

## **RISK ASSESSMENT METHODOLOGY FOR HIGH-PRESSURE CO<sub>2</sub> PIPELINES INCORPORATING TOPOGRAPHY**

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### **SYNOPSIS**

This paper presents a risk assessment methodology for high-pressure CO<sub>2</sub> pipelines developed at the Health and Safety Laboratory as part of the EU FP7 project *CO2Pipehaz*.

Traditionally, consequence modelling of dense gas releases from pipelines at major hazard impact levels is performed using integral models with limited or no consideration being given to the weather bias or topographical features of the surrounding terrain. Whilst dispersion modelling of CO<sub>2</sub> releases from pipelines using three-dimensional CFD models may provide higher levels of confidence in the predicted behaviour of the cloud, the use of such models is resource-intensive. As a consequence, it is usually impracticable to use these 3D CFD models in pipeline risk assessments if the number of potential release points, atmospheric conditions and wind directions are chosen to provide sufficient resolution for quantification of risk, with an acceptable level of accuracy.

An alternative is to use more computationally efficient shallow layer or Lagrangian dispersion models that are able to account for the effects of topography whilst generating results within a reasonably short time frame.

In the present work, the proposed risk assessment methodology for CO<sub>2</sub> pipelines is demonstrated using a shallow-layer dispersion model to generate contours from a sequence of release points along the pipeline. The simulations use realistic terrain taken from UK topographical data. Individual and societal risk levels in the vicinity of the pipeline are calculated using the Health and Safety Laboratory's risk assessment tool QuickRisk.

Currently, the source term for a CO<sub>2</sub> release is not well understood because of its complex thermodynamic properties and its tendency to form solid particles under specific pressure and temperature conditions. This is a key knowledge gap and any subsequent dispersion modelling, particularly when including topography, may be affected by the accuracy of the source term.

**Keywords:** CCS; CO<sub>2</sub>; pipelines; shallow layer; societal risk; QuickRisk

## **1. INTRODUCTION**

The accidental release of CO<sub>2</sub> from high pressure pipelines is an important issue and there are a number of projects currently ongoing to try and resolve knowledge gaps such as the complexity of the source term. One project is CO2Pipehaz, which has been partially funded by the UK's Health and Safety Executive (HSE) and the European Commission (EC). The overall purpose of this project is to address what occurs following the accidental release of CO<sub>2</sub> from high-pressure pipelines, and includes the development of multi-phase heterogeneous discharge and dispersion models that are able to accurately model the formation of solid CO<sub>2</sub>. This paper falls under Work Package 3, where there is an objective to develop a risk assessment methodology that incorporates topography. Currently the effects of topography are a key knowledge gap that applies to all released materials, not just CO<sub>2</sub>.

In the quantitative risk assessment (QRA) exercises carried out as part of onshore major hazards installations' COMAH safety reports, the models used to predict consequences from dispersion of toxic gas releases do not generally take into account the effects of topographical features of the surrounding terrain in a systematic way. This is the case, for example, when integral models are used. Integral models, which have long been the tool of choice in major hazards risk assessment, estimate the bulk properties of the cloud from a relatively small number of variables and physical property data. Some integral models have been extensively validated against experimental studies, although these almost exclusively involve dispersion over flat terrain (Cook & Woodward, 1995; Witlox, 2006, Pandya et al., 2012). These flat-earth models are often used to simulate high-pressure CO<sub>2</sub> releases (Hedlund, 2012) despite the significant influence that topography can have on the dispersion.

When a high-pressure CO<sub>2</sub> pipeline fails, guillotine failure (full-bore rupture) and large and small holes can occur. The full set of scenarios used for this work is defined by McGillivray et al (2013). If, on release, the pressure and the temperature of the CO<sub>2</sub> falls below the triple point (triple point pressure is 4.187 barg and the triple point temperature is 216.6 K), the formation of solid CO<sub>2</sub> occurs. The solid CO<sub>2</sub> can either remain as an evaporating particle within the jet, or it can 'snowout' to form a bank of sublimating CO<sub>2</sub> with low momentum. The dispersion will be affected depending on which scenario occurs, and when topography is also considered, more uncertainties can arise. McGillivray et al (2013) reviewed a number of papers which experimentally explore the possibility of solid CO<sub>2</sub> formation, and found that, typically, unobstructed high momentum jets are unlikely to result in 'snowout', but highly impacted releases, such as those from buried pipelines, are expected to form sublimating solid banks.

## **2. CFD SIMULATIONS**

At the other end of the spectrum of complexity from integral models, for dense gas dispersion, are computational fluid dynamics (CFD) models. The use of CFD models for the modelling of dispersion of dense gases in the presence of obstacles and complex terrain has continued to gather pace in recent years. Chow et al. (2009) modified a mesoscale atmospheric model known as the Advanced Regional Prediction System (ARPS), to model the atmospheric dispersion of low momentum CO<sub>2</sub> that can potentially be released from carbon sequestration sites. The simulations in Chow et

al. (2009) showed that even small topographical features (50 m high hills), significantly affected plume dispersion, leading to accumulations of CO<sub>2</sub> above hazardous levels. This contrasted with the results of dispersion simulations that assumed flat terrain, for which the harm criterion was not exceeded. Although the work did not simulate high-pressure pipeline releases, it does have implications for the EU *CO2Pipehaz project*. For high-pressure pipelines, low momentum releases are possible for obstructed jets from large (unless the release rate approaches that of a full-bore rupture) and small holes, and also from sublimating banks of ‘snowed out’ solid CO<sub>2</sub> (McGillivray et al., 2013). These results indicate that relatively small topographical features may reduce cloud dilution from high-pressure pipeline releases and may cause harm, provided the same hazardous limits as Chow et al (2009) are used. Additionally topographical features may potentially change the direction of the dispersing cloud to that the risk increases for some locations compared with others.

