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Abstract:	This deliverable describes the large-scale evacuation modelling work performed in the GEO-SAFE project. A number of aspects of large-scale evacuation modelling such as the integration of three models used in wildfire management, determination of walking speeds on different terrain slopes and types (paved/unpaved/grass). Finally, the developments are demonstrated using two test cases, one related to Spain and one to Australia.
Keywords:	Large scale evacuation, model, simulation, vehicle evacuation, pedestrian evacuation, wildfire

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Executive Summary

This deliverable describes the large-scale evacuation modelling work performed as part of the GEO-SAFE project. The task addressed in this deliverable is Task 2.6 in Work Package 2 and Work Group 6, Phase 3. A key novelty of this work is the integration of the three models that can be used to manage large scale evacuations due to wildfires and other incidents that require evacuations. The pedestrian evacuation model, urbanEXODUS, the vehicle evacuation model, SUMO and wildfire models such as PHOENIX have been integrated as part of Task 2.6. The accuracy of evacuation model predictions can be enhanced by accurate representation of the walking speeds of people over long distances and on different terrain types and slopes. Thus, walking speed data collected from four different trials are being analysed statistically so the empirical data can be included in the pedestrian evacuation model. The integrated simulation environment was applied to two demonstration cases by modelling hypothetical evacuation scenarios in two urban environments, one in Spain and one in Australia. Finally, the import of Digital Elevation Model (DEM) data into the urbanEXODUS evacuation model was demonstrated enabling the incorporation of terrain slope into the evacuation model. As pedestrian walking speeds are impacted by the slope of the paths, the impact of terrain slope on evacuation was demonstrated using a hypothetical evacuation in the Greenwich (UK) area.

1 INTRODUCTION

This deliverable describes the large-scale evacuation modelling related developments performed in the GEO-SAFE project. Work Package 2 of the GEO-SAFE Description of Actions (DoA) deals with the development of Innovative models that are beneficial to managing Wildfire incidents. In Work Group 6, the specific focus was on evacuation models for large-scale urban environments that could be used to assist in the management of wildfire. The main aim of Work Group 6 was the application of large-scale multi-agent simulation techniques to evacuation scenarios associated with wildfire evacuation incidents. The approach was to adapt the existing state-of-the-art building evacuation simulation software, EXODUS [Veeraswamy, et al., 2018] [Chooramun, et al., 2012] [Pretorius, Gywnne and Galea, 2013], to address the wildfire scenario (e.g. the nature, size, location of the fire, fire spread rate, the population distribution and characteristics, their expected response and the routes available) in order to determine the time for the target population to reach safety. This work involved several research areas which are discussed in the following sections.

Detailed modelling of large-scale evacuation dynamics is extremely challenging, especially when the geometry may be very large, involving thousands of square metres, the terrain consists of changes in grade and complex geometric layout and the size of the population may be measured in many tens of thousands or even hundreds of thousands. When modelling evacuation dynamics of very large crowds in large spaces, computational speed becomes an issue with computations requiring many hours. The reason can be attributed to the underlying complexity at any level of the processes, from data collection to solution analysis. The EXODUS capability of hybrid analysis (where the granularity of the geometry is scalable to meet the computational needs) [Chooramun, et al., 2012] is essential if micro simulation evacuation software is to be applied in real time to simulate large urban-scale evacuation situations such as those involved in wildfires. As a consequence, computing efficiently good solutions for these models is an important milestone for putting it into practice for large open spaces such as found in wildfire applications. This is key to enable crisis managers to generate a new scenario on the fly and utilise the results provided at faster than real time to make informed decisions on the most appropriate evacuation procedures to apply.

1.1 Objectives of D2.6

The objective of this deliverable is: The development of evacuation models for large-scale urban environments that could be used to assist in the management of wildfire. This objective corresponds to the implementation of the research methodology and phases described in WG6: Agent based evacuation models. The main outcome of this work was the development of an agent-based modelling environment suitable for simulating a range of evacuation scenarios appropriate for the management of wildfire situations.

2 LARGE SCALE WILDFIRE EVACUATION MODEL

The key research and development work performed in developing a large-scale evacuation model for the GEO-SAFE project will be described in this section.

2.1 Integration of Pedestrian, Vehicle and wildfire models

Urbanisation of forested regions and regions adjacent to forests, known as the Wildland-Urban Interface or WUI, results in wildfires being increasingly likely to threaten large population centres and hence require the evacuation of large numbers of people. These communities may be particularly vulnerable due to limited infrastructure, such as road networks, increasing the challenge of planning and managing large scale evacuations. Such communities may have only a single route in and out making them particularly susceptible to wildfire. In the devastating 2020 Australian wildfires, thousands of people in the holiday costal area of Mallacoota were impacted [CNN, 2020]. While many people evacuated early via the Princess Highway, the only road out of the area, when this road was closed [Guardian, 2020] due to spreading wildfires, around 4000 people, 1000 locals and 3000 tourists were stranded. The Royal Australian Navy eventually rescued 1200 people by sea using the Australian naval vessels HMAS Choules and MV Sycamore [Maritime-Executive, 2020] while another 500 were evacuated by helicopters and other aircraft. At risk communities may also have multiple road exit routes however, they simply cannot cope with the increased demand resulting from simultaneous mass evacuation. For example, during the 2018 Camp Fire in California, traffic jams forced people to abandon their cars and evacuate by foot [BBC, 2018]. It is thus essential to carefully manage the evacuation to ensure that routes do not become over congested.

When planning evacuation, it is also essential to understand how the wildfire is likely to spread. In the Portuguese fires of 2017, 47 people lost their lives on a rural road in Pedrogao Grande, 30 people died in their cars when they were overtaken by the fires while 17 died trying to escape the fires on foot [Wikipedia, 2017]. In wildfires, particularly in the European setting, people may also attempt to evacuate on foot. In the 2018 Mati fires [Wikipedia, 2020] near Athens Greece, 26 people lost their lives while attempting to evacuate to the beach on foot when they were trapped and overcome by the rapidly advancing fire.

When managing an urban-scale evacuation it is also essential to understand what motivates the at-risk population to respond to the call to evacuate and decide whether to 'go or stay'. Equally it is important to understand how long it may take to decide to 'go or stay' and given they decide to go, how long it takes them to prepare to go. These are extremely complex issues involving a multitude of psychological, emotional, physical and economic factors such as, nature of the warning system/warning message, attachment to the property, prior experience of wildfires, training, whether the property is adequately insured, ownership of pets, proximity to the fire-hazard front (not simply the fire front), co-location of family members, medical condition, number and age of family members, whether they are locals or visitors, whether they will evacuate by private car (and if so, what type of car), public transport, foot or by a combination of means. Of equal importance to the decision to 'go or stay', is the decision, where to go (evacuation destination) and route selection. This may be to a designated place of safety, to a friends or extended family home, to a hotel or to anywhere out of the impacted area. Evacuation journey's may also not be direct, but involve intermediate detours to collect family/friends, provisions, medical supplies or fuel. The evacuation destination and route decisions may be based on local knowledge, public broadcasts, traffic alerts, following the crowd or by direction of emergency services. An understanding of evacuation destinations and route decisions is essential when planning and managing large scale evacuation.

All these factors may be dependent on the nature of the geographical region and the cultural context in which they occur. Thus, insight into these questions gained from one region/culture may not be applicable to a different region/culture. As a result, the urban-scale evacuation process is an extremely complex system involving a mix of human behaviour driving a three-way coupling of hazard (fire and smoke)-pedestrian-vehicle dynamics. Successfully addressing this daunting human behaviour and modelling challenge will enable incident managers to assess alternative evacuation strategies and quantify safety margins associated with the competing strategies. Most importantly, the quantification of safety margins associated with evacuation choices assists incident managers to more reliably select the most appropriate evacuation strategy for the evolving situation.

To date, no software tool has successfully integrated pedestrian-vehicle-wildfire models into a single unified tool. The aim of this work package was to facilitate the development of such a unified tool. It is noted that work on human behaviour associated with wildfires is not part of this deliverable but has been reported in Deliverable 2.5. Integration of pedestrian and vehicle evacuation models

This section discusses the methodology to integrate two well established engineering simulation tools, urbanEXODUS [Veeraswamy, et al., 2018] for pedestrian modelling, based on the well validated EXODUS software, and the well validated SUMO [SUMO, 2018] vehicle model. The integrated software tool can represent the impact of the wildfire on the pedestrian and vehicle evacuation by linking to wildfire data produced by simulation tools such as PHOENIX [Tolhurst et al., 2010] or Prometheus [Tymstra, et al., 2010].

There are a number of vehicle simulation tools [Intini, et al., 2019] however, for this research two open source vehicle simulation tools MATSIM [Lämmel, Klüpfel and Nagel, 2009] and SUMO [SUMO, 2018] were studied in detail. MATSIM is a coarse node model whereas SUMO is a fine node model. SUMO was selected over MATSIM as the vehicle simulation tool to integrate with the urbanEXODUS pedestrian simulation tool since it is important to represent the interaction between pedestrians and vehicles and this interaction can only be represented using fine node models. There are many situations in which pedestrian interaction with vehicles and vehicle interaction with pedestrians can play an important role. For example pedestrians may need to move on foot to where their vehicle or public transport is located, in city and suburban areas, vehicles may interact with the pedestrian population who may be evacuating on foot or relocating to their vehicles/public transport, there may be a mixed mode evacuation where some of the population evacuate by vehicle and some by foot and passengers in vehicles may be forced to abandon their vehicles and proceed on foot.

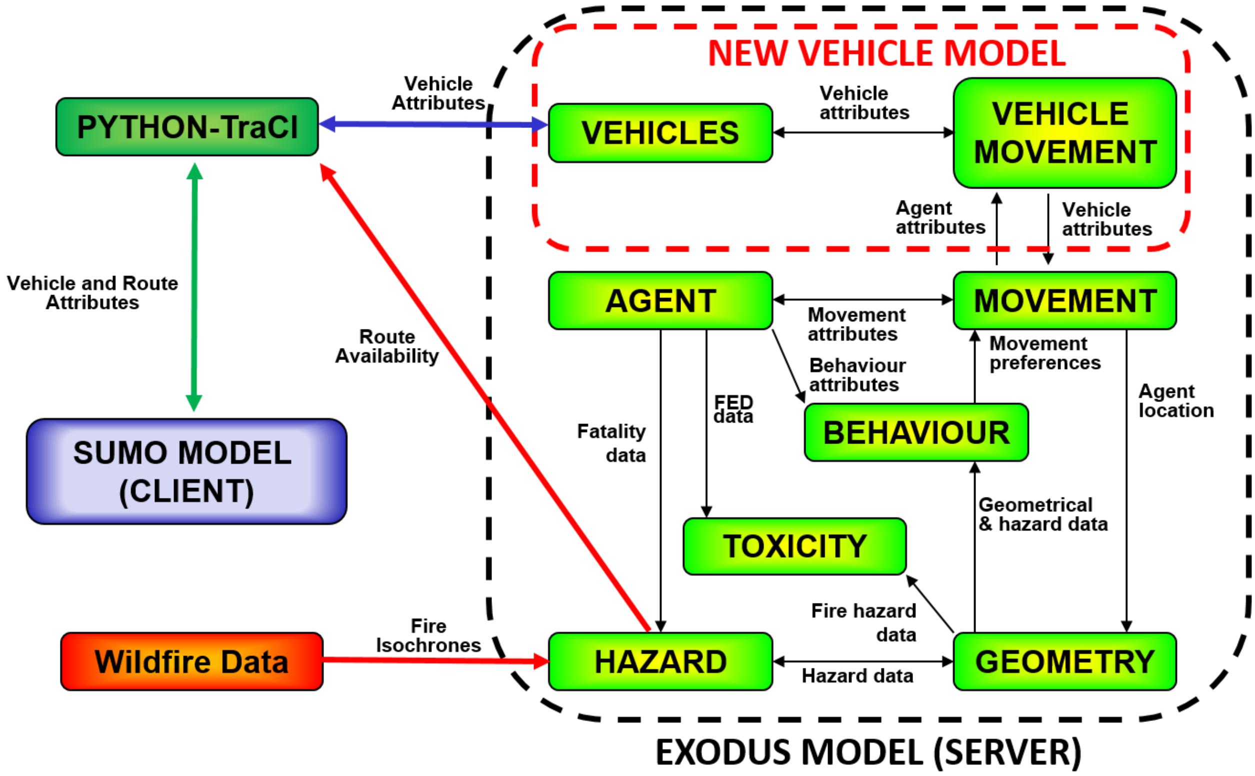


Figure 1: Integration of urbanEXODUS, SUMO and Wildfire models

At the heart of the unified microsimulation pedestrian and vehicle tool is urbanEXODUS (see Figure 1). The SUMO vehicle simulation tool is linked to urbanEXODUS via SUMO's TracCI Interface [SUMO, 2018]. SUMO models the movement and routing of the vehicles in the road network and the interaction of vehicles with other vehicles, whereas urbanEXODUS controls all interactions of the pedestrians with the vehicles [Lawrence, Pellacini and Galea, 2018] and vehicles with pedestrians. In addition, urbanEXODUS determines which roads have been compromised by the fire and signals to SUMO whether a vehicle needs to be re-routed or are assumed to be destroyed by the fire, together with which roads are blocked. The two simulation tools, urbanEXODUS and SUMO, run concurrently and there is a two-way integration between the two tools established using SUMO's TracCI [SUMO, 2018] interface. This interface informs urbanEXODUS at every timestep of the location of vehicles so when pedestrians are about to cross the road they wait for a clearance before crossing. Likewise, urbanEXODUS can control the speed of vehicles in SUMO by slowing them down or stopping when pedestrians are on the road. The developments include pedestrian behaviours such as selecting whether to use a pedestrian crossing, crossing behaviour within or outside a designated crossing area, along with different strategies for how to cross, for example crossing each lane of traffic in stages. Furthermore, these behavioural developments include the impact of time pressure on pedestrian decision making associated with road crossing, a feature which is not currently considered by other pedestrian evacuation models, which include vehicles [Han and Yuan, 2005] [Lämmel, Klüpfel and Nagel, 2009].

Further information concerning the integration of the vehicle and pedestrian models and their application to the modelling of the hypothetical evacuation of Marysville was presented in the GEO-SAFE conference at Melbourne [GEO-SAFE conference, 2019] and the evacuation modelling workshop held in Greenwich [Lawrence, et al., 2020]. In this report, Section 3.2 provides details of some of the preliminary simulation results related to the Marysville demonstration case.

