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A Case Study Based Assessment of Potential Cumulative Impacts on Groundwater from Shale Gas Production in Northern England

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Foreword

This report presents a case study-based assessment of the potential cumulative impacts on groundwater from shale gas production in England. It considers a range of potential industry development scenarios and a range of potential contaminants. Specifically, it considers how the cumulative risks to groundwater might evolve over a geographical area targeted for shale gas development. It is not designed to recommend a regulatory position or establish formal guidance, but aims to provide evidence and information to inform future decision making by regulators, operators and government.

The shale gas sector is an emerging extractive industry in the UK. Over the past 20 years the shale gas sector has developed hugely in the United States of America (USA), but the issue of regional groundwater quality impacts has received relatively limited attention. The present work is am initial study that starts to address the potential impacts of the development of the industry in the UK (England, specifically) and the need for UK-specific information.

Our approach included a review and evaluation of relevant published reports covering development scenarios, impacts, risk mitigation measures and best available techniques. Potential regional groundwater quality impacts have been evaluated using readily available, and widely used, risk assessment tools.

In the case of shale gas development in England, there are major uncertainties about if or how the sector will develop over time and geographically. These complexities and uncertainties mean that it is not possible to make a definitive assessment of impacts due to shale gas. However, a preliminary and indicative assessment is possible to show how the issue can be explored and highlight where concerns might be significant and further information required.

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1 Introduction

1.1 CONTEXT

The UK shale gas industry might see significant growth in the near future, with many energy companies already having gained approval and others in the stages of seeking approval for exploration. Exploratory boreholes have been in place in the Vale of Pickering, North Yorkshire, and the Fylde Basin, Lancashire, since 2013 and 2010 respectively. Since then, several other sites around the UK have been earmarked for future exploration.

The current absence of producing shale gas wells within the UK means it is too early to assess any actual impact of these operations at the local, regional and national scale. However, international analogues may provide some indications based on areas elsewhere in the world where a shale gas industry is more developed (e.g. the Marcellus Shale, USA) albeit with obvious limitations due to differences in geology and setting. While regulation and compliance of shale gas operations varies between countries, the process and method of extraction and the environmental risks are comparable. The general requirements for water, drilling mud/fluids, hydraulic fracturing fluids ("frac fluids") and the design of wells and well pads can all be extracted from an already mature international experience. However, the requirements in the UK will be modified by the regulatory requirements and restrictions that exist.

There are ongoing discussions within the UK to determine whether shale gas is beneficial, economically viable and environmentally safe. In this report, the impact on land use, groundwater quality and water resources of one well in a selection of approved Petroleum Exploration and Development Licence (PEDL) areas will be considered, followed by an estimation of the cumulative impacts that may result from multiple extraction sites within these areas. The exercise will depend on ranges of input parameters informed by international analogues applied in a UK geo-environmental setting. To recognise the variability in parameters and uncertainty in UK industry development, a range of impact scenarios - low, moderate and high – have been considered.

1.2 OBJECTIVES

The overall objective of this study is to evaluate how any cumulative risks to groundwater may evolve in an area that is being developed for shale gas production. This has been achieved by a two-fold approach: an initial literature study into the impacts of shale gas extraction on groundwater, followed by a case study to determine the effects of expansion and growth of shale gas extraction within three defined PEDL areas. Examples from three onshore licence blocks where unconventional shale gas development has been initiated have been used (located in the Fylde Basin, and the Vale of Pickering). A geospatial analysis of potential scope for developments provides the foundation for further conclusions of possible low, moderate and high impact scenarios, developed from the literature review.

The potential cumulative impacts on groundwater resources and groundwater quality in the Vale of Pickering and Fylde Basin have focused on the following list of possible issues, informed by the literature review:

- The volumes of drilling mud and cuttings generated for disposal,
- Water requirements for hydraulic fracturing programmes, and the volumes of waste water generated,
- Well failure scenarios, including blowouts and leakage of contaminants,

- On-site and off-site spill events and possible volumes of material released to the environment.

1.3 METHOD

The terms used throughout the assessment are defined as follows:

- Low impact/pressure scenario: The scenario generated by the lowest calculated number of well pads multiplied by the lowest value for a variable obtained from literature. E.g Lowest number of well pads (2) x lowest required volume of fracture fluid (5,000 m^3)
- Moderate impact/pressure scenario: The scenario generated by the median of the calculated number of well pads multiplied by the median value for a variable obtained from literature. E.g Median of number of well pads (4) x median of required volume of fracture fluid (41,000 m^3)
- High impact/pressure scenario: The scenario generated by the highest calculated number of well pads multiplied by the highest value for a variable obtained from literature. E.g Highest number of well pads (11) x highest required volume of fracture fluid (77,000 m^3)
- Local Scale: The circular area around a shale gas well pad which covers the extent of a lateral well. E.g. For a well that has a 3000 m lateral, the area has a radius of 3000 m with the well/well pad at its centre.
- District Scale: The area encompassed by local authority districts E.g. Ryedale, North Yorkshire or Fylde, Lancashire.
- Regional Scale: The area encompassed by counties in England. E.g. North Yorkshire or Lancashire.

1.3.1 Overall Approach

The approach taken to achieve the project's objective included a systematic review and evaluation of relevant published reports covering impacts, risk mitigation measures and best available techniques (BAT) following the work undertaken by Olsen et al. (2016). The methodology of this project is divided into two distinct sections: a geospatial assessment to determine possible development scenarios; and a cumulative impact assessment to quantify the potential risks and impacts to groundwater. This method has been directed towards the following three case study areas:

- (SD33a, SD34a, SD43b) – PEDL licence area, Lancashire
- (SE77c, SE77d, SE87a) – PEDL licence area, Yorkshire
- (SE78b, SE88e) – PEDL licence area, Yorkshire

The geospatial assessment has been adapted from the approach used in Clancy et al. (2017). Features of interest (including roads, rivers, English Natural Heritage designated sites, and Source Protection Zones) provide the basis for restrictions on the surface development of shale gas extraction sites. In conjunction, the limitations of lateral drilling techniques also provides a subsurface constraint on the extent of these extraction sites. Together, these two sets of restrictions have allowed the determination of a range of possible development scenarios across each study area.

The geospatial assessment provides the basis for the cumulative impact assessment that constitutes the main part of this report. For a range of possible impacts, three different scenarios have been considered; low, moderate, and high potential impact as defined in section 1.3. These have been developed from consideration of the data in Table 1-1 which has been adapted from Olsen et al. (2016). The parameters listed show typical ranges presented in literature from previous shale gas operations from which low, moderate and high potential impact scenarios were developed. As far as possible, they do not include extreme values associated with some site-specific scenarios identified in other countries.

Table 1-1 Potential Commercial Scenarios and development parameters for shale gas development in the England (adapted from Olsen et al., 2016)

	Parameter	Number	Unit	Source of data or assumptions	References
1	Total length of lateral well	1,200–3,000	m	Typical range	AEA (2012a) and AMEC (2014) in Olsen et al., (2016); Kondash et al., (2018); Zou et al (2018); Nicot et al., (2014) in Butkovskyi et al., (2019)
2	Number of wellheads per well pad	2–16	Units/well pad	High range based on industry average and US analogues	NYSDEC (2011), JRC (2013b), AMEC (2014) and Council of Canadian Academies (2014) in Olsen et al., 2016. Clancy et al (2017).
3	Mud and drill cuttings generated	1500–2500	m^3 /well	Typical range	AMEC (2014) and Cuadrilla (2014a) in Olsen et al., (2016).
4	Number of fracturing phases per well during lifetime	1	Times	Typical commercial scenario	NYSDEC (2011) in Olsen et al., (2016).
5	Required volume of fracture fluid per fracture programme	5,000–77,000	m^3 / well	Previous international shale gas operations	Wood et al., (2011); Johnson and Johnson (2012);; Jiang et al., (2013); JRC (2013b); Vengosh et al., (2014); Ziemkiewicz et al., (2014); Gallegos et al.,(2015); AMEC (2014) in Olsen et al., (2016); BCOGC (2016) in Edwards and Celia (2018); Cuadrilla (2018); Kondash et al., (2018).
6	Percentage flowback of fracture fluid per fracture programme	10–40	Percentage	Typical range	JRC (2013b), AMEC (2014) and Cuadrilla (2014a) in Olsen et al., (2016); Mohammad-Pajooh et al., (2018).
7	Estimated flowback and produced water volume	1,300 – 74,500	m^3 / well	Ranges recorded or estimated for international shale gas operations (USA and China)	Kondash et al., (2017), Kondash et al., (2018); Zou et al., (2018)
8	Percentage flowback recycle rate	40–80	Percentage	Reasonable range based on experience in the EU	JRC (2013b), AMEC (2014) and Cuadrilla (2014a) in Olsen et al., (2016).
9	Required volume of water per fracture programme	1,000 – 42,500	m^3	Literature values from previous shale gas operations	Clark et al., (2013); DECC (2014); Yang et al., (2015); Kondash and Vengosh (2015); Olsen et al., (2016); Nicot and Scanlon (2012); Kondash et al., (2018); Zou et al., (2018)
10	Storage capacity per truck	25	m^3	Typical truck capacity	AEA (2012a) and AMEC (2014) in Olsen et al., (2016).
11	No. of truck movements to manage fresh water per fracture programme	180–580	Trucks	Reasonable range based on capacity of truck and some water source availability on site	Olsen et al., (2016). Discussed further in Section 4.3.3.

Parameter		Number	Unit	Source of data or assumptions	References
12	Salinity of produced water	> 8000 to > 400,000	mg/L	Literature values from the Marcellus Shale	Ziemkiewicz and Thomas (2015), Stuart (2011), Haluszcack (2012), Benko and Drewes (2008)
13	Well Failure Rate	1.88 – 9.14	%	Failure rates recorded from Marcellus Shale	Vidic et al., (2013); Ingraffea, (2012) and Considine et al., (2013) in Davies et al., (2014); Davies et al., (2014); Ingraffea et al., (2014).

2 Shale Gas Exploration and Extraction

2.1 BACKGROUND

Shale gas is termed an unconventional gas resource because of its "relative difficulty of extraction" (Grant & Chrisholm, 2014). However, these resources are now being exploited as technological breakthroughs have allowed them to be more readily accessed and more commercially viable. Figure 2.1 shows the onshore PEDL licences for part of the UK in 2018, alongside the prospective regions for shale gas exploration in England.

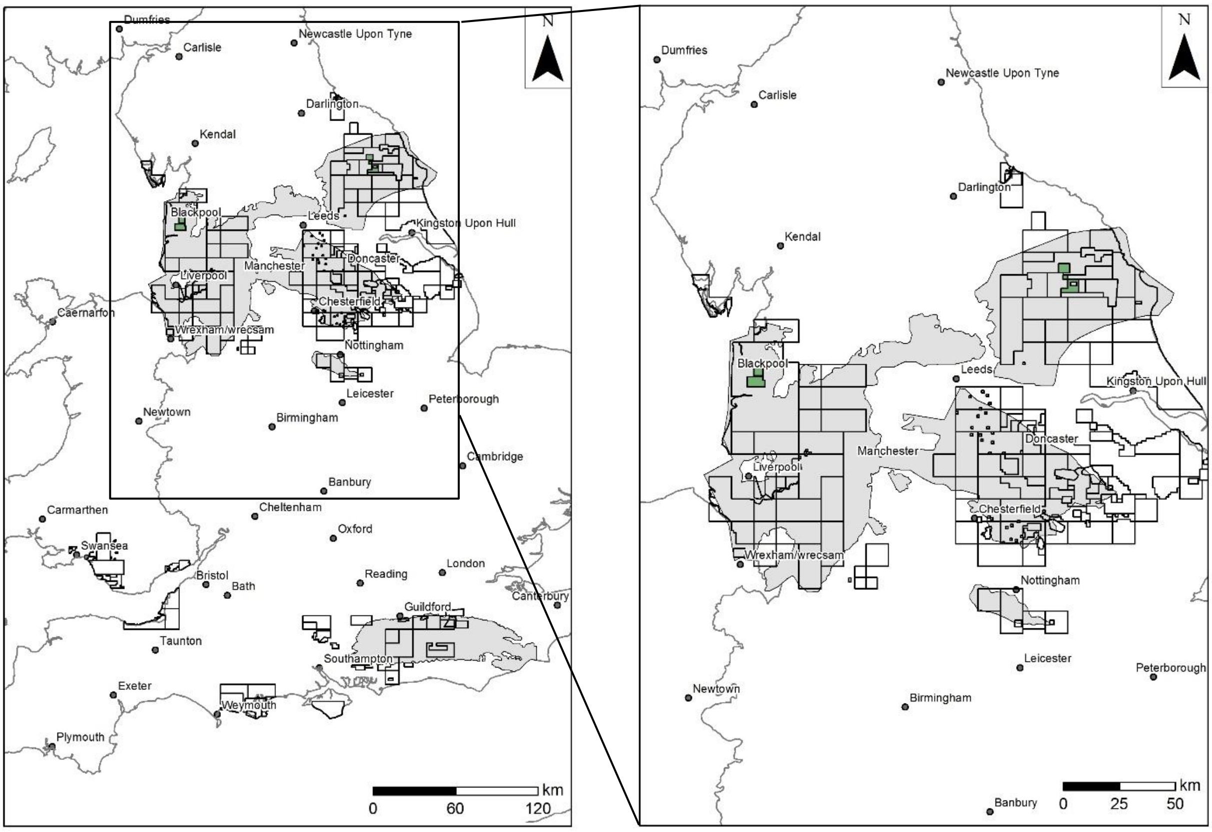


Figure 2.1 Map of UK showing onshore OGA PEDL blocks (black outlines), and BGS prospective shale gas regions (grey). Green highlighted areas on both maps are the locations of the study areas used in this assessment (Section 3). (BGS & OGA, 2018; OGA 2018).

2.1.1 Hydraulic fracturing and shale gas project phases

Hydraulic fracturing is used to create new fractures and open any existing natural fractures within a rock formation. It is typically undertaken by pumping quantities of fluids (water containing a proppant, to hold the fractures open, and other components) down a well at high pressure. The intention of the fracturing is to generate an interconnected, open network of fractures within the rock formation that stimulates the flow of gas and/or fluid to the drilled well(s) or "wellbore(s)", thereby increasing the volumes of oil or gas that can be recovered.

In overall terms, shale gas projects follow the phases described below:

- *Exploratory phase***.** This phase includes (not in sequential order): preliminary site identification and selection; site characterisation of the proposed site; and establishment of baseline conditions for air, water, land, geology and deep-ground conditions. This will be followed by an initial development of a geological conceptual model; geological risk assessment; exploratory boreholes for evaluation of geology and the resource; seismic surveys; initial evaluation of potential environmental impacts; and securing necessary development and operation permits. This phase also includes pad construction and site preparation including construction of roads and any water containment structures.

- *Appraisal Phase*. This stage includes pilot well drilling; drilling initial horizontal wells to determine reservoir properties and required well completion techniques; further development of the geological conceptual model following test fractures; wellhead and well design construction (drilling, casing, cementing, integrity testing); multi-stage hydraulic fracturing (injection of fracture fluid and management of flowback and produced water and emissions); and well completion.
- *Production.* The well pad is expanded and the necessary facilities constructed, including storage tanks, impoundments and secondary containment structures and the commercial production of shale gas takes place.
- *Project cessation (decommissioning/abandonment).* Once economic extraction of gas from the well is no longer viable then the well is decommissioned. The following regulations and guidelines must be followed when decommissioning a well (UKOOG, 2016);
    - "Oil and Gas UK Guidelines on Qualification of Materials for the Suspension and Abandonment of Wells",
    - "Oil and Gas UK Well Suspension and Abandonment Guidelines", and
    - "The Offshore Installations and Wells (Design and Construction, etc.) Regulations 1996".

  Cement is poured into sections of the well to prevent gas flowing into water-bearing zones or up to the surface. A cap is welded into place and then buried, and work is carried out on site to return it to a satisfactory state and to obtain approval for environmental permit surrender.

2.2 WELL CONSTRUCTION, COMPLETION AND OPERATION

Well construction for shale gas exploration and extraction wells must follow current industry and Health and Safety Executive (HSE) standards including the Offshore Installations and Well (Design and Construction) Regulations (1996). The fundamental principle of well design is to "ensure there is no unplanned release of fluids, so far as is reasonably practicable" (HSE, 2015). This is achieved through maximising the efficiency of mud removal, casing installation and cementation all of which are designed to inhibit fluid leakage from the well and into the surrounding formation.

The drilling for a shale gas extraction well comprises successive drilling stages, each reducing the diameter of the well in steps. Within each step, permanent casing is emplaced and cemented, to ensure isolation from groundwater resources, aid well bore stability during drilling, and to provide well integrity during fracturing operations. An initial "conductor" casing is installed first at a large diameter, which forms the foundation of the well. Decreasing casing sizes are used to the required depths, depending on zones of groundwater and structural integrity of the rock mass. This cycle continues until the required number of casing installations are in place to ensure well integrity and formation isolation. The inner-most casing which extends form the surface to the oil/gas source rock is the production casing. The casing must be designed to withstand tensional, compressive and bending forces during well construction and well lifetime and lengths of casing must be screwed tightly together. Acoustic, temperature and pressure testing can be used to check the integrity and presence of the cement, and are an important part of any permit requirements (Environment Agency, 2015; Environment Agency, 2016a; UKOOG 2016).

Initial vertical wells are drilled across an area for exploration, to determine geology, drilling conditions and quality of the shale gas resource at depth. For a production well, following completion of the vertical drilling phase, the drill bit is gradually rotated from a "kick-off point" at a specified depth producing a curved section which eventually becomes horizontal. Once a sufficient length of horizontal drilling has occurred the operation/production phase of shale gas extraction can begin. This will include initial flow testing to determine the quality and ease of extraction of the shale gas.

During the installation and operation of a shale gas well, mitigation strategies are implemented to minimise risk. Within the UK, any mitigation strategies must follow the UK Onshore Shale Gas Well Guidelines (UKOOG, 2016) to ensure the following risks are addressed:

- *Groundwater isolation.* Groundwater and any permeable zones are isolated from the shale gas extraction well. Groundwater and surface water baseline surveys are completed before the construction phase and continued monitoring is undertaken during the appraisal, production and cessation phases. All samples must be analysed by a suitably qualified third party organisation using recognised sampling and analytical methods. Any anomalies detected during the operational phase monitoring must be directly reported to the Environment Agency.

- *Fracture containment.* A Hydraulic Fracturing Plan (HFP) is prepared which describes the geometry of the proposed induced fracture network and highlights the target zones and any related aquifers. Hydraulic fractures are monitored during implementation using microseismic and seismic surveys. The presence of any faults within the extraction area must be included within the HFP.

- *Seismicity induced by hydraulic fracturing.* A risk assessment as part of the HFP is developed using geological maps, field experience and the depth of the proposed fracturing operations prior to drilling. Within this assessment local stresses are characterised using seismic reflection data and background seismicity data and are further refined using stress data from nearby boreholes, including, but not limited to; core data, borehole imaging, caliper logs and evidence of borehole losses. Seismicity is monitored throughout the operation phase as part of the HFP which is approved by the Oil and Gas Authority (OGA) with input from the EA. The seismic monitoring uses equipment which must be able to detect seismic activity of magnitude >0.0 M_L. The OGA has established a traffic light system in which the red light corresponds to a magnitude of 0.5M_L. If a red light or greater is detected, injection is immediately suspended and activities are reviewed. An amber light is currently set at magnitudes between 0.0 and 0.5M_L. If magnitudes are detected within this range injection of fracturing fluid may continue at a reduced rate and monitoring is intensified. The risks associated with the construction and operation phase are summarised in Table 2-1.

Table 2-1 Risks and mitigation measures associated with the product and operation phase of shale gas extraction

Issues	Mitigation Measure
Fluid Leakage	Ensure casing connections are tight
	Use the correct casing material for the formation/groundwater chemistry
	Casing permanently installed with impermeable cement
Well Stability	Cement installed to protect the casing from corrosion
	Acoustic, temperature and pressure testing to check the integrity of cement
	The intermediate casing protects the well from the surrounding formation
Groundwater Isolation	Surface casing and production casing isolates well from the surrounding formation
	Baseline survey and continued monitored surveys completed to detect any anomalies
Fracture Containment	Hydraulic Fracture Plan
	Seismic Monitoring
Seismicity induced by hydraulic fracturing	Characterise local stresses before drilling
	Seismicity monitored throughout the operation phase
	Traffic light system in accordance with OGA guidance

2.2.1 Chemicals used during shale gas operations

Shale gas operations require three main groups of chemicals on site. These are: 1) the chemical additives to engineer the hydraulic fracturing fluid to the necessary specification, 2) compounds such as fuel oils and maintenance chemicals required for equipment operation on site and 3) chemicals used within drilling muds, which are always water based systems when drilling onshore in the UK (UKOOG, 2016). Chemical additives for hydraulic fracturing fluids are subdivided into two main groups: additives that affect the viscosity and performance of the fluid, and additives that keep the well clean and minimise damage to the steel casing. The list of common additives used in fracturing fluids is shown in Table 2-2.

Additives that affect viscosity are required to achieve a fluid with an initial low viscosity and friction, which is later increased in order to aid in transporting the sand (proppant) within the fluid. These include guar gum, potassium chloride salt, ammonium persulfate and polyacrylamide, which also have everyday uses in cosmetics and foodstuffs (Ineos, 2015; FracFocus, n.d.). Additives that keep the well clean typically limit the growth of bacteria, scale and iron oxide compounds inside the well, which can corrode the steel casing. These too, including chemicals such as acetic acid, ethylene glycol and glutaraldehyde, have common everyday uses.

Alongside the chemical additives, petroleum fuels (diesel) and maintenance products like grease and oil will be present on the site. These will be used for the operation and maintenance of equipment on site, and are familiar compounds to any drilling or operational site.

2.2.2 Quantities of chemicals used for hydraulic fracturing

Hydraulic fracturing fluid consists typically of 99.5% water and sand (proppant), and 0.5% chemical additives (Stuart, 2011, INEOS, 2015). A typical fracturing operation will require between 5,000 m^3 and 77,000 m^3 of fluid (Table 1-1, row 5), which would therefore equate to 25 m^3 and 385 m^3 of additives respectively (by volume). The breakdown of the relative percentages of some typical additives is provided in Table 2-3.

The Environment Agency (EA), and other UK agencies that form JAGDAG (Joint Agencies Groundwater Directive Advisory Group) along with industry representatives, considers that the chemicals listed in Table 2-3 are 'non-hazardous pollutants' in respect of groundwater, for the purposes of the Water Framework Directive (WFD) (INEOS, 2015; JAGDAG, 2017). All substances proposed for use as a component of 'frac fluid' will be initially screened by the EA, against the JAGDAG Confirmed Hazardous Substances list or using the JAGDAG assessment methodology, and additionally a risk assessment addressing the proposed use of the chemical (WFD list, DECC, 2014; EA, 2016; JAGDAG, 2017). These chemical additives will be stored on site in a concentrated form and mixed prior to and during injection of the frac fluid.

Table 2-2 List of common additives to hydraulic fracturing fluids (adapted from PubChem, n.d; Stuart, 2011; INEOS, 2015)

Additive	Purpose	Example chemical	Other common uses
Acids	Dissolve rock, ease fracture generation	Hydrochloric acid	Water treatment
Acid Corrosion Inhibitor	Prevents corrosion of steel casing	Acetone	Pharmaceuticals
Biocides	Kill bacteria in well/water, which could otherwise lead to corrosion by-products	Glutaraldehyde	Disinfectant of medical equipment
Breakers	Used to break cross-linkers, decrease viscosity, degrade fracturing fluid	Ammonium persulfate	Bleaching agent in detergents
Clay Control	Prevents clay from swelling/shifting	Sodium chloride/choline chloride	Table salt/animal feed
Cross-linker	Maintains fluid consistency at increasing temperatures. Aids transport of proppants	Borate	Cosmetics
Foamed Gels	Generate bubbles to aid in transporting proppant to fractures	Nitrogen/carbon dioxide w/ alcohols (e.g. ethanol)	Shaving foams, shampoo
Fluid loss additives	Restrict leak-off of fluid into the rock at fracture face(s)	Natural Gums	N/A
Friction reducers	Minimise friction of fluid	Polyacrylamide	Water treatment
Gels	Increase viscosity to aid in transporting proppant	Guar gum	Foodstuffs, cosmetics
Iron Control	Prevents precipitation of metal oxides	Citric or acetic acid	Foodstuffs
Oxygen Scavenger	Deoxygenates the water (removing free oxygen), minimises corrosion	Ammonium bisulphate	Cosmetics
pH adjusting agent	Maintains effectiveness of additives	Sodium/potassium carbonate	Detergents, soap
Proppant	Holds/props open induced fractures	Quartz sand	Water filtration
KCl Salt	Increases viscosity and proppant transport capacity	Potassium chloride	Low-sodium table salt
Surfactant	Increases the stability of the fracture fluid	Isopropyl alcohol	Glass cleaner
Scale Inhibitor	Prevents build-up of scale on the borehole	Ethylene glycol	Anti-freeze

Table 2-3 Percentages of some typical additives in fracturing fluids

Compound	%	Equivalent volume m^3 (Min)	Equivalent Mass (Min) (kg)	Equivalent Mass (Min) (tonnes)	Max Volume m^3 (Min)	Equivalent mass (Max) (kg)	Equivalent Mass (Max) (tonnes)
Gellant (Guar gum)	0.32	16	16000.00	16.00	48	48000.00	48.00
Acid (HCl)	0.044	2.2	2618.00	2.62	6.6	7854.00	7.85
Corrosion inhibitor (methanol)	0.032	1.6	1267.20	1.27	4.8	3801.60	3.80
Friction reducer (polyacrylamide)[1]	0.032	1.6	1776.00	1.78	4.8	5328.00	5.33
Clay control (Choline chloride)	0.022	1.1	2376.00	2.38	3.3	7128.00	7.13
Crosslinker (Potassium metaborate)	0.02	1	2300.00	2.30	3	6900.00	6.90
Scale Inhibitor (Ethylene glycol)	0.015	0.75	832.50	0.83	2.25	2497.50	2.50
Breaker (Ammonium persulfate)	0.013	0.65	1287.00	1.29	1.95	3861.00	3.86
Iron Control (Acetic acid)	0.003	0.15	157.50	0.16	0.45	472.50	0.47
Biocide (Glutaraldehyde)	0.0006	0.03	31.80	0.03	0.09	95.40	0.10

Sources: (PubChem, n.d.; Ineos, 2015). [1]Residual concentrations of acrylamide may exist in association with polyacrylamide. Acrylamide is a hazardous substance, while polyacrylamide is not. Very low residual concentrations of acrylamide (e.g. less than 0.1%) can be shown through hydrogeological risk assessments not to pose a significant risk to groundwater when used in hydraulic fracturing at significant depth.

2.2.3 Flowback fluid and produced water (waste waters)

Waste waters that return to the surface during and after hydraulic fracturing include flowback fluid and produced water. Flowback fluid is primarily composed of the hydraulic fracturing fluid that returns to the surface following a fracturing event. The flowback lasts for a relatively short period of time before transitioning into produced water. Produced water comprises principally the highly saline/mineralised formation waters that are released following hydraulic fracturing and will continue to be produced during the lifetime of the well. Hydraulic fracturing fluid mixes with the produced water, resulting in elevated concentrations of total dissolved solids (TDS, Table 1-1, row 11) within the returned water. Flowback fluid is classified by waste code "01 01 02" in the Waste Framework Directive (2008/98/EC), and is determined to be a non-hazardous waste stream (EA, 2016; SEPA & Natural Scotland, 2015).

The chemical composition of the produced water is largely dependent on the source rock. Deep gas-bearing organic shale formations produce waters containing concentrations of hazardous organic chemicals such as benzene, toluene, ethylbenzene and xylenes (BTEX), (Shores et al., 2017) and Naturally Occurring Radioactive Materials (NORM) such as uranium, thorium and their daughter isotopes (^{226}Ra and ^{228}Ra) (Stuart, 2011). The composition of fracturing fluid will also vary during shale gas operations depending on the stage of development to ensure maximum efficiency is achieved in both development and extraction.

A proportion (up to 90%) of the hydraulic fracturing fluid (Liu et al., 2015) can be lost to the formation along the open horizontal section of the well where hydraulic fracturing is being undertaken. From records of existing shale gas operations in the USA, any flowback fluid returned to the surface is stored within open holding tanks or ponds, analysed, treated and reused or disposed of in deep injection wells. Within the UK, regulations require that flowback fluid and produced water are stored in sealed tanks to minimise the risk of spillages or leaks, and to allow for safe disposal and/or recycling in future fracturing operations (Cuadrilla, 2017).

A range of chemicals detected within produced water is shown in Table 2-4.

