isotopes of iodine by the thyroid gland (IAEA, 2013). Taking PITS fills the thyroid with the medical potassium, which prevents further absorption of radioactive potassium until the medication is metabolised. However, these tablets cannot protect other organs from the effects of exposure and are only effective for iodine radionuclides.

Prussian blue is a medication that removes radioactive caesium and thallium from the body by trapping radionuclides in the intestines and preventing reabsorption (Kamerbeek et al., 1971, Thompson and Church, 2001). The radionuclides are then excreted, reducing the amount of time that the body is exposed to radiation.

Diethyenetriamine pentacetate (DTPA) is an intravenous medicine that binds to radioactive plutonium, americium and curium in a similar way to that which Prussian blue binds to caesium, which decreases the time that isotopes are in the body (Ménétrier et al., 2005). Granulocyte colony-stimulating factor (G-CSF) medication stimulates the growth of white blood cells after depletion due to radiation exposure but does not remove radionuclides (Butturini et al., 1988).

There is currently no treatment that completely removes all radionuclides from the body, which is why emphasis is placed strongly upon reducing exposure and preventative actions. The next section describes the emergency planning and management process for nuclear emergencies.

3.3 Emergency Planning and Management for Radiation Hazards

This section explores the purpose of emergency planning and management, in the context of radiation hazard. An emergency is any unplanned event with the capacity to endanger life, disrupt operations, cause environmental damage and affect reputation, and that requires a significant response (Alexander, 2002). Emergency planning and management is the discipline of applying science, technology, planning and management to enable planning, preparation, mitigation, management and recovery from disaster (Drabek and Hoetmer, 1991, CCS, 2004).

3.3.1 Introduction to Emergency Planning

The emergency management cycle shown in Figure 20 describes emergency planning as a continuous process of mitigation, preparedness, response and recovery over time (Anderson, 1985, Cova, 1999, Cutter, 2003, Alexander, 2009). Mitigation focuses upon long-term measures for reduction or elimination of identified risks and can be legislative, educational, structural or practical. Preparedness is training, exercising, monitoring and evaluation to ensure effective coordination across responders during an emergency. Response is focused upon mobilisation of responders to the incident, including emergency services, military and charitable workers. Finally, recovery restores people, environments and places to normality by improving infrastructure, health and environment (Alexander, 2002).

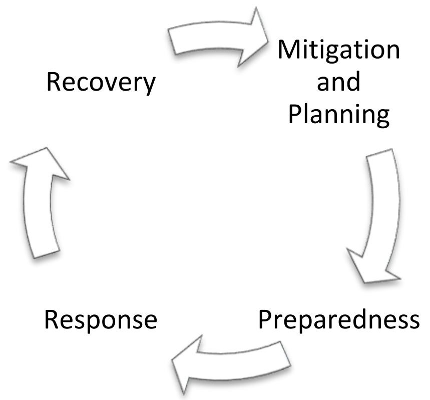


Figure 20: The emergency management cycle (adapted from (Alexander, 2002)

Whilst the emergency management cycle is continuous and generic to facilitate preparedness for any possible hazard, the emergency planning process is incident-specific because different hazards require different types of response.

It is important to identify the whereabouts of vulnerable people during an emergency, to ensure assistance is provided to those who need it most. Methods for identification of vulnerable people include building networks of organisations that hold information; creating data sharing protocols and activation triggers; and determining the scale and requirements of vulnerable people prior to emergency by vulnerable people planning, to specify resource and equipment requirements (CCS, 2008). Current population subgroups subject to specific planning in the UK are children, older people, mobility/mental/cognitive function/sensory impaired and/or ill, tourists, minority languages and non-British-national communities, travelling communities, the homeless, and pregnant women (CCS, 2008). Emergency planning aims to identify locations such as schools and residential care homes, but supporting vulnerable people during an emergency can be difficult due to the number of organisations involved, the diversity of vulnerability, and the changing status of the general population. This leads to increased vulnerability as the disaster becomes more severe, due to people who would not normally be considered vulnerable becoming such as a result of injury. The next section describes radiation hazard specific emergency planning and management.

3.3.2 **Planning for and Managing Radiation Hazards**

Radiation hazards can originate from power generation, medical facilities, scientific work and defence. However, site-specific radiation emergency planning provides information about the potential scope of hazard, incident management procedures, and response requirements across the phases of the emergency management cycle.

In the UK, radiation emergency planning standards are determined by the International Atomic Energy Agency (IAEA). The IAEA has a statutory function to develop standards for protection of health and environment from radiation exposure risk, and to ensure that appropriate monitoring standards and preparedness arrangements are in place for nuclear emergencies. These standards are upheld by the Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPIR) directive, which provides safety standards for protection of the health of workers and the general public against dangers arising from ionising radiation in the UK (HSE, 2002).

The REPPIR regulations define the terms “radiation accident” and “radiation emergency”, where a Radiation Accident is an accident where immediate action is needed to prevent or reduce the exposure to ionising radiation of employees or other persons; and a Radiation Emergency is an event that is likely to result in a member of the public being exposed to ionising radiation in excess of 10 mSv. A radiation accident may, but will not necessarily, result in a radiation emergency (HSE, 2002).

A radiation emergency begins when an incident occurs that leads, or is likely to lead to a member of the public receiving a dose of radiation (HSE, 2002). The immediate response requires urgent protective action, known as countermeasures, to prevent exposure. Countermeasures include warning and informing, sheltering, evacuation and distribution of potassium iodate tablets (PITs). The spatiotemporal extents of the countermeasures are determined by the prior radiation emergency planning and any emerging scientific information, such as plume dispersal data.

Warning and informing countermeasures firstly provide information about the potential for radiation hazard to the local community before an incident occurs (CO, 2014). This information is usually in the form of a leaflet outlining what to do if a radiation emergency occurs, and local public will be made aware of radiation emergency training and exercises in the area, to improve familiarity with procedures (Maiello and Groves, 2006). Following the declaration of a radiation emergency, the nuclear installation will sound an emergency siren, which may be followed by an "All Clear" signal when the emergency is over. This siren is regularly tested to ensure that it is recognised by local people. Simple and accurate information is also broadcast through public warning systems and the media to warn the public to take emergency action. Some of this information is prepared beforehand by an emergency services consortium to ensure that there is no conflicting material, and the message is frequently repeated to ensure maximum public access. Commonly broadcast advice and guidance includes that to avert communication systems overload by not making phone calls, to not leave the area, and to take shelter.

Sheltering for radiation emergencies is the process of staying inside the home or any nearby building, closing all windows and doors, putting out fires and turning off air conditioning. For this scenario, children are held in school and adults would remain at work or education until the emergency has ceased (PCC, 2013). Sheltering protects from radioactive fallout, which is the aerosol particulate matter that sometimes occurs following a nuclear accident. Fallout is deposited during the first 24-48 hours of a nuclear emergency (Maiello and Groves, 2006). After this time, ventilation is important to decrease any radiation that has accumulated in the place of shelter. Potassium iodate tablets might be distributed during the first few hours of an emergency, to prevent uptake of radioactive iodine. Self-evacuation is not advised due to its impact on the roads, which creates traffic jams and otherwise obstructs emergency service access (Maiello and Groves, 2006). However, warning and informing to evacuate will occur if sheltering is not considered adequate for public protection.

In the event of nuclear emergency, emergency planning zones (EPZ) enable the emergency responder to have prior understanding of the potential spatial extent of a radiation hazard. EPZs establish areas across which specific actions are taken during emergency response (Maiello and Groves, 2006). EPZ for radiation hazards are designed to minimise radiation exposure, and are based upon prior scientific assessment of the potential contaminant extent, prevailing meteorological conditions and population density (Tweedie et al., 1986). EPZ include a minimum of four zones shown in Figure 21; an exclusion zone, an automatic countermeasures zone, a pre-planned countermeasures zone and an extendibility zone (ONR, 2012, HSE, 2002).

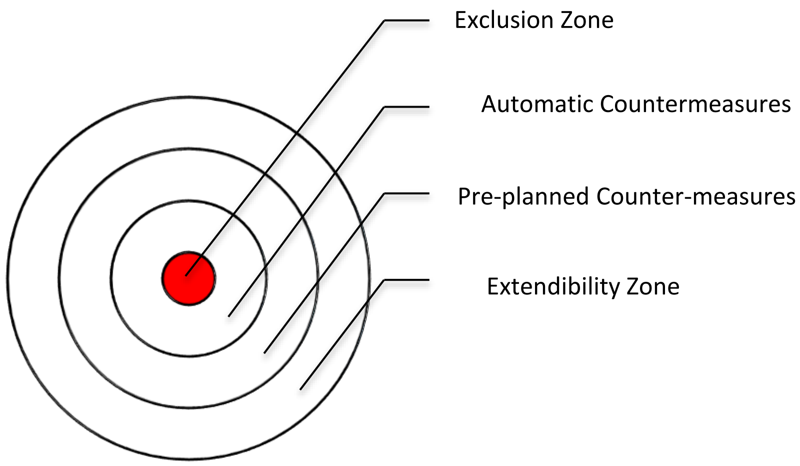


Figure 21: Generic emergency planning zones (EPZ) for radiation emergency planning (HSE, 2002).

The exclusion zone is the actual site of the nuclear installation and is subject to immediate evacuation on declaration of emergency. The automatic countermeasures zone is the proximate area where emergency procedures such as sheltering occur immediately. The pre-planned countermeasures zone is the second radius beyond the nuclear installation site, and has a detailed emergency plan in place, with specific actions to be taken if the incident is of sufficient severity. The extendibility zone has less detailed planning, and is the area for which less specific countermeasures are included as it is most unlikely to be affected (HSE, 2002). However, there is a need for more detailed planning to improve accuracy of emergency response during radiation emergencies (DECC, 2013).

Figure 22 shows an example of a more detailed EPZ map for AWE Plc, Aldermaston, Berkshire UK (WBC, 2011). The map is divided into multiple zones, and each zone has specific planning that is based upon resource availability and knowledge of the local population of that area. Improving EPZ resolution increases prior emergency planning work, but refines the capacity of the response during an emergency.

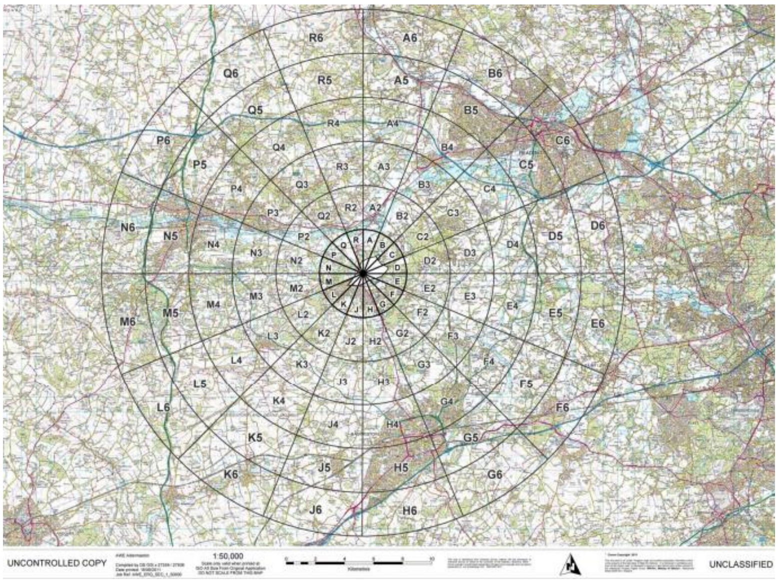


Figure 22: An emergency planning zone (EPZ) map of 3km radius for AWE Plc, Aldermaston, UK (WBC, 2011).

Nuclear installations that could pose a potential hazard to the public are often sited in rural locations with very low population density (Grimston et al., 2014). However, accidents of sufficient severity could impact nearby cities and towns, as the cases of Chernobyl and Fukushima demonstrate. Also, maritime nuclear installations are located out of necessity in close proximity to port cities of high population density. This proximity increases the risk of exposing population to a radiation hazard. The process of radiation emergency planning for nuclear submarines is based around the same principles as described above, but includes some installation-specific parameters. The next section briefly outlines some of the risks and emergency planning associated with nuclear submarines, before reviewing the Chazhma Bay nuclear submarine accident to contextualise the risk from this type of event.

3.3.3 **Nuclear Submarine Radiation Hazards and the Chazhma Bay Accident**

There have been thirty nuclear submarine accidents internationally since 2000 (Hodges and Sanders, 2014). Whilst most accidents have not resulted in a release of radionuclides, this figure is relatively high compared with other nuclear installations and therefore demonstrates the need for effective emergency planning for nuclear submarines.

It is possible that adverse circumstances could lead radiation or radioactive material being present outside the vessel due to release of fission products. Some plausible scenarios for nuclear submarine accident which have occurred in the past include leakage within the primary cooling circuit of the reactor, engineering failure, and fuel damage releasing radioactive material from the reactor and into the environment (Mahaffey, 2014). However, there is still the potential for unknown or unanticipated accident. The likelihood of an incident for an individual nuclear submarine that requires an off-site emergency response is a 1 in 50,000 years of continuous reactor operation event (SCC, 2013). During a nuclear submarine emergency, deposition is locally geographically concentrated downwind, with larger particles deposited close to accident site and smaller particles deposited over a wider area after the first 24 hours (SCC, 2013). Therefore, the first hours of the emergency require urgent protective action to prevent exposure, including sheltering, evacuation and distribution of potassium iodate tablets (PITs). Spatial and temporal extendibility of countermeasures is controlled by local plume dispersal data, which determine the level of intervention required. Emergency Reference Levels (ERLs) are used to indicate how much dose could potentially be averted by specific countermeasures (NRPB, 1990).

The Chazhma Bay Accident is a good example of a nuclear submarine accident that resulted in the exposure of a local population to a radiation hazard, and is therefore examined in more detail in this section. On August 10th, 1985 there was a significant radiation emergency involving a K-431 nuclear-powered submarine that was moored for repairs at Primor'e Dockyard, 1.5km from the town of Shkotovo-22 in Chazhma Cove, East Russia (Sivintsev et al., 1994).

The accident occurred whilst a faulty coolant valve seal was being repaired during refuelling (Takano et al., 2001). There was an explosion and a fire that took four hours to contain (Sivintsev et al., 1994). Approximately 2.6×10^{17}Bq of radioactive material was released across the cove, exposing the local environment, dockyard workers and the coastal population of Shkotovo-22 to isotopes of radioactive iodine, cobalt, tellurium, caesium and manganese (Sivintsev, 2000, Takano et al., 2001, Skaletskiy, 2013). The dockyard population was evacuated following the accident to minimise radiation exposure, and medical attention was provided to exposed populations over the following days (Sivintsev, 2003). A population of approximately 2,000 participated in clean-up after the accident, of which 290 individuals were exposed to high levels of radiation, forty nine exhibited symptoms of acute radiation syndrome, and ten people were killed as a consequence of radiation exposure (Sivintsev et al., 1994). Activity was resumed at the dockyard just four days after the incident (Sivintsev et al., 1994). The Chazhma Bay accident occurred due to system failure and human error, and the outcome of the emergency could have been improved by greater public transparency and emergency planning preparedness.

The next section examines another nuclear accident, Chernobyl. Whilst there is little long-term epidemiological information about the exposed residents and workers of Chazhma Bay, Chernobyl provides a more in-depth understanding of the consequences of radiation exposure, and insight into how understanding population distribution improves the planning process for radiation hazards.

3.3.4 **The Chernobyl Reactor Accident**

The Chernobyl Disaster occurred in Northern Ukraine on April 26th 1986 when Reactor Four exploded during engineering tests, causing a massive release of radionuclides into the atmosphere and environment. Fallout covered 150,000 km^2 of Europe with impacts upon Belarus, Ukraine and the Russian Federation (UNSCEAR, 2000). Figure 23 shows the extent of significant Caesium-137 exposure, where red regions experienced the highest levels, through to orange and green for lower levels of deposition (Moysich et al., 2002, Schmidt-Thomé and Kallio, 2006, UNSCEAR, 2008).

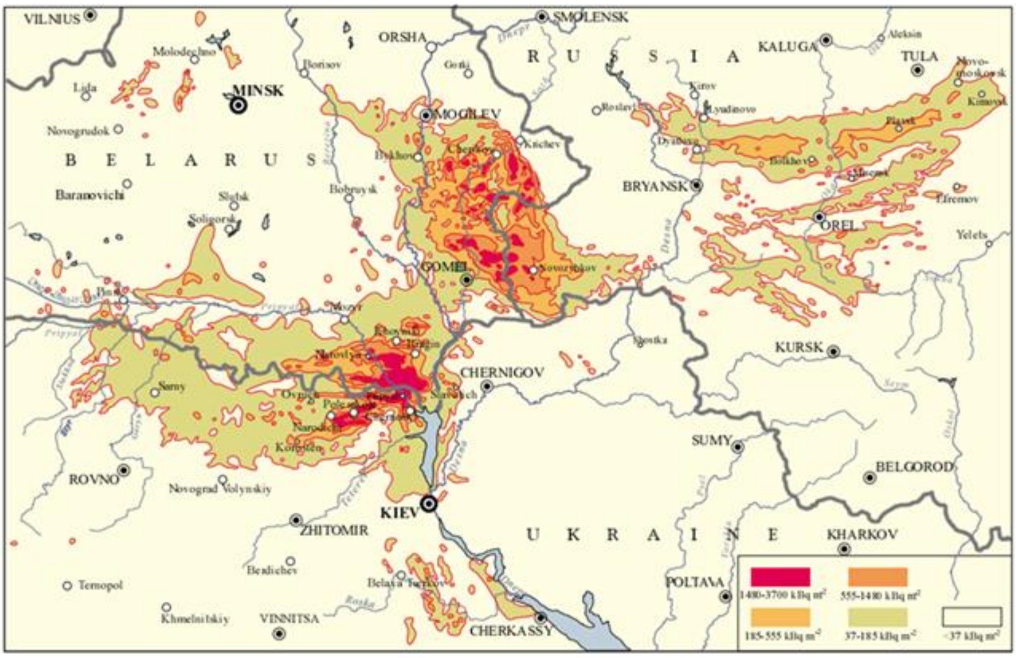


Figure 23: The extent of surface ground deposition of caesium-137 released during the Chernobyl accident (UNSCEAR, 2008).

There were forty-seven deaths from ARS, and further deterministic radiation injuries to 134 people in a few days to weeks of the accident (UNSCEAR, 2000). Average effective doses were 120 mSv for 530,000 registered recovery operation workers, 30 mSv for 115,000 evacuated persons, and 9 mSv to the general population (UNSCEAR, 2008). Stochastic health effects have included thyroid cancer, with approximately 6,000 cases in exposed children and adolescents. However, there is no demonstrable increase in the incidence of solid cancers or leukaemia (UNSCEAR, 2008). The psychological effects of Chernobyl are significant, with increased incidence of mental health problems presenting at two to four times higher in Chernobyl-exposed populations compared to controls (Havenaar et al., 2003, Bromet and Havenaar, 2007). It is estimated that there have been 9,000 deaths in total as a consequence of Chernobyl (UNSCEAR, 2000).

The accident required emergency evacuation of approximately 116,000 people from the nearby towns of Pripyat and Chernobyl, and the permanent relocation of about 220,000 people from nearby parts of Belarus, the Russian Federation and Ukraine (UNSCEAR, 2000). Whilst large-scale evacuation did occur within the first 24-48 hours of a radiation emergency being declared, there was limited warning and informing of immediate precautionary measures, leading to unnecessary population exposure (Island and Accidents, 2014). Additionally, evacuation of smaller rural settlements within the surrounding area was delayed. The accident had international implications but was not immediately declared beyond state boundaries, leading to exposure to the nearby nations of Belorussia and Russia (Island and Accidents, 2014). It is evident how important emergency planning and management for radiation incidents is, from the outcome of Chernobyl.

One of the ways that nuclear and radiation accidents such as Chernobyl and Chazhma Bay can be prepared for is by training and exercising. Training and exercising is the process of testing out potential hypothetical scenarios for an emergency response. For radiation emergencies this involves collaboration with all organisations who might be involved in the emergency response - including emergency services, health protection, environmental organisations and humanitarian groups – to devise and run a hypothetical scenario (HSE, 2002). Training and exercising is divided into table-top and live exercises. Live exercises are costly, time-consuming and require attendance of all relevant groups; whereas table-top exercises are less realistic, but enable emergency responders to consider and assess if strategies are effective. Improving understanding of where vulnerable populations and hazards are likely to be is an essential component of training and exercising, and the use of realistic models is becoming a relevant and useful component of this process by improving the responders' understanding of hazard requirements.

The next section describes approaches for modelling radiation dispersal and modelling populations at risk, for the purpose of understanding the impact of hazard upon vulnerable populations.

3.4 Modelling Radiation Dispersal

Atmospheric dispersion modelling is used to understand the spatiotemporal distribution and behaviour of a radiation hazard in the atmosphere. This type of modelling uses mathematical descriptions to characterise the atmospheric processes which disperse a contaminant (Stockie, 2011). Atmospheric dispersion models use information including meteorological conditions; radiation source term; and emissions parameters such as radiation source location, height and terrain to anticipate the speed and spatial extent of dispersion of a radiation hazard (Chang and Weng, 2013).

Sophisticated spatiotemporal atmospheric dispersion modelling packages already exist, and this thesis will use an existing model to generate maps of hazard. These packages use a combination of Gaussian plume and puff dispersion, and Lagrangian particle dispersion methods. Gaussian plume modelling shows the progression and dispersion of a plume, and uses wind speed; emission weight; speed; and standard deviation of the emission distribution in three dimensions to show the movement of a plume across snapshots of time. Lagrangian particle dispersal modelling estimates the release of a particle at a specific time and rate, and determines its new position in space and time on the basis of characteristics such as particle mass (Holmes and Morawska, 2006). The data requirements of a simple atmospheric radiation dispersion model are shown in

Figure 24.

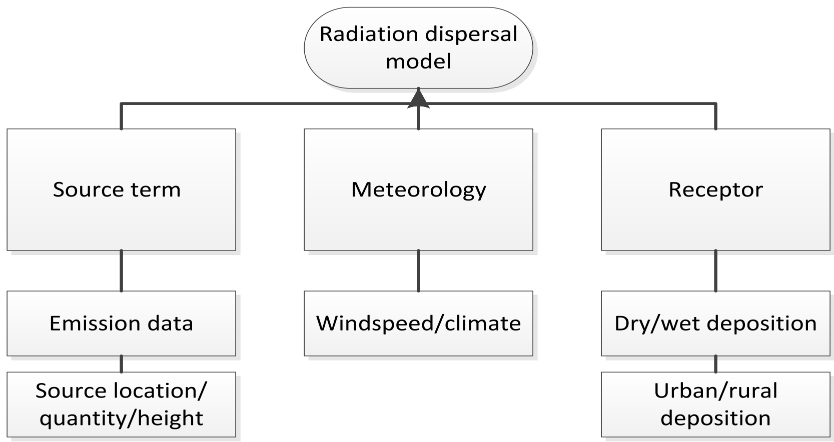


Figure 24: The data components of a model for atmospheric radiation dispersal.

HYSPLIT and NAME are examined as two modelling packages that have the capacity to show the spatiotemporal distribution of a radiation hazard. HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory Model) is a complete system for modelling complex dispersion and deposition simulations from short range to global scale. The dispersion of a pollutant is calculated by assuming either puff or particle dispersion. In the puff model, puffs expand until they exceed the size of a meteorological grid cell and split into several new puffs, each with a share of pollutant mass (NOAA, 2014). In the particle model, a fixed number of particles are advected about the model domain by the mean wind field, and spread by a turbulent component (NOAA, 2014). HYSPLIT has been successfully applied to accurately model emissions from both the Chernobyl and Fukushima accidents and nuclear testing plumes, and has the capacity to model estimates of wet deposition, dry deposition and plume depletion due to radioactive decay (Swanberg and Hoffert, 2001, Kinser, 2001, Moroz et al., 2010). HYSPLIT has also been shown to produce realistic results in comparison with similar packages (Connan et al., 2013).

NAME (Numerical Atmospheric Dispersal Modelling Environment) III is the UK Met Office's atmospheric dispersal model. It is a Lagrangian model that models from short range to global scale. NAME computes pollutant concentrations by Monte Carlo simulation techniques, and has the capacity to estimate wet deposition, dry deposition, plume depletion due to radioactive decay and downwash from buildings. It was originally developed in response to Chernobyl and has a proven track record of modelling radiation dispersal. NAME can offer a more sophisticated analysis of radiation dispersal than HYSPLIT by including half-life decay and cloud gamma radiation (MetOffice, 2014).

NAME has been closely coupled with other risk assessment models in the UK to better understand the effects of radiation exposure to agriculture, economy and society. However, these other models have previously only included residential population datasets which only show the effect upon a night-time population. Recently, NAME has been coupled with the Public Health England PACE (Probabilistic Accident Consequence Estimation) model (Charnock et al 2015). Section 4.3.1 explores the function of this model and its application to the thesis in greater detail, as part of the methodology chapter. The next section reviews the ways that population risk can be modelled for emergency planning.

3.5 Modelling Populations at Risk for Emergency Planning

Spatial models of hazard and population are important for emergency planning to explain and predict the relationships between significant phenomena, and therefore describe risk (Dobson et al., 2000, Hualou, 2011). Spatial data – including maps of transport networks and population – are essential for informing the emergency response and optimising the potential movement of people, goods and services during the emergency response (Dymon and Winter, 1993). However, traditional maps have been gradually superseded by geographic information systems (GIS) which can provide higher quality information about multiple phenomena. For instance, GIS could include demographic, shelter and hazard layers superimposed onto an urban layout (Cova, 1999, Rigina and Baklanov, 2002). The juxtaposition of information about hazard and vulnerability is known a risk map (Cova, 1999). Using GIS it is possible to add, multiply, scale, or weight information to create a composite analysis of risk that is tailored to the specific assessment of a particular hazard (Alexander, 2002, Rigina and Baklanov, 2002).

Figure 25 shows an example of the process for constructing a detailed spatiotemporal map of risk for a radiation hazard using a combination of population modelling, hazard modelling and GIS. The map includes a population model that assesses the distribution of populations in space and time, and a hazard model which assesses the spatiotemporal distribution of hazard. GIS is used to combine the output of the two models. This enables some anticipation of which populations are most vulnerable to hazard exposure, and improves understanding of how vulnerability can change over time.

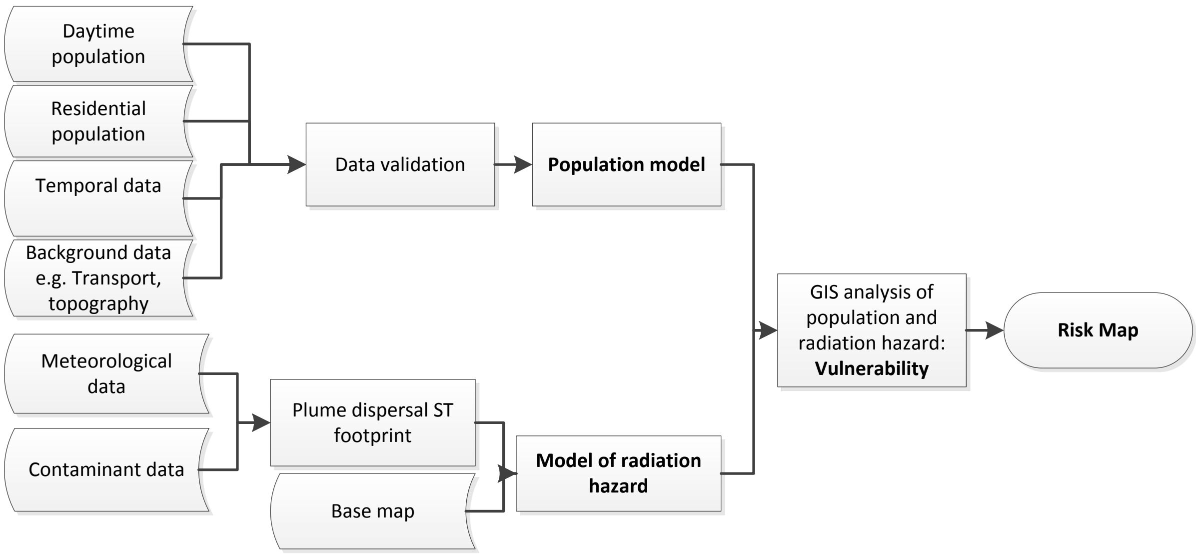


Figure 25: An example of the components of a spatiotemporal risk map for radiation hazard.

It is evident that a risk map of radiation hazard will provide the responder with useful information in the event of an emergency. Risk maps are improved by models that provide more information. For instance, combining risk maps with evacuation maps can help to discern if the spatial extents where risk actions are required have been accurately estimated.

However, most existing risk models are based upon residential or night-time population estimates. Population models have typically been produced from census, survey (Martin, 1992, Coppock and Rhind, 1991) or, increasingly, remotely sensed data (Deng and Wu, 2013), which are all associated with a specific reference time that is not reflective of the constantly changing cyclical population dynamic (Martin et al., 2015). Whilst good static GIS models of risk exist, there remains a need to be able to assess the whereabouts of populations at any specific time, to target resources to areas of high population density during an emergency. It is challenging to model daytime population fluctuation, and current approaches tend to model changes in population at highly aggregated levels (Cova, 1999). There is also a need for improved spatial resolution for the identification of more vulnerable population subgroups. The next section reviews modelling populations at risk. The modelling methods for the approaches described in this section have been previously explored in more depth in “Review One: Modelling Population Distribution in Space and Time”.

3.5.1 Approaches to Modelling Risk to Populations for Emergency Planning

This section reviews approaches that use methods described in Chapter 2, with hazard modelling and GIS, to model populations at risk for emergency planning and management. Spatial models of population for emergency planning exist, but are clearly limited due to representation of only residential population. However, spatiotemporal approaches can provide more insight into population distribution at the time of an emergency. One of the earliest models of population distribution for understanding populations at risk is a t-GIS database system that combines detailed demographic survey data and geospatial information into time-slices, to understand the proportion of a population engaged in specific activities during the daytime (Parrott and Stutz, 1991). This model is known as SANDAG, and was designed for San Diego, USA.

SANDAG identifies the different activities and locations of populations during the daytime, and standardises this information across eighteen cities in San Diego. The SANDAG methodology requires the collection of information about travel and daytime activities, including the number and type of trips and land use at origin and destination locations; vehicular categories; times at which trips were taken; and forty specific demographic and employment characteristics (Parrott and Stutz, 1991). A total of 753 traffic analysis zones were used to survey and construct SANDAG, where hour of day; day of week; and type of trip were recorded (Parrott and Stutz, 1991). This data was used to identify the best places to site emergency service provision for maximum population accessibility.

However, SANDAG’s data approach is only suitable for small-scale modelling because it is infeasible to conduct detailed population surveys on a larger scale. The SANDAG approach is also limited by not including regional commuter populations, and not accounting for population dynamic changes during large events. However, SANDAG offered considerable improvement upon existing models that did not include temporal information about population whereabouts.

Spatiotemporal population modelling approaches have since developed further, as a need has been identified to redistribute populations to more realistic locations where activities take place at specific times of day or week. Sleeter and Wood’s population model determines daytime population estimates by including grid referenced USA employee and education databases, such as parcel land-use codes and business coordinates, whilst using areal interpolation and a three-classification dasymetric approach (Sleeter and Wood, 2006). This model has been applied to tsunami hazard modelling in the Cascadia Subduction Zone. An example of the output of Sleeter and Wood's model is shown in Figure 26, where day and night population distribution for a tsunami inundation hazard is represented. This example shows that daytime populations are at greater risk of being exposed to a tsunami hazard as populations are considerably denser closer to the inundation line (shown in purple) during the daytime, especially to the north of the study site. The model also identifies increased tsunami inundation risk to a smaller area of population south of the study site at night time.

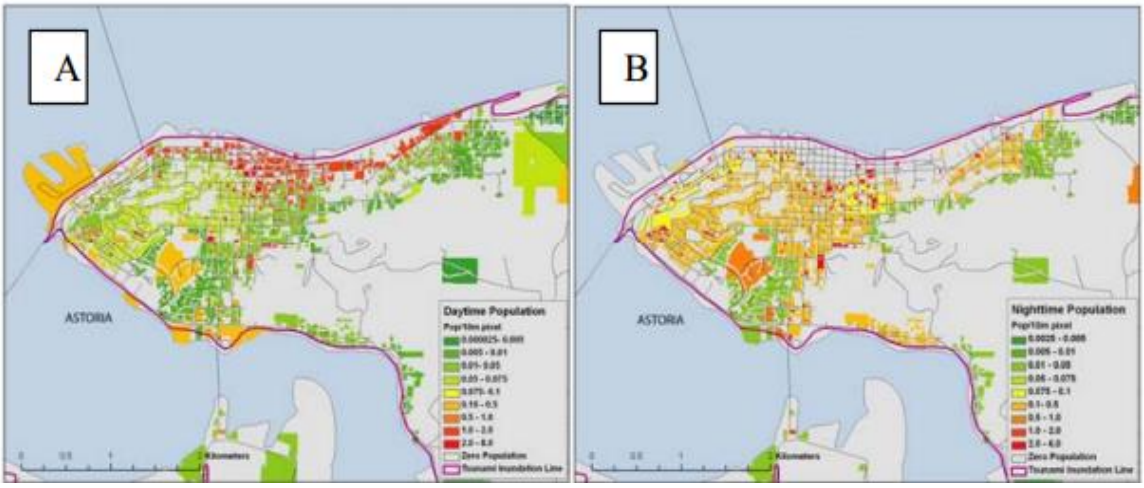


Figure 26: An example of the tsunami hazard model, where tsunami risk is represented by a purple line and the figures represent the following: a) daytime population concentration, b) night time population concentration p. 10 Sleeter and Wood (2006).

This knowledge can be used to improve emergency resource provision and targeting in anticipation of a tsunami inundation for areas identified as being of high risk. However, a method that preserves population volume across source to target zones is required. This approach is small scale, does not represent population distribution in the day time, and requires further refinement to transport layers (Sleeter and Wood, 2006).

McPherson et al. (2006) improve upon Sleeter and Wood's approach by modelling the daytime population from place of residence to place of work, using a grid approach and including redistribution to rasterised residential roads, to create a transport network for populations to flow from one region to another at census and tract county level (McPherson et al., 2006). The daytime model represents peak populations during the working week, and the night-time data model represents peak residential populations (McPherson et al., 2006). This model has been applied to emergency planning for chemical and biological incidents to plot exposed population during an event; their subsequent travel to home or work; and their eventual admittance to a hospital, by mapping the potential spatial distribution of hospital populations as points (McPherson et al., 2006). Figure 27 shows how population and plume hazard are used to anticipate an increase in hospital admittance.

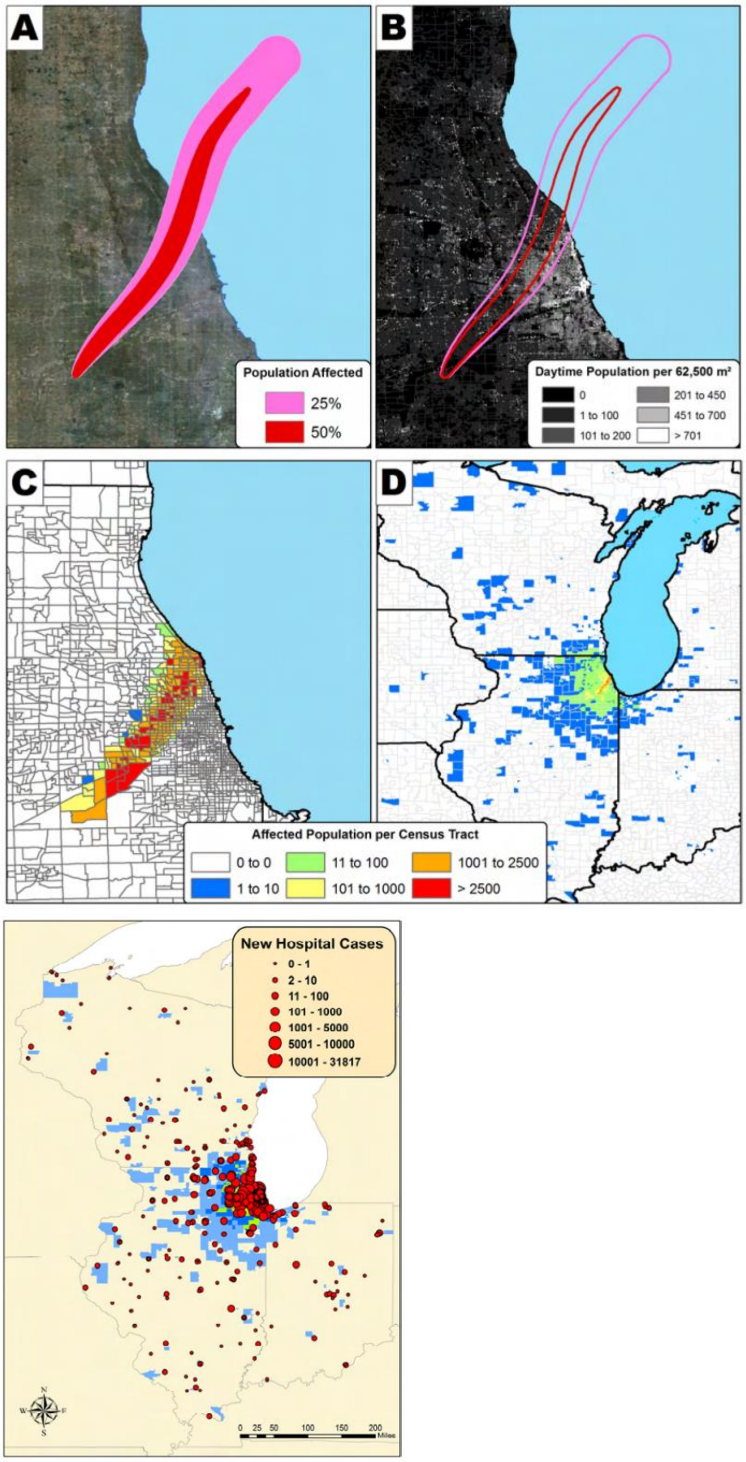
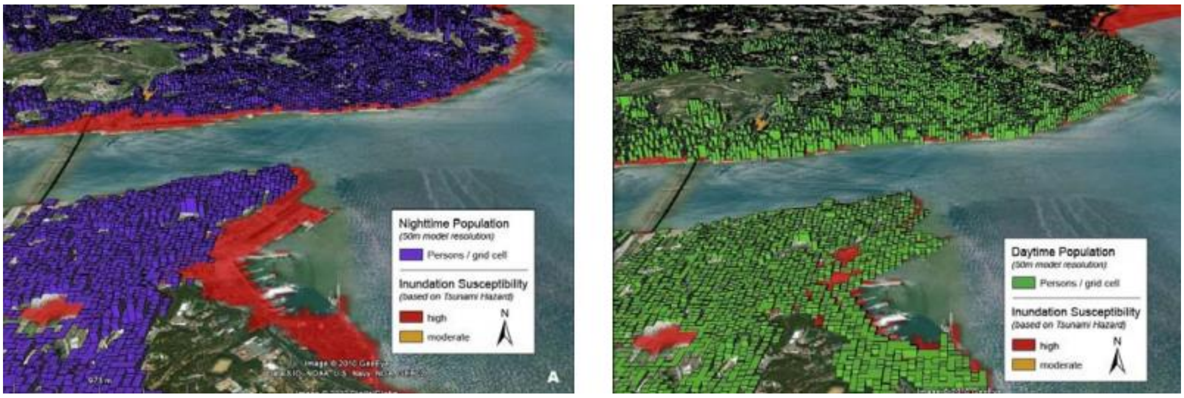


Figure 27: The population exchange model applied to a hypothetical release in the Chicago area, and subsequent anticipated hospital admissions in the area p. 4 (McPherson et al., 2006).

This model provides useful insights into how a chemical emergency could affect patient numbers and the need for emergency medical care in an emergency, which might also be applicable to radiation hazards. However, whilst the model could potentially anticipate where a population is after an emergency, it does not accurately represent hospital population distribution – nor evaluate travelling time to hospital and the impact upon existing service provision – by assessment of hospital capacity. In addition, the model cannot represent specific population subgroups.

The Finnish Fire and Rescue Services model combines population and damage analysis modelling to support long-term planning and decision making for local hazards (Ahola et al., 2007)**.** This approach is flexible and applies a moving kernel density estimation method for population estimation, overlaid with background data such as water areas and roads, to identify hotspots of population density at specific places during the day time or night time (Ahola et al., 2007). However, whilst the Helsinki model offers improved risk assessment it does not provide estimation of population density at a sufficient temporal resolution for emergency planning and management of nuclear emergencies, and cannot identify specific population subgroups.

Freire et al. model daytime and night-time population distribution and evacuation likelihood, for improvement of tsunami risk assessment in the Lisbon metropolitan area, Portugal (Freire et al., 2011). This is a dasymetric approach that uses street centre lines as spatial reference units, to reallocate population counts to residential areas by land use type (Freire, 2010).



a) b)

Figure 28: a) Night-time and b) daytime population density and tsunami inundation susceptibility zones (red), with population density represented in 3D p.3 Freire et al. (2011).

To improve assessment of human exposure and tsunami risk, both exposed population and daytime and night-time evacuation were modelled, and evacuation time was assessed by road network analysis for differences in day and night flow (Freire et al., 2011, Freire et al., 2012).

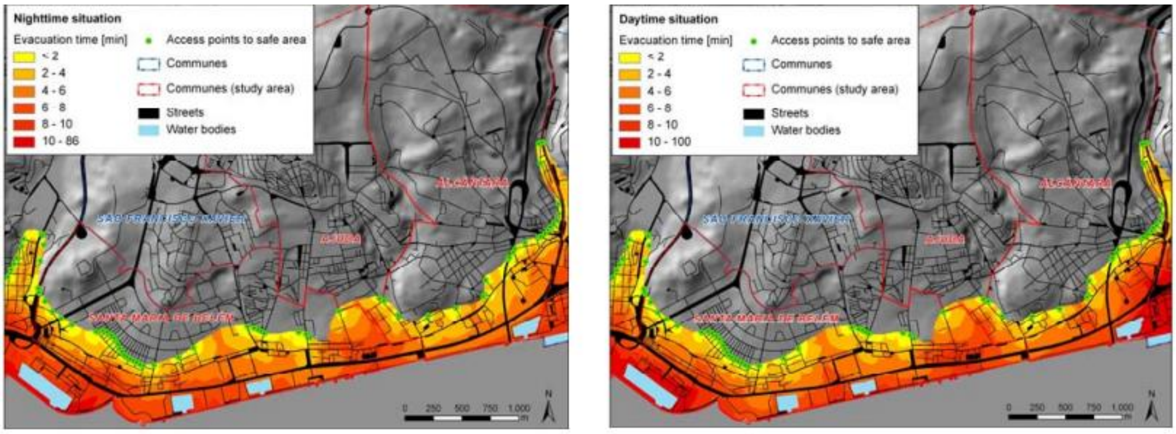


Figure 29: a) Night-time and b) daytime tsunami evacuation modelling p.5 (Freire et al., 2011).

The study also considered horizontal and vertical evacuation, and showed that by considering population density, hazard and evacuation strategy in the same system, it is possible to characterise vulnerability with greater detail. However, whilst the approach is highly detailed, it is not scalable or adaptable to specific population subgroups such as women.

The UK National Population Database (NPD) comprises of a building-level GIS database that includes description of population characteristics interpolated from small census zones and descriptive temporal attributes for spatial objects (Martin et al., 2015). It incorporates residential populations; sensitive and communal populations; retail populations; workplace populations; leisure facilities; and road transport into a multi-layered dasymetric GIS application to estimate populations at risk for Control of Major Accident Hazards (COMAH) and REPPIR planning (Smith and Fairburn, 2008). The database is currently updated and maintained by UK Health and Safety Laboratories (HSL). The NPD models Great Britain at 100m grid, or individual building basis resolution, to provide a regional-scale analysis. It uses a number of sources including maps, census, schools, hospitals, prisons, childcare, and transport data. Figure 30 shows NPD output for a hypothetical tanker accident with contaminant emission, where population at risk is estimated at different times of day. Chemical works, hospitals, schools, residential points and roads are all visible, and there is an estimate of residential and school population numbers under the contaminant plume.

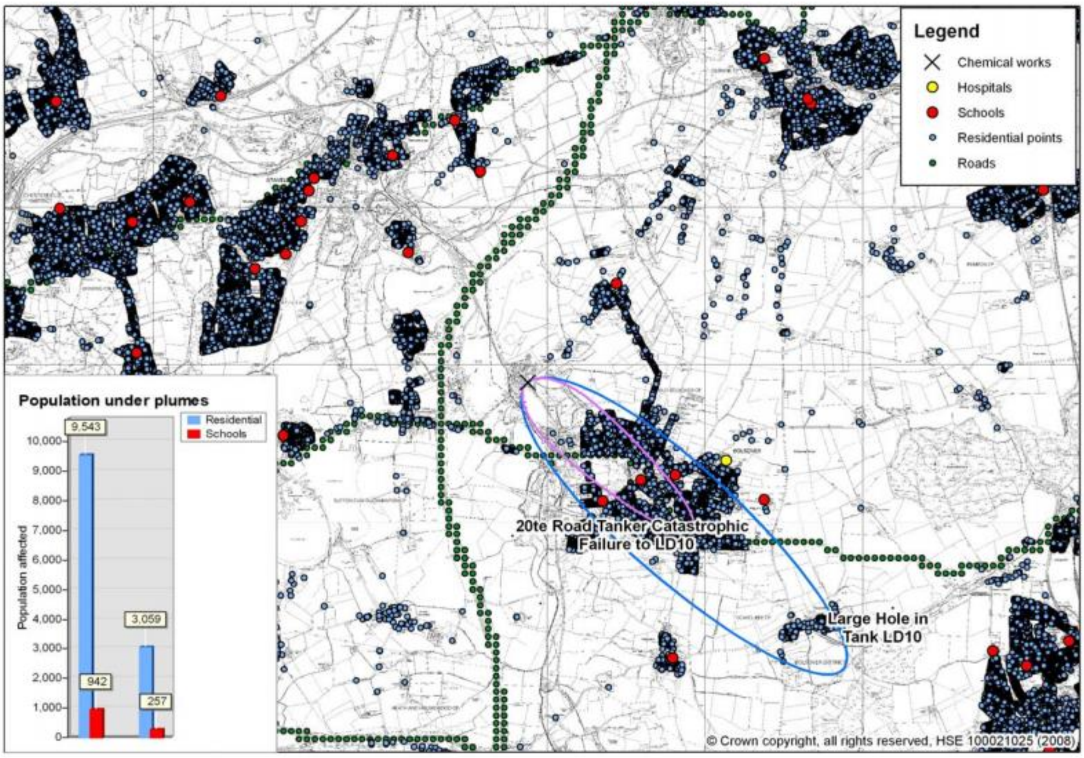


Figure 30: An example of NPD output for major hazard modelling of a fictional site (Smith and Fairburn, 2008).

Residential populations are mapped using OA level census data, and an integrated transport network (ITN) is applied to map transport networks. However, some layers in the model are more accurate than others due to the nature of the model, and there is no way to create a uniform level of scale. The models cannot preserve population volume over time or assess short term changes in population dynamic.