2.1.1 Integration of evacuation and wildfire models

The following wildfire models were analysed:

- **Prometheus** [Tymstra *et al,* 2010] developed by the 'Canadian Interagency Forest Fire Centre'.
- **Phoenix Rapidfire [**Tolhurst *et al*,2010], developed by the 'Bushfires Co-operative Research Centre' from Australia.
- **Farsite [**Finney, 1999] developed by the 'Intermountain Fire Sciences Laboratory' from USA.
- **Spark** [Hilton, *et al.,* 2016], developed by 'Data 61, CSIRO' from Australia
- **Wildfire Analyst** [Monedero, Ramirez and Cardil, 2019] developed by Technosylva.

For incident commanders to make appropriate decisions as to which areas to prioritise for evacuation it is essential to know when the fire is likely to directly threaten the occupied area, when the fire is likely to threaten proposed evacuation routes, how long is it likely to take to clear the threatened areas and how long it will take for the evacuating population to pass through the at risk evacuation routes [Cova et al., 2005] [Pultar et al., 2009].

To enable these decisions it is necessary to predict the location of the hazard front (i.e. the fire front/fire perimeter and the smoke front) in much faster than real time and to do this wildfire models are used [Tolhurst, et al., 2008] [Tymstra, et al., 2010] [Monedero, Ramirez and Cardil, 2019]. In this way the incident commander can determine the temporal and spatial advance of a moving hazard front before it occurs. Crucially, the incident commander can determine when the hazard front is likely to threaten critical locations such as population centres or critical exit route(s) many hours before it actually occurs.

Among the various outputs generated by most widely used wildfire models is the fire perimeter [Tolhurst et al., 2010] [Tymstra, et al., 2010]. The fire perimeter dataset consists of polygons representing the area burnt. These polygons spread out from the ignition start location at regular time intervals and are impacted by the nature of the fuel in the surrounding area and predicted wind conditions.

When imported into evacuation models, the fire perimeter dataset can be used to determine the effect of the spreading fire on the road network, identifying if and when routes are no longer viable and identifying if and when spaces (towns) are likely to be compromised by the spreading fire front. Within the evacuation model, any members of the population (agents) remaining within a region that has been compromised by the fire are considered fatalities.

When used with evacuation models, the fire perimeter dataset can also be utilised to calculate the safety margins [Veeraswamy, et al., 2018] available to at risk populations. The safety margin is defined as the time difference between the time at which the advancing hazard front compromises a road segment or populated area, determined by the fire simulation tool, and the time at which the at risk population have cleared the threatened road segment or populated region, as determined by the evacuation model. This is referred to as the time-based safety margin. Similarly, a safety margin based on distance can be determined. This is the distance between the last agent to clear the region (road segment or populated region) and the compromised region at the time of compromise.

As noted previously, the hazard front consists of the fire front and the smoke front. Furthermore, through spot fires generated by ember attack, the fire front may be beyond the main fire perimeter. However, current wildfire simulation tools do not predict ground level smoke and spotting generated by embers and if they do, they are not considered reliable. Clearly, evacuation models can take these hazards into consideration when determining safety margins and fatality predictions once they can be reliably predicted by wildfire models.

2.2 Data analysis from experimental walking trials

In large scale evacuation models, it is very important to represent the effects of terrain on walking speeds of people. The characteristics of terrains such as varying slopes (upslope/downslope) and terrain types (paved, unpaved, grass) can have a significant influence on the walking speeds of people and route choice. While there are several datasets on walking speeds in the literature, none produce appropriate measures, either because they do not consider all the relevant factors (demographics of people, gradients, surface type) or because the experiment setup is questionable.

In the GEO-SAFE project, the outdoor walking speed data previously collected from four experimental trials were analysed. It is to be noted that these experimental trials were completed prior to the GEO-SAFE project however, the statistical analysis of the trial data is being undertaken as part of the GEO-SAFE project. The aim of the analysis is to measure the walking speeds of individual people along varied upslope and downslope gradients and/or surface types. Nevertheless, relevant differences in the design of the experiments, namely the inclination angle on the sloped walkways and the surface type, led to specific objectives in terms of measuring the walking speeds:

- Two trials measured walking speeds on gentle gradients were carried out in LeMans (France) one in 2011 and another in 2012.

  The trials took place in the car park of the engineering school (ISMAN) in LeMans France. These trials were designed to measure the walking speed over gentle upslope and downslope gradients (from -5.65° to +5.65°). It is worth noting that in both trials the measurement protocols and criteria for the selection of participants were identical, and therefore their results have been merged and treated together for the posterior analyses.

  In total, 227 participants were recruited between both trials (87 in 2011, and 140 in 2012), with a gender distribution of 151 males and 76 females. Their ages spanned from 18 to 53 years old, with very few males and females over 30 years: 6 and 19 respectively. The reason of this is because most of participants were students from the engineering school who were in their early 20s.

- A trial measured walking speeds on steep gradients was carried out again at LeMans France in 2015.

  These trials were designed to measure the walking speed over steep up-slope and down-slope gradients (±8.91° and ±11.34°).

  A total of 175 participants were recruited for the experiment, consisting of 104 males and 71 females. Their age spanned from 20 to 93 years-old, however the sample was unevenly distributed per age groups. There was a high proportion of people aged 20-25 years (especially males), and relatively high aged 55-70 years. In contrast, the proportion of participants aged under 20 and over 70 years was remarkably smaller.

- A trial measured walking speeds on gentle gradients and on different surface types was carried out in Perugia, Italy in 2016.

  These trials were designed to measure the walking speeds along paths with varied gentle inclinations (from -5.3° to +5.3°) over relatively long distances (343m to 600m) in combination with varied surface types (paved, gravel, grass).

In total, 76 participants were recruited for this experiment, 51 males and 25 females. The age of participants varied from 4 years old to 75. Unlike the previous two experiments, there were participants under 18 years old, consisting mostly of males under 15. The distribution of age groups was rather unequal, especially across male participants as more than half were under 15 or over 55.

For all of these trials, the age and gender of each participant was recorded alongside the gradient and/or terrain type to determine whether these parameters influenced the measured walking speeds.

While the review of walking speed literature revealed some important relationships between walking speed and inclination, these results were limited due to either small numbers of participants, or contrived conditions (laboratories) or they made use of atypical population groups e.g. soldiers. Thus, the trials analysed as part of the GEO-SAFE project will provide a more representative dataset, involving relatively larger number of participants and include results for different types of terrain, something not widely reported in the literature. This type of data is necessary for use in urban-scale evacuation models.

While all the walking speed data has now been extracted from each of the raw datasets derived from the trials, they are still undergoing rigorous statistical significance testing to reveal the relationship between walking speed and the abovementioned factors (age and gender of the participants, and gradient and surface type of the walking paths). The results of this analysis will be reported in later journal publications.

2.3 Digital Elevation Model (DEM) datasets

When considering urban-scale evacuation modelling, it is necessary to take into consideration the nature of the terrain over which the population is expected to travel, this is particularly important for pedestrian based evacuation. Thus, the terrain data must be accurately represented within the evacuation model so the walking speeds and distances of population can be accurately represented. Terrain data can be imported into urban-scale evacuation models from Digital Elevation Models (DEM). DEM are digital representations of the ground surface in the form of multiple cells (also called grids), with each cell containing a numerical value indicating elevation [Croneborg, et al., 2015]. Elevation values are calculated at the centre of the cell (see Figure 2). In this study, DEM datasets provide the terrain information required to model the effect of gradients on walking speed and the calculation of accurate distances of the routes.

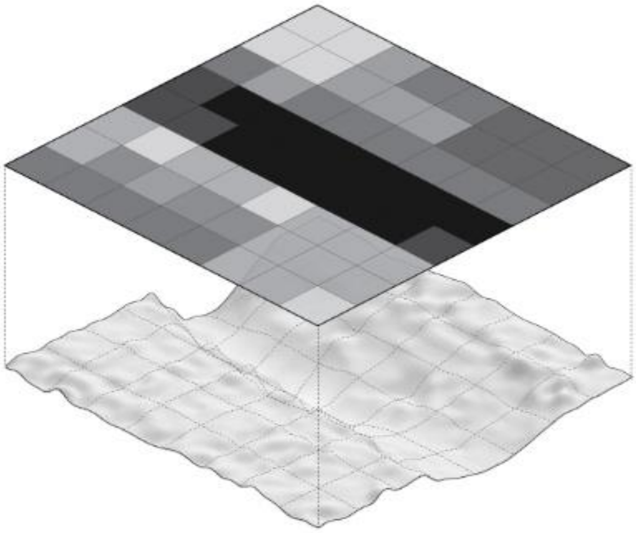


Figure 2: Gridded landscape as represented by Digital Elevation Models. Source: Structures of Coastal Resilience (SCR) [2018].

DEMs can be integrated into a large number of applications such as urban planning, geology, agriculture or hydrology [Croneborg, et al., 2015]. While DEMs can be utilised in wildfire models to determine the fire spread based on terrain characteristics, they can also be used in evacuation models to represent the change of walking speeds due to travelling up or down inclined terrains. However, DEMs have been scarcely applied to pedestrian modelling for emergency evacuation planning purposes [Anguelova, et al., 2010] [Wood and Schmidtlein, 2012]. In order to address this gap, DEMs are introduced in this study to represent the landscape surface that is accessed by pedestrian evacuating agents walking along routes with different slopes. This enables appropriate flow performance for pedestrians during the evacuation.

2.3.1 Importing the DEM data from Ordnance Survey

The Ordnance Survey [OrdnanceSurvey2, 2020] provides the OS Terrain 50 [OrdnanceSurvey3, 2020] product, a Digital Elevation Model (DEM), which is freely downloadable. This DEM data is available in various formats GML [OGC1, 2020], ASCII grid [ESRI, 2020], GeoPackage [OGC2, 2020] and ESRI shapefile contours [ESRI2, 2020]. Among these formats, the ASCII grid format was chosen due to the simplicity and the lightweight (smaller file size) nature of this format.

The Ordnance Survey (OS) maps are overlaid with a series of grid lines as shown in Figure 3. The vertical lines are called 'eastings' as they increase in value in an easterly direction. The horizontal lines are called 'northings' as they increase in value in a northerly direction. These are linked to the British National Grid system which provides a unique reference system and can be applied to all OS maps of Great Britain. Great Britain is covered by grid squares measuring 100 kilometres by 100 kilometres and each grid is identified by two letters, as shown in Figure 3.

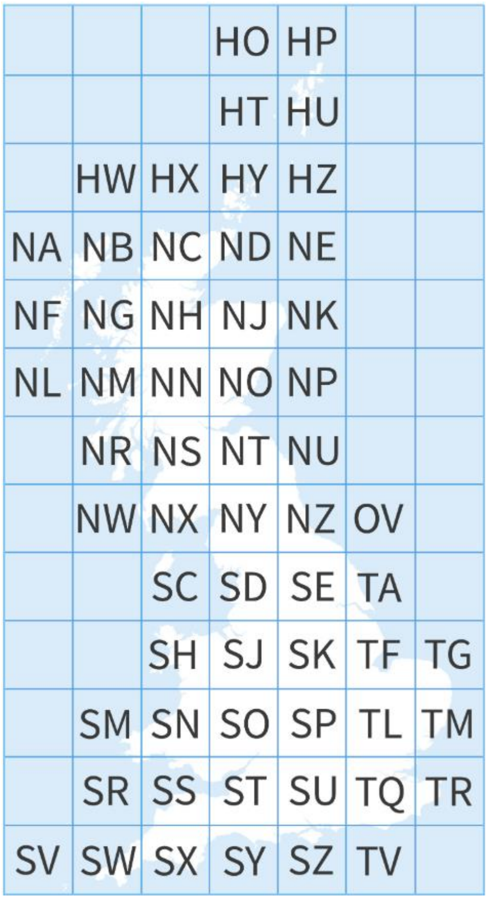


Figure 3: British National Grid system which covers the Great Britain where each cell is of size 100 km by 100 km and identified by two letters.

On the OS maps these 100 km by 100 km grid squares are further divided into smaller squares by grid lines representing 10 km spacing each numbered from 0 to 9 from the south-west corner, in an easterly (left to right) and northerly (upwards) direction as shown in Figure 4.