Table 2-4 Chemicals identified in produced water from previous shale gas extraction operations

Chemical	Concentration	Unit	Reference
Total Radium (^{226}Ra and ^{228}Ra)	6,450,000	piC m^{-3}	Haluszcack et al (2012)
Total Dissolved Solids	8,840 - >400,000	mg l^{-1}	Ziemkiewicz and Thomas (2015), Stuart (2011), Haluszcack (2012), Benko and Drewes (2008)
Benzene	27	mg l^{-1}	Benko and Drewes (2008) in Shores et al (2017)
Toluene	37	mg l^{-1}	
Ethylbenzene	19	mg l^{-1}	
Xylene	0.611	mg l^{-1}	
Strontium ($^{87}Sr/^{86}Sr$)	3,000	mg l^{-1}	Capo et al (2014)

3 Potential Development Scenarios for Shale Gas Extraction across three case study areas

In order to assess the potential cumulative impacts of any shale gas development, an assessment was undertaken using three case study sites to explore the scenario if shale gas extraction was increased. This consisted of a geospatial assessment, using a modified methodology from Clancy et al. (2017), to determine surface and subsurface spatial restrictions on the location of well pads. This generated a number of possible scenarios for the number of well pads across these areas. The following section describes the methodology and summarises the results from the investigation.

3.1 BACKGROUND

Well pads for the exploration and exploitation of shale gas are limited in their location by a number of factors. Sites firstly have to be situated on flat land, assumed to be an incline of less than 5 degrees. Additional spatial constraints on site locations consist of infrastructure and protected land designations, including:

- Roads and rail networks
- Rivers/water courses
- Urban areas
- Public water sources/supply and source protection zones (SPZ)
- English Natural Heritage (ENH) designations
    - AONB (Areas of Outstanding Natural Beauty)
    - SPA (Special Protection Areas)
    - SAC (Special Area of Conservation)
    - SSSI (Special Site of Scientific Interest)

The features of interest suggested above restrict the location of the site at the planning application stage. In the UK, there are no designated minimum distances for shale gas well heads from any of these features of interest. Each site's suitability is agreed on a case-by-case basis with the local planning authority (Cave, 2015 in Clancy, 2017). Clancy et al. (2017) found that existing onshore well heads in the UK were located a minimum of 21 m from non-residential properties and 46 m from residential properties, whilst mean distances were 329 m and 447 m respectively for each property type.

Clancy et al (2017) reported that between 2 – 5 wells on average are sited on pads in the US (Johnson et al, 2010; Drohan et al, 2012; Jantz et al, 2014), whilst Regeneris Consulting (2011) and Taylor & Lewis (2013) report that up to 10 wells could exist per pad in the UK. It is possible that a shale gas exploration and production site in the UK may contain more than one well to enable economic extraction of the resource.

In order to simplify the initial calculations, a site will be assumed to have only one well head. However, since multiple well heads can be assumed to be in close proximity, and laterals will radiate away from each other, multiple wellheads could be present at the number of determined sites. This will be factored into the cumulative impact assessment in the following sections.

3.2 METHODOLOGY

The following methodology was applied to the licence areas listed in section 1.3.1 and below:

- (SD33a, SD34a, SD43b) –Fylde basin, Lancashire
- (SE77c, SE77d, SE87a) –Vale of Pickering, Yorkshire
- (SE78b, SE88e) –Vale of Pickering, Yorkshire

These areas have been chosen based on the proximity to ongoing shale gas developments within the UK.

Suitable areas were first highlighted where the slope angle was less than 5°, using the NextMap™ DTM dataset, and the derived slope model held by the BGS. Buffers around features of interest, which are listed in Table 3-1, defined unsuitable areas for locating a wellhead. OS MasterMap 2015 data was used to delineate road and rail networks, and rivers and water bodies. Buffer distances were simplified from the values proposed by Eshleman & Elsmore (2013, in Clancy et al., 2017). Buffer zones were subtracted from the suitable slope areas to provide a final map of theoretical potential locations for well pad development, and clipped to the defined licence area. This was carried out for all three study areas.

Table 3-1 List of Features of interest, and associated buffer distances

Feature of interest	Buffer distance (simplified from Eshleman & Elsmore, 2013)
Road and Rail networks	150 m
Urban centres	150 m
Rivers and water bodies	150 m
English Natural Heritage designated sites	150 m
Source Protection Zones	600 m

To assess the average and maximum number of well pads that could be located across the study areas, a random point generation tool (Broad, 2015) was used to generate multiple hypothetical scenarios for the possible number of sites distributed across the area remaining outside the buffered zones. Using the guidance in Table 1-1 (row 1), a fixed minimum distance between points was implemented, which was double the distance of the lateral. This was used since laterals cannot intersect, and is therefore a further subsurface constraint on the surface location of the well pad. Values of 1200 m, 2100 m and 3000 m were chosen as lateral lengths (Table 1-1, row 1). While the lateral length within the data sets was generally between 1,000 m and 1,500 m (Kondash et al., 2018; Zou et al; 2018), lateral length is increasing (Kondash et al., 2018) and can reach up to 3000 m (Nicot et al., 2014 in Butovskyi et al., 2019). Incorporating longer laterals allowed for this potential future impact to be assessed.

A sample size of 100 wells was chosen to be fitted within the area, as this would likely exceed the actual number of sites that could be distributed within the determined remaining areas. The tool was run 50 times for each area, to provide a suitable statistical distribution, and to ensure that an absolute maximum could be found. The maximum would represent the highest-impact scenario for each study area.

3.3 RESULTS

3.3.1 Land area outside of setbacks/buffers from features of interest

The available surface area for each case study area, after exclusion using the setbacks and buffers described in section 3.2, is shown in Table 3-2. The remaining surface space across the study areas is less than 15%, on surface constraints alone. Case study area "SE77c, SE77d, SE87a" has the largest remaining surface space of all three of the case study areas (361 ha). "SD33a, SD34a, SD43b" has the second largest remaining surface space, but the lowest percentage of the total area. "SE78b, SE88e" has the largest percentage of the total area, whilst having the smallest remaining surface space.

Table 3-2 Area of each case study site, and remaining surface area from setback analysis

Case Study Licence Blocks	Area of Licence block	Remaining surface area after setback exclusion	Percentage of total area
SE78b, SE88e	2,000 ha	287 ha	14%
SE77c, SE77d, SE87a	3,535 ha	361 ha	10%
SD33a, SD34a, SD43b	5,450 ha	353 ha	6%

Figures 3.1 to 3.3 display the determined area remaining after subtracting the buffered zones from the areas of land with less than 5° slope. The remaining area has been used to determine a possible number of well pads, providing initial surface constraints to their location. The results of this assessment are detailed in section 3.3.2.

The remaining area for "SE78b, SE88e" is predominantly distributed in the SW corner of the study area with large uninterrupted units. For "SE77c, SE77d, SE87a" and "SD33a, SD34a, SD43b", the remaining area is more widely distributed, owing to the dense road network across the study areas. This results, especially in the case of "SD33a, SD34a, SD43b", in smaller regions of remaining land widely distributed across the study area.

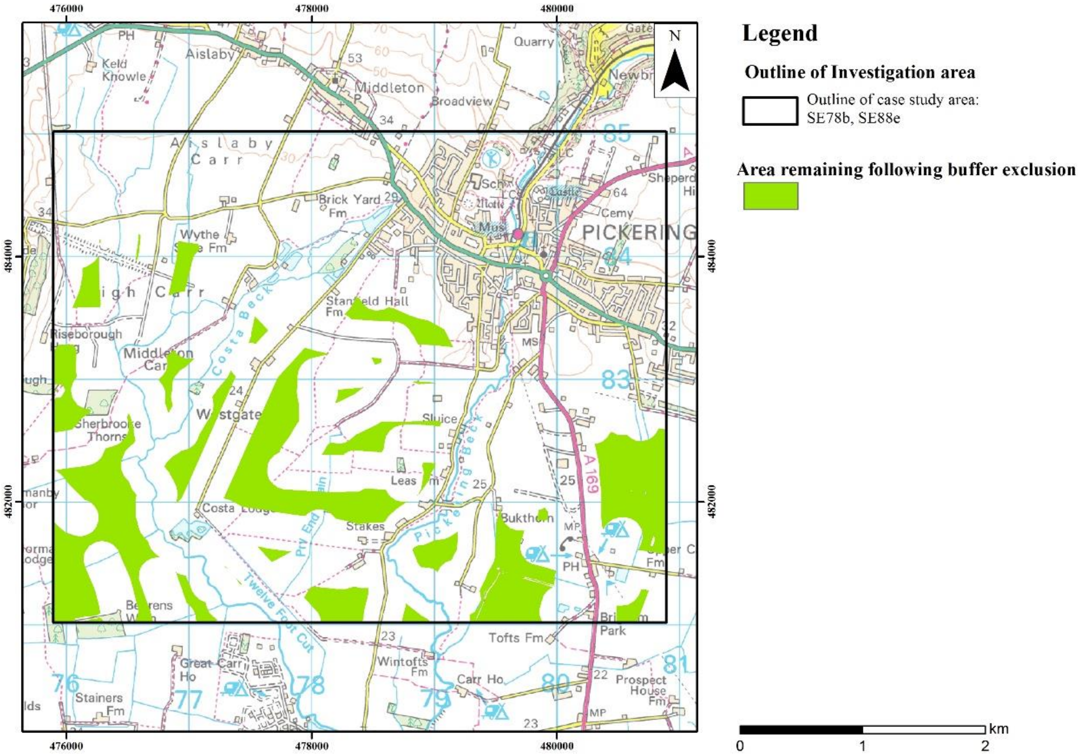


Figure 3.1 Area remaining following buffer exclusion for study area "SE78b, SE88e". Remaining land is typically distributed across the central-to-south areas of the study area. © Crown copyright and database rights [2018] Ordnance Survey [100021290 EUL]. Use of this data is subject to terms and conditions. Additional data from OS MasterMap 2015 © and OGA Opendata (OGA, 2018).

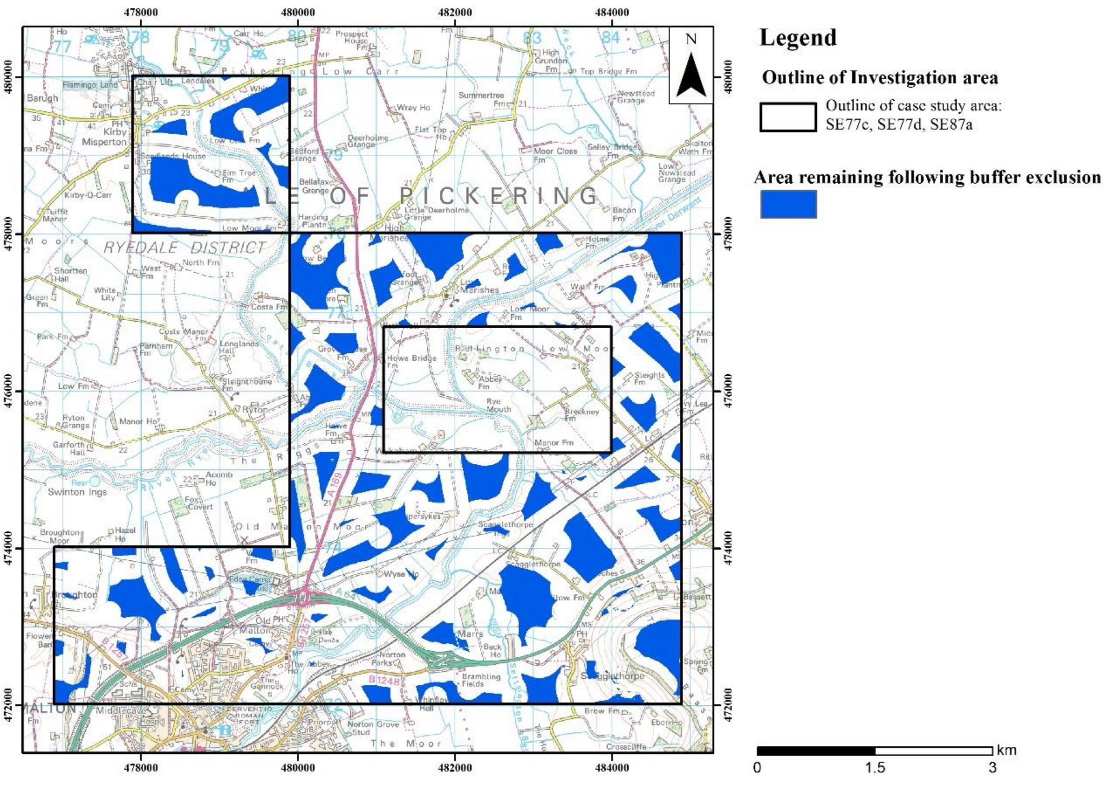


Figure 3.2 Area remaining following buffer exclusion for study area "SE77c, SE77d, SE87a". Remaining land is widely distributed across the study area. The urban centre in the SW corner represents a large area of no development. © Crown copyright and database rights [2018] Ordnance Survey [100021290 EUL]. Use of this data is subject to terms and conditions. Additional data from OS MasterMap 2015 © and OGA Opendata (OGA, 2018).

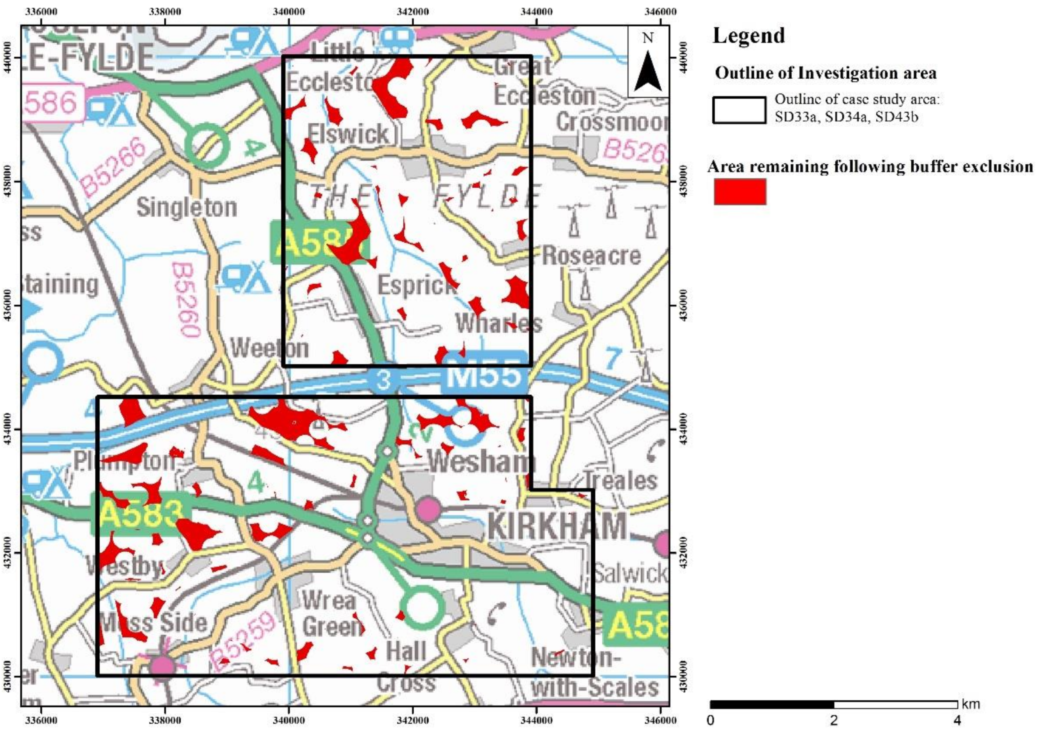


Figure 3.3 Area remaining following buffer exclusion for study area "SD33a, SD34a, SD43b". Remaining land is widely distributed, with minor concentrations in the West and North. The dense road network significantly limits the potential surface development locations. © Crown copyright and database rights [2018] Ordnance Survey [100021290 EUL]. Use of this data is subject to terms and conditions. Additional data from OS MasterMap 2015 © and OGA Opendata (OGA, 2018).

3.3.2 Determination of potential number of well pads

Table 3-3 shows the summary statistics for the possible number of wells pads determined by the random point generation tool, based on subsurface and surface constraints alone. They do not factor in additional constraints such as land agreements, or social influences from the local community and planning authority.

Table 3-3 Summary statistics from Random Point Generation across each case study area

Case Study Licence Blocks	Lateral Length (m)	Mean[1]	Max	Min	Range	Standard Deviation	Variance
SE78b, SE88e	1200	3	4	2	2	0.67	0.45
	2100	1	2	1	1	0.50	0.25
	3000	1	1	1	0	0	0
SE77c, SE77d, SE87a	1200	7	10	6	4	1.03	1.05
	2100	4	5	3	2	0.65	0.43
	3000	3	6	1	5	0.91	0.83
SD33a, SD34a, SD43b	1200	9	11	8	3	0.76	0.57
	2100	3	5	3	2	0.70	0.50
	3000	2	3	2	1	0.50	0.25

[1]Rounded to lowest whole number

Both case study licence blocks “SE77c, SE77d, SE87a” and “SD33a, SD34a, SD43b” have the greatest maximum number of well pads across the remaining surface after setback exclusion with a 1200 m lateral. For all blocks, the number of well pads decreases with increasing lateral distance. Variance, standard deviation and range decrease with lateral length in all instances except for a 3000 m lateral for “SE77c, SE77d, SE87a”, where there is an increase in all three compared to the 2100 m lateral results.

“SE78b, SE88e” has the lowest number of maximum and average sites across the area for a 1200 m lateral. It also has the smallest standard deviation and variance for each lateral distance, with a zero standard deviation and variance value for a 3000 m lateral. This indicates that a 3000 m lateral would only allow for one well pad in the calculated available surface area after setback exclusion.

3.3.3 Cumulative Impact Assessment: scenarios for number of wells in study areas

Using the maximum number of sites for each study area determined in section 3.3.2, Table 3-3, a range of low, moderate and high impact scenarios have been generated for the assessment for section 4 onwards. Table 3-4 displays the number of well heads that could potentially exist across the study areas. The low, moderate and high impact scenarios have been chosen from the range of values listed in Table 1-1 (row 2). The most likely scenario, going by estimates from Taylor & Lewis (2013) and Regeneris Consulting (2011) of 10 wells per pad, is the moderate scenario.

Table 3-4 Table showing low, moderate and high impact scenarios number of wells per study area for calculations in section 4

Licence area	Available area per study area	Max. number of well pads	Wells per pad			Wells per Licence area		
	ha	No.	No.			No.		
			L	M	H	L	M	H
SE78b, SE88e	287	4	2	9	16	8	36	64
SE77c, SE77d, SE87a	361	10	2	9	16	20	90	160
SD33a, SD34a, SD43b	353	11	2	9	16	22	99	176

3.4 DISCUSSION

Comparisons with previous studies and industry estimates

From the results in section 3.3, it can be seen that a defined setback distance from features of interest greatly limits the location of surface works for shale gas developments within a licence area. Less than 20% of land remains for case study areas "SE78b, SE88e" and "SE77c, SE77d, SE87a", and less than 10% remains for "SD33a, SD34a, SD43b". This shows that a setback approach would significantly reduce the potential for surface locations across a PEDL licence area. However, as discussed in section 3.1, there is no defined distance in England for setbacks of well heads from features of interest, with approval for site locations assessed on a case-by-case basis. The number of sites determined from this study may deviate from what a local planning authority may allow, or may be possible due to geological (e.g. faulting) or economic constraints, which is difficult to estimate.

Whilst the setbacks provide one significant restriction, the subsurface constraint of well laterals is even more significant. Without the constraint of laterals, and assuming a well pad size of 1-2 ha, a significant number of sites could theoretically be situated at the surface (Table 3-5). However, the inclusion of laterals reduces this number by a factor of 16 to 70, depending on the site footprint and the study area. This therefore shows that access to the resource is considerably restricted by surface and subsurface constraints and as such there would not be significant numbers of shale gas well pads all in one location.

Table 3-5 Number of well pads (of 1 ha and 2 ha) that could be located in the remaining area for each case study area, ignoring subsurface restrictions from laterals.

Study area	Number of 1 ha well pads	Number of 2 ha well pads
SE78b, SE88e	287	143
SE77c, SE77d, SE87a	361	180
SD33a, SD34a, SD43b	353	176

Clancy et al. (2017) further demonstrated this with their assessment of the footprint and carrying capacity of randomly selected 100 km^2 licence blocks. Using a Buffon's needle approach (probability assessment of chance of intersecting with a feature of interest), they determined values for the number of sites that could be situated within these licence blocks, shown in Table 3-6. Both the assessment detailed in this report, and the study carried out by Clancy et al. (2017) used the Eshleman and Elsmore (2013) guidance for setbacks, but Clancy et al. (2017) assumed a 500 m lateral would be representative of the UK industry. From Table 1-1, this value is well under half of what this assessment has considered likely.

Table 3-6 Results from Clancy et al. (2017) assessment using Buffon's Needle approach. Setback used; 152 m. Lateral used; 500 m

Block Number	Number of well sites
SD33	18
SD52	5
SE70	34
SE77	35
SE88	27
SE91	32
SE93	42
SJ33	21
SJ34	13
SJ44	23
SJ79	9
SK63	26
SK68	32
SK77	31
SK79	28
SK83	31
SK84	36
SK97	34
TA20	28
TA3	24

When scaled up, the number of sites calculated for each study area approximate the results found by Clancy et al. (2017); these are shown in Table 3-7. The number of sites determined from this assessment is moderately lower than those found by Clancy et al. (2017), but this is most certainly down to the difference in the laterals used. Clancy et al. (2017) use study areas of 100 km^2 (10,000 ha) and 500 m laterals, and therefore tend to estimate a greater number of well pads per study area. They also use square outlines for setbacks from the wellhead, rather than buffer from features of interest and radial laterals used throughout this study.

Table 3-7 Results from section 3.3.2, scaled to 10,000 ha sites used in Clancy et al. (2017) study. Comparison with Table 3-6 shows that numbers are moderately lower, but this is due to the significantly greater lateral length used in this assessment. Results are rounded to the lowest whole number.

Case Study Licence Blocks	Lateral Length (m)	Mean number of sites[1]	Mean scaled to 10,000 ha site[1]	Max number of sites	Max scaled to 10,000 ha site[1]	Min number of sites	Min scaled to 10,000 ha site[1]
SE78b, SE88e	1200	3	15	4	20	2	10
	2100	1	5	2	10	1	5
	3000	1	5	1	5	1	5
SE77c, SE77d, SE87a	1200	7	19	10	28	6	16
	2100	4	11	5	14	3	8
	3000	3	8	6	16	1	2
SD33a, SD34a, SD43b	1200	9	16	11	20	8	14
	2100	3	5	5	9	3	5
	3000	2	3	3	5	2	3

[1]Rounded to lowest whole number

Further to the geospatial assessments seen in this study and that of Clancy et al. (2017), the Irish EPA (Olsen et al., 2016) have also conducted their own cumulative impact assessment of shale gas developments for two distinct area along the Northern Ireland border. Looking at two concession areas (equivalent to PEDL blocks within the UK), the Northern Carboniferous Basin (NCB – 222,000 ha total) and the Claire Basin (CB – 50,000 ha total), they estimated that a hypothetical maximum of 60 shale gas pads could be situated within the NCB and 50 pads within the CB. Considering the size of the concession areas, this is a considerably lower distribution density (0.00027 pads/ha for NCB, 0.001 pads/ha for CB), and is significantly lower than estimates from both this study and the study conducted by Clancy et al. (2017). The methodology used by Olsen et al. (2016) was "approximately the number of 1000-m diameter circles per lease area".

When the results from both this assessment and the study carried out by Clancy et al. (2017) are compared with wider industry estimates, there is a notable difference. An Institute of Directors (IoD) study written by Taylor & Lewis (2013), used a hypothetical scenario of 100 shale gas sites by 2028, each consisting of 40 laterals (10 wells per pad, 4 laterals per well). Considering the estimates from both this report, and Clancy et al. (2017), it is a significant reduction compared to what is geospatially possible. However, factors outside of geospatial and subsurface constraints, such as financing and economics, social resistance, environmental regulation and the planning process required to instigate the development and operation of a shale gas site may further limit the number of sites that would be located within a licence block.

Recently revealed, yet unpublished, estimates from the Department for Business, Energy and Industrial Strategy (BEIS) highlight this difference in the expectation even further. Hayhurst (2018a) summarises unpublished material from BEIS 2016 Cabinet Office report, that 30-35 unconventional oil and gas sites are expected to be constructed by 2022, with a total of 155 wells by 2025. These figures were however considered out of date (as of 27th of February, 2018) by the cabinet, and there is no up to date government estimate in publication (Hayhurst, 2018b).

From this study, it can therefore be assumed that the results listed in section 3.3 may be an overestimate for the likely scope of the industry in the UK. However, without significant comparative data, there is not a clear way to define how many of the estimated number of sites per licence block may actually progress, and this is perhaps an aspect for further research. However, for the purpose of this report the results calculated in section 3 will be carried forward into sections 4 and 5 for the cumulative impact assessment.

3.4.1 Future modifications to the methodology

The methodology described in section 3.2 relies directly on the use of defined setbacks/buffers from features of interest, and a random point tool to determine various random scenarios for the number of sites located across a licence area. Of these two, the setbacks are easily modified from possible future defined values, if Government legislation was to introduce fixed distances. At this point in time, geospatial assessments rely on estimates of setbacks, and estimates of possible numbers for shale gas sites will carry this uncertainty.

The second aspect of using the random point tool could be replaced by a program to optimise the distribution of sites across these complex remaining areas (Figures 3.1 to 3.3) to determine a maximum number of sites. This is an optimisation problem, and would require an iterative solution or program to find this result. Otherwise, the random tool could be run for considerably more iterations, but still runs the risk of producing duplicate results, or never achieving the true maximum.

4 Potential Impacts on groundwater quality in the Case Study Areas

4.1 OBJECTIVES

The overall objective of this study is to consider the potential for impacts on groundwater resources arising from multiple shale gas wells across an area, i.e. the cumulative impact. The following section presents the findings of this initial cumulative impact assessment, based on the geospatial assessment results from section 3.

The assessment draws on much of the experience and evidence from jurisdictions where shale gas is at a well-developed stage of production, such as the USA. European analogues and experiences are lacking, with no operational wells and only 50 exploratory wells as of February 2014 (Spencer et al., 2014) with a small number of exploratory wells drilled after this date.

The potential for impacts on groundwater have been evaluated in the context of the following activities:

- Surface chemical and fuel spills and leaks during transport, storage at well pads during drilling and hydraulic fracturing;
- Improper well construction or operation, including failures during drilling, hydraulic fracturing and production;
- Leakage of on-site stored flowback fluids, produced water, drilling muds and cuttings; and
- Leaks, spills or improper disposal of flowback water, produced water, drilling muds and cuttings during off-site treatment, transport and disposal.

4.2 OVERALL METHODOLOGY

The methodology for identifying and assessing potential impacts involved:

- Defining the potential pollutant sources associated with shale gas (e.g. drilling muds, flowback water, produced water, etc.),
- Identifying the leakage pathways to groundwater, and
- Evaluation of potential cumulative impacts in three case study areas.

Potential impacts are initially divided into one of three categories: low, moderate and high impact, which are defined in section 1.3. When multiplying the impact scenarios to another further variable, e.g. varying numbers of wells per pad, and varying numbers of volumes for surface spills, a matrix of scenarios is generated which contains a range of impacts. Table 4-1 provides an example of how each impact scenario is used to create the matrix from the lowest impact scenario (low-low) to the highest impact scenario (high-high).

Certain potential impact scenarios, such as “flowback fluid not recycled” (section 4.6), required a series of matrices to be developed, as they were dependent upon multiple sequential variables. Other impact scenarios, such as the “volume of fluid used per fracturing operation”, required only one input variable, resulting in less complex matrices. The following subsections address in-turn the individual input variables for each aspect of the cumulative impact assessment, with respect to water quality.

Table 4-1 Example for impact assessment methodology. A combination of Input Parameter 1 and Variable 1 results in the impact scenario matrix displayed on the right.

Input Parameter 1			Variable 1	Impact Scenario Matrix		
				L	**M**	**H**
Low Impact	Moderate Impact	High Impact	Low Impact	Low-Low	Mod-Low	High-Low
			Moderate Impact	Low-Mod	Mod-Mod	High-Mod
			High Impact	Low-High	Mod-High	High-High

4.3 IMPACT SCENARIOS FOR VOLUMES OF HYDRAULIC FRACTURING, DRILLING MUD AND FLOWBACK FLUID REQUIRED AND PRODUCED

4.3.1 Methodology

The values shown in Table 4-2 represent the low, moderate and high impact scenarios described in section 4.2, for the following list of calculations:

- Volume of fracture fluid required per study area,
- Volume of mud and drill cuttings generated per study area,
- Volume of flowback fluid not recycled per study area

The values in Table 4-2 have been derived from information collated in Table 1-1, and the statistical results obtained in Table 3-3.