LandScan is a dasymetric population density model with a temporal profile, which has been used to estimate populations at risk in the USA and internationally (Bhaduri et al., 2007). The global model is intended for use in emergency response to natural disasters; chemical, biological, radiological and nuclear incidents (CBRN), humanitarian relief, populations affected by climate change, and protection of civilians during conflict (Dobson et al., 2000). The LandScan USA approach is of higher resolution and has successfully been applied to evacuation planning, relief delivery, and assessment of populations at risk of coastal flood hazards (Bhaduri et al., 2007, Crowell et al., 2013). LandScan has been combined with CBRN hazard prediction model HPAC to estimate anticipated population exposure to chemical, biological, radiological and nuclear hazards. HPAC consists of the SCIPUFF Gaussian puff model for assessment of inhalation dosage and surface deposition. LandScan is extensible and adaptable, and therefore shares some similarities with Population247. However, whilst estimation of exposed population is achieved by HPAC and LandScan, there is no distinction between population subgroup vulnerability or accurate assessment of population distribution following declaration of emergency (Hill, 2003, Nasstrom et al., 2007). However, whilst LandScan has adequate resolution for emergency planning and management in the USA, there is currently no generalised modelling framework and equivalent population model set out for assessment of risk in the UK.

Population247 is an adaptable, extensible, dasymetric and volume-preserving population density model with the capacity to model multiple subgroups and activities (Martin et al., 2009, Martin et al., 2010, Martin et al., 2015). It has been applied to improve understanding of population exposure to coastal and tidal flooding, and an example of typical outputs are shown in Figure 31 (Smith, 2013).

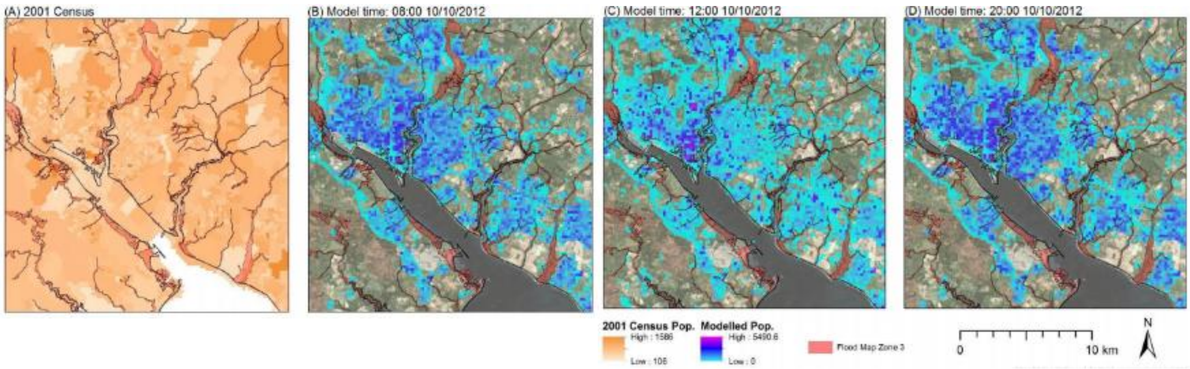


Figure 31: a) Census population; b) Population density and flood risk at 0800; c) 1200; d) 2000 p. 4 (Smith, 2013).

In Figure 31 it is clear that the population distribution changes significantly across the course of day. This study showed that populations are at greatest risk of fluvial flooding during evening and morning, and at greatest risk of exposure to tidal flooding during the day due to changes in population density over time (Smith, 2013). This offers significant improvements on existing methods' estimation of populations at risk of flooding in the UK. However, exposure to CBRN hazards has not yet been investigated with the Population247 approach, although there is much opportunity to understand the impact of hazard upon population health and emergency planning over time in this way. There is also a need to understand whether gender has an effect on population distribution.

To summarise, spatiotemporal population modelling has been applied to attempt to understand the risk to populations from diverse hazards including fire, tsunami, CBRN and flooding. The purpose of modelling is to improve emergency planning and management strategy by understanding the times and places where populations are most at risk. Technology for modelling populations has drastically improved over the last twenty years, including t-GIS databases constructed using survey data (Parrott and Stutz, 1991), dasymetric interpolation approaches that include remotely sensed data, and temporal profiles at high resolution to understand the changing implications of a hazard over time. The next section explores the application of agent-based modelling to risk and emergency planning.

3.6 Modelling Populations at Risk using Agent-Based Modelling

Whilst spatiotemporal population density modelling can accurately represent a normal population at a given time, it is not possible to describe dynamic and emergent population distribution with this type of model. However, agent-based modelling (ABM) can model dynamic changes, and represent population behaviour and locations, when objectives change during an emergency – for instance, from education and employment to sheltering or evacuation.

Emergency planning and management strategy has a significant effect upon the behaviour of populations during emergencies in the UK. Warning and informing enables emergency responders to transmit messages to the public via media including radio, television, automated text message and in person (Cacciapuoti et al., 2013). When justified warning and informing messages are received during emergencies, the majority of a population will acknowledge warnings and adapt their behaviour appropriately. There is a 'myth of panic' that is unaffected by population behaviour during serious emergencies, including the 9/11 terrorist attacks and the 7/7 bombings (Drury et al., 2013). Rather than panic, populations are more likely to adapt their social norms to fit the emergency situation and to behave in a cooperative and predictable manner. Therefore ABM is a suitable method for modelling populations at risk during any emergency, as predictable rules can be used to assess the impact and distribution of the majority of a population in a defined environment.

ABM and GIS have previously been used to investigate populations during emergencies. ABM has several advantages over solely equation-based methods due to an ability to capture emergent phenomena of risk and provide a natural description of a system that is otherwise very challenging to describe (Bonabeau, 2002, Dawson et al., 2011). ABM has been applied to understand populations at risk for hypothetical simulations for over twenty years (Bonabeau, 2002, Dorasamy et al., 2013). Applications for risk assessment and management include warning dissemination, evacuation routing, threat incident simulation, tsunami and flood risk, and generic crowd behaviour, making it well-suited for population modelling for nuclear emergencies (Crooks and Castle, 2012, Dawson et al., 2011, Keon et al., 2014). However, due to a need for accurate population data, ABM is often inconsistent or unrealistic. This section focuses on relevant applications of ABM for emergency planning and management.

The Great East Japan Earthquake and Tsunami ABM is a simple modelling system that demonstrates the power of the approach for improving understanding of risk (Mas et al., 2012).

This model combines tsunami inundation with evacuation to estimate casualties. It was developed in Netlogo, with GIS providing spatial input for road and shelter locations. The model applied residential population data for the Arahama area, including “revealed preference” and “stated preference” location surveys, and compared this information with a Rayleigh distribution for regional evacuation (Mas et al., 2012). The output identified areas of increased risk due to bottlenecks. The simulation estimates the number of evacuees sheltered and the number of evacuees who have successfully retreated to safer locations. However, whilst the underlying principles of the model are effective, there is a lack of daytime population data on a seasonal basis. Therefore, whilst population processes are accurate, population distribution and count are not.

Despite this, daytime population distribution has been considered for an ABM for assessment of flood risk to a population in Towyn, UK. For this model, remotely-sensed topographic data, road network information and hydrodynamic modelling are combined with population and survey data to create a simulation that estimates the vulnerability of individuals to flooding under different storm surge conditions (Dawson et al., 2011). The model provides insights into population vulnerability over time by estimating how population distribution will change during a flood emergency.

The agents in the Towyn model are relocated by transport data, which includes sample diaries of travel patterns; and a proportional number of journeys during the day by purpose, gender, household size, and age and employment status. The model attempts to overcome the aggregate nature of census data by randomly distributing individuals to residential properties in the case study domain according to age, gender and employment (Dawson et al., 2011). Whilst the usual population spatiotemporal distribution is likely to be inaccurate for this model, it does consider how agents might behave both in normal conditions and in response to an emergency.

The model assigns probabilities that the different agent sets – characterised by gender, age, employment and household size – will perform certain routines. An agent may begin a day at 8am, travel to drop children at school, continue to work, and so on. The routine is interrupted when the agent becomes aware of a flood incident, and depending on the time of day the agent may be in one of a variety of different places with different probabilities for evacuation. This is combined with a network model for vehicle movement, which accurately represents the topological connectivity of the transport network. Traffic movement along the road network is simulated using the Nagel and Schreckenberg (N–S) cellular automata pulse model to represent spontaneous jams and the relationship between traffic flow rates and density (Dawson et al., 2011). The model output is shown in Figure 32.

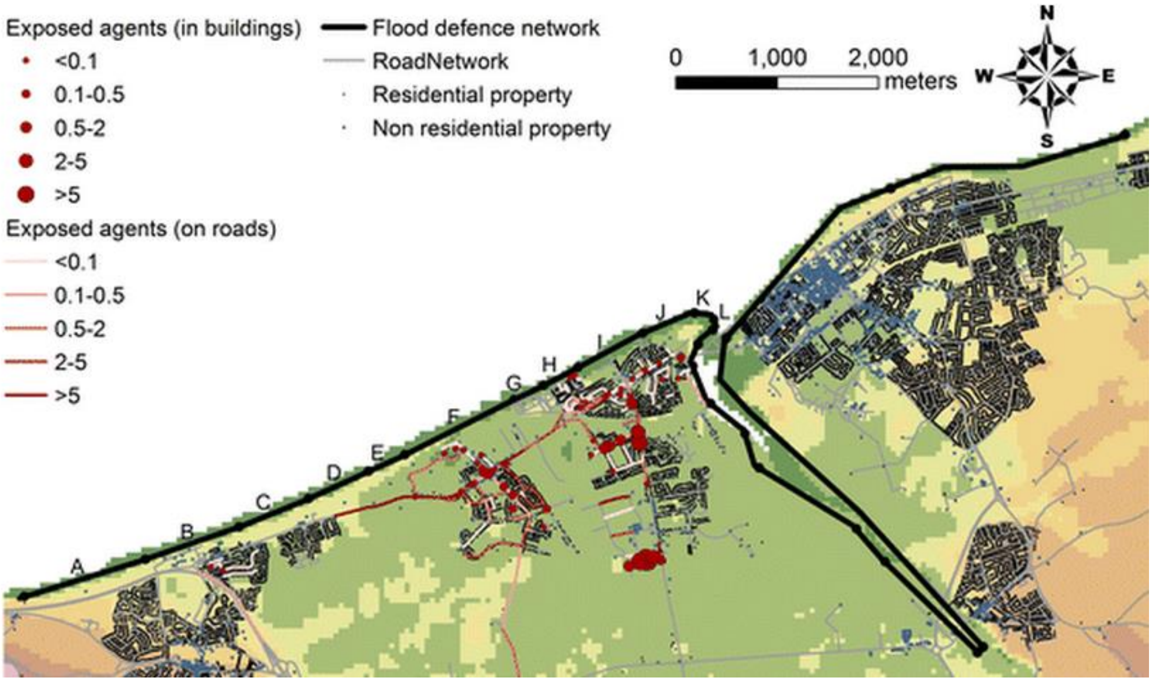


Figure 32: Location of exposed populations during flood defence failure p. 16 Dawson et al. (2011)

In Figure 32, agents that may be exposed to flood risk are identified in buildings and on roads. This model offers improvements upon the Great East Japan Earthquake and Tsunami model described previously (Mas et al., 2012). Whilst it does not accurately represent population distribution, the principles behind this ABM are adaptable and relevant to this thesis. A more accurate prediction of population distribution could be made by seeding an ABM such as this with accurate spatiotemporal population data, such as that generated by Population247.

A study that builds further upon this approach is an ABM of earthquake evacuation for Tehran, Iran (Hashemi and Alesheikh, 2013). This model assesses population before and during an emergency. It contains a GIS of environmental features to map streets, building, and traffic infrastructure; five mobile agent types, specifically citizen, paramedic, traffic control, police and criminal; a stationary agent in the form of gas mains; and five inactive environmental agents with GIS in the form of buildings, street, shelter, hospital and fire station. The algorithm for agent interaction is shown in Figure 33**.** This reveals a simple approach, where behaviours are determined by common stereotypes and are not influenced by the initial population parameters.

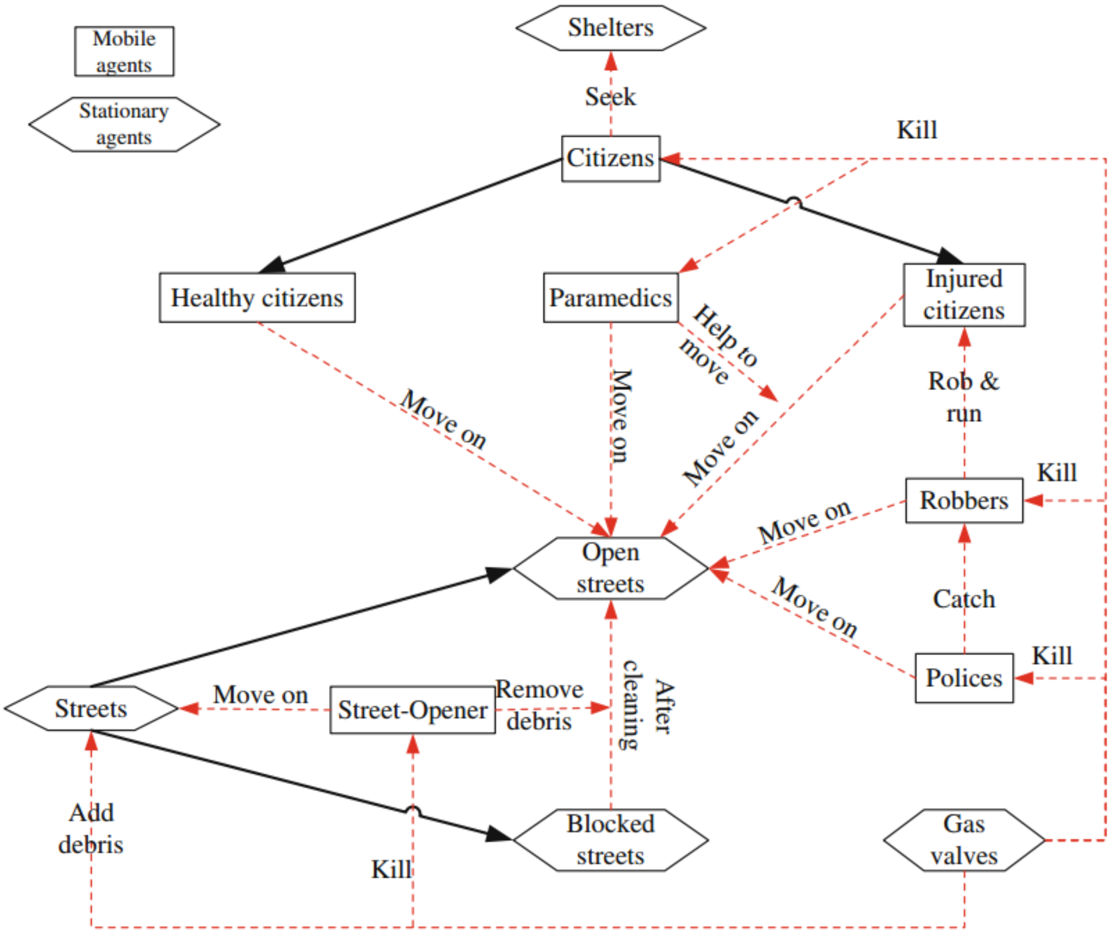


Figure 33: Algorithm for an agent-based model of population behaviour during an earthquake in Tehran p. 1904 (Hashemi and Alesheikh, 2013).

The inactive environmental agents and the algorithm for population behaviour are very relevant to this thesis; the change in population movement from normal distribution for that time to environmental features including hospitals, shelters or evacuation, is a crucial component.

This approach has been advanced by an ABM with GIS to study the populations of people affected by an event, and to assess their needs based on damage to buildings for the 2010 Haiti Earthquake (Crooks and Wise, 2013). The model consists of a GIS that includes hazard, a synthetic population distribution, an evacuation decision module and a pre-evacuation activity module, which is very relevant to this thesis due to interest in the change in population dynamic from the start of declaration of an emergency. The model investigates both organised and shadow evacuation. This model uses a combination of crowd-sourced geographic information and other publically sourced data to assess likelihood of evacuation. The model is based on the principle that evacuation demand is comprised of both evacuation trips and trips derived from pre-evacuation activities, which can span several hours or days and can generate local traffic. Another interesting feature of this model is the economic classification of population decisions based upon estimated household income; determining likelihood to evacuate to a public shelter or a hotel;

and making households with a lower income more likely to evacuate to a local destination or use public sheltering (Crooks and Wise, 2013).

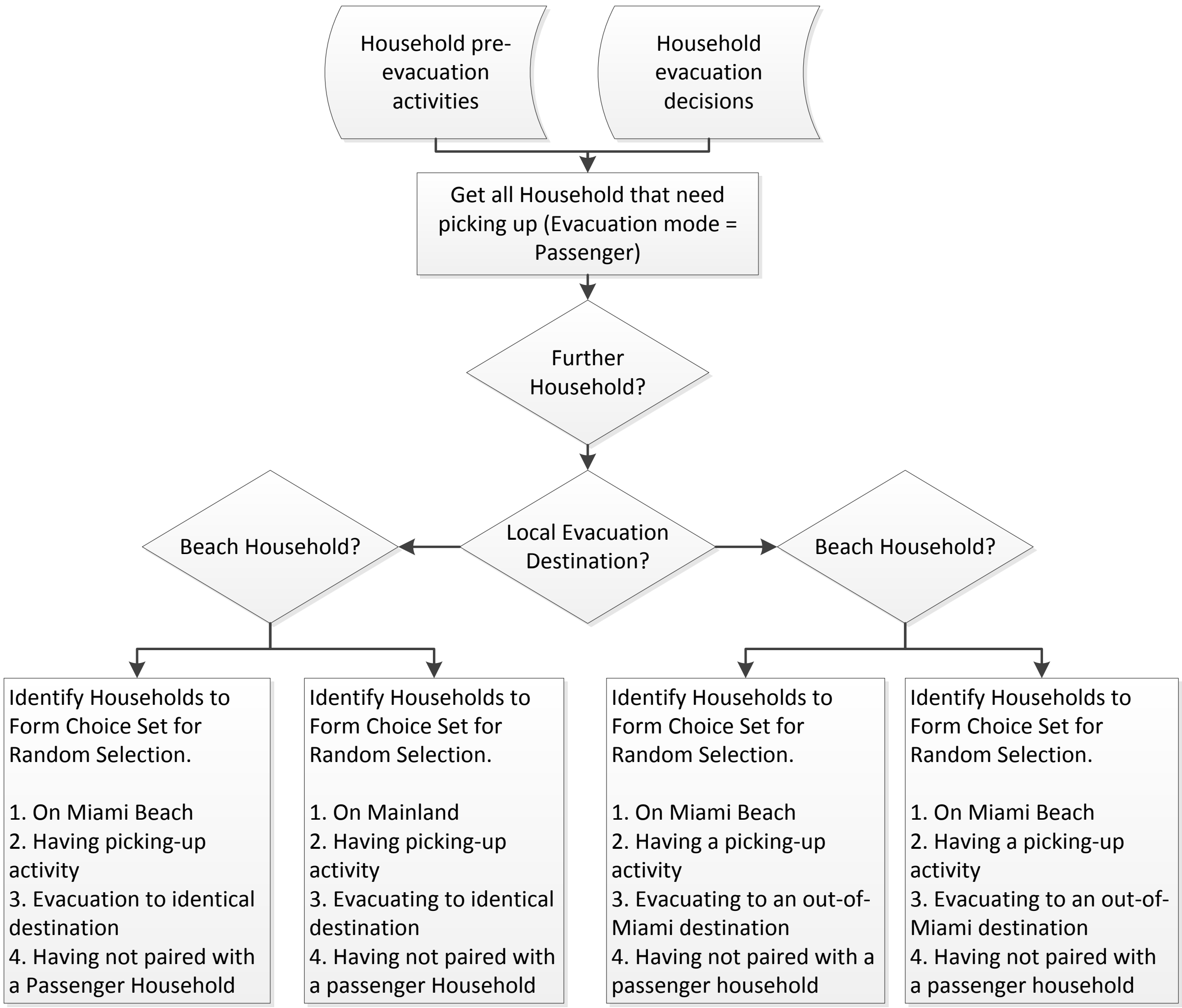


Figure 34: A section of the decision-making algorithm for likelihood of evacuation of households in Haiti p. 49 (Crooks and Wise, 2013)

Figure 34 shows a relevant component of the evacuation algorithm, which takes into account pre evacuation activities and household evacuation decisions, dependent upon location. For validation, the model output was compared for simulated and reported departure time curves. There was found to be a strong correlation between actual reported evacuation activity and simulated evacuation activity, as shown in Figure 35, which goes a long way towards the validation of this model.

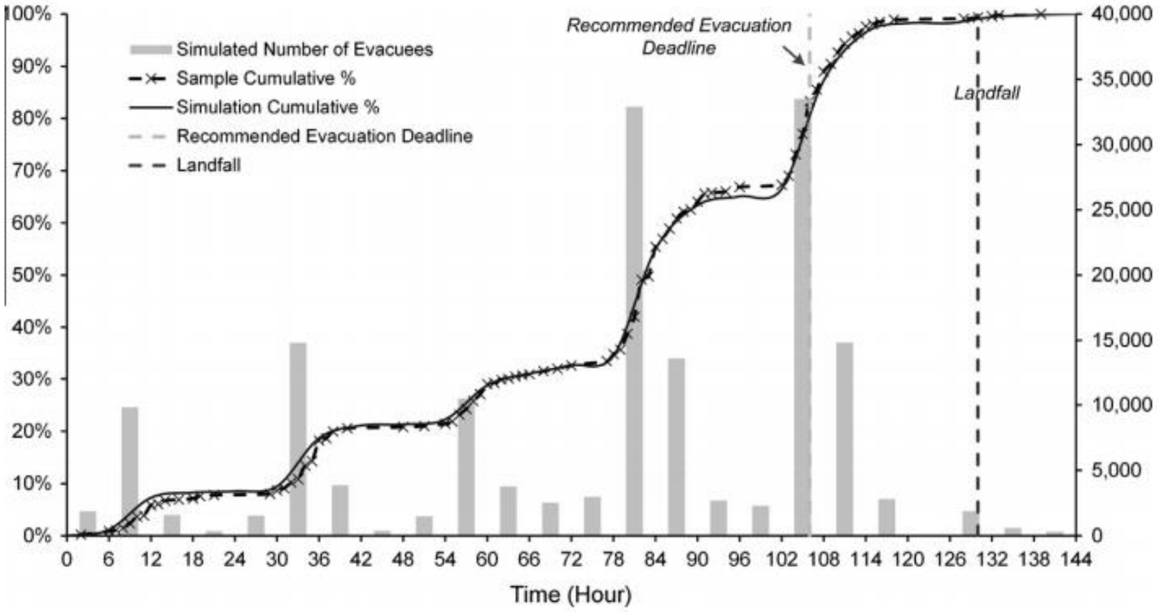


Figure 35: A comparison between simulated and reported departure time curves p. 56 (Crooks and Wise, 2013).

The approach used for this model is very relevant to this thesis, as it accurately depicts evacuation for a specific geographical place using ABM and GIS. However, whilst this model bridges the gap for transport activity prior to and during emergency, there is also a need to understand the entire population demographic before and during an emergency. Also, evacuation warnings are issued prior to hurricanes, due to advanced meteorological understanding of the hazard changing the dimensions of evacuation. Finally, because the model uses a synthetic population distribution for the households, it does not accurately reflect the population distribution at that time.

Population risk of exposure to radiation hazard have been explored by an ABM that investigates human behaviour in the aftermath of a hypothetical nuclear detonation in Washington DC, USA (Parikh et al., 2013). The model describes the interaction of the population with interdependent infrastructures, to understand how response could change incident outcome. Human behaviour interacts with infrastructure in feedback loops, show in Figure 36.

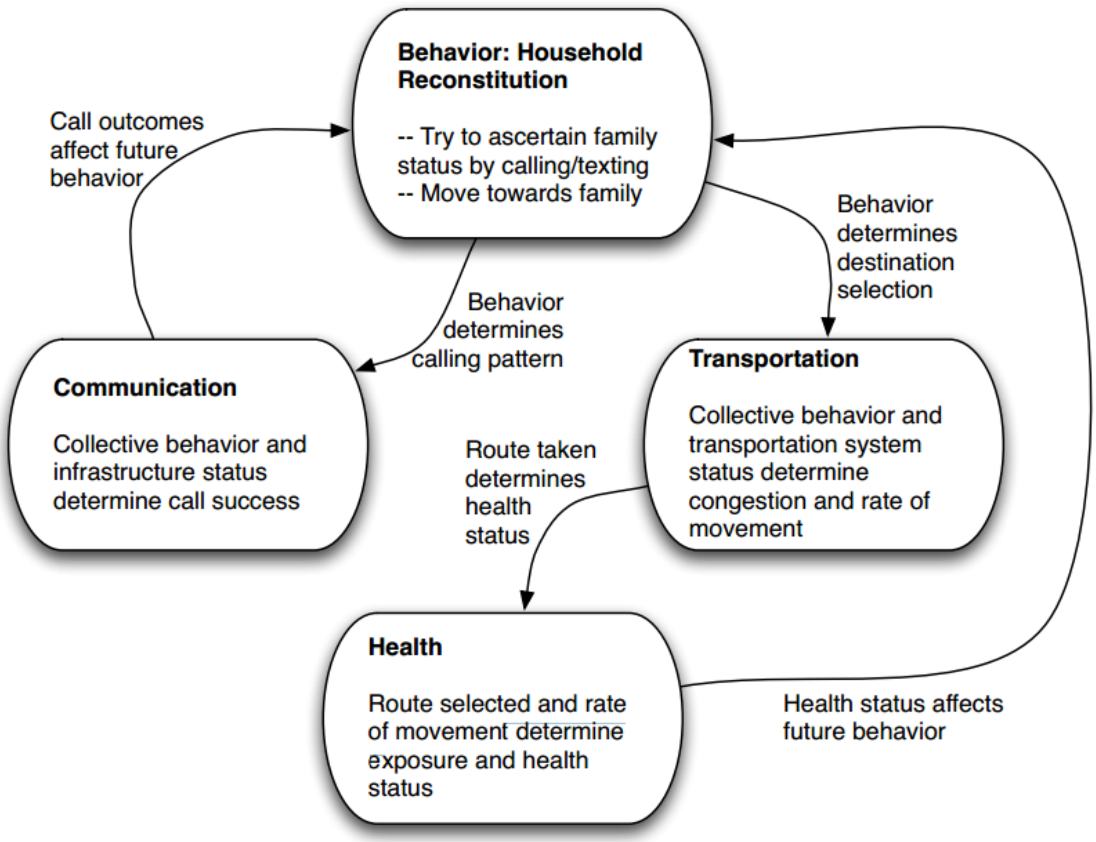


Figure 36: Anticipated human behaviour interactions and feedback for a nuclear incident p. 949 Parikh et al. (2013).

The model developed by Parikh et al. uses a synthetic population of the Washington DC metro area and is assumed to affect all people present at the time of the event, including residents, tourists, business travellers and college students. Their health and behaviour in the aftermath are dependent upon where they are located when the event occurs, so the model includes synthetic data about demographics and routine (Parikh et al., 2013). The model assesses the co-evolution of individual and collective behaviour and interaction with damaged infrastructure, to study short term secondary and tertiary effects (NDSSL, 2014). The model uses synthetic data and visit counts, and agents conduct follow-the-leader behaviour; where agents encounter known individuals, grouping occurs. The behaviour model is based upon a semi-Markovian decision process, which is a probabilistic algorithm that provides six options: household reconstitution, evacuation, shelter seeking, healthcare seeking, panic, and aid and assist (Parikh et al., 2013). Whilst household reconstitution is not relevant to a collective behavioural model, the other five options are relevant as they will affect population movement.

Parikh et al. (2013) also consider how the health of the population will affect behaviours such as mobility and influence time needed for healthcare, using a continuum of agent states from 0 (death) to 7 (full health). The variance in behaviour highlighted initial differences in strategies amongst a population. However, differences become less apparent with increasing numbers of iterations, showing that difference in behaviour is less significant with greater populations.

The model analysis revealed some of the complex interactions between behaviour and infrastructure, where increased movement for attempted evacuation and shelter resulted in the adverse effect of increased exposure and injury (Parikh et al., 2013). The authors note that while the model offers improvements on static models such as LandScan, it does not use real population data, consider optimal deployment of emergency services, or consider how the six different behaviours are demographically affected by features such as gender, age and socioeconomic status.

ABM practice and application to emergency planning and management is diverse, and there is still scope for development. An approach that includes an accurate spatiotemporal estimate at the time of the hypothetical incident, will provide significant improvements upon existing models.

The selection of approaches explored has shown ABM's adaptability to different risk scenarios featuring populations at risk of earthquake, tsunami, flooding and nuclear threats. However, there has been little investigation of technological accident hazard using ABM, and an ABM for radiation accident hazard risk currently does not exist for the specific conditions of the UK. The need for better quality population data before an incident is consistently evident. Whilst the Towyn, UK model has a good structure for a simple evacuation, population data is not adequately sophisticated (Dawson et al., 2011). However, some interesting and diverse sources of information have been applied to model ABM recently (Crooks and Wise, 2013). However, synthetic population distributions are not accurate, and crowd-sourced data only represents a small proportion of a population, which is not necessarily representative of the behaviours of more vulnerable population groups and is only available after an emergency, whereas there is a need to model the anticipated behaviour during the event. The use of a pre-evacuation activity and evacuation decision module provides great insights into the change in population dynamic, and is very relevant to the RADPOP approach that is proposed in this thesis. Another relevant approach is the modelling environment for nuclear threats, which evaluates likelihood of different behaviours during an unanticipated nuclear detonation (Parikh et al., 2013). Whilst behaviour is more conformist and less panicked during nuclear accidents, this is potentially the best approach to take.

3.7 Chapter Conclusions

This section of this thesis has reviewed how disaster, risk and vulnerability impact upon specific population subgroups, then focused upon vulnerability to harm as a consequence of exposure to ionising radiation. The health effects and treatment methods for exposure to ionising radiation have been thoroughly examined, and the process of emergency planning and management for generic and nuclear-specific hazards have been explored. The ways that technologies are used to improve emergency preparedness have also been investigated, with focus upon spatiotemporal models of population, hazard and risk. The next chapter applies the techniques and concepts that have been investigated to create a new methodology for the identification of vulnerable population subgroups in nuclear emergency planning. Whilst a number of population modelling approaches exist, Population247 is a promising and attractive method to employ, as it is volume-preserving; has the greatest flexibility for inclusion of different population subgroup data; offers temporal stability through maintaining the same gridded structure across time; and the output has successfully been combined with hazard modelling in the past. Prior agent-based modelling has been combined with spatiotemporal population modelling to reflect short-term changes in normal population behaviour.

The aim of the next chapter is to describe the methodology required to model a realistic hypothetical case-study of spatiotemporal population subgroup and hazard distribution during a nuclear emergency. The methodology will combine gender-split spatiotemporal population modelling with radiation hazard modelling and agent-based modelling to understand the implications of nuclear emergency management upon radiation exposure. This will be investigated by modelling the spatiotemporal profiles of females across six age groups for nuclear emergency planning. This is also the first time Population247 has been combined with contaminant plume modelling for estimation of radiation hazard distribution and concentration.

Chapter 4: Methodology

4.1 Introduction

The work presented in this chapter provides an overview of the methods used in the RADPOP approach for modelling a realistic hypothetical radiation emergency scenario, introduced in Chapter 1. RADPOP is a modelling system constructed of multiple model components, which represents daily population density demographics, and spatiotemporal radiation exposure to specific population subgroups. The aim of the modelling system is to improve assessment of the likelihood and health effects of radiation exposure to humans during a radiation accident, and to offer insights into how unusual changes in population distribution following declaration of emergency can result in differences in accident outcome. The thesis case studies in Chapters 5 and 6 are focused upon the City of Exeter, UK; therefore, it is necessary to reference some geographically relevant data in the Methodology. The reasons for selecting Exeter and its demographic characteristics are described in Section 5.2.2 of Case Study I. The RADPOP modelling approach comprises three separate components referred to as A, B and C. Figure 37 shows how the different modelling components are combined, in the RADPOP system.

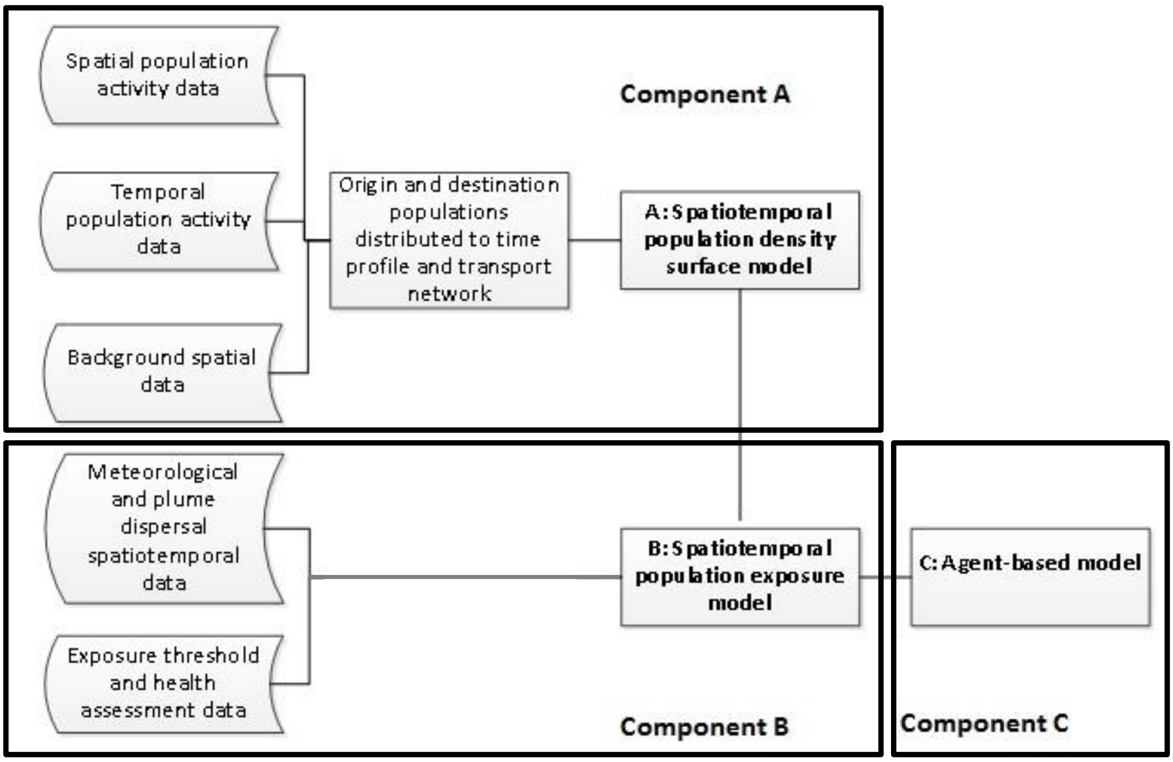


Figure 37: The RADPOP approach for assessment of spatiotemporal population subgroup exposure and radiation health effects.

Component A is a spatiotemporal population density surface model, which is used to identify where different population subgroups are in space and time (Martin et al., 2015). For the purpose of RADPOP, this model applies 2011 UK census and non-census data, and is used to represent the cyclical variations in the distribution of different population subgroups at the start of a radiation emergency.

Component B applies a numerical atmospheric modelling environment and probabilistic consequence analysis, to understand the likelihood of radiation exposure and its impacts, on the population output produced from Component A. The numerical atmospheric modelling environment applies contemporary or archived meteorological data, to predict the trajectory and distribution of a radiation hazard. Probabilistic consequence analysis is used to understand the short-term and long-term effects of hazard exposure upon the population, including fatality and cancer incidence analysis. Consequence analysis is also implemented to understand how exposure reduction due to countermeasures implementation can improve the outcome of a hypothetical emergency.

Component C is an agent-based modelling approach which provides insight into the atypical population distributions that occur when cyclical distributions are disrupted, as populations comply with countermeasures instructions to shelter or evacuate. The agent-based model treats each spatiotemporal population density grid cell as an individual agent, and instigates rules for shelter-seeking or evacuation, dependent upon the demographic present and the extent of the hypothetical scenario.

This chapter therefore provides a more detailed methodology for components A, B and C, and explains the data and processes required for each stage of the RADPOP approach.

4.2 Component A: Modelling Populations in Space and Time

One aspect of spatiotemporal population density modelling is to address the need to understand where different population subgroups are on a daily basis. Population247 has already been identified as a promising population modelling framework in Section 2.4.2 due to its adaptability, extensibility and scalability (Martin et al., 2009, Martin et al., 2015). The core modelling framework for Population247 is presented in Martin et al. (2015), and this thesis focuses upon its specific implementation for the RADPOP modelling framework, rather than reproducing the existing paper. Therefore, the model is applied to understand the whereabouts of different population subgroups at the start of a hypothetical emergency.

Population247 redistributes appropriate proportions of a residential origin population count spatiotemporally to different daily activity destinations such as schools, hospitals and workplaces. The modelling framework is illustrated by Figure 38. In the original implementation of Population247, populations are divided into different age subgroups to represent the demographic variability of different destination activities (Martin et al., 2015). Both origin and destination population counts are spatially referenced to centroids, which are grid-referenced locations of known population counts. Origin populations are redistributed to meet population demand at each destination, according to spatial catchment area and activity time profile information associated with the destinations. A proportion of the count is redistributed across a background layer reflecting the transport network, again informed by the activity time profile. The remainder is reallocated into the immediate locality of the origin centroid, reflecting population that remains in residential areas. The background layer acts as a dasymetric mask, preventing relocation to infeasible locations such as water bodies.

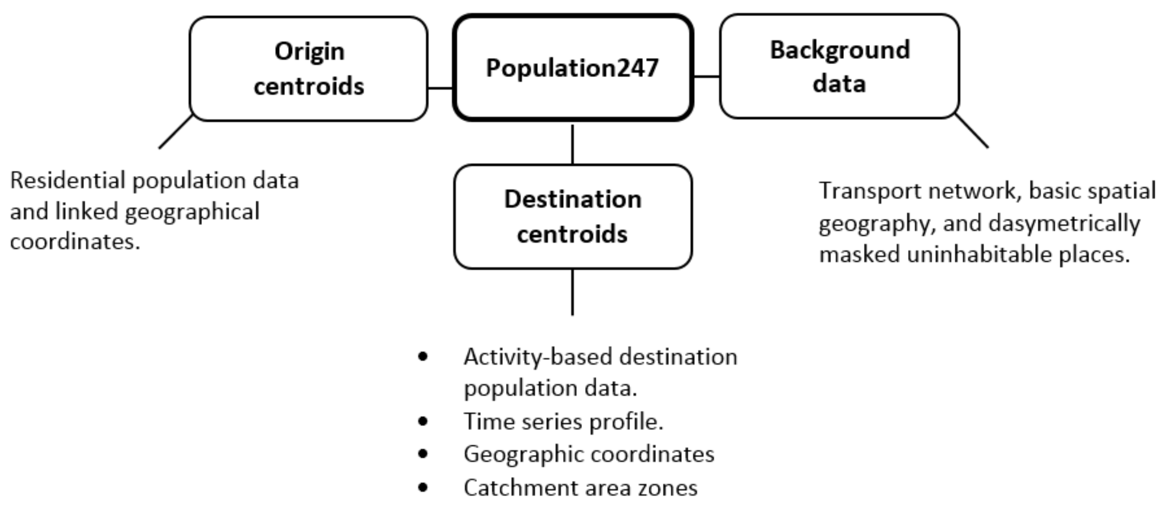


Figure 38: The Population247 framework, adapted from (Martin et al., 2015)

The original implementation of Population247 used 2001 Census and other source data, to represent a spatiotemporal population distribution across seven age subgroups for residential, workplace, education and healthcare activities (Martin et al., 2010) to a reference year of 2006. A novel contribution of this thesis is the application of 2011 spatiotemporal residential, healthcare, education and workplace data to the existing modelling framework. Retail and tourism destinations are included to provide greater breadth and realism of activity (Smith 2015). An additional significant innovation of this thesis is the introduction of male and female population subgroups to Population247, to explore whether gendered differences in daily activity participation can affect vulnerability.

It is helpful to elaborate further upon the relationship between destination centroids and time profile data. For example, a destination centroid for a primary school would accept relevant age subgroups across a relatively small spatial catchment radius and a time profile that reflects the length of the school day. However, a destination centroid for an accident and emergency facility would have a different age subgroup range, a twenty-four hour time profile, and a much larger catchment radius; as hospitals provide for a smaller proportion of the population at any one time, but across a wider spatial area. If suitable data are available, the catchment radius for specific destinations can be subdivided to reflect the different distances that different proportions of a population will travel. Figure 39 shows a hypothetical example of a catchment radius. For this example, 90% of the population travel up to 500m, 5% of the population travel between 500-1000m, and 5% of the population travel between 1000-1500m to reach their destination.

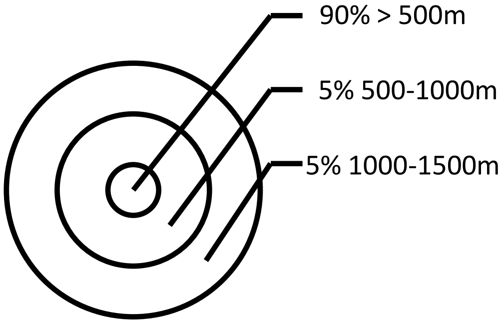


Figure 39: A hypothetical example of a variable catchment radius for a destination centroid, where each percentage represents the proportion of the population travelling to a destination for a specific distance (not to scale). Should there be insufficient population at origins in the catchment radius to meet demand at a destination centroid, further population is sought by expanding the catchment to accept more distant populations.

Population247 includes on-site and in-transit time profiles, which enable the proportion of the origin population associated with a destination centroid to be split between the relevant sites and the surrounding transport network, to reflect the distribution of both the on-site and in-transit population. Figure 40 shows the in-transit and on-site time profiles for populations to be allocated to a university destination centroid (DFT, 2011). In this example, the on-site population gradually increases from 0745 before plateauing at 1130 and then declining from 1600, until the on-site population is zero at 2200. The in-transit population is represented by a number of smaller peaks across the academic day, as the student population travels to and from university to, for example, attend lectures, student activities and to use the library.

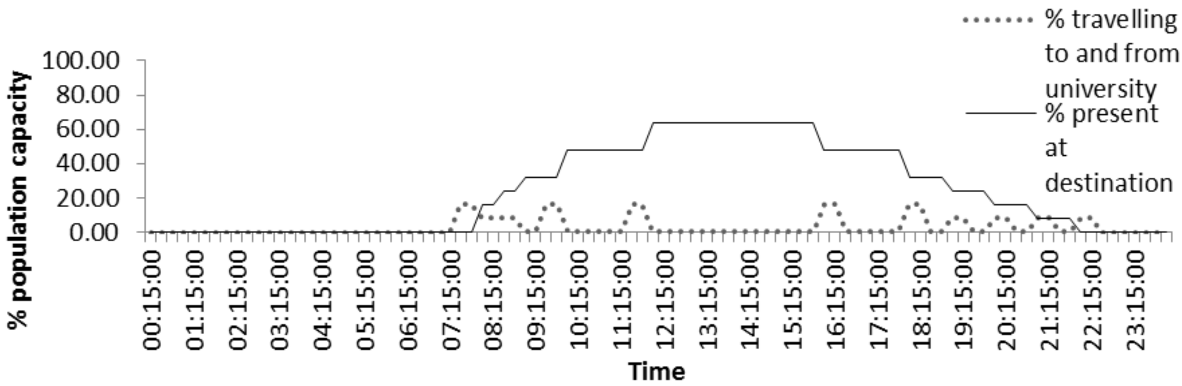


Figure 40: The in-transit and on-site cyclical time profiles for weekday university attendance (DFT, 2011).

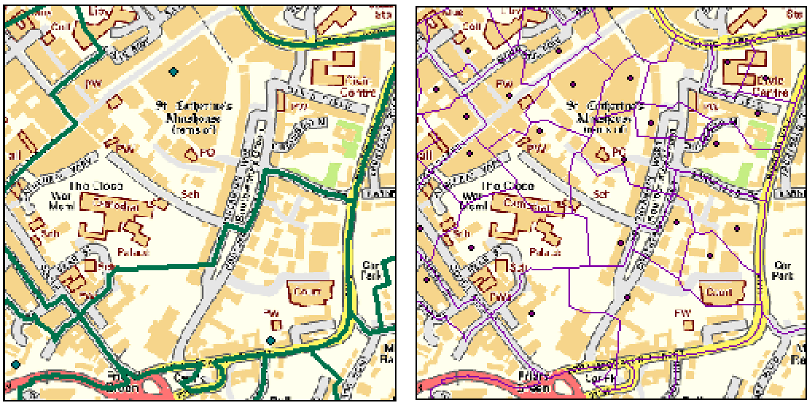
The Population247 approach requires assembly of an extensive library of customised spatiotemporal data to represent relevant origins, destinations and profiles of population subgroup activity. The focus of the next section is on methods for construction of the 2011 population subgroup dataset. Table 5 gives an overview of the wide variety of new data which has been included in the thesis implementation of the Population247 approach. The data includes male and female populations across six age groups, for both origin and destination datasets. An immobile population, residential term-time and non term-time origin data set has been included. In addition to this, destination datasets have been developed which represent the four stages of education from primary to university level, healthcare of in-patients, out-patients and A&E patients, eleven different workplace categories, leisure and tourism attractions and retail centres.

Topic	**Data Source**	**Reference and Source**	**Level**
Residential population (2011 Census)	LC1105EW KS101EW LC4411EW QS421EW ONSPD	Residents, sex by single year of age. Usual resident population. Student accommodation by age (student aged population). Communal establishments https://www.nomisweb.co.uk/census/2011/all_tables Grid reference/OA/PC linkage. https://geoportal.statistics.gov.uk	OA
Non term-time residential population (2011 Census)	OT1117EW OT1101EW LC1106EW ONSPD	OTT population, sex by single year of age. OTT population, sex by five year age group. Schoolchildren and full-time students at non-term time address, by age. https://www.nomisweb.co.uk/census/2011/all_tables Grid reference/OA/PC linkage. https://geoportal.statistics.gov.uk	MSOA
Immobile populations	MoJ Prison Population Figures 2011 HSCIC	Monthly bulletins: March-April. https://www.gov.uk/government/statistics/prison-population-2011 Community Care Statistics, Supported residents (adults) 2011. http://www.hscic.gov.uk/catalogue/PUB13148	Site
Education	EDUBASE2 HESA National Travel Survey	School addresses and population statistics. Higher education statistics. http://www.education.gov.uk/edubase/home.xhtml https://www.hesa.ac.uk/ NTS0614: Trips to school by main mode, length and age, UK 2011. https://www.gov.uk/government/statistical-data-sets/nts06-age-gender-and-modal-breakdown	Site
Healthcare	HSCIC NHS Choices ONSPD	Annual hospital episode statistics for A&E, in- and out-patients. http://www.hscic.gov.uk/hes Healthcare addresses. http://www.nhs.uk/pages/home.aspx Grid reference/PC linkage.	Site
Workplace (2011 Census)	WP1101EW WP605EW WP702EW	Sex by single year of age (workplace pop.). Industry. Distance travelled to work. https://www.nomisweb.co.uk/census/2011/workplace_population	WZ
Leisure, tourism and retail	VisitEngland Retail reporting	GB tourism/day visits survey. https://www.visitengland.com/biz/resources/insights-and-statistics Acorn, Experian, retail reports, UKTUS.	Site
Background	DofT	Average Annual Daily Flow (AADF) http://www.dft.gov.uk/traffic-counts/	N/A

Table 5: The data source archive, for the thesis application of Population247 (Data sources e.g. “LC1105EW” indicate the exact 2011 census aggregate statistics tables from which data were obtained.) Acronyms are Office of National Statistics Postcode Directory (ONSPD), Department of Transport (DofT), UK Time Use Survey (UKTUS), Health and Social Care Information Centre (HSCIC), Higher Education Statistics Authority (HESA).