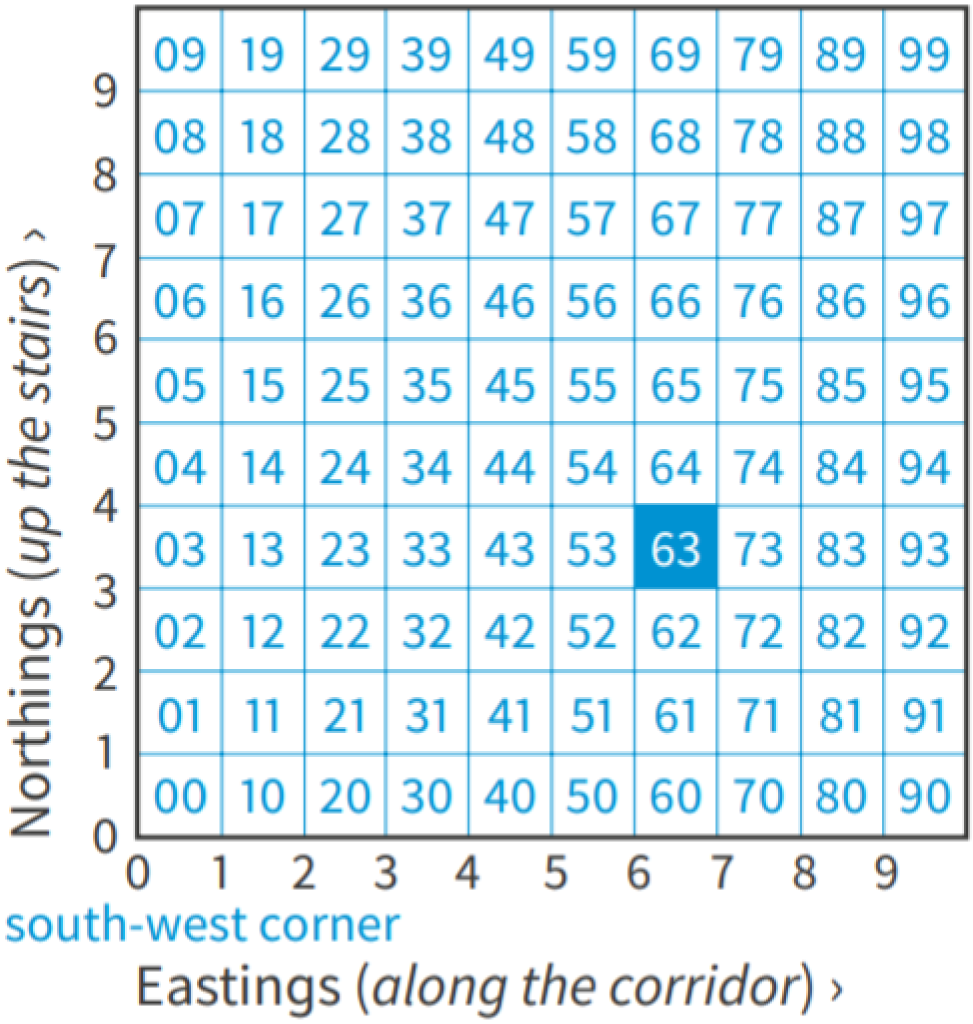


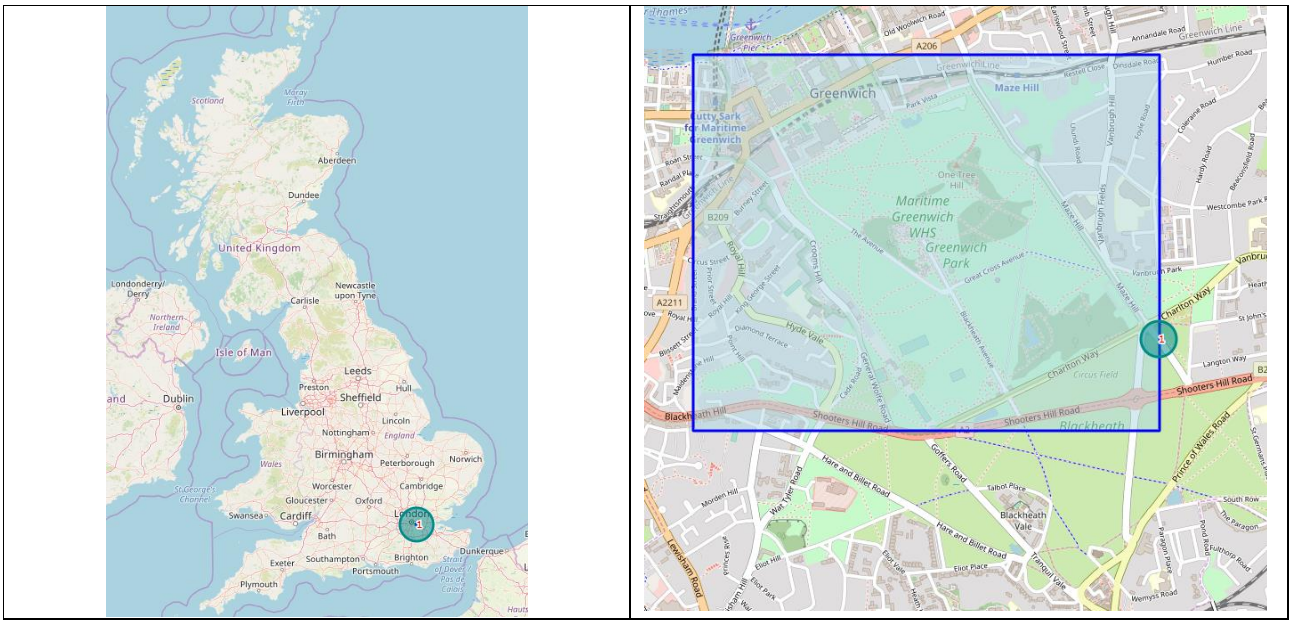
Figure 4: Each 100 km by 100 km square shown in Figure 3 is subdivided into smaller squares of size 10 km by 10 km. And these cells are represented by two letters corresponding to the parent cell and two numbers e.g. TQ63

2.3.2 Importing the DEM data from Ordnance Survey

The import of the DEM data in urbanEXODUS was tested by modelling a part of the Greenwich area in United Kingdom (see Figure 5). The following steps need to be followed to download and import the DEM data for this area.

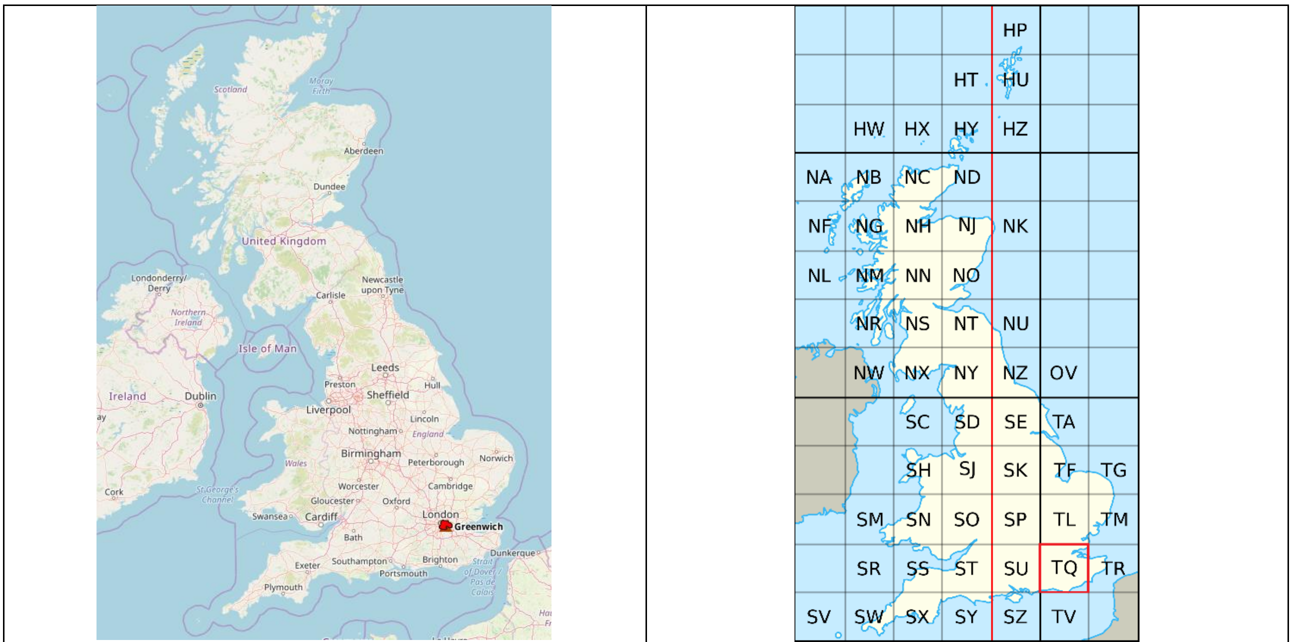
1. Identify the 100 km by 100 km grid square from the OS map. The Greenwich area of interest falls within the OS square TQ as shown in Figure 6. When the DEM data for square TQ is downloaded there is also one file downloaded for each of the 100 sub cells which are 10 km by 10 km (see Figure 4).
2. Identify the 10 km by 10 km grid square within the square TQ which covers the area of interest. The modelled area falls within the OS square TQ37 as shown in Figure 7.
3. Once the 10 km by 10 km square that contains the area of interest has been identified, the ASCII grid data file corresponding to this square can be loaded into urbanEXODUS using a SFE command:
   LoadTerrain <Lat> <Long> <RotationInDegrees> <TERRAIN_FILE>
   The <Lat> and <Long> attributes refer to the x and y coordinates of the lower left (south-west) corner of the grid in this case TQ37. The x and y coordinates

provided in the OS Terrain data file is in the British National Grid (BND) format which needs to be converted to latitude and longitude coordinates. The <RotationInDegrees> attribute is the angle of rotation that needs to be applied in urbanEXODUS since the OS map grids are at an angle since it follows the curvature of the earth. This angle is calculated by using standard trigonometric formulas by considering the DEM square directly above the square that is imported (see Section 2.3.3 for more information).



(a)	(b)

Figure 5: (a) shows the area in Greenwich, UK that is being modelled. (b) shows a close of the same area



(a)	(b)

Figure 6: (a) the red dot shows the area in Greenwich that is being modelled. (b) shows the corresponding Ordnance Map square labelled TQ that contains the modelled area.

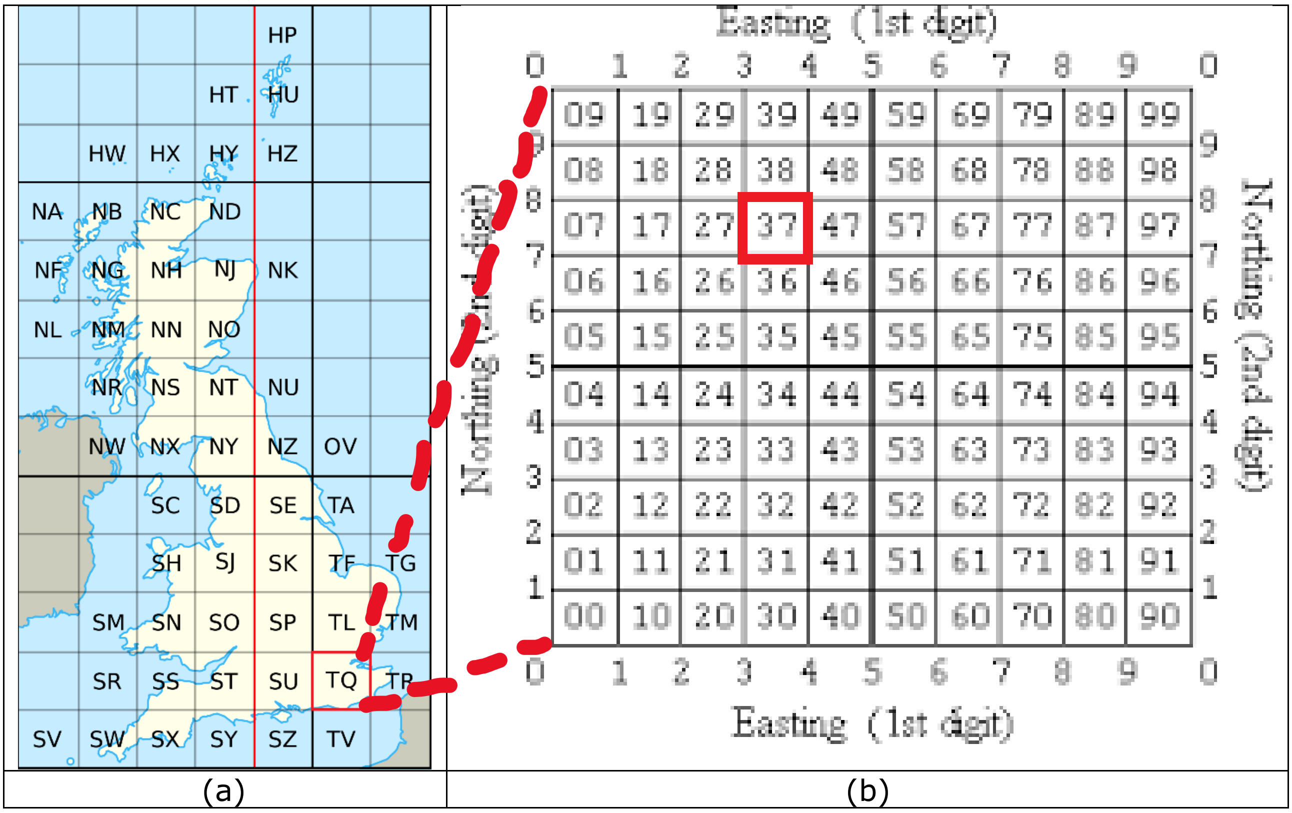


Figure 7: (a) The area modelled in Greenwich falls in the TQ square which is 100 km by 100 km. (b) The TQ37 square which is 10 km by 10 km is the square within the TQ square which is required to model the area.

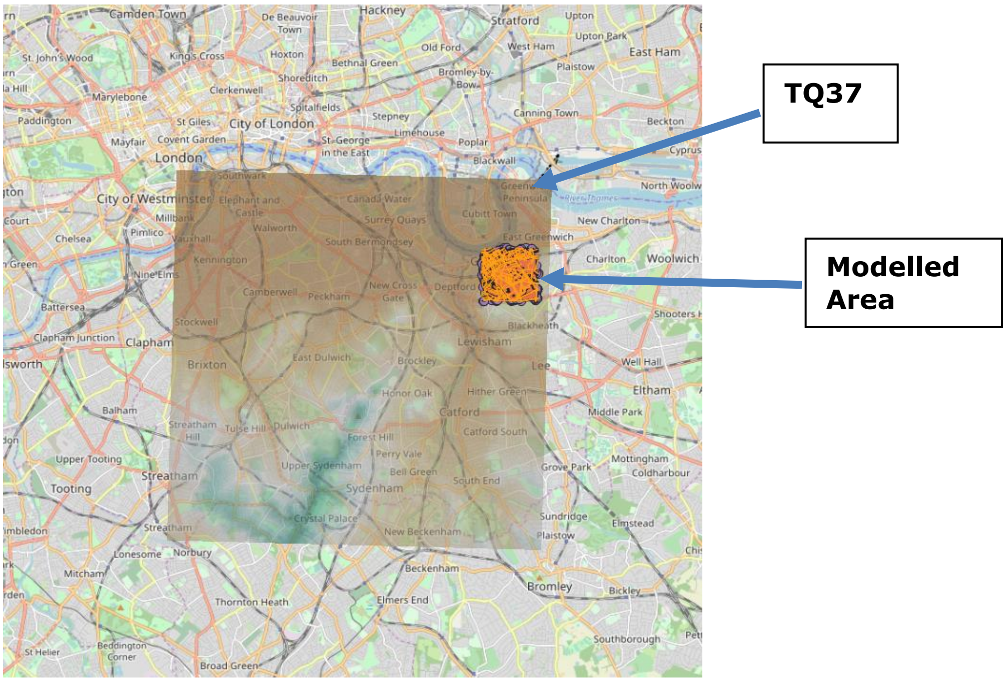


Figure 8: The DEM data for TQ37 square downloaded from the OS Terrain 50 dataset overlaid on OSM background and the modelled area

2.3.3 Determination of the angle of inclination of the DEM data

When the DEM data is imported into urbanEXODUS, it is important to overlay the DEM grid accurately within the spatial data of the modelled region for the correct determination of the slopes. Due to the curvature of the earth, the flattened OS map grids are at a certain angle to the actual map as shown in Figure 10. In order to demonstrate the inclination of the DEM grids, Figure 9 shows how the red square is represented in urbanEXODUS and how the DEM squares TQ37, TQ38, TQ48 and TQ47 are at a certain inclination to it. Therefore, this angle of inclination has to be considered when importing the DEM data in urbanEXODUS. This angle of inclination is calculated by using standard trigonometry equations using two coordinates – the lower left hand (south-west) corner of the DEM cell in consideration and the cell directly above it. For the Greenwich testcase, this will be the lower left-hand corner of the cells TQ37 and TQ38.