Table 4-2 List of input variables for the determination of fracture fluid required, and the volume of mud, drill cuttings and flowback fluid generated

Variable	Impact			Source
	Low	**Moderate**	**High**	
No. of wells per pad	2	9	16	Table 1-1, row 2
No. of well pads	Min for 3000 m	Mean for 2100 m	Max for 1200 m	Table 3-3
Required volume of fracture fluid per fracture programme	5,000 m^3	41,000 m^3	77,000 m^3	Table 1-1, row 5
Mud and drill cuttings generated	1,500 m^3 / well pad	2,000 m^3 / well pad	2,500 m^3 / well pad	Table 1-1, row 3
Percentage flowback of fracture fluid per fracture programme	10%	25%	40%	Table 1-1, row 6
Percentage flowback recycle rate	40%	60%	80%	Table 1-1, row 8

The following equations were used to determine the scenario matrices for each of the potential scenarios:

Equation 4-1 – Determination of the number of well pads per study area:

$$\text{Number of wells per pad} \times \text{number of well pads} = 3 \text{ by } 3 \text{ matrix}$$

Equation 4-2 – Determination of the required volume of fracture fluid per study area:

$$\text{Number of wells per study area} \times \text{Required volume of fracture fluid per fracture programme} = 3 \text{ by } 9 \text{ matrix}$$

Equation 4-3 – Determination of the volume of drilling mud and cuttings generated per study area:

$$\text{Number of well pads per study area} \times \text{mud and drilling cuttings generated} = 3 \text{ by } 3 \text{ matrix}$$

Equation 4-4 – Determination of the volume of flowback fluid not recycled per study area:

$$(\text{Volume of Fracture Fluid per study area} \times \text{Percentage flowback of fracture fluid per fracture programme})$$

$$\times (100\% - \text{Percentage flowback recycle rate}) = 3 \text{ by } 27 \text{ cell matrix } (81 \text{ cells})$$

4.3.2 Results of impact scenarios for volumes of fracture fluid required, and volumes of drilling mud, cuttings, and flowback fluid produced

The results shown in tables 4-3 to 4-5 are presented in the following format. For the lowest returned result, this is the "low-low" scenario (Table 4-1) or equivalent for each matrix. The moderate scenario is the "mod-mod" or equivalent scenario. Lastly, the highest returned result is the "high-high" or equivalent scenario.

The results for each study area are shown in Tables 4-3 to 4-5. The complete matrices for each impact scenario are listed in Appendix 1.

Table 4-3 Results from section 4.3.1 for the "SE78b, SE88e" study area impact scenarios

Description	Unit	Low	Moderate	High
Well pads	No.	1	1	4
Wells per pad	No.	2	9	16
Total wells per study area	No.	2	9	64
Required volume of fracture fluid per study area	m^3	10,000	369,000	4,928,000
Mud and drill cuttings generated per study area	m^3	1,500	2,000	10,000
Flowback of fracture fluid per study area programme not recycled	m^3	200	55,350	1,576,720

Table 4-4 Results from section 4.3.1 for the "SE77c, SE77d, SE87a" study area impact scenarios

Description	Unit	Lowest	Moderate	Highest
Well pads	No.	1	4	10
Wells per pad	No.	2	9	16
Total wells per study area	No.	2	36	160
Required volume of fracture fluid per study area	m^3	10,000	1,476,000	12,320,000
Mud and drill cuttings generated per study area	m^3	1,500	8,000	25,000
Flowback of fracture fluid per study area programme not recycled	m^3	200	221,400	3,942,400

Table 4-5 Results from section 4.3.1 for the "SD33a, SD34a, SD43b" study area impact scenarios

Description	Unit	Lowest	Moderate	Highest
Well pads	No.	2	3	11
Wells per pad	No.	2	9	16
Total wells per study area	No.	4	27	176
Required volume of fracture fluid per study area	m^3	20,000	1,107,000	13,552,000
Mud and drill cuttings generated	m^3	3,000	6,000	27,500
Flowback of fracture fluid per study area programme not recycled	m^3	400	166,050	4,336,640

The results suggest that potential volumes of fracture fluid per study area range from 10,000 m^3 for the lowest impact scenarios in SE78e, SE88e and SE77c, SE77d, SE87a to approximately 13,500,000 m^3 for the highest impact scenario in study area SD33a, SD34a, SD43b. All moderate impact scenarios estimate that less than 1,500,000 m^3 of fracture fluid would be required per study area assuming a moderate number of well pads were present, with less than 400,000 m^3 suggested for study area SE78e, SE88e.

The largest volumes of mud and drill cuttings generated is associated with study area SD33a SD34a, SD43b and SE77c, SE77d, SE87a at approximately 27,000 m^3 for the highest impact scenario. In contrast, only 10,000 m^3 is suggested for the highest impact scenario in study area SE78e, SE88e. The moderate impact scenarios suggest that between 2,000 m^3 to 8,000 m^3 of mud and drilling cuttings could be generated by each study area.

The volume of fracture fluid lost to formation (i.e. not recycled) is less than 500 m^3 across all study areas for the lowest impact scenario. The largest volume of fracture fluid not recycled is approximately 4,500,000 m^3 in study area SD33a, SD34a, SD43b. The moderate impact scenarios range from approximately 55,000 m^3 in study area SE78e, SE88e to approximately 200,000 m^3 in study area SE77c, SE77d, SE87a.

4.3.3 Discussion

With respect to the results shown in section 4.3.2, the following points should be noted. The 'High' scenario for each study area is the least likely to occur, as it exceeds both industry expectations and government expectations for the future development of the shale gas industry in the UK for number of wells and well pads. It represents a maximum exploitation scenario, if the industry were to make maximum use of surface and subsurface space (section 3.3.1), ignoring other constraining factors such as planning and legislation discussed in Section 3.4.1.

Estimates for number of well pads and wells per pad, discussed in section 3.4.1, provided by Taylor & Lewis (2013), Regeneris Consulting (2011) and Olsen et al. (2016) are more in line with the moderate scenarios. The moderate scenario could therefore be considered as being more representative of the industry's expectation of the future development of shale gas extraction across the UK. The lowest scenario is far more akin to the expectations suggested by Hayhurst (2018a; b).

The results show that of the three study areas examined, "SD33a, SD34a, SD43b" could potentially have the greatest number of wells. The initial scenarios for the number of wells per study area, and the number of well pads per study area, have the greatest influence on the further calculations defined in Equations 4-2 to 4-4 (section 4.3.1).

With respect to the volume of fracture fluid required per drilling programme, it can be observed that study area "SE77c, SE77d, SE87a" (Table 4-5) has the greatest potential volumetric requirement, with study area "SD33a, SD34a, SD43b" (Table 4-4) close behind for a moderate scenario. The volume of fracture fluid used for a moderate scenario (41,000 m^3) is slightly overestimated when compared to the planned use for shale gas production at Preston New Road, Lancashire of approximately 34,000 m^3 (Cuadrilla, 2018).

By far the most significant factor related to these scenarios is the resulting effects on water supply and truck movements. Table 1-1 (row 10) provides some initial estimates for the truck requirements per fracture programme. Table 4-6 provides a summary of the potential number of truck movements for each scenario, using the storage capacity of one truck (25 m^3; Table 1-1, row 9). It is assumed, from Table 1-1 (row 4), that there is only one fracture programme per well over the duration of the lifetime of the well.

Table 4-6 Estimated number of truck movements required per study area

	Number of truck movements for each impact scenario (25 m^3 / truck)		
Study Area	**Lowest**	**Moderate**	**Highest**
SE78b, SE88e	400	14,760	197,120
SE77c, SE77d, SE87a	400	59,040	492,800
SD33a, SD34a, SD43b	800	44,280	542,080

For a moderate impact scenario a maximum number of approximately 59,000 truck movements is suggested for study area SE77c, SE77d, SE87a over the lifetime of a well. It is assumed that most of the truck movements would be in the early stages of development as water is not required while the well is producing. If freshwater was to be abstracted locally, at each site, this would reduce the number of tankers journeys required but place stress on the water resources within each study area if permitted. This potential impact on water resources is further addressed in section 6, which explores the water resources impacts and requirements of shale gas operations.

The significance of the results from the volume of mud and drill cuttings generated, and the volume of flowback fluid not recycled, highlight the issue of waste stream management, storage and disposal. Prior to disposal off-site, these materials will have to be stored at surface on site.

4.4 IMPACT SCENARIOS FOR WELL FAILURE

It is difficult to predict the likelihood of a well failure in any shale gas production operation. Regulations are in place to mitigate the risk of well integrity issues and these apply throughout the lifetime of the well. The design, construction and operation of wells utilise prevention measures as far as is reasonably practicable to reduce the risk of well failure (Section 2.2.). Therefore when attempting to provide insight on well failure rates for an emerging shale gas industry in England, these factors must be taken into account and also discussions must consider the fact that each operation is different (geological and environmental setting, etc.). Furthermore, data for failure rates of onshore unconventional shale gas wells are relatively sparse, especially within a UK setting (Davies et al., 2014).

However, in the interests of completeness there is merit in evaluating potential failure rates and the potential impacts. Thorogood and Younger (2014), suggest that applying international data sets to England is unjustifiable due to the differences across operations and nations, as previously highlighted. But, as well failure rates for onshore unconventional shale gas wells in England are unavailable, analogous data sets must be used. However, it is important that their limitations are taken into consideration.

For this impact assessment multiple data sets have been examined (Vidic et al., 2013; Ingraffea, 2012 and Considine et al., 2013 in Davies et al., 2014; Davies et al., 2014; Ingraffea et al., 2014) to identify the most applicable setting to an unconventional shale gas industry in England. Firstly, data associated with conventional oil and gas wells were dismissed due to their different reservoir characteristics (Thorogood and Younger, 2014). Secondly modern unconventional shale gas data sets were preferred such as in Vidic et al., 2013 and Ingraffea et al., 2014, which detail failure rates for the Marcellus Shale, Pennsylvania, between 2000 and 2012. The former data set was dismissed as it accounts for notice of violations (NOVs) only and is suggested to be an underestimate (Ingraffea et al., 2014). As such, the data selected was for failure rates between 2009 and 2012 (Ingraffea et al., 2014) of 1.88% to 9.14% (Table 1-1, row 12). However, it is important to note that USA shale gas environmental regulations are different to England and are generally considered to be less stringent.

4.4.1 Methodology

In order to determine an initial estimate of well failures per study area, the methodology described in section 4.2 was used to develop scenario matrices. Table 4-7 summarises the list of input parameters for the well failure scenario calculations.

Table 4-7 Input parameters for well failure scenarios

Variable	Impact			Source
	Low	Moderate	High	
Number of wells per pad	2	9	16	Table 1-1, row 2
No. of well pads	Min for 3000 m	Mean for 2100 m	Max for 1200 m	Table 3-3
Percentage of well failures per study area	1.88%	5.51%	9.14%	Table 1-1, row 13

The following equation was used to determine the range in the number of wells that might fail per study area.

Equation 4-5 – Determination of the number of wells per study area that could fail:

$$\text{Number of wells per pad} \times \text{Number of well pads per study area} \times \%\ \text{rates of well failures per study area} = 3 \text{ by } 9 \text{ matrix (27 cells)}$$

4.4.2 Well Failure Results

The results in tables 4-8 to 4-10 shown are presented in the following format. For the lowest returned result, this is the "low-low-low" scenario (Table 4-1) for each impact scenario matrix. The moderate scenario is the "mod-mod-mod" result. Lastly, the highest impact scenario is the "high-high-high" result.

The complete matrices for each impact scenario are listed in Appendix 2.

Table 4-8 Results from section 4.4.1 for the "SE78b, SE88e" study area well failure scenarios

Description	Unit	Lowest	Moderate	Highest
Well pads	No.	1	1	4
Wells per pad	No.	2	9	16
Total wells per study area	No.	2	9	64
Number of wells that could potentially fail per study area (rounded to the nearest whole number)	No.	0.038 (0)	0.496 (0)	5.850 (6)

Table 4-9 Results from section 4.3.1 for the "SE77c, SE77d, SE87a" study area well failure scenarios

Description	Unit	Lowest	Moderate	Highest
Well pads	No.	1	4	10
Wells per pad	No.	2	9	16
Total wells per study area	No.	2	36	160
Number of wells that could potentially fail per study area (rounded to the nearest whole number)	No.	0.038 (0)	0.169 (0)	14.624 (15)

Table 4-10 Results from section 4.3.1 for the "SD33a, SD34a, SD43b" study area well failure scenarios

Description	Unit	Lowest	Moderate	Highest
Well pads	No.	2	3	11
Wells per pad	No.	2	9	16
Total wells per study area	No.	10	27	176
Number of wells that could potentially fail per study area (rounded to the nearest whole number)	No.	0.075 (0)	1.488 (1)	16.086 (16)

For the majority of lowest and moderate impact scenarios it is estimated that no wells will fail, with the exception of study area SD33a, SD34a, SD43b that suggest one well could fail based on a moderate number of well pads and a moderate failure rate of 5.51%.

4.4.3 Discussion

As discussed in section 4.3.3, the results from Table 3-3 significantly impact on the results obtained for the potential number of wells that could fail per study area, with the highest impact scenario considered the most unlikely to occur. As can be seen from tables 4-8 to 4-10, and the input variables in Table 4-7, the well failure percentages are low, resulting in very few potential well failures per study area. It should be noted that the percentages used have been derived from considerably larger datasets, in excess of 3000 documented wells. However, in the absence of more local data, analogues derived from the Marcellus Shale have been used to provide a preliminary estimate for a UK setting.

A well failure does not necessarily lead to adverse environmental impacts. There are additional factors that must be considered when assessing risk to the environment or human health. These factors are discussed throughout section 4.5 and section 5. Furthermore, the risks of well failures are mitigated by the adherence to strict controls required by the Health and Safety Executive (HSE), which consist of the "Borehole Sites and Operations Regulations 1995" and "Offshore Installations and Wells (Design and Construction etc.) Regulations 1996" (HSE, n.d.) and "Control of Major Accident Hazards Regulations 2015" (HSE, 2015). All installations must ensure the protection of the natural environment, the nearby public, and the workforce in proximity to the operation. Further conditions are imposed by the Environment Agency, under separate regulations (Water Resources Act, 1991; Environmental Permitting Regulations (England and Wales), 2010) and the Oil and Gas Authority, who provide the final consent for the operation once the regulators' conditions have been satisfied by the operator (BEIS, 2017).

As described in section 2.2, the use of multiple casing completions is one such method to mitigate the risk of leaks. These provide multiple barriers to prevent the contact of borehole fluids with groundwater. The casing must be tested to confirm its integrity using well-integrity tests. These conditions can be defined in the Environment Agency permit as part of an operator's application (Environment Agency, 2015).

4.5 CHEMICAL SPILLS AND LEAKS

Failures during shale gas extraction, associated with equipment, well integrity or tanker spills ultimately lead to the release of chemicals at the point of the failure. At the surface, mitigation measures are in place to capture these spills such as low permeability/impermeable geotextile membranes around the well pad. However, there is still a potential risk of polluting the environment if the mitigation measures are not sufficient or fail (e.g. Ziemkiewicz et al., 2014). In the subsurface these mitigation measures are absent and a well failure could produce a release of chemicals into the subsurface rock formation or aquifer depending on depth.

The potential for chemical spills is dependent on many factors and can be reviewed using the Source Pathway Receptor (SPR) model (Gormley et al. 2011). A simple overview in terms of shale gas extraction is described below.

- Source (the chemical spill/leak). In this impact assessment, a spill/leak refers to the release of chemicals from flow back fluid, produced water and drilling fluid, or from storage in a concentrated form. They may occur due to equipment failure, during transport to and from the site or due to failures in well integrity.
- Pathway (geology, soil, topography). Factors that encourage or inhibit the migration of a chemical spill include; permeability of rock formation and soil/superficial deposits, topography of the land, presence of mitigation measures e.g. engineered impermeable geotextile at the surface and weather conditions at the time of the spill.
- Receptor (aquifer, private/public drinking water supply, streams or rivers, humans). The closest proximity of these receptors to the chemical spill will affect the significance of a hazardous chemical spill.

Using published data the number of spills and cumulative volumes of spills have been examined and applied to the three study areas. For this assessment, it is assumed the volume of spill not recovered is equivalent to the volume of spilled material that enters the environment and can reach a sensitive receptor.

A conceptual "source, pathway, receptor" model for a single shale gas extraction well and pad is shown in Figure 4.1.

4.5.1 On-site spills methodology

In order to determine an estimate of the volume of spill/leak not recovered, the methodology described in section 4.2 was applied to develop scenario matrices. Table 4-11 summarises the list of input parameters for the on-site spill scenario calculations.

Table 4-11 Input parameters and variables for volume of on-site spills not recovered

Variable	Impact			Source
	Low	Moderate	High	
No. of wells per pad	2	9	16	Table 1-1, row 2
No. of well pads	Min for 3000 m	Mean for 2100 m	Max for 1200 m	Table 3-3
Spills per well	7.7×10^{-3}	9.9×10^{-3}	1.2×10^{-2}	Derived from Clancy et al. (2018)
Volume of material per spill	3 m^3			Derived from Clancy et al. (2018)
Percentage recovery of spilled material	90%	55%	20%	Derived from Clancy et al. (2018)

The three required initial input parameters were obtained from Clancy et al. (2018). In 2015, The Texas Railroad Commission reported that 1485 spills were associated with 193,807 production wells and that 4441m^3 of fluid was cumulatively spilt. This data shows that there were 7.7 x 10^{-3} spills per well which equates to an average volume of 2.99 m^3 per spill. Recovery rates of spills ranged from 20% to 91% between 2009 and 2015. The Colorado Oil and Gas Commission reported that there were 623 spills in 2015 for 53,054 production wells equating to 1.2 x 10^{-2} spills per well. These two values have been used to provide the maximum and minimum values for the impact scenario range, with the value of 9.9×10^{-3} representing a middle value.

The following equations were used to determine the scenario matrices for each of the potential impacts:

Equation 4-6 – Number of spills per study area

$$\big((\text{wells per pad} \times \text{well pads per study area}) \times \text{spills per well}\big) = 3 \text{ by } 9 \text{ matrix } (27 \text{ cells})$$

Equation 4-6 – Volume of material spilled per study area

$$\text{Number of spills per study area} \times \text{volume of material per spill} = 3 \text{ by } 9 \text{ matrix } (27 \text{ cells})$$

Equation 4-7 – Volume of spill not recovered per study area

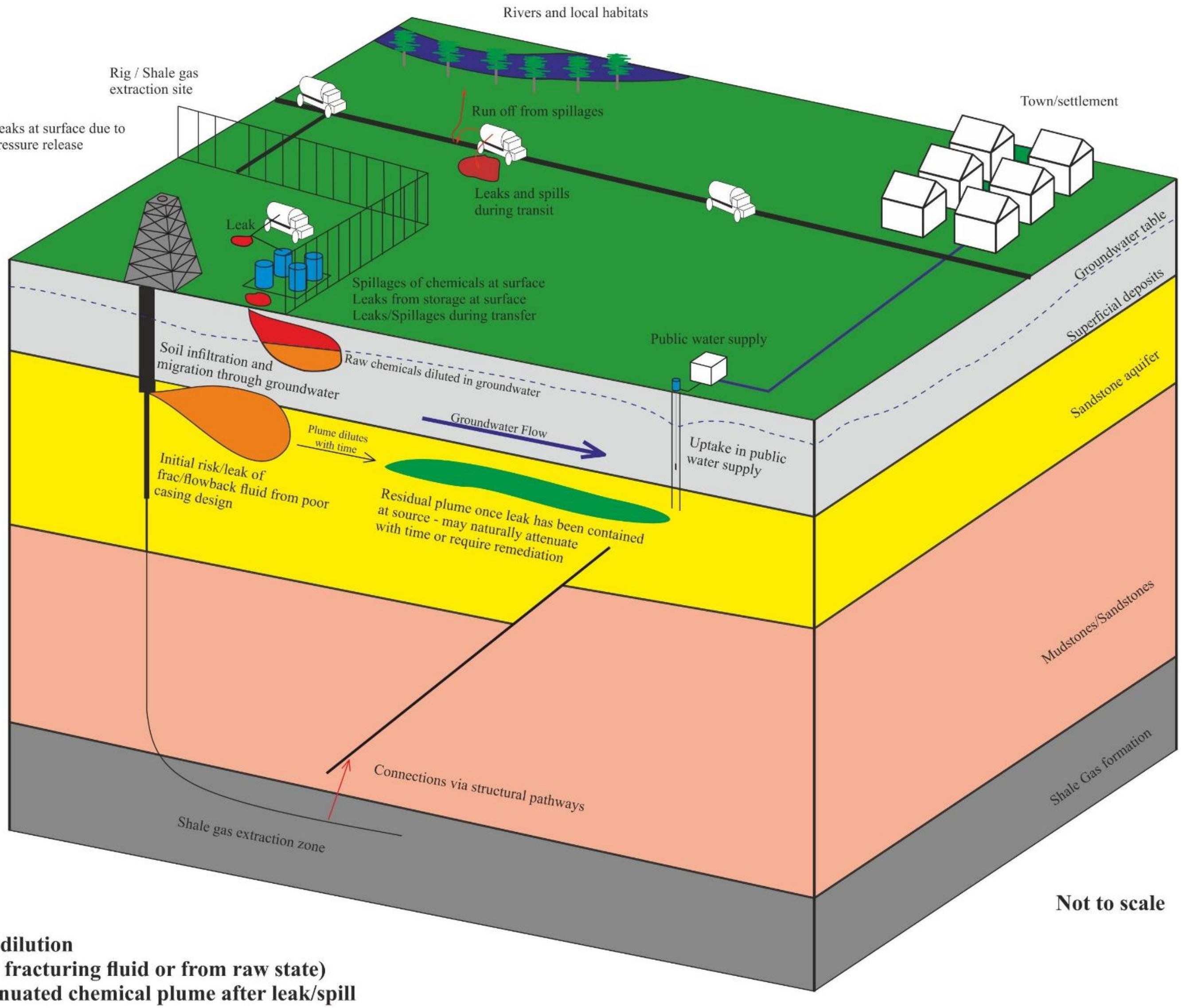
$$\text{Volume of material spilled per study area} \times (100\% - \text{percentage recovery of spilled material}) = 3 \text{ by } 27 \text{ matrix } (81 \text{ cells})$$

Main Sources:
(Raw chemicals)
- Spillages/leaks on site from storage
- Spillages/leaks during transit
- Spillages/leaks during transfer to storage

Diluted chemicals
- Well integrity leaks
- Leaks within fracturing zone

Main pathways:
- Soil infiltration
- Groundwater Flow
- Run off / rainwater
- Evaporation/volatilisation - vapour/gas phases (organic compunds)

Main receptors:
- Groundwater
- Soil
- Surface water courses
- Local habitats/ecology
- Groundwater supplies
- Local residents
- Air



Key:
Red = Raw chemical, minimal dilution
Orange = Chemical diluted (in fracturing fluid or from raw state)
Green = Diluted/naturally attenuated chemical plume after leak/spill contained at source

Figure 4.1 3D Conceptual Model demonstrating Sources, Pathways and Receptors in the vicinity of shale gas operations

4.5.2 On-site spills results

The results in tables 4-12 are presented in the following format. For the lowest returned result, this is the "low-low" scenario (Table 4-1) or equivalent for each return matrix. The moderate scenario is the "mod-mod" or equivalent scenario. Lastly, the highest returned result is the "high-high" or equivalent scenario.

The complete matrices for each impact scenario are listed in Appendix 3.

Table 4-12 On-site chemical spills for each of the three study areas

Study Area	Spills Per study area[1]			Volume spilt per study area			Volume not recovered per study area		
	No.			m^3			m^3		
	Lowest	Moderate	Highest	Lowest	Moderate	Highest	Lowest	Moderate	Highest
SE78b, SE88e	0.02 (0)	0.09 (0)	0.77 (1)	0.05	0.27	2.30	0.005	0.12	1.84
SE77c, SE77d, SE87a	0.02 (0)	0.35 (0)	1.92 (2)	0.05	1.06	5.76	0.005	0.479	4.608
SD33a, SD34a, SD43b	0.03 (0)	0.27 (0)	2.11 (2)	0.09	0.80	6.34	0.01	0.36	5.07

[1]Rounded to the nearest whole number

The results for the on-site spill cumulative impact assessment are shown in Table 4-12. The largest number of spills was associated with study area "SD33a, SD34a, SD43b" and "SD77c, SE77d, SE87a" with approximately 2 spills for the highest impact scenario. The lowest and moderate impact scenarios suggest that no spills would occur across all study areas. If a spill was to occur for a moderate impact scenario it is suggested between 0.1 m^3 and 0.5 m^3 would not be recovered across all study areas.

4.5.3 Off-site spills methodology

In order to determine an estimate of volume of spill not recovered off-site, the methodology described in section 4.2 was used to develop scenario matrices. Table 4-13 summarises the list of input parameters for the off-site spill scenario calculations.

Table 4-13 Variables for the determination of the volume of material potentially spilled off-site per study area

Variable	Impact			Source
	Low	Moderate	High	
No. of wells per pad	2	9	16	Table 1-1, row 2
No. of well pads	Min for 3000 m	Mean for 2100 m	Max for 1200 m	Table 3-3
Number of road spills per number of wells	1 spill per 19 wells (divide by 19)			Derived from Clancy et al. (2018)
Volume of material per spill	12.50 m^3	18.75 m^3	25 m^3	Table 1-1, row 10; 50%, 75%, 100% of volume lost

The volume of material per spill has been estimated on the following grounds. Using the value from Table 1-1 (row 10), a typical tanker can hold 25 m^3. The following estimation assumes that a range between 50% - 100 % of the tanker's contents could be lost to the environment as a result of a spill. A 100% loss scenario may be a major road traffic accident (RTA) resulting in significant damage to the storage unit. The 50% loss scenario may comprise a minor RTA, tampering, or a leak over the duration of the transport.

The following equations were used to determine the volume of material that could be spilled from an off-site source:

Equation 4-8 – Potential number of off-site spills per study area

$$\frac{\text{No. of wells per pad} \times \text{No. of well pads}}{\text{Number of road spills per number of wells (19)}} = \text{3 by 3 matrix (9 cells)}$$

Equation 4-9 – Potential volume of material released from off-site spills per study area

$$\text{Potential number of off-site spills per study area} \times \text{volume of material per spill} = \text{3 by 9 matrix (27 cells)}$$

4.5.4 Off-site spills results

The results for estimated off-site spills is shown in Table 4-14. The complete matrices for each impact scenario are listed in Appendix 4.

Table 4-14 Cumulative volumes of spills off-site for each study area

Study Area	Spills Per Study Area[1]			Cumulative Volume Spilt		
	No.			m^3		
	Lowest	Moderate	Highest	Lowest	Moderate	Highest
SE78b, SE88e	0.11 (0)	0.47 (0)	3.37 (3)	1.3	8.9	84.2
SE77c, SE77d, SE87a	0.11 (0)	1.89 (2)	8.42 (8)	1.3	35.5	210.5
SD33a, SD34a, SD43b	0.21 (0)	1.42 (1)	9.26 (9)	2.6	26.6	231.6

[1]Rounded to the nearest whole number

Study areas "SD33a, SD34a, SD43b" and "SE77c, SE77d, SE87a" again suggest the largest number of spills, with moderate scenarios suggesting one or two off-site spills, respectively. This results in a spilt volume of approximately 25 m^3 and 35 m^3.

4.5.5 Chemical spills discussion

As an initial estimate, the cumulative volumes of chemical spills provide insight into potential scenarios for a UK shale gas industry. As there are multiple input parameters that may vary significantly between sites and over time, the volumes should only be considered as indicative.

There are many factors which the estimates do not account for. For example, the type of spill/leak is not stated and could either be flow back fluid, produced water, fracturing fluid or fuel. The composition of the spill is a significant factor when considering the potential environmental and health impact. The number of spills is also derived from a data set, which is suggested to be an underestimate as certain spills go unreported due to either being unnoticed or unregulated (Clancy et al., 2018).

The ‘clean-up’ rate of off-site spills is also unknown, but are likely lower than those recorded on-site for multiple reasons. The mitigation measures off-site are significantly reduced as no capture points or other spill recovery procedures are available. A spill occurring off-site is also likely to be mobilised more quickly as it interacts with low permeability road surfacing which encourages run-off, subsequently infiltrating through soil or entering surface water bodies.

However, based on values given by Clancy et al (2018) using data from the US shale gas industry for on-site spills and data associated with the number of off-site spills from milk and fuel tankers in the UK, the estimates generated are using the most reliable available data.

5 Preliminary Hydrogeological Risk Assessment

The following section investigates the risk to groundwater resources, in the vicinity of proposed shale gas developments, which are protected under the Water Framework Directive (WFD). It assesses the potential for deterioration from 'good' groundwater body chemical status as part of the UK's River Basin Management Plans (RBMPs) (Environment Agency, 2016b) by screening contaminant concentrations against WFD Threshold Values.