Pontiggia et al. (2010) presented a methodology for modelling dispersion in urban areas considering topographical features and other obstacles such as buildings. The authors modelled the dispersion behaviour of releases of ammonia-water solutions, using both integral and CFD models, under two distinct atmospheric conditions: stable stratification with limited atmospheric turbulence represented by F2 (Pasquill atmospheric stability class ‘F’ and 2 m/s wind speed) and neutral stratification, D5 (Pasquill atmospheric stability class ‘D’, and a 5 m/s wind speed).

Papanikolaou et al. (2011), presented the results of CFD modelling, using ANSYS-CFX, of a short-duration small release of CO<sub>2</sub> (3.7 kg/s) in open terrain, and studied the effect of wind and obstacles. The 1995 Kit Fox set of experiments (WRI, 1998) were used for validation. Comparisons of experimental versus modelled sensor measurements of (CO<sub>2</sub>) concentrations were provided, using the statistical performance indicators proposed by Hanna (1993) and Hanna et al. (2004). Representations of the Geometric Mean Variance (VG) vs Geometric Mean Bias (MG) usually met the threshold of model performance. Predicted values were usually within a factor of 2 of the experimental ones. However, model performance deteriorated rapidly for downwind distances furthest away from the source (225 m). The best results were obtained using a variable wind profile and fully resolved obstacles; however this came at a very high computational effort, of almost 25 days using a 2.93 GHz system with 8 cores. This comparison used a release rate of 3.7 kg/s which was obtained from Mazzoldi et al. (2008), and although small, it was calculated for a 10 mm diameter leak in a 100 bar CO<sub>2</sub> transportation system module. This suggests that the results may be relevant for a similarly sized hole in a high-pressure CO<sub>2</sub> pipeline, such as those in the *CO2Pipehaz project*. The poor model performance in the far-field implies that further investigation into the effects of obstacles is required.

It is the high computational effort required for CFD simulations that make their systematic use almost impractical in the risk assessment of long (e.g.  $\approx 10^2$  km), high-pressure, CO<sub>2</sub> pipelines when sufficient resolution (e.g. <200m distance between potential release points) over complex topography is necessary. This resolution in the risk assessment results is required, for instance, when transport of CO<sub>2</sub> in dense phase is planned to take place in close proximity to densely populated areas. In the case of highly urbanised countries such as the UK, these areas of population can extend over long distances, both along and from the pipeline. BSI (2008) gives guidance on pipeline route selection and also what is considered to be acceptable pipeline proximity to significant inhabited areas. As part of the *CO2PipeHaz* project team, the

Health and Safety Laboratory (HSL) has studied the potential use of “short-cut” risk assessment methodologies to incorporate the effects of topography, in other words, it is aimed at an efficient and not overly conservative model that enables rapid estimations of risk. HSL has also identified two types of dispersion codes that are able to account for the effects of topography whilst having the potential to generate results within a reasonably short time frame: *shallow layer* dispersion codes and *Lagrangian particle-tracking* models.

This paper presents the results of a brief literature review on shallow-layer and Lagrangian models for dense gas dispersion and describes a proposed risk assessment methodology. The methodology has been applied in a test case, using the publicly available shallow-layer dispersion code (TWODEE-2) as an example. From a sequence of release points along the pipeline, contours were generated with TWODEE-2 using realistic terrain taken from UK topographical data and harm criteria based on different probabilities of fatality. The contours were input to HSL’s risk assessment tool QuickRisk (Lisbona et al., 2011a) and the individual and societal risk levels in the vicinity of the pipeline were calculated.

### **3. LAGRANGIAN PARTICLE-TRACKING MODELS**

The literature review of gas dispersion codes identified a number of Lagrangian particle-tracking models (Anfossi et al., 2010 & 2011; Sykes et al., 1997; LANL, 2012) that are able to account for topography and therefore had the potential to be used as an input to the proposed risk assessment methodology. Among them, a model based on the MicroSpray code was developed by Anfossi et al. (2010 & 2011) to account for obstacles or complex terrain such as that of urban or industrial developments. The validation exercise used in the aforementioned publications, however, used a Thorney Island experiment over flat terrain.