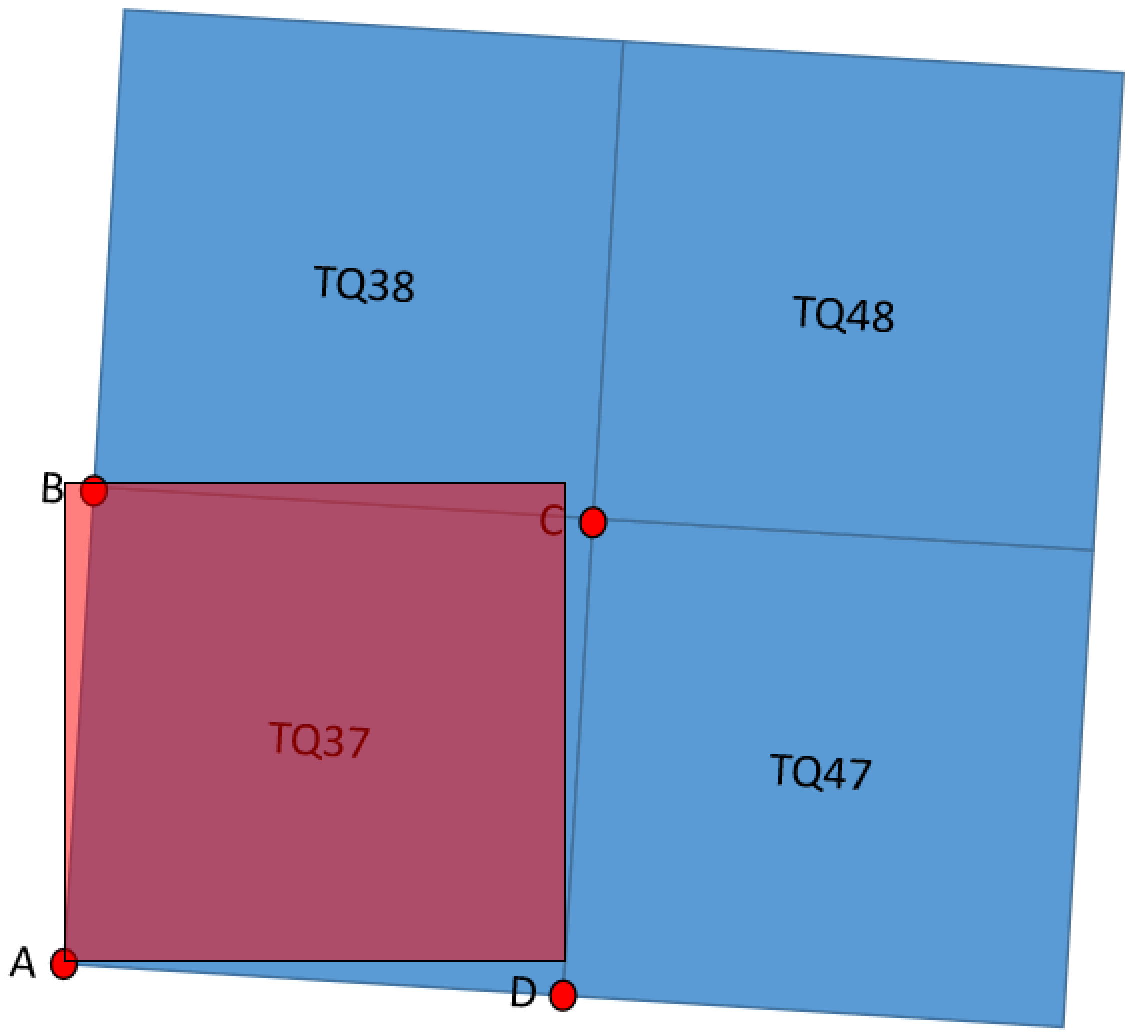


Figure 9: The DEM data is at an angle to the modelled area

2.3.4 Merging DEM datasets

The area of interest within Greenwich fell within one grid cell TQ37 (see Figure 8)) however, it is noted that this area is quite close to the western side of the cell. Therefore, it is possible for the modelled area to span across 2 to 4 grid cells. A hypothetical modelled area of size 11 km^2 spans across 4 grid cells TQ37, TQ38, TQ47 and TQ48 as shown in Figure 10. Therefore, the import of DEM data should consider the merging of 2 or more DEM data files. A python program has been written that can merge two or more DEM data files. These merged files can be imported into urbanEXODUS when the modelled area falls inside two or more DEM cells.

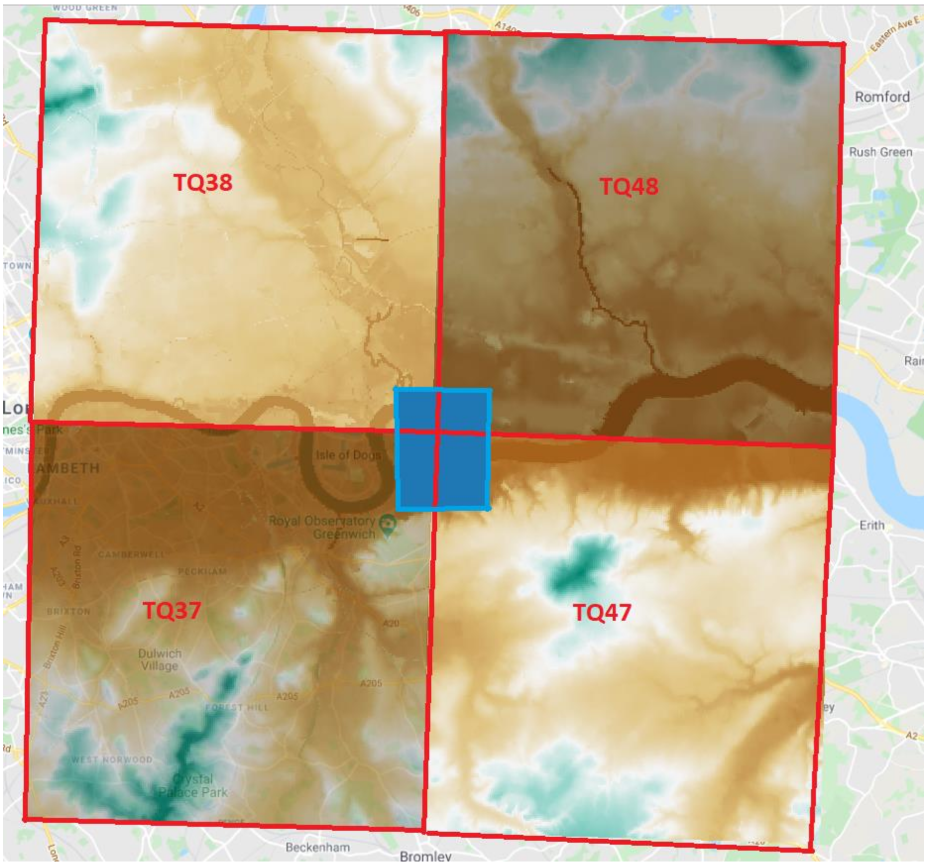


Figure 10: The modelled area in blue spans across four 10 km by 10 km DEM grid cells TQ37, TQ38, TQ47 and TQ48

2.3.5 *Structure of the ASCII Grid DEM data files*

The ASCI grid files (see Figure 11) starts with a set of header information and in the files provided by the OS Terrain 50 product the header information consists of the following:

- ncols – the number of columns in this dataset
- nrows – the number of rows in this dataset
- xllcorner – the x coordinate of the lower left (south-west) corner of the dataset

- yllcorner – the y coordinate of the lower left (south-west) corner of the dataset
- cellsize – the size of the cells in metres in the dataset

The number of columns and rows in this dataset for the square TQ37 is 200 and the cell size is 50 m. Therefore, the total size of this dataset is 200 X 50 m or 10 km by 10 km. The x and y coordinates of the lower left-hand corner of the dataset is in the EPSG27700 [Spatialreference, 2020] coordinate system which is the OSGB1936 or British National Grid system which is a local coordinate system that is used in Britain.

```
ncols 200
nrows 200
xllcorner 530000
yllcorner 170000
cellsize 50
4.1 5.3 4.9 5.8 5.4 4.7 3.9 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 5.8 5.6 4.8 4.8 4.8 5.1 11 11.8 11.8 11.6 4.6 4.1
4.9 5 5.3 5.3 5.1 4.7 5 5.5 5.3 5 4.9 5.2 5 4.9 4.9 4.9 4.8 4.5 4.5 4.9 5 5.1 5.3 5.4 5.5 5.9 6.2 6.2 5.5 5.
-2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -0.5 3.4 3.6 3.7 4 4 4.
5.9 5.6 3.4 5.4 3.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.5 4.5 5.2 5.8 6.3 6.2 3.9 3.9 7.1 7.1 4.9 4.9 4.9 4.9 4.
-2.3 -2.3 -2.3 -2.3 -2.3 2.8 6.8 5.4 4.6 5.1 6.5 6.6 6.6 6.7 6.8 6.5 6.3 6.1 6.7 6.7 1.6 -2.3 -2.3 -2.3 -2.
3.9 5.2 5.5 5.3 5.3 5 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 5.5 4.5 4.8 4.8 4.8 3.8 11.7 11.5 11.2 11.4 11.6 4.
5.1 5.2 5.2 5.5 5.5 5.4 5.1 5.2 5.5 5.6 5.6 5.4 5.1 4.9 4.7 4.7 4.6 4.5 4.4 4.3 4.7 4.8 4.9 4.9 5 5.1 5.4 5.
-2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 2 3.5 4.6 4.2 4.1 4.1 4
7.3 6.6 5.6 6.3 3.6 5.5 3.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.4 3.5 4 4.1 4.3 5.8 6.1 6.1 6.6 6.7 4.9 4.9 4.9
-2.3 -2.3 -2.3 -2.3 -2.3 -2.3 6 5.3 5 5 4.3 5.9 6 6.4 6.5 6.5 6.4 6.3 6.2 6.2 6.3 6.3 -2.3 -2.3 -2.3 -2.3 -2
3.8 4.8 5.1 5.3 4.9 5.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 4 4.5 4.7 4.8 4.3 11.8 11.5 11 10.7 10.6 11.3 4.1
5.5 5.6 5.6 5.7 5.7 5.3 5.2 5.4 5.4 5.4 5.3 5 4.8 4.5 4.4 4.5 4.5 4.2 3.8 4.1 4.3 4.6 4.6 4.7 4.9 5 4.1 4.9
-2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.3 3.4 3.8 4 4.2 4.1 4.2 4.
6.6 4.6 4.2 3.3 5.4 3.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.5 4.2 3.7 3.4 3.3 3 3.6 5.6 5.5 5.8 5.1 5.1 5.4 5.5
-2.3 -2.3 -2.3 -2.3 -2.3 3.5 4.3 4.6 4.4 4 4.7 5.2 5.9 6.1 6.1 6.4 6.4 6.1 5.9 5.3 5.8 2.7 -2.3 -2.3 -2.3 -2
3.9 4.5 5 5.3 4.5 5.8 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 5.9 5.2 4.5 4.2 4.2 4.2 11.5 11.5 11.1 10.5 10 0.3 4.3 4
4.6 4.8 5.1 5.4 5.4 5.3 5.2 4.9 5.1 5.1 5.1 5.1 5 4 4 4 4.2 4.3 4.5 3.5 3.2 3.4 3.7 3.9 4 4.2 4.5 4.4 3.9 4.
-2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.4 3.6 3.5 3.6 3.2 3.5 3.8 4 4.1 4.4 4.6 6
3.8 3 3.1 5.5 3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.5 4.3 3.7 3.4 3.1 2.9 2.6 3.4 4.4 5 5.2 5.5 5.9 6.3 6.2 5.8
-2.3 -2.3 -2.3 3.3 3.9 4.3 3.8 4 4.5 5 5.4 5.7 5.6 5.7 5.8 5.9 5.6 5.3 5.4 5.8 2.7 -2.3 -2.3 -2.3 -2.3 -2.3
4.2 4.3 5.3 5.6 5 6.4 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 4.9 5.1 4.6 4.5 4.5 4.8 11 11.1 11.2 10.7 10.7 1.2 4.1 4
4.2 4.6 5 5 4.8 4.7 4.2 4.1 4.6 4.8 4.8 4.8 3.6 3.3 3.7 4 4.3 4.5 3.4 2.9 2.8 3.1 3.2 3.4 3.8 4.1 4.2 3.7 3.
-2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.6 4 4.1 3.8 4 3.6 3.2 2.5 -1.4 3.4 3.7 3.8 4 6.2 6 5.8 5
2.9 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3 3.5 4.2 3.4 2.9 3 2.9 2.6 2.3 3.2 4.8 5 5.3 5.8 6.4 6.5 6 5.2 4.2 5.3 6.3
4.2 4 3.3 3.7 4 4.6 5.1 5.2 5.1 5.3 5.3 5.2 5.5 5 5 5.2 5.4 1.7 -2.3 -2.3 -2.3 -2.3 -2.3 -2.3
```

Figure 11: A part of the ASCII grid data contained in the TQ37 dataset.

The header information is then followed by the data which for the DEM files is height or elevation in meters at the centre of each cell. Since the coordinates of the lower left-hand corner of the grid, the number of rows and columns of the dataset and the cell size are specified in the header information it is easy to calculate the coordinates of the cells in the entire grid. The ASCII grid file format is thus a very simple file format and best suited for the purpose of obtaining the heights from the DEM data.

2.3.6 Calculation of slopes from the DEM data

The DEM datasets specify the height or elevation at the centre of each cell. The size of the cells in the OS terrain 50 dataset is 50 m. So, each of the 10 km by 10 km square is further sub divided into 50 m cells and the height at the centre of each cell is specified in the DEM data files.

Therefore, the terrain data consisting of the heights at the centre of each cell in the DEM dataset can be obtained for the modelled area in urbanEXODUS. This height data is then utilised to develop a series of cubic equations [Wikipedia, 2019] which effectively smooth out the surface so that any point on it will be relatively smooth and generates a 3D object defining the smoothed terrain data surface. It is to be noted that this smoothing of the terrain data does not alter the heights at the data points from the DEM dataset. The cubic equations are only used for estimating the heights at locations between the data points, which depending upon the distance between data points, might be quite large. In the case of the OS Terrain 50 dataset which is freely available the distance between the data points are 50 meters apart since the cell size of this dataset is 50 meters. Ordnance Survey also provide another product – OS terrain 5 dataset. However, this dataset is not free but does reduce the cell size to 5 metres. While the OS Terrain 5 dataset was not tested, as it is not freely available, a spot check of the heights and slopes of the terrain for the Greenwich model determined using the OS Terrain 50 dataset closely matched those generated using data from GoogleMaps.