WFD environmental objectives for groundwater include preventing or limiting inputs of pollutants and preventing deterioration of status (EA, 2016c). In this context, an emerging shale gas industry introduces a new pressure that needs to be considered as part of the risk assessment and compliance process. The release of chemicals into groundwater that is evaluated in the following section is hypothetical, and is assumed to result from an unexpected or unintended incident such as well failure in the subsurface. Many controls are in place to ensure that release of pollutants to the environment does not occur and does not adversely impact WFD environmental objectives, including:

- Local governments and/or the EA review operator plans to assess the environmental impacts under the England and Wales Environmental Permitting Regulations (Environmental Permitting (England and Wales) Regulations 2016);
- Governments and agencies restrict the use of hazardous substances for hydraulic fracturing; and
- The WFD states that hazardous substances must be prevented from entering groundwater and non-hazardous pollutants limited so as not cause pollution ('prevent or limit', Environment Agency, 2017). Therefore control measures are selected to achieve this objective, as described in Section 2.2 and within Section 4.

Throughout this assessment it is assumed all pollution prevention measures have been undertaken prior to and during shale gas operation and a rare incident (e.g. well failure or leak) has produced an unplanned release of pollutants into the sub-surface which enters groundwater. In terms of a shale gas well, this represents a leak which goes unnoticed and continually adds contaminants into an aquifer. However in reality, any leak which is detected would be fixed as soon as possible to limit any further release. As such, a continuous leak is considered the 'worst case scenario'.

Using the analytical Environment Agency Remedial Targets Methodology (RTM) (Carey et al., 2006) and the Ogata-Banks equation (Ogata and Banks, 1961), the risk associated with this incident is assessed to provide a preliminary assessment of the impact on local, district and regional scales as defined in section 1.3. Chemical spills at the surface were not assessed within this risk assessment.

5.1 METHODOLOGY

Three aquifers were selected based on their proximity to the areas where shale gas exploration activity has started. Two aquifers were selected in the Fylde Basin, Lancashire; a glacial sand and gravel aquifer which forms a Secondary Aquifer and the Sherwood Sandstone Group which forms a Principal Aquifer. The sand and gravel aquifer is utilised for private supply and the Sherwood Sandstone is used for public supply where it is close to the surface, although this groundwater is primarily anoxic (Ward et al., 2018).

For the Vale of Pickering, the main aquifer in the region is the Corallian Group which is currently utilised for public supply around the margins of the Vale where it crops out. In the centre of the Vale, the Corallian Group is much deeper and is overlain by the West Walton, Ampthill Clay and Kimmeridge Clay Formations (Reeves et al, 1978; Bearcock et al, 2016). Here the groundwater is anoxic (Ward et al., 2017) due to the confined nature of the aquifer.

To assess the hydrogeological risk associated with a pollutant release, the following conditions were assumed. The release occurs due to a well failure at the depth at which the aquifer is present, therefore modelling a release which directly enters groundwater. Under this assumption the release does not interact with unsaturated or saturated soil. As the soil pathway is not relevant, only the "level three groundwater" assessment within the RTM was completed.

5.1.1 Aquifers

Aquifer specific data were selected from published literature where available (Allen et al., 1997; Bishop and Lloyd 1990 in Steventon-Barnes; 2001; Steventon-Barnes, 2001; Wang et al., 2013; Bearcock et al., 2016; Ward et al., 2018). However, where data for specific aquifers was unavailable, more general data was selected (Lewis, 1989) or calculated where appropriate. For example, the geometric mean for hydraulic conductivity of the Corallian Oolite Formation, based on 25 core plug samples, was 1.8 x 10^{-4} md^{-1} (Allen et al., 1997). This is relatively low, and is thought not to represent the fractured nature of the Corallian Group, which can dominate groundwater flow, and lead to transmissivity values of 3500 m^2 d^{-1} (Allen et al., 1997). Previously measured high flow rates, coupled with the limited number of samples and lack of field tests suggest that the hydraulic conductivity value may be unrepresentative of the wider aquifer, and therefore was omitted from the risk assessment.

Using the thickness of the Corallian Group (168 m, in Bearcock et al., 2015) and the geometric mean of measured transmissivity (318 m^2 d^{-1} in Allen et al., 1997) and assuming T = Kb, where b is aquifer thickness, the calculated hydraulic conductivity is approximately 1.89 m d^{-1}. This is also in the range for a karstic limestone (Lewis, 1989) and given the Corallian Group is likely karstic (Lewis et al., 2006), the calculated hydraulic conductivity was used within the RTM.

The conceptual model for the Corallian group differs from the aquifers of the Fylde Basin. It is assumed that the Corallian Group is a dual domain aquifer, with matrix porosity assumed to be zero (immobile domain). As such, all flow is assumed to occur through the fracture porosity (mobile domain) with advection being the sole transport mechanism. Diffusion between the matrix and fractures is assumed to be negligible. By using this approach, the transmissivity values given by Allen et al., (1997) are satisfied and fracture flow can be modelled.

Fracture porosity is unavailable for the Corallian Group in Yorkshire, therefore the following assumptions are made. It is assumed that all fractures are linear, laterally continuous and all have the same aperture size and fracture spacing. All fracture dimensions and properties are validated by the following criteria:

1. Most fracture porosity is within the range of 0.001 – 1% (Freeze and Cherry, 1979 in Worthington, 2015);
2. Common fracture spacing in bedrock aquifers is around 10 m (Buckley, 2000, Marice et al, 2012, Paillet, 2004 in Worthington 2015); and
3. Geometric mean for transmissivity of the Corallian Group is around 320 m^2 d^{-1} (Allen et al., 1997).

Using the equation 5-1, where ρ is the density of water, g is acceleration due to gravity, a is fracture aperture and μ is dynamic viscosity (1.3×10^{-3} Pa s at 10°C) a fracture aperture of 2 mm gives a transmissivity of approximately 435 m^2 d, close to criteria number 3, listed above.

Equation 5-1 – Fracture Transmissivity

$$T = \frac{\rho g a^3}{12\mu}$$

Therefore an aperture of 2 mm and a fracture spacing of 10 m was selected to estimate effective porosity. Fracture porosity, (f_n) was calculated from the number of fractures present (equation 5-2, f_D) and the resultant void space (equation 5-3, V_v) as a fraction of the effective aquifer width (equation 5-4), where b is aquifer thickness (168 m) and d is fracture spacing (10 m).

Equation 5-2 – Number of fractures

$$f_D = \frac{b}{(a + d)}$$

Equation 5-3 – Void volume

$$V_v = a \times f_D$$

Equation 5-4 – Fracture porosity

$$f_n = \left(\frac{V_v}{b}\right) \times 100$$

From the assumptions regarding fracture properties and using the equations above, a fracture porosity of 0.02% was calculated for the Corallian Group. This is within the range given by Freeze and Cherry (1979), with an aperture which yields a similar transmissivity to the geometric mean given by Allen et al., (1997).

It was assumed the aquifer is homogenous and isotropic with steady state flow. The aquifer specific parameters (hydraulic conductivity, porosity, f_{oc}) are constant over the length of the flow path.

5.1.2 Contaminants and Guidance Values

The chemicals assessed were selected based on their detrimental effect to human health or the environment and due to their presence in produced water and/or flowback water from previous shale gas operations in North America. BTEX (benzene, toluene, ethylbenzene and xylene), chloride anions (Cl^-) and sodium cations (Na^+) have all been detected at elevated concentrations. BTEX is toxic to human health (WHO, 2003a; WHO, 2003b, WHO, 2003c, WHO 2003d) and the environment, whereas chloride within groundwater is generally more of a concern to the environment only (WHO, 2003e, WHO, 2013f). At elevated concentrations chloride is toxic to aquatic life (Collins and Russel, 2009; Corsi et al., 2010; Elphick et al., 2011) and can corrode pipes leaching metals into groundwater (WHO, 2003e). Elevated sodium has also been linked to hypertension in humans (e.g. Sung Kyu Ha, 2014) which overtime may cause cardiovascular diseases.

The initial concentrations of BTEX were chosen based on Benko and Drewes (2008, in Shores et al., 2017), which are displayed in Table 2-4. For chloride and sodium, a value of 200,000 mg/L was selected which is within the range given in Table 1-1 (>8,000 - >400,000 mg/L). Half-life and organic carbon partition coefficients were selected from literature (Thierrin et al., 1993; Aronson and Howard, 1997; Poulson et al., 1997; Lui and Mao, 2000; CL:AIRE, 2011; EPA, 2014). Half-life for anaerobic degradation in groundwater was selected due to the presence of anoxic groundwater.

An accurate half-life was not assigned to the chloride or sodium cation spreadsheets as chloride does not naturally degrade in groundwater or adsorb onto surfaces. However in order for the spreadsheets to function a value must be entered. Therefore to simulate a lack of degradation, the half-life for chloride and sodium cations was set at 9.99×10^{99} days.

To simulate a release through a well failure at aquifer depth, it was assumed a two metre section of casing failed producing a constant plume of 0.15 m width perpendicular to the flow direction. Dispersivity was modelled in two directions and values were based on percentages of the flow path length (Table 5-1).

The set of guidance values selected for the hydrogeological risk assessment were the WFD threshold values for the general chemical (status) test (UKTAG, 2012). Whilst it is acknowledged that a release might impact on drinking water sources and/or surface waters, the groundwater body is the initial receptor following a release of pollutants and development of a plume within the scenario considered here.

5.1.3 Compliance Point

For each of the aquifers considered, the compliance point was gradually increased from 10 m to 250 m allowing concentration changes to be investigated. The compliance point was then adjusted to find the distance at which the concentration of the pollutant fell below the relevant WFD threshold value. If concentrations were below their respective threshold values before 250 m than the modelling exercise was stopped.

The input parameters used across the RTM is shown in Table 5-1. Conceptual models for each aquifer are shown in Figures 5.1 to 5.3.

Table 5-1 Input parameters and justification for the hydrogeological risk assessment using the EA RTM

Properties	Parameter	Value	Units	Reference/Justification
Fylde Permo-Triassic Sandstone Aquifer	Saturated aquifer thickness	200	m	Allen et al (1997) state the actual thickness of the Fylde PTS is 200m. The effective aquifer thickness depends on the maximum depth of a pumping well due to the presence of anisotropy in the form of low permeability clay layers. However, as local site specific data is limited 200m was selected.
	Hydraulic conductivity (K)	5.3	m d^{-1}	Geometric mean of pumping test data for the Fylde PT-Sst (Allen et al., 1997). Pumping test data was selected over core data as the whole aquifer is being tested. The high hydraulic conductivity is reflecting the fractured nature of the sandstone.
	Effective porosity (n)	23	%	Geometric mean for core porosity data in the Fylde sandstone (Allen et al., 1997)
	Fraction of organic carbon (f_{oc})	0.08	fraction	Within range in Steventon-Barnes (2001) for Triassic Sandstone
	Bulk density (ρ)	2.65	g cm^{-3}	Density of sandstone
	Hydraulic gradient	0.001	-	Value selected for a decrease in 1 m per 1000 m (R. Ward, pers. comm. Dec 2018)

Properties	Parameter	Value	Units	Reference/Justification
Fylde Sand and Gravel Aquifer	Saturated aquifer thickness	30	m	Estimated from cross-section in Ward et al (2018)
	Hydraulic conductivity (K)	10	m d^{-1}	Within range for sand and gravel (Lewis, 1989).
	Effective porosity (n)	30	%	Within range for porosity of sand and gravel (Fetter, 1994)
	Fraction of organic carbon (f_{oc})	0.0005	fraction	Measured for sand and gravel (Wang et al., 2013).
	Bulk density (ρ)	1.68	g cm^{-3}	Within range for bulk density of sand and gravel
	Hydraulic gradient	0.001	-	Value selected for a decrease in 1 m per 1000 m (R. Ward, pers. comm. Dec 2018)
Corallian Limestone Aquifer	Saturated aquifer thickness	168	m	Thickness of Corallian Group (Bearcock et al., 2016)
	Hydraulic conductivity (K)	1.89	m d^{-1}	Calculated using T=kb. T = 318 m^2/d (Allen et al., 1997), b = 168 m (Bearcock et al., 2016)
	Effective porosity (n)	0.02	%	Estimated based on assumptions regarding fracture aperture and spacing over the aquifer thickness
	Fraction of organic carbon (f_{oc})	0.45	fraction	Within range for Lincolnshire Limestone (Bishop and Lloyd, 1990 in Steventon-Barnes, 2001). F_{oc} for Corallian unavailable
	Bulk density (ρ)	2.71	g cm^{-3}	Bulk density of limestone
	Hydraulic gradient	0.001	-	Value selected for a decrease in 1 m per 1000 m (R. Ward, pers. comm. Dec 2018)
	Fracture Aperture	0.0002	m	Estimated using Equation 5-1.
	Fracture Spacing	10	m	Assumed (Buckley, 2000, Marice et al, 2012, Paillet, 2004 in Worthington 2015)
Source Zone Dimensions	Width of plume in aquifer in aquifer at source	0.15	m	Simulating perforation of 2.0 m of well screen and estimating the volume likely to be released.
	Plume thickness at source	2.0	m	
-	Time since pollutant entered groundwater	$1x10^{100}$	days	Recommended time within RTM spreadsheets.
Dispersivities	Longitudinal	10% of flow path	m	Standard method in RTM spreadsheets. No other data available.
	Transverse	1% of flow path	m	
Benzene	Half-life ($t_{1/2}$)	210	days	Mean value for measured anaerobic degradation (Aronson and Howard, 1997)
	Organic carbon partition coefficient (K_{oc})	67.61	l kg^{-1}	Literature value (CL:AIRE, 2011)
	Threshold Value	0.75	µg l^{-1}	Water Framework Directive (2015)
	Concentration	27	mg l^{-1}	Benko and Drewes (2008) in Shores et al (2017) (Table 2-4)

Properties	Parameter	Value	Units	Reference/Justification
Toluene	Half-life ($t_{1/2}$)	100	days	Anaerobic degradation rates in groundwater (Thierrin et al., 1993)
	Organic carbon partition coefficient (K_{oc})	166	$l\ kg^{-1}$	Literature value (Poulson et al., 1997)
	Threshold Value	4.0	µg/l	UKTAG (2013)
	Concentration	37	$mg\ l^{-1}$	Benko and Drewes (2008) in Shores et al (2017) (Table 2-4)
Ethylbenzene	Half-life ($t_{1/2}$)	230	days	Anaerobic degradation rates in groundwater (Thierrin et al., 1993)
	Organic carbon partition coefficient (K_{oc})	295	$l\ kg^{-1}$	Literature value (Poulson et al., 1997)
	Threshold Value	0.75	$\mu g\ l^{-1}$	Water Framework Directive (2015), value for benzene used
	Concentration	19	$mg\ l^{-1}$	Benko and Drewes (2008) in Shores et al (2017) (Table 2-4)
Xylene	Half-life ($t_{1/2}$)	225	days	Anaerobic degradation rates in groundwater (Thierrin et al., 1993)
	Organic carbon partition coefficient (K_{oc})	158	$l\ kg^{-1}$	Within range of literature values for m-p- and-o-Xylene.
	Threshold Value	15.5	µg/l	Water Framework Directive (2015)
	Concentration	0.611	$mg\ l^{-1}$	Benko and Drewes (2008) in Shores et al (2017) (Table 2-4)
Chloride (Cl^-)	Half-life ($t_{1/2}$)	9.9×10^{99}	days	Simulate lack of degradation.
	Organic carbon partition coefficient (K_{oc})	-	$l\ kg^{-1}$	Unavailable / N/A
	Threshold Value	188	mg/l	Water Framework Directive (2015)
	Concentration	200,000	mg/l	Within range given in table 1-1 (Adapted from Olsen et al., 2016)
Sodium Cation (Na^+)	Half-life ($t_{1/2}$)	9.9×10^{99}	days	Simulate lack of degradation.
	Organic carbon partition coefficient (K_{oc})	-	$l\ kg^{-1}$	Unavailable / N/A
	Threshold Value	150	mg/l	Water Framework Directive (2015)
	Concentration	200,000	mg/l	Within range given in table 1-1 (Adapted from Olsen et al., 2016)

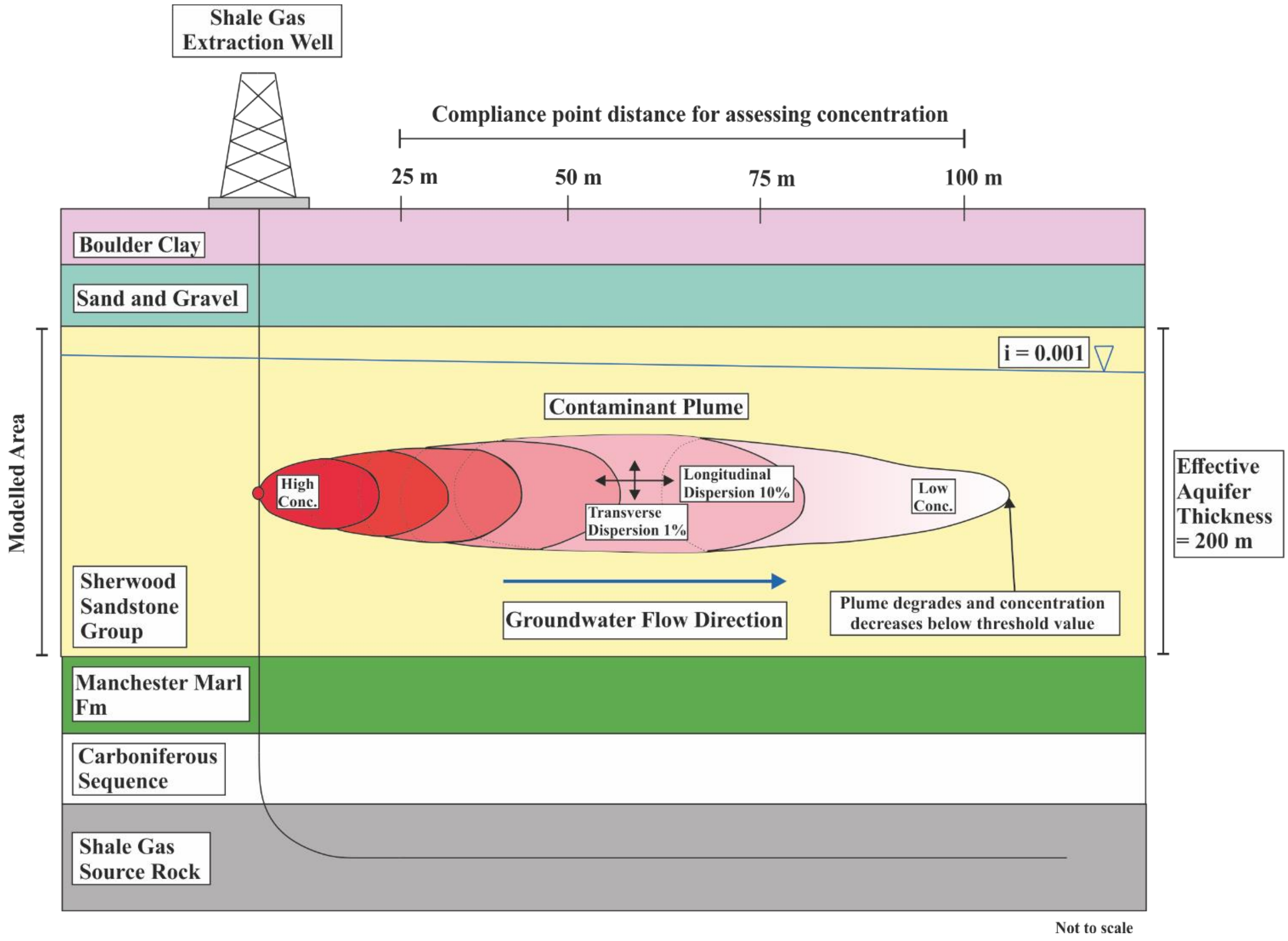


Figure 5.1 Conceptual Model for Fylde Permo-Triassic Sandstone Aquifer showing a continuous release of contaminants. Shown is a snapshot in time where the plume has migrated towards the compliance point, at which concentration is below the threshold value.

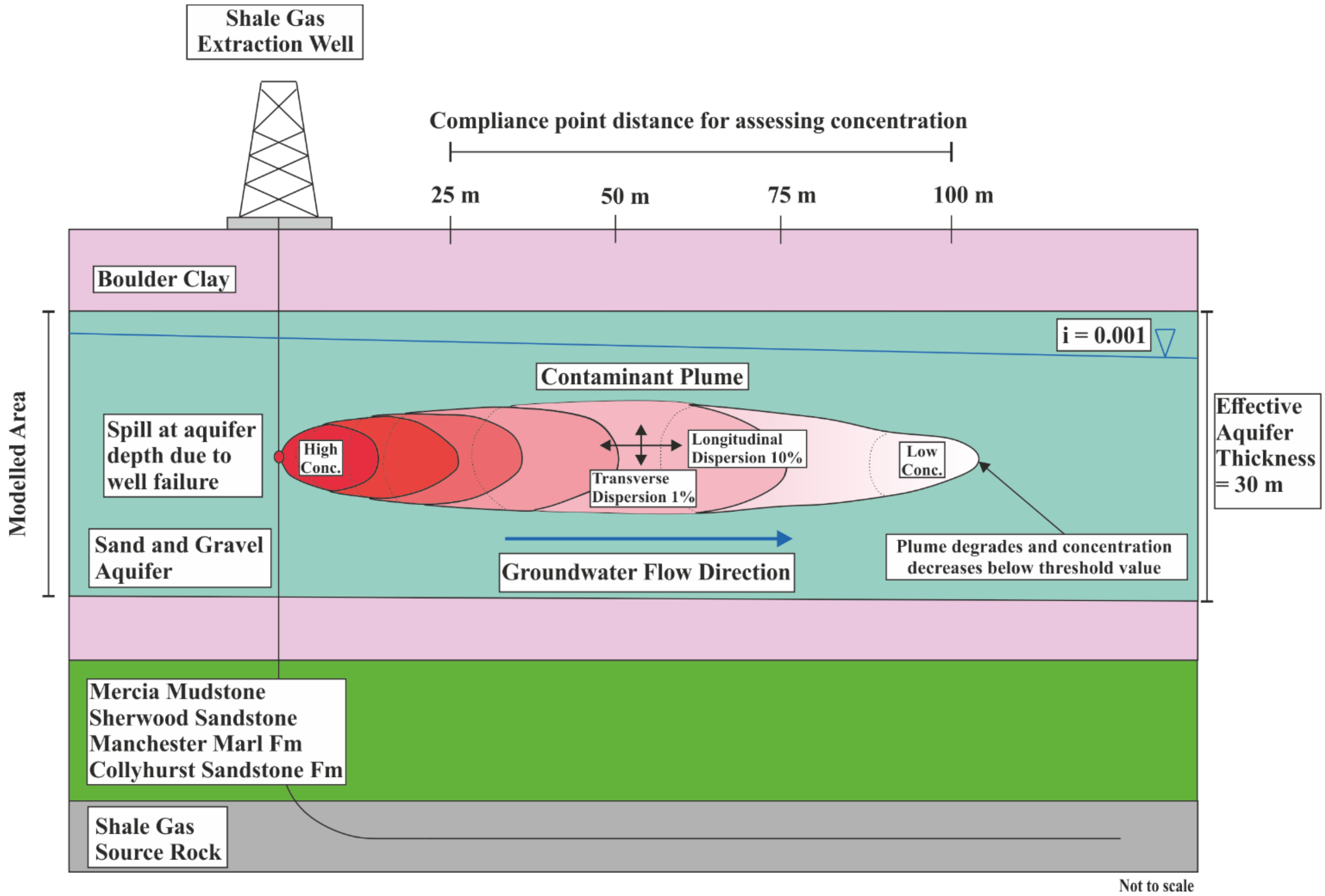


Figure 5.2 Conceptual Model for Fylde Sand and Gravel Aquifer showing a continuous release of contaminants. Shown is a snapshot in time where the plume has migrated towards the compliance point, at which concentration is below the threshold value.

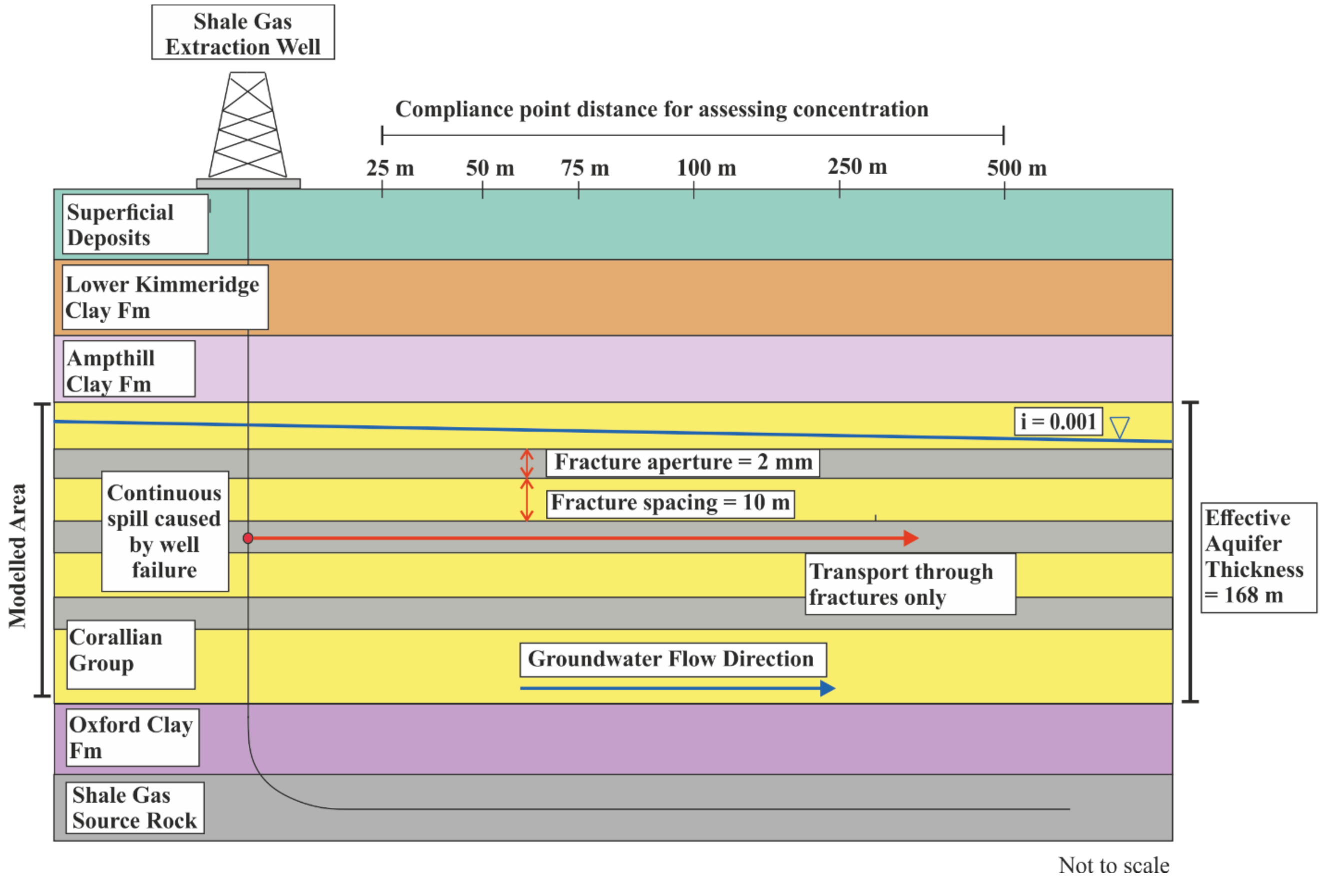


Figure 5.3 Conceptual Model for the Corallian Group Aquifer showing a continuous release of contaminants. Shown is the set-up of the model. Flow occurs only through fractures, with matrix porosity assumed to be zero (immobile domain).

5.2 RESULTS

The results from the three modelled aquifers is shown in table 5-2.

Table 5-2 Results from the RTM spreadsheets showing concentrations of BTEX, Cl^- and Na^+ at different compliance points for the three modelled aquifers. (Abbreviations: C_0 = Initial Concentration, TV = Threshold Value, PT Sst = Permo-Triassic Sandstone, SG = Sand and Gravel, CG = Corallian Group, B = Benzene, T = Toluene, X = Xylene,). The WFD threshold value for ethylbenzene is unavaible. *Threshold value for benzene used.