Another model within this category is QUIC (Williams et al., 2005; LANL, 2012), a Lagrangian atmospheric dispersion model that can be used to model releases in complex terrain (including buildings and slopes). Typical run times of minutes and inputs for weather data to allow multiple runs for risk analysis suggest that it offers promise for CO<sub>2</sub> dispersion modelling. More generically, it can handle releases of material that are dense, buoyant and particulate (with multiple size spectrums) and also infiltration into buildings. However, it cannot model the detail of the initial high momentum jet

### **4. SHALLOW-LAYER MODELS**

A number of shallow layer models for dense gas dispersion, which use depth-averaged variables to describe the behaviour (Hankin, 2003c), have been developed in recent years. These have been generally described as *computationally cheap* and more *physically realistic* than integral models (Hankin, 2003c). Despite these advantages, they do not appear to be widely used in major hazard consequence assessments, whereas integral models and, to a lesser extent, CFD models are.

Due to the inherent assumptions made in the development of a shallow layer model, they will never be able to model the near field behaviour of a high momentum jet. Therefore their use will be dependent on some sub-model to account for the jet

behaviour or assumptions will need to be made about how the source term is represented within the shallow layer model.

A comparison of shallow layer models was reported by Ross et al. (2002), who, as part of an experimental study into gravity currents, used a dense gas release on a slope as their base case. The experimental results thus obtained were compared against an integral model developed by the authors, as well as shallow-water models available at the time (Webber et al., 1993; Tickle, 1996). According to Ross et al. (2002), Webber et al.'s model did not take into account air entrainment and, as a result, could not accurately model the reducing velocity of the gravity current as it flowed down the slope. The authors noted that Tickle's model, although it over-predicted the width of the plume and could not replicate the shape of the gravity current, performed better in comparison.

Another shallow layer code, known as DISPLAY-2, was proposed by Venetsanos et al. (2003) to take into account obstacles and inclined ground in the dispersion of two-phase pollutants. Venetsanos et al. (2003) presented the results of a comparison of DISPLAY-2 against experimental data that included obstacles and/ or terrain: Thorney Island trial 21, Desert Tortoise (two-phase ammonia releases) and a Hamburg instantaneous inclined plate experiment (DAT-638). Table 1 is a summary of the results presented by Venetsanos et al. (2003), and in general the authors state that DISPLAY-2 shows fairly good agreement when compared to the experimental data, despite the variations in experimental results due to processes such as atmospheric dispersion. The model underestimates the dose for Thorney Island trial 21 and the Hamburg (DAT-638) trial. The Thorney Island trial presented in Table 1 shows the best comparison because 78.6% of the points predicted by DISPLAY-2 are within a factor of 2 of the experimental results, whereas for Desert Tortoise, only 40% of points are within a factor of 2. For the Hamburg (DAT-638) trial, all the DISPLAY-2 points are within a factor of 5 of the experimental data.

**Table 1 Comparison of DISPLAY-2 predictions against experimental data**

Experimental trial	Percentage (%) of points calculated by DISPLAY-2 within a factor of <i>FAC</i> of the experimental data:		
	<i>FAC</i> =2	<i>FAC</i> =5	<i>FAC</i> =10
Thorney Island trial 21 <sup>a</sup>	78.6	78.6	85.7
Desert Tortoise <sup>b</sup>	40	60	70
Hamburg (DAT-638) <sup>a</sup>	62.5	100	100

<sup>a</sup>These are instantaneous trials and the statistical measure variable is the dose

<sup>b</sup>This is a continuous release and the statistical measure variable is the average concentration

More recently, Brambilla et al. (2009) published a shallow layer gas dispersion model developed to simulate dense gas dispersion in urban areas. The authors reported that the solution to the shallow water equations was verified against the box model of Hanna and Drivas (1987) for instantaneous releases, and announced their intention to

integrate the shallow layer model with QUIC's wind solver to model air entrainment around buildings.

A shallow layer model that has frequently appeared in the open literature is TWODEE. TWODEE was presented by Hankin and Britter (1999a, 1999b, 1999c), who also published comparisons of the model results with experimental wind tunnel data from Schatzmann et al. (1991) (available from REDIPHEM (RISO, 2009)) for both instantaneous and continuous releases (Hankin 2003a, 2003b, 2003c; Hankin 2004a, 2004b).

A more recent implementation of the code in FORTRAN 90 programming language, known as TWODEE-2, has been released into the public domain. TWODEE-2 has been used to model dispersion of naturally occurring CO<sub>2</sub> from volcanic (Folch et al., 2009) and non-volcanic (Chiodini et al., 2010) sources. In the work of Chiodini et al. (2010), TWODEE-2 was used to predict the 50,000 ppm concentration contour, which largely followed the outline of the valley down from the source and the vegetation damage showed in satellite images. Comparison between measured concentrations and those predicted by TWODEE-2 were provided for a cross-section of the valley close to the CO<sub>2</sub> source. Integrating the measured fluxes over the area of interest resulted in a 928 tonne/day release rate (equivalent to 11 kg/s), which was considered to be a minimum estimated release rate due to a significant part of the released CO<sub>2</sub> not being accounted for in the measurements. A new value for the source strength, 2,000 tonne/day (equivalent to 23 kg/s), was calculated to match the dispersion results. Although the results of this work are not relevant for high momentum jets and ruptures from CO<sub>2</sub> pipeline releases, such as those in *CO2Pipehaz*, it may be useful for comparison against the low momentum releases that are possible from banks of sublimating CO<sub>2</sub>.