It is evident that several different data sources have been identified, and it is necessary to adjust the resolution of some of these sources to generate centroids at an appropriate scale. Some destination population counts are naturally in centroid form, such as a tourist attraction which already exists at a single grid-referenced point. However, Census Output Areas (OA), Middle Layer Super-Output Areas (MSOA), and Workplace Zones (WZ) are area-based aggregations of population, which require prior disaggregation and adjustment to obtain postcode-level centroid estimates before modelling. MSOAs are largest and may contain several OAs and WZs. OAs contain residential data, whereas Workplace Zones (WZ) include workplace data. Each OA has a minimum of 100 resident individuals, to protect privacy. (ONS, 2014a). WZ are a new output geography for 2011, aggregated from workplace postcodes to reflect locations of economic activity (ONS, 2014b). a) b)

Figure 41 shows a) OAs and b) WZs. The greater number of WZ compared to OA suggests that this area may have commercial land-use.



a)

b)

Figure 41: The same area showing a) 2011 Census OAs and b) WZs. Contains Ordnance Survey data © Crown Copyright and database rights 2014

Uniform resolution across spatial datasets is therefore a consideration of this approach, to ensure that data are redistributed as far as possible between comparably sized spatial units, and that there is therefore a similar level of precision. On-site temporal datasets have been sourced from the census, VisitEngland, Time Use Survey and National Transport Survey, and fortunately require very little adjustment (Table 5). Annual Average Daily Flow (AADF) transport data is used in conjunction with these other sources, for weighting the locations of the in-transit population. The next section describes the data and processes required for the production of origin, destination and transport network datasets for this thesis.

4.2.1 Constructing Datasets for Population247

This section describes the creation of residential origin datasets, workplace, education, health, leisure, tourism and retail destination datasets; and transport networks. Some commonalities have been developed across origin and destination population datasets, to ensure comparability of scale. This means that populations are maintained at the same level of granularity. The scale of input and output population densities needs to be of high resolution, to provide adequate spatial definition across localised activities and subgroups. A common input scale for origin and destination data was developed at postcode level, to provide a high level of resolution without individual-level modelling. This enables small-scale aggregation of population data, to realistically represent population movement.

4.2.1.1 Origin Populations

Two origin population datasets were created. These represent the origin, or 'residential', population at unit postcode (UPC) level for both term and non-term time populations. The datasets were constructed using 2011 census data, which provide a comprehensive estimate of residential population at OA level. Table 6 shows the datasets used for construction of the origin population dataset.

Dataset	Data	Original scale	Final scale
LC1105EW OT1117EW	6 age groups, male and female populations	OA	Postcode centroids

Table 6: Datasets applied for the production of an origin population.

Dataset LC1105EW (Residence type by age) classfies usual residents by residence type (household or communal resident), by sex and by age at OA level, and contains the information needed to produce the term-time residential population origin centroids for this version of the Population247 modelling framework.

LC1105EW data is available in 21 age groups, by gender and OA. The R statistical package is used to merge and combine data from LC1105EW for the South West region into twelve different subgroups, consisting of six age groups across two gender groups. The outcome of this is shown in Table 7. The six age groups include children of three different school ages, university age, adults of working age, and adults of retirement age and older. These twelve groups have been chosen to reflect the differing vulnerabilities of the populations, with respect to radiation exposure and spatiotemporal activity. In this context, younger people and children are most vulnerable, are subject to the greatest subdivision, as the determinstic and stochastic effects of radiation exposure are more significant to children. It is also notable that the majority of adult students will be young within the 16-64 age range, but have distinctive term/non-term time patterns, which is why it makes sense to separate them from the working population rather than to subdivide by age.

LC1105EW: Residence by age 2011	**Population247 RADPOP age and gender subgroups**	
0 to 4	0 to 4 M and 0 to 4 F	
5 to 7	5 to 9 M and 5 to 9 F	
8 to 9		
10 to 14	10 to 15 M and 10 to 15 F	
15		
16 to 17	16 to 64 university M and 16 to 64 university F	16 to 64 Work M and 16 to 64 Work F
18 to 19		
20 to 24		
25 to 29		
30 to 34		
35 to 39		
40 to 44		
45 to 49		
50 to 54		
55 to 59		
60 to 64		
65 to 69	Over 65 M and Over 65 F	
70 to 74		
75 to 79		
80 to 84		
85 and over		

Table 7: Comparison of LC1105EW and RADPOP age subgroups.

The regrouped LC1105EW output needs to be linked to postcode locations. Postcodes starting with EX, TQ, PL and TR have been identified as relevant to the study area. Office of National Statistics Postcode Data (ONSPD) (November 2013) is used to match OAs to postcode, and to link this information to a grid reference. It is necessary to calculate the number of males and females in each postcode. An equation has been devised to calculate the ratio of each age group, male and female which should be assigned to postcodes within OA as a proportion of the OA.

$$\text{Population assigned to PC unit for a specifc age and gender} \quad = P_{OAG} * \left(\frac{P_{PO}}{P_{OAT}}\right)$$

Equation 1

PC is postcode, OA is output area, G is gender, P_{OAG} is population within OA for a specific age group and gender (e.g. 0 to 4 and female); P_{PO} is the population within postcode for a specific gender; and P_{OAT} is the total number of a specific gender in an OA.

4.2.1.2 **Origin Population: Non Term-Time**

Educational term-times have a major influence on the termly redistribution of young people across England and Wales, particularly among university students living away from home. The standard census population base is term-time. It is therefore necessary to reprocess the data to produce a suitable non term-time origin population dataset. Students are removed from the 16 to 64 OA-level dataset KS101EW to create a student population. The population needs to be disaggregated to postcode level and grid referenced using the same methods as for the residential population, before deducting students from the 16 to 64 dataset, to represent non term-time population at postcode level.

Type	Origin														
Title	School Term-Time All Resident Population Counts for OAs in England and Wales 2011 South West RegionDatasets: KS601EW, KS603EWBecky Martin 2014														
Comment	Population counts for school term time at OA level from census data, 5 age group and 2 sex breakdowns expressed in percentages, total 10 groups. School														
Data block	23	24	53517												
IdentifyingCoc	2														
X	3														
Y	4														
PopTotal	5														
PopSubGroups	12														
PopSubGroups	2	2	4.5	4.5	3	3	10	10	21.5	21.5	9	9	6	7	8
TimeProfiles															
LocalDispersio	N	30													
LocalDispersio	250	19													
WideAreaDispersalFunction															
MajorFlows															
DOfA	Census 2011	29													
Mobility	100	100	100	100	100	100	100	100	100	100	90	90	29	30	31
RegionalIdent	UK	20													
RegionalAdj															
UK>97|A>98|B>107|D>104||E>97|F>97|G>102|H>93|J>97|K>108															
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
OANAME	POSTCODE	OSEAST	OSNRTH	POP01	0_4M	0_4F	5_9M	5_9F	10_15M	10_15F	16_64UNIM	16_64UNIF	16_64WM	16_64WF	OV65M
E00075894	PL5 4PE	246223	60264	81	3.833	0.614	1.0455	0	1.393939	0.614035	1.26315789	1.8421053	34.1515152	29.1666667	5.57575758
E00075894	PL5 4LA	246239	60087	1	0.083	0	0.0227	0	0.030303	0	0.56140351	1.2894737	0.74242424	0	0.12121212
E00075894	PL5 4PD	246253	60188	35	1.417	0.3158	0.3864	0	0.515152	0.315789	2.38596491	2.9473684	12.6212121	15	2.06060606

Figure 42: Age and gender-split term-time origin population data for the RADPOP thesis study, at postcode level.

The Population247 approach is implemented using the SurfaceBuilder model, which has been described in Section 2.4.2. SurfaceBuilder uses an adaptive kernel-based interpolation approach that includes dasymetric classification to redistribute populations across urban areas and a transport network to a time profile. Figure 42 shows the first few records of a SurfaceBuilder input data file, following processing and preparation. Each OA (OANAME) has relevant postcode and grid reference links, and population is split into gender and age groups; where, for example, 5_9M would represent males between the ages of 5 to 9. This is used to provide the resident population when SurfaceBuilder247 is run.

4.2.2 Destination Populations

The destination populations are the locations that different population subgroups travel to for different activities. Table 8 shows the datasets included in the RADPOP application of Population247, by activity subgroup, temporal profile and scale.

Dataset	Activity subgroups	Temporal profiles	Scale
Edubase2 and HESA	Primary, secondary, university and college, boarding	School and university opening hours.	Postcode centroids
HES, HSCIC, NHS Choices	Inpatients, outpatients, A&E, social care	Social care and inpatients are immobile. A&E have 24-hour variability, outpatients have weekday working hour attendance.	Postcode centroids
WP605, ONS, HETUS	Workplace population by industry.	Working time patterns by sector.	WZ postcode centroids
VisitEngland, Experian, individual shopping centre reports.	Leisure and retail.	Leisure and retail opening hours.	Postcode centroids

Table 8: The datasets applied for the production of destination populations.

4.2.2.1 Workplace

The 16-64 workplace population will, mostly, be attending a place of work in the daytime. The census workplace population represents those people reporting that they work in an area, and this is reported by aggregation to WZs by 21 industry types in table WP605EW (ONS, 2014b). This thesis application of WZ data is designed to understand the likelihood of exposure, based upon spatiotemporal activity. It is therefore not relevant to this study to model all industries separately, as some industries share time profiles and working conditions e.g. outdoor workers would receive a higher dose of radiation than office workers, during a hypothetical radiation emergency. Therefore, these industry types may be reduced to 6 workplace types with comparable temporal profiles, which are shown in Table 9 (ONS, 2014b, ONS, 2011).

WP605EW Workplace by Industry	**RADPOP workplace subgroups**
A - Agriculture, forestry and fishing	1. Outdoor work
B - Mining and quarrying	
D - Electricity, gas, steam and air conditioning supply	
E - Water supply, sewerage, waste management and remediation activities	
F - Construction	
G - Wholesale and retail trade; repair of motor vehicles and motor cycles	
H - Transport and storage	
C- Manufacturing	2. Manufacturing
C- Manufacturing: Food, beverages and tobacco	
C- Manufacturing: Textiles, wearing apparel and leather and related products	
C- Manufacturing: Wood, paper and paper products	
C- Manufacturing: Chemicals, chemical products, rubber and plastic	
C- Manufacturing: Low tech	
C- Manufacturing: High tech	
C- Manufacturing: Other	
I - Accommodation and food service activities	3. Hospitality
J- Information and communication K- Financial and insurance activities L- Real estate activities M- Professional, scientific and technical activities N – Administrative and support service activities	4. Office-based
O - Public administration and defence; compulsory social security P - Education Q - Human health and social work activities	5. Essential services
R, S, T, U - Other	6. Other

Table 9: Table to show derivation of RADPOP workplace population subgroups, from WP605EW workplace by industry data (ONS, 2014b, ONS, 2011).

Again, a gender split population is needed to reflect gender differences in the workforce of particular interest for this thesis. Census table DC6110 gives industry by sex by age but is not available at the WZ level, only Ward/MSOA and above. The RADPOP age and gender divisions have been derived from this table. Whilst the locations of individual employees are unknown, WZ-level sex by age groups, can be allocated to the industries to reflect the splits between industries at local authority level. The proportion of each gender split in the WZs in WP1101EW is applied to equivalent WZs in WP605EW, for each sector in the zone. The WZs are linked to postcode and grid reference using NSPL as above. This assumes that the gender profile of each industry is uniform for each MSOA, in the absence of more detailed data.

Whilst WZ data is available for each age, the age ranges are condensed into the adult age groups for higher education, working age and pensionable male and female populations, for each industry.

4.2.2.2 **Education**

Education data has been sourced from EDUBASE2 which is the Department for Education's register of establishments providing compulsory, higher and further education in England and Wales (DofE, 2014). This dataset provides information about school capacity, gender and age range of pupils in attendance for each establishment. Further information has also been included from HEIDI, the Higher Education Information Database for Institutions (HEIDI, 2014) from the Higher Education Statistics Agency (HESA).

The education datasets are primary and secondary school population counts at postcode level, split by gender and school year. Schools data was retrieved from https://www.gov.uk/government/publications/schools-pupils-and-their-characteristics-january-2011 From Underlying Data: SFR12/2011. Data for the south-west was linked by school by postcode, to grid references. School years were combined to reflect RADPOP age groups. Data shows both full and part time students, and boarding students for primary, secondary and boarding schools. Postcode data originated from EduBase2 http://www.education.gov.uk/edubase/public/quickSearchResult.xhtml?myListCount=0. University and college student populations are also required for destinations. Higher education population statistics have been included from enrolment figures from HESA https://www.hesa.ac.uk/ of which 2011 statistics are available, by postcode and gender. The Higher Education Information Database for Institutions (HEIDI) http://www.heidi.ac.uk/ was used to gain more information about the gender and age split for specific universities and colleges, where information was not available from EDUBASE. Further gender data was gained from individual university reports from the universities of Exeter and Plymouth.

4.2.2.3 **Healthcare**

Healthcare data has been sourced from the Health and Social Care Information Centre (HSCIC) data catalogue (HSCIC, 2014). These data are provided by age and by gender. HSCIC data has been supplemented by information from NHS Choices, a website that provides resources for the public and healthcare professionals about NHS services in England (NHS, 2012). Data from the Nuffield Trust has also been included to understand the trends in hospital use by older people in England in more detail (NuffieldTrust, 2010).

Healthcare data was prepared for healthcare sites across the study region, including hospitals with inpatient, outpatient and accident and emergency facilities. Relevant healthcare destinations for inclusion in the model were identified using NHS Choices. For example, the Royal Devon and Exeter hospital is included in this dataset http://www.nhs.uk/Services/hospitals/Overview/DefaultView.aspx?id=1963 (Accessed 05/12/2014). However, GP surgeries were not included in the dataset as the population density of a single site during the day is too small to make a significant contribution. Departments and services, facilities and location are listed, which improve understanding for selection. Postcodes from this source are linked to a grid reference using the ONSPD. The chosen sites were then identified using HES http://www.hscic.gov.uk/hes (Accessed 07/01/2015). This source provides information about the use of each healthcare facility. Table 10 provides more information about the data sources included in the new 2011 Population247 healthcare input.

Dataset	**Purpose**
NHS Choices	Hospital location and grid reference
Hospital Episode Statistics	Inpatient/outpatient/accident and emergency population count
Hospital Episode Statistics	Inpatient/outpatient/accident and emergency demographics
TUS 2011	Inpatient/outpatient/accident and emergency time profile

Table 10: Healthcare data included in the thesis implementation of Population247.

The temporal profile was derived from Royal Devon and Exeter inpatient, outpatient and A&E time of admission statistics for March 2011. The existing local dispersion and wide area dispersal (WAD) were retained from the original Population247 project as there has not been significant redevelopment of healthcare facilities across the study site since 2006.

4.2.2.4 **Leisure, Tourism and Retail**

Leisure and tourism data has been sourced primarily from VisitEngland and The National Trust. VisitEngland is England's tourist board, and provides statistical publications and reports on domestic overnight tourism, day visits and visitor attractions that include visitor activities, locations, numbers and time spent on leisure and tourism (VisitEngland, 2014). The National Trust is a conservation charity that protects historic sites in the UK and a source of heritage tourism data (NT, 2014). The National Trust provides information about its sites, which complements visitor data from VisitEngland. Whilst leisure and tourism data are readily available, gaining reliable retail data is more challenging due to issues of commercial confidentiality. Therefore, a combination of shopping centre reports and footfall data have been combined to describe the spatial distribution of retail centres. Destination population for leisure has been estimated mostly by obtaining annual figures and deriving daily figures. All attractions with fewer than 20,000 visitors per year have been removed, as daily visitor numbers would be too small to model meaningfully. VisitEngland data are from http://www.visitengland.org/insight-statistics/major-tourism-surveys/attractions/Annual_Survey/index.aspx. The gender and age group splits have been identified by using proxies from other studies, which reflect the general patterns of attendance at different attractions.

Retail footfall was modelled by using the footfall data available for each shopping centre in the area. Footfall data sources include verified individual retail centre reports, Acorn reports and Experian footfall data, which were provided for this research by the retail centres for use in the model. Gendered data was developed by using proportional proxies from literature, where exact numbers of each gender and age group were not available, for the specific purpose of this thesis. An overview of data sources is provided in Table 11.

Dataset	**Purpose**
VisitEngland	Population count for specific tourism locations
ExperianFootfall	Retail footfall for specific retail centres
Retail centre reports	Retail footfall for specific retail centres

Table 11: Sources of data for leisure, tourism and retail.

4.2.2.5 **Transport**

A transport layer is included in the Population247 model which encompasses motorways and A-roads, which form the major structure for the UK primary route network (Government, 2002). The model road network has been weighted with spatiotemporal population transport data, to reflect the changes in transport population density at different times of day. Road traffic population estimates were obtained from published Department for Transport National Transport Model survey data, to produce time-specific background transport layers. Data was used from collection points for Devon, for March and April 2011. http://www.dft.gov.uk/traffic-counts/cp.php?la=Devon. This data is Average Annual Daily Flow (AADF) which estimates the total traffic count for each motorway and A-road in the UK, at a specific point for one year. AADF data includes a grid referenced location, road type, junction start and end and link length, and vehicle count information for a variety of different modes of transport including pedal cycles, motorcycles, cars, buses and coaches, light goods vehicles, HGV, articulated lorries, all HGVs and all motor vehicles (DFT, 2011). This information is provided across 19 National Transport Model time periods.

Vehicle count and type data was converted to population estimates on the road network, based upon vehicle occupancy, by using a database which was developed by Smith (2015). The data was then distributed across the road network for the relevant time periods, resulting in different background layers for different times of week. The data distribution required an explicitly spatial approach, compared to other layers in Population247, and was therefore performed using GIS instead of a-spatial analytical methods with statistical packages.

A rasterised landmass with a vector layer of motorways and A-roads was used by a previous implementation of Population247 (Smith, 2015). This was applied to add AADF data, which was proportionally adjusted for each of the National Transport Model time series. A population estimate was then assigned to each data point, based upon vehicle occupancy and time of day. The final population estimates were then distributed onto the road network using inverse-distance weighting in GIS, as described in section 2.3.2. This creates an output of weightings to guide the allocation of the population, and therefore estimate the proportion of the population that is in-transit for a specific time. The AADF data includes bus passenger numbers as captured by the DfT travel survey data, and the region is rural therefore local and regional transport is via the road network. It is not in the scope of this study to develop a model that includes other modes of transport, such as rail networks.

4.3 Component B: Assessment of Hazard Distribution and Health Effects

Radiation hazard modelling addresses the need to understand the spatiotemporal dispersion of radiation, in the context of population distribution. This is an important feature of this thesis, as it provides the basic information required to anticipate spatial changes in the velocity and concentration of a radiation plume over time as a consequence of weather, dispersion and deposition. This enables estimation of radionuclide exposure to a population, and therefore health effects. It is important to note that whilst gamma radiation cannot be estimated by plume dispersion methods, its impact is significantly limited by distance from source, in urban areas.

4.3.1 **PACE**

PACE (Probabilistic Accident Consequence Evaluation) is a model which has been designed by Public Health England (PHE) for the probabilistic safety analysis of nuclear power stations in the UK. The model improves upon an original, similar, COCO2 economic model of accident consequences costs (Jones, 2008). However, PACE has the capacity to assess both tangible and intangible effects including dose, health effects and economic endpoints, including agricultural and residential impact (Charnock et al., 2013). The approach is designed to provide a measure of loss across multiple indicators, which is appropriate for informing future policy and planning decisions, rather than just estimation of loss to the economy. However, the RADPOP approach is primarily focused upon dose and health effects to populations, and therefore economic endpoint assessment has not been included in this thesis.

PACE combines several different models into one application. These models include NAMEIII for the simulated atmospheric dispersal of the source term (Jones et al., 2007), ADEPT for Gaussian atmospheric modelling, should NWP data not be available (Jones, 1981), FARMLAND for food modelling and the COCO-2 economic model for nuclear accidents (Jones, 2008). PACE also makes use of extensive datasets in spatial and non-spatial formats, for geospatial representation. As an alternative to using NAMEIII, this step can be omitted and PACE will use ADEPT, which is a simpler Gaussian dispersion model, to estimate atmospheric dispersion for each met sequence. The rest of this section describes the PACE methodology.

There are four stages to the analysis process for the PACE model. The first stage is called Source Term, and is implemented to define the original amount of released radioactive material from a source. The Source Term tool determines the most significant radionuclides, and allows less significant radionuclides to be removed, to help to speed up the analysis process. The second stage uses a Pre-process Tool to specify a nested grid, across which all PACE calculations are performed. The Pre-process Tool re-samples input spatial data to conform to the grid. For each grid square, PACE calculates the distance of that square from the point of release.

Figure 43 illustrates a nested grid of grid squares with three different resolutions, known as nest factors. Nested grid squares improve computational efficiency, as high resolution can be focused upon the urban area, allowing surrounding rural areas and unpopulated areas to be represented at lower resolution.

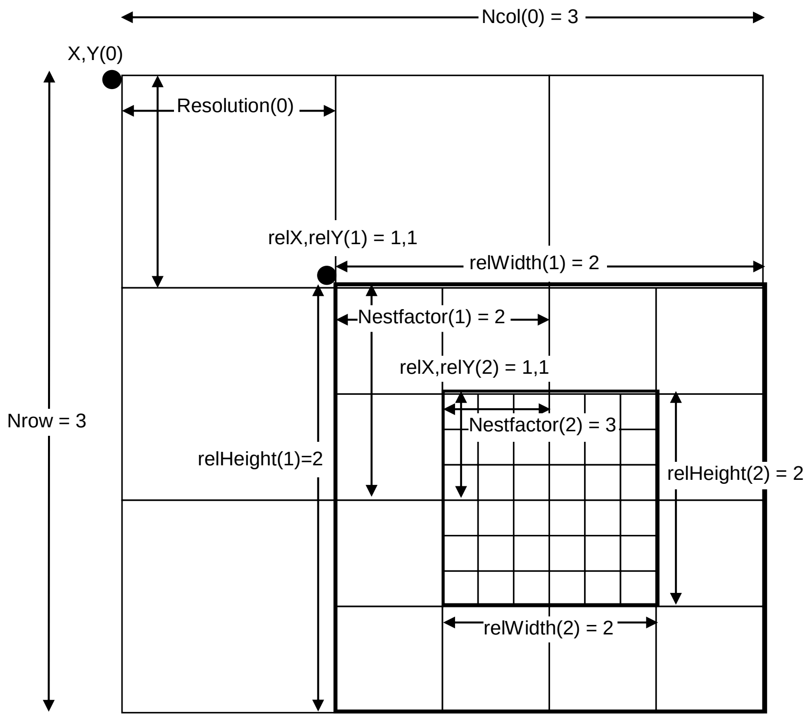


Figure 43: An example of a nested spatial grid (Charnock et al., 2013).

The third stage uses the PACErun tool. The main input is a geodatabase array, which has been set up and populated by meteorological and population data in the previous stages. Gaussian or NAME modelling outputs can be selected, dependent upon whether archive Numerical Weather Prediction (NWP) data is included. PACErun uses meteorological data, and population and environment feature classes, to calculate required dose, health effects and economic endpoints, which are stored as a results geodatabase. The final stage is Analyse Results. This aggregates the data outputs and enables the production of simple summary statistics, including percentile analysis, which describe the probabilities of outcomes (Charnock et al., 2013). PACE produces an output for each grid square for the time slices of a spatiotemporal meteorological sequence.

These outputs provide a comprehensive assessment of exposure impacts. However, this thesis will focus on dose, health effects, dose with countermeasures, and dose without countermeasures. In the context of PACE, dose includes dose endpoints from various pathways assuming no countermeasures; Health effects (HE) includes stochastic and deterministic risks and health effects assuming no countermeasures; Countermeasures (CM) includes the application and timescale of potential countermeasures; Dose with countermeasures (DSCM) includes dose, assuming countermeasures are applied; and Health effects with countermeasures (HECM) includes stochastic and deterministic health effects whilst assuming countermeasures (Charnock et al., 2013).

PACE undertakes a very simple assessment of population exposure over time, which does not include time-specific population data. PHE provides a residential 2001 Census dataset for input, which is not suited to the present purpose for a number of reasons. This is because the current population distribution is in reality dynamic across space and time. There is also no representation of specific population subgroups, such as children and the elderly of either gender. Finally, 2001 population data is no longer representative of the contemporary population. However, the framework of PACE is sufficiently adaptable for new population libraries to be developed and included for it, such as 2011 Census or Population247 modelling outputs.

In the PACE model, time is set to zero at the start of the modelled accident. The source term in PACE consists of a number of phases of defined length, where the sum of all the phases is the total release time (Jones, 2008, Charnock et al., 2013). Countermeasures are applied for a specific timescale, and are then removed by 'Emergency Ends'. This is defined in PACE as the time when evacuation and sheltering are lifted and when relocation begins, and requires user judgement in including the total timescale of release (Charnock et al., 2013).

The next section of this chapter describes the methods and data required to produce output for DS, HC, CM, DWCM and HEWCM in more detail, with a focus on dose, health effects and counter-measures. The section ends with a description of the innovative population data updates made to the model by this thesis, to include a spatiotemporal population distribution that reflects the demographic diversity of a real city population. Although it is not the focus of the thesis, running the model still requires input of agricultural data, such as land-type classification geodatabase files. PACE standard land-type data from 2003 is included, as it has no influence on health effects, which are of the topic of interest.

4.3.2 **Health Effects Methodology for PACE**

The focus of this thesis is on the health effects of radiation exposure to different population subgroups, and this is reflected in the abridged methodological overview of PACE. The calculation of health effects due to accidental radiation exposure is a complex process. The PACE model includes calculation of loss of labour due to illness, cost of treatment, and personal loss to those suffering radiation induced morbidity or death . The scope of calculations for probabilistic health effects for PACE includes: total number of non-fatal deterministic effects, total deaths from deterministic health effects, total incidence of solid cancers, total deaths from solid cancers, total incident of leukaemia, total deaths from leukaemia, first generation heritable effects, and second generation heritable effects. Table 12 shows the probabilistic factors included to assess these characteristics (Charnock et al., 2013).

PACE Assessment Resource	**Methodology**
Total number of non-fatal deterministic effects	Sum of lung impairments, hypothyroidism, cataracts, mental retardation, and non-fatal skin burns.
Total deaths from deterministic health effects	Sum of deaths from pulmonary syndrome, haematopoietic syndrome, gastro-intestinal syndrome, pre-natal and neo-deaths and fatal skin burns.
Total incidence of solid cancers	Sum of all cancers from all stochastic effects other than cancers of bone marrow.
Total deaths from solid cancers	Sum of fatal cancers from all stochastic effects other than cancers of bone marrow.
Total incidence of leukaemia	Incidence of cancers of bone marrow.
Total deaths from leukaemia	Deaths from cancers of bone marrow.
1st generation hereditary effects	There is no methodology for estimation therefore all hereditary effects are assumed to be first generation.
Second generation hereditary effects	Assumed to be zero.

Table 12: The health assessment criteria included for the PACE model, and basic probabilistic methodology (Adapted from (Charnock et al., 2013).

The next section describes NAME, which is an important component of PACE and is applied by the thesis to model the dispersion of radionuclides during a hypothetical nuclear accident.

4.3.3 **NAME**

NAME (the Numerical Atmospheric Dispersal Model), was initially referred to in Section 3.4. The UK Met Office, in response to Chernobyl, developed NAME for the purpose of emergency response prediction. It has since been used to model the atmospheric transport and dispersion of a range of gases and particles and scenarios (Maryon, 1999, Jones et al., 2007). There have been a number of previous versions, with the current version being NAMEIII. NAMEIII is a spatiotemporal

Lagrangian air pollution dispersal model with the capacity to model at short range to global range scales across a 3D grid. The Lagrangian approach represents pollutants as a finite number of discrete particles, which are tracked individually through flow. This means that there are limits on minimum concentrations, and issues with statistical noise in the tails of plumes, where particle number densities are low by definition. Lagrangian models offer distinct benefits over other dispersion modelling strategies as they can deal naturally with localised releases such as point sources, and they are efficient at accurately representing relatively narrow plumes encountered near to point sources and multiple species.

NAMEIII calculates dispersion by tracking modelled particles through a modelled atmosphere. These particles move with the resolved wind described by the meteorology, which can vary in space and time. The particles' motion also has a random component to represent the effects of atmospheric turbulence. A consequence of this is that no assumptions need to be made about the shape of the concentration distribution, such as are required in Gaussian plume models. Pollutants can also be removed from the model atmosphere by several processes: (i) fall out due to gravity, (ii) impaction with the surface, (iii) washout where the pollutant is 'swept out' by falling precipitation; and (iv) "rainout" where the pollutant is absorbed directly into cloud droplets as they form. In addition each model 'particle' can have its own characteristics; for example particles can represent different compounds or chemicals, and particles can have specific particulate sizes (Jones et al., 2007).

NAMEIII uses a simulation method, rather than solving equations, by following the 3D trajectories of a contaminant plume and computing the pollutant concentrations by Monte Carlo methods. A puff method is applied to model dispersion over a short range, which reduces the time required to compute pollutant concentration at the receptors. NAMEIII has the capacity to calculate the rise of buoyant plumes, the deposition of pollution plumes due to wet deposition and dry deposition, plume chemistry, downwash effects and plume depletion due to radioactive decay (Jones et al., 2007). The capability of NAMEIII for modelling radionuclide dispersal has been tested recently during the aftermath of Fukushima, where daily “What If?” simulations formed an important component of the UK government’s emergency response following the accident (Draxler, 2015).

NAMEIII uses NWP, which provides three-dimensional gridded meteorological fields for dispersion from global, to kilometre scale across the UK. Dispersion quality is dependent upon the standard of NWP, and high resolution limited area data are not always required for every application (Jones et al., 2007). It is possible to model 31 physical parameters in NAMEIII, including velocity, temperature, pressure, cloud amount and height and precipitation. However, many different interactions contribute to atmospheric dispersal. Figure 44 provides insight into how advection, dispersion, mixing height, chemical transformations and wash out combine to result in the final deposition.

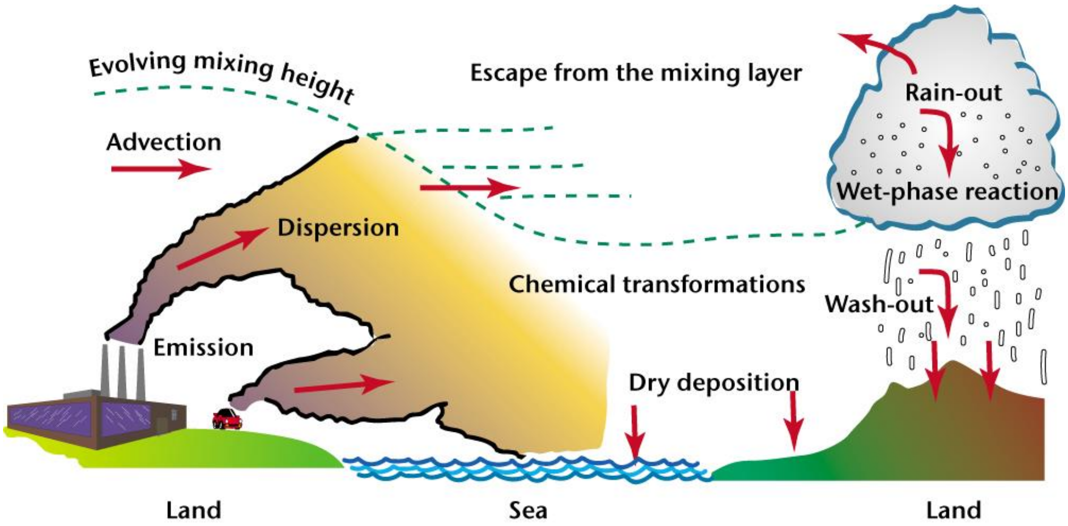


Figure 44: The dispersal pathways of a hypothetical contaminant from source to target (Jones et al., 2007).

NAMEIII is applied to a wide variety of atmospheric dispersion events including emergency response air quality modelling for nuclear incidents, volcanic eruptions, chemical accidents, smoke from fires, airborne animal disease vectors, forest fires and ash (Jones et al., 2007).

4.3.3.1 **Using NAME with PACE for RADPOP**

A GUI (graphic user interface) version of NAMEIII is included with the PHE PACE package, to provide accurate models of radionuclide dispersal (Jones et al., 2007, Draxler, 2015). This version of NAME has been selected, as some of the necessary parameters for radiation accidents are included as pre-sets by the PACE NAMErun interface. Figure 45 shows the basic interface of the PACE NAMErun extension, and provides insight into its extent and capacity.

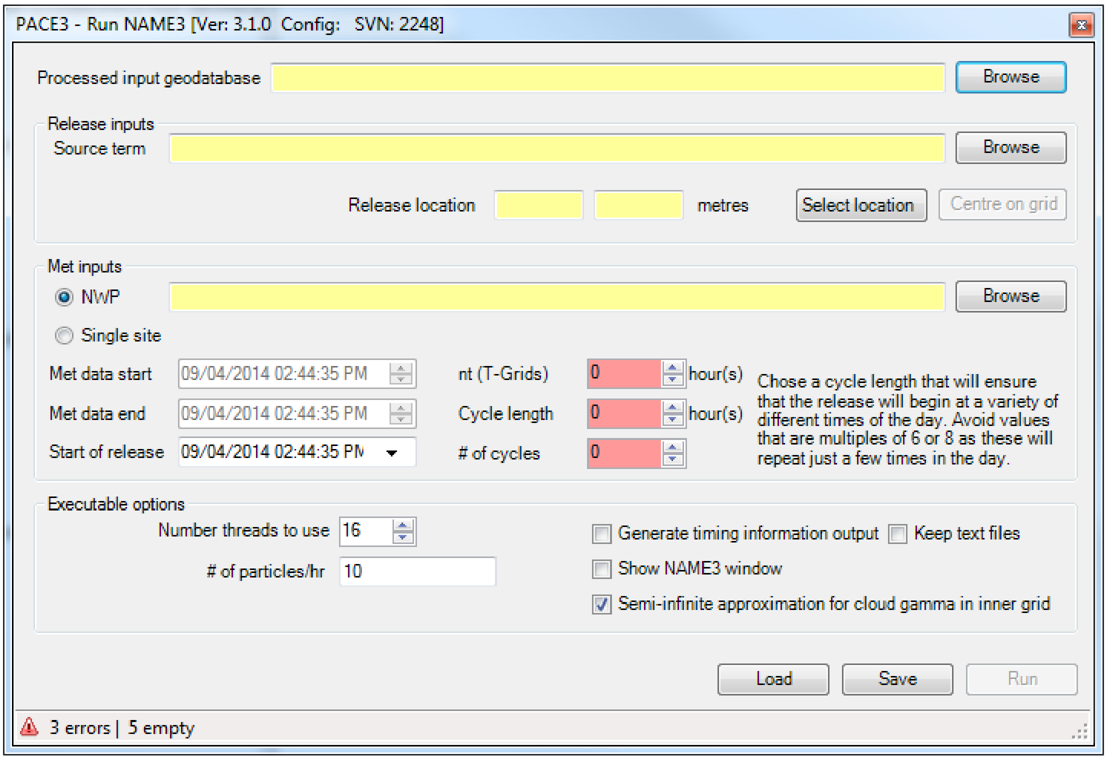


Figure 45: The PACE NAMErun interface (Draxler, 2015).

It is possible to select meteorological data for a particular time, and then to specify release inputs, location and the cycle length, number of cycles and temporal grids (T-grids) by the application.

The source term is a description of the radionuclides released. It takes the form of an XML file but can also be created using the PACE Sourceterm tool for input into NAMEIII. Met data parameters, including start and end times are loaded from a selected folder. Nt (T-Grids) stores the maximum temporal domain used by the NAMEIII model. At the end of the temporal domain, all particles are removed. A shorter temporal domain will reduce run times but will truncate the doses from all pathways as well. The cycle length determines the difference in time between the start of the current NAME run, to the start of the next NAME run i.e. the length of each run. To ensure that a good variation of times, (and to ensure a range of different meteorological conditions are used), it is recommended not to use multiples of 6 or 8 since these divide into the 24 hour timescale in a way that means the same time will be sampled (Draxler, 2015, Charnock et al., 2013). Selecting a greater number of particles tends to give more reliable and less noisy results, however takes longer to process. Generally a few thousand is acceptable.

NAMEIII can define a model atmosphere by single site or NWP meteorology. For the RADPOP modelling of UK weather conditions in 2011, for this thesis NWP data for the end of March 2011 is implemented through access to CEDA JASMIN servers. JASMIN is a storage and computing platform managed by the Centre for Environmental Data Archival (CEDA). The purpose of JASMIN is to facilitate access to data archives, group workspaces, analysis servers and specialised virtual servers for specific projects (Lawrence, 2013). The data is sourced from UMNEA Mk3 R meteorological datasets via JASMIN access:

```
/group_workspaces/jasmin/name/met_archive/LimitedArea/MESUM5
/group_workspaces/jasmin/name/met_archive/LimitedArea/UMNAE_Mk3_R
```

The UMNAE_Mk3_R set for the UK was downloaded from JASMIN and implemented in PACE to produce a NAME output. The PACE NAME extension timescale is specified to an absolute time of 07:00, on 29th March 2011, for hourly time intervals across a 24-hour period. The purpose of timescale specification is to match with spatiotemporal population density outputs, produced with Population247 as described in Section 4.2.

PHE and PACE software developers were worked with closely to define parameters. A restricted source term is defined by PACE NAMEIII, which is constructed using the source term tool. The source term comprises several phases, defined on an hourly basis. Each phase has a release height restricted to between 0 and 2000m, and whilst PACE NAMEIII can handle a long release of up to 30 days, this is very resource intensive. The model can estimate the trajectories of up to 30 different radionuclides, including daughters. However, this is also very resource intensive, therefore a single isotope, or collaboration of common isotope types is usually selected (Charnock et al., 2013).

It is important to define the spatial and temporal parameters for NAMEIII appropriately, to ensure that a realistic and appropriate model is produced. Large spatial and temporal domains are associated with long model runs, and may generate excessive data (Charnock et al 2015). (Charnock et al., 2013). The spatial domain is automatically defined by NAMErun for PACE. For the purpose of this thesis, the model is set to a British National Grid coordinate system (BNG) for the British Isles, bounded between longitudes 4°W to 10°E and 48°N to 62°N. PACE guidelines recommend a temporal domain of a few hours longer than the release period for nearby receptors, and a temporal domain of 24 to 48 hours for national scale or REPPIR determined incidents (Charnock et al., 2013). The finite cloud model is used for a 7km^2 inner grid of RADPOP

Exeter at 100m^2 resolution to match the resolution of the 100m^2 [g] Population247 gridded outputs.

Whilst the finite cloud model is more computationally demanding, it is more accurate at higher resolutions close to the source. However, beyond 7km from the release, the semi-infinite approach is as representative (Charnock et al., 2013). It is possible to select the type of urban environment available in PACE, which enables assessment of shielding and building type. For the purpose of the case studies, brick built houses (1) are selected, to accurately represent the structures in the city of Exeter.

A variety of input fields are required to run NAMEIII for PACE. Table 13 shows the inputs needed to produce a realistic source term dispersal for this thesis. In the table, the pre-processor output geodatabase is a component of the PACE model and provides background environmental and geographical information. The NAMEIII tool takes the geodatabase generated by the pre-processor tool as an input, to describe the calculation grid. It then adds a number of feature classes to this geodatabase, which represent hourly-integrated concentrations of radioactivity in air, ground deposition and cloud gamma dose for each radionuclide released, for each met sequence. It was necessary to work closely with PHE and PACE designers to implement a suitable source term for use within the thesis. The source term for this thesis is parameterised in more detail in the implementation of Case Study I, Chapter 5.

Field	**Input**	
Input geodatabase	Pre-processor output geodatabase	
Source term	PHE source term xml.	
Release location (x,y)	297396	083844
Met inputs	MESUM5 NWP for UK	
nt (T-Grids)	24	
Cycle length	10	
# of cycles	20	
# of particles/hr	2000	

Table 13: PACE NAMErun inputs for the thesis case studies.

Model fields are output for NAMEIII at a temporal resolution of 3 h, and archive data therefore consist of alternating model analyses and 3-h forecasts. Meteorological fields from the global model have an approximate horizontal resolution of 25 km in the mid-latitudes, with 70 vertical levels extending to an altitude of 80 km (but only the lowest 59 model levels up to approximately

30 km are used for NAMEIII applications). Meteorological data is interpolated in both space and time by NAMEIII (Draxler, 2015).

The PACE NAMErun process begins by running through each meteorological sequence in the NAMEIII run. For each meteorological sequence, the raw output from the runs are stored as text files within subdirectories of the input geodatabase. After the raw output is generated, the PACE NAMErun tool reads the data into feature classes in the input geodatabase (Charnock et al., 2013). For each met sequence, two feature classes are generated; TD_metx which contains the hourly time deposition concentration in Bq/m^2 and an integrated concentration in air in Bq/s/m^3 for each radionuclide for meteorological sequence x; and CG_metx, which contains the hourly dose from external exposure to airborne radionuclides (cloud gamma) for each radionuclide, for met sequence x. By this process, a usable GIS plume dispersal output is produced, which can then be combined with Population247 data output using GIS, to estimate exposure to a population at specific and parallel times for population and hazard.

The next section explores the final methodological approach, which uses the outputs of Components A and B to create an agent-based model (ABM) of population subgroup density change and exposure, from to different population dynamics due to implementation of countermeasures during a radiation emergency.

4.4 Component C: Understanding changes in population distribution during emergencies

Sections 4.2 and 4.3 have provided the approaches for the production of realistic models of spatiotemporal population densities and radiation hazard. However, the distribution of a population will change upon declaration of emergency, as the population cooperates with countermeasures advice. Section 4.4 therefore delivers a modelling approach that investigates the movement of populations from a known spatiotemporal whereabouts to other locations. This approach enhances existing understanding of exposure during radiation emergencies by implementing standalone data produced from Sections 4.2 and 4.3 for an agent-based modelling environment. The agent-based model uses spatiotemporal data, countermeasures data and behaviour to predict time travelled to shelter, and therefore exposure. The original spatiotemporal population and agent-based modelling populations are compared to assess realism and identify differences in patterns of exposure.

4.4.1 Introduction

Understanding the whereabouts and exposure of populations during an emergency is a significant real-life challenge to emergency responders. Currently list-based datasets are used by emergency responders, to identify groups of vulnerable people such as those in care homes or schools (CCS, 2008, SCC, 2013). However these lists are not comprehensive or spatiotemporally defined, and do not provide insight as to the whereabouts of different population subgroups as a whole. There is a need for an alternative approach that improves guidance for the purposes of training and exercising. Component C addresses this need by providing an approach for assessment of the whereabouts and exposure of a population and its subgroups during a hypothetical emergency, by using spatiotemporal hazard and population datasets to seed a geospatial simulation of sheltering countermeasures for a radiation emergency. This simulation has been developed using agent based modelling (ABM), a modelling approach which can simulate the actions of autonomous agents, which may be individual or collective, to assess the impacts upon the system as a whole (Bonabeau, 2002).This section describes the methodology applied to Case study II in Chapter 6.

4.4.2 Agent based modelling

ABM has the capacity to adapt, change or learn, to form dynamically changing relationships, create organisations, include spatial interactions, have arbitrarily large populations, or simulate structural changes across scenarios, where numerical modelling methods may be impossible or unwieldy to implement (Macal, 2014). Netlogo and Repast (Recursive Porous Agent Simulation Toolkit) are two ABM interfaces, which are discussed from a review and application approach in Sections 2.5 and 3.6, and are explored further in this section. In this thesis, Netlogo is applied to create models that test the viability of different approach prototypes (Wilensky, 1999, Tisue and Wilensky, 2004, Railsback and Grimm, 2011, Ozik, 2013, Jackson, 2014). However, ReLogo in the Repast suite is social sciences orientated, more sophisticated and has therefore been applied to the case study modelling process. The next section describes and examines the application of Netlogo and Repast ReLogo for the construction of a geospatial model of evacuation.

4.4.3 **Netlogo**

Netlogo is employed to implement agent-based modelling in Component C. Netlogo is a programmable environment which was originally designed for modelling natural and social phenomena over time (Wilensky, 1999, Tisue and Wilensky, 2004). It is an open-source platform, accessible at https://ccl.northwestern.edu/netlogo/, which implements an extended version of Logo language. Netlogo has been applied to model evacuation previously by several authors, notable examples include pedestrian modelling, integrated models of tsunami evacuation, and coupled behavioural and structural emergency response modelling (Li, 2015, Pluchino, 2015, Mas et al., 2012, Liu, 2015). Netlogo is currently at version 5. In Netlogo, link agents are used to connect mobile agents, to create networks, graphs and aggregates, using a large vocabulary of primitives and function values. The Netlogo environment is simple and consists of a GUI builder with buttons, sliders, switches, choosers, monitors, text boxes, notes, and an output area, as shown in Figure 46.

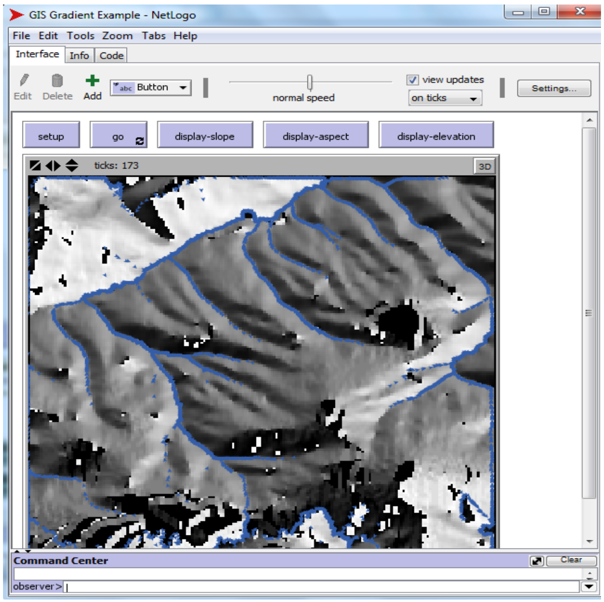


Figure 46: An example of a simple interface, constructed using Netlogo ABM software.

It is possible to control and monitor individual agents, there are import and export functions, and an extension called BehaviourSpace can be used to collect and analyse data from multiple model runs. Another of Netlogo's advantages is the extensive documentation and tutorials that surround the modelling system. Existing simulations in the Netlogo model library and community can therefore be readily adapted to test relevant ideas quickly.

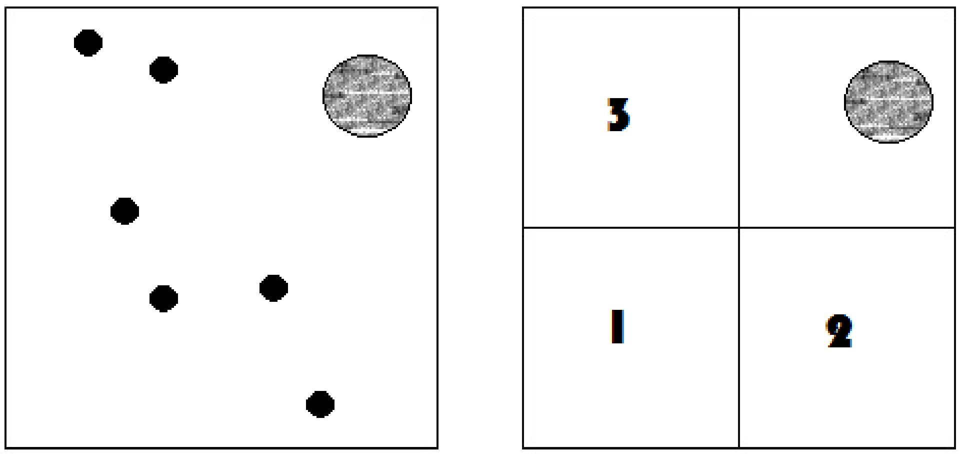
Netlogo uses a combination of GUI input and programming to create models constructed of agents in an environment. It has a variety of different types of agent, including turtles, patches, links and observer agents. Turtles are individual social agents, patches are environmental agents, links represent relationships between the agents, and the observer is the overarching command agent. Netlogo is programmed by using primitives, procedures and reporters to create larger blocks of code. Whitespace is used to separate out the different primitives and variables, which are used to construct a line of code unless the code is part of a string. This forms the basis of all other operations in the system (Lytinen and 2012).