Release		C_0	Concentration at set distance away from spill (µg/L)						WFD TV	Distance where concentration < TV
		µg/L	25m	50m	75m	100 m	250 m	500 m	(µg/L)	(m)
PTS	B	27,000	17.50	0.63	-	-	-	-	0.75	49
	T	37,000	2.63	-	-	-	-	-	4.0	24
	E	19,000	15.10	0.612	-	-	-	-	0.75	49
	X	611	0.462	-	-	-	-	-	15.5	8
	Cl^-	200,000,000	2,130,000	584,000	264,000	150,000		-	188,000	90
	Na^+	200,000,000	2,130,000	584,000	264,000	150,000	-	-	150,000	101
SG	B	27,000	36.90	2.09	0.25	-	-	-	0.75	62
	T	37,000	9.04	0.18		-	-	-	4.0	30
	E	19,000	30.30	1.89	0.24	-	-	-	0.75	61
	X	611	0.94	-	-	-	-	-	15.5	9
	Cl^-	200,000,000	2,130,000	584,000	264,000	150,000		-	188,000	90
	Na^+	200,000,000	2,130,000	584,000	264,000	150,000	-	-	150,000	101
CG	B	27,000	285.00	77.5	34.800	19.5	2.99	0.69	0.75	481
	T	37,000	387	104	46.3	25.8	3.73	-	4.0	243
	E	19,000	201.00	54.6	24.5	13.8	2.12	0.49	0.75	411
	X	611	6.45	-	-	-	-	-	15.5	16
	Cl^-	200,000,000	2,130,000	584,000	264,000	150,000	-	-	188,000	90
	Na^+	200,000,000	2,130,000	584,000	264,000	150,000			150,000	101

For both aquifers in the Fylde, BTEX concentrations are below their respective threshold value at distances less than 65 m and less than 10 m for xylene. In the Corallian Group, BTEX concentrations were above threshold values at a significantly greater distance with benzene present at elevated concentrations up to 481 m. Out of all the BTEX chemicals, benzene and ethylbenzene were above their threshold values over the greatest distance, with elevated concentrations still present at 400 m and beyond within the Corallian Group aquifer. The Permo-Triassic Sandstone aquifer had the shortest compliance point distance for BTEX with all concentrations below threshold values before 50 m.

Chloride and sodium behaved identically in all models and was consistently below its threshold value at 90 m and 101 m, respectively.

The change in contaminant concentrations between each compliance point for all aquifers and distances is shown in Table 5-3. The RTM spreadsheets are included as Appendix 6.

Aquifer	Spill	C_0	Change in contaminant concentrations between each compliance point (μg/L)					
		μg/L	25m	50m	75m	100 m	250 m	500 m
PTS	B	27,000	26,983	16.9	-	-	-	-
	T	37,000	36,997	-	-	-	-	-
	E	19,000	18,985	14.5	-	-	-	-
	X	611	-	-	-	-	-	-
	Cl^-	200,000,000	197,870,000	1,546,000	320,000	114,000	-	-
	Na^+	200,000,000	197,870,000	1,546,000	320,000	114,000	-	-
SG	B	27,000	26,963	34.8	1.8	-	-	-
	T	37,000	36,991	9	0	-	-	-
	E	19,000	18,970	28.4	1.7	-	-	-
	X	611	-	-	-	-	-	-
	Cl^-	200,000,000	197,870,000	1,546,000	320,000	114,000	-	-
	Na^+	200,000,000	197,870,000	1,546,000	320,000	114,000	-	-
CG	B	27,000	26,715	208	43	15.3	16.5	2.3
	T	37,000	36,613	283	58	20.5	22.1	-
	E	19,000	18,799	146	30	10.7	11.7	1.6
	X	611	605	-	-	-	-	-
	Cl^-	200,000,000	197,870,000	1,546,000	320,000	114,000	-	-
	Na^+	200,000,000	197,870,000	1,546,000	320,000	114,000	-	-

Table 5-3 Change in contaminant concentrations between each compliance point for all three modelled aquifers

5.2.1 Scenario Analysis

Within the hydrogeological risk assessment a specific set of values are inputted into the RTM spreadsheets. They are based on measured data where available, but in essence only provide insight into one unique scenario, for example one measurement of BTEX concentrations in produced water. There is also uncertainty regarding the aquifer property parameters used within the assessment. In some instances data is readily available for porosity and hydraulic conductivity (Allen et al., 1997), in others, data was selected from typical ranges of values (Lewis, 1989) or calculated from other measured parameters such as transmissivity. With the latter, there are increased underlying uncertainties and as such, different scenarios must be investigated to further understand any potential risk.

Two new scenarios are generated and termed as ‘low’ and ‘high’, with the moderate scenario considered to be the main assessment used to produce the results in section 5.2. Both scenarios are selected to test the range of values in any data sets selected, if available. Where a range of reference values was unavailable, arbitrary values were selected to produce one of two outputs. The low scenario is designed to produce a leak containing a low concentrations of BTEX, chloride and sodium which has mobility restricted by unfavourable aquifer transport conditions. The high scenario investigated the opposite; a leak containing a significantly high concentration of all chemical species which enters an aquifer with favourable transport conditions. The input parameters used for each scenario are shown in Table 5-3.

Aquifer	Parameter	Scenario			Units	Reference
		Low	Moderate	High		
Permo-Triassic Sandstone	K	3.4	5.3	7.4	$m\ d^{-1}$	Range given in Allen et al., (1997)
	n_e	5.4	23	31	%	
Sand and Gravel	K	5	10	100	$m\ d^{-1}$	Range given in Lewis (1989)
	n_e	20	30	50	%	Range in Fetter (1994)
Corallian Group	K	0.1	1.89	100	$m\ d^{-1}$	Within range given by Lewis (1998) for Karstic Limestone
	α	1	2	3.5	mm	Calculated from transmissivity data (Allen et al., 1997) using equation 5-1.
	n_e	0.01	0.02	0.035	%	Calculated using equation 5-2 to 5-4.
All	i	0.0001	0.001	0.01	N/A	Arbitrary
	Benzene	1	27	100	$mg\ l^{-1}$	Arbitrary low and high values
	Toluene	1	37	100	$mg\ l^{-1}$	
	Ethylbenzene	1	19	100	$mg\ l^{-1}$	
	Xylene	0.1	0.661	50	$mg\ l^{-1}$	
	Cl^-	8,000	200,000	400,000	$mg\ l^{-1}$	Table 1-1 (adapted from Olsen et al., 2016)
	Na^+	8,000	200,000	400,000	$mg\ l^{-1}$	

Table 5-4 Input values for the low and high scenario analysis. The moderate scenario was within the initial assesment.

For the Corallian Group, as a range of fracture apertures and fracture porosity are not available, input variables were calculated using equations 5-1 to 5-4 and were constrained by transmissivity data for the area (Allen et al., 1997). In the Corallian Group, the lowest and highest transmissivity values are given as 38 $m^2\ d^{-1}$ and 2249 $m^2\ d^{-1}$, respectively (noted as the 25th and 75th percentile). Using a fracture aperture of 1 mm for the low scenario and 3.5 mm for the high scenario produces transmissivity values of approximately 50 $m^2\ d^{-1}$ and 2,300 $m^2\ d^{-1}$ and equates to a fracture porosity of 0.01% and 0.035%.

Parameters associated with retardation were not altered for each new scenario as the spreadsheets are modelling steady state conditions with the pollutant present in groundwater for $1x10^{100}$ years. All contaminant concentrations eventually reaches the compliance point and retardation has no effect on the results.

The results of the scenario analysis are shown in Figure 5-4

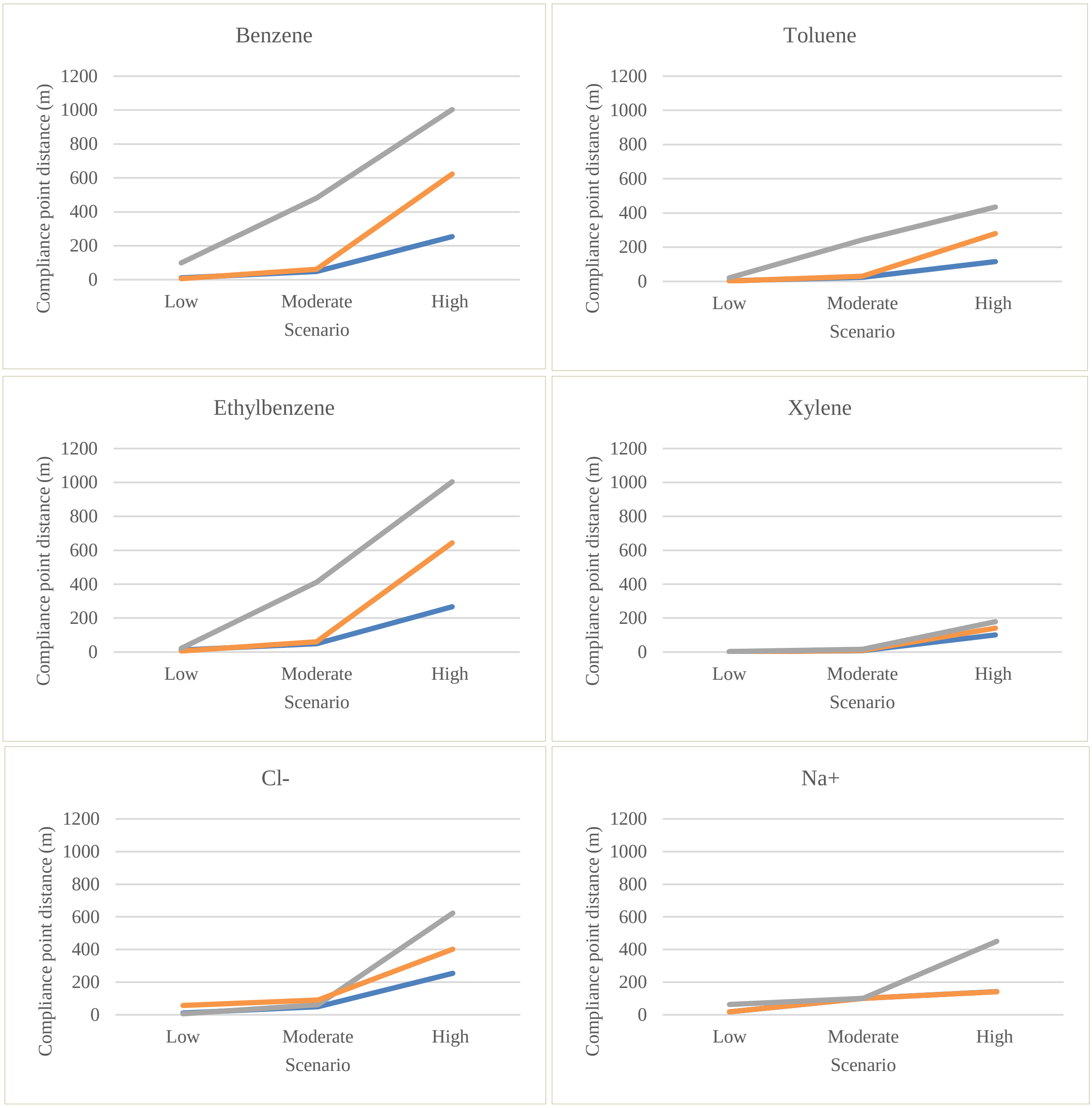


Figure 5.4 Results for all chemical species for the Scenario Analysis (Grey line represents the Corallian, the Orange line Sand and Gravel and the blue line represents the Permo-Triassic Sandstone Aquifer)

The results for the low scenario shows that all concentrations were below their threshold values before 100 m, with the highest compliance point distance associated with benzene in the Corallian Group which was above threshold values up to 99 m. The Permo-Triassic sandstone aquifer showed the smallest increase in compliance point distance when compared to the other two aquifers even under the high scenario. Here, all concentrations were below threshold values before 150 m, with the exception of benzene and ethylbenzene which fell below their respective values at 254 m and 267 m.

The sand and gravel aquifer showed a large increase in compliance point distance with an order of magnitude increase associated with benzene and ethylbenzene at around 620 m and 640 m, respectively. The compliance point for toluene increased significantly under the high scenario, but was below threshold values at 280 m. Xylene, chloride and sodium were all below their threshold values before 150 m.

In the Corallian Group under a high scenario, the largest increases in compliance point distance was encountered on average, with benzene and ethylbenzene still above threshold values at 1,000 m. Toluene, chloride and sodium were also above threshold values at 450 m.

5.3 DISCUSSION

The results of the preliminary hydrogeological risk assessment suggest that a risk from an unplanned release of BTEX, chloride and sodium from a single shale gas well is not significant at a district or regional scale due to the size of a release and attenuation processes. At a local scale and on the basis of the moderate scenario considered, an impact could be observed a distance of up to approximately 90 m for chloride and between maximum distances of 62 m (sand and gravel aquifer) and 481 m (Corallian Group) for BTEX.

In aquifers in which groundwater has a lower mean advective velocity ($\bar{\mathrm{v}}$), the risk is reduced further due to slower travel times allowing for increased attenuation (degradation) over shorter distances. The relationship between mean advective velocity, specific discharge (Darcy flux) (q) and effective porosity (n_e) is given in equation 5-5.

Equation 5-5 Linear Velocity

$$\bar{\mathrm{v}} = \frac{q}{n_e}$$

Accordingly, any aquifer with a low porosity is likely to produce high velocities within groundwater making it more difficult for degradation processes to occur.

In the Permo-Triassic Sandstone aquifer the porosity is moderately sized at 23%. As a result a low mean advective velocity is produced, allowing contaminants to become degraded and fall below threshold values over a shorter distance. In comparison, the Corallian Group has elevated concentrations of contaminants over the largest distance and the lowest degradation of all three aquifers (Table 5-3), due to a low effective porosity (0.02%) and hence slower degradation rates. This is evident, for example, as benzene is below its threshold value after an additional 485 m in the Corallian, when compared to the sandstone and sand and gravel aquifer. It is also shown in Table 5-3.

The scenario analysis indicated that the risk associated with the Permo-Triassic sandstone aquifer is lower when compared to the sand and gravel or the Corallian aquifer. Even under a high scenario, with large concentrations of BTEX, compliance point distances were all below 300 m due to the low intergranular hydraulic conductivity within this aquifer (Allen et al., 1997). The risk is suggested to be higher in the remaining two aquifers which saw compliance point distances increase by 600 m in some instances. These aquifers have a large range of potential hydraulic conductivities and porosities, especially in the fractures of the Corallian Group, and even though input variables were constrained using references, there is a large underlying uncertainty. However, as many arbitrary values are used for the high scenario, it is considered to be unrepresentative of actual conditions within these areas and included for illustrative purposes only. The moderate scenario is considered to be the most representative of risk within the assessment.

Of course there are many additional factors which must be considered when assessing the contaminant risk to the environment and human health. By examining the source pathway receptor model discussed in section 4.5, this risk can be further examined. For example, the source of elevated BTEX concentrations originates in the shale gas source rock which can have variable effects on produced water chemistry. High BTEX concentrations within source rocks elevate the risk as contaminants are leached into produced water at higher concentrations. The high scenario analysis attempted to investigate this by including an initial concentration of BTEX between 50 and 100 mg L^{-1}. Conversely, if BTEX are absent, or exist at low concentrations, the risk is significantly reduced, shown by the low scenario analysis with BTEX concentrations at 1 mg L^{-1} or lower.

In most cases the pathway expressed in the methodology will not exist. A well failure is an unplanned incident with preventative measures in place to inhibit fluid loss. Predicting well failures as a result, is difficult, as previously discussed (Section 4.4). However, in the event of a well failure the magnitude of the incident and hence the mass of fluid released, as well as transport mechanisms and ease of flow within any aquifer, will govern any associated risk.

The final link to consider is the receptor. The presence, as well as nature, of a sensitive receptor in proximity to a shale gas well must be considered in any risk assessment. If sensitive receptors are present within 65 m to 485 m then, suggested by the modelled results, a risk associated with BTEX, sodium and chloride exists. If a sensitive receptor is absent, the risk is automatically mitigated.

Given the modelled concentrations, a well failure at aquifer depth is thought to present an acute high level impact up to 65 m away for the Fylde and 485 m for the Vale of Pickering. It is expected that a chronic low level impact to aquifers on a district or regional scale would not be produced even if a moderate number of wells fail, given the large area of land covered by each of the RBMPs. The best case scenario, i.e. no failures or release of contaminants, is the most likely to occur due to strict regulations within the UK. However if a failure was to occur, it is suggested by the modelled results, that there is a possibility of a very rare acute and high level impact on local scales in the vicinity of the modelled loss.

The results from the Corallian Group identify that a more persistent risk is associated with a contaminant spill within an aquifer with significant fracture flow. Analogous settings, with fractures of a similar aperture and spacing, are likely to experience a similar circumstance, with contaminant concentrations above threshold values over larger distances when compared to a sandstone, a sand and gravel or other matrix flow dominated aquifer settings.

Further evidence is required to assess the risk on district or regional scales and to assess the impact if multiple wells fail simultaneously.

6 Impacts on Groundwater Resources in the Case Study Areas

6.1 BACKGROUND

Shale gas operations require water for several purposes, including drilling and well construction operations, hydraulic fracturing, sanitation and equipment washing. As stated in Section 1 and 2 definitive plans for, and details of, future shale gas operations in England are as yet unknown. Site-specific circumstances will determine the actual demand for water at any given well pad.

For this study, the range of requirements of water for shale gas operations was informed by published literature.

6.2 WATER USE FOR HYDRAULIC FRACTURING

6.2.1 Methodology

The following methodology is described in section 4.2. A low, moderate and high pressure/impact scenario was applied to estimate probable volumes of water that would be required at different scales, for each of the three case study areas. The volume of water per well was selected from Table 1-1 and three impact scenarios were generated accordingly, shown in Table 6-1.

Table 6-1 Input parameters and variables for volume of water consumed during fracturing

Variable	Impact			Source
	Low	Moderate	High	
No. of wells per pad	2	9	16	Table 1-1, row 2
No. of well pads	Min for 3,000 m	Mean for 2,100 m	Max for 1,200 m	Table 3-3
Volume of water required per fracture programme per well	10,000 m^3	26,250 m^3	42,500 m^3	Table 1-1, Row 9

The lower limit of water volume usage in Table 1-1 of 1,000 m^3 was dismissed. A lower limit of 10,000 m^3 was selected instead which is more in line with previous operations (DECC, 2014; Yang et al., 2015; Kondash et al., 2018).

6.2.2 Water Use Results

The results of the water use cumulative pressure scenarios are given in Table 6-2 for all three licence areas. As shown in Table 6-2 the maximum theoretical volume of water used is associated with SD33a, SD34a, SD43b at approximately 7,500,000 m^3 per well for a high pressure scenario. The moderate pressure scenarios suggested water volume usage of between approximately 235,000 m^3 in study area SE78b, SE88e to approximately 945,000 m^3 in study area SD77c, SE77d, SE87a, assuming a water use per well of 26,250 m^3. All low pressure scenarios suggested water consumption volumes of less than 50,000 m^3 for two to four wells within a licence area, assuming a water use of 10,000 m^3 per well.

The water use results and matrices are included as Appendix 5.

Table 6-2 Water use scenarios for each study area

Description	Unit	Low	Moderate	High
SE78b, SE88e				
Well pads	No.	1	1	4
Wells per pad	No.	2	9	16
Total wells per study area	No.	2	9	64
Total volume of water for fracture programme's for study area	m^3	20,000	236,250	2,720,00
SE77c, SE77d, SE87a				
Well pads	No.	1	4	10
Wells per pad	No.	2	9	16
Total wells per study area	No.	2	36	160
Total volume of water for fracture programmes for study area	m^3	20,000	945,000	6,800,000
SD33a, SD34a, SD43b				
Well pads	No.	2	3	11
Wells per pad	No.	2	9	16
Total wells per study area	No.	4	27	176
Total volume of water for fracture programmes for study area	m^3	40,000	708,750	7,480,000

6.2.3 Water Use Discussion

As previously stated in Section 4 the highest pressure scenario within this assessment is unlikely, with the moderate pressure scenarios representing the most representative case.

In order to assess the pressure that water demand may have within an area of shale gas production, the generated estimates were compared to national water usage data. To provide an initial comparison, the required water for all wells in the individual regions have been compared with DEFRA estimated groundwater abstraction in 2016. Within the estimate the Environment Agency Regions are used which combine the North East and Yorkshire as one region (EA, 2014) (Figure 6-1). Water volumes for study areas SE78b, SE88e and SE77c, SE77d, SE87a have been combined as they are both within the same region. The comparison of water volume usage is shown in Table 6-3.

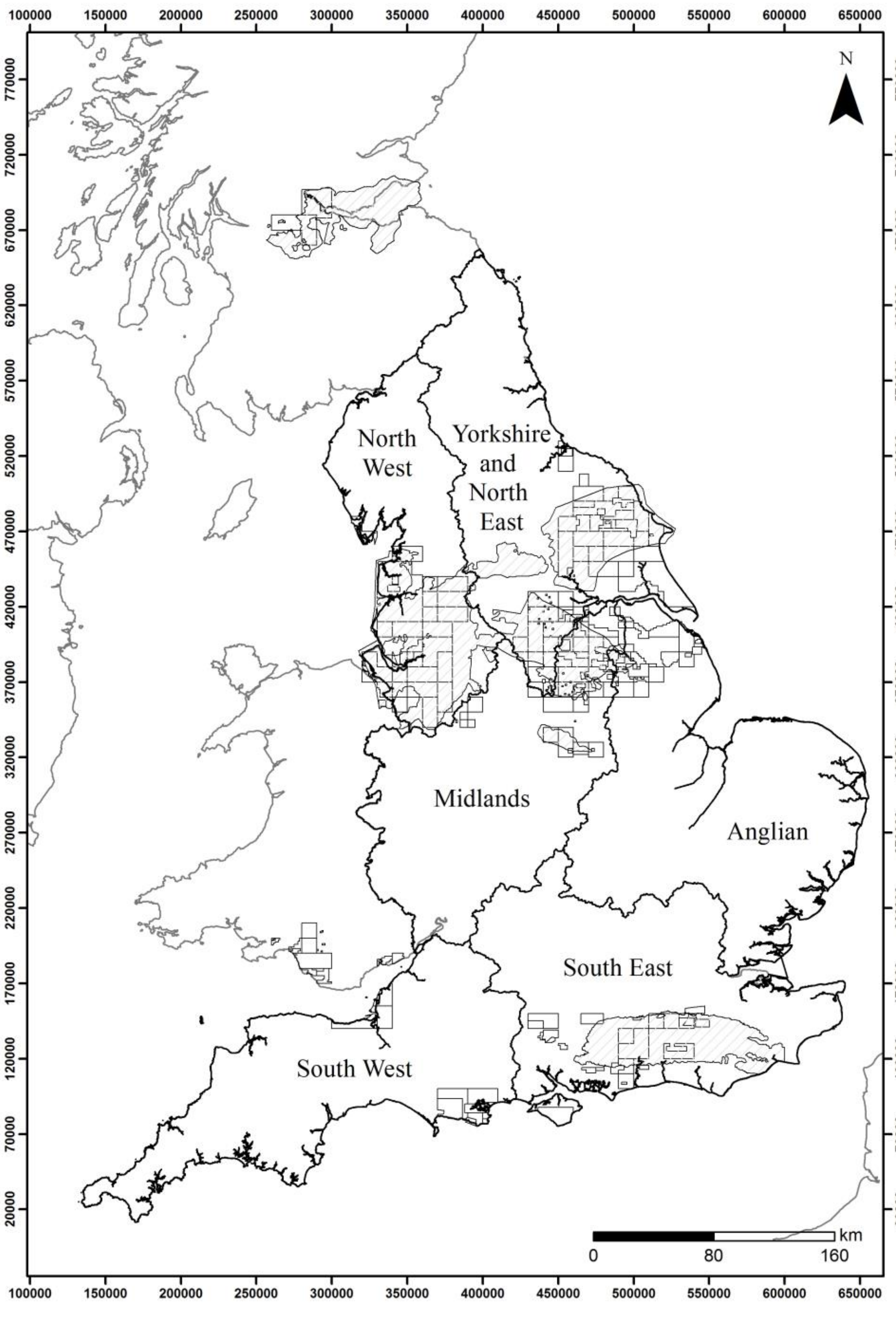


Figure 6.1 Environment Agency Regional Areas for estimated groundwater abstractions in England in 2016. (EA, 2014; BGS & OGA, 2018; OGA 2018; DEFRA, 2018) Rectangles show PEDL areas, while the grey highlighted areas show the extent of the Bowland Shale.

Table 6-3 Comparison between water use estimated for a moderate pressure scenario (m^3) with estimated yearly groundwater abstractions for England (DEFRA, 2018).

Study Area	Water use for a moderate pressure scenario (Table 6-1)	Estimated total groundwater abstractions in England in 2016 (DEFRA, 2018)	Required water use compared to DEFRA abstraction estimates.
	m^3	m^3 per region	%
SE78b, SE88e and SE77c, SE77d, SE87a	1.18×10^6	1.52×10^8 (North East)	0.78
SD33a, SD34a and SD43b	7.08×10^5	8.90×10^7 (North West)	0.79

This comparison suggests that the water required locally for a shale gas well is not significant on the regional scale with required water volumes less than 0.8% of yearly abstraction estimates. But, two vastly different areas of land are being compared here. The study areas cover around 55 km^2 each (if study areas SE78b, SE88e and SE77c, SE77d, SE87a are combined) (Table 3-2), while the North West region alone covers approximately 15,000 km^2. To provide a clearer insight into the pressure generated from potential water volumes, the water use based on land area is presented in Table 6-4 and 6-5.

Table 6-4 Estimated water use for a moderate pressure scenario based on land area of each study area.

Licence block	Estimated Water Consumption	Area (km^2)	Water Required
	m^3		$m^3\ km^{-2}$
SE78b, SE88e and SE77c, SE77d, SE87a	1,181,250	55.35	21,341
SD33a, SD34a, SD43b	708,750	54.5	13,005

Table 6-5 Estimated groundwater abstraction volumes (DEFRA, 2018) based on land area of each region

Region	Groundwater Abstraction 2016 (DEFRA, 2018)	Area	Water Abstracted
	m^3	km^2	$m^3\ km^{-2}$
North East (inc. Yorkshire)	1.52×10^8	22,637	6,715
North West	8.90×10^7	14,838	5,998

When assessing the water consumption for a moderate pressure scenario based on land area within each study area, it is evident that a fully formed shale gas industry in England will be water intensive with the total volume of water used per land area greater than the volume of groundwater abstracted per land area on local scales. This has the potential to lead to a deficit of water resources if local groundwater resources are used for multiple shale gas developments simultaneously. The probability of this deficit occurring depends on the speed of development. In order to achieve the number of wells suggested for a moderate pressure scenario (9 to 36), development will naturally be staggered, with total water use spread over multiple years as new wells begin production, lessening any associated pressures. The majority of water use will be in the early stages of a well development, probably the first two years, as shale gas well are not water intensive once production has started. In addition, and as highlighted in section 4.3.3, pressure on local water resources can be alleviated by the use of tankers that source water from wider regions or alternative suppliers and transport it to the well pad.

Although shale gas activity is water intensive, a water supplier in the region of development may be able to provide the required water resources. Yorkshire Water and United Utilities estimate a total deployable output of approximately 5.0×10^8 m^3 and 7.5×10^8 m^3, respectively, for the year 2015 into 2016. When compared to water consumption for a moderate pressure scenario, the resultant pressure on local utility companies are again, minimal, with all study areas requiring less than 0.25% of total deployable output (Table 6-6). However, as shown in Figure 6-2, the study areas used throughout this assessment contribute a limited area to the total PEDL blocks in both regions. A more distinct analogy would be produced if two regional scales are compared, for example, by scaling up the moderate pressure scenario to all PEDL blocks in their respective region.

Using the water required per land area calculated in Table 6-4, the total water use for all PEDL blocks in both regions is generated and compared to Yorkshire Water and United Utilities deployable output estimates. The results are presented in Table 6-7.