A more systematic comparison between experimental and predicted dispersion results was published by Hankin (2003c). TWODEE outputs were produced for a set of four release scenarios and compared against the results from integral models reported by Mercer (1991). The comparison was presented in terms of 'cloud averaged concentration' and 'downwind distance'. As a general rule, TWODEE performed within the window defined by the results from integral models, with the exception of two cases: an instantaneous release of  $2 \times 10^3 \text{ m}^3$  of gas from a 7 m source radius at a wind speed of 1 m/s (TWODEE predicted the highest value of cloud average concentration at distances over 3,000 m away from the release point); and a release of  $2 \times 10^3 \text{ m}^3$  of gas under high wind speeds (8 m/s). In the latter case, the cloud averaged concentration from TWODEE was generally below the lower range of the values predicted by the integral models.

While TWODEE-2 looks generally suitable for the application required of it here (accepting the assumptions that need to be made regarding representation of the high momentum source), an internal, unpublished review of TWODEE carried out at HSL about 12 years ago highlighted a number of deficiencies in the physical and numerical model. It is unclear whether these problems have been addressed in the new version of the model, TWODEE-2. Therefore, while the model has been used here to demonstrate the principle of embedding dense gas dispersion models into a QRA, we would not use it, nor recommend its use, in practice.

## **5. CASE STUDY**

Through the literature review of shallow-layer and Lagrangian models, the authors identified two publicly available codes that may be suitable for use in a QRA: the QUIC modelling tool (version 5.81) kindly provided under licence agreement for research and non-commercial purposes, and TWODEE-2, which is in the public domain (Folch et al., 2009).

In the second stage of the work, wind tunnel data for a continuous release of SF<sub>6</sub> (density 6.27 kg/m<sup>3</sup>) on a slope (4.8°) from REDIPHEM (RISO, 2009) was used by the authors to gain familiarity with the models' performance and compare results with the 3D CFD code Star-CCM+<sup>1</sup>.

Following the initial stage of checks and familiarisation with the models, TWODEE-2 was used to demonstrate the principle of embedding a shallow layer model, that can take into account the effects of topography, into a QRA for a set of representative releases of CO<sub>2</sub> from a hypothetical high-pressure pipeline.

## 5.1 Source term

There is considerable uncertainty surrounding the source terms from a high-pressure pipeline, such as the thermodynamic complexities of the CO<sub>2</sub> itself and the calculation of the subsequent vaporisation rate from any 'snowed out' CO<sub>2</sub>. In addition to this, currently there is a lack of understanding regarding how craters formed by the initial blast will influence the release, although this is only likely to occur for full-bore rupture and large holes with correspondingly large release rates. The event trees derived by McGillivray et al. (2013), and used in this case study, show that a high momentum jet is likely to occur for full-bore rupture of the pipeline, regardless of whether the release is obstructed or not. Any bank of sublimating CO<sub>2</sub> that is formed will be low momentum in nature. For leaks from large and small holes, an unobstructed jet will result in a high momentum release, but if the jet is obstructed in any way (e.g. due to the crater), a low momentum release is possible (however, if the release rate of the large hole approaches that of the full-bore rupture, then the release will have high momentum). This case study uses these described scenarios, but because a high momentum jet model was not available in the shallow water model and the fact that low momentum scenarios dominated the risk in McGillivray et al. (2013), only the low momentum releases have been considered in the calculations. The effects of topography are likely to be greatest for low momentum releases, and therefore, the exclusion of high momentum releases is not expected to greatly impact the results. The risk assessment described here is for the purposes of demonstrating the feasibility of embedding dispersion models that take some account of topography into QRA results, and should be reviewed once more accurate source terms for high-pressure pipelines are made available.

## 5.2 Input data formats

A series of VBA codes coupled with an Excel interface were developed to automatically perform the consequence assessment at a number of points along the pipeline for each scenario and weather condition in turn. From the pipeline trajectory, defined in a GIS format (e.g. Surfer BLN, ESRI SHP), the location of each potential release point on the pipe is determined by the VBA code according to the selected spacing/segmentation distance chosen. TWODEE-2 input files, including topography data from OS LandForm Profile Panorama tiles, are automatically created

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<sup>1</sup> [www.cd-adapco.com/products/star\\_ccm\\_plus](http://www.cd-adapco.com/products/star_ccm_plus) (accessed 15 April 2013)

for each scenario, weather combination and wind direction, and TWODEE-2 is run to generate indoor and outdoor dose contours.

In addition to the topography inputs, TWODEE-2 can also take into account the nature or features of the terrain by assigning an equivalent surface roughness value to areas of land. The surface roughness input can be specified at the same level of resolution as the topography input file, or lower. For example, using the Surfer (ASCII text) GRD file format, a constant surface roughness value for the entire domain can be defined (using a  $2 \times 2$  grid). Alternatively, finer resolutions can be specified as Surfer grid files with the z parameter being the equivalent surface roughness at that cell location. A surface roughness of 0.05 m was used for the case study presented here.

The dense gas source is described in TWODEE-2 in an ASCII text file that requires the following information:

- The x and y coordinates of the source.
- The flux (according to the selected units) and source size (in x and y dimensions).

The source can be defined as an area source where the flux is assumed uniform (dimensions of mass per area per time) or a point source (dimensions of mass per time). TWODEE-2 can also handle sources specified as upward gas velocities but, like all shallow layer models, it will not be able to directly model the effects of the initial high momentum.