These cubic equations help interpolate the heights at any point on the terrain. The cell size or the size of nodes in urbanEXODUS is 0.5 meters and these cells do not overlap with the DEM data cells of size 50 meters not only because the cell sizes are different but also because the orientation and alignment of the cells in the two models are different. Therefore, to calculate the slope of any two nodes in urbanEXODUS it is necessary to determine the heights of these nodes which are between the data points provided in the DEM dataset. The cubic equations thus assist in the determination of the height at any coordinate in the DEM cell and thus the urbanEXODUS cells. As a result it is possible to calculate the slope of the routes taken by agents in urbanEXODUS and modify their walking speeds appropriately which should be based on empirical data obtained from analysing the walking speed data from experimental surveys (see Section 2.2). Further to calculating the slopes of the routes in urbanEXODUS, the DEM data also allows the calculation of the real or physical distance between nodal locations in urbanEXODUS. Without the inclusion of the DEM data the distance calculation in urbanEXODUS is based on a 2D model of space however, with the import of the DEM data the distance calculations are based on the 3D model of space and hence are more accurate.

2.3.7 Visualisation of the DEM data in urbanEXODUS

It is also possible to visualise the imported DEM data in urbanEXODUS which is useful for users to verify that the imported data is correct by verifying the location of water bodies and tall structures are in the correct locations. For example, Figure 12 shows the 3D view of the imported DEM data within urbanEXODUS. In Figure 12(b) it is observed there is a hill around the Greenwich Royal observatory which confirms that the imported data is correct. Similarly the DEM data around other hills and water bodies can be used to verify that the accuracy of the imported DEM data. The user can control the visual appearance of the terrain surface within urbanEXODUS's 3D view. Users can also control how finely sub-divided the cells are which will help them to visualise the DEM data better. For example, the user may decide to partition every data cell (i.e. for example 50 X 50 metre cells) into 10 sub regions in the x and y directions respectively (i.e. into 100 separate squares/areas). The heights of each of the sub-region vertices are then calculated using the cubic equations and the triangles are generated between the corresponding vertices. It is to be noted that this subdivision of the DEM cells is only for visualisation purposes and has no influence on the accuracy of the slope or distance calculations. In this manner a 3D object defining the smoothed terrain data surface is generated enabling it to then be visualised within urbanEXODUS's 3D view. The surface data can then also be output as a .OBJ file, thereby enabling it to be loaded into a 3D modelling software such as Blender [Blender, 2020].

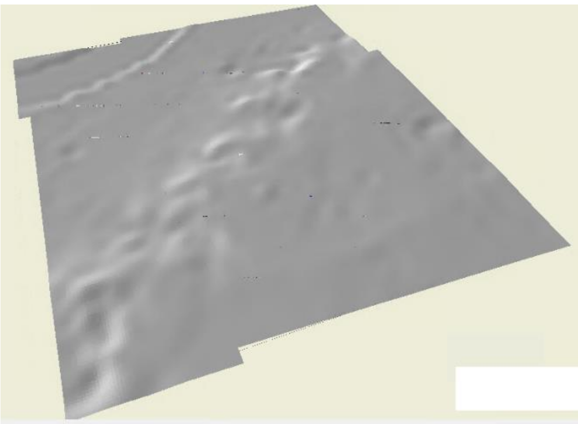
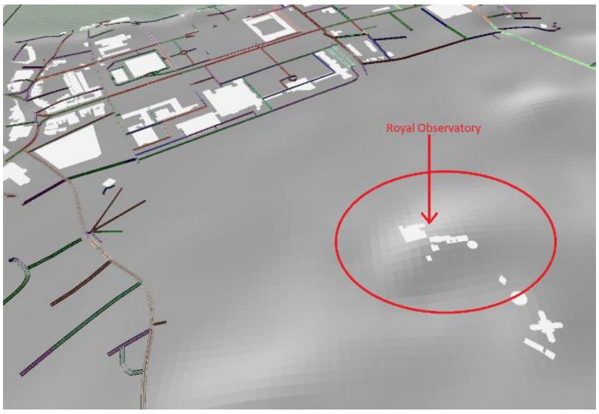
	
(a) The DEM data for the entire modelled area	(b) The DEM data Zoomed into the Greenwich Royal Observatory

Figure 12: Visualisation of the DEM data in urbanEXODUS 3D view

2.3.8 Major outcomes of importing DEM data

The following summarises the major outcomes of importing DEM data into urbanEXODUS:

- The import of DEM data allows urbanEXODUS to automatically calculate the slopes and physical distances between points on routes.
- The user simply needs to identify, download and specify the location of the DEM data files to be imported into urbanEXODUS.
- The user currently needs to calculate the angle of inclination of the DEM dataset (see Section 2.3.3) which will be automated in future.
- A set of python programs have been developed to merge DEM datasets (Section 2.3.4) when the modelled area falls on more than one datafile. This process will be automated in future.
- It is possible to visualise the imported DEM dataset within urbanEXODUS's 3D view. This data can be exported so that is can be analysed in 3D modelling softwares.

Section 3.3 of this report provides details of some preliminary simulation results incorporating terrain slope for a demonstration case involving the Greenwich area.

2.3.9 Future work

The following identifies future work associated with importing DEM datasets within urbanEXODUS:

- While the importing of DEM dataset has been tested in urbanEXODUS for an area in UK and this should work for any location in UK for which the OS

Terrain 50 dataset is available, the model needs to be tested for other countries which will differ in the following:

  - The cell size of the DEM dataset will differ – this should not be an issue since the importing module does consider the different cell sizes. However, the accuracy of the slope calculation should be tested for different cell sizes especially for cell sizes larger than 50 meters.
  - The inclination of the DEM dataset for different countries may differ, however, the method to calculate the angle of inclination will be the same.
  - The coordinates of the DEM datasets for different countries will differ however, the importing module utilises the converted latitude and, longitude coordinates of the local coordinate system, so this should not be an issue.

- The importing module can be utilised with very little adjustments of the parameters - cell size, angle of inclination, coordinates for different countries and the DEM datasets available in those countries. These DEM datasets will be identified and the appropriate parameters required to import the data.
- The importing module can be made completely automated by automating the calculation of the angle of inclination and the merging of the DEM datasets when the modelled area spans across more than one DEM datafile.
- Verification of the calculated slopes and distances for the UK and other countries using locally available DEM datasets.
- Appropriate walking speed data will be implemented within urbanEXODUS when available (see Section 2.2), that takes into consideration the slope (and nature) of the terrain.

3 DEMONSTRATION CASES

Three hypothetical urban-scale evacuation scenarios have been developed to demonstrate the capabilities of urbanEXODUS.

The first case involves a pedestrian based evacuation of 16,982 people located in an area of 7.84 km^2 located in the Ruidera Natural Park in Spain. In this case, the urbanEXODUS evacuation model is coupled with data from the Wildfire Analyst [Monedero, Ramirez and Cardil, 2019] fire model. The geometry for the environment is created using OpenStreetMap and the hypothetical fire is modelled using Wildfire Analyst. The demonstration case includes the estimation of required evacuation times, safety factors and estimated number of fatalities.

The second test case involves a mixed pedestrian-vehicle evacuation of 519 people located in an area of 3.28 km^2 in the town of Marysville Australia. In this case, the urbanEXODUS evacuation model is coupled with data from the PHOENIX fire model and the vehicle/traffic model SUMO. The geometry for the environment is created using OpenStreetMap and the hypothetical fire is modelled using PHOENIX. The demonstration case includes the estimation of required evacuation times for an evacuation by foot, by private car and by mixed mode (foot and vehicle), safety factors associated with each case and estimated number of fatalities.

The third test case involves a pedestrian based evacuation of 100 agents located in an area of 1.96 km^2 in Greenwich, United Kingdom. In this case, the DEM data from Ordnance Survey was imported into urbanEXODUS and three scenarios involving differing the slopes of the paths traversed was modelled. The simulation results with and without the import of DEM data was analysed.

3.1 Pedestrian Evacuation modelling of the Ruidera Natural Park, Spain

3.1.1 Demonstration case Objective

This hypothetical demonstration case was suggested by GEO-SAFE partner Pau Costa Foundation (PCF). The Ruidera Natural Park in the region of Castilla La Mancha, Spain has been modelled since it is considered to be at high-risk of wildfires. The region is considered high-risk due to its proximity to a forested area with only a single road in and out. Furthermore, the Natural Park has a large influx of tourists unfamiliar with the region during the peak summer season.

3.1.2 Input data

The key input data used within the demonstration case are the spatial data, population distribution data and fire simulation data.

3.1.2.1 Spatial data

OpenStreeMap data was utilised for modelling the spatial data of the area in urbanEXODUS. Within the region are a collection of 11 refuge locations which are considered to be places of relative safety from wildfire. The region modelled is indicated by the blue polygon while the refuge locations are indicated by the and green circles shown in Figure 13.

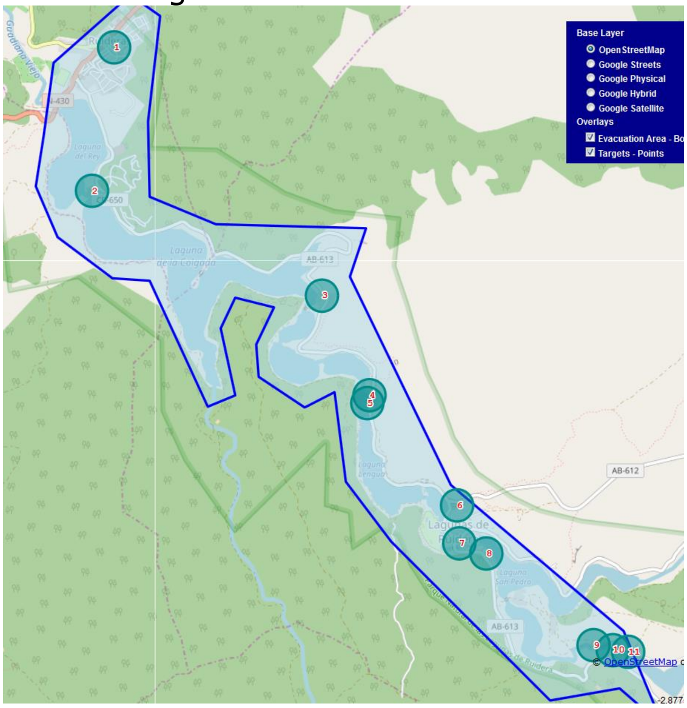


Figure 13: *Region of Ruidera Natural Park modelled (indicated by the blue polygon) and the refuge locations (indicated by the green circles)*

3.1.2.2 Population distribution data

The population distribution data was provided in a shapefile and the data is as shown in Table 1.

Table 1: *Population dataset*

ID	Name of the area	Number of people in the area	type of area
1	Perca Rosa	500	swimming areas
3	Las Eras	500	swimming areas
2	Camping Molinos	0	camping
4	Ruidera	400	the main settlement
6	Entrelagos	800	swimming areas
7	La isla	100	swimming areas
8	La Colgada	600	swimming areas
0	Castillo Peñaroya	100	monument

5	Restaurante Matias	200	swimming areas
9	Santo Morcillo	2000	swimming areas
10	La Salvadora	800	swimming areas
11	La Lengua	500	swimming areas
13	Quebrada del Toro	25	lookout
19	Camping Montesinos	200	camping
21	Cueva Montesinos	100	cave
14	La Redondilla	900	swimming areas
12	Laguna de San Pedro	50	swimming areas
16	Laguna La Tinaja	1300	swimming areas
17	Laguna Tomilla	200	swimming areas
18	Laguna Conceja	1200	swimming areas
22	Laguna Blanca	7	swimming areas
15	Camping Los Batanes	1100	Camping
20	Aldea de San Pedro	200	settlement
23	Carretera	1200	road
24	Viviendas	4000	buildings+A2AA6:E26
Total		16982	

Table 2: *Demographics of the population*

Sex	Male			Female		
Age	0-14	15-64	>64	0-14	15-64	>64
Ruidera	29	202	51	31	183	62

Visitors:

Visitors to the region come in small groups of average 4.33 persons.

The distribution of visitors by age is:

- 0-16 years old: 33%
- 16-35 years old: 53%
- >35 years old: 14%

50% of the visitors during summertime (fire season) are expected to visit the park for the day.

The remaining 50% of the visitor population spend more than one day in the park.

- Cottages: 15%
- Campgrounds: 20%
- Hotels: 12%
- Friend’s house: 3%

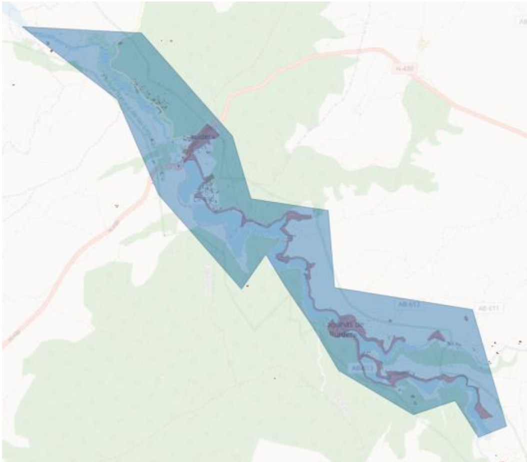


Figure 14: Population data in shapefile format. The polygons in red denote the locations of the people

The population data format was provided as shapefiles (see Figure 14). There are numerous polygons and each polygon has a number of people in it. In the case of buildings, all the houses form a collection of polygons (multipolygon). There are 4000 people in 725 buildings. Therefore, 5.5 (4000/725) people were placed in each building.

3.1.2.3 Fire simulation data

The fire simulation results was generated using the Wildfire Analyst [Monedero, Ramirez and Cardil, 2019] fire model produced by the Spanish company Technosylva.

The fire output used was the time-based fire perimeter output which shows the affected areas at every 1 hour timestep.

Table 2 shows the spread of the fire as simulated in the Wildfire Analyst fire simulation tool at time intervals of 1,2,3 and 4 hours after the start of the fire. It takes 4 hours for the fire to reach the populated area shown as a blue polygon. Based on this fire simulation, this suggests that the population in the target area has at least four hours to evacuate the region. The fire scenario used in this case study is based on a study [PCF, 2018] by PCF about the fire risk in the Ruidera Natural Park and represents the situation of highest fire risk that can potentially occur in the area.