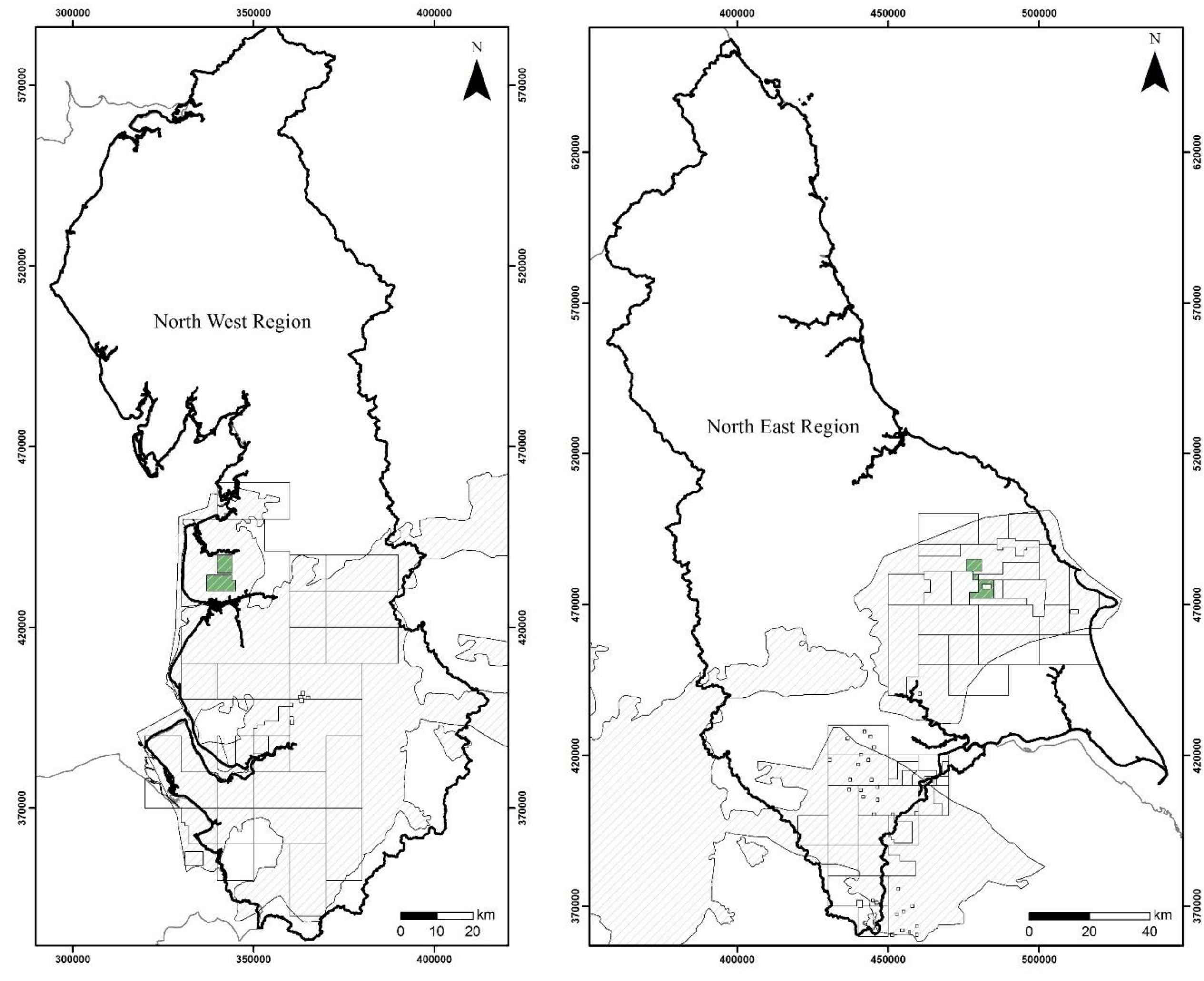


Figure 6.2 PEDL Blocks within each of their respective Environment Agency Regions (EA, 2014; BGS & OGA, 2018; OGA 2018; DEFRA, 2018). Rectangles show PEDL areas, Green rectangles show study areas used within this assessment, while grey highlighted areas show the extent of the Bowland Shale.

Table 6-6 Comparison between required water estimated for a moderate pressure scenario (m^3) with utility companies deployable output.

Study Area	Water use for a moderate pressure scenario (Table 6-1)	Deployable output	Required water use compared to deployable output	Reference
	m^3	m^3	%	
SE78b, SE88e and SE77c, SE77d, SE87a	1.18×10^6	5.13×10^8	0.23	Yorkshire Water (2018)
SD33a, SD34a and SD43b	7.09×10^5	7.71×10^8	0.09	United Utilities (2018)

Table 6-7 Water use required for all of the PEDL blocks within a region, assuming they are all developed for shale gas

Licence block	Water Required	Area of all PEDL blocks in Region (km^2)	Water required for all PEDL blocks	Deployable Output	Required water use compared to deployable output
	$m^3\,km^{-2}$		m^3	m^3	%
SE78b, SE88e and SE77c, SE77d, SE87a	21,341	5,074	1.08×10^8	5.13×10^8	21.1
SD33a, SD34a, SD43b	13,005	4,752	6.18×10^7	7.71×10^8	8.0

By scaling up required water volumes across all PEDL blocks in both regions, the pressure put on regional water suppliers is significant with 21% of Yorkshire Waters deployable output being used by shale gas wells in every PEDL block. Case by case assessments with the Environment Agency would be undertaken to determine whether regional supplies would accommodate the number of wells proposed by this assessment, with water demands spread over several years, significantly reducing this percentage. While water demands are not this intensive simultaneously, it is however important to highlight that total water volumes required by a fully realised shale gas industry are significant, with shale gas wells being water intensive based on the area of land they occupy.

7 Summary

The cumulative impact of a UK shale gas industry, which complies with current UK industry guidelines, is largely dependent on the number of wells present and the rate of failure/pollutant release that occurs. The assessment is based on datasets from previous shale gas operations, mainly in the USA, and has examined many sources when deciding which data was suitable for this assessment. The number of well pads used for the scenario modelling in this report, based on the case studies considered, ranged from 1 pad (SE78b, SE88e) to 11 pads (SD33a, SD34a and SD43b). This reflects available land use and placement conditions only within the licence blocks. Social factors were not considered which may reduce the number of well pads placed within an area.

The arrangement of wells per pad and laterals per well can be optimised to fit available land space; however, these are still limited by placement conditions such as a 1200 m distance between lateral sections and well pads. Industry studies have previously used 4 laterals per well for a high impact scenario whereas only one lateral per well, but with increased well numbers, was chosen in this assessment. The generated number of wells for each licence area allowed the volumes of water and fluid required across all licence areas to be assessed.

The volumes of fracture fluid required varied from 1.0 x 10^4 m^3 for a low impact scenario and 1.3 x 10^7 m^3 for a high impact scenario. Most of this fracture fluid is lost to formation with data ranging from 40% to 80% lost/non-recovered. This equates to between 200 m^3 to 4.3 x 10^6 m^3 of flowback fluid returned to the surface or lost to formation (not recovered or not recycled). There is potential for fracture fluid to enter the environment through leaks or spills at the surface or in the subsurface due to well failure. It was estimated that, for a moderate impact scenario, using a well failure rate of approximately 5.5%, there may be one failure across all study areas associated with cement or casing barriers. The magnitude and risk of this failure was not assessed and results were calculated using failure rates for the Marcellus Shale, Pennsylvania between 2009 and 2012. It was suggested that failure rates may be much lower in the UK due to stricter regulations.

An assessment of the potential risk of contamination to groundwater from a spill containing BTEX, chloride and sodium was undertaken using the EA Remedial Targets Methodology (RTM). The aquifers used within this assessment were based on their proximity to the locations of shale gas activity in the Fylde Basin, Lancashire and Vale of Pickering, Yorkshire. For both aquifers in the Fylde, the results indicated that all concentrations of BTEX were below Water Framework Directive threshold values at distances less than 65 m away from the projected point of chemical release (i.e. the well failure in the subsurface). Within the Corallian Group aquifer in Yorkshire, elevated concentrations of BTEX were present over larger distances. The results suggested that concentrations were below threshold values at a maximum distance of approximately 480 m. In all aquifers sodium and chloride were below their respective threshold values at distances less than 105 m. All results suggested that a risk to groundwater could exist up to approximately 60 m or 480 m away for BTEX, depending on local geology and additional risk factors which must be further quantified on a site-by-site basis using a detailed source pathway risk assessment.

The cumulative estimated water volumes required over the entirety of shale gas operations for all study areas ranged from 2.0 x 10^4 m^3 to 7.4 x 10^6 m^3. The high pressure scenario was considered unlikely with the moderate pressure scenario being carried forward for analysis and further discussion. Moderate pressure scenarios were compared to regional estimates of water abstraction using the Environment Agency Regions and estimates from DEFRA. Comparisons suggested that water use required for shale gas wells within the study areas comprised less than 0.8% of yearly abstractions in 2016 for the North East and North West of England. As vastly different areas of land were being compared, water volumes were examined based on their land use. Shale gas wells were identified as being water intensive, with greater volumes of water required per land area than that being abstracted across one year. Further comparisons examined the deployable output from water suppliers in the region. The moderate pressure scenario was extrapolated over the entirety of all PEDL blocks within both regions to reveal the amount of water required is significant, at around 20% for Yorkshire (i.e. PEDL blocks in Yorkshire Water's territory). It was highlighted that water use would be spread out over the development cycle of an emerging industry as all wells would not all be developed simultaneously and additionally, water is not required when a well is producing further reducing the yearly volumes required. The water requirements per well pad must each be examined to determine how best to manage the required water sources.

The cumulative impact assessment has assessed potential factors that could have an adverse effect on groundwater quality and groundwater resources in the area of potential shale gas developments. It has highlighted potential local associated with groundwater contamination (that are similar to hydrocarbon contamination associated with leaking underground tanks at petrol stations or from spills and leaks in industry) and illustrated that select water use scenarios do exist. Yet, as there are no data currently available to date within the UK for a producing unconventional shale gas well, international analogies must be used as a placeholder. Previous operations, within the USA for example, are under different jurisdiction and regulation, as well as geological setting. With this in mind, it is clear that data produced from a shale gas industry within England may vary significantly when compared to previous operations. However, regulations are considered much more stringent within the UK.

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Appendix 1 Impact scenarios for volumes of fracture fluid, volumes of drilling mud cuttings and flowback fluid produced

A1.1 SE78B, SE88E

Volume of fracture fluid

License area	Max. number of well pads	Wells per pad			Wells per License area			Volume of Fracture Fluid	Volume of fracture fluid per Pad			Volume of fracture fluid per licence area			Impact Scenario
	No.	No.			No.			m^3 / well	m^3			m^3			
		L	M	H	L	M	H		L	M	H	L	M	H	
SE78b, SE88e	4	2	9	16	8	36	64	5,000	10,000	45,000	80,000	40,000	180,000	320,000	Low
								41,000	82,000	369,000	656,000	328,000	1,476,000	2,624,000	Moderate
								77,000	154,000	693,000	1,232,000	616,000	2,772,000	4,928,000	High

Drilling mud and cutting

License area	Max. number of well pads			Volume of Drilling mud and cuttings	Volume of drilling mud and cuttings per Licence area			Impact Scenario
	No.			m^3 / well pad	m^3			
	L	M	H		L	M	H	
SE78b, SE88e	1	1	4	1,500	1,500	1,500	6,000	Low
				2,000	2,000	2,000	8,000	Moderate
				2,500	2,500	2,500	10,000	High

Fluid flow back

License area	Max. number of well pads	Wells per pad			Wells per License area			Flowback of Fracture Fluid			Volume of fracture fluid per licence area	Fluid flow back per licence area			Impact Scenario
	No.	No.			No.			%			m^3	m^3			
		L	M	H	L	M	H	L	M	H		L	M	H	
SE78b, SE88e	4	2	9	16	8	36	64	10	25	40	40,000	4,000	10,000	16,000	
											328,000	32,800	82,000	131,200	
											616,000	61,600	154,000	246,400	Low
											180,000	18,000	45,000	72,000	
											1,476,000	147,600	369,000	590,400	
											2,772,000	277,200	693,000	1,108,800	Medium
											320,000	32,000	80,000	128,000	
											2,624,000	262,400	656,000	1,049,600	
											4,928,000	492,800	1,232,000	1,971,200	High

Fluid Flow back not recycled

License area	Max. number of well pads	Wells per pad			Wells per License area			Percentage of flow back recycle rate			Fluid flow back per licence area	Fluid Flow back recycled per pad licence area			Impact Scenario	Fluid Flow back not recycled per licence area		
	No.	No.			No.			%			m^3	m^3				m^3		
		L	M	H	L	M	H	L	M	H		L	M	H		L	M	H
SE78b, SE88e	4	2	9	16	8	36	64	80	40	20	4,000	3,200	1,600	800	Low	800	2,400	3,200
											10,000	8,000	4,000	2,000		2,000	6,000	8,000
											16,000	12,800	6,400	3,200		3,200	9,600	12,800
											32,800	26,240	13,120	6,560		6,560	19,680	26,240
											82,000	65,600	32,800	16,400		16,400	49,200	65,600
											131,200	104,960	52,480	26,240		26,240	78,720	104,960
											61,600	49,280	24,640	12,320		12,320	36,960	49,280
											154,000	123,200	61,600	30,800		30,800	92,400	123,200
											246,400	197,120	98,560	49,280		49,280	147,840	197,120
											18,000	14,400	7,200	3,600	Medium	3,600	10,800	14,400
											45,000	36,000	18,000	9,000		9,000	27,000	36,000
											72,000	57,600	28,800	14,400		14,400	43,200	57,600
											147,600	118,080	59,040	29,520		29,520	88,560	118,080
											369,000	295,200	147,600	73,800		73,800	221,400	295,200
											590,400	472,320	236,160	118,080		118,080	354,240	472,320
											277,200	221,760	110,880	55,440		55,440	166,320	221,760
											693,000	554,400	277,200	138,600		138,600	415,800	554,400
											1,108,800	887,040	443,520	221,760		221,760	665,280	887,040
											32,000	25,600	12,800	6,400	High	6,400	19,200	25,600
											80,000	64,000	32,000	16,000		16,000	48,000	64,000
											128,000	102,400	51,200	25,600		25,600	76,800	102,400
											262,400	209,920	104,960	52,480		52,480	157,440	209,920
											656,000	524,800	262,400	131,200		131,200	393,600	524,800
											1,049,600	839,680	419,840	209,920		209,920	629,760	839,680
											492,800	394,240	197,120	98,560		98,560	295,680	394,240
											1,232,000	985,600	492,800	246,400		246,400	739,200	985,600
											1,971,200	1,576,960	788,480	394,240		394,240	1,182,720	1,576,960

A1.2 SE77C, SE77D, SE87A

Volume of fracture fluid

License area	Max. number of well pads	Wells per pad			Wells per License area			Volume of Fracture Fluid	Volume of fracture fluid per Pad			Volume of fracture fluid per licence area			Impact Scenario
	No.	No.			No.			m^3 / well	m^3			m^3			
		L	M	H	L	M	H		L	M	H	L	M	H	
SE77c, SE77d, SE87a	10	2	9	16	20	90	160	5,000	10,000	45,000	80,000	100,000	450,000	800,000	Low
								41,000	82,000	369,000	656,000	820,000	3,690,000	6,560,000	Moderate
								77,000	154,000	693,000	1,232,000	1,540,000	6,930,000	12,320,000	High

Drilling mud and cuttings

License area	Max. number of well pads			Volume of Drilling mud and cuttings	Volume of drilling mud and cuttings per Licence area			Impact Scenario
	No.			m^3 / well pad	m^3			
	L	M	H		L	M	H	
SE77c, SE77d, SE87a	1	4	10	1,500	1,500	6,000	15,000	Low
				2,000	2,000	8,000	20,000	Moderate
				2,500	2,500	10,000	25,000	High

Fluid flow back

License area	Max. number of well pads	Wells per pad			Wells per License area			Flowback of Fracture Fluid			Volume of fracture fluid per Pad	Volume of fracture fluid per licence area	Fluid flow back per licence area			Impact Scenario
	No.	No.			No.			%			m^3	m^3	m^3			
		L	M	H	L	M	H	L	M	H			L	M	H	
SE77c, SE77d, SE87a	10	2	9	16	20	90	160	10	25	40	10,000	100,000	10,000	25,000	40,000	
											20,000	820,000	82,000	205,000	328,000	
											30,000	1,540,000	154,000	385,000	616,000	Low
											45000	450,000	45,000	112,500	180,000	
											90000	3,690,000	369,000	922,500	1,476,000	
											135000	6,930,000	693,000	1,732,500	2,772,000	Medium
											80000	800,000	80,000	200,000	320,000	
											160000	6,560,000	656,000	1,640,000	2,624,000	
											240000	12,320,000	1,232,000	3,080,000	4,928,000	High

Fluid flow back not recycled

License area	Max. number of well pads	Wells per pad			Wells per License area			Percentage of flow back recycle rate			Fluid flow back per licence area	Fluid Flow back recycled per licence area			Impact Scenario	Fluid Flow back not recycled per licence area		
	No.	No.			No.			%			m^3	m^3				m^3		
		L	M	H	L	M	H	L	M	H		L	M	H		L	M	H
SE77c, SE77d, SE87a	10	2	9	16	20	90	160	80	40	20	10,000	8,000	4,000	2,000	Low	2,000	6,000	8,000
											25,000	20,000	10,000	5,000		5,000	15,000	20,000
											40,000	32,000	16,000	8,000		8,000	24,000	32,000
											82,000	65,600	32,800	16,400		16,400	49,200	65,600
											205,000	164,000	82,000	41,000		41,000	123,000	164,000
											328,000	262,400	131,200	65,600		65,600	196,800	262,400
											154,000	123,200	61,600	30,800		30,800	92,400	123,200
											385,000	308,000	154,000	77,000		77,000	231,000	308,000
											616,000	492,800	246,400	123,200		123,200	369,600	492,800
											45,000	36,000	18,000	9,000	Medium	9,000	27,000	36,000
											112,500	90,000	45,000	22,500		22,500	67,500	90,000
											180,000	144,000	72,000	36,000		36,000	108,000	144,000
											369,000	295,200	147,600	73,800		73,800	221,400	295,200
											922,500	738,000	369,000	184,500		184,500	553,500	738,000
											1,476,000	1,180,800	590,400	295,200		295,200	885,600	1,180,800
											693,000	554,400	277,200	138,600		138,600	415,800	554,400
											1,732,500	1,386,000	693,000	346,500		346,500	1,039,500	1,386,000
											2,772,000	2,217,600	1,108,800	554,400		554,400	1,663,200	2,217,600
											80,000	64,000	32,000	16,000	High	16,000	48,000	64,000
											200,000	160,000	80,000	40,000		40,000	120,000	160,000
											320,000	256,000	128,000	64,000		64,000	192,000	256,000
											656,000	524,800	262,400	131,200		131,200	393,600	524,800
											1,640,000	1,312,000	656,000	328,000		328,000	984,000	1,312,000
											2,624,000	2,099,200	1,049,600	524,800		524,800	1,574,400	2,099,200
											1,232,000	985,600	492,800	246,400		246,400	739,200	985,600
											3,080,000	2,464,000	1,232,000	616,000		616,000	1,848,000	2,464,000
											4,928,000	3,942,400	1,971,200	985,600		985,600	2,956,800	3,942,400

A1.3 SD33A, SD34, SD43B

Volume of Fracture Fluid

License area	Max. number of well pads	Wells per pad			Wells per License area			Volume of Fracture Fluid	Volume of fracture fluid per Pad			Volume of fracture fluid per licence area			Impact Scenario
	No.	No.			No.			m^3 / well	m^3			m^3			
		L	M	H	L	M	H		L	M	H	L	M	H	
SD33a, SD34a, SD43b	11	2	9	16	22	99	176	5,000	10,000	45,000	80,000	110,000	495,000	880,000	Low
								41,000	82,000	369,000	656,000	902,000	4,059,000	7,216,000	Moderate
								77,000	154,000	693,000	1,232,000	1,694,000	7,623,000	13,552,000	High

Drilling mud and cuttings

License area	Max. number of well pads			Volume of Drilling mud and cuttings	Volume of drilling mud and cuttings per Licence area			Impact Scenario
	No.			m^3 / well pad	m^3			
	L	M	H		L	M	H	
SD33a, SD34a, SD43b	2	3	11	1,500	3,000	4,500	16,500	Low
				2,000	4,000	6,000	22,000	Moderate
				2,500	5,000	7,500	27,500	High

Fluid flow back

License area	Max. number of well pads	Wells per pad			Wells per License area			Flowback of Fracture Fluid			Volume of fracture fluid per Pad	Volume of fracture fluid per licence area	Fluid flow back per licence area			Impact Scenario
	No.	No.			No.			%			m^3	m^3	m^3			
		L	M	H	L	M	H	L	M	H			L	M	H	
SD33a, SD34a, SD43b	11	2	9	16	22	99	176	10	25	40	10,000	110,000	11,000	27,500	44,000	
											20,000	902,000	90,200	225,500	360,800	
											30,000	1,694,000	169,400	423,500	677,600	Low
											45000	495,000	49,500	123,750	198,000	
											90000	4,059,000	405,900	1,014,750	1,623,600	
											135000	7,623,000	762,300	1,905,750	3,049,200	Medium
											80000	880,000	88,000	220,000	352,000	
											160000	7,216,000	721,600	1,804,000	2,886,400	
											240000	13,552,000	1,355,200	3,388,000	5,420,800	High

Fluid flow back not recycled

License area	Max. number of well pads	Wells per pad			Wells per License area			Percentage of flow back recycle rate			Fluid flow back per licence area	Fluid Flow back recycled per pad licence area			Impact Scenario	Fluid Flow back not recycled per licence area		
	No.	No.			No.			%			m^3	m^3				m^3		
		L	M	H	L	M	H	L	M	H		L	M	H		L	M	H
SD33a, SD34a, SD43b	11	2	9	16	22	99	176	80	40	20	11,000	8,800	4,400	2,200	Low	2,200	6,600	8,800
											27,500	22,000	11,000	5,500		5,500	16,500	22,000
											44,000	35,200	17,600	8,800		8,800	26,400	35,200
											90,200	72,160	36,080	18,040		18,040	54,120	72,160
											225,500	180,400	90,200	45,100		45,100	135,300	180,400
											360,800	288,640	144,320	72,160		72,160	216,480	288,640
											169,400	135,520	67,760	33,880		33,880	101,640	135,520
											423,500	338,800	169,400	84,700		84,700	254,100	338,800
											677,600	542,080	271,040	135,520		135,520	406,560	542,080
											49,500	39,600	19,800	9,900	Medium	9,900	29,700	39,600
											123,750	99,000	49,500	24,750		24,750	74,250	99,000
											198,000	158,400	79,200	39,600		39,600	118,800	158,400
											405,900	324,720	162,360	81,180		81,180	243,540	324,720
											1,014,750	811,800	405,900	202,950		202,950	608,850	811,800
											1,623,600	1,298,880	649,440	324,720		324,720	974,160	1,298,880
											762,300	609,840	304,920	152,460		152,460	457,380	609,840
											1,905,750	1,524,600	762,300	381,150		381,150	1,143,450	1,524,600
											3,049,200	2,439,360	1,219,680	609,840		609,840	1,829,520	2,439,360
											88,000	70,400	35,200	17,600	High	17,600	52,800	70,400
											220,000	176,000	88,000	44,000		44,000	132,000	176,000
											352,000	281,600	140,800	70,400		70,400	211,200	281,600
											721,600	577,280	288,640	144,320		144,320	432,960	577,280
											1,804,000	1,443,200	721,600	360,800		360,800	1,082,400	1,443,200
											2,886,400	2,309,120	1,154,560	577,280		577,280	1,731,840	2,309,120
											1,355,200	1,084,160	542,080	271,040		271,040	813,120	1,084,160
											3,388,000	2,710,400	1,355,200	677,600		677,600	2,032,800	2,710,400
											5,420,800	4,336,640	2,168,320	1,084,160		1,084,160	3,252,480	4,336,640

Appendix 2 Well Failure Result

A2.1 SE78B, SE88E

License Block	Max. number of well pads	Wells per pad			Wells per License block			Well Failure Rate	Well failures per License Block			Well Failure Scenario	Well Pad Scenario
	No.	No.			No.			%	No.				
		L	M	H	L	M	H		L	M	H		
SE78b, SE88e	1	2	9	16	2	9	16	1.88	0.038	0.169	0.301	Low	Low
								5.51	0.110	0.496	0.882	Moderate	
								9.14	0.183	0.823	1.462	High	
	1	2	9	16	2	9	16	1.88	0.038	0.169	0.301	Low	Moderate
								5.51	0.110	0.496	0.882	Moderate	
								9.14	0.183	0.823	1.462	High	
	4	2	9	16	8	36	64	1.88	0.150	0.677	1.203	Low	High
								5.51	0.441	1.984	3.526	Moderate	
								9.14	0.731	3.290	5.850	High	

A2.2 SE77C, SE77D, SE87A

License Block	Max. number of well pads	Wells per pad			Wells per License block			Well Failure Rate	Well failures per License Block			Well Failure Scenario	Well Pad Scenario
	No.	No.			No.			%	No.				
		L	M	H	L	M	H		L	M	H		
SE77c, SE77d, SE87a	1	2	9	16	2	9	16	1.88	0.038	0.169	0.301	Low	Low
								5.51	0.110	0.496	0.882	Moderate	
								9.14	0.183	0.823	1.462	High	
	4	2	9	16	8	36	64	1.88	0.150	0.677	1.203	Low	Moderate
								5.51	0.441	1.984	3.526	Moderate	
								9.14	0.731	3.290	5.850	High	
	10	2	9	16	20	90	160	1.88	0.376	1.692	3.008	Low	High
								5.51	1.102	4.959	8.816	Moderate	
								9.14	1.828	8.226	14.624	High	

A2.3 SD33A, SD34A, SD43B

Licence	Max. number of well pads	Wells per pad			Wells per License block			Well Failure Rate	Well failures per License Block			Well Failure Scenario	Well Pad Scenario
	No.	No.			No.			%	No.				
		L	M	H	L	M	H		L	M	H		
SD33a, SD34a, SD43b	2	2	9	16	4	18	32	1.88	0.075	0.338	0.602	Low	Low
								5.51	0.220	0.992	1.763	Moderate	
								9.14	0.366	1.645	2.925	High	
	3	2	9	16	6	27	48	1.88	0.113	0.508	0.902	Low	Moderate
								5.51	0.331	1.488	2.645	Moderate	
								9.14	0.548	2.468	4.387	High	
	11	2	9	16	22	99	176	1.88	0.414	1.861	3.309	Low	High
								5.51	1.212	5.455	9.698	Moderate	
								9.14	2.011	9.049	16.086	High	

Appendix 3 On-Site Spill Results

A3.1 SE78B, SE88E

License area	Max. number of well pads	Wells per pad			Wells per License area			Spills per well	Spills per Licence Area			Volume per spill	Volume spilt per licence area			Volume Recovered	Volume not recovered per licence area			Impact Scenario
	No.	No.			No.			No.	No			m^3	m^3			%	m^3			
		L	M	H	L	M	H	No.	L	M	H		L	M	H		L	M	H	
SE78b, SE88e	1	2	9	16	2	9	16	0.0077	0.02	0.07	0.12	3	0.05	0.21	0.37	90	0.00	0.02	0.04	Low
								0.0099	0.02	0.09	0.16		0.06	0.27	0.47		0.01	0.03	0.05	
								0.0120	0.02	0.11	0.19		0.07	0.32	0.58		0.01	0.03	0.06	
	1	2	9	16	2	9	16	0.0077	0.02	0.07	0.12		0.05	0.21	0.37		0.00	0.02	0.04	
								0.0099	0.02	0.09	0.16		0.06	0.27	0.47		0.01	0.03	0.05	
								0.0120	0.02	0.11	0.19		0.07	0.32	0.58		0.01	0.03	0.06	
	4	2	9	16	8	36	64	0.0077	0.06	0.28	0.49		0.18	0.83	1.48		0.02	0.08	0.15	
								0.0099	0.08	0.35	0.63		0.24	1.06	1.89		0.02	0.11	0.19	
								0.0120	0.10	0.43	0.77		0.29	1.30	2.30		0.03	0.13	0.23	
																55	0.02	0.09	0.17	Moderate
																	0.03	0.12	0.21	
																	0.03	0.15	0.26	
																	0.02	0.09	0.17	
																	0.03	0.12	0.21	
																	0.03	0.15	0.26	
																	0.08	0.37	0.67	
																	0.11	0.48	0.85	
																	0.13	0.58	1.04	
																20	0.04	0.17	0.30	High
																	0.05	0.21	0.38	
																	0.06	0.26	0.46	
																	0.04	0.17	0.30	
																	0.05	0.21	0.38	
																	0.06	0.26	0.46	
																	0.15	0.67	1.18	
																	0.19	0.85	1.51	
																	0.23	1.04	1.84	