Spatial data can be imported into Netlogo in two ways. The program can detect spatial layers based upon their pixilation, which whilst beneficial for programming, is not useful for geospatial information such as satellite imagery or OS maps, due to a wide variety of colours and colour-sharing being present between different objects in the layer. The other method is the Netlogo GIS extension, which can import GIS data into the model as a shape file or ascii file. This enables representation of vector and raster based geographic data. However, it is worth noting that Netlogo is not compatible with Google Earth KML file spatial data, and therefore a KML-to-shape file converter is required to include this information.

Rather than just using the original Netlogo software, Netlogo was applied within this thesis by using the Repast Eclipse GUI and ReLogo (Ozik et.al. 2013). ReLogo combines the sophisticated and powerful ABM infrastructure and capabilities of the Repast suite, with the ease of use of the Logo programming language and its associated programming idioms. Relogo includes object-oriented programming, simple integration of existing code libraries, statically and dynamically typed languages, domain specific languages, and the use of integrated development environments to create an ABM tool that is easy but also capable of creating large scale ABMs of real world complex systems. Relogo also has a comparable GIS extension for geospatial modelling. The next section describes an approach for using Netlogo to model an evacuation.

4.4.4 Modelling evacuation in Netlogo

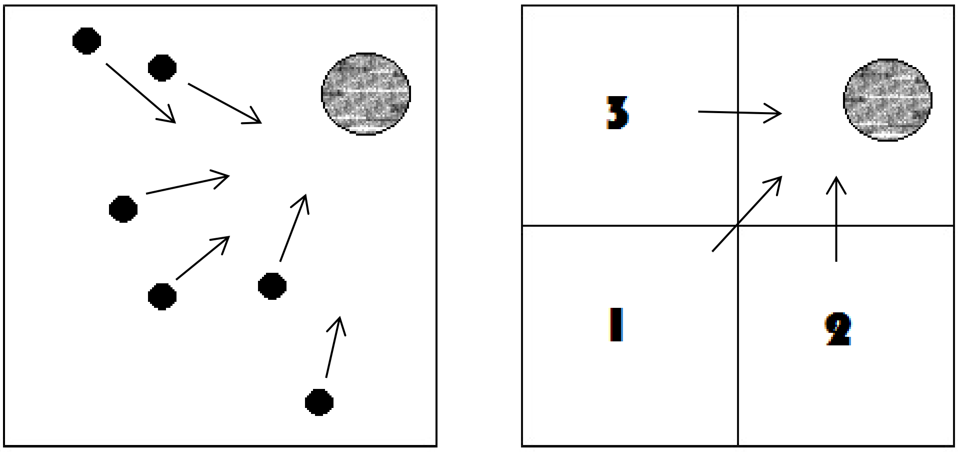
The RADPOP ABM must integrate geospatial and GIS output from Population247, PACE and NAMEIII. The model needs to be able to represent change in aggregate population across a gridded population density layer and road network, as the population moves to evacuation and shelter sites over time. The model includes an origin population which, in this context, is the population at the start time of declaration of emergency which has been seeded from Population247 output data. Two different approaches were considered to represent population change due to sheltering in the ABM. An agent-based model consisting of individual population agents interacting across an environment was used as a prototype. However, this approach was limited in agent numbers to a maximum of a couple of thousand individuals, and was therefore not scalable to city size. Other issues included excess complexity, which resulted in undesirable agent behaviours. Another ABM approach was tested, which used cells of aggregate population data as individual agents, similarly to a cellular automata, but with considerably more scope for movement across a transport network, and for sensing of shelter site across the entire model environment.



a) b)

Figure 47: The difference between the design of population representation and movement for a) the ABM prototype, b) and the final model.

For a) dark points represent the population agents, each equivalent to one individual. Each agent has an individual behaviour and can interact with its environment, to seek shelter, the larger dot. For b) individuals have become values attributed to agent cells, and the values can appreciate or depreciate accordingly.



a) b)

Figure 48: a) Original trial population modelling concept for RADPOP, and b) The final gridded modelling approach.

A simple modelling framework has been developed for the RADPOP ABM, shown in Figure 49. Across this framework, spatial, population and hazard data is included into the Netlogo model, with more data about exposure produced by the movement of the population to seek countermeasures, in the ABM. In the context of the final model, the number of grid cells produced by Population247 output corresponds to the number of agents in b), with the same range of population characteristics. For example, if different age and gender layers are included, then this creates corresponding agent layers for those layers.

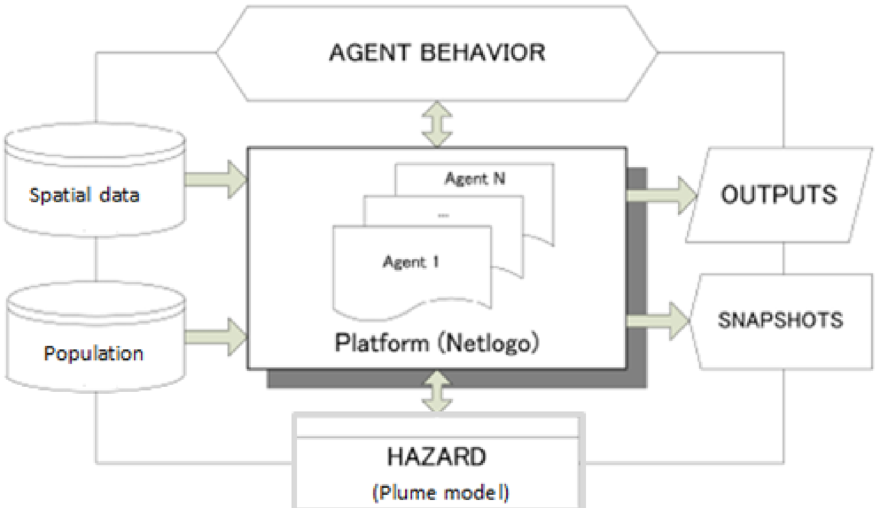


Figure 49: The RADPOP ABM modelling framework.

This forms the basic design of the model. One of the most important features of the ABM is how population density change is modelled. The population needs to be represented as a density layer, but to also include change, as the population changes due to seeking shelter. Figure 51 shows a snapshot of cells from an original 100*100m population density grid surface produced by SurfaceBuilder. These units are maintained in the ABM, and each individual grid squares act as an agent, which can gain or lose value as populations remain in-situ or travel to shelter.

Overview	**Purpose** To explore spatiotemporal population movement for and exposure for different subgroups during a hypothetical nuclear accident.
	State variables and scales **Agents**: Population agents of different genders and ages; and contaminant plume agent. **Spatial units and temporal units**: Meters and minutes (ticks). **Patches:** Dasymetric environment with simple transport network and shelter sites.
	Process overview and scheduling Spatial representation and communication of mechanisms
Design Concepts	**Design concepts** **Emergence:** None **Adaptation:** Agents seek nearest shelter and avoid plume agent. **Objectives:** To discover how different demographics, travelling at different speeds, reach shelter during a hypothetical nuclear accident. **Sensing:** Agents sense shelter and plume agent. **Interactions:** None between population agents. **Collectives:** Demographic grouping (e.g. Females of working age) **Observation:** Visual inspection, and output of time taken to travel to shelter sites for different population agent classifications.
Details	**Initialisation:** Started at t=0, however initial temporal, population and spatial values are provided by prior Population247, PACE and NAME modelling outputs
	Input: Annotated GIS, population and plume polygon data.
	Submodels: None

Figure 50: The ODD protocol for RADPOP (Grimm et al., 2010)

It is also important to revisit the ODD protocol, as this enables some guidelines to be set out for the design of the model (Grimm et al., 2010). The ODD for RADPOP is shown in

Figure 50. The agents operate within a limited set of rules, with the ability to sense and seek transport networks and shelter sites, to sense and avoid the contaminant plume and with limited

agent interactions. Figure 51 provides insights into how spatiotemporal population data was integrated into the ABM.

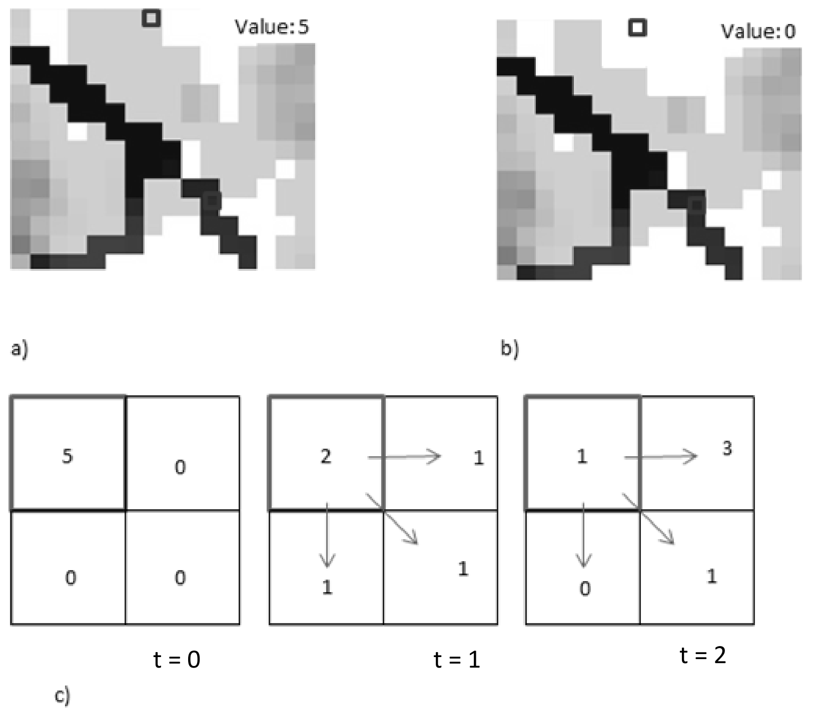


Figure 51: Integrating Population247 spatiotemporal data into the RADPOP ABM.

In Figure 51, a) represents a sample of population density output at t= 0, when spatiotemporally relevant origin population data is initially seeded into the ABM. Population densities for grid cells are represented by a gradient of colour, where paler cells are less densely populated, and darker cells are more densely populated. A selected grid cell is delineated within the top right hand corner of both a) and b). One cell is in a populated area, and the other in the transport network. Figure 51 b) represents the population at t= n. Population has moved from one grid cell to the transport network, as the model population seeks shelter. The populations move across the grid as shown by Figure 51 c), with a random nearest neighbour distribution, whilst seeking transport network flow to reach shelter, or a shelter cell. As the population travels across population agent cells, exposure is accumulated. It is important to note that whilst the model is cellular in structure, it differs to cellular automata approaches due to the integration of a transport network, and capacity to seek shelter beyond the nearest neighbour.

The origin population density layer, seeded from Population247 for a specific, represents the ABM population at t= 0 and is categorised as sheltered, or travelling to shelter, dependent upon the initial population activity in the subgroup. For example, the proportion of the population that is at home or residential is already sheltered, as are immobile populations such as prison or boarding school inhabitants. However, populations engaging in workplace, education and leisure and retail activities will require shelter, and therefore need to seek shelter at designated sites in the model environment. Only populations in the plume environment will need to act upon countermeasures, and those that are beyond these areas will remain inactive and in-situ.

Separate spatial layers for the background, population, and hazard plume are included in the model, to provide a simple but realistic simulation environment. The population input to the model is from the original Population247 data format of 100m^2 units of population density, which become agents in the model, across the population grid, with values that can increase or decrease as populations relocate to shelter. There are a number of entities in the model layers, which are described in the next section.

4.4.5 Model entities and processes

Each of the spatiotemporal layers of the model has specific attributes and entities of positionality and visualisation, which are the physical characteristics of each attribute. The model also includes entity characteristics for population and plume layers, which determine their nature and value in the model environment. For example, the individual units or agents in the population layer have the capacity to spatially change in value over model time. The model also has intelligence attributes, which define the behaviour of population attributes by sensing the location of plume distribution and of shelter sites. The rest of this section describes the agents in the layers of the model and their behaviour. The different features of the model are shown by Figure 52, where interactions between the model environment, plume agents, population agents and shelter agents are described visually as layers in the whole model.

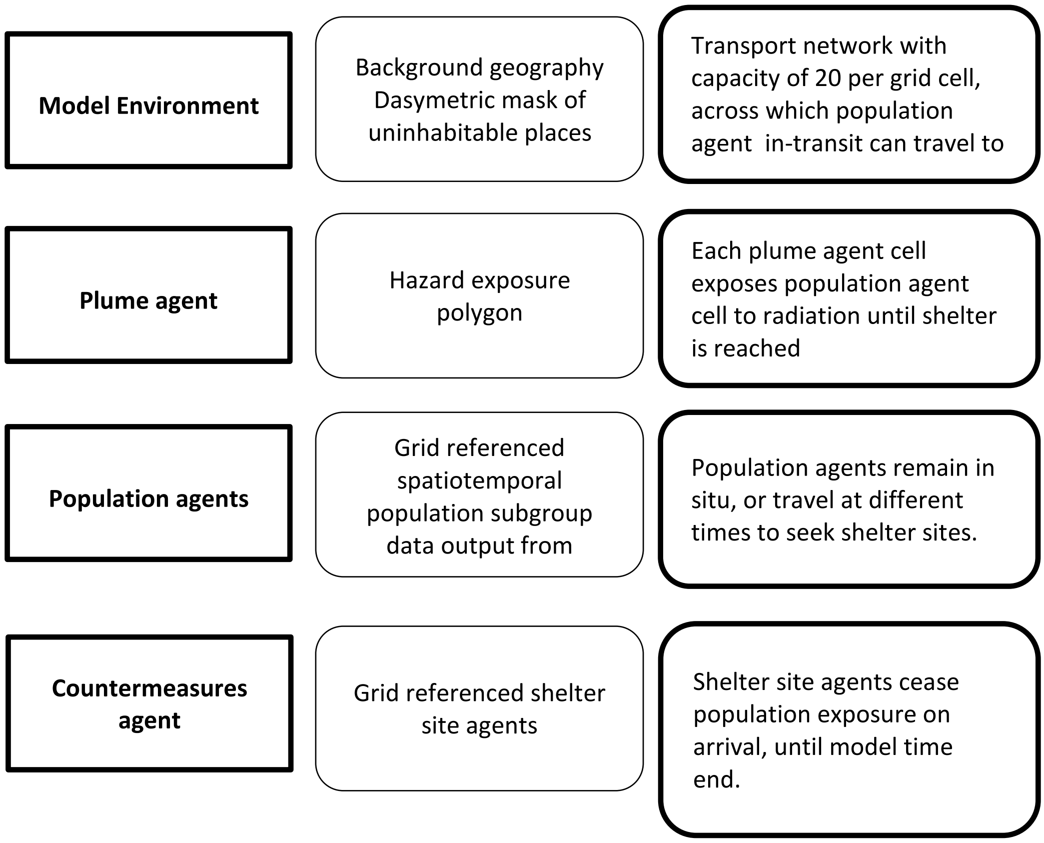


Figure 52: Agent and environmental interactions in the RADPOP geospatial ABM.

Human agent cells are created from the gridded population layer produced by Population247, which is seeded at the start of each model run. Human agents are one of the most important features of the model, and the model uses individual population density unit cells as agents with aggregated population values. The value of human agent cells can increase or decrease, as a population migrates to shelter, and decisions made by human agents will impact upon exposure outcomes. Human agents have the capacity to decide whether to remain in situ, or to identify the best route to shelter via the background transport network. The speed of movement to shelter is demographically determined by the activity that the agents are undertaking. For example, working-age agents will migrate to shelter more rapidly than agents over 65.

The plume agent is a spatiotemporal agent with spatial values that change as the plume disperses over time. This agent has the capacity to expose human agents to radiation. Human agents under the plume are exposed, and exposure ceases once the human agents are inside a shelter patch or beyond the domain of the plume. These agents interact in an environment that includes a transport network layer, background geography, and shelter site agents. The transport network layer is derived from the Population247 road network and is constructed of edges and vertices for roads and junctions for major transport routes, and the network has a maximum capacity which prevents all agents from immediately seeking shelter, adding realism to the model. The background geography exists to provide an environment in which the agents interact. Agents can only travel across the road network, beyond urban areas. Shelter sites agent cells do not have a maximum capacity. Shelter sites receive no radiation exposure, even when located in the plume. Shelter agents protect Human agents from exposure. Upon reaching a shelter agent the human agent will be classified as safe, and exposure will cease.

The model environment has a need for spatial and temporal scales. The spatial scale is determined by the background geography and is measured in scaled meters, with the capacity to zoom and inspect specific population agent cells. The temporal scale is broken down into hourly increments from the start of model time, which are described as “ticks” in the model environment. One model cycle takes 12 hours, to represent the movement of population subgroups to shelter during the crucial first 12 hours of a radiation emergency scenario. The simulation begins at declaration of emergency, which can be initiated by the model GUI. The end of model time may not correspond with the end of the emergency scenario, and the model will have the capacity to run for longer. However, in the context of this work a 12 hour model cycle provides insight into the most important phase of a hypothetical radiation emergency, whilst representing the change in daytime population distribution. The simulation begins at “declaration of emergency” and ends at “end of emergency”. Human behaviour is in reality very complex. However, for the purpose of the model and in contrast to our whole population approach for previous methodologies, our focus is upon evacuation behaviours of female population subgroups. There are four particular behaviours that have been identified as relevant to understanding the behaviour of populations during a radiation emergency:

1. Stay in Place: Stay in Place behaviour will include the proportion of the population who are at home, in an immobile population such as a prison, or in hospital. This proportion of the population will remain sheltered at their existing location during the model time.
2. Change Activity to Seek Shelter: This behaviour will represent the movement of working, leisure and tourism population groups as they seek shelter. When capacity is reached at one shelter site, the next nearest site is sought. Once Shelter is reached, the Human agents remain there and do not accumulate any further exposure.
3. Follow: Follow behaviour is initiated by proximity to other similar population subgroups with the same traits. This will change the behaviour of the agent, to follow to shelter.
4. Delay: Some population subgroups, such as the elderly, may have a delayed response to warning and informing. Therefore, these groups will have a slower rate of movement for seeking home.

This model will explore the impacts of staying in place or changing activity to seek exposure, as whilst feasible, it is not desirable to model following or delay behaviours in the context of this thesis.

4.4.6 **Model outputs**

The model output features a new spatiotemporal population density distribution, based upon the movement of the population, and which includes a more accurate representation of population in-transit to shelter, and a new population subgroup of those who have reached shelter.

Figure 53 shows a prototype model which was developed in Netlogo to test concepts before case study development. This model includes environment, population, plume and shelter entities. Whilst Population247 data was integrated into the prototype, the transport network is not evident in the GUI, and the hazard plume was represented as a polygon of exposure, rather than including more sophisticated information about radioactivity concentrations generated by plume modelling. However, NAME plume dispersal polygon is included in Case study II to improve realism, and to create spatiotemporal estimates of likelihood of exposure for the different population subgroups.

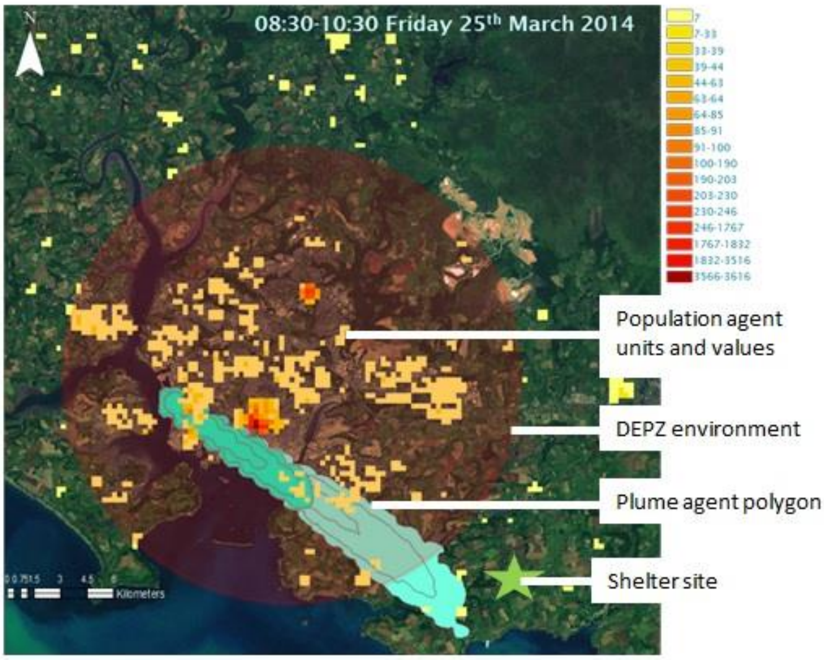


Figure 53: A prototype of the RADPOP ABM environment, including a background map, hazard plume, DEPZ, shelter sites and a female working-age population.

The next chapter presents the first case study, which whilst being a stand-alone study of radiation exposure and health effects to spatiotemporal population subgroups; also provides data for Chapter 6, Case study II that presents the RADPOP agent-based model.

Chapter 5: Case study I: Daytime exposure during a hypothetical radiation emergency

5.1 Overview

This chapter introduces the first case study, which applies the modelling approaches discussed in Sections 4.2 and 4.3. The purpose of this study is to test a novel combination of modelling approaches, to gain insights into how gender could impact upon the likelihood of radiation exposure during a hypothetical nuclear accident scenario in Exeter, UK. This study examines the intersections between spatiotemporal population and meteorological dispersal modelling, to analyse how the different spatiotemporal trends demonstrated by male and female populations may impact upon these two groups likelihood exposure to ionising radiation. Atmospheric dispersal modelling has been applied to simulate the accidental dispersal of a source term, which has been integrated with population modelling output of comparable spatiotemporal granularity to assess outcomes to the population.

In this chapter, Section 5.2 provides background information and justification for the choice of case study site, Section 5.3 describes a study-specific setup and any additional data included in the case study, and Section 5.4 presents a study of spatiotemporal population exposure to Caesium-134 during the first 12 hours of a hypothetical radiation emergency. Section 5.5 examines the health effects of accidental radiation exposure to a population during the first 1 hours of a hypothetical radiation emergency, and section 5.6 summarises the outcomes of the case study presented within Chapter 5.

5.2 Case study I context

The UK began the world's first civil nuclear energy production programme in 1956 and has a successful legacy of power generation spanning 60 years, to date. Nuclear energy currently contributes approximately 18.5% of the UK's electricity portfolio by providing 10 gigawatts of electric energy (GWe) per annum. However, a new phase of nuclear reactors with increased energy generation is anticipated in the near future, following publication of the UK Nuclear Industrial Strategy (Horvath, 2016, HMGovernment, 2013). This phase of nuclear energy will consist of three new nuclear power stations on existing NI sites with a total capacity of 19 GWe, 16 GWe of which will be operational by 2030 (WNA, 2016). The new nuclear energy will be implemented by third generation plus pressurised water reactors (PWR). These reactors are considerably safer than light water-cooled graphite moderated reactors (LGWR), such as Chernobyl Reactor 4, which is discussed in Section 3.3.4.

However, no technology is infallible. Whilst the safety of nuclear reactors has improved and nuclear power is arguably now one of the safest forms of energy generation, emergency planning is still determined by the IAEA to be an international requirement for every PWR reactor (IAEA, 2008). One of the most important objectives of the IAEA accident management programme for PWRs is the minimisation of on-site and off-site releases, and their adverse consequences IAEA (IAEA, 2008). As discussed previously in Section 3.3.2, nuclear accidents and other radiation emergencies are low frequency but extremely high impact events. Whilst the likelihood of an accident scenario of equivalent scale to Fukushima or Chernobyl in the UK is very low, the potential short-term and long-term adverse consequences are significant. To ensure UK radiation emergency preparedness, every nuclear installation (NI) must have a formal offsite radiation emergency plan (REPPIR legislation). Each plan will include a component of training and exercising to examine and prepare for the consequences of hypothetical scenarios to improve the outcome of any real emergency that may occur.

A hypothetical accident site and scenario has been developed for application to Study I and II. A careful hypothetical site selection process has been implemented to ensure optimum suitability. To identify the relevant geographical characteristics of a suitable hypothetical location, an initial comparative study was conducted into UK NI sites which is included in Appendix B. Several significant criteria were assessed, including NI type, location, proximity to a settlement large enough to qualify as a town, and existing detailed emergency planning zone (DEPZ) guidelines. In total nineteen existing sites were identified, eleven of which are coastal and located within 15km of a settlement with a population of 15,000 or greater. DEPZ radius ranges from 1 to 3km, dependent upon NI size. Whilst several current UK nuclear power stations are situated away from populations, nearly all naval facilities are located near the populations of port cities which may increase the scale of exposure should an accident occur. The requirements identified for the hypothetical site are proximity to the coast, and proximity to a settlement of population greater than 15,000. Of existing UK NI sites, the PWR reactor at Her Majesty's Naval Base (HMNB) and Royal Dockyard Devonport, Plymouth, UK was identified as relevant for informing the final hypothetical scenario and site choice. The next section provides an overview of HMNB Devonport, to provide relevance and context to a similar hypothetical NI radiation emergency scenario site in Section 5.2.2.

5.2.1 HMNB Royal Dockyard Devonport, a relevant existing nuclear installation site

Her Majesty's Naval Base (HMNB) and Royal Dockyard Devonport, UK is located in the City of Plymouth. Plymouth is a city with a residential population of 256,384 individuals (PCC, 2011). The population has an even gender split, and employment primarily occurs within UK economic sectors including public administration, education, retail, and manufacturing (PCC, 2011). Figure 54 shows the city of Plymouth, with HMNB Devonport highlighted centrally.

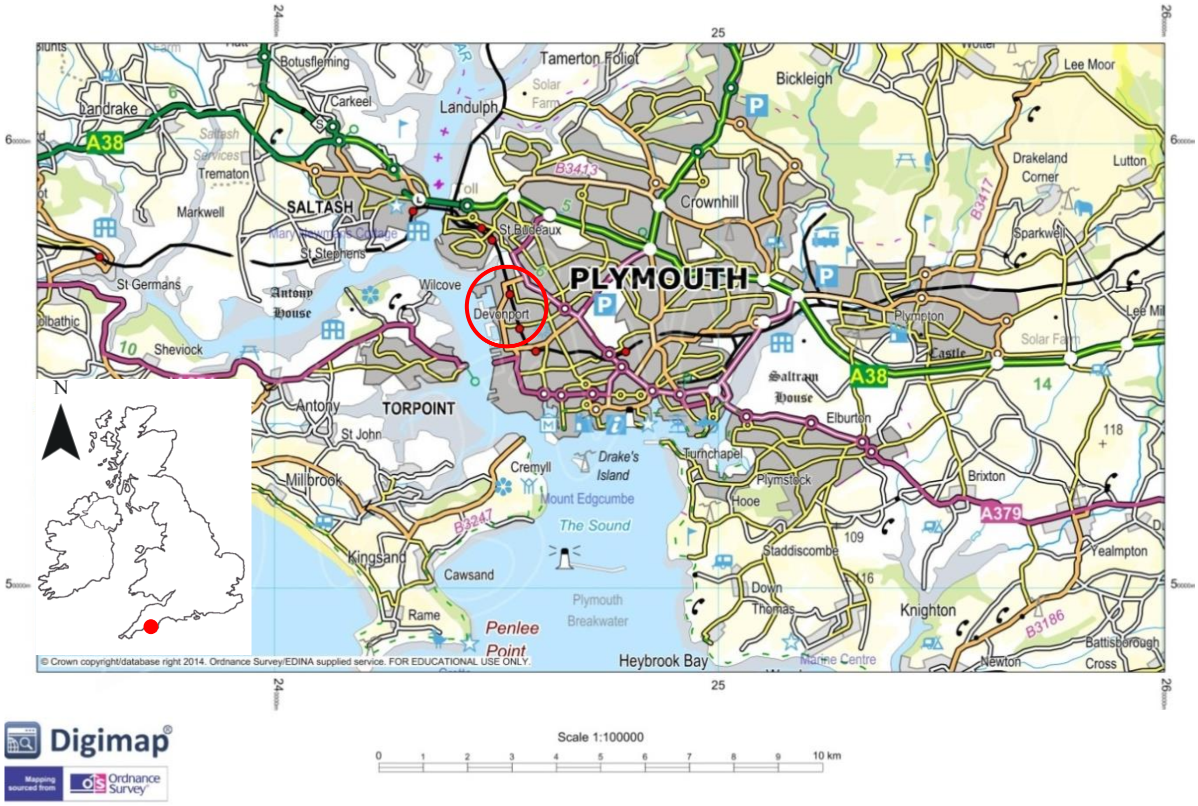


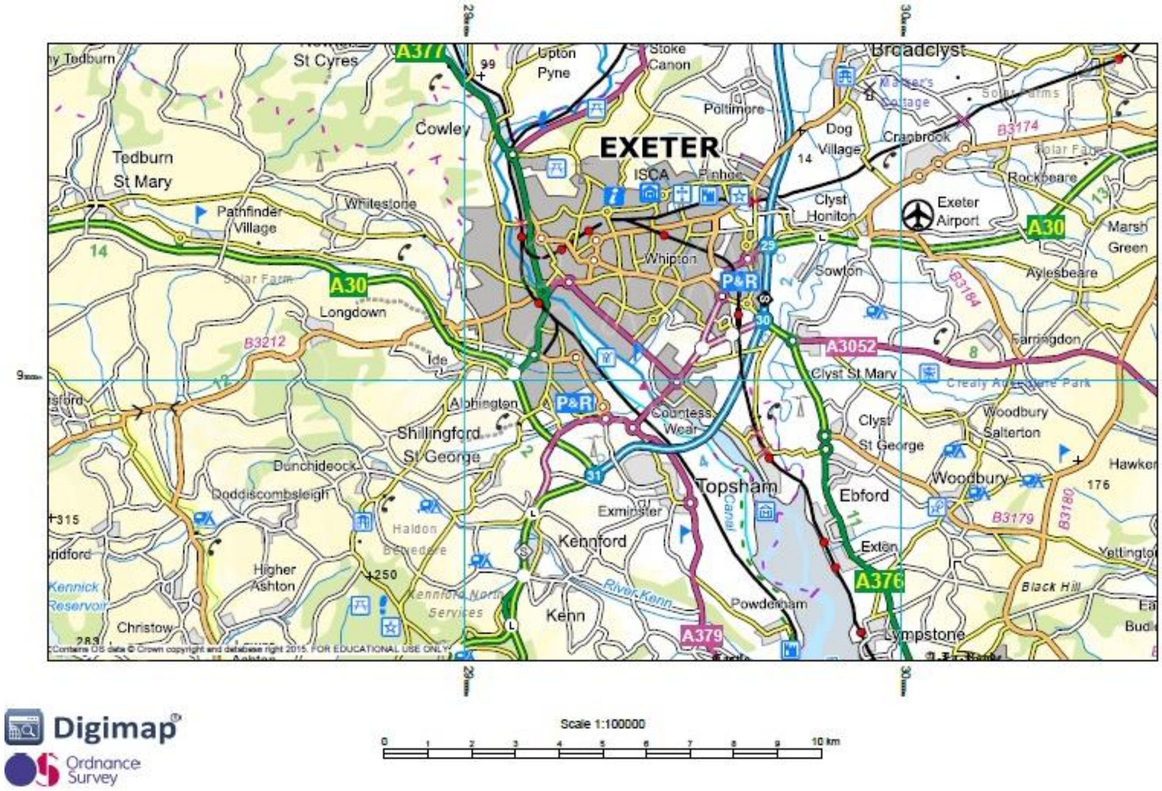
Figure 54: The City of Plymouth with HMNB Devonport highlighted in red (DigiMap, 2014). Contains OS data Crown Copyright © Ordnance Survey 2014.

The site operates within REPPIR, and a public version of Devonport Off-Site Emergency Plan (DOSEP) is available from Plymouth County Council (PCC, 2013). A Reference Accident is used to describe a worst-case scenario for the purposes of training and exercising (PCC, 2013). HMNB Devonport's current Reference Accident anticipates a scenario of radiation exposure across a radius of 10km (PCC, 2013). The facility has a recent accident record which includes a number of 'near-miss' scenarios, where a potentially severe accident has been averted. There have been Type B events at the facility; which are accidents that have a significant impact, or the potential for significant impact, upon safety or regulatory compliance (DE&S, 2010). These include 90 minute of power loss to coolant for a PWR in July 2012, a fire which required the evacuation of HMS Torbay on 26th April 2013, and an accidental firing of an unarmed torpedo by the dockyard on 12th March 2014 (BBC, 2011, BBC, 2013). HMNB Devonport was issued with an improvement notice by ONR on 16th July 2013 with a requirement to meet site-operating criteria by 31st March 2014. The current accident record for HMNB Devonport demonstrates that there are smaller scale accidents associated with NI sites in the UK, which helps to justify developing a more advanced understanding of potential radiation emergencies. The offsite DOSEP radiation emergency plan associated with this site provides useful reference information such as envisaged scale of Reference Accident, which will be incorporated into the hypothetical scenario within both studies.

Whilst the circumstances and plans surrounding HMNB Devonport are used to inform a realistic study scenario, modelling a hypothetical accident inclusive of the actual HMNB Devonport site and surrounding population would be inappropriate. This thesis will be in the public domain, therefore direct modelling of a hypothetical nuclear accident at HMNB Devonport may result in misinterpretation which could cause unnecessary concern across Plymouth, and may even pose a risk to existing nuclear security and emergency planning measures. For these reasons, a comparative study site has been selected which shares attributes with the city of Plymouth but does not include an NI site within the study boundaries. A realistic but hypothetical NI site source term will be located in the chosen study site instead, to enable the methods described within Chapter 4 to be explored in a neutral environment.

5.2.2 **The City of Exeter, the case study hypothetical scenario site**

The previous section conducted a careful examination of the criteria required for a realistic hypothetical scenario site by identification of important characteristics of an existing UK NI site. The selection requirements for this hypothetical study site are proximity to coastline, population of greater than 15,000, potential for implementation of a DEPZ of 1 to 3km and a Reference Accident radius of 10km, availability of a locally relevant regional radiation emergency plan for a comparable existing NI site beyond the geographic boundaries of the study, and a comparable current economic and demographic structure to Plymouth, UK. Appendix B was applied to identify locations with regional radiation emergency plans, and similar settlements with emergency plans but without NI sites were identified. Initially suitable locations included Blackpool, Bournemouth, Brighton, Exeter, Grimsby, Skegness and Swansea. However, the most comparable location is the small city of Exeter, Devon, UK. Exeter was therefore selected as the most suitable location for the hypothetical case study scenario site. A map of the city is shown in Figure 55.



OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

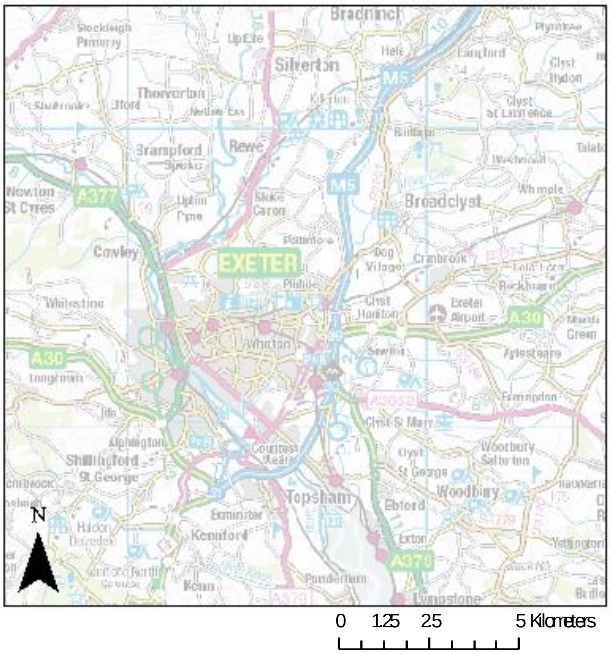
Figure 55: A map of the City of Exeter, UK.

Exeter is a historic city with a population of approximately 117,800 individuals (ONS, 2012). Similarly to Plymouth, the city is not demographically diverse and major ethic groups being represented during the 2011 Census were 93.1% White, 1.7% Chinese, 1.2% Polish and 0.5% German (ONS, 2012). Exeter has a well-developed transport infrastructure that includes road, rail, bus, and international flight networks. Exeter has an economy that prioritises tertiary sector industries, including the University of Exeter, the Met Office and Devon County Council as three main employers. There is also a substantial science park, an intermodal freight depot and a business park within the city bounds. Approximately 35,000 individuals commute daily to work in Exeter, and like much of Devon, but unlike Plymouth, tourism is a major economy, constituting 7% of employment. Despite this, the city is home to several culturally significant tourism features such as Exeter Cathedral, the ruins of Rougemont castle, Northernhay gardens, the Royal Albert Memorial Museum and three theatres. There are two hospitals, the privately-run Nuffield Hospital, and the NHS Royal Devon and Exeter Hospital with 797 inpatient beds and 80 day case beds. Exeter is a city that has plenty of higher education opportunities, including the University of Exeter, satellite campuses of the University of Plymouth, and Exeter College.

The city of Exeter has a prison, which has an operational capacity of 533 male individuals, including young and adult offenders (http://www.justice.gov.uk/contacts/prison-finder/exeter accessed 17/12/2015). An additional feature of interest is the direct comparability of population size between the city of Exeter, UK and that of Pripyat and Chornobyl in Ukraine, which was affected by the Chernobyl accident and subject to large-scale evacuation, which is described in greater detail in Section 3.3.4. The next section describes the study setup, thereby identifying the most significant parameters within which to work.

5.3 Study setup

The study methodology has been explored within Chapter 4. However, specific parameters are required to create a robust study. Parameters are required for geography, population and radiation hazard, and this section describes the parameterisation process. The general geographical region of the case study has been defined and demographically explored in Section 5.2.2. However, more detail is required to define the suitability of the specific location, including study site size, shape and Population247 grid cell resolution. A study area of 15km^2, centred upon the City of Exeter (BNG origin X: 286000, Y: 079500m), was selected. This site area provides a workable region within which to investigate how population varies across a city, providing scope for both a larger-scale urban overview and the investigation of smaller scale population dynamics. The specific study area is shown in Figure 56.



OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

Figure 56: The specific 15km^2 study area for Case Study 1.

The next sections explore the specific parameters for population density and radiation plume dispersal.

5.3.1 **Population modelling**

The processes for producing a spatiotemporal population density layer using Surfacebuilder in the context of the Population247 modelling system have been described in Section 4.3. of the thesis. However, there are specific parameters for this, which have not as yet been explored. This section describes these parameters and contextualises them within the remit of the study.

The purpose of this study is to discover the whereabouts of an existing population and its subgroups, for greater understanding of population distribution during a radiation emergency. For this scenario, the first twelve hours are critical for assessment of population whereabouts, to improve emergency service provision by the enactment of countermeasures such as sheltering or evacuation. The residential population density is already known. However, the day-time population remains unknown, and is therefore the focus of this study. Time slices of population subgroup density are therefore produced on an hourly basis, from 0700 to 1800. Table 14 provides an overview of the different types of demographic population data which has been included in Case Studies 1 and 2.

Topic	**Data Source**	**Reference**	**Level**
Residential population (2011 Census)	LC1105EW KS101EW LC4411EW QS421 EW ONSPD	Residence, sex by single year of age. Usual resident population. Student accommodation by age (student aged population). Communal establishments. Grid reference/OA/PC linkage.	OA
Education	EDUBASE2 HESA National Travel Survey	School addresses and population statistics. Higher education statistics. NTS0614: Trips to school by main mode, length and age, UK 2011.	Site
Healthcare	HSCIC NHS Choices ONSPD	Annual hospital episode statistics for A&E, in- and out-patients. Healthcare addresses. Grid reference/PC linkage.	Site
Workplace (2011 Census)	WP1101EW WP605EW WP702EW	Sex by single year of age (workplace pop.). Industry. Distance travelled to work.	WZ
Leisure, tourism and retail	VisitEngland Retail reporting	GB tourism/day visits survey. Acorn, Experian, retail reports, UKTUS.	Site
Background	DofT	Average Annual Daily Flow (AADF)	Network

Table 14: Parameters for population data included with Case study 1.

Population densities have been produced at hourly intervals to provide compatibility with hazard modelling outputs, and to show incremental day-time population change. Census day 2011 occurred on Sunday 27th March 2011, and therefore population is modelled for both case studies for a reference date of Monday 28th March 2011, which was the first working and educational day following the census, where the purpose of selecting this data is to showcase the most accurate representation of population density on hourly intervals for a typical term-time weekday population.

5.3.2 Population247 study specific parameters

This section describes the exact parameters employed to produce spatiotemporal population density surfaces by the Population247 framework. The modelled area of Exeter and the surrounding region (BNG origin X: 286000, Y: 079500m) consists of a 15km by 15km grid of 100m cells (n cells: 22,500). A 25km buffer zone is included to mitigate the effects of peripheral population movements into and out of the study area. The specific parameters for times and subgroups of population modelling within the Population247 framework are shown within Table 15. This table shows the types of population subgroup modelled, and the specific modelling times. This produced a wide variety of population density outcomes, the most relevant and interesting of which are included in this chapter.

Population Activity	**Subgroup participation**	**Gender**	**Modelled times**	**Outputs**
Education: 4 ST classifications	0-4, 5-9, 10-15, 16-64UNI	Male and female	0700, 0800, 0900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800	96 layers, across 12 times
Healthcare: 3 ST classifications	0-4, 5-9, 10-15, 16-64UNI, 16_64W, OV65	Male and female	0700, 0800, 0900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800	144 layers, across 12 times
Workplace: 6 ST classifications	16_64W	Male and female	0700, 0800, 0900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800	24 layers, across 12 times
Leisure and retail: 1 ST classification	0-4, 5-9, 10-15, 16-64UNI, 16_64W, OV65	Male and female	0700, 0800, 0900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800	144 layers, across 12 times

Table 15: Spatiotemporal modelling parameters for Case Studies 1 and 2, using Population247 system (ST: Spatiotemporal).

Whilst this study includes population data about the overall whereabouts of the whole population, which is contrasted with the female population engaged in education, retail and leisure, and health based activities. The reason for focus upon the female population is due to the potentially greater consequences of radiation exposure to this cohort, which have been explored in Section 3.2.2.

Figure 56 shows a snapshot of spatiotemporal population modelling output by the Population247 system, for the female population in education of Exeter, within the parameters presented earlier by this section. The population is represented across 12 hours from 0700, and there are observable differences in transport network loading and population density, as the resident and commuter populations engage in different activities. This output is included to provide observable insights into the way that the model shows changes in spatiotemporal population density over time, before the study examines differences within the female population subgroup, and its impact upon likelihood of exposure.

OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

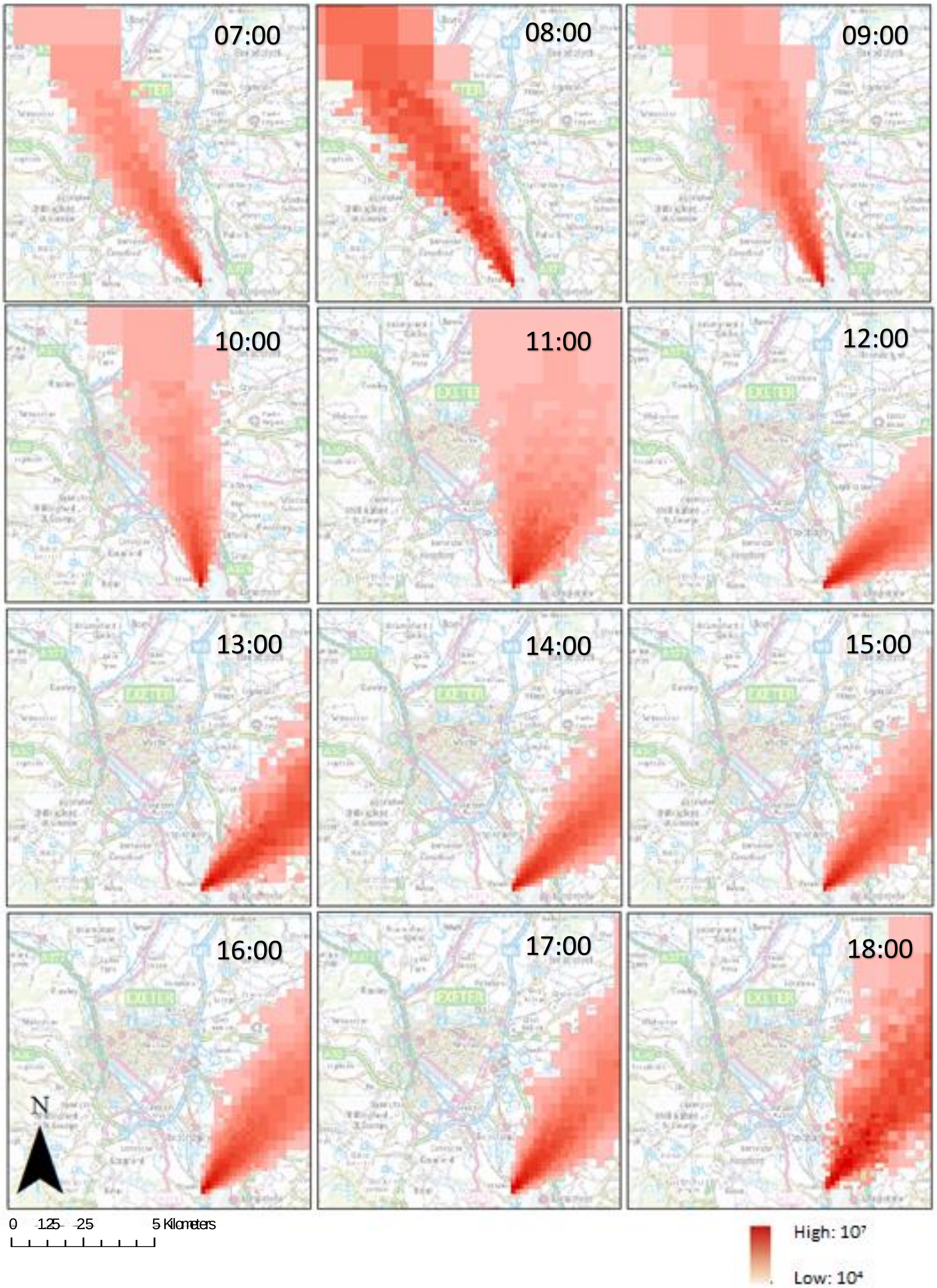
Figure 57: An example of spatiotemporal population modelling for this thesis across 12 time slices from 0700 to 1800, for the whole workplace female population of Exeter on 28th April 2011.

5.3.3 Radiation plume dispersal parameters for Caesium-137

The required case study parameters for modelling an urban spatiotemporal population density have been described within the previous section. However, it is equally important to define specific and complementary parameters for radiation plume dispersal, to discern the potential impacts over time of such a hypothetical scenario. Whilst a multitude of radioisotopes could potentially be released during an accident, this thesis has focused upon the dispersal and effects of one specific common isotope, Caesium-137 (Cs-137). Including a full suite of radioisotopes within both the case studies would introduce excessive and unnecessary complexity to the hypothetical scenario, however a wide variety of different meteorological and isotopic outputs were produced in conjunction with PHE radiation protection team, for the purpose of understanding the different health impacts of more realistic scenarios included in a radiation incident.