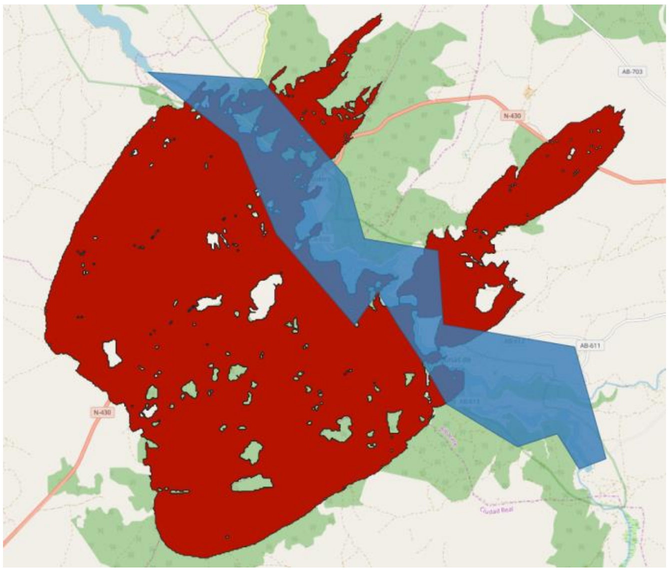
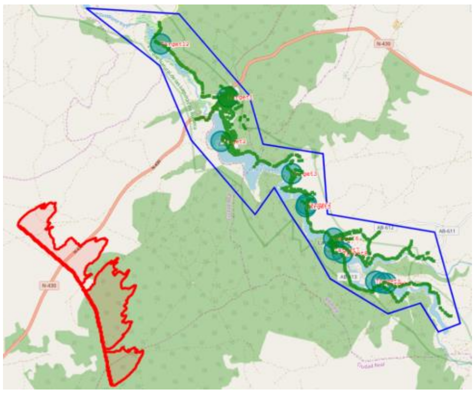
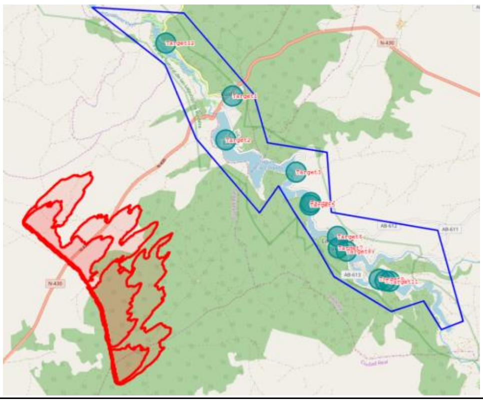
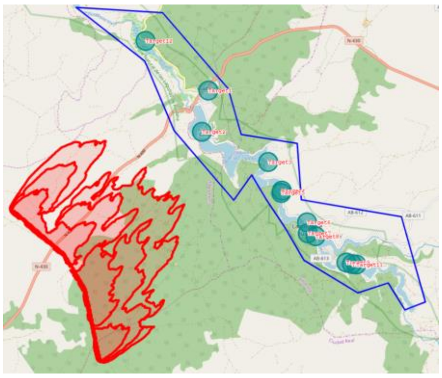
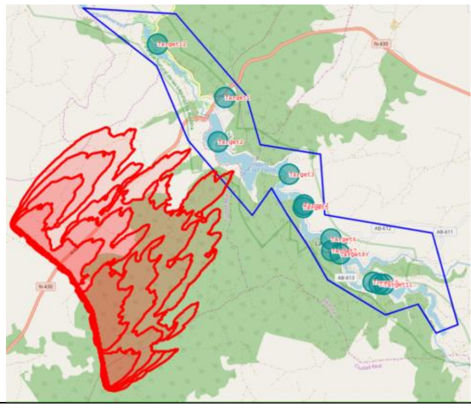


Figure 15: Fire simulation results from the Wildfire Analyst fire simulation tool. The red polygons show the spread of the fire 15 hours after the start of the fire and the blue polygon shows the modelled evacuation region.

Table 3: Images showing the fire spread after 1,2,3 and 4 hours after the start of the fire.

	
a) 1 hour after fire start	b) 2 hours after fire start
	
c) 3 hours after fire start	d) 4 hours after fire start

3.1.2.4 Evacuation simulation scenario and results

The demonstration case made use of three hypothetical response time distributions. It is noted that the response times are not based on real data but are arbitrary and used for demonstration purposes. Three response time distributions were used, the first assumed that the population responded instantly at the time of the fire initiation, the second assumed that the population responded between 1 to 2 hours after the time of fire initiation and the third assumed that the population started to respond nine hours after fire initiation with response times varying from 0 to 30 minutes after being alerted. In all the scenarios the evacuating population are assumed to take the shortest path to their nearest refuge/gathering location (see Figure 13). Thus, it is assumed that the population is familiar with the location of the 11 refuge areas.

All the simulation results presented here are based on a single simulation. As many of the parameters within urbanEXODUS are stochastic in nature, it is recommended that each simulation is repeated a number of times for each scenario and the results averaged.

The main results for the three scenarios can be summarised as follows:

Scenario 1: Instant response time, the population is assumed to commence their evacuation at the same time as fire initiation. Total evacuation time, 1 hr 45 min with no predicted fatalities.

Scenario 2: Response time 1 to 2 hours, the population are randomly assigned response times of between 1 to 2 hours after fire initiation. Total evacuation time, 2 hr 38 min with no predicted fatalities.

Scenario 3: Response time starts nine hours after fire initiation and population responds within 30 min. The population response time after notification is shown in Table 4. Total evacuation time measured from notification is 2 hr 14 min with 1433 predicted fatalities.

Summary Scenario 1: All people in the modelled area are assumed to evacuate instantly when the fire starts. While not intended to be a realistic scenario it provides an estimate of the time required to evacuate the population. The total time required to evacuate the area in this scenario was 1 hr 45 mins. Considering that the fire reaches the modelled area 4 hrs after the start of the fire, the population has cleared the area with a safety margin of 2 hrs 15 mins.

Summary Scenario 2: The population within the modelled area are assigned randomly a response time of 1 to 2 hrs from fire initiation. The average response time of the people was therefore 1 hour 30 mins. The total evacuation time in this scenario was 2 hrs 38 mins. This scenario provides the population with a safety margin of 1 hr 22 mins.

Summary Scenario 3: In this scenario the evacuation is assumed to start 9 hrs after fire initiation and the population have response times of up to 30 min, according to the distribution shown in Table 4. In this scenario it requires 2 hrs 14 min for the survivors to evacuate the area resulting in a predicted 1433 fatalities. While this again is an unrealistic scenario as the population would be alerted well before 9 hrs it serves to demonstrate the impact of delaying the start of the evacuation. In this case it is predicted that there will be a total of 1433 potential fatalities. Potential fatalities are defined as agents that remain in a region covered by the advancing fire polygons.

Table 4: Response time distribution for Scenario 3

Percentage of entire population	**Response time range in minutes**
1	0-1
9	1-4
55	5-10
15	10-15
9	15-20
1	20-30
10	>30

3.1.2.5 Future work

The above analysis assumed that the entire population evacuated to a place of safety on foot. In reality, many of the population are likely to attempt to evacuate by private car. A coupled vehicle and pedestrian based evacuation simulation is planned after completion of GEO-SAFE.

3.2 Coupled Pedestrian and Vehicle Evacuation modelling applied to a Hypothetical Wildfire near Marysville, Australia

While the Ruidera demonstration case discussed in the previous section modelled only pedestrian evacuation on foot, the Marysville demonstration case discussed in this section includes coupled pedestrian and vehicle evacuation. Marysville was chosen as it previously suffered a major fire in February 2009, referred to as the Murrindindi Mill Fire which is one of the several major fires that occurred during the Black Saturday bushfires, which has been well documented [Jim McLennan]. However, it is important to note that the simulations presented here are purely hypothetical, they are not intended to be a representation of the actual fire from 2009.

3.2.1 Input data

The key input data used in this demonstration case are the spatial data, population and vehicle distribution data and fire simulation data.

3.2.1.1 Spatial data

The modelled area consisting of the entire Marysville town and the refuge locations are shown in Figure 16. Within the hypothetical simulation, the population attempt to reach one of two target locations labelled 1 and 2 in Figure 16. These locations are actual safe locations as designated during the 2009 Black Saturday bushfires. Target location 1 is an open ground/park called the Oval which was the unofficial gathering point in case of a wildfire. Target Location 2 was considered a safe location by the population as they fled in their cars from the approaching fire. People who managed to pass this location were considered safe from the advancing fire front. Within the evacuation simulation these two targets were modelled as the goal for the fleeing agents.

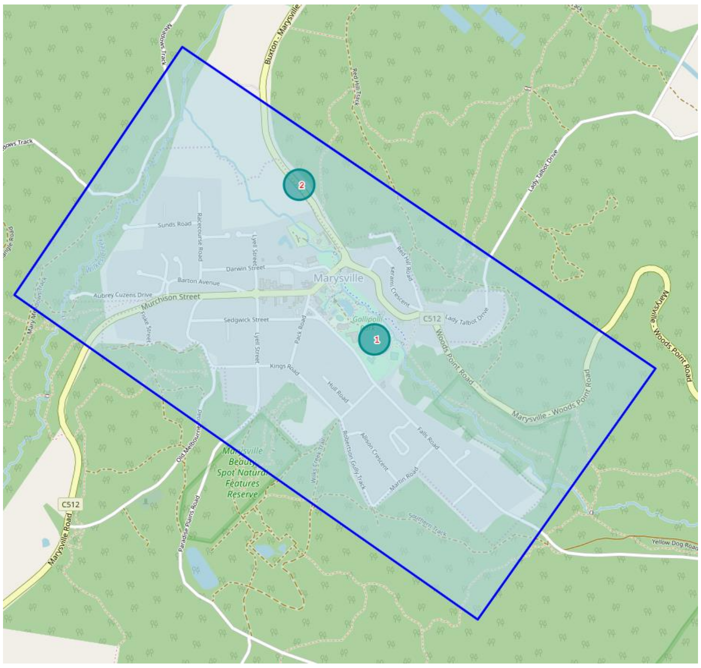


Figure 16: Modelled area and the refuge locations shown by the blue polygon and green circles

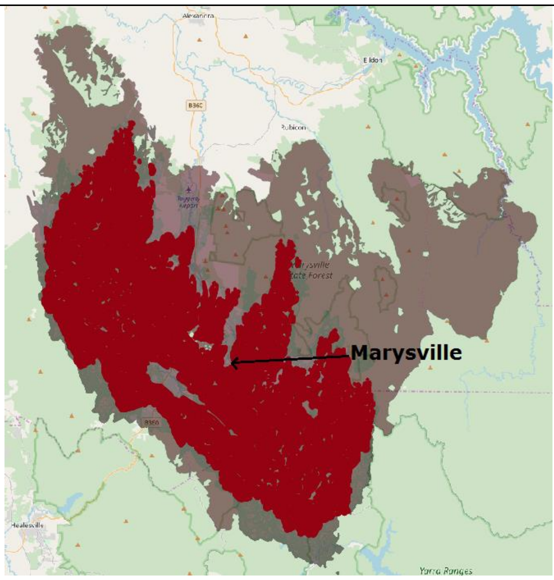
3.2.1.2 Population data and response times

The modelled region consists of 3.28 km^2. A total of 519 people were distributed in the modelled area at the locations shown in Figure 17. The population was arbitrarily distributed in groups ranging from 1-5 representing family units. They were randomly positioned at locations identified in Figure 17. This is not intended to represent the actual population distribution in the town but is hypothetical distribution intended for demonstration purposes only. A more realistic population distribution can be derived from census data linked to an analysis activity they may be involved in depending on the time of the day, day of the week and week of the year. The population response times used in these demonstration simulations are arbitrarily set to between 1 hr 0 min and 1 hr 45 min after notification of the need to evacuate. As with the previous analysis, these response times are not intended to represent a real situation but are used simply for demonstration purposes. Actual response times are dependent on the nature of the alert system, experience of the population, whether the population is made up of visitors or locals, nature of environmental cues (visibility of smoke, ember, etc) and the nature of the tasks that people perform prior to evacuating (see Deliverable 2.5).

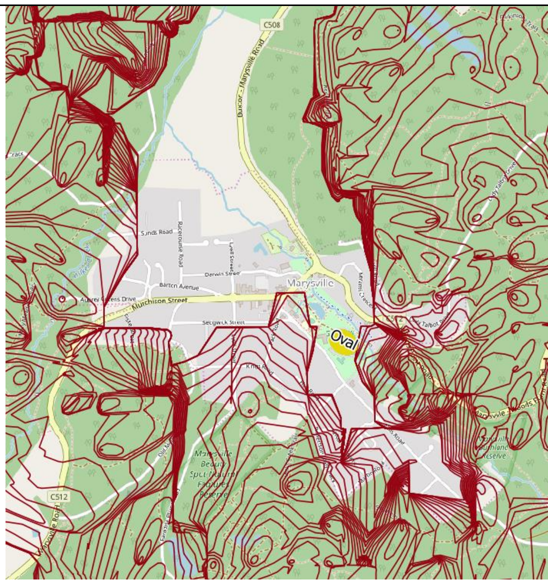
Figure 17: Population data in the Marysville town

3.2.1.3 Fire simulation data

The fire simulation data was generated by Thomas Duff [Thomas Duff 2017, University of Melbourne, email correspondence, 17 November] using the PHOENIX fire simulation tool [Tolhurst, et al., 2008]. The fire simulation is an attempt at representing a situation similar to that which occurred during the Black Saturday incident, in terms of wind speeds and fire spread.



a) Murrindindi Fire Burn Area, the smaller red area represents the spread of the simulated fore boundary while the shaded region represents the actual spread of the wildfire



b) Close up of fire simulation Isochrones (red lines) in the vicinity of Marysville.

Figure 18: Fire spread simulation obtained from the Phoenix fire simulation tool

3.2.1.4 Evacuation simulation scenarios and results

Three basic scenarios were performed differing by the evacuation mode – pedestrian only, vehicle only and multimodal involving 10% evacuating on foot and 90% evacuating by vehicle. For each basic scenario there were two variations differing by notification times, in the first case the notification time was 2 hrs after fire initiation while in the second case the notification time was 3 hrs. Each scenario consisted of a population of 519 agents and the population had the same starting location in each scenario and in each repeat simulation for the scenario. However, population characteristics such as walking speeds and response times were randomly distributed in each simulation run. The response times were randomly distributed to be between 60 min and 90 min and response times were allocated to family groups so everyone in a family would respond at the same time. The details of the various scenarios considered can be summarised as follows:

Pedestrian Only Scenario: All 519 agents are pedestrians, they are allocated random response times as family units ranging between 60 min and 90 min after notification. All the pedestrians have target location 1 as their goal (the oval), where they take refuge.