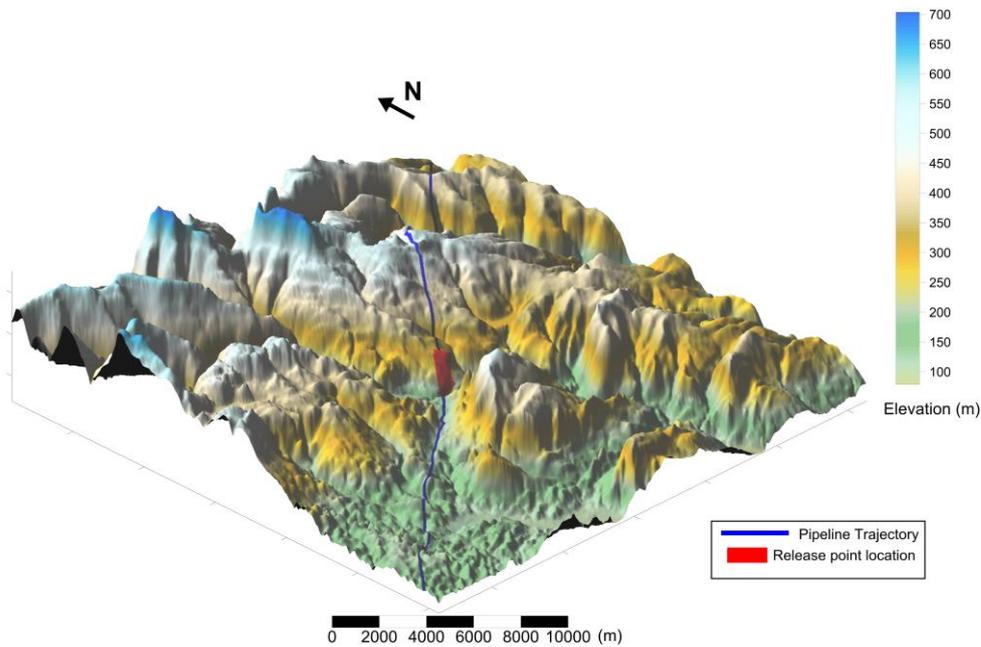
Using the custom VBA codes, toxic dose contours (generated by TWODEE-2 in Surfer's ASCII.GRD file formats) are extracted at 1%, 10% and 50% fatality risk levels according to published CO<sub>2</sub> toxicity data (HSE, 2012). HSE represent 1% fatalities using the Specified Level of Toxicity (SLOT), which is normally used for Land Use Planning purposes (Franks et al, 1996). Another measure used by HSE is the Significant Likelihood of Death (SLOD) which is equivalent to 50% fatalities. For risk assessment purposes, a 10% fatality level is sometimes included, and taken with the other two levels, forms the basis of the Total Risk of Death (TROD) approach (Rushton and Carter, 2009) for estimating the total number of fatalities.

Individual risk levels and computation of the number of potential fatalities was done using the major hazards quantitative risk assessment tool QuickRisk (Wardman et al, 2007; Lisbona et al. 2011a). Population data representative of a UK location was extracted from the National Population Database (NPD) (Smith et al, 2005, 2008), hosted by HSL, and used to generate the societal risk results. The following population categories/ layers were taken into consideration in the societal risk calculation, typically using a grid-based format (100 m  $\times$  100 m resolution):

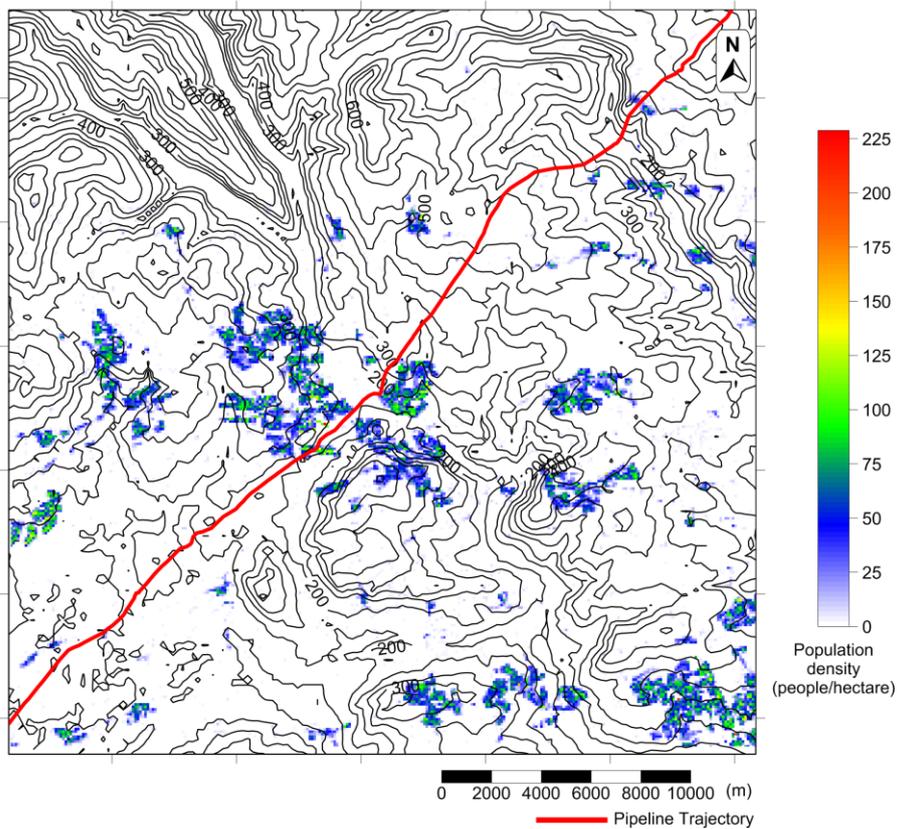
- Residential
- Workplace
- Schools
- Hospitals
- Roads