For the spatiotemporal modelling of exposure element of the study, Caesium 137 (Cs-137) was selected, because it features as an emission during nearly all nuclear tests and accidents, notably Chernobyl and Fukushima. Cs-137 is a bioavailable radioisotope, which means that it can be absorbed and distributed across the body upon exposure, with the highest concentrations occurring within soft tissue. The usual biological half-life, or time that Cs-137 remains within the body before excretion is approximately 70 days, however Cs-137 exposure can be treated with Prussian Blue, described in Section 3.2.3 of the thesis, which is used to decrease the biological half-life of Cs-137 to 30 days. The external dose for Cs-137 is comprised of gamma rays, whereas β-particles are an issue for internal exposure. A source term of 0.47PBq ($1.0x10^{15}$Bq) of Cs-137, which is equivalent to ≈1% of Chernobyl emissions for this isotope, was selected with guidance from PHE as a realistic amount for an accident scenario in the UK (PHE, 2015).

Cs-137 was modelled across the study area on Monday 28th March 2011 for a meteorological sequence twelve times on an hourly basis, by implementing the PACE NAME extension in conjunction with MESUM5 meteorological data, discussed in Section 4.3.1. The modelling output generated occurs in equivalent time slices as for the population density layers, with the t=1 layer representing the first hour of potential exposure. The meteorological sequence of modelling output for Cs-137 is shown in Figure 58.



OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

Figure 58: An example of Cs-137 Bq/m^3 modelling outputs produced by the PACE NAME extension for sequence Met-1, from 0700 to 1800 for Monday 28th March 2011.

Options were available to model atmospheric and deposited Cs-137. Both outputs were produced, as included in Appendix C, however atmospheric Cs-137 was selected for inclusion within the first component of the case study, to better represent the immediate hazard to exposure and inhalation. It is important to note that the purpose of this modelling output is to test the feasibility of a modelling framework for a hypothetical scenario. Also, local meteorology exhibits short-term variability and therefore may not be representative of prevailing conditions for the region. However, representative data was included for the day of hypothetical exposure, the weather was dry with hazy sunshine and a peak temperature of 19^{o}C, which would have good conditions for dry deposition, which can be a source of external exposure in urban environments.

5.4 Spatiotemporal population exposure to Caesium-137 during the first 12 hours of a radiation emergency

This section of the case study presents estimated exposure by combining Population247 spatiotemporal population modelling outputs and PACE NAME outputs for Cs-137 radiation plume hazard to male and female populations, for a hypothetical radiation accident on Monday 28th March 2011. The population estimates are analysed with Cs-137 PACE NAME outputs using ArcGIS to assess the risk of exposure.

5.4.1 Estimating risk from exposure

Risk of exposure is estimated by examining the concentration of Cs-137 above the population for each specific time. The underlying spatiotemporal population density layer below the contaminant plume is assessed, and populations exposed to concentrations above threshold values for atmospheric concentration are determined as being at risk. In the context of this study, IAEA guidelines are implemented which assume that any level of radiation above 200 Bq/m^3 which would classify as a high natural background radiation level, and therefore may the capacity to create risk. In the context of this study, this means that concentrations above 20,000Bq per 100 m^2 population density unit are identified as containing populations that are at risk. Section 3.2 explores the different ways that radiation exposure can be assessed. In the context of this case study, the concentration of radiation is assessed in Becquerel SI units, which are equivalent to one nuclear disintegration per second. Becquerel are used to explore the risk of exposure to a radiation hazard. Becquerel (Bq) are also used as the measurement for this study, as this reflects the UK requirement for all radioactive sources in the UK to be measured in Bq. However, one Bq is a very small quantity of radioactivity, and therefore most sources have activities of millions or billions of Bq. The second component of this study examines dose and health effects due to radiation exposure more closely.

The atmospheric concentration of Cs-137 was initially modelled from 0700 to 1800 for Monday 28th March 2011. The outcomes of this modelling were shown visibly in Figure 58, but the change in concentration over time has also been graphed in Figure 59, to show how concentration, and therefore exposure, has changed over the time of the model. The time-integrated air concentration (TIAC) is the output of interest, rather than deposition, which can also be modelled, due to its more significant immediate health impacts. It is evident from the graph that there is initial peak in Cs-137 concentration start of release 07:00, which then sharply declines, and peaks again at 13:00 due to a second release.

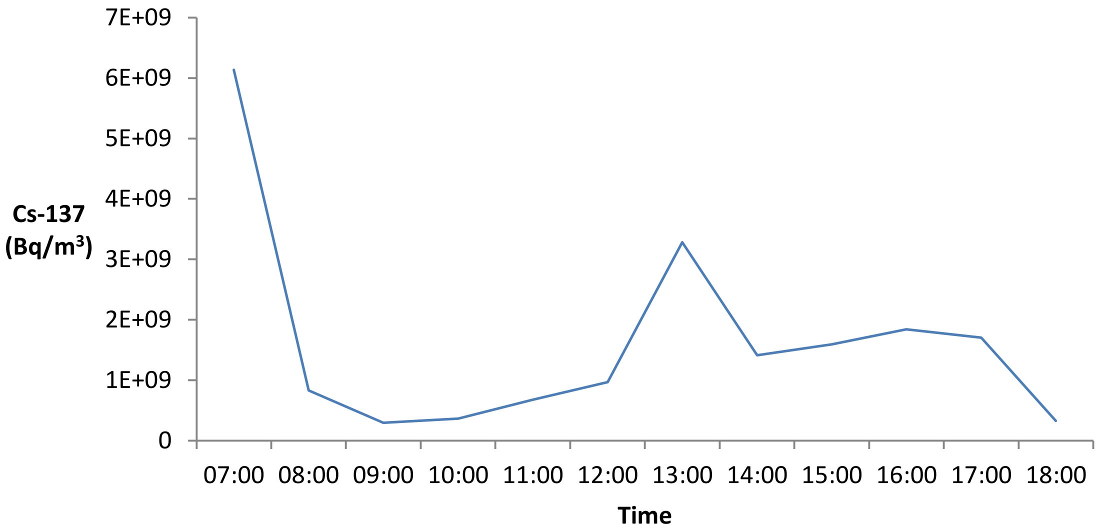
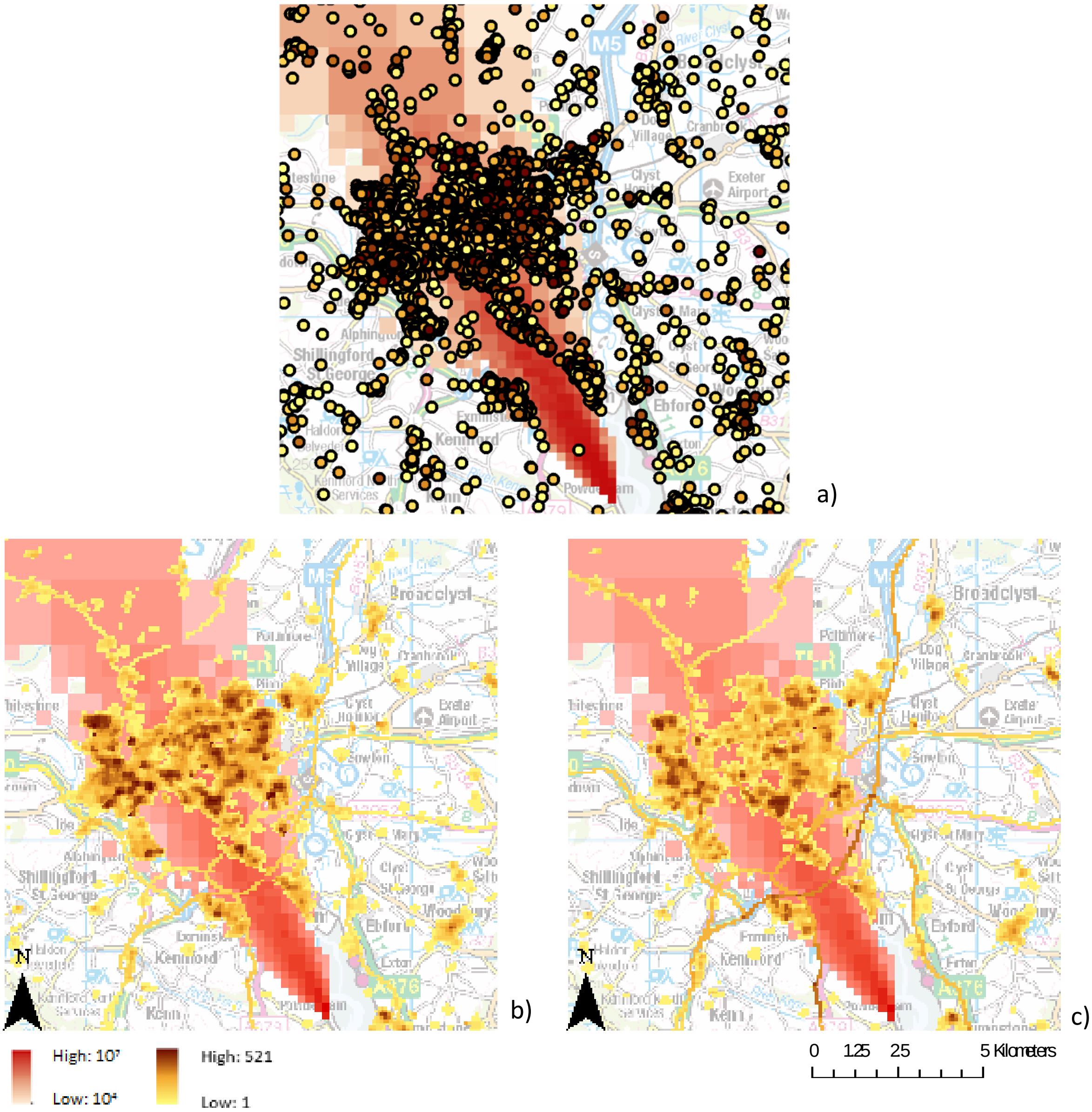


Figure 59: A graph of time-integrated air concentration (TIAC) of Cs-137 (Bqsm^3) within the case study location of Exeter for a specific dispersal, generated by PACE NAME from 0700 to 1800 on Monday 28th March 2011.

The NAME output for Cs-137 for 0700 was combined with population outputs from Population247 for the whole male and whole female populations at 0700 and 0900 on 28th March 2011 to identify if population distribution, and therefore exposure, is different. The same plume from 0700 was intentionally used for comparative purposes, to reflect how the same stage of accident could affect a population at different times. Selected results are shown within the next figures.

The purpose of these results is to demonstrate that these approaches have been integrated to produce a more realistic scenario for radiation protection and emergency planning, and to showcase the marked differences in population distribution that occur when comparing a residential and a spatiotemporal population modelling output. The results are compared with a 2011 Census residential dataset. Within the Census residential dataset the population is represented as point values, rather than a gridded population density, and is representative of the night-time residential population.



OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

Figure 60: An example of spatiotemporal population modelling for Cs-137 and a) Census 2011 residential population b) the male population redistributed using Pop247 at 0700 c) the female population of Exeter redistributed using Pop247 at 0700 on 28th April 2011.

Within Figure 60, it is visually evident that the populations are spatiotemporally different. This is significant as if the result was modelled with a Census population there would be no variation, and therefore no difference in population exposure. Interestingly, this figure demonstrates that for this specific spatiotemporal scenario there is actually a larger proportion of the male population within the plume pathway, and therefore potentially vulnerable to exposure, than for the female population. Whilst these results could be useful for emergency planning purposes, it is important to note that the Cs-137 results are hypothetical and for demonstrative purposes only, as they do not include the full suite of radioisotopes with health effects and therefore cannot provide insight into any anticipated health effects.

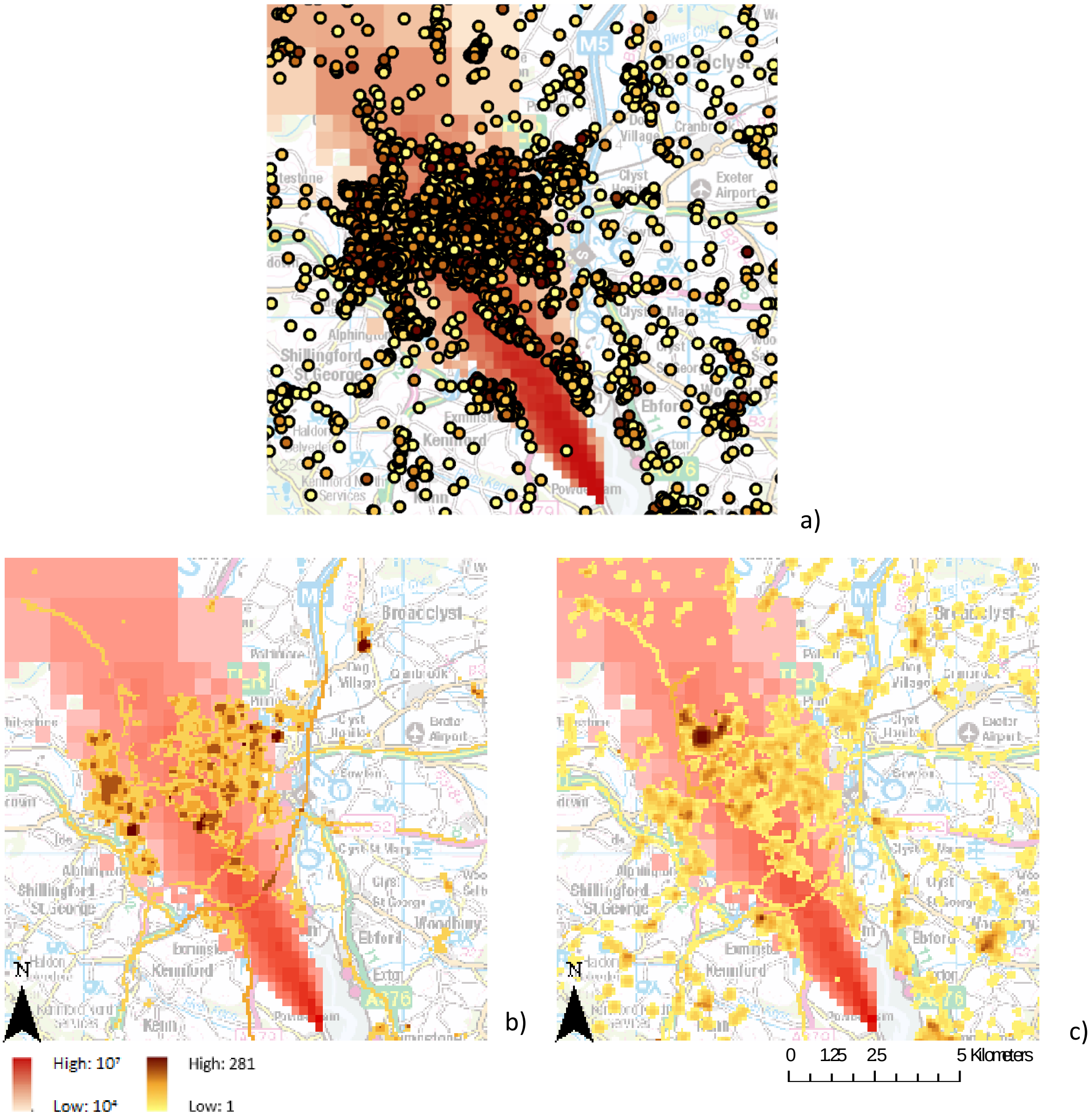


Figure 61: An example of spatiotemporal population modelling for Cs-137 and a) Census 2011 residential population a) the female workplace population at 0900 b) the female population in education of Exeter at 0900 on 28th April 2011.

Another insight into the differences that occur across a spatiotemporal population is shown within Figure 61. Here, the female workplace and education populations were compared for Exeter at 0900 on 28th April 2011. This is of interest as the population in education are younger and potentially more vulnerable to exposure than the adult population, as described in section 3.2.2. of Chapter 3. Again, these different patterns of exposure could be beneficial for targeting and developing emergency planning.

The next section of this chapter extends upon spatiotemporal approaches for understanding of exposure, to include PHEs PACE framework for the assessment of likelihood of health effects.

5.5 Health effects of accidental radiation exposure to a population during the first 12 hours of a radiation emergency

This section of the case study presents the results of health effects modelling of the impact of a typical suite of accidentally released radionuclides by implementing PACE with Population247 modelling outputs. The study assesses impacts to male and female populations, for a hypothetical radiation accident on Monday 28th March 2011.

The spatiotemporal population modelling layers were included within the PACE model, at PACErun stage, to understand the impact of exposure to a full suite of radionuclides. In this section of the study, the purpose is not just to assess how the spatial extent of exposure changes to the female and male population subgroups, but also to demonstrate how PACE can be combined with spatiotemporal population modelling to understand health outcomes. These bespoke source terms were selected in conjunction with PHE, to provide a realistic representation of a hypothetical UK accident scenario, and are shown for reference in Table 16. This enables a realistic reconstruction of potential exposure from all radionuclides during a radiation emergency to be developed.

Source term	**Phase**	**Release height (m)**	**Release duration (hr)**	**Release concentration (Bq)**
Isotope	**1**	**10**	**5**	
I-131				3.52E+15
I-133				1.82E+15
Cs-134				9.40E+13
Cs-137				7.20E+13
Te-132				2.30E+15
Ba-140				5.00E+14
Mo-99				1.44E+14
Ru-103				3.36E+14
Ru-106				1.46E+14
Ce-141				1.68E+14
Ce-144				1.00E+14
	2	**10**	**7**	
I-131				8.80E+14
I-133				4.55E+14
Cs-134				2.35E+13
Cs-137				1.80E+13
Te-132				5.75E+14
Ba-140				1.25E+14
Mo-99				3.60E+13
Ru-103				3.70E+13
Ru-106				8.40E+13
Ce-141				4.20E+13
Ce-144				2.50E+13

Table 16: The source term types, quantities and times of release, included within health effects assessment in Case Study 1 as advised by PHE, 2015.

The parameters within Table 16 produced an output in two distinct phases, and the concentration of each isotope was mapped over time, to understand the change in air concentration. This is shown in Figure 62, which provides insight into the changes in concentration that may occur during a hypothetical radiation emergency.

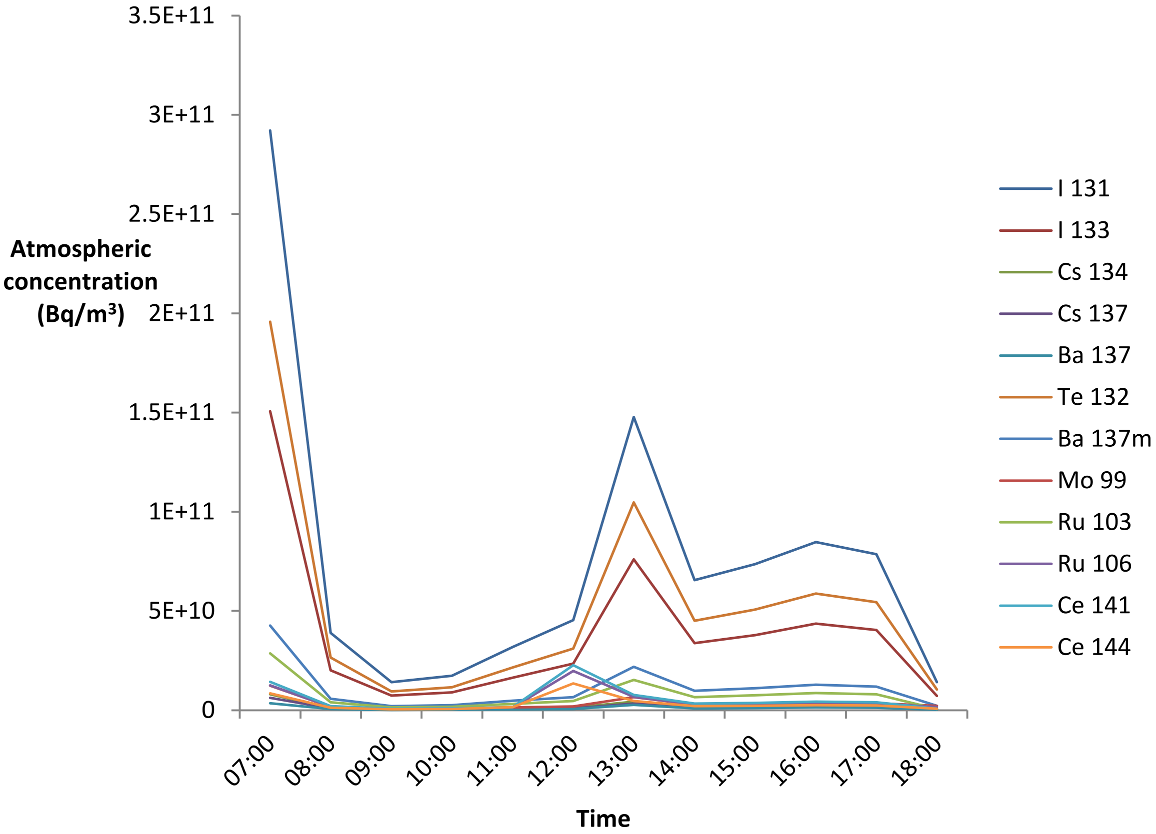


Figure 62: Spatial concentration within the case study location, for the twelve different isotopes featured for comprehensive assessment of health effects due to radiation exposure using PACE (PHE 2015).

Population247 modelling outputs for different population subgroups were used to replace the PACE Census 2001 residential origin population, within the PACE modelling system using Python scripting. The model was run, and the new population inputs were analysed by PACE to provide health impact assessments of the following: total number of population exposed to a deterministic radiation dose, number of fatalities from deterministic effects, and the number of leukaemia cases, across the population input. However, there are a more extensive variety of health assessment options described in Section 4.3.2, which have not been included as they are beyond the scope and timescale of this study. The specific parameters of this case study were selected to gain insights into the immediate impacts of radiation exposure, and to provide a long-term context of the effects of a radiation accident to specific population subgroups. These criteria were examined with and without countermeasures, to investigate if countermeasures have more beneficial impacts to specific population subgroups. The outputs for total incidence of leukaemia are focused around outcomes for the under-five age group, as leukaemia risk is greatest for those exposed before five years of age (WHO, 2012a). This is a beneficial way of providing assessment to this specific demographic subgroup, and also for demonstrating the usefulness and relevance of spatiotemporal population subgroup estimates from radiation protection. It should be noted that whilst spatiotemporal information can be included to anticipate exposure time within the PACE modelling system, the final output is spatial but not temporal.

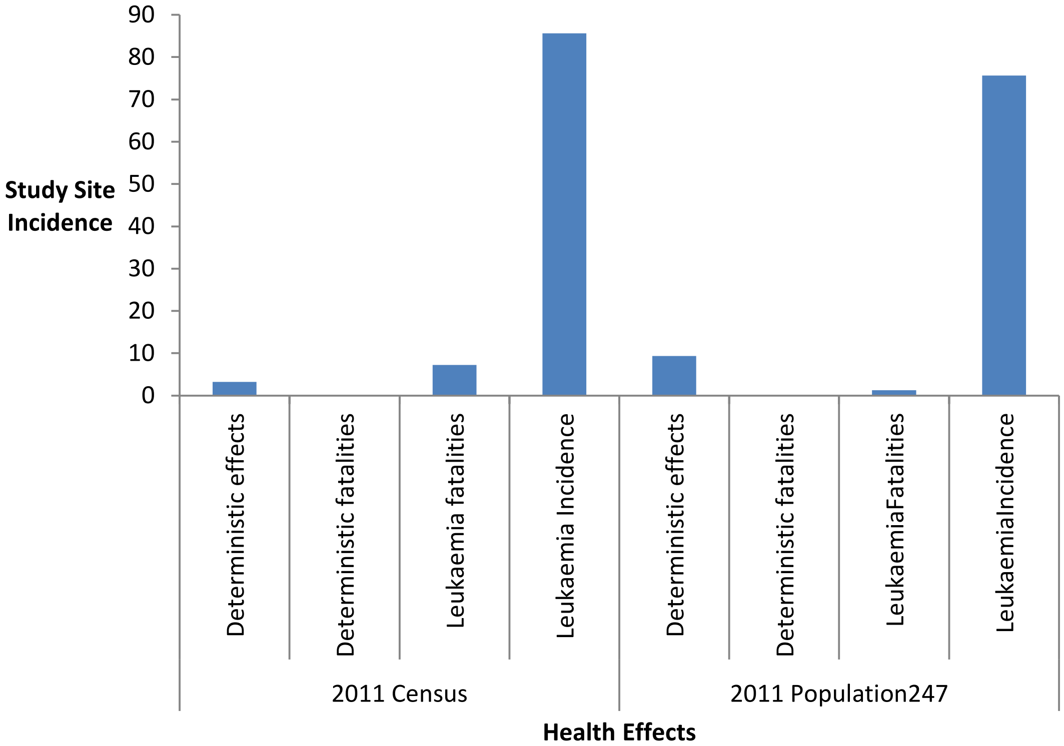
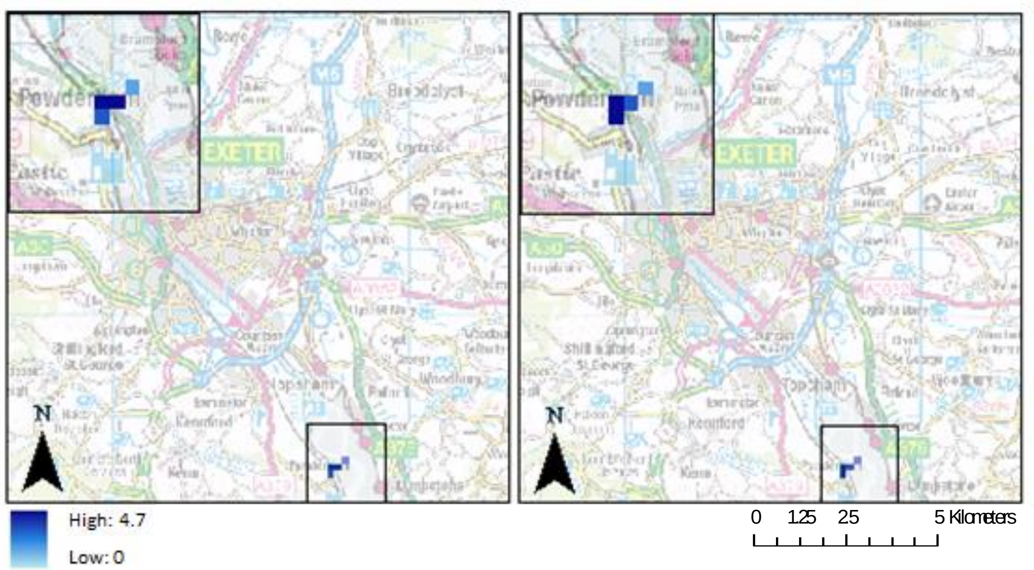


Figure 63: Comparison of health statistics generated by PACE for 2011 Census residential data and 2011 Population247 whole population data, modelled from 0700 to 1800 on Monday 28th March 2011.

In Figure 63, it is evident that the number of the population affected by deterministic effects is higher, when comparing 2011 residential population density dataset within the PACE modelling framework, with outputs produced by the inclusion of Population247 modelling framework population density estimates. This demonstrates that the nature of the data included within the model does affect the outcomes. However, it is interesting to note that whilst the incidence of leukaemia is higher within the 2011 census modelled output, the number leukaemia fatalities decreases when 2011. There is a slightly increased incidence of leukaemia and leukaemia fatalities within the 2011 census dataset modelled output. This may be due to the difference in population distribution away from residential areas, which are also away from the accident source, due to attendance at work and education activities. It is worth noting the total number of deterministic fatalities produced by this scenario are sufficiently low within the population, for both 2011 Census (0.003 deaths within the study region) and 2011 Population247 (0.001 deaths within the study region) PACE outputs, to not be of further relevance to this study. Therefore, focus is upon non-fatal deterministic effects to males and females, and leukaemia incidence and fatalities within the male and female population.

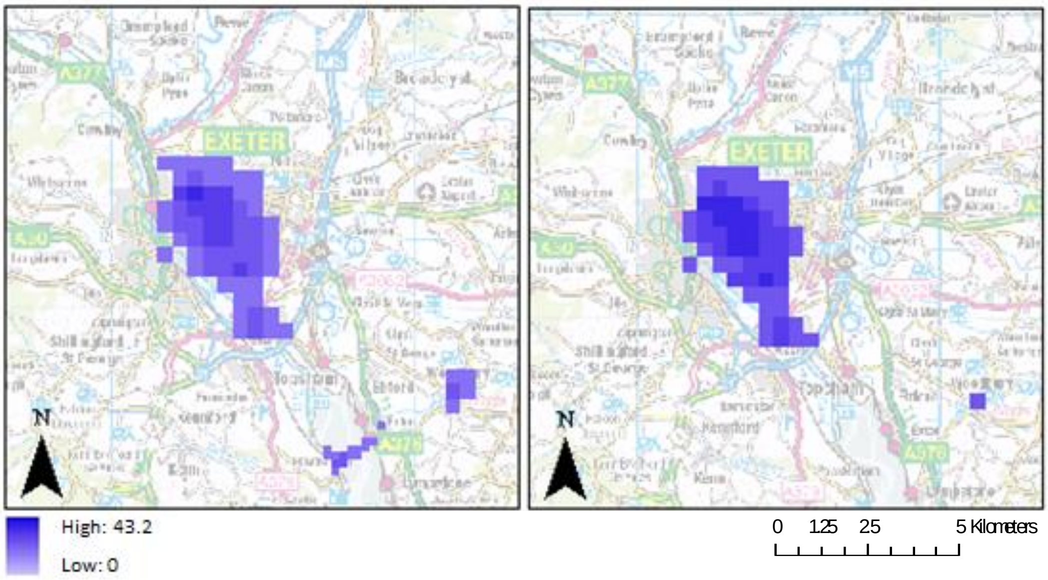


OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

a) b)

Figure 64: Density and location of occurrences non-fatal deterministic effects within, a) male and b) female populations, due to radiation exposure from 0700 to 1800 on 28th March 2011. The spatial extent is small, the box in the top left hand corner provides zoom.

Figure 63 shows that in the context of this case study scenario, there is little spatial difference in non-fatal deterministic effects, between genders. Interestingly, effects are most prominent around the source of the accident, towards the south of the map. This is to be expected, as the most significant exposure would have occurred before dispersion, close to the source.

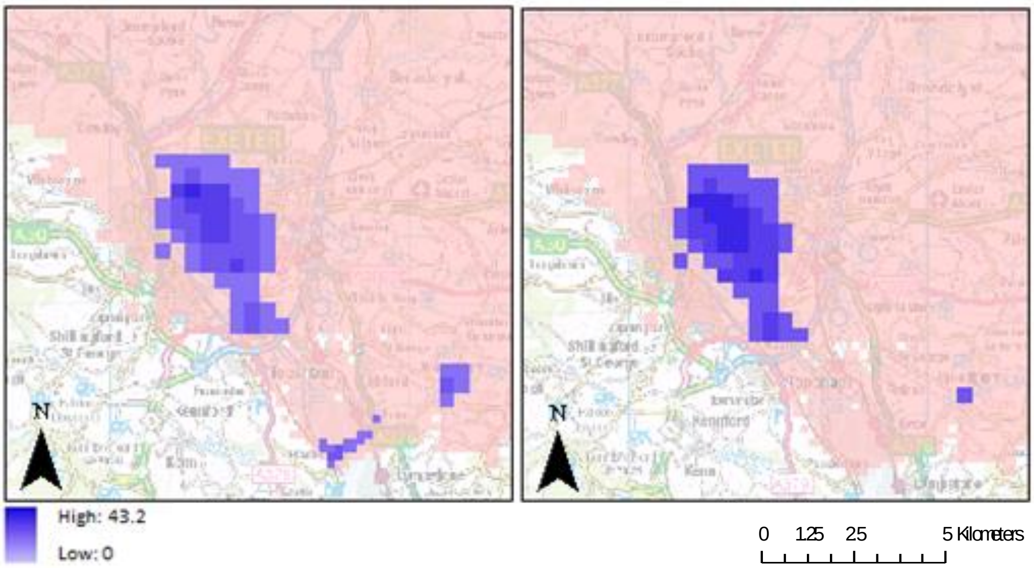


a) b)

OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

Figure 65: Density and location of leukaemia incidence for a) male and b) female populations due to radiation exposure, from 0700 to 1800 on 28th March 2011.

Figure 64 shows that gender may be significant to this scenario, as far as leukaemia incidence is concerned. The spatial distribution of male leukaemia incidence is more disparate than female. The effects are centred upon the city, as this is where the highest population densities are usually found. There is a small pocket of increased incidence in males, around the source of the accident. This may be due to a male bias in workforce across this area, due to the presence of a maritime environment. It is likely that the prevailing wind has also affected the likelihood of exposure at sufficient levels to cause long-term effects, as the locations of incidence correspond with spatiotemporal patterns of exposure across the twelve hours, as shown by Figure 65.



OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

a) b)

Figure 66: Radiation plume spatial total extent across 12 hours, and density and location of leukaemia incidence for a) male and b) female populations due to radiation exposure, from 0700 to 1800 on 28th March 2011.

This short study demonstrated that for all hypothetical scenarios examined, doses would decrease rapidly with distance from the plant. From an emergency response perspective, for some scenarios, evacuations of up to 3 km would be needed and are sensibly included within current DEPZ design. With respect to human health, it would be nearly impossible to distinguish most radiation-induced cancers that have been modelled from baseline incidence of the cancers examined in this study, as the frequency of incidence is too low to be significant. Another challenge with this study is its size, as it is not representative of a whole population. However, it gives an insight into what can be done by combining different modelling framework, and builds on some more realistic data assumptions than the insights that could be gained through PACE alone.

5.6 Summary

This chapter has presented one possible hypothetical radiation emergency scenario, which has been examined from the perspectives of spatiotemporal population exposure to a specific isotope by meteorological plume dispersal modelling with PACE NAME; and spatiotemporal population risk by probabilistic health assessment modelling by implementing PACE. However, this study intends to demonstrate the versatility of combining modelling techniques for the purposes of emergency planning, and therefore does not represent a single plausible accident outcome, instead being constructed using best available data to consider the challenges surrounding the issue. The primary focus of this chapter was to assess how vulnerability changes over time, and subsequently impacts upon health, for a hypothetical radiation hazard.

This study has demonstrated that the different genders may be subject to different exposure and health outcomes, due to differences in population whereabouts during a hypothetical emergency. Populations show a strong spatiotemporal variability to risk of radiation exposure, as would be anticipated in reality. However, health effects are shown to be less variable between genders than previously anticipated from literature in Section 3.2. This may be because the movements that different genders take in space and time are actually less variable in urban areas, than might be demographically anticipated, as the gender gap in employment and other activities closes.

Chapter 6: Case study II: An agent-based model of sheltering during a radiation emergency

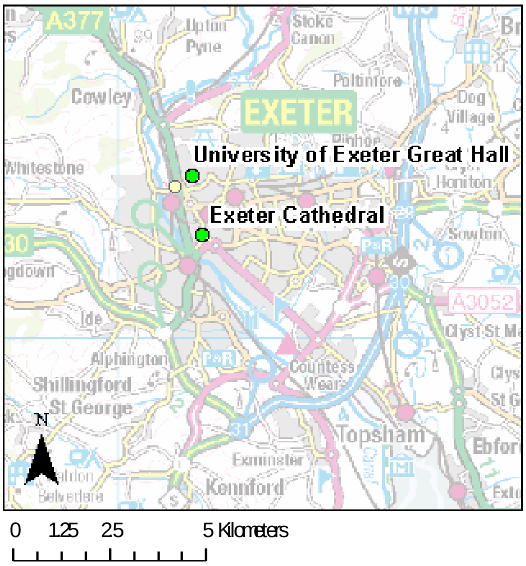
6.1 Overview

This chapter introduces the second case study, which applies an agent-based modelling approach to discern how improved knowledge of the usual whereabouts of a spatiotemporal population can influence the outcomes of a behavioural agent-based model for change in population distribution during a hypothetical radiation emergency scenario. Case study II is the natural extension of Case study I. Chapter 5 provided an original insight into the difference between estimation of exposure and health effects when contrasting census residential population density data, and Population247 modelled spatiotemporal population density outcomes. In this chapter, Section 6.2 provides background context and justification for the specific spatiotemporal and behavioural parameters of the agent-based model. Section 6.3 presents the model design and the results of a study of the application of spatiotemporal population data for improved estimation of population subgroup whereabouts. The chapter concludes with a summary of the significant aspects of the study.

6.2 Case study II context and setup

The spatiotemporal parameters of Case study II are similar to those of Case Study I, which are described in more detail in Section 5.3 of the thesis. The purpose of implementing similar parameters for both case studies is to maintain consistency across the approach, from the initial spatiotemporal population density output to the final agent-based modelling assessment. This will mean that the results of Case study I are in some ways comparable in geography and approach to Case study II. Therefore, the study site still encompasses the City of Exeter UK. However, there are some parameters in Case study II that are different, due to the nature of the modelling approach. This section provides context for those differences.

Whilst Case study I provided insights into population distribution for a variety of different activities, Case study II focuses upon how initial differences in the whereabouts of the female population, at one specific time, can result in differences in countermeasures success. Therefore, the different age and activity groups (Female 0-4, 5-9, 10-15, 16-64 Edu, 16-64 work, 65+) that are representative of the female Population247 modelling output are included, to provide a more accurate estimate of the combined female population distribution at that point in time than would be given by existing census residential datasets. The female population is the focus of this thesis case study, as the literature explored in Section 3.1.1. suggests that women and children are more vulnerable during the evacuation process. It is therefore significant to test this model upon a population that is historically at greater risk. Whilst both case studies include a twelve-hour timeline of emergency, from 0800 to 2000 for modelling purposes, this Chapter only includes spatiotemporal population density data which was generated for 0800. The reason for this difference of inclusion is to gain some perspective on how population distribution changes in comparison to usual, as a consequence of implementation of state of emergency. This is done by comparing hourly agent-based modelling population distribution outputs for countermeasure-seeking behaviour, produced from an original 0800 population distribution, with the equivalent spatiotemporal population density generated by Population247. Suitable sheltering and rest centre site(s) were identified and placed within the modelling environment. Sheltering sites are significant, as by going indoors and limiting ventilation the exposure dose can be reduced. To improve realism, the sites selected were those that could plausibly be implemented for sheltering within the city. Shelter site 1 is the Great Hall of the University of Exeter, EX4 4QJ (X: 291819, 093967) and shelter site 2 is Exeter Cathedral, EX1 1HS (X: 292061, Y: 092517) as shown in the close-up of the City of Exeter in Figure 66. These facilities have been selected over retail and industrial sites of equivalent size, due to their provision of vital amenities and catering facilities.



OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

Figure 67: The location of Exeter Cathedral and the University of Exeter, which are the two designated shelter sites in this hypothetical case study.

The next section explores approaches to including spatiotemporal populations in an agent-based model for evacuation.

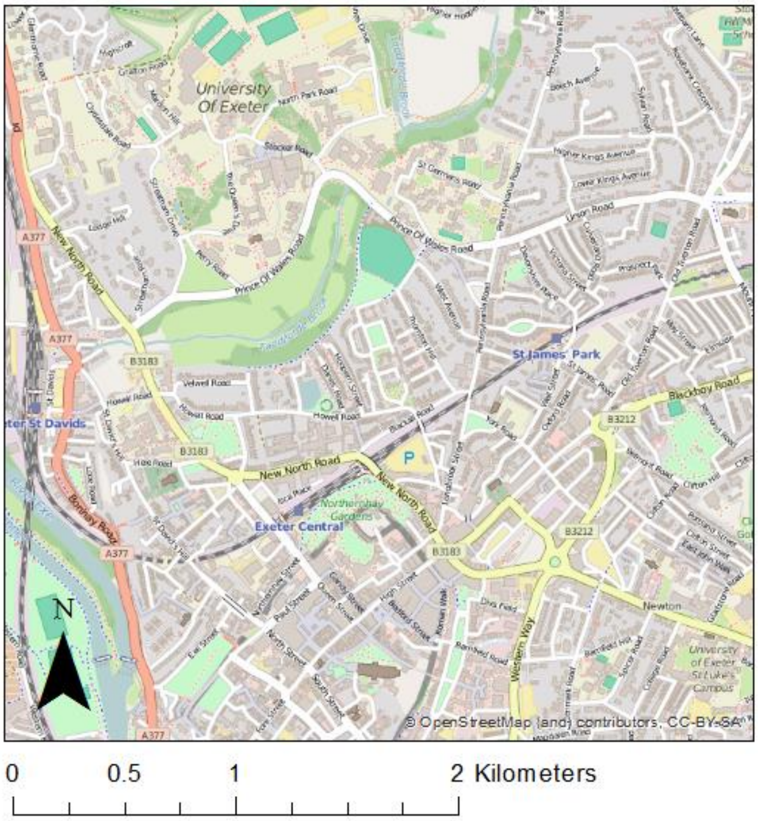
6.3 Inclusion of spatiotemporal populations in an agent-based model, to improve understanding of shelter-seeking during a radiation emergency scenario

This section describes the process for implementing an ABM in Netlogo for the assessment of change in the spatiotemporal population distribution during a radiation emergency scenario. A loose-coupling approach was selected for this study. This means that whilst additional modelled data is imported into the Netlogo modelling environment, there is no direct interaction between Netlogo and any other modelling environments such as NAME or Population247. Instead, loose-coupling of previous modelled outputs was selected, as whilst it reduces inter-model interaction it is a more efficient and flexible approach (Castle and Crooks, 2006, Brown et al., 2005). The relevant geography, and population and hazard outputs from Case Study I were imported into the Netlogo environment by implementing the Netlogo GIS extension package. This enabled an original model environment to be set up. Table 17 shows the original data library that was imported into Netlogo to create the model.

Data	File type
Population247 spatiotemporal modelling output (Female 0-4, 5-9, 10-15, 16-64 Edu, 16-64 work, 65+) 0800 28/03/2011	.ascii
Population247 transport network	.shp
NAME plume extent polygon	.shp
Background map of Exeter with shelter sites manually demarcated.	.shp

Table 17: Original and adapted data from Case Study I included within the ABM approach.

The model was set up to run for 720 ticks (model minutes), which enabled the population to seek shelter across this time, where the total number of ticks are equal to the first twelve hours of a hypothetical emergency from 0800 to 2000. The model environment excludes the rural environment surrounding the urban area of Exeter by classification of rural regions by colour in Netlogo as places that populations cannot explore. Within the environment represented in Case Study 1 there is a total capacity for 22,500 individual 100m^2 density units, which for the purpose of this study are referred to as patches, in keeping with Netlogo modelling language. A zone of 3km^2, which is equivalent to 30x30 100m patches, has been selected within the original study site to reduce the patch density to a manageable total of 900 patches. The geographical extent of this modelling environment is shown within Figure 68.



OS Map data ©Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

Figure 68: The 3km extent of the modelling environment for Case Study 2.

This is still a significant quantity, but maintains the Population247 scale whilst providing insight into population distribution for this area. As discussed in Section 4.4 of the methodology, individual population values are created by seeding data into the ABM as gridded population density patches (units) of 100m^2 which contain individual population agents that are capable of seeking the transport network, then shelter, with decreasing or increasing values dependent upon population movements. Each patch gains or loses population density as the agents travel across the model environment. Each patch can be inspected to assess the total population density, and each agent can be inspected to assess the agent type (female and age classification). Patches of population that are intersected by a contaminant plume are classified as “exposed”, whereas patches of population that are not, are classified as unexposed. Once a population is exposed, it cannot be unexposed. All individual agents are seeking shelter at two unlimited capacity shelter sites, to investigate how the location of sheltering in a city could impact upon the speed of access by different population subgroups. The population247 female subgroup modelling output is compared with female residential population data from 2011 Census, to identify any notable differences in population distribution and how that may impact upon understanding of shelter-seeking. The original difference in population count between the two inputs are shown within Table 18. The Census residential population reflects the local night-time population count, whereas the Population247 population takes into account the proportion of the population who are undertaking different activities at this time, and is therefore lower for this area.

Population247 female modelled output 0800 Exeter 3km^2	2011 Census female residential population Exeter 3km^2
8,056	10,013

Table 18: Original difference in population count between inputs for Population247 and Census 2011 residential female population subgroup

The female population agents are designed to travel at different subgroup-specific speeds. These speeds may not be directly reflective of the movement of different subgroups, but are an approximation to demonstrate the potential for understanding how different standards of mobility behaviour may impact upon shelter-seeking. Speeds are defined in km/hr, and each group has a different speed. A uniform speed of 5km/hr is maintained for whole female Population247 and 2011 census residential datasets. The speeds have been selected to represent the movement of different population groups. For example, young children will travel more slowly as they are smaller, whereas the older population will travel more slowly due to an increased likelihood of mobility challenges.

Female population subgroup agent	Speed (km/hr)
0-4	2
5-9	4
10-15	5
16-64 education and workplace groups	6
65 and over	3

Table 19: Difference in designated speed between the Population247 female agent subgroups.

The model was run for 100 iterations for both 2011 Census residential datasets and for Population247 outputs, and an average was taken for each result set to produce estimates of time taken to travel and distance travelled to shelter.

The model is setup by calling a procedure to reset the model prior to running, and to set the relevant population, geographical and hazard datasets. The setup is designed to "clear-all- but-globals" which maintains the model startup parameters. Specific population parameters (e.g. Female population 0-4) are selected and imported by the "population" button within the GUI. The "Go" button runs the procedure that enables the population to travel across patches, and via the transport network to reach shelter. Each population group "senses" the transport network and shelter sites, and uses a sensing "radius" to seek the most efficient route to the nearest shelter site. Once a shelter site is reached, the population remains in-situ until end of emergency, which is also the end of the model time. Each population subgroup is run individually as a "population", which is extracted from that specific subgroup file rather than creating a selection of different breeds with different properties. The plume polygon is included as an environmental agent, which is again "sensed" by population agents. Populations are either exposed or not exposed, as it would be beyond the remit of this thesis and require a much more extensive dynamic coupling approach with meteorological modelling outputs to attempt to estimate specific exposure.

6.3.1 **Results**

The modelled outcomes for this study showed that different population subgroups took different times to reach shelter, and that there was a discernible difference between time outcomes for 2011 census and Population247 female population counts. Figure 69 shows some of the model outputs, for four different times across an hour within model time. It is evident that the population has relocated across the site, in response to the plume polygon (highlighted in purple shading). The overall population density has increased as the population has moved towards places that are beyond the polygon. Remaining populations within the polygon are travelling to shelter.