Vehicle Only Scenario: All 519 agents make use of personal vehicles to evacuate and are allocated response times as in the pedestrian only scenario. All the vehicles have target location 2 as their goal. Once they have passed target location 2, they are deemed to be safe. This means that the population in the vehicle only scenario must travel a greater distance to reach a place of relative safety.

In urbanEXODUS, vehicles are programmed to redirect to an alternative target when a route is blocked by fire. In these simulations, if the primary target becomes cut off due to the advancing fire front, the vehicles will attempt to redirect to target location 1. To simplify the demonstration, it was assumed that there was no background traffic or traffic caused by emergency vehicles entering the region.

Within these demonstration simulations, to further simplify the analysis, all vehicles have the same characteristics (e.g. acceleration and braking abilities). The speed of the vehicles is determined by the road type and congestion experienced. The vehicles adhere to the speed limits and slow down when they encounter congestion. In addition, should the vehicles encounter pedestrians for example crossing the road, the vehicles will slow down and stop if necessary. Similarly, pedestrians will generally give way to vehicles. Within the simulation vehicles will normally adopt the shortest route to their destination however, congestion encountered on the shortest routes can result in the vehicles redirecting to alternative routes or destinations. However, in these scenarios given the absence of background traffic or emergency vehicles entering the region, the small number of vehicles originating within the simulation and the staggered start times (due to the response times of the family groups) road congestion is not expected to be an issue and hence it is unlikely that vehicles will stray from their ideal shortest distance routes in all the simulations.

Multimodal Scenario: 10% or 52 agents evacuate as pedestrians while 90% or 467 evacuate by vehicle. The precise family groups that evacuate by vehicle is randomly distributed between repeat simulations. All agents are allocated response times as in the pedestrian only scenario. All pedestrians adopt target location 1 as their goal while all vehicles have target location 2 as their goal. In the multimodal scenario it is possible for the vehicles to interact with pedestrians as described above. However, given the small numbers of pedestrians and vehicles in this simulation and the staggered response times, this is unlikely to be significant.

For each of the three scenarios, it is expected that there will be considerable variation between each repeat simulation and so it is necessary to run a number of repeat simulations in order to generate representative results for the scenario.

However, only 10 repeat simulations were performed for this demonstration. It is noted that more repeat simulations would be required to make definitive conclusions for each scenario. It is also noted that the fire in each scenario and each repeat simulation is identical. Variations in possible fire spread are not considered in this demonstration.

The main results for these scenarios are summarised in Table 5.

Table 5: Results for the hypothetical Marysville wildfire evacuation scenarios. (Average distance travelled by the overall population (O), average distance travelled by fatalities(F), Total Evacuation Time (TET)).

Scenario	**Parameters Examined**	**Notification Time 2 hrs**	**Notification Time 3 hrs**
Pedestrian Only	**TET (hh:mm)**	02:16	02:04
	Potential Fatalities	0	25
	Average distance travelled (km)	1.22 (O)	0.45 (F)
Vehicles Only	**TET (hh:mm)**	01:39	01:34
	Potential Fatalities	0	40 (12.56 vehicles)
	Average distance travelled (km)	3.93 (O)	0.92 (F)
Multimodal (10% pedestrian and 90% vehicle)	**TET (hh:mm)**	02:04	01:53
	Potential Fatalities	0	38 (4.5 ped and 35 in vehicles, 12.56 vehicles)
	Average distance travelled (km)	3.28 (O)	0.76 (F)

When the population is notified 2 hrs after fire initiation, there are no fatalities in any of the scenarios. The shortest average distance travelled by the population occurs in the pedestrian only case (1.2 km) but results in the longest time to evacuate (2 hr 16 min). This is because target location 1 is the closer of the two target locations, hence resulting in the shortest distance travelled, but as the entire population is using the slowest mode of evacuation, it takes the longest time. In contrast the vehicle only scenario results in the greatest average travel distance (3.9 km) but the shortest evacuation time (1hr 39 min). Clearly the vehicles only case offers the fastest mode of evacuation but requires that the population travel the greatest distance to reach target location 2. Thus, using vehicles only, the population can reach a place of safety some 37 min sooner than if the population evacuated on foot only.

As expected, the multimodal case falls between the two extremes, but as most of the population use vehicles and hence adopt target location 2, the travel distance is closer to the vehicle only case, but given that the pedestrians are inherently slower than the vehicles, the time for the last person to reach safety is closer to the pedestrian only case.

The longer routes taken by the vehicles compared to the pedestrians may result in hazardous situations if the start of the evacuation is delayed. This is because there is potentially more spatial opportunity for the routes to be compromised by the fire compared to the pedestrian only case. However, because the travel time is shorter in the vehicle only case, this reduces the temporal opportunity for the vehicles to be compromised by the fire compared to the pedestrian only case. Whether the advantage offered by the vehicles in this scenario (shorter evacuation time) is off-set by the disadvantages (longer travel distance) is dependent on the nature of the fire spread and how this impacts the routes taken by both pedestrians and vehicles.

When the population is notified 3 hrs after fire initiation, fatalities occur in all scenarios. Assuming the population can be alerted before 3 hrs after fire initiation the model predicts that the entire population can safely evacuate using any of the available evacuation modes. However, if the start of the evacuation is delayed by 3 hrs or more, fatalities can be expected. Furthermore, the greater the delay in starting the evacuation (above 3 hrs), the greater the number of fatalities expected. The predicted fatalities are a result of the late notification time, the time required for the population to respond and the initial proximity of agents to the start of the fire.

It is also interesting to note the significant differences between the various evacuation modes, with the pedestrian only case resulting in the smallest number of fatalities (25) and the vehicle only case resulting in the highest number of fatalities (40) with the mixed mode being between the two and closer to the vehicle only case (38). In the multimode evacuation, the number of fatalities is between the pedestrian only case and the vehicle only case. 38 fatalities are predicted, 4.5 pedestrians and 35 in vehicles.

There are many possible reasons why in this particular wildfire scenario, the pedestrian only case results in the lowest number of predicted fatalities. This could be due to the routes taken by the pedestrians being less affected by the predicted fire development than the routes taken by the vehicles. However, there is also a significant difference in how the model works for pedestrian and vehicle only scenarios. In both cases the family units react as a group, but once responded, the pedestrians do not maintain their social group and travel at their maximum walking speeds, thus the group can become separated. In contrast, in the vehicle only case, the family group is maintained during the evacuation as they are all in the vehicle. Thus in the vehicle only case, if one member of a family group perishes, the entire family group perishes. The average of 40 fatalities in the vehicle only case occur in an average of 12.6 vehicles, indicating multiple fatalities occurring in each vehicle. In the buildingEXODUS software, family groups can be maintained during the evacuation, with the family group travelling at the speed of the slowest member of the group. This feature will be implemented within urbanEXODUS in a future release.

It is also interesting to note that none of the fatalities in any of the simulations were a result of the exit route being cut-off, effectively trapping the evacuees. All fatalities occurred on-route to safety, the predicted fatalities occurring as the agents were overrun by the spreading fire. This can be seen by the relatively short distance from their starting locations that the fatalities are predicted to occur. In the pedestrian only case, the fatalities occur on average 0.45 km from the starting location, 37% of the required distance to safety, in the vehicle only case, the fatalities occur 0.92 km from the starting location, 23% of the required distance to safety while in the multimodal case, the fatalities occur at an average of 0.76 km or 23% of the required safe distance.

In all scenarios, all fatalities occur due to a combination of late notification time, long population response times and the population proximity to the fire start location.

3.2.1.5 Future work

The urbanEXODUS model will be enhanced to include a capability to allow family groups to evacuate as a family unit. Simulations involving vehicles and mixed pedestrian-vehicle scenarios will explore the impact on evacuation efficiency of larger populations, different types of vehicles, including public transportation, include background traffic and will consider the impact of changing fire scenarios resulting from for example different wind conditions.

3.3 Walking speeds analysis

The ability to import DEM data into urbanEXODUS was described in Section 2.3. The aim of importing the DEM data was to represent appropriate walking speeds of pedestrians for different slopes (see Section 2.2). While the empirical data from the statistical analysis of the walking speed trials for different slopes is currently not available (see Section 2.2), data from maritime applications was to demonstrate the approach. This data was extracted from maritimeEXODUS [Galea *et al* 2003], which is a ship evacuation model. This contains walking speed data for people walking relatively short distances up and down slopes of various inclinations. While this is not indicative of outdoor walking speeds over large distances and appropriate surfaces, it was considered appropriate for demonstration purposes.

Because of the limitations posed by the use of maritime walking speed data, it is important to note that these demonstration simulations are not intended to represent expected evacuation performance. Applying the maritime based walking speed data in urbanEXODUS helps determine if changes to the walking speeds based on slopes have a significant impact on total evacuation times. Furthermore, when the empirical data of walking speeds for outdoor environments is available the old dataset will simply be replaced by the new dataset into the model.

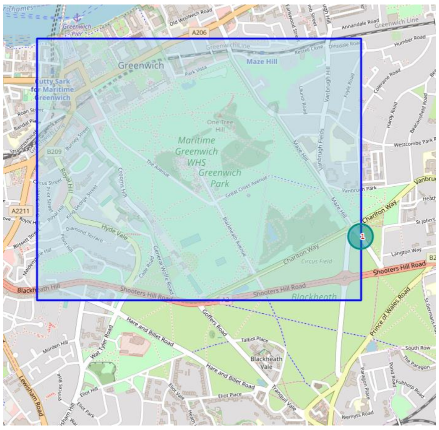
The walking speed data that is used in maritimeEXODUS is presented in Table 7. The values in this table are the walking speed reductions that are to be applied for different slopes, with the walking speed at flat terrains being taken as a reference. For example, if the walking speed over a flat terrain is 1.5 m/s then at -20^0 slope the walking speed will be 1.41 m/s (1.5*0.94) for pedestrian agents aged 18 to 40. While there are only a few data points (-20^0, -10^0, 10^0, 20^0) in the walking speed dataset (see Table 7), the walking speed data for the intermediate points areinterpolated. For instance, for a 25 year old man walking downslope -10º, urbanEXODUS would use a reduction factor of 0.99; and for a slope of -20º, a reduction factor of 0.94; but on -15º it would use a reduction factor of 0.965 ((0.99+0.94)/2). It should also be noted that this interpolation method was applied to all angles. In reality, it is expected that gentle slopes below about 5^O will have no impact on walking speed. However, the interpolation approach has been applied to all angles.

Table 6: Walking speed reductions from flat terrain walking speeds for different age groups based on maritime data. Note negative slopes indicate movement down the incline while positive slopes indicate movement up the incline

Slope (in degrees)	Young (18 – 40)	Middle Aged (41-60)	Senior (61 – 83)
-20	0.94	0.94	0.88
-10	0.99	0.99	0.97
10	0.88	0.86	0.86
20	0.73	0.67	0.67

3.3.1 Simulation setup

A number of simulation test cases were run using urbanEXODUS to demonstrate how the software currently determines the walking speed as a function of the slope. The modelled area and one of the roads in the modelled area that was used in the simulations is shown in Figure 19. The section of the road from A to C has a slope of 1.70 and conversely the route C to A has a slope of -1.70. The section of the route from A to B has a slope of 5.10 and conversely the route B to A has a slope of -5.10. In the simulations, 100 agents with a random distribution of age and other characteristics were placed at one of these points A, B or C. The routes that agents took in the simulations were: A-C (1.70), C-A (-1.70), A-B (5.10) and B-A (-5.10). For each of these routes, two sets of simulations were performed, one without importing the DEM data and another with the import of the DEM data (see Table 7). The scenarios that do not import the DEM data will be different to those that import the DEM data in two ways: walking speed reductions will be applied to the scenarios that import the DEM data (see Table 6) and the distance travelled will generally be longer in cases that utilise DEM data (see Table 7).



(a) Area in Greenwich that was modelled

(b) The road in the modelled area that was tested

Figure 19: The area and the road in Greenwich that was tested

To illustrate the difference in distance travelled between two points with and without the DEM data consider a simple example. The distance travelled by a single agent walking between two points determined using urbanEXODUS (uEX), Googlemaps (GM) and OpenStreetMap (OSM) is shown in Table 7. As can be seen, the travel distance as determined by uEX is generally longer when DEM data is incorporated in the model. To evaluate the accuracy of the distance data, the travel distance determined by uEX is compared to that determined by OSM and GM.

GM takes into consideration the elevation data when reporting the distance of routes while OSM does not. As GM considers elevation data, the distances without DEM data cannot be determined using it, conversely since OSM does not consider elevation data, the distance including DEM data cannot be determined using it. In all cases examined, uEX produces a slightly higher estimation of the distance (between 0.3% and 18%) of the routes compared to GM. There are several possible reasons to explain the noted difference in distance estimations. Firstly, GM determines the straight line distance between two points, however, in uEX agents do not necessarily walk in a straight line between two fixed points. Secondly, while it is not known what DEM data GM makes use of it is likely to be different to the Ordnance Survey DEM data used by uEX. Similarly, there are small differences (1.4% to 6.2%) between the uEX distance estimations and the OSM estimations. Here again, OSM assumes a straight path between two points while in uEX the agent may follow a different path. Also, the positional accuracy of OSM data which is imported into uEX is known to have errors of up to 10m.

Table 7: Scenarios modelled for testing the application of walking speeds on routes with different slopes.

Scenarios	Route	Slope	DEM data imported?	uEX (km)	GM (km)	uEX - GM (m)	OSM (km)	uEX - OSM (m)
1a	A-C	1.7^0	No	1.066	--	--	1.081	-15 (1.4%)
1b	A-C	1.7^0	Yes	1.109	1.016	93 (9.1%)	--	
2a	C-A	-1.7^0	No	1.066	--	--	1.081	-15 (1.4%)
2b	C-A	-1.7^0	Yes	1.075	1.028	47 (4.6%)	--	
3a	A-B	5.1^0	No	0.379	--	--	0.357	22 (6.2%)
3b	A-B	5.1^0	Yes	0.420	0.356	64 (18%)	--	
4a	B-A	-5.1^0	No	0.379	--	--	0.357	22 (6.2%)
4b	B-A	-5.1^0	Yes	0.379	0.378	1 (0.3%)	--	

3.3.2 Simulation results

Each simulation was run two times and the average results from these simulations are shown in Table 9. The scenarios 1a, 2a and 3a do not utilise the DEM data, which means that slope has no effect, and therefore the distance travelled by the agents is shorter than the scenarios importing the DEM data (see Table 9). The scenarios 1b, 2b and 3b utilise the DEM data, which allow the application of the walking speed reductions (see Table 6), and therefore the distance calculations are more accurate and generally longer.

