Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development

Information Guidelines Explanatory Note

Characterisation and modelling of geological fault zones

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The Department acknowledges the traditional owners of country throughout Australia and their continuing connection to land, sea and community. We pay our respects to them and their cultures and to their elders both past and present.

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Images

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Overview

The role of the IESC

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) is a statutory body under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act). The IESC's key legislative functions are to:

- provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on coal seam gas (CSG) and large coal mining (LCM) development proposals that are likely to have a significant impact on water resources
- provide scientific advice to the Commonwealth Environment Minister on bioregional assessments (CoA 2018) of areas of CSG and LCM development
- provide scientific advice to the Commonwealth Environment Minister on research priorities and projects
- collect, analyse, interpret and publish scientific information about the impacts of CSG and LCM activities on water resources
- publish information relating to the development of standards for protecting water resources from the impacts of CSG and LCM development
- provide scientific advice on other matters in response to a request from the Commonwealth or relevant state ministers.

Further information on the IESC's role is on the IESC website (CoA 2022).

The purpose of the Explanatory Notes

One of the IESC's key legislative functions is to provide scientific advice to the Commonwealth Environment Minister and relevant state ministers in relation to CSG and LCM development proposals that are likely to have a significant impact on water resources.

The IESC outlines its specific information requirements in the IESC *Information Guidelines for proponents preparing coal seam gas and large coal mining development proposals* (IESC 2018) (the Information Guidelines). This information is requested to enable the IESC to formulate robust scientific advice for regulators on the potential water-related impacts from CSG and LCM developments.

For some topics, Explanatory Notes have been written to supplement the IESC Information Guidelines, giving more detailed guidance to help the CSG and LCM industries prepare environmental impact assessments. These topics are chosen based on the IESC's experience of providing advice on over 100 development proposals.

Explanatory Notes are intended to assist proponents in preparing environmental impact assessments. They provide tailored guidance and describe up-to-date, robust, scientific methodologies and tools for specific components of environmental impact assessments on CSG and LCM developments. Case studies and practical examples of how to present certain information are also discussed.

Explanatory Notes provide guidance rather than mandatory requirements. Proponents are encouraged to refer to issues of relevance to their particular project.

The tools and methods identified in this document are provided to help explain to proponents the range of available approaches to determine, at the highest level, the role faults may play in impeding or propagating pressure and groundwater flow impacts from proposed project developments. Proponents are encouraged to refer to specialised literature and engage with their relevant state regulators.

The IESC recognises that approaches, methods, tools and software will continue to develop. The Information Guidelines and Explanatory Notes will be reviewed and updated as necessary to reflect these advances.

Legislative context

The EPBC Act states that water resources in relation to CSG and LCM developments are a matter of national environmental significance.

A water resource is defined by the *Water Act 2007* (Cth) as '(i) surface water or groundwater; or (ii) a water course, lake, wetland or aquifer (whether or not it currently has water in it); and includes all aspects of the water resource (including water, organisms and other components and ecosystems that contribute to the physical state and environmental value of the resource)'.

Australian and state regulators who are signatories to the National Partnership Agreement seek the IESC's advice under the EPBC Act at appropriate stages of the approvals process for a CSG or LCM development that is likely to have a significant impact on water resources. The regulator determines what is considered to be a significant impact based on the *Significant Impact Guidelines 1.3*.

Contents

Executive summary

Coal seam gas (CSG) and large coal mining (LCM) developments may disrupt water resources through diversion of surface water and groundwater drawdown. Understanding whether the impacts of drawdown will propagate to valued groundwater assets such as springs, wetlands, aquifers or groundwater-dependent ecosystems (GDEs) forms a vital part of environmental impact assessments for these projects. The scope of the *Information Guidelines Explanatory Note: Characterisation and modelling of geological fault zones* (Explanatory Note) is restricted to the assessment of the impact of faults on groundwater assets because of CSG or LCM project development. It does not extend to considering surface water or highly detailed risk assessments or the consideration of environmental consequences for groundwater assets and GDEs.

Geological faults are displacements within otherwise intact rock material. The potential influence of faults on surface and groundwater systems is variable. In some cases, faults can have little to no influence on groundwater flow, and in other situations faults can provide a barrier, a flow pathway or a combination of a barrier (to horizontal flow) and a conduit (upward or downward flow via the damage zone) that results in significant changes to water assets and GDEs. Further, the influence of faults can be cumulative – for example, a fault acting as a barrier could enhance the hydrogeological effects and flow paths for an adjacent conductive fault.

Faults may enable groundwater flow connection between mining excavations or coal seams and key water assets and GDEs; and exacerbate impacts related to CSG and LCM developments. Changes to groundwater pressures that occur during mining or extraction can also activate flow along discontinuities that were not active prior to coal projects. Faults are not perfectly planar or linear, and fault behaviour may vary spatially along the fault and could change during a coal development project. Depending on the disposition of the fault relative to the groundwater flow system, the same fault may form a fluid flow barrier in some locations along its length while enabling or enhancing flow at other locations.