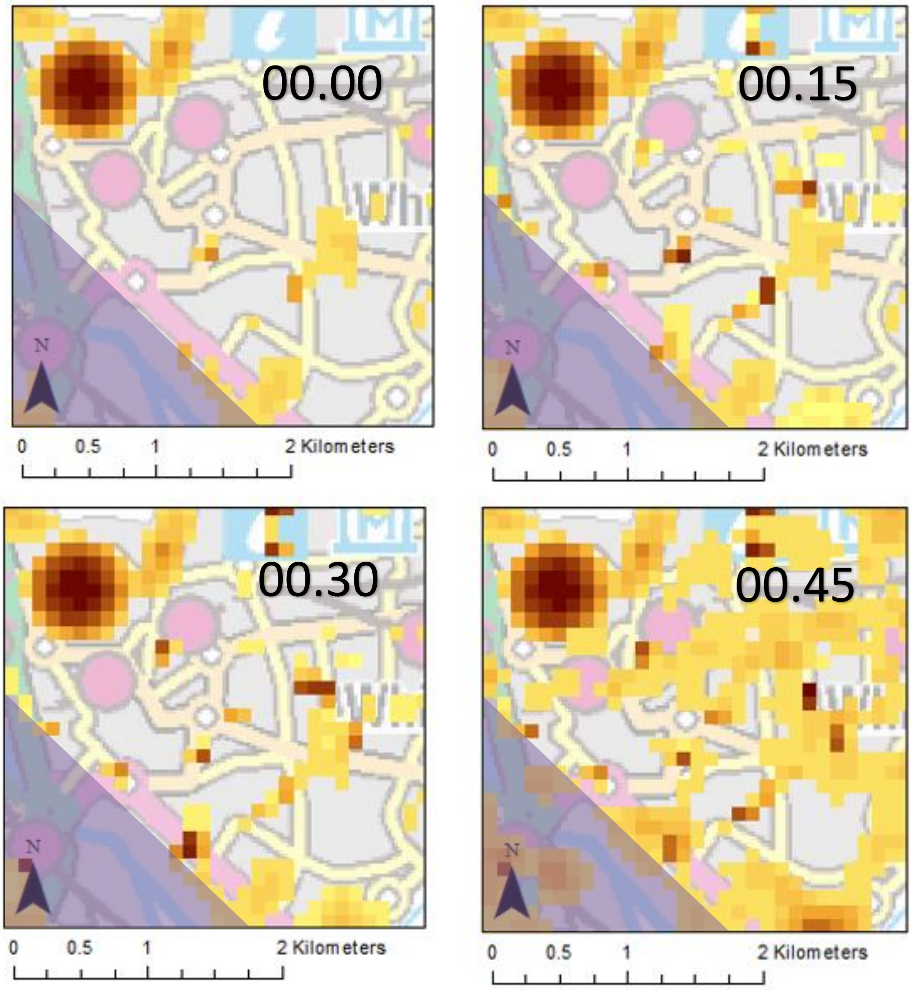


Figure 69: A mapped example of modelling output from the RADPOP approach across 45 minutes from the start of a test model time.

This difference is also evident in the graph for Figure 69. It appears that for this scenario, the Population247 population reaches shelter sooner than the Census 2011 population, which could be due to the difference in original population count of each group, but could alternatively be due to differences in starting location. There were also differences in shelter-seeking times for each population subgroup due to differences in travelling speed and the total population count at the start of model time. It is likely that the 16-64 education subgroup has an unusually low shelter-seeking time due to that population subgroup being small and already located near to the university shelter site at the start of model time.

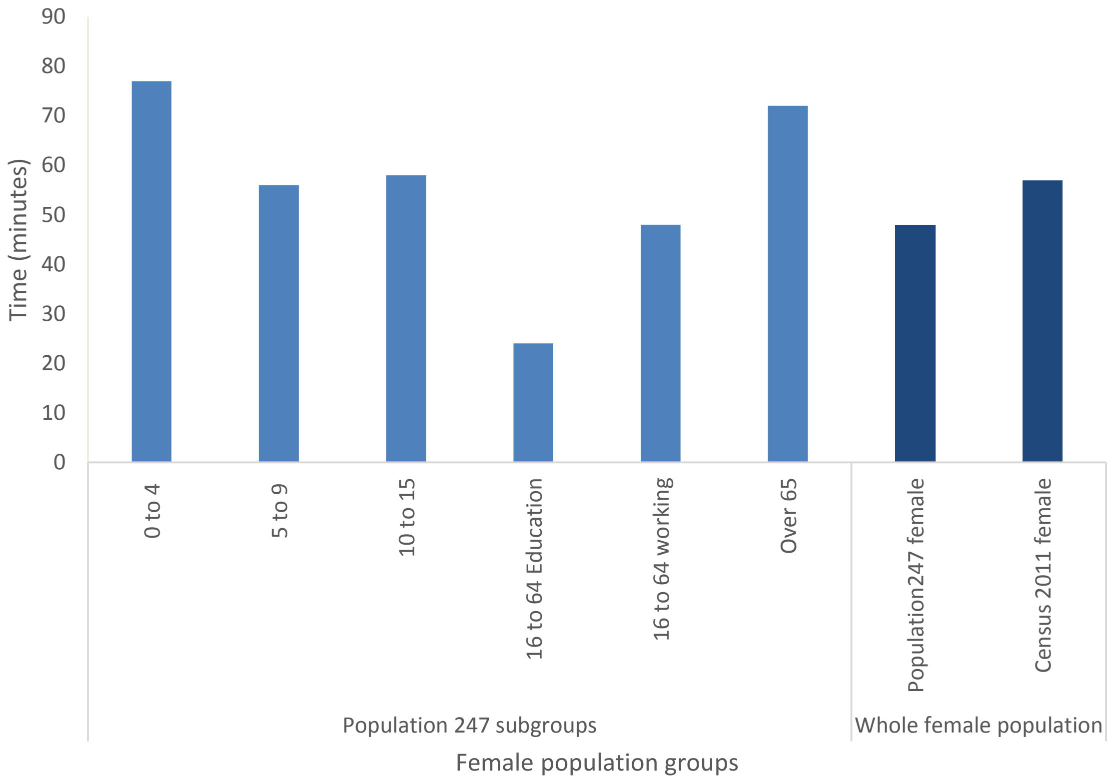


Figure 70: Average time taken for different population subgroups (0800, 28/3/2011), whole female population (0800, 28/03/2011) and Female 2011 census population to reach shelter.

The model was re-run for each of the Population247 subgroups at a standardised 5km/hr travelling speed, to identify if travelling speed or original location produced a more significant impact upon shelter-seeking. The results of this investigation are shown in Figure 70.

The difference in time to seek shelter between the different population subgroups becomes flattened when each subgroup travels at 5km/hr. It is evident that including specific behavioural traits such as speed of movement does have an impact, but the original location and size of the population subgroup still affects shelter-seeking. Providing more information about behavioural traits can benefit the model by increasing its intelligence, but if this other information is not accurate then the benefit of using accurate original population data could be lost.

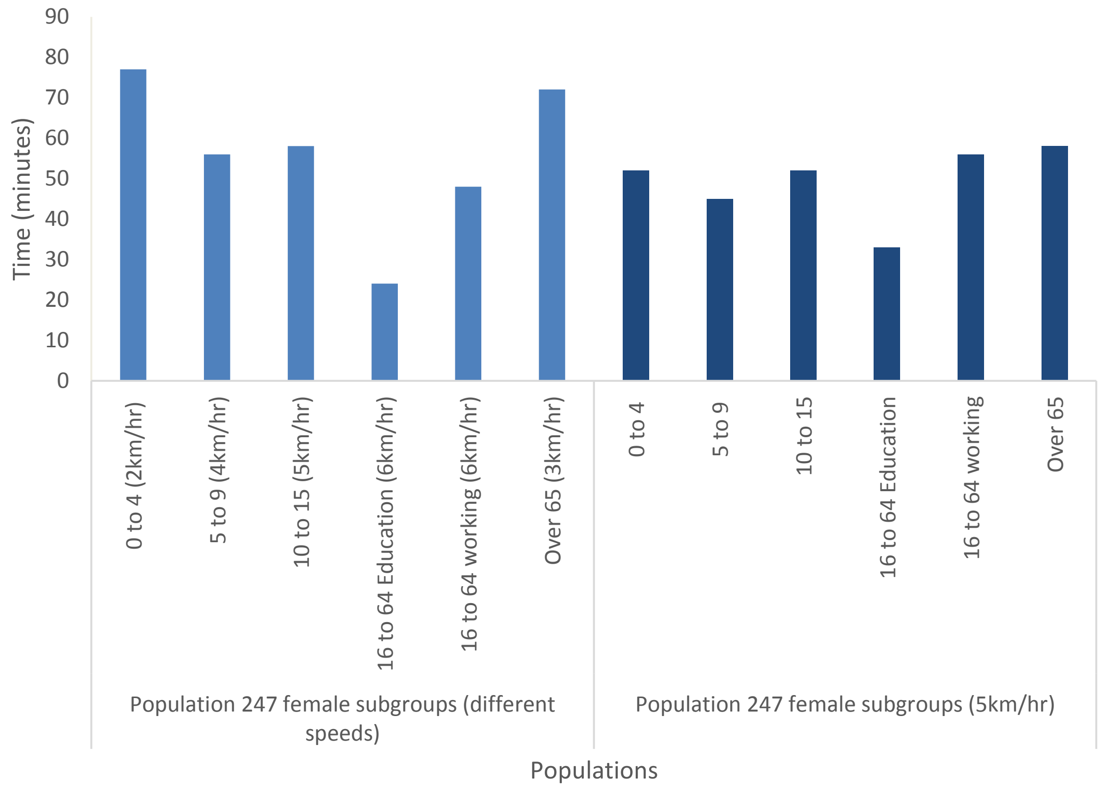


Figure 71: Comparison of Population247 female subgroup modelling outcomes for shelter-seeking at different speeds, and at 5km/hr across all population subgroups.

Distance travelled by the different population agents is affected similarly, where adult education takes considerably less distance to travel to shelter, due to original proximity to the shelter site, as shown in Figure 71. The Census 2011 female population travels slightly further on average to reach shelter, which may reflect the location of Shelter site 2 within the city centre, whereas residential populations are greater beyond this zone.

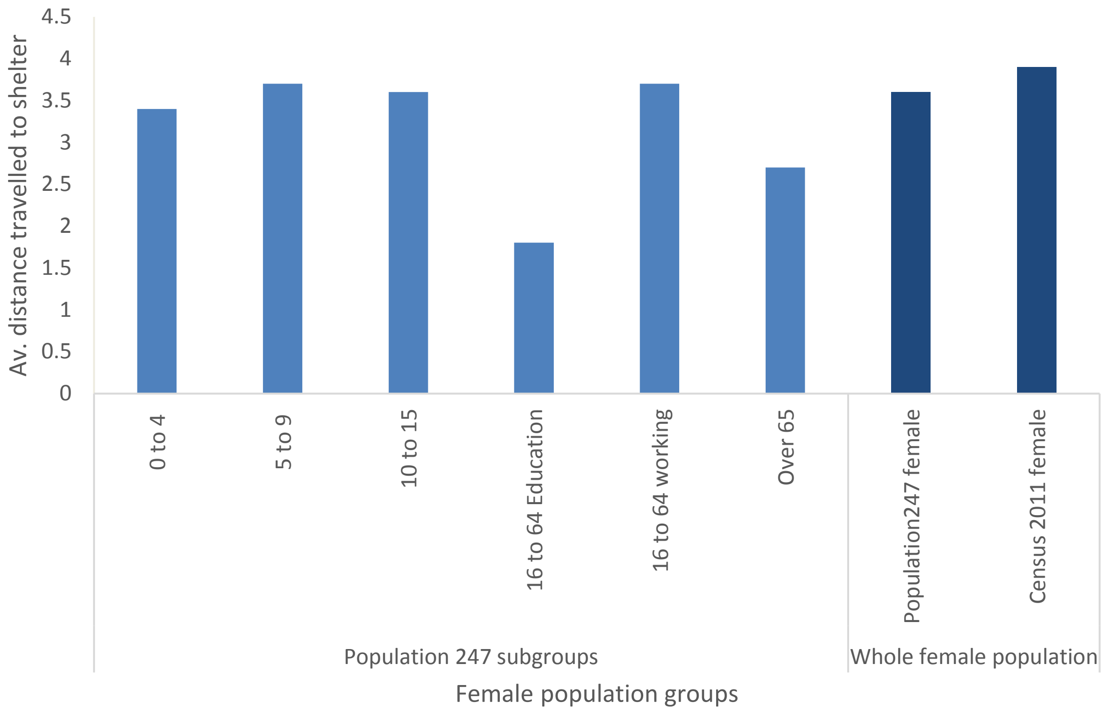


Figure 72: Average distance travelled by an individual agent for different population subgroups (0800, 28/3/2011), whole female population (0800, 28/03/2011) and Female 2011 census population to reach shelter.

The population exposed to radiation in this scenario is dependent upon the location of the plume. For this investigation, populations that exist under the plume at the start of the model time are automatically exposed. However, the entire population will subsequently seek routes to shelter that do not intersect with the plume, to reduce exposure likelihood, and will move away from the plume to prevent exposure even if this increases journey distance and time. Whilst it is not possible for a population to identify the most contaminated areas individually, the purpose of plume avoidance behaviour is to mimic cordons that may be set up to prevent the population moving into the most contaminated areas after a radiation emergency. Apart from females in education 16-64, who have a considerably lower likelihood of exposure due to proximity to shelter and distance from plume, the exposed proportion of each population subgroup is similar. The whole female Population247 has a slightly lower exposure likelihood, and the Census 2011 female residential population has a slightly higher level of exposure likelihood. The outputs of this investigation are shown in Figure 73.

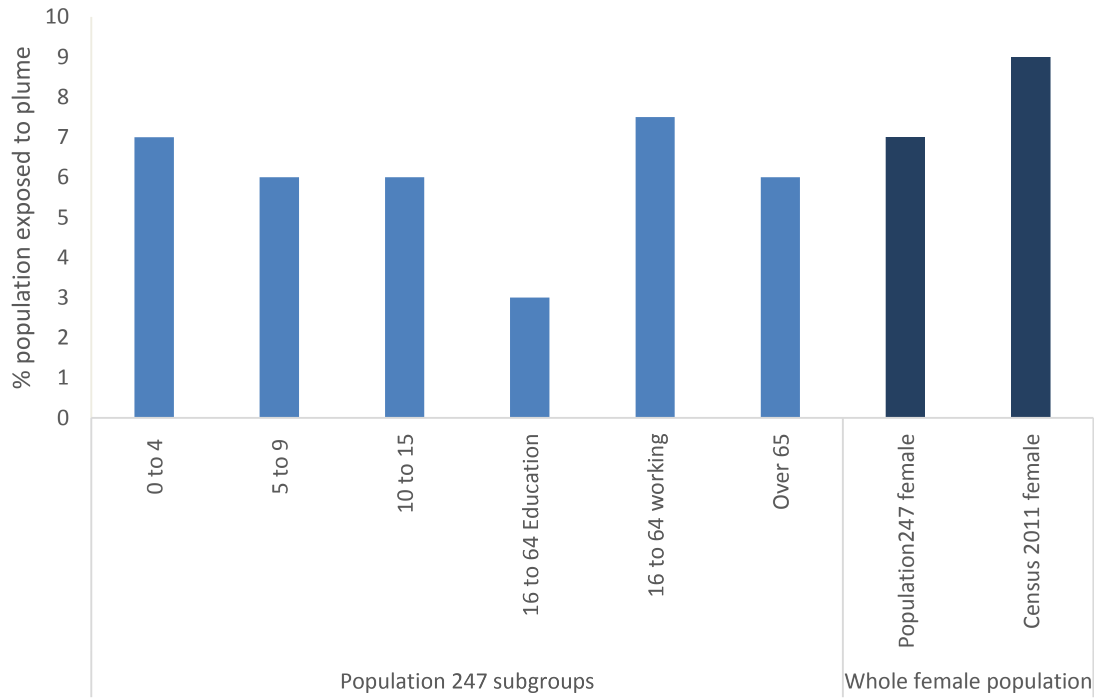


Figure 73: Percentage of total population exposed to radiation for different population subgroups (0800, 28/3/2011), whole female population (0800, 28/03/2011) and Female 2011 census residential population.

Figure 74 illustrates how the population count across two differently located shelter sites changes, as the population relocates to a nearby shelter. The pattern of sheltering is determined by the original whereabouts of the population. For this reason, shelter site 1 (University of Exeter) has gained a significantly larger population than shelter site 2 (Exeter Cathedral) when Population247 datasets are included, as university education is included as a daily activity for a proportion of the population for this data. This may provide a more realistic representation of anticipated shelter capacity than 2011 census residential datasets, as the original daytime whereabouts of the population are more clearly understood. This could have useful implications for emergency planning.

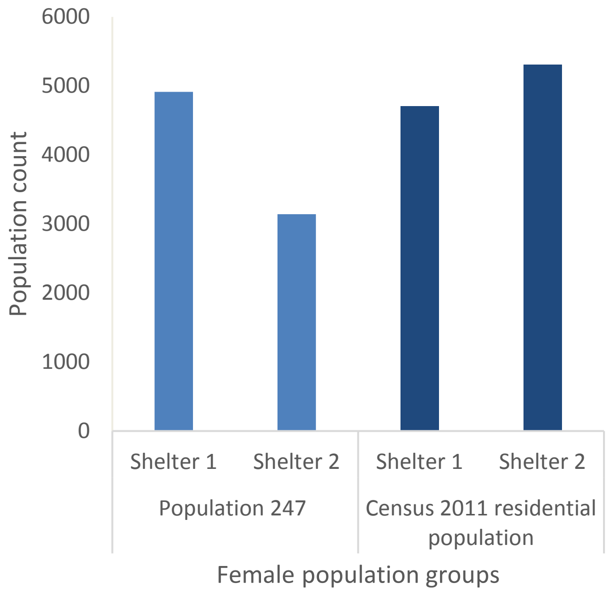


Figure 74: Difference in total capacity across Shelter 1 and Shelter 2 at the end of emergency for the whole female Population 247 population (0800, 28/03/2011) and Female 2011 census residential population.

The results of this study show that there are potential differences in population distribution during emergencies, reflected by the difference in Census 2011 and Population 247 seeded agent-based modelling outputs. The next section summarises the case study.

6.4 Summary

This chapter has presented an agent-based model which includes day-time spatiotemporal population data for the assessment of how spatiotemporal population distribution changes, and likelihood of exposure to radiation whilst shelter-seeking during a radiation emergency. The agent-based model has been implemented with both female 2011 census residential data, and female Population247 data which was generated in Case study I for assessment of exposure and impacts of a hypothetical emergency. The results of the case study demonstrate that there is a discernible difference in the times taken and distances travelled during shelter-seeking across different population subgroups, due to their differences of original location in space and time. There are also differences in likelihood of exposure to radiation. However, whilst this ABM provides new insights into potential differences in population distribution during an emergency, it is a hypothetical example of what could be done if spatiotemporal population data is applied to seed an agent-based model. The next Chapter discusses both case studies in more detail.

Chapter 7: Discussion

This chapter of the thesis provides reflection upon important broader issues which have emerged from previous chapters. Sections 7.1 and 7.2 critically appraise the methods and results of Case studies I and II, and identify relevant challenges.

One of the most significant and cross-cutting features that requires discussion is the innate human and societal sensitivity of the radiation emergency planning research process (Tschurlovits, 2006, Turcanu, 2016). As discussed within Chapter 3, radiation emergency planning is an emotive topic, due to the exceptionally low frequency but dramatic severity of incidents, and the societal perception of radiation risk as unknowable and other. It is therefore important to apply verified methodologies whilst examining radiation risk, and to exercise due diligence to prevent causing either a security risk or public concern due to the critical nature of the research topic. To improve the accessibility of this project and demonstrate the usefulness of the approach whilst reducing likelihood of undue alarm, following consultation with experts in radiation protection, it was decided to create a hypothetical scenario around a location without a nuclear installation. This decision introduced new challenges, including the need to identify a suitable analogous modelling site without an existing nuclear installation, and the need to design a realistic study whilst modelling a site without existing radiation emergency countermeasures in place. To resolve these challenges a combination of REPPIR planning for the comparable location of Plymouth, UK, and existing major incident planning approaches for the City of Exeter were examined to create a realistic scenario. However, this also means that some unique features of radiation emergencies, including routes potassium iodate tablet distribution, were not suitable for inclusion in this thesis. Exeter has many features that are comparable to other cities and therefore transferrable, including rivers, major hospitals and a university. As with any city, some of Exeter's features are unique and would therefore influence the outcomes of a radiation emergency, meaning that the specific results of this thesis are not directly transferrable to another city or another emergency. However, the purpose of the study site is to provide an analogue upon which to test the modelling methods, and the example included within the thesis is not designed for implementation as a relevant emergency planning or management scenario within radiation protection.

Chapter 2 examined the theory behind a number of different methodologies for modelling spatiotemporal populations, including interpolation, kriging, Hagerstrand's space-time geography, temporal GIS and dynamic modelling approaches. Chapter 3 considered the societal and health impacts of nuclear accident, and explored approaches for modelling nuclear accident hazard in the context of meteorological dispersal, likelihood of exposure and health effects. The inherent diversity and complexity of approaches has meant that whilst existing literature has been thoroughly addressed to identify the most suitable approaches for the purpose of this thesis, these are not the only plausible modelling choices. For example, an alternative approach could have implemented Kriging as a spatiotemporal population redistribution approach, and may have combined this with NOAA Hysplit atmospheric dispersal modelling environment to gain similar results to those in Case Study I. However, this means that there is potential for adaptation and extension of the existing RADPOP framework to test other modelling approaches. However, at the time of writing, it should be noted that there is no probabilistic accident consequence analysis tool that is equivalent to PHE's PACE modelling system. Whilst the ABM in Case Study II has been designed to display the output of Population247 spatiotemporal population density modelling, it is not infeasible to consider making further adaptations to the existing ABM or implementing Population247 modelling output into an alternative new and recently-developed radiation protection ABM framework (Parikh, 2016).

A further overarching challenge relates to short-term accuracy of modelling predictions, and to the relevance of exposure thresholds for radiation protection, as dose projections may soon be changing in light of recent work, which suggests adaptations to estimations for child exposure (DeCair, 2016). Approaches for the estimation of radiation exposure face a number of challenges, especially when modelling is produced for the first few hours of a radiation emergency (Haywood, 2008, Haywood, 2010). These challenges arise due to the limited availability of information about the nature of the emergency, the weather and innate modelling imprecision. In the event of an accident certain information is likely to be rapidly available, including the location and start time of a release, the current weather conditions, wind speed and likelihood of rain (Haywood, 2008). However, other crucial decision-making criteria are harder to obtain, including release duration, height, deposition velocity and location specific effects (Haywood, 2008). For these reasons, this model is designed for methodological testing and exercise scenario guidance rather than emergency management, as despite methodological advances it is not possible to include sufficient criteria to produce a completely watertight modelling outcome. Therefore, the data produced for this thesis highlights new approaches for the understanding of potential scenarios, rather than providing a significant solution. Despite these challenges, considerable progress has been made in the development of a new set of tools, which could be used or extended by emergency planning and management practitioners.

7.1 Case study I

Case study I demonstrates some of the significant research possibilities which arise when spatiotemporal population modelling and spatiotemporal radiation protection modelling are combined, to assess exposure likelihood and the specific health effects that may occur as a result of a hypothetical radiation exposure. This section discusses the findings with reference to literature, theory and practice; and identifies the challenges and limitations associated with Case Study I. The first section of Case study I examined how radiation exposure to a spatiotemporal aggregate female and male population differs and changes over time. Whilst modelling approaches were combined successfully to produce estimates of radiation exposure, there are outstanding questions that need to be considered.

One of the notable outcomes of the first component of this study was the discovery of a gender difference in potential exposure likelihood, due to the difference in whereabouts of male and female populations in space and time. This has significant implications, as currently women and men are not included as individual vulnerable population subgroups within REPPIR documentation (HSE, 2002). However, one of the more interesting findings of the modelling output was that the male population may actually be more likely to experience exposure, due to a predominantly male workforce being located at industrial sites which are in closer proximity to the hypothetical nuclear installation. It is envisaged that this spatiotemporal population distribution could actually be a more realistic representation of the whereabouts of a population during a radiation emergency. This suggests that the initial thesis hypothesis that working-age females may be more vulnerable than working-age males during a hypothetical radiation emergency in the UK may not be correct. Potentially, the location of males in space and time could increase risk of exposure during a day-time incident, above that of females, who may be biologically more vulnerable to infertility and birth defects (Stabin, 1997, AFRRI, 2011). As nuclear installations still feature workforces with a male gender bias and may be situated near similarly gender-biased industrial sites, this is a thought-provoking development. However, this may not necessarily be the case for other locations, and the inherently increased biological vulnerability of females and children suggests that an approach which determines the whereabouts of different population subgroups in space and time is still a much-needed development.

The results of the second component of this study are somewhat reflective of the results of the first component, by representing a larger spatial distribution of leukaemia incidence across the working male population subgroup. This study also demonstrated that updating residential population density estimates from 2001 to 2011 census estimates within the Population247 modelling approach produced different health outcomes, and despite the overall increase in population density, the estimated likelihood of leukaemia decreased. This may be due to a change in population distribution, which has occurred due to the change in the density and distribution of the original population. The next sections examine some of the more signifcant methodological limitations of this study in more detail.

7.1.1 Study challenges

Case study I presents a new approach for the assessment of impacts of radiation exposure to specific population subgroups. However, there are limitations associated with this study, which are explored in this section. This section considers how constraints upon study site geography and parameters, data availability, and the decision to implement specific modelling approaches may have limited this work. Review Section 2.1 examined the effects of scale and areal unit shape upon the representation of any spatial unit, by introduction of the Modifiable Areal Unit Problem (MAUP). This has some relevance to the results of Case study I due to one spatially defined and specific geographical area, Exeter in the UK being selected to assess the success of all modelling outcomes. Whilst this decision provided consistency to test modelling approaches, a multi-site study with equivalent population density and areal unit size and shape could have provided opportunities to contrast modelling outcomes for other locations with different spatial and demographic structures. Unfortunately, this was not possible within the methodological focus and time constraints. However, an applied multi-site study, which includes sites of alternative scale and dimension, could provide further opportunities to test the spatial parameters of approaches.

7.1.2 Population247

Whilst Population247 is an adaptable and extensible spatiotemporal population modelling framework, the date, scale, and type of population data available for use by this study has created further limitations (Martin et al., 2015). Spatiotemporal population modelling outputs within Study I were also designed to inform the modelling inputs for Study II. At the time of study development, the most contemporary and diverse open-source population data available originated from the 2011 census. Therefore hourly spatiotemporal population density estimates were produced for 28th March 2011, which was the first working day following Census data collection. However, at the time of writing in 2016 this demographic data has become less relevant and suitable over time. The opportunity to remodel this work with more recent population data would be time-consuming, but could improve the accuracy of estimation. Whilst these temporal constraints are limiting, Case study I still offers improvements upon the approaches discussed in Section 3.5.1. Scale of data is another significant limitation, as it is challenging to produce comparative and uniform gridded models of different population density subgroups, with initial activity datasets that span a continuum of different scales. This limitation was somewhat overcome by subjecting some original population data to necessary adjustments and processing for spatial consistency, prior to modelling. The ability to apply the Population247 approach to create spatially uniform gridded population density estimates across different activity types, also improved the uniformity of modelled outcomes. Whilst the underlying extensible and adaptable framework for Population247 is excellent, there are limitations associated with this modelling approach, which are generated due to data availability. Whilst the modelling outcomes of this approach are more realistic than others to date, it would be impossible to produce a completely "real-world" output.

The type of data included in Case study I could have created further limitations, as only open-source data was included in the population data library. Whilst commercial sources of population data exist, these were intentionally not selected for use by this study, which enables an extensive range of open-source data to be showcased instead. Further to this, there is additional scope to consider the ethical implications surrounding public availability of population data. Despite the potential benefits of using commercial data, using this type of data for research can significantly limit the capacity for replicability and future use of that work by others. There are also sourcing issues associated with implementing open-source commercial data, such as retail footfall reports, which were implemented to generate the retail and tourism sections of the population modelling output. This is because this type of data may be generated by using "black box" systems, which make it challenging to understand and trace the original source data. This contrasts with large-scale public access population datasets such as those generated by ONS, which have more robust collection and analysis procedures in place to improve the accuracy of the resulting data (ONS, 2014b). It is also significant the data environment within the study could be internationally replicable, as demonstrated by some of the examples within Chapter 3. Finally, it should be noted that traditional data sources applied to this framework could be replaced by 'big data' in the future, however it is currently challenging to obtain and calibrate these datasets.

7.1.3 **PACE-NAME**

PACE-NAME was the meteorological and probabilistic health assessment component of the thesis. NAME was implemented through the PACE modelling framework to produce a series of meteorological outcomes which were included in both case studies, and which were not associated with any specific population. PACErun was applied to create a probabilistic health assessment using Population247 spatiotemporal population input data, which was scripted to replace the existing 2001 population data in the PACErun framework.

There are limitations associated with PACE-NAME, The NAME component of this framework applies Lagrangian particle dispersal modelling to predict the dispersal of an atmospheric contaminant. A diverse array of outputs have been produced for this thesis, but any modelling system which integrates a Lagrangian particle puff approach is inherently computationally demanding and time-consuming, therefore more iterations are needed to improve the accuracy of assessment. Whilst accurate historical meteorological data has been included in this thesis, the modelled output is only as good as the data input. The modelled outputs from PACE-NAME are therefore spatiotemporally constrained, and would not be applicable to other spatiotemporal scenarios. There are also challenges associated with realistically modelling the first hour of radionuclide dispersal, due to the shorter dispersal range and environmental uncertainties associated with small-scale (100m or less) plume dispersal modelling (Haywood et al., 2010). Finally, modelling process from PACE-NAME generated spatiotemporal hazard plumes with concentrations represented in Bq/m^3, which is an environmental monitoring measure rather than a radiation exposure parameter. Whilst Bq/m^3 is useful for understanding the extent and concentration of the hazard, it provides little information about the impacts of the exposure to the underlying spatiotemporal population. An alternative assessment of radiation distribution by Sievert could have instead taken into account the biological effectiveness of the ionising radiation exposure by converting the amount of radiation into a dose (Haywood et al., 2010).

There are limitations to the PACE health assessment aspect of the modelling approach. PACE is a state-of-the art modelling system for probabilistic assessment, which produces a spatiotemporal grid of health effects to a population. However, individual health assessment methods are applied in this approach to assess the health impacts to collective population units or spatial groups. A variety of different population, economic, health and agricultural datasets, which span from 2001 to 2007 are integrated into the original model parameters (Charnock et al., 2013). Whilst this data was the best available at the time that PACE was developed and implemented, updates to every dataset, beyond the inclusion of 2011 population data, could improve the consistency and relevance of modelling outputs and enable more extensive investigation of other parameters. However, the study potentially improved upon original PACE population distribution outputs, by implementing a 2011 regional spatiotemporal population dataset. Whilst PACE is applied to gain further insight into potential health outcomes in the context of radiation protection, the system is expansive and it would not be possible to gain insight into every aspect of it in the thesis timescale. This means that it is somewhat of a “black box” modelling system, as population data is included and redistributed within the model using a different approach to Population247. This also links into the approaches for assessment, as it is not feasible to create accurate assessments for something as precise as the exposure burden to individual organs in the human body using PACE-NAME (Haywood et al., 2010).

PACE was included in the modelling framework for the second part of Case Study I to investigate the likelihood of non-fatal deterministic effects, leukaemia incidence, deterministic fatalities and leukaemia fatalities for 2001 and 2011 census populations. Non-fatal deterministic effects and leukaemia incidence were also explored by gender. These criteria were selected to provide an overview of some of the more significant health effects which can be investigated by combining Population247 modelling framework outputs in the population component of the PACE modelling system. Whilst these provide an overview of health effects, there are many other different health effects which can be modelled by PACE, and which could have been selected. These alternative outputs are documented in Appendix C. However, the integration of spatiotemporal population modelling layers is not the main focus of this thesis, as more work needs to be done to improve the integration of new population data. To conclude, it is not possible to produce an accurate predictive output based upon a single hypothetical scenario, therefore many repeat model runs under a variety of alternative meteorological conditions are needed to actually understand the health effects. However, these studies demonstrate the possibilities of combining different data and model types to improve, or at least change, our understanding of radiation exposure.

7.2 Case study II

Case study II provides insights into the potential for a new agent-based spatiotemporal population modelling framework for radiation protection. This study has shown that it is possible to include realistic and sophisticated spatiotemporal population and hazard modelling data in an agent-based modelling framework, to provide a more accurate simulation of population whereabouts and potential exposure during a hypothetical radiation emergency. This section discusses the notable findings, challenges and limitations that are relevant to Case study II.

An agent-based modelling approach was included in an attempt to replicate some of the complex dynamics that arise during radiation emergencies, by implementing the hypothesis that emergent phenomena will occur when individual agents follow simple and interactive rules of behaviour. However, any agent-based model is only as good as its design and effective integration of suitable and relevant statistical and behavioural information. It is difficult to plan and model what populations will actually do in an emergency, opposed to what the academic, public health expert or emergency planner envisages will occur. Therefore, one of the defining challenges with this approach is that whilst basic human behaviour has been considered, more insight is needed into how these specific behaviours differ between different population subgroups, and how this could be integrated into the RADPOP modelling framework.

The modelling outputs of Case study II demonstrate that the original spatiotemporal location of a population has an impact upon the time taken and distance travelled for that population to relocate to designated shelter sites. This has significant implications for emergency planning policy, the study provided a framework that not only allowed better spatiotemporal insights, but that is also rich enough to allow investigation of the experiences of specific population subgroups such as women and children. However, the specific distances and times of this study are hypothetical, and therefore should not be used to inform policy in themselves. This study focused upon female spatiotemporal vulnerability during radiation emergencies, and aimed to explore how the whereabouts of this population can impact upon evacuation success. However, the findings of this study are not representative and therefore should not detract from the inherently increased biological vulnerability exhibited by females, as discussed in Section 3.2.2. The next section explores some of the specific challenges associated with Case Study II.

7.2.1 **Study challenges**

Case Study II includes many challenges that are specifically associated with the nature of the modelling approach, and also with the parameters of the hypothetical scenario that was designed for the purpose of this thesis. This section explores these limitations.

Agent-based modelling can help to overcome reliance upon purely statistical data to infer emergency outcomes, and can provide insights into otherwise unknown behavioural outcomes. However, a significant challenge associated with ABM is linking the findings from a simulated and abstract world to the realities of a complex and diverse society. Beyond referring to expert opinion and previous literature, it is impossible to validate the behaviours which are represented in the RADPOP approach by comparison to an equivalent emergency scenario. This is because there has been no equivalent historical incident that has been documented in sufficient detail. The modelling approach cannot be directly informed by, for example, filmed footage of human behaviour during a comparable radiation emergency, and the RADPOP framework is unlikely to be tested physically by a specific practical emergency planning exercise in the City of Exeter, due to the scale of resources required. However, this does not detract from its relevance as a desktop tool for future emergency planning exercises. There are also challenges associated with practical model testing as populations behave differently during emergency planning exercises with no risk present, when compared to an actual emergency. Whilst this initially appears to be a research limitation, it actually allows scope to integrate contemporary thought on human behaviour during emergencies, without requiring the production of an exact simulation of a known and predetermined outcome or scenario.

Another challenge is the chosen parameters which are used to determine constraints and instructions to the ABM environment. These constraints are designed by the research author and are inherently inclusive of bias, due to limitations of contemporary understanding of radiation protection and emergency planning. Emergency professionals rely upon experience gained from previous exercises, which is combined with expert opinion. As such, there is a gap between the theory and practice, as the real world environment is complex and cannot be described without loss of realism. The total extent of the model is defined by a set of initial constraints and instructions, which are limited to a specific set of behaviours in order to create understanding of these specific actions upon the sheltering scenario. However, the allocation of particular significance to certain actions over others may be at the expense of more significant theories and mechanisms, which could potentially have a more significant influence upon the behaviours of different demographics during radiation emergencies. Whilst it is not feasible to represent an entire population inclusive of every behaviour within the scope of this thesis, considerable progress is evident, compared to existing approaches, in the understanding of the whereabouts of spatiotemporal aggregate populations and subgroups during a hypothetical radiation emergency scenario.

7.2.2 **RADPOP**

The development of an agent-based modelling system such as RADPOP introduces a number of challenges relating to realism and accuracy. There are both model-specific and generic limitations associated with this approach. Netlogo was implemented for ABM for the RADPOP framework, due to its open-source, versatile and accessible nature. However, whilst Netlogo is gradually gaining recognition within the academic community, it still does not have the comparable computational or mathematical sophistication of systems such as Repast or MASON.

There are also issues associated with modelling of the movement of a spatiotemporal population within the RADPOP framework, as the combination of ABM and transport network modelling does not realistically reflect the actual population flow across an urban area. Whilst the approach improves our understanding of how the population dynamic might change across time, it is too simplistic to provide true insights into significant questions surrounding emergency planning, such as how the speed of population movement changes across an extensive road network, or how different population subgroups may adopt alternative modes of transport. The inclusion of a more developed spatiotemporal transport network of all motorways, A roads, B roads, public railways, flights and ferry transport could offer further realism to this approach. Another significant limitation of this ABM approach is that whilst it shows changes in spatiotemporal population distribution, there is little urban infrastructure included in the model beyond the transport network and two shelter sites. This does not reflect the diversity of multi-level buildings present in any city, which are significant as containers of dense population that may have challenges and benefits for sheltering and evacuation. The RADPOP approach demonstrates that combining demographic and spatiotemporal data in this way is possible, and there is therefore potential to individually improve and develop each individual element later. Further developments could include the different networks and dynamics of a greater diversity of different population subgroups, such as the sheltering behaviours of the family unit, disabled people, and different ethnic groups. This further development would improve understanding of the whereabouts of a greater diversity of vulnerable population subgroups.

Within the ABM approach, both designated shelter sites were designed to accept populations without any maximum capacity, in order to explore how the local geography of the hypothetical scenario may impact upon shelter site demand. Whilst this enabled changes in population distribution to be explored, which could have useful applications for future identification of suitable shelter sites, this is not a realistic scenario because both locations would have a maximum capacity.

Realism could be improved by implementing a maximum capacity, and then relocating excess populations to a greater number of additional limited capacity shelter sites. Another challenge is the realistic modelling of radiation exposure to a population with the ABM environment. A loosely-coupled modelling approach was integrated to include modelling outputs from Case Study II, therefore it was not possible to dynamically model the changes in radiation concentration across ABM time. This means that the population was classified as exposed or unexposed, without including the specific concentration changes that would occur across time as the plume extent and concentration changed. This meant that it was not possible to assess potential health effects to the population in the plume environment, over time. A significant improvement to this approach would be to develop or include a more dynamic contaminant plume modelling environment, for instance by creating a model that is closely-coupled with NAME, which would again improve the realism of this approach and further understanding of the specific health impacts of an exposure over time. However, this would be an extensive project in itself and is therefore something that could be considered for further research in future. However, the significant challenge of including a more realistic spatiotemporal population in an ABM for assessment of likelihood of radiation hazard exposure has been achieved, and this offers the opportunity for further modelling and further understanding of the outcomes and experiences of radiation emergency for different spatiotemporal population subgroups, during a hypothetical radiation emergency.

Finally, RADPOP could also be extended though the development of more sophisticated agent rules that could produce emergency behaviours. Within a human context, emergent behaviours include crowd movement, where a number of individual agents interact to produce more complex collective behaviours (Castle and Crooks, 2006). This would be beneficial for understanding the impact of crowd behaviour upon city evacuation. These rules could be implemented by providing different behavioural and interactive characteristics to different demographic agent groups. For example, females of childbearing age could seek their children, or children could seek their teachers, as part of the evacuation process. However, there are limits to agent rules and RADPOP complexity more generally.More generically, it is not desirable to produce an agent-based model or simulation with too much complexity, as it can result in loss of understanding of the modelled outputs, due to an excess of conflicting and interacting features. Pattern-oriented modelling can be used to evaluate the appropriate level of complexity for a spatial agent-based model, by considering the Medawar framework (Grimm et al., 2005, Magliocca and Ellis, 2013). This framework has been successfully implemented within computational ecology and biosciences, and posits that a model is too simple if it addresses a single problem, whereas it can become too complex if it includes all available data. There is therefore a Medawar "middle" zone of aptitude, where the advantages of modelling are not overridden by the complex nature of the multiple phenomena presented(Magliocca and Ellis, 2013).Since this thesis was begun, it is notable that there are now also other researchers in the process of developing similar agent-based modelling approaches to radiation protection, who are tackling slightly different challenges. This recent work includes a comparative study of behavioural modelling approaches for the aftermath of a nuclear detonation, improvements in atmospheric control modelling for radiation protection, and the development of communication management modelling approaches for radiation emergency planning (Parikh, 2016, Shunxiang, 2015, Ruiz-Martin, 2015). This bodes well for the future, as new approaches are developed and tested which could improve our understanding of the radiation emergency scenario. The next chapter concludes this thesis by providing some final thoughts and last words.

Chapter 8: Conclusions

Chapter 8 reviews and concludes the work completed in fulfilment of the thesis “RADPOP: A New Modelling Framework for Radiation Protection”. For this section, the key research findings are summarised, the greater importance of the work is contextualised and key contributions to knowledge and policy are identified. Section 8.1 re-examines the original aims and objectives of this work, and discerns the ways by which these have been fulfilled by the thesis, Section 8.2. explores some significant opportunities for future research, Section 8.3. identifies the key contributions to knowledge that have been presented by this thesis, and Section 8.4 concludes this body of work with a few final words.

8.1 Review of original research aims

The overarching aim of this thesis is to develop and demonstrate a novel spatiotemporal modelling framework for assessment of the spatiotemporal distribution of populations during a radiation emergency.

Chapter 1 identified objectives pertaining to the main thesis aims. The first aim of the thesis was to review existing literature of relevance to methods in spatiotemporal population modelling, radiation protection, radiation emergencies, and methods of determining radiation exposure. This aim has been achieved by Chapters 2 and 3, which provide a comprehensive review of relevant modelling and radiation protection literature. Chapter 2 explores both geostatistical and dynamic spatiotemporal population modelling methods, and thereby provides insight into the origin and applicability of relevant approaches. Unsuitable methods have also been identified, and justification has been provided in this chapter for the exclusion of these methods in the greater thesis. In this chapter, Population247 and agent-based modelling were identified as suitable approaches for further methodological development. Chapter 3 examines radiation protection and society, thereby contextualising the processes behind emergency planning for radiation protection, and the relevant social and health impacts of ionising radiation. Chapter 3 justifies the choice of thesis topic, by reference to international historical case studies of radiation emergency management. Chapter 3 also explored relevant approaches that have previously been applied to model other populations at risk from other emergency scenarios, to improve understanding of some of the universal underlying challenges of population modelling for public health and emergency planning.

The second aim of the thesis was to explore gender and radiation exposure, through the construction and implementation of a new spatiotemporal data library. This aim was fulfilled by the development of a new age and gender-specific spatiotemporal model, which has enabled the exploration of differences in exposure likelihood with focus upon the female population subgroup, in Chapter 4. This methodology included the development of a new population data library, which consisted of 2011 residential, education, healthcare, workplace, retail and tourism datasets. The purpose of this library was to create new male and female population subgroups for implementation by the Population247 approach to spatiotemporal modelling, and therefore improve understanding of the differences in extent of radiation exposure for spatiotemporal radiation plume dispersal modelling. In Chapter 5 of the thesis, the new 2011 data library was implemented to model daytime population exposure during a radiation emergency. An important development of the approach is the capacity to examine each demographic subgroup individually and by gender, however this was not the purpose of the thesis. Instead, it was to create aggregate male and female populations that have been constructed from the unique compositions of each of the different population subgroups.

The third aim of the thesis was to develop a new and improved approach for modelling change in spatiotemporal demographic subgroup population density, during implementation of countermeasures during a hypothetical emergency. The purpose of this approach was to demonstrate the relevance and efficacy of the methods described in Chapter 4, which have not previously been applied to the challenge of understanding where women are during radiation emergencies. This aim was addressed by the development of the RADPOP modelling framework approach, which combines spatiotemporal population modelling and agent-based modelling to explore how the original distribution of a spatiotemporal population subgroup can affect evacuation outcomes. Chapter 6 produced and implemented an agent-based modelling study that highlights some of the possibilities of this new modelling framework, therefore meeting this aim.

It was learnt that the whereabouts of a population in space and time at the start of an emergency will influence likelihood of exposure, that different population subgroups can experience different likelihoods of exposure and health effects due to their locations; and that the movement of a population during emergency countermeasures will again change the population dynamic and likelihood of exposure when compared to a scenario without countermeasures.

8.2 Further research

There is considerable scope for further research that arises from this thesis. Whilst the original case studies in this thesis are hypothetical and UK-based, a significant opportunity to validate and test the RADPOP modelling approach could be by its application to a relevant international historical radiation emergency scenario.

The Fukushima Daiichi accident of 2011 would be the most suitable scenario for approach testing, due to its contemporary nature, the availability of high-quality data for spatiotemporal population modelling, and the existence of accurate and contemporary meteorological radiation dispersal datasets. Relevant literature could be applied to the existing agent-based modelling framework to create further behavioural sophistication of the modelling process, and to enhance existing data and knowledge about Fukushima. The application of the RADPOP modelling framework to a specific real emergency scenario could also refine the model parameterisation, whilst testing the realism and accuracy of the current approach.

The extensibility and the adaptability of the model parameters could be tested, by exploring different geographical spaces within the UK, and including a larger spatial area of study. However, there are limits to the success of large complex models, and the model would there require considerable careful development of rules, within the constraints of the Medawar zone.

Another opportunity for further research presents itself in the extended development and refinement of the original RADPOP agent-based modelling approach, in a hypothetical domain. The existing approach is relatively concise due to being designed for the purposes of concept testing in the constraints of the thesis timescale, rather than exemplifying the absolute diversity of human behaviour during a radiation emergency. However, there are a multitude of other behaviours and attitudes evident across different population subgroups that could provide considerable scope for further research. These include challenges associated with understanding the countermeasures behaviour of elderly populations and family groups during radiation emergencies. Further developments of the existing agent-based modelling approach could include assessment of health impacts to specific population subgroups and differences in access to healthcare provision during a radiation emergency. The need for hospitalisation and medical treatment due to both radiation exposure and any underlying health challenges to the population could be investigated in this way.

A final suggestion for further research is focused around enhancements to the Population247 spatiotemporal population modelling framework. This framework is extensible and adaptable, and could be developed to model countermeasures population distributions by the inclusion of new spatiotemporal population data, transport networks and time profiles, which could reflect the population density during a radiation emergency and therefore provide a valid alternative to agent-based modelling. Implementing this approach could also be an alternative method to validate the outcomes from agent-based modelling, alongside the reproduction of a historical case study. This approach would provide novel enhancements to the existing application of Population247, and may be applicable to a variety of other emergency scenarios, such as the anticipation of the distribution of population countermeasures activities during flood hazard events. These are just a few possible suggestions for further research; however, there are many more possibilities for the application of the RADPOP modelling framework that are beyond the domain of radiation protection, including inclusion of future 2021 census data, the use of real-time population data and multi-scale urban modelling.

8.3 Key contributions to knowledge

This thesis has developed contributions to knowledge of spatiotemporal population modelling for radiation protection. These are the most significant accomplishments of the thesis:

- The development and inclusion of detailed gendered and demographic subgroup data libraries for a spatiotemporal population modelling framework. This is the first time that female and male population subgroups have been modelled in this way.
- The first implementation of a spatiotemporal population density modelling approach in the domain of radiation protection.
- The first inclusion of spatiotemporal population density modelling outputs for an agent-based modelling approach to understand evacuation.

8.4 Applied significance of this work

This work is significant to the emergency planning and public health sectors, as it could enable these groups to improve their understanding of the of the locations of different population subgroups during a radiation emergency. This work is relevant to UK governmental policy, as it may have the capacity to inform current REPPIR legislation and the designation of DEPZ and evacuation emergency planning. There is potential for future versions of the data framework and methods used by this thesis to be adapted to provide site-specific insights in an applied context. Specific relevant stakeholders could potentially include the emergency services, transport managers, healthcare providers and local government, as well as the wider academic community.