Figure 1 shows a three-dimensional view of the section of pipeline chosen for the case study. Releases at 100 m intervals along this section (each individual point is not

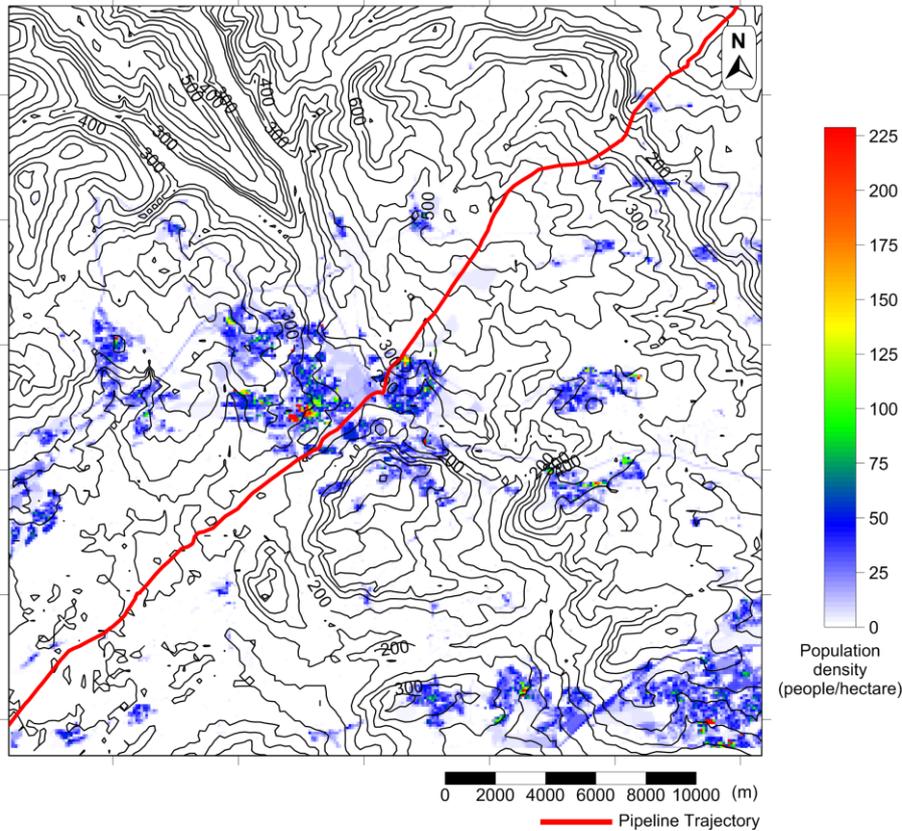
shown here) and the topography of the surrounding terrain are entered into TWODEE-2 (using  $200\text{ m} \times 200\text{ m}$  computational cells). Figures 2 and 3 represent the night time and daytime population densities in persons per hectare, respectively, as extracted from the NPD.



**Figure 1** Section of pipeline chosen for the case study, showing the location of the release points (100 m intervals) and topography of the surrounding terrain.



**Figure 2** Night time population density (in persons per ha), from the NPD.



**Figure 3 Daytime population densities (in persons per hectare), from the NPD.**

### 5.3 Individual and Societal Risk results

The low momentum release scenarios described by McGillivray et al. (2013) were modelled with TWODEE-2 for two weather conditions (D5 and F2). Indoor and outdoor contours for 1%, 10% and 50% fatalities were obtained for each potential wind direction ( $5^\circ$  precision) around each release point (100 m spacing, 1 km section of pipeline) and were extracted from TWODEE-2's dose GRD outputs and expressed as ESRI SHP vector files using custom VBA codes. The set of 1%, 10% and 50% fatality risk contours (per weather condition and release point) were used by QuickRisk to generate individual and societal risk results for the 1 km section of the hypothetical high-pressure CO<sub>2</sub> pipeline.