Predicting the range of possible groundwater behaviours during and after a coal development therefore requires the identification and characterisation of faults in the area of study or, alternatively, consideration of evidence that faults are absent or cannot have a significant influence on groundwater systems. It is important to consider faults, and extraction-induced subsidence and fracturing, in the context of a risk assessment approach that evaluates the likelihood and consequences of potential impacts. Environmental studies for CSG and LCM developments should specifically assess the likelihood that faults could be a barrier or flow pathway, or both, and account for this likelihood in any assessment of the potential consequences a development may have on groundwater assets and GDEs. This risk assessment informs management of water resources as well as their conservation and can also inform mining guidelines to minimise or mitigate impact(s).

For any proposal, there will be a mix of pre-existing public domain data and private or confidential data which should be considered as part of the risk assessment. Faults and the propensity for fracture development and propagation during coal or gas extraction are also geotechnical issues, so information can serve multiple purposes. It is recommended that proponents outline all data used in the study; summarise any proprietary data available; and describe a plan for the collection of new data that could be required to minimise uncertainty. A list and discussion of potentially important data types is thus recommended, considering that each project site and conditions will be unique. A partial list of useful data for structural analysis and interpretation might include:

- a geological summary of known faults annotated by their nature, their scale and which strata they displace, the lithology and lateral continuity of aquitards and aquifers, and their stratigraphic order
- contextual regional-scale geological outcrop and sub-surface mapping and underlying public domain data used for interpretation

- Digital Terrain Models (DTM) from aerial photography, topography and LiDAR
- regional to mine-scale geophysical surveys (e.g. ground or airborne magnetics, electromagnetics, gravity, electrical resistivity tomography)
- seismic surveys
- in situ stress, field orientation and magnitude of stresses, pore fluid pressure and relationship to fault orientation (dip and strike) and geometry
- pit and underground mapping
- hydrogeological tests and groundwater level observations
- tracer studies, including water chemistry and time-based geophysical surveys.

This Explanatory Note also contains information and methods to help assess the risk of a fault or faults providing a barrier or flow path, or both. A general method is summarised as:

1. Ensure the integration of geological and hydrogeological understanding of the geometry and distribution of faults, major rock types, stratigraphic units and their hydrogeological characteristics.
2. Where necessary, expand the area or depth of geological investigation to include the key groundwater assets, coal seams or excavations and nearby faults.
3. Based on geological information and hydrogeological tests and observations, estimate the properties of the aquifers and aquitards, e.g. vertical and horizontal hydraulic conductivity and specific yield or specific storage characteristics.
4. Conceptualise how known faults may currently be influencing groundwater flow and connectivity to environmental assets and the plausibility of this changing due to a proposed CSG or LCM development. This may include faults either connecting assets to the coal seams or excavations or acting as barriers.
5. Test the conceptualisation using 3-dimensional (3D) geometry and modelling, considering the behaviour of groundwater and potential pathways across or along the faults.
6. Assess the risk to groundwater assets through groundwater flow modelling that incorporates representation of the fault system(s). How faults are represented and parameterised needs careful consideration during the model design stage, and this may include some simplification of the fault systems. The modelling assessment can quantify potential changes to flow rates, groundwater levels and concentrations of chemical species that may result from a LCM or CSG development, given the presence of a fault(s). Such modelling generally falls into the following two categories of general methods:
   - ‘Single continuum’ or ‘Equivalent porous medium models’ rely on approximating the properties of faults, as equivalent porous media (EPM) hydraulic properties, such as permeability and porosity. This approach can be adopted for large regional or subregional scale models (e.g. a model domain extending tens of kilometres), where the investigation scale and approximation of porous media flow are appropriate (Bense et al. 2013).
   - Dual continuum models rely on representing dual flow regimes, one through a fracture network and the other through a matrix. One flow regime represents the rock matrix, which has a small hydraulic conductivity and a large porosity (diffuse flow regime); the other regime has a large hydraulic conductivity and small porosity to represent the higher velocity flow (conduit or pipe flow) through fractures. Fractures may be represented explicitly in space, e.g. using a discrete fracture network (DFN). Alternatively, fractures may be represented implicitly using a dual porosity representation. Where the impact predictions are sensitive to the processes occurring in the fracture and matrix flow regimes, these approaches can be useful.

Table 1 in section 3 of the report is replicated below. It provides a summary of high-level scenarios that illustrate differing situations and degrees of fault risk, from essentially no faults to faults potentially acting as causal pathways connecting coals to a groundwater asset. For this range of scenarios, the table sets out features that may cause connection, analyses that a proponent may consider and suggested approaches for characterisation of uncertainty and risk. The table highlights, at the highest level, a range of available approaches and these are described in more detail within the Explanatory Note and appendices.