8.5 Final words

When I began work on this thesis, UK 2011 census data was being prepared for release, and the best approximation of the whereabouts of a population by Population247 did not reflect gendered differences in the spatiotemporal location of that population. It has been an incredible adventure to have the opportunity to explore new open-source data, to update the data library of such a powerful spatiotemporal population model, and to experiment with combining just a couple of the wide variety of contemporary population and hazard modelling approaches for radiation protection. This thesis provides a small contribution to knowledge, which has been built upon an incredible and vast legacy of international work. My hope is that my work has improved our understanding of the ways that spatiotemporal change in population may be represented and simulated for radiation protection. Whilst I enjoy learning and applying new modelling approaches, my final words look to the future, and return to the reason why I began this thesis in the first place. Whilst there are benefits associated with the simplification of reality by modelling, we will never be able to encapsulate the experience of being a radiation emergency survivor in this way. I genuinely care about the outcomes of emergencies and I am passionate about developing our understanding, not for the sake of knowledge or because of a great fascination with theory alone, but to improve the lives of others and reduce the impacts of future hazards. We must continue to develop new approaches, to hope for the best but prepare for the worst, to improve our understanding of the geography of nuclear accidents and to share this knowledge with policy-makers and practitioners.

Appendices

Appendix A: Alexis-Martin, B (2015) The Chernobyl necklace: the psychosocial experiences of female radiation emergency survivors. Belgeo. Revue belge de géographie, (1)

This appendix includes the academic paper based upon Chapter 3 of this thesis, Alexis-Martin, B (2015) The Chernobyl necklace: the psychosocial experiences of female radiation emergency survivors. Belgeo. Revue belge de géographie, (1).

This appendix also includes the Guardian article which is linked to the published paper, Alexis-Martin B (2015) “Nuclear Fallout: The Mental Health Consequences of Ionising Radiation” which was published on 9th August 2015 (https://www.theguardian.com/science/brain-flapping/2015/aug/09/nagasaki-anniversary-radiation-nuclear-mental-health).

Belgeo
2 (2015)
Hazards and Disasters

Becky Alexis-Martin

The Chernobyl necklace: the psychosocial experiences of female radiation emergency survivors

Avertissement

Le contenu de ce site relève de la législation française sur la propriété intellectuelle et est la propriété exclusive de l'éditeur.
Les oeuvres figurant sur ce site peuvent être consultées et reproduites sur un support papier ou numérique sous réserve qu'elles soient strictement réservées à un usage soit personnel, soit scientifique ou pédagogique excluant toute exploitation commerciale. La reproduction devra obligatoirement mentionner l'éditeur, le nom de la revue, l'auteur et la référence du document.
Toute autre reproduction est interdite sauf accord préalable de l'éditeur, en dehors des cas prévus par la législation en vigueur en France.
Revues.org est un portail de revues en sciences humaines et sociales développé par le Cléo, Centre pour l'édition électronique ouverte (CNRS, EHESS, UP, UAPV).

Référence électronique
Becky Alexis-Martin, « The Chernobyl necklace: the psychosocial experiences of female radiation emergency survivors », *Belgeo* [En ligne], 2 | 2015, mis en ligne le 30 juin 2015, consulté le 17 septembre 2015. URL : http://belgeo.revues.org/14441
Éditeur : National Committee of Geography of Belgium / Société Royale Belge de Géographie
http://belgeo.revues.org
http://www.revues.org
Document accessible en ligne sur :
http://belgeo.revues.org/14441
Document généré automatiquement le 17 septembre 2015.
© NCG with the SRBG

Becky Alexis-Martin

The Chernobyl necklace: the psychosocial experiences of female radiation emergency survivors

Introduction

1 A modern mythology surrounds the perception of risk from exposure to ionising radiation. Fear of radiation may originate from its implementation as weaponry, during the atomic bombing of Hiroshima and Nagasaki in Japan (Slovic, 2012). However, the unusual properties, potentially mutagenic capacity and comparative newness of the radioactive materials used for energy production and defence may also contribute towards this concern. The perception of radiation as unnatural and "other" causes greater anxiety towards this hazard than most, regardless of likelihood and scale of exposure (Mobbs, Muirhead and Harrison, 2010). Attitudes towards radiation are strongly societally and culturally determined. Experience and knowledge of radiation risk is formed through both the collective opinion of a society and the individual's understanding, which may be though medical or occupational routes, media interpretation, attitudes toward resilience, and social norms. This paper characterises the way that differences in society can determine the impact that a radiation emergency will have upon women. The differences and similarities of experience are described for the two most significant nuclear accidents in history, the Chernobyl Reactor Four explosion in Ukraine and the Fukushima Daiichi accident in Japan (Sarin, 2011). Both accidents are both rated 7 on the International Nuclear and Radiological Event Scale (INES). Chernobyl and Fukushima are separated by over twenty-six years and thousands of miles, and there are also notable differences in emergency management strategy, incident severity and cultural response to these accidents. However, both accidents demonstrate parallels of experience for women, which may be common to female survivors of any radiation emergency.

2 The world's most significant accidental release of radiation occurred due to the Chernobyl Reactor Four explosion on 26th April 1986. This accident happened as a consequence of a combination of human error and mechanical failure (Salge and Milling, 2006). An unanticipated surge of power ruptured a reactor vessel, and this ignited the combustible graphite moderator, which emitted radioactive particles and gases into the atmosphere. Radioactivity was deposited patchily across a large area of the Northern Hemisphere for two weeks after the accident (Anspaugh, Catlin and Goldman, 1988). The most significant fallout occurred across western Soviet Russia, Belarus and Ukraine; and the nearby settlements of Chornobyl and Pripyat (Clark and Smith, 1988).

3 The international response to Chernobyl was delayed because President Mikhail Gorbachev chose to defer the declaration of emergency for political reasons. This was despite the recently implemented Soviet policy of Glasnost, which aimed to improve transparency, decrease censorship and improve freedom of information. The emergency response was instead representative of the previous culture of within-state and beyond-state secrecy, and so information was delayed and withheld from both affected Soviet citizens and internationally (Shlyakhter and Wilson, 1992). Within Ukraine and Belorussia, the scale of the accident was played down by short news bulletins, which understated the severity of Chernobyl and claimed that it was possible to "eliminate the consequences of the accident" (Phillips, 2004). However, when large-scale evacuation of the accident's exclusion zone began, it was no longer possible to hide the scale of consequence of the accident from affected Soviet nations. The first international sign of emergency occurred when Scandinavian nuclear power stations began to report unusually high levels of background radiation. This provoked an international investigation to identify the source of the radionuclides, which eventually resulted in the Soviet's admission of the nuclear power station accident to the international community.

4 Meanwhile, forty-eight hours after the accident, the large-scale evacuation of Ukrainian and Belorussian civilians was implemented across a thirty kilometre radius surrounding the Chernobyl reactor. This radius became an exclusion zone, from which it is estimated, over 400,000 individuals were evacuated and resettled permanently (Likhtarev, Chumack and

Repin, 1994). The reactor fire was initially managed by facility workers and the emergency services, but a much greater workforce was required for the emergency management effort. Members of the wider emergency services, local community, military, scientists and additional supplementary workers were conscripted to work within the exclusion zone, and were collectively known as liquidators. In total, over 300,000 individuals are estimated to have participated in liquidation work (Belyakov, Steinhäusler and Trott, 2000). Liquidators were often unaware of the health effects of excess radiation exposure and, therefore, undertook the work without adequate personal protective awareness or equipment. As a consequence, 237 liquidators suffered acute radiation syndrome (ARS), with 31 individuals dying due to exposure related pathologies within three months of the accident (Anspaugh *et al.,* 1988; Bromet and Havenaar, 2007). It is difficult to identify the exact number of casualties and fatalities due to the physical effects Chernobyl, as there are many confounding lifestyle factors including malnourishment and high rates of alcohol and tobacco use, which all contribute to poor health (Petryna, 2011). However, some deaths should be attributed not just to exposure, but also to the opaqueness of the contemporary Soviet political machine, which had resulted in a culture of unwitting and unquestioning compliance amongst workers (Shlyakhter and Wilson, 1992). Across the wider population, approximately 4,000 individuals, including children and women, were diagnosed with thyroid cancer in the years following the accident (Ron *et al.*, 1995). However, there has been a survival rate of 99% amongst this cohort (Jacob *et al.*, 1999: Baverstock, 1992; Little *et al.,* 2014). One of the greatest fears following the accident was of infertility and birth defects similar to those witnessed after Hiroshima and Nagasaki, when seemingly healthy women, who were pregnant at the time of the bombing, gave birth to children with deformities as a result of radiation exposure during the first and second trimester of pregnancy (Todeschini, 1999). However, there is currently no evidence of an increase in infertility, or of birth defects amongst children born to mothers who were pregnant within the exclusion zone, during the Chernobyl accident (Cardis *et al.*, 2006). However, the culture of secrecy within the Soviet Union at the time was ideal for the propagation of false rumour. This created unnecessary concern amongst the unexposed and allowed opportunists to exploit anxiety by peddling false 'radioprotective' cures in the wake of the accident (Phillips, 2002).

5 The most significant consequence of Chernobyl has definitely been psychosocial, with longterm social and mental health impacts upon both evacuees and the wider Soviet population. These effects are life-limiting and have resulted in increased incidence of poverty, isolation, stigma, depression, anxiety and lifestyle-related health conditions across affected regions (Bromet and Havenaar, 2007; Danzer and Danzer, 2014). The population subgroups that were most vulnerable to the psychosocial effects of the accident were evacuees, liquidators and women. Evacuees experienced the loss of control, social ties and sense of home during forced evacuations, and were subsequently labelled as helpless victims and stigmatised as unclean "Chernobylites" by residents within resettlement areas (Mould, 2000). Whilst publically feted as heroes, who were awarded state pensions and medals, many liquidators suffered posttraumatic stress disorder (PTSD) and other mental health effects, as the severity and potential health impacts of the accident gradually came to light (Kryzhanovskaya and Nakano, 1996). The social and mental health impacts upon the women of Chernobyl have been significantly greater across the spectrum of psychopathological diagnoses, which bears resemblance to the experiences of the women of Fukushima.

6 The Fukushima Daiichi nuclear accident was the most severe since Chernobyl. However, whilst Fukushima and Chernobyl are of equivalent INES, there are marked differences between the two events. The Fukushima Daiichi accident began on 11th March 2011 due to cascading earthquake and tsunami hazards during the Great East Japan Earthquake, which was the strongest ever recorded in Japan. The Fukushima Daiichi nuclear power station was designed to withstand severe natural hazards. However, the extremity of this event resulted in damage to Fukushima Daiichi, the meltdown of three of six reactors, and the subsequent explosion of the Unit 1 reactor on 12th March 2011 (Holt, Campbell and Nikitin, 2012). Fukushima is therefore, arguably, a more complex, if less severe, accident than Chernobyl. Japan is located on the Pacific Ring of Fire, which has converging tectonic plate boundaries and a long social and cultural legacy of seismic hazard resilience (Lay and Kanamori, 2011). Transferrable knowledge of natural hazard disaster management may have contributed to the success of Fukushima Daiichi's emergency management strategy; however, the severity of the accident was underestimated and its international significance was downplayed. This may be due, in part, to the challenge of accurately estimating atmospheric radiation following an accident but may also have a political component, as at the time of accident Japan was heavily reliant upon nuclear energy (Hindmarsh, 2013). However, in contrast to Chernobyl,

Japanese authorities rapidly implemented an effective local emergency management plan, which included the distribution of potassium iodate tablets to block radioactive iodine uptake, restrictions upon the transport and sale of produce from the region, and the evacuation of approximately 210,000 individuals across a 20km zone surrounding Fukushima Daiichi (Hamada and Ogino, 2012). Individuals living between 20 km and 30 km from the site were instructed to stay indoors and were subsequently evacuated on 25th March 2011. After the accident occurred, a number of employees chose to remain and manage the incident. Additionally, Japanese pensioners with awareness of the potential risks of exposure and experience of the nuclear industry volunteered to form a Skilled Veterans Corps, who were referred to as the “Fukushima Fifty” (Cook and Halsall, 2012). Therefore, there was very little that unknowing about the experiences of the Fukushima emergency management workers, in contrast to the experiences of the poorly informed liquidators of Chernobyl. Fukushima Daiichi was the first time that public understanding of accidental radiation exposure was shaped by both traditional media sources and the information available on the internet. This meant that information about the accident travelled further, faster and by different pathways, due to non-traditional active citizen journalism methods including blogs, Facebook, YouTube and Twitter (Friedman, 2011). The coverage of Fukushima is therefore more extensive than that of any other previous nuclear accident, and contrasts with the glasnost violations of Chernobyl.
7 Japan’s national historical experience of radiation is considerably more complex than that of Chernobyl. Whilst harnessing the power of energy generation, Japan’s nuclear legacy also includes the devastating 1945 atomic bombings of Nagasaki and Hiroshima, which killed over 129,000 people. Individuals who survived the bombings were stigmatised as impure and capable of transferring their radiation exposure to others via contagion or bodily contact (Todeschini, 1999). Hiroshima and Nagasaki had a disproportionately larger population of women and children at the time, as many men were conscripted into wartime activity in the Pacific (Stimson, 1985). The Shinto cultural attitude of female uncleanliness associated with menstruation was prevalent at the time of the bombings, and radiation exposure amplified and conflated existing contamination anxieties for both genders (Todeschini, 1999). Female survivors were stigmatised and collectively called the Hibakusha, which is a derogatory term that means “the exposed”, by the general population (Todeschini, 1996). Unfortunately, these beliefs were amplified when survivors who were pregnant at the time of the bombings gave birth to children with congenital defects. Consequently, women survivors were considered unfit to have children and remained unmarried; the maidens of Hiroshima (Todeschini, 1996).
8 Whilst there have been no physical casualties officially reported post-Fukushima, there have been significant impacts upon the position in society and mental health of female survivors, which have affected their general wellbeing and opportunities to have children and a normal family life (Ben-Ezra *et al.*, 2015). The parallels become evident as the experiences of the women of Chernobyl and Fukushima are explored further.

The Women of Chernobyl and Fukushima

9 There is no such thing as an average radiation emergency and the experiences of female survivors are individually very diverse. However, there are a number of recurrent themes that arise regardless of the specific radiation emergency, which are associated with the processes of temporary or permanent evacuation, the disruption of home life, children and health. Common awareness of the potentially permanent sterilising effects of radiation and the possibility of child birth defects, are significant to the wellbeing of women, following a radiation emergency. Although improved transparency and information availability has improved the female experience of radiation emergency, there is still a great deal of stigma and misunderstanding attached to the fate of women who have been accidentally exposed to radiation.

10 The experiences of female survivors of Chernobyl can be categorised by differences that arise due to the various roles of women in society at the time of the accident. Approximately 3,000 women were conscripted for liquidation work within the exclusion zone following the accident (Welner and Page, 2013). Typically, these women were tasked with cleaning, decontamination and environmental monitoring duties, for periods ranging from a couple of weeks to several years (Kryzhanovskaya and Nakano, 1996). Women who were liquidators display both physical and psychosocial effects from their involvement of Chernobyl. Female liquidators exhibit a higher frequency of thyroid cancer and the scars from thyroid gland removal, as a result of cancer treatment, have been described by this cohort as the “Chernobyl Necklace” (Welner and Page, 2013). The social consequences for those who bear the

Chernobyl necklace have not been studied, however, it is an interestingly feminised term that the women themselves use to describe their injuries. The experience of being a female liquidator may have been quite isolating, as women represented only 1% of the total number of liquidation workers (Belyakov *et al.*, 2000). This could go some way to explain the increased incidence of PTSD amongst this group of women, the majority of whom did not have any mental health problems before the accident (Kryzhanovskaya and Nakano, 1996).

11 It is difficult to estimate the full extent of mental health effects to female survivors after Chernobyl, as conditions such as PTSD take time to manifest and there may be reluctance to share experiences of difficulty. However, women evacuees have exhibited demonstrably higher levels of long-term psychopathology than men (Viinamäki *et al.*, 1995; Bromet and Havenaar, 2007). Some of the psychosomatic and psychological conditions that women evacuees have experienced include: depression, headaches, dizziness, fatigue, poor concentration, memory loss, irritability, mood swings, anxiety, sleep disorders, high blood pressure, dysphoria and lack of libido (Kryzhanovskaya and Nakano, 1996). Risk of poor mental health is particularly increased for women with children under the age 18, who have lived in exposed regions (Havenaar *et al.*, 2014). It is likely that mother's concern for the health and wellbeing of their children and the consequences of exposure to radiation for the next generation are important contributory factors. However, the effects of relocation, stigma, increased stress, change in circumstance and livelihood, and increased likelihood of exposure to gendered domestic violence are also very significant to women's mental health outcomes after Chernobyl (Petryna, 2013).

12 Chernobyl also affected women's fertility. Women within the exclusion zone were not sterilised by exposure to radiation. However, the possibility of foetal exposure caused anxiety to pregnant women, who sought abortions due to concerns about potentially mutagenic defects to the foetus. There was, therefore, a large increase in abortions, delays in planned pregnancies, and a greater demand for prenatal screening following the accident (Castronovo, 1999). This fear persisted, despite evidence that children born within one year of the accident to mothers evacuated from the 30km exclusion zone did not display more birth defects (Kreisel, 1995). Almost 30 years on from Chernobyl, exposed men are more satisfied with their lives than women, although this may be due to women's opportunities in Ukrainian society rather than the accident (Danzer and Danzer, 2014).

13 Whilst evacuation was compulsory and permanent after Chernobyl, over 1,200 older people defied the concerns of the Soviet authorities and returned home to their villages within the exclusion zone. The majority of the resettlers were women (Petryna, 2013). These women were ignorant of the risks of radiation exposure and proceeded to grow vegetables in the contaminated soil of their gardens and to forage within the forests for mushrooms and berries upon their return home. Many of the resettlers had lived in their villages for their entire lives before the evacuation and felt that being within the familiar confines of home was more important than evading an invisible hazard, curated by a distant and potentially untrustworthy government. Approximately 230 resettlers remain within the exclusion zone, the majority of which are elderly women who create a unique micro-society of independent and strong babusyas (Petryna, 2013). Health effects to these women are poorly documented, due to their existence on the margins of Ukrainian society. However, anecdotal evidence suggests that the babusyas of the exclusion zone are not suffering the consequences of their toxic homeland and have more fulfilling lives and better mental health than their evacuee contemporaries, so perhaps this is a victory of self-determinism over perceived risk (Petryna, 2011).

14 Japan is the only country that has experienced two major nuclear disasters, the atomic bombings of Nagasaki and Hiroshima in 1945, and the Fukushima Daiichi accident in 2011. Despite historical experience of the consequences of stigmatisation, it appears that women are again being more affected by the consequences of the accident (Ben-Ezra *et al.*, 2015). Interestingly, the same themes of pregnancy, family, home and mental health reappear when the impact of Fukushima Daiichi is considered. However, the motives for these concerns are dissimilar to those of Chernobyl due to cultural and social differences.

15 The incidence of PTSD and depression has dramatically increased following Fukushima, due to the trauma of evacuation and resettlement (Kukihara *et al.*, 2014). However, Japan is well-equipped to manage mental health effectively and it is likely that the one of the longterm outcomes of Fukushima may be a less significant mental health burden due to good support networks and effective public health facilities that do not stigmatise mental health (Ben-Ezra *et al.*, 2015). However, a general stigma exists towards the evacuees of Fukushima and more can be learnt through this about the social conditions that may have led to poor

mental health amongst the mothers of Chernobyl. Evacuee mothers with children have been subject to the same stigma as their Chernobylite equivalents, as resident Japanese mothers have informed evacuees that that they must not allow their children to interact with the local children, for fear of contamination (Bromet, 2011). This creates a culture of exclusion and isolation, which undoubtedly impacts upon women's mental health. After Fukushima, mothers have become more protective of their children and have restricted their activities due to concerns about radiation exposure. The Japanese Ministry of Education revealed that Fukushima schoolchildren experience the highest rates of childhood obesity in Japan, which may be a consequence of a cautionary and sedentary new lifestyle, following the accident (Sakai *et al.*, 2014). Unfortunately, the health problems associated with obesity may have a more significant impact upon this generation of children than any potential radiation exposure.

16 Whilst the Chernobylite evacuees experienced discrimination regardless of gender, female Fukushima survivors have been subject to a resurgence of gendered negative attitudes, especially from the older generations. Hibakusha, the derogatory term for a woman exposed to radiation during the atomic bombings, has been resurrected and is now applied to describe the women of Fukushima (Ben-Ezra *et al.*, 2015). There is evidence of gender-specific stigma against marrying women from Fukushima due to the inaccurate preconception that genetic defects can be attributed to the mother, who may consequently give birth to affected children (Ben-Ezra *et al.*, 2015). Therefore, women from Fukushima might be perceived as damaged goods and marriage discrimination may become a future problem (Tone and Stone, 2014). In parallel with Chernobyl, there has also been an increase in gendered violence towards women following Fukushima Daiichi (Yoshihama, 2014). It can be anticipated that increased stigma, discrimination and violence towards women following Fukushima has the potential capacity to create a future legacy of mental health challenges for Japan, but only time will tell.

Conclusions

17 This paper has described and contrasted the experiences of women during the radiation emergencies of Chernobyl and Fukushima. There are a number of important parallels, which focus around the process of evacuation, the consequences of displacement and loss of home. Relocation, following the Chernobyl accident, had permanent implications for Chernobylites but, hopefully, the consequences will be shorter-term for the displaced of Fukushima. This has significant implications for the women of Fukushima as it offers hope that original family home and local social networks may someday be resumed.

18 Interestingly, the women survivors of Fukushima appear to experience greater external negative judgment and stigma than those of Chernobyl. This may be due to the scale of the incident as many more women were affected by Chernobyl than by Fukushima. Culture and history may also have an important part to play in determining stigma, as Japan's Shinto culture and atomic history have increased the likelihood of a repeat of negative female experience. Much of this stigma is mired in ignorance of the scale of effects of radiation upon women and is often a subconscious, rather than direct, prejudice.

19 The social attitudes of the two different places are also significant. Japan has a more obedient culture with very well defined social norms and there has been considerably less unregulated activity and rebellion than Ukraine. However, existing cynicism of the Soviet regime was compounded amongst the older generations and there was a significant backlash by women against the compulsory evacuation policies. This prioritisation of home over perceived safety is, currently, particular to Chernobylites within the radiation emergency scenario. However, as time progresses it may be that Fukushima survivors will also begin to relocate illicitly to their homes. Prior knowledge of Chernobyl is influencing Japan's decision to reclaim the home lands of those within the evacuation zone, by expensive decontamination of housing.

20 However, the women of Chernobyl fare much worse when the likelihood of depression is considered. This is due to the relatively underdeveloped mental health service provision available in Soviet Russia. In contrast to this, a comprehensive mental healthcare service is available to female Fukushima survivors. Additionally, the culture of Japan shows more acceptance and less stigma towards mental health, encouraging reporting and management. Both Chernobyl and Fukushima show considerably higher levels of mental health reporting and documentation for women compared to men. Perhaps there is actually a hidden and unreported mental health crisis of men following radiation emergencies? This could, potentially, go some way towards explaining the increased rates of gendered domestic violence which followed the atomic bombing, Chernobyl and Fukushima. It is also interesting to

note that women affected solely by the tsunami are showing significant improvements and are developing more positive attitudes about the future, whereas nuclear evacuees have become more depressed with time. Perhaps it is too soon to truly understand the long-term psychological effects of Fukushima upon women, and only time will reveal if Fukushima has an impact upon the attitudes of fertile women, causing further birth decline in a nation of already stagnant birth rates.

21 However, there is a great need for further study, for while this paper begins to provide comparative insights, a complete understanding of the psychosocial experiences of women during radiation emergencies is not yet available. There is, therefore, a need to collate and contrast the diverse personal experiences of these women, from the Hibakusha of Hiroshima and Fukushima, to the female liquidators, and of course, the stealthy babusyas of the Chernobyl exclusion zone.

Bibliographie

ANSPAUGH L.R., CATLIN R.J. & GOLDMAN M. (1988), “The global impact of the Chernobyl reactor accident”, *Science, 242*, pp. 1513-1519.
BAVERSTOCK K. (1992), “Thyroid cancer in children in Belarus after Chernobyl”, *World health statistics quarterly. Rapport trimestriel de statistiques sanitaires mondiales, 46*, pp. 204-208.
BELYAKOV O.V., STEINHÄUSLER F. & TROTT K.-R. (2000), “Chernobyl liquidators. The people and the doses”, *Proceedings of the Tenth International Congress of the International Radiation Protection Association, Hiroshima, Japan, 14-19 May 2000*.
BEN-EZRA M., SHIGEMURA J., PALGI Y., HAMAMA-RAZ Y., LAVENDA O., SUZUKI M. & GOODWIN R. (2015), “From Hiroshima to Fukushima: PTSD symptoms and radiation stigma across regions in Japan”, *Journal of psychiatric research, 60*, pp. 185-186.
BROMET E.J. (2011), “Lessons learned from radiation disasters”, *World Psychiatry, 10*, pp. 83-84.
BROMET E. J. & HAVENAAR J.M. (2007), “Psychological and perceived health effects of the Chernobyl disaster: a 20-year review”, *Health physics, 93*, pp. 516-521.
CARDIS E., HOWE G., RON E., BEBESHKO V., BOGDANOVA T., BOUVILLE A., CARR Z., CHUMAK V., DAVIS S. & DEMIDCHIK Y. (2006), “Cancer consequences of the Chernobyl accident: 20 years on”, *Journal of radiological protection, 26*, 127.
CASTRONOVO F.P. (1999), “Teratogen update: radiation and Chernobyl”, *Teratology, 60*, pp. 100-106.
CLARK M. & SMITHv (1988), *Wet and dry deposition of Chernobyl releases*.
COOK I. G. & HALSALL J. (2012), “Aging in Japan”, *Aging in comparative perspective*, Springer, pp. 37-45.
DANZER A.M. & DANZER N. (2014), “The Long-Run Consequences of Chernobyl: Evidence on Subjective Well-Being, Mental Health and Welfare”, *Mental Health and Welfare (June 25, 2014). CESIFO Working Paper Series*.
FRIEDMAN S. M. (2011), “Three Mile Island, Chernobyl, and Fukushima: An analysis of traditional and new media coverage of nuclear accidents and radiation”, *Bulletin of the atomic scientists, 67*, pp. 55-65.
HAMADA N. & OGINO H. (2012), “Food safety regulations: what we learned from the Fukushima nuclear accident”, *Journal of environmental radioactivity, 111*, pp. 83-99.
HAVENAAR J.M., RUMYANTZEVA G.M., VAN DEN BRINK W., POELIJOE N.W., VAN DEN BOUT J., VAN ENGELAND H. & KOETER M.W. (2014), *Long-term mental health effects of the Chernobyl disaster: an epidemiologic survey in two former Soviet regions.*
HINDMARSH R. (2013), *Nuclear disaster at Fukushima Daiichi: social, political and environmental Issues*, Routledge.
HOLT M., CAMPBELL R.J. & NIKITIN. M.B. (2012), *Fukushima nuclear disaster*, Congressional Research Service.
JACOB P., KENIGSBERG Y., ZVONOVA I., GOULKO G., BUGLOVA E., HEIDENREICH W., GOLOVNEVA A., BRATILOVA A., DROZDOVITCH V. &. KRUK J. (1999), “Childhood exposure due to the Chernobyl accident and thyroid cancer risk in contaminated areas of Belarus and Russia”, *British journal of cancer, 80*, 9, pp. 1461-1469.
KREISEL W. (1995), “International program on the health effects of the Chernobyl accident”, *Stem cells (Dayton, Ohio), 13*, pp. 33-39.
KRYZHANOVSKAYA L. & NAKANO Y. (1996), “Mental health of liquidators of the Chernobyl disaster”, *Acta medica nagasakiensia, 41*, pp. 15-19.
KUKIHARA H., YAMAWAKI N., UCHIYAMA K., ARAI S. & HORIKAWA E. (2014), “Trauma, depression, and resilience of earthquake/tsunami/nuclear disaster survivors of Hirono, Fukushima, Japan”, *Psychiatry and clinical neurosciences, 68*, pp. 524-533.
LAY T. & KANAMORI H. (2011), “Japan earthquake”, *Physics today, 64*, 33.
LIKHTAREV I.A., CHUMACK V.V. & REPIN V.S. (1994), “Analysis of the effectiveness of emergency countermeasures in the 30-km zone during the early phase of the Chernobyl accident”, *Health physics, 67*, pp. 541-544.
LITTLE M.P., KUKUSH A.G., MASIUK S.V., SHKLYAR S., CARROLL R.J., LUBIN J.H., KWON D., BRENNER A.V., TRONKO M.D. & MABUCHI K. (2014), “Impact of Uncertainties in Exposure Assessment on Estimates of Thyroid Cancer Risk among Ukrainian Children and Adolescents Exposed

from the Chernobyl Accident", *PLoS ONE, 9*, e85723.
MOBBS S., MUIRHEAD C. & HARRISON J. (2010), *Risks from ionising radiation,* Health Protection Agency.
MOULD R.F. (2000), *Chernobyl record: the definitive history of the Chernobyl catastrophe*, CRC Press.
PETRYNA A. (2011), "Chernobyl's survivors: Paralyzed by fatalism or overlooked by science", *Bulletin of the atomic scientists, 67*, pp. 30-37.
--- (2013), *Life exposed: Biological citizens after Chernobyl,* Princeton University Press.
PHILLIPS S.D. (2002), "Half-Lives and Healthy Bodies: Discourses on Contaminated Food and Healing in Postchernobyl Ukraine", *Food and foodways, 10*, pp. 27-53.
PHILLIPS S.D. (2004), "Chernobyl's Sixth Sense: The Symbolism of an Ever-Present Awareness", *Anthropology and humanism, 29*, pp. 159-185.
RON E., LUBIN J.H., SHORE R.E., MABUCHI K., MODAN B., POTTERN L.M., SCHNEIDER A.B., TUCKER M.A. & BOICE J.D. Jr (1995), "Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies", *Radiation Research, 141*, pp. 259-277.
SAKAI A., OHIRA T., HOSOYA M., OHTSURU A., SATOH H., KAWASAKI Y., SUZUKI H., TAKAHASHI A., KOBASHI G. & OZASA K. (2014), "Life as an evacuee after the Fukushima Daiichi nuclear power plant accident is a cause of polycythemia: the Fukushima Health Management Survey", *BMC Public health, 14*, 1318.
SALGE M. & MILLING P.M. (2006), "Who is to blame, the operator or the designer? Two stages of human failure in the Chernobyl accident", *System Dynamics Review, 22,* pp. 89-112.
SARIN R. (2011), "Chernobyl, Fukushima, and beyond: A health safety perspective", *Journal of cancer research and therapeutics, 7*, 109.
SHLYAKHTER A. & WILSON R. (1992), "Chernobyl and glasnost: the effects of secrecy on health and safety", *Environment: science and policy for sustainable development, 34*, pp. 25-30.
SLOVIC P. (2012), "The perception gap: Radiation and risk", *Bulletin of the atomic scientists, 68,* pp. 67-75.
STIMSON H.L. (1985), "The decision to use the atomic bomb", *SAIS Review, 5*, pp. 1-15.
TODESCHINI M. (1996), "Death and the Maiden: Female Hibakusha as Cultural Heroines and the Politics of A-Bomb Memory", *Hibakusha cinema: Hiroshima, Nagasaki and the nuclear image in Japanese film*, pp. 222-252.
TODESCHINI M.M. (1999), *Bittersweet crossroads: women of Hiroshima and Nagasaki,* Harvard University.
TONE M. & STONE T. (2014), "What we can learn about recovery: Lessons from the Fukushima survivors", *Nursing & health sciences, 16*, pp. 52-55.
VIINAMÄKI H., KUMPUSALO E., MYLLYKANGAS M., SALOMAA S., KUMPUSALO L., KOLMAKOV S., ILCHENKO I., ZHUKOWSKY G. & NISSINEN A. (1995), "The Chernobyl accident and mental wellbeing—a population study", *Acta Psychiatrica Scandinavica, 91*, pp. 396-401.
WELNER M. & PAGE J. (2013), "Disaster Psychiatry" *Disaster preparedness for health care facilities*, *469*.
YOSHIHAMA M. (2014), "Gender-based violence following the Great East Japan Disasters of March 2011", *142nd APHA Annual Meeting and Exposition (November 15-November 19, 2014)*, APHA.

Pour citer cet article

Référence électronique
Becky Alexis-Martin, « The Chernobyl necklace: the psychosocial experiences of female radiation emergency survivors », *Belgeo* [En ligne], 2 | 2015, mis en ligne le 30 juin 2015, consulté le 17 septembre 2015. URL : http://belgeo.revues.org/14441

À propos de l'auteur

Becky Alexis-Martin
University of Southampton, UK, Becky.Martin@soton.ac.uk

Droits d'auteur

© NCG with the SRBG

Résumés

Whilst the significance of physical exposure to ionising radiation can be empirically ascertained, radiation emergencies also have significant psychosocial impacts which are politically, socially and culturally determined. The nuclear reactor accidents of Chernobyl in 1986 and Fukushima in 2011 have had differential consequences for women, due to differences in space, place and time. This paper characterises, contextualises and compares the psychosocial effects of Chernobyl and Fukushima for female survivors, demonstrating the significant impacts of radiation emergencies.

Les impacts psychosociaux des accidents nucléaires sur les femmes

Une compréhension plus profonde des effets des accidents nucléaires sur les femmes peut améliorer les résultats des urgences de radiations dans l'avenir, en particulier pour ce sousgroupe démographique. Les accidents de réacteurs nucléaires de Tchernobyl en Ukraine (1986), et de Fukushima au Japon (2011) ont eu des impacts différentiels sur les femmes à proximité immédiate et au-delà de l'accident. Cet exposé décrit, contextualise et compare les conséquences de ces deux accidents de réacteurs nucléaires sur les femmes.

Entrées d'index
Mots-clés : femmes, Fukushima, Tchernobyl, spatio-temporel, urgence, protection contre les radiations, risques
Keywords : women, Fukushima, Chernobyl, spatiotemporal, emergency, radiation

protection, risk

theguardian

Nuclear fallout: the mental health consequences of radiation

70 years on from the destruction of Nagasaki, much of the attention regarding radiation is still directed to the physical dangers, but the psychological consequences can also be damaging.

Becky Martin

Sunday 9 August 2015 09.00 BST

Radiation protection research has been focused upon the bodily effects of exposure to ionising radiation, rather than upon the psychology of survivors. However, recent work, including my own, has shown that the most significant impacts of radiation emergencies are often in our minds.

The physical consequences of radiation exposure are well documented, from radiation sickness to cancer. However, there is another insidious and debilitating impact upon the people in areas affected by nuclear accident, regardless of proximity to hazards and actual exposure; something that has a greater prevalence and a higher rate of morbidity and mortality than all physical health cases combined - mental health effects.

Ionising radiation and mental health are both sorry subjects of misunderstanding and flagrant misinformation. The immediate physical wellbeing of radiation emergency survivors is rightly prioritised, with the aim of preventing and minimising exposure. Unfortunately, this has historically meant mass-evacuation of whole populations to unfamiliar locations, the disruption of day-to-day life, and the loss of social support networks. Imagine that you've been informed that your land, your water, the air that you have breathed may have been polluted by a deadly and invisible contaminant. Something with the capacity to take away your fertility, or affect your unborn children. Even the most resilient of us would be concerned, and many thousands of radiation emergency survivors have subsequently gone on to develop PTSD, depression and anxiety disorders as a result of their experiences and the uncertainty surrounding their health.

There is a distinct demographic bias, where women appear to be significantly more susceptible to mental health challenges following radiation emergencies. However, I suspect that there is actually greater parity of experience than is shown by the statistics. Men are less likely than women to disclose their mental health status to professionals, and that trend may continue following disasters. There has also been a reported increase in alcoholism and drug abuse amongst men following major accidents, which would suggest that the burden is in some ways equivalent.

Regardless, a greater psychological impact has been reported among women - a pattern that appears to have repeated in incidents from Chernobyl to Fukushima. The causes of this have been hypothesised to be due to the burden of responsibility for home, the young and the elderly falling upon women during crisis. Women survivors also appear to experience greater stigma attached to their status than men, which can make it challenging to engage in normal life - like dating, marriage and having children. Much of this stigma is mired in ignorance of the scale of radiation effects upon women and is often a subconscious, rather than direct prejudice.

In Japan, Hibakusha is derogatory term which is usually specific to women and children, originating from bombing of Nagasaki 70 years ago. This term - literally meaning "explosion-affected people" - has experienced a resurgence following Fukushima in 2011, and there is evidence that it has returned to the dialogue of female survivors from interviews. While there have been few physical casualties post-Fukushima, there have been significant impacts on the mental health of female survivors, affecting their general wellbeing and opportunities to have children and a normal family life. Risk of poor mental health was particularly increased for women with children under the age 18, who have lived in exposed regions. Short-term displacement has less severe consequences, but the return to home can also have its own challenges. One example is an increase in childhood obesity, as rationally protective parents keep their children indoors unnecessarily due to perceived contamination outside.

Perhaps it is now time to reconsider the ways by which we help people to recover from radiation emergencies. It is known that the negative mental health and stigmas faced by the Chernobylites, a derogatory term for the Chernobyl evacuees, lasted for decades after the disaster. Whilst evacuation from the exclusion zone was compulsory and permanent following the accident, over 1,200 older people defied the concerns of Soviet authorities and returned home to their villages. The majority of these resettlers were women. They proceeded to grow vegetables in the contaminated soil of their gardens, and to forage within the stricken forests for mushrooms and berries, as is usual for their society.

Many of the resettlers would have lived in their villages for their entire lives before the evacuation, and therefore felt that being within the familiar confines of home was more important to them than evading an invisible danger, curated by a distant and potentially untrustworthy government. Approximately 230 resettlers still remain within the exclusion zone, the majority of whom are elderly women who have created a unique micro-society of independent and strong babusyas. The health effects of their exposure to elevated levels of radiation are poorly documented, due to their existence on the margins of Ukrainian society. However, anecdotal evidence suggests that the babusyas lead more fulfilling lives and have better mental health than their evacuee contemporaries. It raises the question that perhaps their's is a victory of self-determinism over risk?

I'm not for a minute suggesting that evacuation is not an important and potentially life-saving strategy, but we need to provide greatly improved social support following resettlement and extensive long-term psychological care to all radiation emergency survivors, to improve their health outcomes and preserve their futures.

Becky Martin is a PhD researcher at the University of Southampton and an expert in radiation protection. More information about her current project, RADPOP, and her conferences and talks can be found at www.radpop.co.uk. You can Tweet her your thoughts about radiation emergencies @CalamityCake.

More blogposts

Topics

Mental health Health Nuclear waste

Save for later Article saved
Reuse this content

Appendix B: Catalogue of UK nuclear installations

NI	Postcode	Type	Status		Move ment	15km proximity to significant population	DEPZ (km)	Case study suitability
Hunterston A & B	KA23 9RA	NPP	A	0	Static	No	2.4	Low
			B	1				
Dungeness A & B	TN29 9PP	NPP	A	0	Static	No	2.4	Low
			B	1				
Hinkley A & B	TA5 1YA	NPP	A	0	Static	No	3.5	Low
			B	1				
Sizewell A & B	IP16 4UE	NPP	A	0	Static	No	2.4	Low
			B	1				
Heysham 1 & 2	LA3 2XQ	NPP	1	1	Static	Yes	1	Moderate
			2	1				
Hartlepool	TS25 2BZ	NPP	Active	1	Static	Yes	1	Moderate
Torness	EH42 1QS	NPP	Active	1	Static	No	3	Low
Sellafield	CA20 1PG	Chemical	Active	1	Static	No	2	Low
Springfields	PR4 0XJ	Chemical	Active	1	Static	Yes	1	Moderate
Aldermaston	RG7 4PR	Defence	Active	1	Static	Yes	3	Moderate
Burghfield	SU6668	Defence	Active	1	Static	Reading	1.5	Moderate
Devonport		Defence	Active		Mobile	Plymouth	2	**High**
Portsmouth		Defence	Active		Mobile	Portsmouth	2	**High**
Rosyth		Defence	Active		Mobile	Dunferm-line, Edinburgh	2	**High**
Clyde		Defence	Active		Mobile	Barrow in Furness	2	Moderate
Barrow		Defence	Active		Mobile	Ulverston, Barrow in Furness	2	Moderate
Southampton		Defence	Active		Mobile	Southamp-ton	2	Moderate
Portland		Defence	Active	1	Mobile	Yes	1.5	Moderate

NB: Only sites that have designated DEPZ as determined by ONR have been included. “Proximity” is the direct distance to a settlement of larger than 15,000 individuals.

Appendix C: Library of modelling outputs

This appendix archives the complete library of modelling outputs produced for this thesis. Parameters included from PACE and NAME modelling outputs in the final versions of Case study I and Case study II have been bolded.

Population247 spatiotemporal modelling	Male population: 0-4, 5-9, 10-15, University and college 16-64, Working 16-64, Over 65 Female population: 0-4, 5-9, 10-15, University and college 16-64, Working 16-64, Over 65 Education, healthcare, leisure and tourism, retail and workplace activity subsets Data from 0700 to 1800 was included in the studies.
NAME PACE radioisotope dispersal output	Isotope species: *Xe133, I131, Cs134,* **Cs137**, *Ba137m ,Te132, Ba140, Mo99, Ru103, Ru106, Ce141 and Ce144* Total modelled time on hourly intervals across 24 hours. Data from 0700 to 1800 was included in the studies.
PACE probabilistic health effects modelling output categories	**Deterministic, Deterministic (CM), Fatalities, Fatalities (CM)**, Non-Fatal Reactions, Non-Fatal Reactions (CM), First Generation Effects, First Generation Effects (CM), Cost Fatalities, Cost Fatalities (CM), Cost Non-Fatal Reactions, Cost Non-Fatal Reactions (CM), Total Cost Deterministic, Total Cost Deterministic (CM), Cost First Generation Effects, Cost First Generation Effects (CM), Leukaemia Fatalities, Leukaemia Fatalities (CM),Solid Cancer Fatalities, Solid Cancer Fatalities (CM), Total Cancer Fatalities, Total Cancer Fatalities (CM), **Leukaemia Incidence, Leukaemia Incidence (CM),** Solid Cancer Incidence, Solid Cancer Incidence (CM), Total Cancer Incidence, Total Cancer Incidence (CM), Cost Solid Cancer Fatalities, Cost Solid Cancer Fatalities (CM), Cost Solid Cancer Incidence, Cost Solid Cancer Incidence (CM), Cost Leukaemia Fatalities, Cost Leukaemia Fatalities (CM), Cost Leukaemia Incidence, Cost Leukaemia Incidence (CM), Total Cost Cancer, Total Cost Cancer (CM), Number Evacuated, Area Evacuated, Number Sheltered, Area Sheltered Modelled on hourly intervals across 24 hours.
Agent-based modelling framework	Census 2011 residential population dataset (0700-1800) 0700 Population247 female population dataset (0700-1800)

Glossary of Terms

Accident: Unplanned, unexpected, unintended and undesirable happening which results in or has the potential for injury, harm, ill-health or damage.

Civil Contingencies Act (2004): Act of 2004 which established a single framework for Civil Protection in the United Kingdom. Part 1 of the Act establishes a clear set of roles and responsibilities for Local Responders; Part 2 of the Act establishes emergency powers.

DEPZ: Area surrounding a nuclear licensed site for which detailed plans for emergencies have been prepared. The area covered by the DEPZ is agreed with the nuclear regulator and is based on the reference accident for that site.

Disaster: Emergency causing, or threatening to cause, widespread and serious disruption to community life through death, injury, and/or damage to property and/or the environment.

Emergency Plan: A document or collection of documents that sets out the overall framework for the initiation, management, co-ordination and control of personnel and assets to reduce, control or mitigate the effects of an emergency.

ERL: Quantitative criteria used to plan for the introduction of urgent countermeasures in the event of a radiation emergency.

Evacuation Shelter: Building in an area out of danger providing basic accommodation for up to 48 hours after an emergency.

Extendibility: A characteristic of emergency plans that may be been developed for specific circumstances but are able to be applied, or 'scaled up' to larger, or otherwise different circumstances.

GIS: Computer based system that supports the capture, management; analysis and modelling of geographically referenced data.

INES: A tool for communicating in consistent terms the safety significance of reported nuclear and radiological incidents and accidents.

Mass Evacuation: Evacuation of a large number of people (100,000+) from a place of danger to a place of relative safety.

NARO: Ministry of Defence (MOD) agency responsible for response to an accident or incident, including one arising through terrorist acts, involving defence nuclear assets.

NAME: The Met Office's atmospheric dispersion model used to provide predictions of the spread of airborne radioactivity or other hazardous materials.

Off-Site Nuclear Emergency: Declaration state definition: A hazardous condition which results, or is likely to result, in the need to consider urgent countermeasures to protect the public outside the site security fence from a radiological hazard.

Onset: The beginning of an emergency or disaster.

Potassium Iodate tablets (PITS): A stable form of iodine, which can bind to and protect the thyroid gland, preventing uptake of radioactive iodine by the gland and the increased likelihood of thyroid cancer in the future.

Radiation emergency: Event likely to result in a member of the public receiving an effective dose of 5 MSv during the year immediately following.

Rapid onset emergency: Emergency which develops quickly and usually with immediate effects, thereby limiting the time available to consider response options.

Reference Accident: Worst possible accident considered reasonably foreseeable for a nuclear licensed site.

REPPIR: UK legislative framework of emergency preparedness measures to ensure that members of the public are properly prepared for a possible radiation emergency, and properly informed if one occurs.

Responder: Organisation required to plan and prepare a response to an emergency.

Response Phase: Phase in which decision making and actions are focused on response to an actual emergency or disaster.

RIMNET: The national radiation monitoring and nuclear and radiation emergency response system.

Risk: Measure of significance of a potential emergency in terms of assessed likelihood and impact.

Risk Rating Matrix: Table showing the likelihood and potential impact of events or situations, in order to ascertain the risk.

Science and Technical Advice Cell (STAC): Group of technical experts from those agencies involved in an emergency response that may provide scientific and technical advice.

Technological Hazard: Hazard arising from technological or industrial conditions; including accidents, dangerous procedures, infrastructure deficiencies, and specific human activities.

Vulnerability: Susceptibility of individuals or community, services or infrastructure to damage or harm arising from an emergency or other incident.

Vulnerable Person: A person who is less able to help themselves in the circumstances of an emergency.

Warning and Informing: Arrangements to make the public aware of risks and for responders to warn, inform and advise the public when an emergency is likely to occur or has occurred, and to provide them with information and advice subsequently.

References and Bibliography

ADGER, W. N. 2006. Vulnerability. *Global environmental change,* 16**,** 268-281.

AFRRI 2011. AFRRI Pocket Guide - Emergency Radiation Medicine Response. *In:* UNIFORMED SERVICES UNIVERSITY OF THE HEALTH SCIENCES, U. (ed.) *Armed Forces Radiobiology Research Institute.*

AHOLA, T., VIRRANTAUS, K., KRISP, J. M. & HUNTER, G. J. 2007. A spatio-temporal population model to support risk assessment and damage analysis for decision-making. *International Journal of Geographical Information Science,* 21**,** 935-953.

ALEXANDER, D. 2009. *Principles of Emergency Planning* [Online]. http://www.slideshare.net/dealexander/principles-of-emergency-planning: SlideShare. Available: http://www.slideshare.net/dealexander/principles-of-emergency-planning [Accessed 21st October 2013].

ALEXANDER, D. E. 2002. *Principles of emergency planning and management*, Oxford University Press.

ALEXANDER, J. W. & ZAHORCHAK, G. A. 1943. Population-density maps of the United States: techniques and patterns. *Geographical Review,* 33**,** 457-466.

ANDERSON, M. B. 1985. A reconceptualization of the linkages between disasters and development. *Disasters,* 9**,** 46-51.

ARMSTRONG, M. P. Temporality in spatial databases. Proceedings: GIS/LIS, 1988. 880-889.

ATSDR. 1999. *Toxological Profile for Ionising Radiation PB/99/163388* [Online]. USA: Agency for Toxic Substances and Disease Registry. Available: http://www.atsdr.cdc.gov/ToxProfiles/tp.asp?id=484&tid=86 [Accessed 1st April 2014].