The simulations results are shown in Table 9. The Personal Elapsed Time (PET) is the time that each person spends in the simulation from the start of the simulation until they reach their target destination. As can be seen the average PET for scenarios involving agents moving up slope (scenarios 1 and 3) is significantly more (4 min 47 s and 5 min 19 s) in the scenarios which utilise the DEM data. This represents an increase in average PET of 33% for 1.7^0 slope and 92% for 5.1^0 slope. This is because of the walking speed reductions and also the longer distances travelled, both of which increase the PET with the introduction of the DEM data. The PETs for scenarios where the agents are moving down the slope also increases with the introduction of the DEM data. However, for the downslope scenarios (Scenarios 2 and 4) the PET is not significantly different (30 s and 49 s) for the scenarios with and without the import of DEM data. This represents an increase in average PET of 3.3% for 1.7^0 slope and 14% for 5.1^0 slope. This is primarily because the reduction factors for walking speeds is significantly less for downslope movement compared to upslope movement. Therefore, for both moving up and down the inclines, the

PET increases with the use of DEM data however, the PET increase is significantly greater for movement up the incline (33% and 92%) compared to movement down the incline (3.3% and 14%). Also, the greater the slope, the greater the increase in PET (33% (up) and 3.3%(down) compared with (92% (up) and (14% (down).

Table 8: PET and TET for scenarios involving flat ground representation and sloped terrains (1.70 and 5.10 slopes) of the Greenwich environment.

Scenario	Slope angle (°)	Average Distance Travelled (m)	Difference In Distance Travelled (m)	Average PET	Difference in Average PET (mm:ss) and % increase	Average TET	Difference in Average TET (mm:ss) and % increase
1a	1.7 (slope has no effect)	1086.81	44.71	14:36	04:47 33%	16:13	12:00 74%
1b	1.7 (Upslope)	1131.52		19:22		28:12	
2a	-1.7 (slope has no effect)	1110.90	12.28	15:19	00:30 3.3%	16:53	01:06 6.5%
2b	-1.7 (Downslope)	1122.28		15:49		17:59	
3a	5.1 (slope has no effect)	395.75	41.74	05:46	05:19 92%	06:31	11:29 176%
3b	5.1 (Upslope)	437.49		11:06		18:00	
4a	-5.1 (slope has no effect)	399.42	13.02	05:52	00:49 14%	06:39	01:45 26%
4b	-5.1 (Downslope)	412.44		06:42		08:23	

Similar trends are also found in the Total Evacuation Time (TET) which is the total time it takes to evacuate the entire population in the simulation. In all cases, the increase in TET is significantly larger than the corresponding increase in PET. This is because the TET is driven by the last person to complete the evacuation. This is typically the slowest person and since the travel speeds are age related, this will typically be the oldest individuals. Furthermore, the walking speed reduction factors increase with age. So the older members of the population are more significantly impacted by the slope than the younger members of the population. So we expect to see a greater increase in the average TET compared to the average PET.

It should be noted that these simulations do not take into consideration the impact of fatigue. It may be appropriate that walking speed may gradually reduce when walking over longer distances e.g. approximately 1.1 km in scenarios 1 and 2 and approximately 0.43 km in scenarios 3 and 4. If fatigue is a factor over these type of distances it may be reflected in the real data collected in the trials described in Section 2.2. This analysis will be repeated and reported in a publication (currently in preparation) once the statistical analysis of the walking speed data is completed.

4 CONCLUSIONS

This deliverable has reported on the work completed in Task 2.6 concerned with large-scale evacuation modelling. This has included a brief description of an integrated urban-scale evacuation simulation environment involving, for the first time, a three-way coupling of wildfire-pedestrian-vehicle simulation models. To date, no software tool has successfully integrated these three components into a single unified tool. Furthermore, the integration of terrain slope information in the form of Digital Elevation Model (DEM) data has been demonstrated. For the first time, the adverse effects of terrain slope on large-scale evacuation can be incorporated into urban-scale evacuation models.

The integrated modelling environment was demonstrated using two hypothetical wildfire scenarios, one involving a town in Spain and the other a town in Australia. The demonstrations highlighted how the integrated modelling environment can be used to predict time required to safely evacuate a region, the time available to safely evacuate a region, safety factors associated with evacuation scenarios involving delayed alert times and the number of fatalities that may result given delays in starting the evacuation process. Finally, the importance of incorporating DEM data into urban-scale pedestrian evacuation simulation was demonstrated using a hypothetical evacuation in the Greenwich (UK) area. The test case demonstrated the significant impact that terrain slope can have on both personal and total evacuation times.

While GEO-SAFE has made significant contributions to the advancement of urban-scale evacuation models enhancing their usability in wildfire scenarios, much additional research is still required. In particular, improvements to the applicability and reliability of urban-scale agent based evacuation simulation models requires, improved understanding and quantification of; response phase behaviour, the representation of vehicles, road networks and traffic, evacuation destination decisions, evacuation route choices, the interaction of vehicles with pedestrians, walking behaviour of pedestrians over long distances and different types of terrain, the representation and impact of smoke in wildfire simulations and the speed and performance of large-scale agent based simulation models.

Only with these improvements to our computer simulation tools for wildfire evacuation will they be able to reliably be used by the authorities in training, planning and live incident management and in educating the public to respond appropriately to wildfire emergencies. In this way, we hope that urban-scale evacuation modelling can improve the resilience of WUI communities to wildfire.

References

[Anguelova, et al., 2010] Anguelova, Z., Stow, D. A., Kaiser, J., Dennison, P. E. and Cova, T. (2010). Integrating Fire Behavior and Pedestrian Mobility Models to Assess Potential Risk to Humans from Wildfires Within the U.S.– Mexico Border Zone *, 62(August 2008), 230–247.

[BBC, 2018]https://www.bbc.co.uk/news/world-us-canada-46198286 [last accessed 11 June 2019].

[Blender, 2020] https://www.blender.org/ [Accessed October 28, 2014].

[CBSNews, 2018] https://www.cbsnews.com/news/greece-athens-fires-death-toll-anger-greek-government-response-preparedness/ [last accessed 11 June 2019].

[Chooramun, et al., 2012] Chooramun, N., Lawrence, P.J. & Galea, E.R., 2012. An agent based evacuation model utilising hybrid space discretisation. Safety Science, 50(8), pp.1685–1694. Available at: http://www.sciencedirect.com/science/article/pii/S0925753511003419 [Accessed October 28, 2014].

[CNN, 2020] https://edition.cnn.com/2019/12/30/australia/australia-mallacoota-beach-fire-intl-hnk-scli/index.html [Accessed April 02, 2020].

[Croneborg, et al., 2015] Croneborg, L., Saito, K., Matera, M., McKeown, D. and VanAardt, J. (2015). DIGITAL ELEVATION MODELS. A Guidance Note on how Digital Elevation Models are created and used. Washington, DC.

[Durst,Lämmel and Klüpfel, 2012] Durst D, Lämmel G, Klüpfel H, Large-Scale Multi-modal Evacuation Analysis with an Application to Hamburg. In: Weidmann U., Kirsch U., Schreckenberg M. (eds) Pedestrian and Evacuation Dynamics 2012. Springer, Cham.

[ESRI1, 2020] http://resources.esri.com/help/9.3/arcgisengine/java/GP_ToolRef/spatial_analyst_tools/esri_ascii_raster_format.htm [Accessed April 07, 2020].

[ESRI2, 2020] https://www.esri.com/library/whitepapers/pdfs/shapefile.pdf Accessed April 07, 2020].

[Finney and Andrews, 1999] Finney, M. A. and Andrews, P. L. (1999). FARSITE—a program for fire growth simulation. Fire Management Notes, 59(2), 13–15.

[Galea et al 2003] Galea, E.R., Lawrence, P., Gwynne, S., Filippidis, L., Blackshields, D., Sharp, G., Hurst, N., Wang, Z., and Ewer, J. (2003). Simulating ship evacuation under fire conditions. In: E.R. Galea, Editor, Proc Second Int Pedestrian and Evacuation Dynamics Conference, CMS Press, Greenwich (2003), pp. 159 – 172.

[GEO-SAFE conference, 2019] https://geosafe.lessonsonfire.eu/fireconference/ [Accessed April 07, 2020].

[Guardian, 2020] https://www.theguardian.com/australia-news/2019/dec/31/mallacoota-fire-mayhem-armageddon-bushfires-rage-victoria-east-gippsland [Accessed April 02, 2020].

[Han and Yuan, 2005] Han L D, Yuan F, "Evacuation modeling and operations using dynamic traffic assignment and most desirable destination approaches", in Proceedings of the 84th Annual Meeting Transportation Research Board, Washington, DC, USA, November 2005.

[Hilton, et al., 2016] Hilton, J.E., Swedosh, W., Hetherton, L., Sullivan, A. and Prakash, M. (2016). Spark user guide 0.9.4. CSIRO, Australia.

[Intermap, 2018] Worldwide One Meter DSM and DTM 3D Elevation Data. [online] Retrieved from: https://www.intermap.com/product/nextmap/one [Accessed 29 Aug. 2018].

[Intini, et al., 2019] Intini P, Ronchi E, Gwynne S, Adam P, Traffic Modeling for Wildland-Urban Interface Fire Evacuation. Journal of Transport Engineering, Part A: Systems 145(3) 2019.

[Lämmel, Klüpfel and Nagel, 2009] Lämmel G, Klüpfel H, Nagel K, "The MATSim Network Flow Model for Traffic Simulation Adapted to Large-Scale Emergency Egress and an Application to the Evacuation of the Indonesian City of Padang in Case of a Tsunami Warning", Chapter 11, pages 245-265, Emerald Group Publishing Limited, DOI:10.1108/9781848557512-011, 2009.

[Lawrence, et al., 2020] Lawrence P J, Veeraswamy A, Gallego D M, Blackshields D, Filippidis L, Galea E R, Coupled Pedestrian, Wildfire and Vehicle Modelling for WUI Crisis Management – The urbanEXODUS evacuation simulation environment. Galea, E.R. Editor; Proceedings of workshop, 'Wildfire: Human Behaviour and Evacuation Modelling GEO-SAFE Workshop 2020', Published by, University of Greenwich, London, UK, 20th Feb 2020.

[Lawrence, Pellacini and Galea, 2018] Lawrence P J, Pellacini V, Galea E R, The Modelling of Pedestrian Vehicle Interaction for Post-Exiting Behaviour, to appear in the Proceedings of the 9th International Conference on Pedestrian and Evacuation Dynamics (PED2018), Lund, Sweden – August 21-23, 2018.

[Maritime-Executive, 2020] https://www.maritime-executive.com/article/australian-navy-deploys-two-ships-to-help-wildfire-evacuees [Accessed April 02, 2020].

[Monedero, Ramirez and Cardil, 2019] Monedero, S., Ramirez, J. and Cardil, A., 2019. Predicting fire spread and behaviour on the fireline. Wildfire analyst pocket: a mobile app for wildland fire prediction. Ecological modelling, 392, pp.103-107.

[OGC1, 2020] http://www.ogc.org/standards/gml [Accessed April 07, 2020]

[OGC2, 2020] https://www.geopackage.org/ [Accessed April 07, 2020]

[OrdnanceSurvey1, 2020] https://www.ordnancesurvey.co.uk/business-government/products/terrain-50 [Accessed April 07, 2020]

[OrdnanceSurvey2, 2020] https://www.ordnancesurvey.co.uk/documents/resources/guide-to-nationalgrid.pdf [Accessed April 07, 2020]

[OrdnanceSurvey3, 2020] https://www.ordnancesurvey.co.uk/business-government/products/terrain-50

[PCF, 2018] Pau Costa Foundation, PCF (2018), Forest fire risk analysis in Lagunas de Ruidera Natural Park and proposals to mitigate the impacts on the population. Unpublished manuscript. Taradell (Barcelona), 15th of November 2018.

[Pretorius, Gywnne and Galea, 2013] Pretorius, M., Gwynne, S. & Galea, E.R., 2013. Large crowd modelling: an analysis of the Duisburg Love Parade disaster. Fire and Materials, 39(4), pp.301–322. Available at: http://doi.wiley.com/10.1002/fam.2214 [Accessed November 13, 2014].

[Spatialreference, 2020] spatialreference.org/ref/epsg/osgb-1936-british-national-grid/ [Accessed April 08, 2020].

[SUMO, 2018] SUMO, Simulation of Urban Mobility, http://sumo.dlr.de/userdoc, 4th September 2018, accessed on 24 September 2018.

[Tolhurst et al., 2010] Tolhurst K, Shields B, Chong D, Phoenix: development and application of a bushfire risk management too. The Australian Journal of Emergency Management 23, 47–54, 2008.

[Tolhurst, et al., 2008] Tolhurst, K. G., Shields, B. J. and Chong, D. M. (2008). Phoenix: development and application of a bushfire risk management tool. The Australian Journal of Emergency Management 23(4): 47-54.

[Tymstra, et al., 2010] Tymstra C, Bryce R W, Wotton, B M, Taylor S W, Armitage O B. Armitage, Development and structure of Prometheus, the Canadian wildland fire growth simulation model. Natural Resources Canada Information Rep. NOR-X-417, 102 pp, 2010.

[Tymstra, et al., 2010] Tymstra, C., Bryce, R.W., Wotton, B.M., Taylor, S.W. and Armitage, O.B. (2010). Development and Structure of Prometheus: the

Canadian Wildland Fire Growth Simulation Model. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-417. 88 p.

[Veeraswamy, et al., 2018] Veeraswamy A, Galea E R, Filippidis L, Lawrence P J, Haasanen S, Gazzard R J. The simulation of urban-scale evacuation scenarios with application to the Swinley Forest fire. Safety Science 102:178–193 (2018)

[Wikipedia, 2017] https://en.wikipedia.org/wiki/June_2017_Portugal_wildfires [Accessed April 02, 2020].

[Wikipedia, 2020] https://en.wikipedia.org/wiki/2018_Attica_wildfires [Accessed April 02, 2020].

[Wikipedia, 2019] https://en.wikipedia.org/w/index.php?title=Spline_%28mathematics%29&oldid=288288033#Algorithm_for_computing_natural_cubic_splines [Accessed April 02, 2019].

[Wood and Schmidtlein, 2012]Wood, N. J. and Schmidtlein, M. C. (2012). Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest. Natural Hazards, 62(2), 275–300. http://doi.org/10.1007/s11069-011-9994-2.