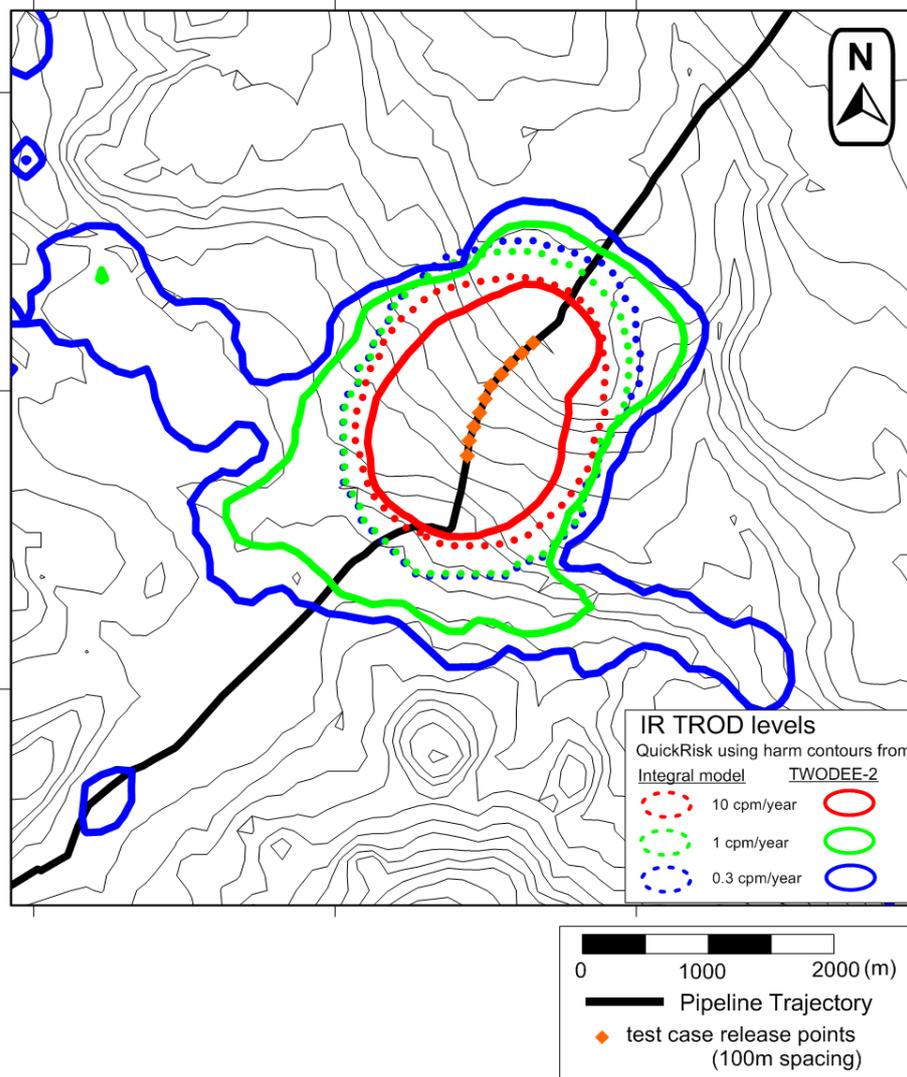
Computation of the individual risk levels at each cell location was performed using the geographical extent of the 6 contours (1%, 10% and 50% fatality for indoor and outdoor recipients) for TROD-based individual risk. The individual risk calculation is performed with Eq. (1), which uses the likelihood of a unidirectional event ( $f(\text{event})$ ), such as is the case for the CO<sub>2</sub> releases modelled in this paper, materialising in each direction around the release point. The summation of these will equal the total/overall frequency of the event (individual risk).

$$f = f(\text{event}) \times P_{\text{weather}} \times P_{\text{wind direction}} / (P \times n_{\text{sectors}}) \quad (1)$$

where  $f$  is the modified (non-cumulative) frequency,  $P_{\text{weather}}$  is the probability of the atmospheric stability class and wind speed combination that is being considered,  $P_{\text{wind direction}}$  is the probability of the wind direction according to the sector being considered and  $n_{\text{sectors}}$  is the number of sectors.  $P$  is the precision value chosen. Precision is the number of subdivisions per wind rose sector that are considered in the calculation

of the frequency (Precision=6, with 12 sectors, means calculations would be performed at five degree intervals around the release point). The higher the precision value, the larger the number of f,n pairs.