BACKUS, G. A. & GLASS, R. J. 2006. An agent-based model component to a framework for the analysis of terrorist-group dynamics. *Sandia Report, SAND2006-0860P*.

BARNETT, D. J., PARKER, C. L., BLODGETT, D. W., WIERZBA, R. K. & LINKS, J. M. 2006. Understanding radiologic and nuclear terrorism as public health threats: preparedness and response perspectives. *Journal of Nuclear Medicine,* 47**,** 1653-1661.

BATTY, M., XIE, Y. & SUN, Z. 1999. Modeling urban dynamics through GIS-based cellular automata. *Computers, environment and urban systems,* 23**,** 205-233.

BAVERSTOCK, K. 1992. Thyroid cancer in children in Belarus after Chernobyl. *World health statistics quarterly. Rapport trimestriel de statistiques sanitaires mondiales,* 46**,** 204-208.

BBC 2011. Devonport nuclear submarine dismantling details on show. *BBC News Devon*.

BBC 2013. HMS Torbay nuclear submarine evacuated. *BBC News Devon*.

BEIR, V. 1990. Health effects of exposure to low levels of ionizing radiation. *Washington, DC: National Academy of Sciences*.

BENENSON, I., BIRFUR, S. & KHARBASH, V. 2006. Geographic Automata Systems and the OBEUS software for their implementation. *Complex artificial environments.* Springer.

BHADURI, B., BRIGHT, E., COLEMAN, P. & URBAN, M. L. 2007. LandScan USA: a high-resolution geospatial and temporal modeling approach for population distribution and dynamics. *GeoJournal,* 69**,** 103-117.

BLOOM, W. 1947. Histological changes following radiation exposures. *Radiology,* 49**,** 344-348.

BOICE, J. D. 1990. Studies of atomic bomb survivors understanding radiation effects. *JAMA,* 264**,** 622-623.

BOLIN, B. 2007. Race, class, ethnicity, and disaster vulnerability. *Handbook of disaster research.* Springer.

BONABEAU, E. 2002. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America,* 99**,** 7280-7287.

BONANNO, G. A., GALEA, S., BUCCIARELLI, A. & VLAHOV, D. 2007. What predicts psychological resilience after disaster? The role of demographics, resources, and life stress. *Journal of consulting and clinical psychology,* 75**,** 671.

BONANNO, G. A., WESTPHAL, M. & MANCINI, A. D. 2011. Resilience to loss and potential trauma. *Annual Review of Clinical Psychology,* 7, 511-535.
BORDEN 2012. *Medical Consequences of Radiological and Nuclear Weapons,* USA, Medical Department of the Army, USA.
BRACKEN, I. & MARTIN, D. 1989. The generation of spatial population distributions from census centroid data. *Environment and Planning A,* 21, 537-543.
BRACKEN, I. & MARTIN, D. 1995. Linkage of the 1981 and 1991 UK Censuses using surface modelling concepts. *Environment and Planning A,* 27, 379-379.
BROMET, E. J. 2014. Emotional consequences of nuclear power plant disasters. *Health physics,* 106, 206-210.
BROMET, E. J. & HAVENAAR, J. M. 2007. Psychological and perceived health effects of the Chernobyl disaster: a 20-year review. *Health physics,* 93, 516-521.
BROWN, D. G., RIOLO, R., ROBINSON, D. T., NORTH, M. & RAND, W. 2005. Spatial process and data models: Toward integration of agent-based models and GIS. *Journal of Geographical Systems,* 7, 25-47.
BUTTURINI, A., GALE, R., LOPES, D., CUNHA, C., HO, W., SANPAI, J., DE SOUZA, P., CORDIERO, J., NETO, C. & DE SOUZA, C. 1988. Use of recombinant granulocyte-macrophage colony stimulating factor in the Brazil radiation accident. *The Lancet,* 332, 471-475.
CACCIAPUOTI, A. S., CALABRESE, F., CALEFFI, M., DI LORENZO, G. & PAURA, L. 2013. Human-mobility enabled wireless networks for emergency communications during special events. *Pervasive and Mobile Computing,* 9, 472-483.
CAHALAN, C. & RENNE, J. 2007. *Emergency evacuation of the elderly and disabled*, National Emergency Training Center.
CARUTH, G. D. 2013. Demystifying Mixed Methods Research Design: A Review of the Literature. *Mevlana Intenational Journal of Education (MIJE)*.
CASTIGLIONE, F. 2006. Agent based modeling. *Scholarpedia,* 1, 1562.
CASTLE, C. J. & CROOKS, A. T. 2006. Principles and concepts of agent-based modelling for developing geospatial simulations.
CCS 2004. Civil Contingencies Act 2004. *In:* OFFICE, C. (ed.). London, UK: UK Government.
CCS 2008. Identifying people who are vulnerable in a crisis: guidance for emergency planners and responders. *In:* SECRETARIAT, C. C. (ed.). London: Cabinet Office.
CHANG, N.-B. & WENG, Y.-C. 2013. Short-term emergency response planning and risk assessment via an integrated modeling system for nuclear power plants in complex terrain. *Frontiers of Earth Science,* 7, 1-27.
CHARNOCK, T., BEXTON, A., SHERWOOD, J., HIGGINS, N. & FIELD, S. 2013. PACE: A Geographic Information System Based Level 3 Probabilistic Accident Consequence Evaluation Program. *International Topical Meeting on Probabilistic Safety Assessment and Analysis.* Columbia, SC, USA: American Nuclear Society.
CHATTOE-BROWN, E. 2013. Why Sociology Should Use Agent Based Modelling. *Sociological Research Online,* 18, 3.
CO. 2014. *Preparation and planning for emergencies: the National Resilience Capabilities Programme* [Online]. London: Cabinet Office. Available: https://www.gov.uk/preparation-and-planning-for-emergencies-the-capabilities-programme [Accessed 28/06/2014 2014].
CONNAN, O., SMITH, K., ORGANO, C., SOLIER, L., MARO, D. & HÉBERT, D. 2013. Comparison of RIMPUFF, HYSPLIT, ADMS atmospheric dispersion model outputs, using emergency response procedures, with< sup> 85</sup> Kr measurements made in the vicinity of nuclear reprocessing plant. *Journal of environmental radioactivity,* 124, 266-277.
COPPOCK, J. T. & RHIND, D. W. 1991. The history of GIS. *Geographical information systems: Principles and applications,* 1, 21-43.
COUCLELIS, H. 2002. Modeling frameworks, paradigms, and approaches. *Geographic information systems and environmental modeling*, 36-50.
COVA, T. J. 1999. GIS in emergency management. *Geographical information systems,* 2, 845-858.
CROOKS, A., CASTLE, C. & BATTY, M. 2008. Key challenges in agent-based modelling for geo-spatial simulation. *Computers, Environment and Urban Systems,* 32, 417-430.

CROOKS, A. T. & CASTLE, C. J. 2012. The integration of agent-based modelling and geographical information for geospatial simulation. *Agent-based models of geographical systems*, 219-251.

CROOKS, A. T. & WISE, S. 2013. GIS and agent-based models for humanitarian assistance. *Computers, Environment and Urban Systems,* 41**,** 100-111.

CROWELL, M., WESTCOTT, J., PHELPS, S., MAHONEY, T., COULTON, K. & BELLOMO, D. 2013. Estimating the United States population at risk from coastal flood-related hazards. *Coastal Hazards.* Springer.

CULLINGS, H. M. 2014. Impact on the Japanese Atomic Bomb Survivors of Radiation Received From the Bombs. *Health physics,* 106**,** 281-293.

CUTTER, S. L. 2003. GI science, disasters, and emergency management. *Transactions in GIS,* 7**,** 439-446.

CUTTER, S. L., BORUFF, B. J. & SHIRLEY, W. L. 2003. Social vulnerability to environmental hazards. *Social science quarterly,* 84**,** 242-261.

DAWSON, R. J., PEPPE, R. & WANG, M. 2011. An agent-based model for risk-based flood incident management. *Natural hazards,* 59**,** 167-189.

DE&S 2010. HM Naval Base Devonport: Safety Statement for Proposed EfW Plant at North Yard. Ministry of Defence.

DECAIR, S., 2016. 2016. Updating Dosimetry for Emergency Response Dose Projections. *Health physics,* 110**,** 217-221.

DECC 2013. Nuclear Emergency Planning Liaison Group Consolidated Guidance: Chapter 8: Early Countermeasures *In:* GOVERNMENT, H. (ed.). London: Department of Energy and Climate Change.

DENG, C. & WU, C. 2013. Improving Small-Area Population Estimation: An Integrated Geographic and Demographic Approach. *Annals of the Association of American Geographers,* 103**,** 1123-1141.

DFT. 2011. *National Travel Survey: 2011* [Online]. Department for Transport. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/35738/nts2011-01.pdf [Accessed].

DIETZEL, C., HEROLD, M., HEMPHILL, J. J. & CLARKE, K. C. 2005. Spatio-temporal dynamics in California's Central Valley: Empirical links to urban theory. *International Journal of Geographical Information Science,* 19**,** 175-195.

DIGIMAP. 2014. *Map of Plymouth*. EDINA Digimap.

DITTRICH, K. R. Object-oriented database systems (extended abstract): the notions and the issues. Proceedings on the 1986 international workshop on Object-oriented database systems, 1986. IEEE Computer Society Press, 2-4.

DOBSON, J. E., BRIGHT, E. A., COLEMAN, P. R., DURFEE, R. C. & WORLEY, B. A. 2000. LandScan: a global population database for estimating populations at risk. *Photogrammetric engineering and remote sensing,* 66**,** 849-857.

DOFE. 2014. *EduBase2* [Online]. Available: http://www.education.gov.uk/edubase/home.xhtml [Accessed].

DONNER, W. & RODRÍGUEZ, H. 2008. Population composition, migration and inequality: The influence of demographic changes on disaster risk and vulnerability. *Social Forces,* 87**,** 1089-1114.

DORASAMY, M., RAMAN, M. & KALIANNAN, M. 2013. Knowledge management systems in support of disasters management: A two decade review. *Technological Forecasting and Social Change,* 80**,** 1834-1853.

DRABEK, T. E. & HOETMER, G. J. 1991. *Emergency management: Principles and practice for local government*, International city management association Washington, DC.

DRAXLER, R., ARNOLD, D., CHINO, M., GALMARINI, S., HORT, M., JONES, A., LEADBETTER, S., MALO, A., MAURER, C., ROLPH, G. AND SAITO, K. 2015. World Meteorological Organization's model simulations of the radionuclide dispersion and deposition from the Fukushima Daiichi nuclear power plant accident. *Journal of environmental radioactivity,* 139**,** 172-184.

DRURY, J., NOVELLI, D. & STOTT, C. 2013. Representing crowd behaviour in emergency planning guidance:'mass panic'or collective resilience? *Resilience,* 1**,** 18-37.
DYMON, U. J. & WINTER, N. L. 1993. Evacuation mapping: the utility of guidelines. *Disasters,* 17**,** 12-24.
EADE, D. & WILLIAMS, S. 1995. *The Oxfam handbook of development and relief. 2*, Oxfam.
EICHER, C. L. & BREWER, C. A. 2001. Dasymetric mapping and areal interpolation: implementation and evaluation. *Cartography and Geographic Information Science,* 28**,** 125-138.
ELIAS, N. & JEPHCOTT, E. 1992. *Time: an essay*, Blackwell Oxford.
ENARSON, E. 1998. Through women's eyes: A gendered research agenda for disaster social science. *Disasters,* 22**,** 157-173.
ENARSON, E. P. 2000. *Gender and natural disasters*, ILO Geneva.
EPA 2012. Radiation: Facts, Risks and Realities. *In:* RADIATION, U. S. E. P. A. O. O. A. A. (ed.) EPA-402-K-10-008 ed.
ETZEL, R. & BALK, S. 1998. RISK OF IONIZING RADIATION EXPOSURE TO CHILDREN: A SUBJECT. *Pediatrics,* 101**,** 717-719.
FINUCANE, M. L., SLOVIC, P., MERTZ, C. K., FLYNN, J. & SATTERFIELD, T. A. 2000. Gender, race, and perceived risk: The'white male'effect. *Health, risk & society,* 2**,** 159-172.
FLOWERDEW, R. 2011. How serious is the Modifiable Areal Unit Problem for analysis of English census data? *Population trends,* 145**,** 106-118.
FLOWERDEW, R., GREEN, M. & KEHRIS, E. 1991. Using areal interpolation methods in geographic information systems. *Papers in regional science,* 70**,** 303-315.
FORD, K. 2008. *Emergency planning for people with disability* [Online]. Iowa: Iowa Public Health Preparedness Program. Available: http://www.idph.state.ia.us/bh/common/pdf/disability_health/emergency_planning.pdf [Accessed 24/03/2014 2014].
FREIRE, S. 2010. Modeling of Spatiotemporal Distribution of Urban Population at High Resolution–Value for Risk Assessment and Emergency Management. *Geographic Information and Cartography for Risk and Crisis Management***,** 53-67.
FREIRE, S., AUBRECHT, C. & WEGSCHEIDER, S. Spatio-temporal population distribution and evacuation modeling for improving tsunami risk assessment in the Lisbon Metropolitan Area. Proceedings of Gi4DM 2011, international symposium on geoinformation for disaster management, Antalya, 2011. 6.
FREIRE, S., AUBRECHT, C. & WEGSCHEIDER, S. 2012. When the tsunami comes to town—improving evacuation modeling by integrating high-resolution population exposure. *Proceedings of ISCRAM***,** 22-25.
FUCIC, A., BRUNBORG, G., LASAN, R., JEZEK, D., KNUDSEN, L. E. & MERLO, D. F. 2008. Genomic damage in children accidentally exposed to ionizing radiation: a review of the literature. *Mutation Research/Reviews in Mutation Research,* 658**,** 111-123.
GOODCHILD, M. F., ANSELIN, L. & DEICHMANN, U. 1993. A framework for the areal interpolation of socioeconomic data. *Environment and Planning A,* 25**,** 383-397.
GOODCHILD, M. F., LAM, N. S. & GEOGRAPHY, U. O. W. O. D. O. 1980. *Areal interpolation: a variant of the traditional spatial problem*, London, Ont.: Department of Geography, University of Western Ontario.
GOVERNMENT, H. 2002. Traffic Signage Regulations: Statutory Instrument 2002 No. 3113
GOVERNMENT, H. 2010. A Strong Britannia in an Age of Uncertainty: The National Security Strategy. HMSO: HMSO.
GREEN, M. & FLOWERDEW, R. 1996. New evidence on the modifiable areal unit problem. *Spatial analysis: Modelling in a GIS environment***,** 41-54.
GREGORY, I. N. 2002. The accuracy of areal interpolation techniques: standardising 19th and 20th century census data to allow long-term comparisons. *Computers, environment and urban systems,* 26**,** 293-314.
GRIMM, V., BERGER, U., DEANGELIS, D. L., POLHILL, J. G., GISKE, J. & RAILSBACK, S. F. 2010. The ODD protocol: a review and first update. *Ecological Modelling,* 221**,** 2760-2768.

GRIMM, V., REVILLA, E., BERGER, U., JELTSCH, F., MOOIJ, W. M., RAILSBACK, S. F., THULKE, H.-H., WEINER, J., WIEGAND, T. & DEANGELIS, D. L. 2005. Pattern-oriented modeling of agent-based complex systems: lessons from ecology. *science,* 310**,** 987-991.

GRIMSTON, M., NUTTALL, W. J. & VAUGHAN, G. 2014. The siting of UK nuclear reactors. *Journal of Radiological Protection,* 34**,** R1.

HAGERSTRAND, T. 1982. Diorama, path and project. *Tijdschrift voor economische en sociale geografie,* 73**,** 323-339.

HÄGERSTRAND, T. 1975. Space, time and human conditions.

HÄGERSTRAND, T. 1985. Time-geography: focus on the corporeality of man, society, and environment. *The science and praxis of complexity***,** 193-216.

HASHEMI, M. & ALESHEIKH, A. A. 2013. GIS: agent-based modeling and evaluation of an earthquake-stricken area with a case study in Tehran, Iran. *Natural hazards,* 69**,** 1895-1917.

HAVENAAR, J., DE WILDE, E., VAN DEN BOUT, J., DROTTZ-SJÖBERG, B. & VAN DEN BRINK, W. 2003. Perception of risk and subjective health among victims of the Chernobyl disaster. *Social science & medicine,* 56**,** 569-572.

HAYWOOD, S. 2008. Key sources of imprecision in radiological emergency response assessments. *Journal of Radiological Protection,* 28**,** 169-183.

HAYWOOD, S. 2010. A method for displaying imprecision in early radiological emergency measurements. *Journal of Radiological Protection,* 30**,** 673-685.

HAYWOOD, S., BEDWELL, P. & HORT, M. 2010. Key factors in imprecision in radiological emergency response assessments using the NAME model. *Journal of Radiological Protection,* 30**,** 23-36.

HEIDI. 2014. *HEIDI* [Online]. Available: http://www.heidi.ac.uk/ [Accessed].

HILL, A. 2003. Using the Hazard Prediction and Assessment Capability (HPAC) hazard assessment program for radiological scenarios relevant to the Australian Defence Force. DTIC Document.

HMGOVERNMENT 2013. Nuclear industrial strategy: the UK's nuclear future. *Department for Business, Innovation & Skills and Department of Energy & Climate Change,* BIS/13/627.

HODGES, M. S. & SANDERS, C. E. 2014. Nuclear criticality accident safety, near misses and classification. *Progress in Nuclear Energy,* 76**,** 88-99.

HOFFMAN, S. 2008. Preparing for disaster: protecting the most vulnerable in emergencies. *UC Davis L. Rev.,* 42**,** 1491.

HOHENEMSER, C., KATES, R. W. & SLOVIC, P. 1983. The nature of technological hazard. *Science,* 220**,** 378-384.

HOLMES, N. S. & MORAWSKA, L. 2006. A review of dispersion modelling and its application to the dispersion of particles: an overview of different dispersion models available. *Atmospheric Environment,* 40**,** 5902-5928.

HORVATH, A. A. R., E. 2016. Nuclear power in the 21st century: Challenges and possibilities. *Ambio,* 45**,** 38-49.

HPA 2005. Ionising Radiation Exposure of UK Population: 2005 Review. *In:* AGENCY, H. P. (ed.). Oxfordshire: Centre for Radiation, Chemical and Environmental Hazards.

HSCIC. 2014. *Who We Are and What We Do* [Online]. HSCIC. Available: http://www.hscic.gov.uk/whoweare [Accessed].

HSE 2002. *A guide to the Radiation (Emergency Preparedness and Public Information) Regulations 2001 Guidance on Regulations*, HSE Books.

HUALOU, L. 2011. A Geographical Perspective.

HUNTER, G. J. & WILLIAMSON, I. P. 1990. The development of a historical digital cadastral database†. *International Journal of Geographical Information System,* 4**,** 169-179.

HUNTER, L. M. 2005. Migration and environmental hazards. *Population and Environment,* 26**,** 273-302.

IAEA 2007. IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection. Vienna, Austria: IAEA.

IAEA 2008. Analysis of Severe Accidents in Pressurized Heavy Water Reactors.

IAEA. 2013. *Emergency preparedness* [Online]. Austria: International Atomic Energy Agency. Available: http://www-ns.iaea.org/tech-areas/emergency/preparedness.asp?s=1&l=1 [Accessed 9th April 2014].

IAEA. 2014. *The International Nuclear and Radiological Event Scale* [Online]. International Atomic Energy Agency. Available: http://www-ns.iaea.org/tech-areas/emergency/ines.asp [Accessed 9th April 2014].

ISLAND, C. & ACCIDENTS, F. R. 2014. Emergency Management for Radiological Events. *Crisis and Emergency Management: Theory and Practice*, 245.

JACKSON, P. J. 2014. Software Solutions for Computational Modelling in the Social Sciences. . *Theories and Simulations of Complex Social Systems,* Springer Berlin Heidelberg**,** 5-17.

JACQUEZ, G. 2011. It's About Space and Time: From the Modifiable Areal Unit Problem (MAUP) to the Modifiable Temporal Unit Problem (MTUP) to the Modifiable Spatio-Temporal Unit Problem (MSTUP).

JANSSEN, M. A. 2005. Agent-based modelling. *Modelling in ecological economics***,** 155-172.

JONES, A. R., THOMSON, D. J., HORT, M. & DEVENISH, B. 2007. The U.K. Met Office's next-generation atmospheric dispersion model, NAME III. *In:* BORREGO, C. & NORMAN, A.-L. (eds.) *Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application.* Springer.

JONES, C., MUNDAY, M., BALMFORTH, H., WATSON, W., PFUDERER, S., HARVEY, L.M.M. AND CHARNOCK, T. 2008. COCO-2: a Model to Assess the Economic Impact of an Accident. *Health Protection Agency.*

JONES, J. A. 1981. The second report of a Working Group on Atmospheric Dispersion: A procedure to include deposition in the model for short and medium range atmospheric dispersion of radionuclides. Chilton, UK.

KAMERBEEK, H., RAUWS, A., HAM, M. T. & HEIJST, A. V. 1971. Prussian Blue in therapy of thallotoxicosis. *Acta Medica Scandinavica,* 189**,** 321-324.

KEON, D., STEINBERG, B., YEH, H., PANCAKE, C. M. & WRIGHT, D. 2014. Web-based spatiotemporal simulation modeling and visualization of tsunami inundation and potential human response. *International Journal of Geographical Information Science***,** 1-23.

KINSER, A. M. 2001. Simulating wet deposition of radiocesium from the Chernobyl accident. DTIC Document.

KRAAK, M.-J. The space-time cube revisited from a geovisualization perspective. Proc. 21st International Cartographic Conference, 2003. 1988-1996.

KYRIAKIDIS, P. C. 2004. A Geostatistical Framework for Area-to-Point Spatial Interpolation. *Geographical Analysis,* 36**,** 259-289.

LAM, N. S.-N. 1983a. Spatial interpolation methods: a review. *The American Cartographer,* 10**,** 129-150.

LAM, N. S. N. 1983b. Spatial interpolation methods: a review. *Cartography and Geographic Information Science,* 10**,** 129-150.

LANGFORD, M. 2005. Dasymetric mapping of industry and commerce across Wales, UK, using geospatial integration of national mapping agency products. Citeseer.

LANGFORD, M., MAGUIRE, D. J. & UNWIN, D. J. 1991. The areal interpolation problem: estimating population using remote sensing in a GIS framework. *Handling geographical information: Methodology and potential applications***,** 55-77.

LANGFORD, M. & UNWIN, D. J. 1994a. Generating and mapping population density surfaces within a geographical information system. *The Cartographic Journal,* 31**,** 21-26.

LANGFORD, M. & UNWIN, D. J. 1994b. Generating and mapping population density surfaces within a geographical information system. *Cartographic Journal, The,* 31**,** 21-26.

LANGRAN, G. 1989. A review of temporal database research and its use in GIS applications. *International Journal of Geographical Information System,* 3**,** 215-232.

LANGRAN, G. 1992. Time in Geographic Information Systems.

LANGRAN, G. & CHRISMAN, N. R. 1988. A framework for temporal geographic information. *Cartographica: The International Journal for Geographic Information and Geovisualization,* 25**,** 1-14.

LAWRENCE, B. N., BENNETT, V.L., CHURCHILL, J., JUCKES, M., KERSHAW, P., PASCOE, S., PEPLER, S., PRITCHARD, M. AND STEPHENS, A. 2013. Storing and manipulating environmental big data with JASMIN. *Big Data IEEE International Conference*

IEEE**,** 68-75.

LI, M., DENG, J., LIU, L., LONG, Y. AND SHEN, Z. 2015. Evacuation Simulation and Evaluation of Different Scenarios based on Traffic Grid Model and High Performance Computing. *International Review for Spatial Planning and Sustainable Development,,* 3**,** 4-15.

LIU, X., KYRIAKIDIS, P. C. & GOODCHILD, M. F. 2008. Population-density estimation using regression and area-to-point residual kriging. *International Journal of Geographical Information Science,* 22**,** 431-447.

LIU, Z., JACQUES, C.C., SZYNISZEWSKI, S., GUEST, J.K., SCHAFER, B.W., IGUSA, T. AND MITRANI-REISER, J. 2015. Agent-based simulation of building evacuation after an earthquake: coupling human behavior with structural response. *Natural Hazards Review,* 4**,** 15-19.

LONGLEY, P., GOODCHILD, M. F., MAGUIRE, D. & RHIND, D. 2005. *Geographic information systems and science*, Wiley.

LOPEZ-FERNANDEZ, O. & MOLINA-AZORIN, J. F. 2011. The use of mixed methods research in the field of behavioural sciences. *Quality & Quantity,* 45**,** 1459-1472.

LYTINEN, S. R., S. & 2012. The evolution of agent-based simulation platforms: a review of NetLogo 5.0 and ReLogo. *Proceedings of the fourth international symposium on agent-based modeling and simulation.* .

MACAL, C. A. N., M. 2014. Introductory tutorial: Agent-based modeling and simulation. *Winter Simulation Conference,* IEEE Press**,** 6-20.

MACAL, C. M. & NORTH, M. J. 2010. Tutorial on agent-based modelling and simulation. *Journal of Simulation,* 4**,** 151-162.

MACEACHREN, A. M. & DAVIDSON, J. V. 1987. Sampling and isometric mapping of continuous geographic surfaces. *Cartography and Geographic Information Science,* 14**,** 299-320.

MAGLIOCCA, N. R. & ELLIS, E. C. 2013. Using Pattern-oriented Modeling (POM) to Cope with Uncertainty in Multi-scale Agent-based Models of Land Change. *Transactions in GIS,* 17**,** 883-900.

MAGUIRE, D. J., BATTY, M. & GOODCHILD, M. F. 2005. GIS, spatial analysis and modelling. *ESRI, Redlands, CA*.

MAHAFFEY, J. 2014. *Atomic Accidents: A History of Nuclear Meltdowns and Disasters: from the Ozark Mountains to Fukushima*, Open Road Media.

MAIELLO, M. L. & GROVES, K. 2006. Resources for nuclear and radiation disaster response. *Nuclear News,* 49**,** 29-34.

MARTIN, D. 1989. Mapping population data from zone centroid locations. *Transactions of the Institute of British Geographers***,** 90-97.

MARTIN, D. 1992. Postcodes and the 1991 Census of Population: issues, problems and prospects. *Transactions of the Institute of British Geographers***,** 350-357.

MARTIN, D. 1995. *Geographic information systems: socioeconomic applications*, Routledge.

MARTIN, D. & BRACKEN, I. 1991. Techniques for modelling population-related raster databases. *Environment and Planning A,* 23**,** 1069-1075.

MARTIN, D., COCKINGS, S. & LEUNG, S. 2009. Population 24/7: building time-specific population grid models.

MARTIN, D., COCKINGS, S. & LEUNG, S. 2010. Progress report: 24-hour gridded population models. *European Forum for Geostatistics.* Estonia.

MARTIN, D., COCKINGS, S. & LEUNG, S. 2015. Developing a Flexible Framework for Spatiotemporal Population Modelling. *Annals of the Association of American Geographers,* 105**,** 754-772.

MARYON, R. H., RYALL, D.B. AND MALCOLM, A.L. 1999. The NAME 4 dispersion model: Science documentation. *Met Office turbulence and diffusion note, 262, p.45.*

MAS, E., SUPPASRI, A., IMAMURA, F. & KOSHIMURA, S. 2012. Agent-based Simulation of the 2011 Great East Japan Earthquake/Tsunami Evacuation: An Integrated Model of Tsunami Inundation and Evacuation. *Journal of Natural Disaster Science,* 34**,** 41-57.

MAYHORN, C. B. 2005. Cognitive aging and the processing of hazard information and disaster warnings. *Natural Hazards Review,* 6**,** 165-170.

MCPHERSON, T. N., RUSH, J., KHALSA, H., IVEY, A. & BROWN, M. J. A day-night population exchange model for better exposure and consequence management assessments. 86th AMS (American Meteorological Society) Annual Meeting, Atlanta, GA, 2006. 1-6.

MÉNÉTRIER, F., GRAPPIN, L., RAYNAUD, P., COURTAY, C., WOOD, R., JOUSSINEAU, S., LIST, V., STRADLING, G., TAYLOR, D. & BÉRARD, P. 2005. Treatment of accidental intakes of plutonium and americium: guidance notes. *Applied radiation and isotopes,* 62**,** 829-846.

MENNIS, J. 2003. Generating Surface Models of Population Using Dasymetric Mapping∗. *The Professional Geographer,* 55**,** 31-42.

MENNIS, J. & HULTGREN, T. 2006. Intelligent dasymetric mapping and its application to areal interpolation. *Cartography and Geographic Information Science,* 33**,** 179-194.

METOFFICE. 2014. *Met Office Dispersion Model* [Online]. UK: UK Met Office. Available: http://www.metoffice.gov.uk/research/modelling-systems/dispersion-model [Accessed June 29th 2014].

METTLER, F. A. & UPTON, A. C. 1995. *Medical effects of ionizing radiation*, WB Saunders Philadelphia, USA.

METTLER JR, F. A. & VOELZ, G. L. 2002. Major radiation exposure—what to expect and how to respond. *New England Journal of Medicine,* 346**,** 1554-1561.

MITAS, L. & MITASOVA, H. 1999. Spatial interpolation. *Geographical Information Systems: Principles, Techniques, Management and Applications, Wiley,* 481.

MOBBS, S., MUIRHEAD, C. & HARRISON, J. 2010. *Risks from ionising radiation*, Health Protection Agency.

MOROZ, B. E., BECK, H. L., BOUVILLE, A. & SIMON, S. L. 2010. Predictions of dispersion and deposition of fallout from nuclear testing using the NOAA-HYSPLIT meteorological model. *Health physics,* 99.

MOYSICH, K. B., MENEZES, R. J. & MICHALEK, A. M. 2002. Chernobyl-related ionising radiation exposure and cancer risk: an epidemiological review. *The lancet oncology,* 3**,** 269-279.

MROZINSKI, R. D. & CROMLEY, R. G. 1999. Singly-and Doubly-Constrained Methods of Areal Interpolation for Vector-based GIS. *Transactions in GIS,* 3**,** 285-301.

NASSTROM, J. S., SUGIYAMA, G., BASKETT, R. L. & LARSEN, S. C. 2007. The National Atmospheric Release Advisory Center modelling and decision-support system for radiological and nuclear emergency preparedness and response. *International Journal of Emergency Management,* 4**,** 524-550.

NDSSL. 2014. *Disaster Resilience* [Online]. Network Dynamics and Simulation Science Laboratory. Available: http://ndssl.vbi.vt.edu/research/disaster-resilience/ [Accessed 28th April 2014].

NEUTENS, T., VAN DE WEGHE, N., WITLOX, F. & DE MAEYER, P. 2008. A three-dimensional network-based space–time prism. *Journal of Geographical Systems,* 10**,** 89-107.

NHS. 2012. *NHS Choices for professionals* [Online]. UK. Available: http://www.nhs.uk/aboutNHSChoices/professionals/healthandcareprofessionals/Pages/resources-guide.aspx [Accessed].

NOAA. 2014. *HYSPLIT - Hybrid Single Particle Lagrangian Integrated Trajectory Model* [Online]. USA. Available: https://ready.arl.noaa.gov/HYSPLIT.php [Accessed].

NRC 2005. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII-Phase 2*, Washington, DC.

NRPB 1990. Board Statement on Emergency Reference Levels *In:* BOARD, N. R. P. (ed.).

NT. 2014. *About Us* [Online]. Available: http://www.nationaltrust.org.uk/about-us/ [Accessed 29th October 2014].

NUFFIELDTRUST. 2010. *Social care and hospital use at the end of life* [Online]. Available: http://www.nuffieldtrust.org.uk/publications/social-care-and-hospital-use-end-life [Accessed 28th October 2014].

ONR 2012. Project Assessment Report: Assessment of the Low Level Refuelling Facility Periodic Review of Safety Submission. *In:* REGULATION, O. F. N. (ed.). Health and Safety Executive.

ONS 2011. Annual Survey of Hours and Earnings, 2011 Provisional Results (SOC 2000)

ONS 2012. Census shows increase in population of the South West as it tops 5 million.

ONS. 2014a. *Output areas (OAs)* [Online]. Office of National Statistics, UK. Available: http://www.ons.gov.uk/ons/guide-method/geography/beginner-s-guide/census/output-area--oas-/index.html [Accessed October 21st 2014].

ONS 2014b. Workplace Population Analysis, 2011 Census. *In:* STATISTICS, O. F. N. (ed.).

OPENSHAW, S. 1984. Concepts and techniques in modern geography number 38: the modifiable areal unit problem. *Norwick: Geo Books*.

OZIK, J., COLLIER, N.T., MURPHY, J.T. AND NORTH, M.J., 2013, DECEMBER. IN 2013 WINTER (PP. 1560-1568). IEEE. 2013. The relogo agent-based modeling language. *Simulation Conference (WSC) IEEE*, 1560-1568.

PARIKH, N., HAYATNAGARKAR, H.G., BECKMAN, R.J., MARATHE, M.V. AND SWARUP, S. 2016. A comparison of multiple behavior models in a simulation of the aftermath of an improvised nuclear detonation016. *Autonomous Agents and Multi-Agent Systems*, 1-27.

PARIKH, N., SWARUP, S., STRETZ, P. E., RIVERS, C. M., LEWIS, B. L., MARATHE, M. V., EUBANK, S. G., BARRETT, C. L., LUM, K. & CHUNGBAEK, Y. Modeling human behavior in the aftermath of a hypothetical improvised nuclear detonation. Proceedings of the 2013 international conference on Autonomous agents and multi-agent systems, 2013. International Foundation for Autonomous Agents and Multiagent Systems, 949-956.

PARROTT, R. & STUTZ, F. 1991. Urban GIS applications. *Geographical information systems,* 2**,** 247-60.

PCC 2011. KNOWING OUR COMMUNITIES TOOLKIT.

PCC 2013. Devonport Off-Site Emergency Plan (DOSEP). 4.0 ed. Plymouth: Plymouth City Council (PCC).

PEEK, L. 2008. Children and disasters: Understanding vulnerability, developing capacities, and promoting resilience-an introduction. *Children Youth and Environments,* 18**,** 1-29.

PELEKIS, N., THEODOULIDIS, B., KOPANAKIS, I. & THEODORIDIS, Y. 2004. Literature review of spatio-temporal database models. *The Knowledge Engineering Review,* 19**,** 235-274.

PEUQUET, D. & WENTZ, E. An approach for time-based analysis of spatiotemporal data. Proceedings of Sixth International Symposium of Spatial Data Handling, SDH'94, 1994. 489-504.

PEUQUET, D. J. 2002. *Representations of space and time*, Guilford Press.

PEUQUET, D. J. 2005. Theme section on advances in spatio-temporal analysis and representation. *ISPRS Journal of Photogrammetry and Remote Sensing,* 60**,** 1-2.

PEUQUET, D. J. & DUAN, N. 1995. An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. *International journal of geographical information systems,* 9**,** 7-24.

PIDGEON, N. & O'LEARY, M. 2000. Man-made disasters: why technology and organizations (sometimes) fail. *Safety Science,* 34**,** 15-30.

PLUCHINO, S., C. M. G. TRIBULATO, A. CAVERZAN, A. MC QUILLAN, G. P. CIMELLARO, AND S. MAHIN. 2015. Agent-Based Model for Pedestrians' Evacuation after a Blast Integrated with a Human Behavior Model. *Structures Congress,* ASCE**,** 1506-1517.

PRED, A. 1977. The choreography of existence: comments on Hägerstrand's time-geography and its usefulness. *Economic geography***,** 207-221.

RAILSBACK, S. F. & GRIMM, V. 2011. *Agent-based and individual-based modeling: a practical introduction*, Princeton University Press.

RASE, W.-D. 2001. Volume-preserving interpolation of a smooth surface from polygon-related data. *Journal of Geographical Systems,* 3**,** 199-213.

RASE, W.-D. 2009. Visualization of polygon-based data as a continuous surface. *Manuscript*.

REIBEL, M. & BUFALINO, M. E. 2005. Street-weighted interpolation techniques for demographic count estimation in incompatible zone systems. *Environment and Planning A,* 37**,** 127-139.

RENOLEN, A. 1999. *Concepts and methods for modelling temporal and spatiotemporal information*, NTNU.

RIGINA, O. & BAKLANOV, A. 2002. Regional radiation risk and vulnerability assessment by integration of mathematical modelling and GIS analysis. *Environment International,* 27**,** 527-540.

RUBIN, C. B. 1998. *What Hazards and Disasters are Likely in the 21st Century, Or Sooner?*, Natural Hazards Research and applications Information Center, Institute of Behavioral Science, University of Colorado.

RUIZ-MARTIN, C., RAMIREZ-FERRERO, M., GONZALEZ-ALVAREZ, J.L. AND LÓPEZ-PAREDES, A. 2015. Modeling of a Nuclear Emergency Plan: Communication Management. . *Human and Ecological Risk Assessment: An International Journal,* 21**,** 1152-1168.

SAALFELD, A. 1991. An application of algebraic topology to an overlay problem of analytical cartography. *Cartography and Geographic Information Systems,* 18**,** 23-36.

SADAHIRO, Y. 2000. Accuracy of count data transferred through the areal weighting interpolation method. *International Journal of Geographical Information Science,* 14**,** 25-50.

SAPIR, D. G. 1993. Natural and man-made disasters: the vulnerability of women-headed households and children without families. *World health statistics quarterly. Rapport trimestriel de statistiques sanitaires mondiales,* 46**,** 227.

SCC 2013. PORT OF SOUTHAMPTON OFF-SITE REACTOR EMERGENCY PLAN : SotonSafe. *In:* COUNCIL, S. C. (ed.). Southampton.

SCHMIDT-THOMÉ, P. & KALLIO, H. 2006. Natural and technological hazard maps of Europe. *SPECIAL PAPER-GEOLOGICAL SURVEY OF FINLAND,* 42**,** 17.

SHEPARD, D. A two-dimensional interpolation function for irregularly-spaced data. Proceedings of the 1968 23rd ACM national conference, 1968. ACM, 517-524.

SHUNXIANG, H., LIU FENG, ZENG QINGCUN, HU FEI, AND WANG ZIFA 2015. "Modeling and Optimal Control of Atmospheric Pollution Hazard in Nuclear and Chemical Disasters.". *Procedia IUTAM 17***,** 79-90.

SIVINTSEV, Y. 2000. Number of Fissions in the Chazhma Bay Accident in 1985. *Russian Journal of Atomic Energy,* 89**,** 269.

SIVINTSEV, Y. V. 2003. Was the Chazhma accident a Chernobyl of the far east? *Atomic Energy,* 94**,** 421-427.

SIVINTSEV, Y. V., VYSOTSKII, V. & DANILYAN, V. 1994. Radioecological consequences of a radiation accident in a nuclear-powered submarine in Chazhma cove. *Atomic Energy,* 76**,** 157-160.

SKALETSKIY, Y. 2013. Doses of Emergency Exposure to the USSR Navy Personnel. *旧ソ連の原子力開発にともなう放射能災害とその被害規模に関する調査研究***,** 83.

SLEETER, R. & WOOD, N. Estimating daytime and nighttime population density for coastal communities in Oregon. 44th Urban and Regional Information Systems Association Annual Conference, British Columbia, 2006.

SLOVIC, P. 2000. The Perception of Risk (Earthscan Risk and Society Series).

SMITH, A. D. 2013. 24/7 population modelling to assess exposure to natural hazards. *Colloquium on Spatial Analysis.* University of Copenhagen, Denmark

SMITH, A. D. 2015. Spatiotemporal population modelling to assess exposure to flood risk. *Doctoral dissertation,* University of Southampton.

SMITH, G. & FAIRBURN, J. 2008. Updating and improving the national population database to national population database 2.

SNODGRASS, R. T. 1992. Temporal databases. *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space.* Springer.

STABIN, M. G. 1997. Health concerns related to radiation exposure of the female nuclear medicine patient. *Environmental health perspectives,* 105**,** 1403.

STOCKIE, J. M. 2011. The mathematics of atmospheric dispersion modeling. *Siam Review,* 53**,** 349-372.

SWANBERG, E. L. & HOFFERT, S. G. 2001. Using Atmospheric (137) Cs Measurements and Hysplit to Confirm Chernobyl as a Source of (137) Cs in Europe. DTIC Document.

TAKANO, M., ROMANOVA, V., YAMAZAWA, H., SIVINTSEV, Y., COMPTON, K., NOVIKOV, V. & PARKER, F. 2001. Reactivity accident of nuclear submarine near Vladivostok. *Journal of Nuclear Science and Technology,* 38**,** 143-157.

THOMPSON, D. E., MABUCHI, K., RON, E., SODA, M., TOKUNAGA, M., OCHIKUBO, S., SUGIMOTO, S., IKEDA, T., TERASAKI, M. & IZUMI, S. 1994. Cancer incidence in atomic bomb survivors. Part II: Solid tumors, 1958-1987. *Radiation research,* 137**,** S17-S67.

THOMPSON, D. F. & CHURCH, C. O. 2001. Prussian blue for treatment of radiocesium poisoning. *Pharmacotherapy: The Journal of Human Pharmacology and Drug Therapy,* 21**,** 1364-1367.

TISUE, S. & WILENSKY, U. NetLogo: A simple environment for modeling complexity. International Conference on Complex Systems, 2004. 16-21.

TOBIN, G. A. & WHITEFORD, L. M. 2001. The Role of Women in Post-Disaster Environments: Health and Community Sustainability. *The Center for Disaster Management and Humanitarian Assistance, November***,** 17.

TOBLER, W. R. 1970. A computer movie simulating urban growth in the Detroit region. *Economic geography,* 46**,** 234-240.

TOBLER, W. R. 1979. Smooth Pycnophylactic Interpolation for Geographical Regions. *Journal of the American Statistical Association,* 74**,** 519-530.

TORRENS, P. M. 2006. Simulating sprawl. *Annals of the Association of American Geographers,* 96**,** 248-275.

TSCHURLOVITS, M. A. T., R. 2006. Communication on radiation risk as an area of conflict between radiological, sociological and perceptional issues.

TURCANU, C., SCHRÖDER, J., MESKENS, G., PERKO, T., ROSSIGNOL, N., CARLÉ, B. AND HARDEMAN, F. 2016. Like a bridge over troubled water–Opening pathways for integrating social sciences and humanities into nuclear research. . *Journal of environmental radioactivity,* 153**,** 88-96.

TWEEDIE, S. W., ROWLAND, J. R., WALSH, S. J., RHOTEN, R. P. & HAGLE, P. I. 1986. A methodology for estimating emergency evacuation times. *The Social Science Journal,* 23**,** 189-204.

ULAM, S. M. & VON NEUMANN, J. 1947. On combination of stochastic and deterministic processes. *Bull. Amer. Math. Soc,* 53**,** 1120.

UN 2013. Global Assessment Report on Disaster Risk Reduction: From Shared Risk to Shared Value: The Business Case for Disaster Risk Reduction. Geneva, Switzerland: UNISDR.

UNICEF 2011. Children's Vulnerability to Climate Change and Disaster Impacts in East Asia and the Pacific. *UNICEF East Asia and Pacific Regional Office*

UNISDR 2009. UNISR Terminology on Disaster Risk Reduction Geneva, Switzerland.

UNSCEAR 2000. Sources, effects and risks of ionizing radiation, 2000: report to the General Assembly. New York United Nations Scientific Committee on the Effects of Atomic Radiation.

UNSCEAR. 2008. *Maps of radionuclide deposition* [Online]. United Nations Scientific Committee on the Effects of Atomic Radiation. Available: http://www.unscear.org/unscear/en/chernobylmaps.html [Accessed 10th April 2014].

VAN BENTHEM, J. F. 1983. The Logic of Time. A Model-Theoretic Investigation into the Varieties of Temporal Antology and Temporal Discourse.

VISITENGLAND. 2014. *What is VisitEngland?* [Online]. UK. Available: http://www.visitengland.org/about/ [Accessed October 28th 2014].

WALLER, L. A. & GOTWAY, C. A. 2004. *Applied spatial statistics for public health data*, John Wiley & Sons.

WBC 2011. Atomic Weapons Establishments Off-Site Emergency Response Plan. Newbury: West Berkshire Council.

WHO 2012a. Children and Radiation. *In:* ORGANISATION, W. H. (ed.) *Children's Health and the Environment- WHO Training Package for the Health Sector.*

WHO. 2012b. *Ionizing radiation, health effects and protective measures* [Online]. Switzerland: World Health Organisation. Available: http://www.who.int/mediacentre/factsheets/fs371/en/ [Accessed 01/04/2014].

WIEST, R. 1998. A comparative perspective on household, gender, and kinship in relation to disaster. *The Gendered Terrain of Disaster: Through Women's Eyes, Westport: Praeger***,** 63-79.

WILENSKY, U. 1999. {NetLogo}.
WISNER, B. 1998. Marginality and vulnerability: Why the homeless of Tokyo don't ‘count’in disaster preparations. *Applied Geography,* 18**,** 25-33.
WISNER, B. 2004. *At risk: natural hazards, people's vulnerability and disasters*, Psychology Press.
WISNER, B. & LUCE, H. R. 1993. Disaster vulnerability: Scale, power and daily life. *GeoJournal,* 30**,** 127-140.
WITTEK, P. & RUBIO-CAMPILLO, X. Scalable agent-based modelling with cloud HPC resources for social simulations. Cloud Computing Technology and Science (CloudCom), 2012 IEEE 4th International Conference on, 2012. IEEE, 355-362.
WNA 2016. Nuclear Power in the United Kingdom. *World Nuclear Association Information Library / Country Profiles / Countries T-Z / United Kingdom*.
WOLFRAM, S. 1984. Universality and complexity in cellular automata. *Physica D: Nonlinear Phenomena,* 10**,** 1-35.
WORBOYS, M. F. Object-oriented models of spatiotemporal information. GIS LIS-INTERNATIONAL CONFERENCE-, 1992. AMERICAN SOCIETY FOR PHOTOGRAMMETRY AND REMOTE SENSING, 825-825.
WORBOYS, M. F. 1994. A unified model for spatial and temporal information. *The Computer Journal,* 37**,** 26-34.
WORBOYS, M. F. & DUCKHAM, M. 1995. Geographic Information Systems: a computing perspective. *Taylor and Francis, London, ISBN,* 748400648**,** 0748400656.
WU, B., BIRKIN, M. & REES, P. 2008. A spatial microsimulation model with student agents. *Computers, Environment and Urban Systems,* 32**,** 440-453.
WU, F. & MARTIN, D. 2002. Urban expansion simulation of Southeast England using population surface modelling and cellular automata. *Environment and Planning A,* 34**,** 1855-1876.
YAUKEY, D., ANDERTON, D. L. & LUNDQUIST, J. H. 2001. *Demography: The study of human population*, Waveland Press Prospect Heights, IL.
YODMANI, S. & CENTER, A. D. P. 2001. *Disaster risk management and vulnerability reduction: protecting the poor*, The Center.
YUAN, M. Temporal GIS and spatio-temporal modeling. Proceedings of Third International Conference Workshop on Integrating GIS and Environment Modeling, Santa Fe, NM, 1996.
YUAN, M. 1999. Use of a Three-Domain Repesentation to Enhance GIS Support for Complex Spatiotemporal Queries. *Transactions in GIS,* 3**,** 137-159.
YUAN, M. 2002. Use of a Three-Domain Repesentation to Enhance GIS Support for Complex Spatiotemporal Queries. *Transactions in GIS,* 3**,** 137-159.
ZHENG, X., ZHONG, T. & LIU, M. 2009. Modeling crowd evacuation of a building based on seven methodological approaches. *Building and Environment,* 44**,** 437-445.
ZVOLEFF, A. & AN, L. 2013. Analyzing Human–Landscape Interactions: Tools That Integrate. *Environmental management***,** 1-18.