A3.2 SE77C, SE77D, SE87A

License area	Max. number of well pads	Wells per pad			Wells per License area			Spills per well	Spills per Licence Area			Volume per spill	Volume spilt per licence area			Volume Recovered	Volume not recovered per licence area			Impact Scenario
	No.	No.			No.			No.	No			m^3	m^3			%	m^3			
		L	M	H	L	M	H	No.	L	M	H		L	M	H		L	M	H	
SE77c, SE77d, SE87a	1	2	9	16	2	9	16	0.008	0.02	0.07	0.12	3	0.05	0.21	0.37	90	0.00	0.02	0.04	Low
								0.010	0.02	0.09	0.16		0.06	0.27	0.47		0.01	0.03	0.05	
								0.012	0.02	0.11	0.19		0.07	0.32	0.58		0.01	0.03	0.06	
	4	2	9	16	8	36	64	0.008	0.06	0.28	0.49		0.18	0.83	1.48		0.02	0.08	0.15	
								0.010	0.08	0.35	0.63		0.24	1.06	1.89		0.02	0.11	0.19	
								0.012	0.10	0.43	0.77		0.29	1.30	2.30		0.03	0.13	0.23	
	10	2	9	16	#	90	##	0.008	0.15	0.69	1.23		0.46	2.08	3.70		0.05	0.21	0.37	
								0.010	0.20	0.89	1.58		0.59	2.66	4.73		0.06	0.27	0.47	
								0.012	0.24	1.08	1.92		0.72	3.24	5.76		0.07	0.32	0.58	
																55	0.02	0.09	0.17	Moderate
																	0.03	0.12	0.21	
																	0.03	0.15	0.26	
																	0.08	0.37	0.67	
																	0.11	0.48	0.85	
																	0.13	0.58	1.04	
																	0.21	0.94	1.66	
																	0.27	1.20	2.13	
																	0.32	1.46	2.59	
																20	0.04	0.17	0.30	High
																	0.05	0.21	0.38	
																	0.06	0.26	0.46	
																	0.15	0.67	1.18	
																	0.19	0.85	1.51	
																	0.23	1.04	1.84	
																	0.37	1.66	2.96	
																	0.47	2.13	3.78	
																	0.58	2.59	4.61	

A3.3 SD33A, SD34A, SD43B

License area	Max. number of well pads	Wells per pad			Wells per License area			Spills per well	Spills per Licence Area			Volume per spill	Volume spilt per licence area			Volume Recovered	Volume not recovered per licence area			Impact Scenario
	No.	No.			No.			No.	No			m³	m³			%	m³			
		L	M	H	L	M	H		L	M	H		L	M	H		L	M	H	
SD33a, SD34a, SD43b	2	2	9	16	4	18	32	0.008	0.03	0.14	0.25	3	0.09	0.42	0.74	90	0.01	0.04	0.07	Low
								0.010	0.04	0.18	0.32		0.12	0.53	0.95		0.01	0.05	0.09	
								0.012	0.05	0.22	0.38		0.14	0.65	1.15		0.01	0.06	0.12	
	3	2	9	16	6	27	48	0.008	0.05	0.21	0.37		0.14	0.62	1.11		0.01	0.06	0.11	
								0.010	0.06	0.27	0.47		0.18	0.80	1.42		0.02	0.08	0.14	
								0.012	0.07	0.32	0.58		0.22	0.97	1.73		0.02	0.10	0.17	
	11	2	9	16	#	99	##	0.008	0.17	0.76	1.36		0.51	2.29	4.07		0.05	0.23	0.41	
								0.010	0.22	0.98	1.73		0.65	2.93	5.20		0.07	0.29	0.52	
								0.012	0.26	1.19	2.11		0.79	3.56	6.34		0.08	0.36	0.63	
																55	0.04	0.19	0.33	Moderate
																	0.05	0.24	0.43	
																	0.06	0.29	0.52	
																	0.06	0.28	0.50	
																	0.08	0.36	0.64	
																	0.10	0.44	0.78	
																	0.23	1.03	1.83	
																	0.29	1.32	2.34	
																	0.36	1.60	2.85	
																20	0.07	0.33	0.59	High
																	0.09	0.43	0.76	
																	0.12	0.52	0.92	
																	0.11	0.50	0.89	
																	0.14	0.64	1.13	
																	0.17	0.78	1.38	
																	0.41	1.83	3.25	
																	0.52	2.34	4.16	
																	0.63	2.85	5.07	

Appendix 4 Off-Site Spill Results

A4.1 SE78B, SE88E

License area	Max. number of well pads	Wells per pad			Wells per License area			Road spill for every 19 well pads	Spills per licence area			Volume released per spill	Volume released per licence area			Impact Scenario
	No.	No.			No.				No.			m^3	m^3			Number of well pads
		L	M	H	L	M	H	No.	L	M	H		L	M	H	
SE78b, SE88e	1	2	9	16	2	9	16	19	0.11	0.47	0.84	12.5	1.3	5.9	10.5	Low
													1.3	5.9	10.5	
													5.3	23.7	42.1	
	1	2	9	16	2	9	16	19	0.11	0.47	0.84	18.75	2.0	8.9	15.8	Moderate
													2.0	8.9	15.8	
													7.9	35.5	63.2	
	4	2	9	16	8	36	64	19	0.42	1.89	3.37	25	2.6	11.8	21.1	High
													2.6	11.8	21.1	
													10.5	47.4	84.2	

A4.2 SE77C, SE77D, SE87A

License area	Max. number of well pads	Wells per pad			Wells per License area			Road spill for every 19 well pads	Spills per licence area			Volume released per spill	Volume released per licence area			Impact Scenario
	No.	No.			No.				No.			m^3	m^3			Number of well pads
		L	M	H	L	M	H	No	L	M	H		L	M	H	
SE77c, SE77d, SE87a	1	2	9	16	2	9	16	19	0.11	0.47	0.84	12.5	1.3	5.9	10.5	Low
													5.3	23.7	42.1	
													13.2	59.2	105.3	
	4	2	9	16	8	36	64	19	0.42	1.89	3.37	18.75	2.0	8.9	15.8	Moderate
													7.9	35.5	63.2	
													19.7	88.8	157.9	
	10	2	9	16	20	90	160	19	1.05	4.74	8.42	25	2.6	11.8	21.1	High
													10.5	47.4	84.2	
													26.3	118.4	210.5	

A4.3 SD33A, SD34A, SD43B

License area	Max. number of well pads	Wells per pad			Wells per License area			Road spill for every 19 well pads	Spills per licence area			Volume released per spill	Volume released per licence area			Impact Scenario
	No.	No.			No.				No.			m^3	m^3			Number of well pads
		L	M	H	L	M	H	No	L	M	H		L	M	H	
SD33a, SD34a, SD43b	2	2	9	16	4	18	32	19	0.21	0.95	1.68	12.5	2.6	11.8	21.1	Low
													3.9	17.8	31.6	
													14.5	65.1	115.8	
	3	2	9	16	6	27	48	19	0.32	1.42	2.53	18.75	3.9	17.8	31.6	Moderate
													5.9	26.6	47.4	
													21.7	97.7	173.7	
	11	2	9	16	22	99	176	19	1.16	5.21	9.26	25	5.3	23.7	42.1	High
													7.9	35.5	63.2	
													28.9	130.3	231.6	

Appendix 5　Groundwater Resources Results

A5.1 SE78B, SE88E

License area	Max. number of well pads	Wells per pad			Wells per License area			Volume of water per fracture programme	Volume of water per fracture programme			Volume of water per fracture programme		
	No.	No.			No.			m^3 / well	m^3 / pad			m^3 / licence area		
		L	M	H	L	M	H		L	M	H	L	M	H
SE78b, SE88e	4	2	9	16	8	36	64	10000	20,000	90,000	160,000	80,000	360,000	640,000
								26250	52,500	236,250	420,000	210,000	945,000	1,680,000
								42500	85,000	382,500	680,000	340,000	1,530,000	2,720,000

A5.2 SE77C, SE77D, SE87A

License area	Max. number of well pads	Wells per pad			Wells per License area			Volume of water per fracture programme	Volume of water per fracture programme			Volume of water per fracture programme		
	No.	No.			No.			m^3 / well	m^3 / pad			m^3 / licence area		
		L	M	H	L	M	H		L	M	H	L	M	H
SE77c, SE77d, SE87a	10	2	9	16	20	90	160	10000	20,000	90,000	160,000	200,000	900,000	1,600,000
								26250	52,500	236,250	420,000	525,000	2,362,500	4,200,000
								42500	85,000	382,500	680,000	850,000	3,825,000	6,800,000

A5.3 SD33A, SD34A, SD43B

License area	Max. number of well pads	Wells per pad			Wells per License area			Volume of water per fracture programme	Volume of water per fracture programme			Volume of water per fracture programme		
	No.	No.			No.			m^3 / well	m^3 / pad			m^3 / licence area		
		L	M	H	L	M	H		L	M	H	L	M	H
SD33a, SD34a, SD43b	10	2	9	16	20	90	160	10000	20,000	90,000	160,000	200,000	900,000	1,600,000
								26250	52,500	236,250	420,000	525,000	2,362,500	4,200,000
								42500	85,000	382,500	680,000	850,000	3,825,000	6,800,000

Appendix 6 RTM Spreadsheets

6i) Permo-Triassic Sandstone Aquifer

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Environment Agency

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Benzene		from Level 1
Target Concentration	C_T	7.50E-04	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.70E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.10E+02	days	" "
Calculated decay rate	λ	3.30E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	2.00E+02	m	" "
Bulk density of aquifer materials	ρ	2.65E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.30E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	5.30E+00	m/d	" "
Distance to compliance point	x	4.90E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	5.41E+00	l/kg	*see options*
Longitudinal dispersivity	ax	4.90E+00	m	*see options*
Transverse dispersivity	az	4.90E-01	m	*see options*
Vertical dispersivity	ay	4.90E-02	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	8.00E-02	fraction
Organic carbon partition coefficient	Koc	6.76E+01	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc,n}$		l/kg
Sorption coefficient for ionised species	$K_{oc,i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	5.41E+00	l/kg

Define dispersivity (click brown cell and use pull down list)

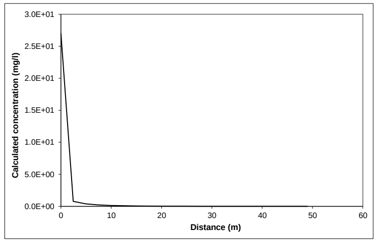
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	4.90E+00	2.95E+00	m
Transverse dispersivity	**az**	0.00E+00	4.90E-01	2.95E-01	m
Vertical dispersivity	**ay**	0.00E+00	4.90E-02	2.95E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	2.7E+01
2.5	7.88E-01
4.9	3.90E-01
7.4	2.25E-01
9.8	1.39E-01
12.3	9.07E-02
14.7	6.08E-02
17.2	4.17E-02
19.6	2.91E-02
22.1	2.06E-02
24.5	1.47E-02
27.0	1.06E-02
29.4	7.70E-03
31.9	5.63E-03
34.3	4.14E-03
36.8	3.05E-03
39.2	2.26E-03
41.7	1.68E-03
44.1	1.26E-03
46.6	9.40E-04
49.0	7.05E-04

Calculated Parameters

	Variable	Value	Unit
Groundwater flow velocity	v	2.30E-02	m/d
Retardation factor	Rf	6.33E+01	fraction
Decay rate used	λ	5.21E-05	d^{-1}
Rate of contaminant flow due to retardation	u	3.64E-04	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	7.05E-04	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**3.83E+04**	

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Remedial Targets

Remedial Target	**2.87E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**49**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**7.05E-04**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Environment Agency

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Toluene		from Level 1
Target Concentration	C_T	4.00E-03	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	3.70E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+02	days	" "
Calculated decay rate	λ	6.93E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	2.00E+02	m	" "
Bulk density of aquifer materials	ρ	2.65E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.30E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	5.30E+00	m/d	" "
Distance to compliance point	x	2.40E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	1.33E+01	l/kg	*see options*
Longitudinal dispersivity	ax	2.40E+00	m	*see options*
Transverse dispersivity	az	2.40E-01	m	*see options*
Vertical dispersivity	ay	2.40E-02	m	*see options*

Calculated Parameters

	Variable		
Groundwater flow velocity	v	2.30E-02	m/d
Retardation factor	Rf	1.54E+02	fraction
Decay rate used	λ	4.50E-05	d^{-1}
Rate of contaminant flow due to retardation	u	1.50E-04	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	3.28E-03	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**1.13E+04**	

Remedial Targets

Remedial Target		**4.51E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks				
Distance to compliance point		**24**	**m**	
Concentration of contaminant at compliance point	C_{ED}/C_0	**3.28E-03**	**mg/l**	Ogata Banks
after		**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	8.00E-02	fraction
Organic carbon partition coefficient	Koc	1.66E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	1.33E+01	l/kg

Define dispersivity (click brown cell and use pull down list)

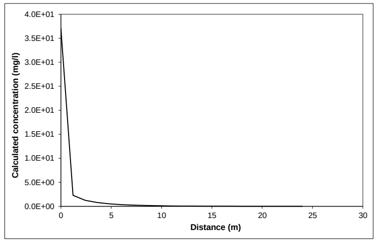
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	2.40E+00	1.81E+00	m
Transverse dispersivity	**az**	0.00E+00	2.40E-01	1.81E-01	m
Vertical dispersivity	**ay**	0.00E+00	2.40E-02	1.81E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared
with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**3.7E+01**
1.2	**2.28E+00**
2.4	**1.26E+00**
3.6	**7.99E-01**
4.8	**5.31E-01**
6.0	**3.63E-01**
7.2	**2.53E-01**
8.4	**1.78E-01**
9.6	**1.27E-01**
10.8	**9.12E-02**
12.0	**6.60E-02**
13.2	**4.81E-02**
14.4	**3.52E-02**
15.6	**2.59E-02**
16.8	**1.91E-02**
18.0	**1.41E-02**
19.2	**1.05E-02**
20.4	**7.83E-03**
21.6	**5.85E-03**
22.8	**4.38E-03**
24.0	**3.28E-03**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

Parameter	Variable	Value	Unit	Source
Contaminant		**Ethylbenzene**		from Level 1
Target Concentration	C_T	**7.50E-04**	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

Parameter	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	1.90E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.30E+02	days	" "
Calculated decay rate	λ	3.01E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	2.00E+02	m	" "
Bulk density of aquifer materials	ρ	2.65E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.30E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	5.30E+00	m/d	" "
Distance to compliance point	x	4.90E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	2.36E+01	l/kg	*see options*
Longitudinal dispersivity	ax	4.90E+00	m	*see options*
Transverse dispersivity	az	4.90E-01	m	*see options*
Vertical dispersivity	ay	4.90E-02	m	*see options*

Calculated Parameters

Parameter	Variable	Value	Unit
Groundwater flow velocity	v	2.30E-02	m/d
Retardation factor	Rf	2.73E+02	fraction
Decay rate used	λ	1.10E-05	d^{-1}
Rate of contaminant flow due to retardation	u	8.44E-05	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	6.82E-04	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**2.79E+04**	

Remedial Targets

Remedial Target	**2.09E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**49**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**6.82E-04**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	8.00E-02	fraction
Organic carbon partition coefficient	Koc	2.95E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	2.36E+01	l/kg

Define dispersivity (click brown cell and use pull down list)

Dispersivities 10%, 1%, 0.1% of pathway length

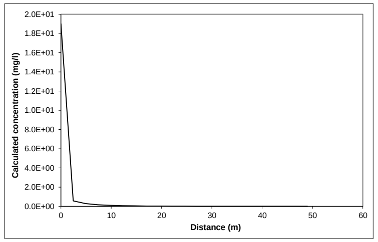
		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	4.90E+00	2.95E+00	m
Transverse dispersivity	**az**	0.00E+00	4.90E-01	2.95E-01	m
Vertical dispersivity	**ay**	0.00E+00	4.90E-02	2.95E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed

Environment Agency



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared
with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**1.9E+01**
2.5	**5.63E-01**
4.9	**2.83E-01**
7.4	**1.66E-01**
9.8	**1.05E-01**
12.3	**6.91E-02**
14.7	**4.71E-02**
17.2	**3.28E-02**
19.6	**2.33E-02**
22.1	**1.67E-02**
24.5	**1.21E-02**
27.0	**8.89E-03**
29.4	**6.56E-03**
31.9	**4.87E-03**
34.3	**3.64E-03**
36.8	**2.73E-03**
39.2	**2.05E-03**
41.7	**1.55E-03**
44.1	**1.18E-03**
46.6	**8.95E-04**
49.0	**6.82E-04**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Xylene		from Level 1
Target Concentration	C_T	1.55E-02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	6.11E-01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.25E+02	days	" "
Calculated decay rate	λ	3.08E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	2.00E+02	m	" "
Bulk density of aquifer materials	ρ	2.65E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.30E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	5.30E+00	m/d	" "
Distance to compliance point	x	9.00E+00	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	1.26E+01	l/kg	*see options*
Longitudinal dispersivity	ax	9.00E-01	m	*see options*
Transverse dispersivity	az	9.00E-02	m	*see options*
Vertical dispersivity	ay	9.00E-03	m	*see options*

Calculated Parameters

	Variable		
Groundwater flow velocity	v	2.30E-02	m/d
Retardation factor	Rf	1.47E+02	fraction
Decay rate used	λ	2.10E-05	d^{-1}
Rate of contaminant flow due to retardation	u	1.57E-04	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	9.57E-03	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**6.38E+01**	

Remedial Targets

Remedial Target	**9.89E-01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**9**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**9.57E-03**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	8.00E-02	fraction
Organic carbon partition coefficient	Koc	1.58E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	1.26E+01	l/kg

Define dispersivity (click brown cell and use pull down list)

Dispersivities 10%, 1%, 0.1% of pathway length

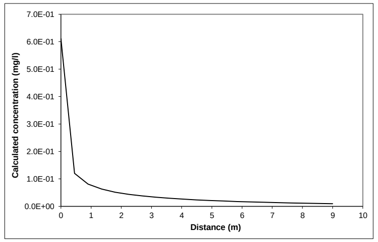
		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	9.00E-01	7.41E-01	m
Transverse dispersivity	**az**	0.00E+00	9.00E-02	7.41E-02	m
Vertical dispersivity	**ay**	0.00E+00	9.00E-03	7.41E-03	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed

Environment Agency



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	6.1E-01
0.5	1.20E-01
0.9	8.10E-02
1.4	6.28E-02
1.8	5.16E-02
2.3	4.37E-02
2.7	3.78E-02
3.2	3.32E-02
3.6	2.94E-02
4.1	2.62E-02
4.5	2.36E-02
5.0	2.13E-02
5.4	1.93E-02
5.9	1.75E-02
6.3	1.60E-02
6.8	1.46E-02
7.2	1.34E-02
7.7	1.23E-02
8.1	1.13E-02
8.6	1.04E-02
9.0	9.57E-03

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Chloride		from Level 1
Target Concentration	C_T	1.88E+02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

				Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.00E+05	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+100	days	" "
Calculated decay rate	λ	6.93E-101	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	2.00E+02	m	" "
Bulk density of aquifer materials	ρ	2.65E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.30E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	5.30E+00	m/d	" "
Distance to compliance point	x	9.00E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	0.00E+00	l/kg	*see options*
Longitudinal dispersivity	ax	9.00E+00	m	*see options*
Transverse dispersivity	az	9.00E-01	m	*see options*
Vertical dispersivity	ay	9.00E-02	m	*see options*

Calculated Parameters

	Variable		
Groundwater flow velocity	v	2.30E-02	m/d
Retardation factor	Rf	1.00E+00	fraction
Decay rate used	λ	6.93E-101	d^{-1}
Rate of contaminant flow due to retardation	u	2.30E-02	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.85E+02	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**1.08E+03**	

Remedial Targets

Remedial Target	**2.04E+05**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**90**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**1.85E+02**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	8.00E-02	fraction
Organic carbon partition coefficient	Koc		l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc,n}$		l/kg
Sorption coefficient for ionised species	$K_{oc,i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	0.00E+00	l/kg

Define dispersivity (click brown cell and use pull down list)

Dispersivities 10%, 1%, 0.1% of pathway length

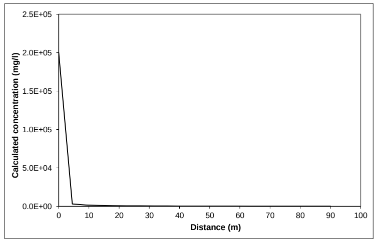
		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	9.00E+00	4.18E+00	m
Transverse dispersivity	**az**	0.00E+00	9.00E-01	4.18E-01	m
Vertical dispersivity	**ay**	0.00E+00	9.00E-02	4.18E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed

Environment Agency



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	2.0E+05
4.5	3.08E+03
9.0	1.69E+03
13.5	1.16E+03
18.0	8.86E+02
22.5	7.16E+02
27.0	6.01E+02
31.5	5.17E+02
36.0	4.54E+02
40.5	4.05E+02
45.0	3.65E+02
49.5	3.33E+02
54.0	3.05E+02
58.5	2.82E+02
63.0	2.62E+02
67.5	2.45E+02
72.0	2.30E+02
76.5	2.17E+02
81.0	2.05E+02
85.5	1.94E+02
90.0	1.85E+02

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Environment Agency

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

Parameter	Variable	Value	Unit	Source
Contaminant		Na+		from Level 1
Target Concentration	C_T	1.50E+02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

Parameter	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.00E+05	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+100	days	" "
Calculated decay rate	λ	6.93E-101	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	2.00E+02	m	" "
Bulk density of aquifer materials	ρ	2.65E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.30E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	5.30E+00	m/d	" "
Distance to compliance point	x	1.01E+02	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	0.00E+00	l/kg	*see options*
Longitudinal dispersivity	ax	1.01E+01	m	*see options*
Transverse dispersivity	az	1.01E+00	m	*see options*
Vertical dispersivity	ay	1.01E-01	m	*see options*

Calculated Parameters

Parameter	Variable	Value	Unit
Groundwater flow velocity	v	2.30E-02	m/d
Retardation factor	Rf	1.00E+00	fraction
Decay rate used	λ	6.93E-101	d^{-1}
Rate of contaminant flow due to retardation	u	2.30E-02	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.47E+02	mg/l
Attenuation factor (two way vertical dispersion, C0/CED)	**AF**	**1.36E+03**	

Remedial Targets

Remedial Target	**2.04E+05**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			

Distance to compliance point **101** **m**

Concentration of contaminant at compliance point C_{ED}/C_0 **1.47E+02** **mg/l** Ogata Banks
after **1.0E+100** **days**

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

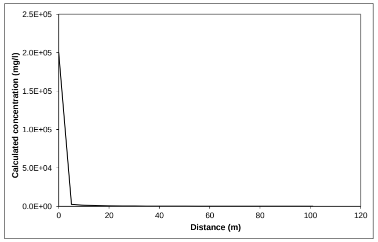
Parameter	Variable	Value	Unit
Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	8.00E-02	fraction
Organic carbon partition coefficient	Koc		l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	0.00E+00	l/kg

Define dispersivity (click brown cell and use pull down list)

Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	1.01E+01	4.45E+00	m
Transverse dispersivity	**az**	0.00E+00	1.01E+00	4.45E-01	m
Vertical dispersivity	**ay**	0.00E+00	1.01E-01	4.45E-02	

Note values of dispersivity must be > 0
For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x
Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	2.0E+05
5.1	2.54E+03
10.1	1.37E+03
15.2	9.36E+02
20.2	7.11E+02
25.3	5.73E+02
30.3	4.80E+02
35.4	4.13E+02
40.4	3.63E+02
45.5	3.23E+02
50.5	2.91E+02
55.6	2.65E+02
60.6	2.43E+02
65.7	2.25E+02
70.7	2.09E+02
75.8	1.95E+02
80.8	1.83E+02
85.9	1.72E+02
90.9	1.63E+02
96.0	1.54E+02
101.0	1.47E+02

6ii) Sand and Gravel Aquifer

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Environment Agency

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Benzene		from Level 1
Target Concentration	C_T	7.50E-04	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.70E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.10E+02	days	" "
Calculated decay rate	λ	3.30E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	3.00E+01	m	" "
Bulk density of aquifer materials	ρ	1.68E+00	g/cm^3	" "
Effective porosity of aquifer	n	3.00E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.00E+01	m/d	" "
Distance to compliance point	x	6.20E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	2.50E-07	l/kg	*see options*
Longitudinal dispersivity	ax	6.20E+00	m	*see options*
Transverse dispersivity	az	6.20E-01	m	*see options*
Vertical dispersivity	ay	6.20E-02	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	5.00E-04	fraction
Organic carbon partition coefficient	Koc	5.00E-04	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc,n}$		l/kg
Sorption coefficient for ionised species	$K_{oc,i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	2.50E-07	l/kg

Define dispersivity (click brown cell and use pull down list)

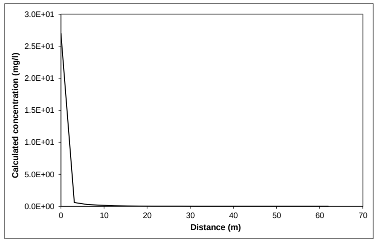
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	6.20E+00	3.40E+00	m
Transverse dispersivity	**az**	0.00E+00	6.20E-01	3.40E-01	m
Vertical dispersivity	**ay**	0.00E+00	6.20E-02	3.40E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report ax = $0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared

with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	2.7E+01
3.1	5.94E-01
6.2	2.83E-01
9.3	1.62E-01
12.4	1.01E-01
15.5	6.67E-02
18.6	4.54E-02
21.7	3.17E-02
24.8	2.26E-02
27.9	1.63E-02
31.0	1.19E-02
34.1	8.74E-03
37.2	6.48E-03
40.3	4.84E-03
43.4	3.63E-03
46.5	2.74E-03
49.6	2.08E-03
52.7	1.58E-03
55.8	1.21E-03
58.9	9.22E-04
62.0	7.08E-04

Calculated Parameters

	Variable	Value	Unit
Groundwater flow velocity	v	3.33E-02	m/d
Retardation factor	Rf	1.00E+00	fraction
Decay rate used	λ	3.30E-03	d^{-1}
Rate of contaminant flow due to retardation	u	3.33E-02	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	7.08E-04	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**3.81E+04**	

Site being assessed:	Fylde Quaternary Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Remedial Targets

Remedial Target	**2.86E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			

Distance to compliance point **62** **m**

Concentration of contaminant at compliance point C_{ED}/C_0 **7.08E-04** **mg/l** Ogata Banks
after **1.0E+100** **days**

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		**Toluene**		from Level 1
Target Concentration	C_T	**4.00E-03**	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	3.70E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+02	days	" "
Calculated decay rate	λ	6.93E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	3.00E+01	m	" "
Bulk density of aquifer materials	ρ	1.68E+00	g/cm^3	" "
Effective porosity of aquifer	n	3.00E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.00E+01	m/d	" "
Distance to compliance point	x	3.00E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	8.30E-02	l/kg	*see options*
Longitudinal dispersivity	ax	3.00E+00	m	*see options*
Transverse dispersivity	az	3.00E-01	m	*see options*
Vertical dispersivity	ay	3.00E-02	m	*see options*

Calculated Parameters

	Variable	Value	Unit
Groundwater flow velocity	v	3.33E-02	m/d
Retardation factor	Rf	1.46E+00	fraction
Decay rate used	λ	4.73E-03	d^{-1}
Rate of contaminant flow due to retardation	u	2.28E-02	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	3.67E-03	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**1.01E+04**	

Remedial Targets

Remedial Target	**4.03E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**30**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**3.67E-03**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	5.00E-04	fraction
Organic carbon partition coefficient	Koc	1.66E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	8.30E-02	l/kg

Define dispersivity (click brown cell and use pull down list)

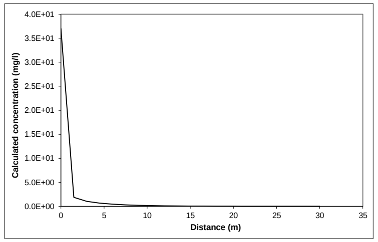
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	3.00E+00	2.13E+00	m
Transverse dispersivity	**az**	0.00E+00	3.00E-01	2.13E-01	m
Vertical dispersivity	**ay**	0.00E+00	3.00E-02	2.13E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared
with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Quaternary Model
Completed by:	Jack Elsome
Date:	########
Version:	0.1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**3.7E+01**
1.5	**1.87E+00**
3.0	**1.05E+00**
4.5	**6.64E-01**
6.0	**4.42E-01**
7.5	**3.04E-01**
9.0	**2.14E-01**
10.5	**1.53E-01**
12.0	**1.10E-01**
13.5	**8.06E-02**
15.0	**5.94E-02**
16.5	**4.41E-02**
18.0	**3.29E-02**
19.5	**2.47E-02**
21.0	**1.86E-02**
22.5	**1.41E-02**
24.0	**1.07E-02**
25.5	**8.17E-03**
27.0	**6.24E-03**
28.5	**4.78E-03**
30.0	**3.67E-03**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

Parameter	Variable	Value	Unit	Source
Contaminant		**Ethylbenzene**		from Level 1
Target Concentration	C_T	**7.50E-04**	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

Parameter	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	1.90E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.30E+02	days	" "
Calculated decay rate	λ	3.01E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	3.00E+01	m	" "
Bulk density of aquifer materials	ρ	1.68E+00	g/cm^3	" "
Effective porosity of aquifer	n	3.00E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.00E+01	m/d	" "
Distance to compliance point	x	6.10E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	1.48E-01	l/kg	*see options*
Longitudinal dispersivity	ax	6.10E+00	m	*see options*
Transverse dispersivity	az	6.10E-01	m	*see options*
Vertical dispersivity	av	6.10E-02	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Parameter	Variable	Value	Unit
Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	5.00E-04	fraction
Organic carbon partition coefficient	Koc	2.95E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	1.48E-01	l/kg