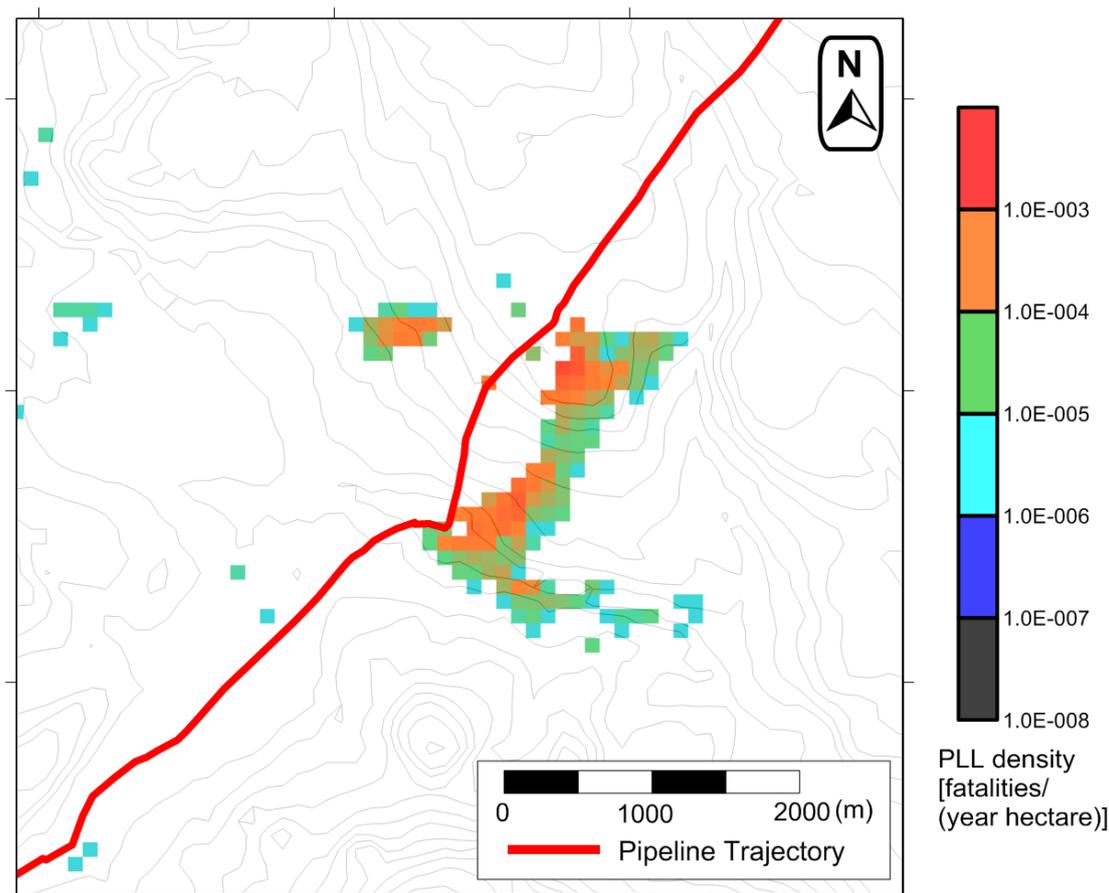
Figure 4 shows the individual risk contours obtained, using QuickRisk and TWODEE-2 harm contours, in the form of 10 cpm/year, 1 cpm/year and 0.3 cpm/year. These values are measured in chances per million per year, and are standard HSE risk levels normally used for Land Use Planning purposes. These individual risk contours are compared against those obtained using an integral model and the differences can be seen.



**Figure 4 Individual risk contours (10 cpm/year, 1 cpm/year and 0.3 cpm/year) using TWODEE-2 dose results.**

The potential number of fatalities per year that are expected from the realisation of the scenarios modelled, also known as *expectation value* (EV) or *potential loss-of-life* (PLL) can be calculated for each geographical location defined by the resolution of the computational domain and output geographically (Lisbona et al, 2011b), and is shown in Figure 5. Due to the relatively low population densities in the vicinity of the pipeline, the PLL values are relatively low in comparison with potential societal risk

criteria, such as the value of  $10^{-5}$  fatalities per year per hectare proposed by Atkins (2009) or  $10^{-6}$  fatalities per year per hectare proposed by Wiersma et al. (2007), although there are areas where the criterion is clearly exceeded (as shown by locations shaded orange-red in Figure 5).



**Figure 5 Geographical distribution of the *Potential loss-of-life* (PLL) or EV density map.**

## 6. CONCLUSIONS

HSL, as part of the EU's *CO2Pipehaz* project, has studied the use of dispersion tools that are able to account for the effect of topography in risk assessment methodologies applicable to high-pressure CO<sub>2</sub> pipelines. HSL has identified two-types of dispersion code that have the potential to generate results within a reasonably short time frame: *shallow layer* dispersion codes and *Lagrangian particle-tracking* models.

A number of models have been briefly reviewed including QUIC and TWODEE-2. While TWODEE-2 appears to be well-suited for this particular application, issues with the model have been previously identified that mean that the model could not be recommended for use in practice. On-going work at HSL is seeking to develop an alternative. In the meantime TWODEE-2 has been used here to demonstrate the principle of embedding an integral model into a QRA.

TWODEE-2 has been used to generate 1%, 10% and 50% fatality risk contours for a series of release points along a hypothetical but representative, 1 km-long section of a CO<sub>2</sub> pipeline. Individual and societal risk values were calculated and represented geographically using HSL's quantitative risk assessment tool QuickRisk and dose

contours extracted from TWODEE-2 outputs. The risk values obtained have been compared with those generated when dose contours from integral models were used. This comparison study has highlighted the effects that topography can have on dispersion results and on the calculated individual and societal risk levels in the vicinity of CO<sub>2</sub> pipelines.

It is recommended that, ideally, risk assessment of high-pressure CO<sub>2</sub> pipelines uses consequence assessment tools that are able to account for the effect of topography in an appropriate manner, since the use of integral models may not ensure that adequately realistic/ conservative harm contours are used to calculate risk in areas of unfavourable topography. However, until suitable models become available that can take into account the effects of topography 'flat-earth', integral models should continue to be used.

Shallow layer codes can provide dispersion results within the timeframes required for QRA. However, CFD models are generally too slow to run to be used for QRA purposes but with little practical alternative currently available, CFD may be necessary where the topography is likely to have a significant effect on the risk assessment. Further work is needed to develop more sophisticated dense gas dispersion shallow layer codes that incorporate source terms relevant to high-pressure CO<sub>2</sub> pipelines.

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