Define dispersivity (click brown cell and use pull down list)

Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	6.10E+00	3.36E+00	m
Transverse dispersivity	**az**	0.00E+00	6.10E-01	3.36E-01	m
Vertical dispersivity	**ay**	0.00E+00	6.10E-02	3.36E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed

Calculated Parameters

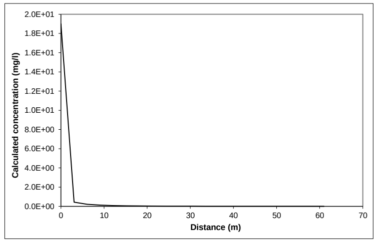
Parameter	Variable	Value	Unit
Groundwater flow velocity	v	3.33E-02	m/d
Retardation factor	Rf	1.83E+00	fraction
Decay rate used	λ	1.65E-03	d^{-1}
Rate of contaminant flow due to retardation	u	1.83E-02	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	7.24E-04	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**2.62E+04**	

Remedial Targets

Remedial Target		**1.97E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks				
Distance to compliance point		**61**	**m**	
Concentration of contaminant at compliance point	C_{ED}/C_0	**7.24E-04**	**mg/l**	Ogata Banks
after		**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Environment Agency



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Quaternary Model
Completed by:	Jack Elsome
Date:	########
Version:	0.1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**1.9E+01**
3.1	**4.35E-01**
6.1	**2.12E-01**
9.2	**1.23E-01**
12.2	**7.85E-02**
15.3	**5.26E-02**
18.3	**3.65E-02**
21.4	**2.59E-02**
24.4	**1.88E-02**
27.5	**1.38E-02**
30.5	**1.02E-02**
33.6	**7.66E-03**
36.6	**5.78E-03**
39.7	**4.39E-03**
42.7	**3.35E-03**
45.8	**2.57E-03**
48.8	**1.98E-03**
51.9	**1.53E-03**
54.9	**1.19E-03**
58.0	**9.27E-04**
61.0	**7.24E-04**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Xylene		from Level 1
Target Concentration	C_T	1.55E-02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	6.11E-01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.25E+02	days	" "
Calculated decay rate	λ	3.08E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	3.00E+01	m	" "
Bulk density of aquifer materials	ρ	1.68E+00	g/cm^3	" "
Effective porosity of aquifer	n	3.00E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.00E+01	m/d	" "
Distance to compliance point	x	9.00E+00	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	7.90E-02	l/kg	*see options*
Longitudinal dispersivity	ax	9.00E-01	m	*see options*
Transverse dispersivity	az	9.00E-02	m	*see options*
Vertical dispersivity	ay	9.00E-03	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	5.00E-04	fraction
Organic carbon partition coefficient	Koc	1.58E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	7.90E-02	l/kg

Define dispersivity (click brown cell and use pull down list)

Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	9.00E-01	7.41E-01	m
Transverse dispersivity	**az**	0.00E+00	9.00E-02	7.41E-02	m
Vertical dispersivity	**ay**	0.00E+00	9.00E-03	7.41E-03	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed

Calculated Parameters

	Variable		
Groundwater flow velocity	v	3.33E-02	m/d
Retardation factor	Rf	1.44E+00	fraction
Decay rate used	λ	2.14E-03	d^{-1}
Rate of contaminant flow due to retardation	u	2.31E-02	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.31E-02	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**4.67E+01**	

Remedial Targets

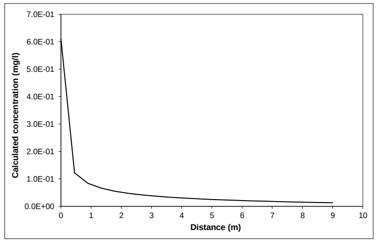
Remedial Target	**7.23E-01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			

Distance to compliance point **9** **m**

Concentration of contaminant at compliance point C_{ED}/C_0 **1.31E-02** **mg/l** Ogata Banks
after **1.0E+100** **days**

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Environment Agency



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared
with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**6.1E-01**
0.5	**1.22E-01**
0.9	**8.36E-02**
1.4	**6.58E-02**
1.8	**5.49E-02**
2.3	**4.73E-02**
2.7	**4.15E-02**
3.2	**3.70E-02**
3.6	**3.33E-02**
4.1	**3.02E-02**
4.5	**2.76E-02**
5.0	**2.53E-02**
5.4	**2.33E-02**
5.9	**2.15E-02**
6.3	**1.99E-02**
6.8	**1.85E-02**
7.2	**1.72E-02**
7.7	**1.60E-02**
8.1	**1.50E-02**
8.6	**1.40E-02**
9.0	**1.31E-02**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

Parameter	Variable	Value	Unit	Source
Contaminant		Chloride		from Level 1
Target Concentration	C_T	1.88E+02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

Parameter	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.00E+05	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+100	days	" "
Calculated decay rate	λ	6.93E-101	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	3.00E+01	m	" "
Bulk density of aquifer materials	ρ	1.68E+00	g/cm^3	" "
Effective porosity of aquifer	n	3.00E-01	fraction	" "
Hydraulic gradient	i	1.00E-02	fraction	" "
Hydraulic conductivity of aquifer	K	1.00E+01	m/d	" "
Distance to compliance point	x	9.00E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	0.00E+00	l/kg	*see options*
Longitudinal dispersivity	ax	9.00E+00	m	*see options*
Transverse dispersivity	az	9.00E-01	m	*see options*
Vertical dispersivity	av	9.00E-02	m	*see options*

Calculated Parameters

Parameter	Variable	Value	Unit
Groundwater flow velocity	v	3.33E-01	m/d
Retardation factor	Rf	1.00E+00	fraction
Decay rate used	λ	6.93E-101	d^{-1}
Rate of contaminant flow due to retardation	u	3.33E-01	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.85E+02	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**1.08E+03**	

Remedial Targets

Remedial Target	**2.04E+05**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**90**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**1.85E+02**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Parameter	Variable	Value	Unit
Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	5.00E-04	fraction
Organic carbon partition coefficient	Koc		l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	0.00E+00	l/kg

Define dispersivity (click brown cell and use pull down list)

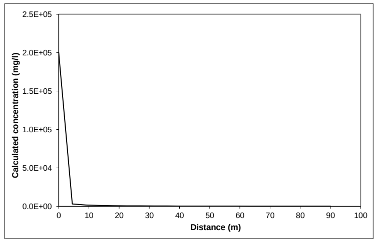
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	9.00E+00	4.18E+00	m
Transverse dispersivity	**az**	0.00E+00	9.00E-01	4.18E-01	m
Vertical dispersivity	**ay**	0.00E+00	9.00E-02	4.18E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Quaternary Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	2.0E+05
4.5	3.08E+03
9.0	1.69E+03
13.5	1.16E+03
18.0	8.86E+02
22.5	7.16E+02
27.0	6.01E+02
31.5	5.17E+02
36.0	4.54E+02
40.5	4.05E+02
45.0	3.65E+02
49.5	3.33E+02
54.0	3.05E+02
58.5	2.82E+02
63.0	2.62E+02
67.5	2.45E+02
72.0	2.30E+02
76.5	2.17E+02
81.0	2.05E+02
85.5	1.94E+02
90.0	1.85E+02

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Environment Agency

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Na+		from Level 1
Target Concentration	C_T	1.50E+02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.00E+05	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+100	days	" "
Calculated decay rate	λ	6.93E-101	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	3.00E+01	m	" "
Bulk density of aquifer materials	ρ	1.68E+00	g/cm^3	" "
Effective porosity of aquifer	n	3.00E-01	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.00E+01	m/d	" "
Distance to compliance point	x	1.01E+02	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	0.00E+00	l/kg	*see options*
Longitudinal dispersivity	ax	1.01E+01	m	*see options*
Transverse dispersivity	az	1.01E+00	m	*see options*
Vertical dispersivity	ay	1.01E-01	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	5.00E-04	fraction
Organic carbon partition coefficient	Koc		l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc,n}$		l/kg
Sorption coefficient for ionised species	$K_{oc,i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	0.00E+00	l/kg

Define dispersivity (click brown cell and use pull down list)

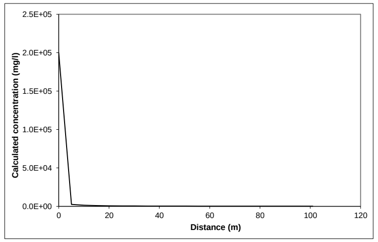
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	1.01E+01	4.45E+00	m
Transverse dispersivity	**az**	0.00E+00	1.01E+00	4.45E-01	m
Vertical dispersivity	**ay**	0.00E+00	1.01E-01	4.45E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report ax = $0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**2.0E+05**
5.1	**2.54E+03**
10.1	**1.37E+03**
15.2	**9.36E+02**
20.2	**7.11E+02**
25.3	**5.73E+02**
30.3	**4.80E+02**
35.4	**4.13E+02**
40.4	**3.63E+02**
45.5	**3.23E+02**
50.5	**2.91E+02**
55.6	**2.65E+02**
60.6	**2.43E+02**
65.7	**2.25E+02**
70.7	**2.09E+02**
75.8	**1.95E+02**
80.8	**1.83E+02**
85.9	**1.72E+02**
90.9	**1.63E+02**
96.0	**1.54E+02**
101.0	**1.47E+02**

Calculated Parameters

	Variable	Value	Unit
Groundwater flow velocity	v	3.33E-02	m/d
Retardation factor	Rf	1.00E+00	fraction
Decay rate used	λ	6.93E-101	d^{-1}
Rate of contaminant flow due to retardation	u	3.33E-02	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.47E+02	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**1.36E+03**	

Site being assessed:	Fylde Quaternary Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Remedial Targets

Remedial Target	**2.04E+05**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			

Distance to compliance point		**101**	**m**	
Concentration of contaminant at compliance point	C_{ED}/C_0	**1.47E+02**	**mg/l**	Ogata Banks
after		**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

6iii) Corallian Group Aquifer

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

Parameter	Variable	Value	Unit	Source
Contaminant		**Benzene**		from Level 1
Target Concentration	C_T	**7.50E-04**	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

Parameter	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.70E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.10E+02	days	" "
Calculated decay rate	λ	3.30E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	1.68E+02	m	" "
Bulk density of aquifer materials	ρ	2.71E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.00E-04	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.89E+00	m/d	" "
Distance to compliance point	x	4.81E+02	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	3.04E+01	l/kg	*see options*
Longitudinal dispersivity	ax	4.81E+01	m	*see options*
Transverse dispersivity	az	4.81E+00	m	*see options*
Vertical dispersivity	ay	4.81E-01	m	*see options*

Calculated Parameters

Parameter	Variable	Value	Unit
Groundwater flow velocity	v	9.45E+00	m/d
Retardation factor	Rf	4.12E+05	fraction
Decay rate used	λ	8.01E-09	d^{-1}
Rate of contaminant flow due to retardation	u	2.29E-05	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	7.47E-04	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**3.62E+04**	

Remedial Targets

Remedial Target	**2.71E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**481**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**7.47E-04**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	4.50E-01	fraction
Organic carbon partition coefficient	Koc	6.76E+01	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	3.04E+01	l/kg

Define dispersivity (click brown cell and use pull down list)

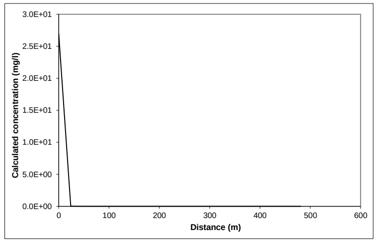
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	4.81E+01	8.98E+00	m
Transverse dispersivity	**az**	0.00E+00	4.81E+00	8.98E-01	m
Vertical dispersivity	**ay**	0.00E+00	4.81E-01	8.98E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared
with the Level 3 remedial target to determine the need for further action.
Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Corallian Limestone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**2.7E+01**
24.1	**1.74E-02**
48.1	**8.63E-03**
72.2	**5.72E-03**
96.2	**4.25E-03**
120.3	**3.38E-03**
144.3	**2.79E-03**
168.4	**2.37E-03**
192.4	**2.06E-03**
216.5	**1.82E-03**
240.5	**1.62E-03**
264.6	**1.46E-03**
288.6	**1.33E-03**
312.7	**1.22E-03**
336.7	**1.12E-03**
360.8	**1.04E-03**
384.8	**9.64E-04**
408.9	**9.00E-04**
432.9	**8.43E-04**
457.0	**7.92E-04**
481.0	**7.47E-04**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Toluene		from Level 1
Target Concentration	C_T	4.00E-03	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	3.70E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+02	days	" "
Calculated decay rate	λ	6.93E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	1.68E+02	m	" "
Bulk density of aquifer materials	ρ	2.71E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.00E-04	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.89E+00	m/d	" "
Distance to compliance point	x	2.43E+02	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	7.47E+01	l/kg	*see options*
Longitudinal dispersivity	ax	2.43E+01	m	*see options*
Transverse dispersivity	az	2.43E+00	m	*see options*
Vertical dispersivity	ay	2.43E-01	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	4.50E-01	fraction
Organic carbon partition coefficient	Koc	1.66E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	7.47E+01	l/kg

Define dispersivity (click brown cell and use pull down list)

Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	2.43E+01	6.77E+00	m
Transverse dispersivity	**az**	0.00E+00	2.43E+00	6.77E-01	m
Vertical dispersivity	**ay**	0.00E+00	2.43E-01	6.77E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed

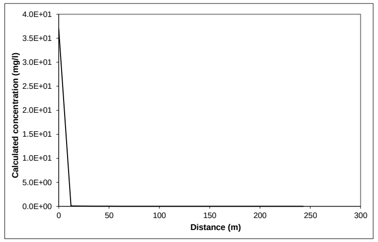
Calculated Parameters

	Variable		
Groundwater flow velocity	v	9.45E+00	m/d
Retardation factor	Rf	1.01E+06	fraction
Decay rate used	λ	6.85E-09	d^{-1}
Rate of contaminant flow due to retardation	u	9.34E-06	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	3.96E-03	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**9.33E+03**	

Remedial Targets

Remedial Target		**3.73E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks				
Distance to compliance point		**243**	**m**	
Concentration of contaminant at compliance point	**C_{ED}/C_0**	**3.96E-03**	**mg/l**	Ogata Banks
after		**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Fylde Sandstone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**3.7E+01**
12.2	**9.12E-02**
24.3	**4.58E-02**
36.5	**3.04E-02**
48.6	**2.27E-02**
60.8	**1.80E-02**
72.9	**1.49E-02**
85.1	**1.27E-02**
97.2	**1.10E-02**
109.4	**9.68E-03**
121.5	**8.64E-03**
133.7	**7.79E-03**
145.8	**7.08E-03**
158.0	**6.48E-03**
170.1	**5.97E-03**
182.3	**5.52E-03**
194.4	**5.13E-03**
206.6	**4.79E-03**
218.7	**4.48E-03**
230.9	**4.21E-03**
243.0	**3.96E-03**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Ethylbenzene		from Level 1
Target Concentration	C_T	7.50E-04	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	1.90E+01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.30E+02	days	" "
Calculated decay rate	λ	3.01E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	1.68E+02	m	" "
Bulk density of aquifer materials	ρ	2.71E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.00E-04	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.89E+00	m/d	" "
Distance to compliance point	x	4.11E+02	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	1.33E+02	l/kg	*see options*
Longitudinal dispersivity	ax	4.11E+01	m	*see options*
Transverse dispersivity	az	4.11E+00	m	*see options*
Vertical dispersivity	ay	4.11E-01	m	*see options*

Calculated Parameters

	Variable	Value	Unit
Groundwater flow velocity	v	9.45E+00	m/d
Retardation factor	Rf	1.80E+06	fraction
Decay rate used	λ	1.68E-09	d^{-1}
Rate of contaminant flow due to retardation	u	5.25E-06	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	7.46E-04	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**2.55E+04**	

Remedial Targets

Remedial Target	**1.91E+01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**411**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**7.46E-04**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	4.50E-01	fraction
Organic carbon partition coefficient	Koc	2.95E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	1.33E+02	l/kg

Define dispersivity (click brown cell and use pull down list)

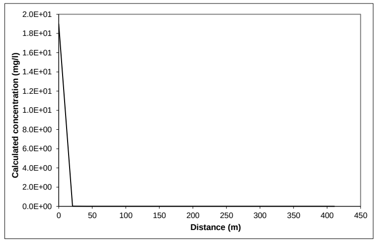
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	4.11E+01	8.44E+00	m
Transverse dispersivity	**az**	0.00E+00	4.11E+00	8.44E-01	m
Vertical dispersivity	**ay**	0.00E+00	4.11E-01	8.44E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Corallian Limestone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**1.9E+01**
20.6	**1.67E-02**
41.1	**8.34E-03**
61.7	**5.53E-03**
82.2	**4.13E-03**
102.8	**3.28E-03**
123.3	**2.72E-03**
143.9	**2.32E-03**
164.4	**2.01E-03**
185.0	**1.78E-03**
205.5	**1.59E-03**
226.1	**1.44E-03**
246.6	**1.31E-03**
267.2	**1.20E-03**
287.7	**1.11E-03**
308.3	**1.03E-03**
328.8	**9.56E-04**
349.4	**8.94E-04**
369.9	**8.39E-04**
390.5	**7.90E-04**
411.0	**7.46E-04**

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Xylene		from Level 1
Target Concentration	C_T	1.55E-02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — Equations in HRA publication

Approach for simulating vertical dispersion: Simulate vertical dispersion in 2 directions

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: Apply degradation rate to dissolved pollutants only

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	6.11E-01	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	2.25E+02	days	" "
Calculated decay rate	λ	3.08E-03	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	1.68E+02	m	" "
Bulk density of aquifer materials	ρ	2.71E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.00E-04	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.89E+00	m/d	" "
Distance to compliance point	x	1.60E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	7.11E+01	l/kg	*see options*
Longitudinal dispersivity	ax	1.60E+00	m	*see options*
Transverse dispersivity	az	1.60E-01	m	*see options*
Vertical dispersivity	ay	1.60E-02	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	4.50E-01	fraction
Organic carbon partition coefficient	Koc	1.58E+02	l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	7.11E+01	l/kg

Define dispersivity (click brown cell and use pull down list)

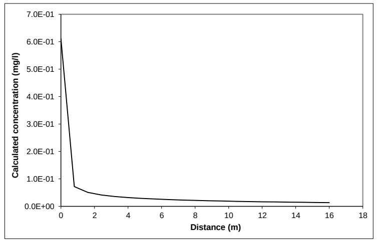
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	1.60E+00	1.30E+00	m
Transverse dispersivity	**az**	0.00E+00	1.60E-01	1.30E-01	m
Vertical dispersivity	**ay**	0.00E+00	1.60E-02	1.30E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	6.1E-01
0.8	7.20E-02
1.6	5.10E-02
2.4	4.16E-02
3.2	3.60E-02
4.0	3.21E-02
4.8	2.91E-02
5.6	2.68E-02
6.4	2.48E-02
7.2	2.31E-02
8.0	2.17E-02
8.8	2.04E-02
9.6	1.93E-02
10.4	1.83E-02
11.2	1.74E-02
12.0	1.66E-02
12.8	1.59E-02
13.6	1.52E-02
14.4	1.46E-02
15.2	1.40E-02
16.0	1.35E-02

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Calculated Parameters

	Variable	Value	Unit
Groundwater flow velocity	v	9.45E+00	m/d
Retardation factor	Rf	9.63E+05	fraction
Decay rate used	λ	3.20E-09	d^{-1}
Rate of contaminant flow due to retardation	u	9.81E-06	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.35E-02	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**4.54E+01**	

Site being assessed:	Corallian Limestone Model
Completed by:	Jack Elsome
Date:	########
Version:	0.1

Remedial Targets

Remedial Target		**7.03E-01**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks				
Distance to compliance point		**16**	**m**	
Concentration of contaminant at compliance point	**C_{ED}/C_0**	**1.35E-02**	**mg/l**	Ogata Banks
after		**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Chloride		from Level 1
Target Concentration	C_T	1.88E+02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.00E+05	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+100	days	" "
Calculated decay rate	λ	6.93E-101	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	1.68E+02	m	" "
Bulk density of aquifer materials	ρ	2.71E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.00E-04	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.89E+00	m/d	" "
Distance to compliance point	x	9.00E+01	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	0.00E+00	l/kg	*see options*
Longitudinal dispersivity	ax	9.00E+00	m	*see options*
Transverse dispersivity	az	9.00E-01	m	*see options*
Vertical dispersivity	ay	9.00E-02	m	*see options*

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	4.50E-01	fraction
Organic carbon partition coefficient	Koc		l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	0.00E+00	l/kg

Define dispersivity (click brown cell and use pull down list)

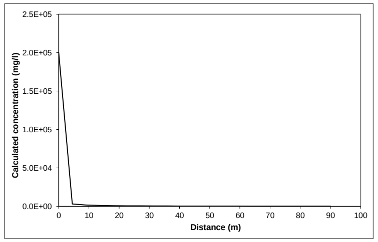
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	9.00E+00	4.18E+00	m
Transverse dispersivity	**az**	0.00E+00	9.00E-01	4.18E-01	m
Vertical dispersivity	**ay**	0.00E+00	9.00E-02	4.18E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared

with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	**Concentration**
	mg/l
0	**2.0E+05**
4.5	**3.08E+03**
9.0	**1.69E+03**
13.5	**1.16E+03**
18.0	**8.86E+02**
22.5	**7.16E+02**
27.0	**6.01E+02**
31.5	**5.17E+02**
36.0	**4.54E+02**
40.5	**4.05E+02**
45.0	**3.65E+02**
49.5	**3.33E+02**
54.0	**3.05E+02**
58.5	**2.82E+02**
63.0	**2.62E+02**
67.5	**2.45E+02**
72.0	**2.30E+02**
76.5	**2.17E+02**
81.0	**2.05E+02**
85.5	**1.94E+02**
90.0	**1.85E+02**

Calculated Parameters

	Variable		
Groundwater flow velocity	v	9.45E+00	m/d
Retardation factor	Rf	1.00E+00	fraction
Decay rate used	λ	6.93E-101	d^{-1}
Rate of contaminant flow due to retardation	u	9.45E+00	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.85E+02	mg/l
Attenuation factor (two way vertical dispersion, CO/CED)	**AF**	**1.08E+03**	

Site being assessed:	Corallian Limestone Model
Completed by:	Jack Elsome
Date:	########
Version:	1

Remedial Targets

Remedial Target	**2.04E+05**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			

Distance to compliance point **90** **m**

Concentration of contaminant at compliance point C_{ED}/C_0 **1.85E+02** **mg/l** Ogata Banks
after **1.0E+100** **days**

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

R&D Publication 20 Remedial Targets Worksheet, Release 3.2

Level 3 - Groundwater

See Note

Input Parameters (using pull down menu)

	Variable	Value	Unit	Source
Contaminant		Sodium		from Level 1
Target Concentration	C_T	1.50E+02	mg/l	from Level 1

Select analytical solution (click on brown cell below, then on pull-down menu)

Ogata Banks — **Equations in HRA publication**

Approach for simulating vertical dispersion: **Simulate vertical dispersion in 2 directions**

Select nature of decay rate (click on brown cell below, then on pull-down menu)

Approach for simulating degradation of pollutants: **Apply degradation rate to dissolved pollutants only**

	Variable	Value	Unit	Source of parameter value
Initial contaminant concentration in groundwater at plume core	C_0	2.00E+05	mg/l	*Table 5-1*
Half life for degradation of contaminant in water	$t_{1/2}$	1.00E+100	days	" "
Calculated decay rate	λ	6.93E-101	$days^{-1}$	
Width of plume in aquifer at source (perpendicular to flow)	Sz	1.50E-01	m	" "
Plume thickness at source	Sy	2.00E+00	m	" "
Saturated aquifer thickness	da	1.68E+02	m	" "
Bulk density of aquifer materials	ρ	2.71E+00	g/cm^3	" "
Effective porosity of aquifer	n	2.00E-04	fraction	" "
Hydraulic gradient	i	1.00E-03	fraction	" "
Hydraulic conductivity of aquifer	K	1.89E+00	m/d	" "
Distance to compliance point	x	1.01E+02	m	" "
Distance (lateral) to compliance point perpendicular to flow direction	z	0.00E+00	m	" "
Distance (depth) to compliance point perpendicular to flow direction	y	0.00E+00	m	" "
Time since pollutant entered groundwater	t	1.00E+100	days	*time variant options only*
Parameters values determined from options				
Partition coefficient	Kd	0.00E+00	l/kg	*see options*
Longitudinal dispersivity	ax	1.01E+01	m	*see options*
Transverse dispersivity	az	1.01E+00	m	*see options*
Vertical dispersivity	ay	1.01E-01	m	*see options*

Calculated Parameters

	Variable	Value	Unit
Groundwater flow velocity	v	9.45E+00	m/d
Retardation factor	Rf	1.00E+00	fraction
Decay rate used	λ	6.93E-101	d^{-1}
Rate of contaminant flow due to retardation	u	9.45E+00	m/d
Contaminant concentration at distance x, assuming two-way vertical dispersion	C_{ED}	1.47E+02	mg/l
Attenuation factor (two way vertical dispersion, C0/CED)	**AF**	**1.36E+03**	

Remedial Targets

Remedial Target	**2.04E+05**	**mg/l**	For comparison with measured groundwater concentration.
Ogata Banks			
Distance to compliance point	**101**	**m**	
Concentration of contaminant at compliance point C_{ED}/C_0	**1.47E+02**	**mg/l**	Ogata Banks
after	**1.0E+100**	**days**	

Care should be used when calculating remedial targets using the time variant options as this may result in an overestimate of the remedial target.
The recommended value for time when calculating the remedial target is 9.9E+99.

Select Method for deriving Partition Co-efficient (using pull down menu)

Calculate for non-polar organic chemicals

Entry if specify partition coefficient (option)			
Soil water partition coefficient	Kd		l/kg
Entry for non-polar organic chemicals (option)			
Fraction of organic carbon in aquifer	foc	4.50E-01	fraction
Organic carbon partition coefficient	Koc		l/kg
Entry for ionic organic chemicals (option)			
Sorption coefficient for related species	$K_{oc.n}$		l/kg
Sorption coefficient for ionised species	$K_{oc.i}$		l/kg
pH value	pH		
acid dissociation constant	pKa		
Fraction of organic carbon in aquifer	foc		fraction
Soil water partition coefficient	Kd	0.00E+00	l/kg

Define dispersivity (click brown cell and use pull down list)

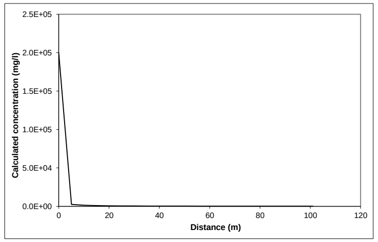
Dispersivities 10%, 1%, 0.1% of pathway length

		Enter value	Calc value	Xu & Eckstein	m
Longitudinal dispersivity	**ax**	0.00E+00	1.01E+01	4.45E+00	m
Transverse dispersivity	**az**	0.00E+00	1.01E+00	4.45E-01	m
Vertical dispersivity	**ay**	0.00E+00	1.01E-01	4.45E-02	

Note values of dispersivity must be > 0

For calculated value, assumes ax = 0.1 *x, az = 0.01 * x, ay = 0.001 * x

Xu & Eckstein (1995) report $ax = 0.83(\log_{10}x)^{2.414}$; az = ax/10, ay = ax/100 are assumed



Note graph assumes plume disperses vertically in one direction only. An alternative solution assuming the centre of the plume is located at the mid-depth of the aquifer is presented in the calculation sheets.

Note

This sheet calculates the Level 3 remedial target for groundwater, based on the distance to the receptor or compliance located down hydraulic gradient of the source Three solution methods are included, the preferred option is Ogata Banks.

By setting a long travel time it will give the steady state solution, which should be used to calculate remedial targets.

The measured groundwater concentration should be compared with the Level 3 remedial target to determine the need for further action.

Note if contaminant is not subject to first order degradation, then set half life as 9.0E+99.

This worksheet should be used if pollutant transport and degradation is best described by a first order reaction. If degradation is best desribed by an electron limited degradation such as oxidation by O2, NO3, SO4 etc than an alternative solution should be used

Site being assessed:	Corallian Limestone Model
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Environment Agency

Calculated concentrations for distance-concentration graph

Ogata Banks
From calculation sheet

Distance	Concentration
	mg/l
0	2.0E+05
5.1	2.54E+03
10.1	1.37E+03
15.2	9.36E+02
20.2	7.11E+02
25.3	5.73E+02
30.3	4.80E+02
35.4	4.13E+02
40.4	3.63E+02
45.5	3.23E+02
50.5	2.91E+02
55.6	2.65E+02
60.6	2.43E+02
65.7	2.25E+02
70.7	2.09E+02
75.8	1.95E+02
80.8	1.83E+02
85.9	1.72E+02
90.9	1.63E+02
96.0	1.54E+02
101.0	1.47E+02