Table 1: Case studies/scenarios that illustrate differing situations and fault risk character

Case studies	Diagnostic for scenario	Fault flow groundwater phenomena	Site-based evidence and geological products to justify the choice of this scenario	Suggested approaches for characterisation of uncertainty for risk
Scenario A-1: Faults are unlikely to affect groundwater flow	**There are no faults**	• No faults and/or few faults with negligible displacement	• Documentation of flat-lying or essentially undeformed stratigraphy, represented by a series of cross-sections parallel and perpendicular to strike, that illustrate the relative lack of faults • Provide complementary data (e.g. potentiometric maps that display presence or absence of anomalies)	• Assess the likelihood that faults exist that have not been observed • Explore alternative interpretations, then use one of the following scenarios to characterise the probability of critical repercussions of an unobserved fault on predicted impacts to environmental receptors
Scenario A-2: Faults are unlikely to affect groundwater flow and impact assessment due to an aquitard	**There is a regional aquitard separating the groundwater asset or aquifer from the coal seam or excavation, and this aquitard is not breached by faults. No primary juxtaposition of flow units across the faults is present**	• An aquitard separates the groundwater asset from the coal seam or excavation • Vertical fault offset (throw) is smaller than the thickness of aquitards and any slip along strike is minimal • Faults are therefore unlikely to form vertical *causal pathways*	• Geological, hydrogeological and geochemical evidence for a regionally extensive valid aquitard • A set of regional cross-sections showing faulting that is geometrically and kinematically consistent • A comprehensive description of the aquitard, including, if possible, a description of the depositional environment • Fault statistics, including length and throw ratios/distributions • Systematic analysis of fault displacement profiles, stress regime • Structure contour maps for the top and base of the aquitard • Isopach map of all regional aquitards	• Risk assessment of potential aquitard breach through analysis of the likely range of fault offset relative to aquitard thickness. A range of 1D, 2D and 3D techniques can be used to assess the probability that the aquitard has, or has not, been breached • Should a significant probability of this be shown then an uncertainty analysis based on scenario C would be required • Baseline geochemistry and pressure data from above and below aquitard
Scenario B: Faults are potentially relevant to impact assessment within aquifer systems	**There are no regional aquitards in the development region that segregate the groundwater asset or aquifer from the coal seam or excavation**	• Flow parallel to faults may be enhanced laterally and vertically in fault damage zones that contain fractures • Drawdown impacts may be greater or lesser in the presence of a fault barrier, depending on the relative placement of the development compared to the fault	• Site-based hydrogeological characterisation of damage zones with multiple lines of evidence • Displacement analysis assessing lateral continuity of faults • Analysis of the significant uncertainties that arise from the character of the fault damage zone(s), including the thickness and continuity of the damage zones, fracture density and effective fracture transmissivity within given stress regime • Analog studies of similar faults in outcrop, documenting damage zone architecture, fracturing and any fault rocks • Characterisation of the mechanical stratigraphy of the aquifers and thus their propensity to fracture during dewatering/depressuring	• Stochastic modelling may be used to model the probability that an identified fault or an unidentified fault intersects an asset • In the case of a fault intersecting an asset, a stochastic modelling approach that represents the potential repercussions of the fault on the groundwater flow system, potentially based on Cubic Law assumptions, can be used to derive distributions of the conservative estimates of flow from a source depressurisation effect, as an initial check on the potential significance of the fault(s) on an impact assessment • Ideally this approach would be validated through monitoring of a long-term pumping testing in the vicinity of key groundwater assets • If faults are identified as being material to the impact assessment, ensure any numerical groundwater modelling accounts for the repercussions of the fault presence, using information from the above assessments along with other hydrologic information. Stochastic or worst case numerical modelling approaches would be required to allow uncertainty of impacts to be considered in the risk assessment
Scenario C: Faults are important to impact assessment within aquifer–aquitard systems	**Faulting displaces regional aquitards, thus connecting the asset or aquifer to the coal seam by generating primary juxtaposition**	• Flow may occur across faults between aquifers through juxtaposition windows • Depressurisation at the coal seam or excavation may draw down shallower aquifers that would otherwise be separated by aquitards • Aquifers may be fully juxtaposed with aquitards to form primary juxtaposition/no-flow barriers	• A set of regional cross-sections showing geologically consistent faulting kinematics, architecture and the deposition environment of the aquitard • Depth structure contour maps for the top and base of aquitards • Isopach map for the aquifers and aquitards • As with scenario A-2, description and assessment of all aquitards. Quantitative juxtaposition analysis of aquifers, seams and aquitards across faults should document the locations of juxtapositions and then estimate the areas of these juxtapositions • For the case of 'no-flow' fault barriers, juxtaposition analysis and extensive site-specific pumping tests from both sides of the fault and along strike of the fault. Studies using hydrochemistry and water tracers (e.g. helium and radon) may be useful • Baseline geochemistry and pressure data	• Fault juxtaposition occurrence and area are the key uncertainties in this scenario. The construction of Allan Maps for key faults is encouraged, or else generating a series of cross-sections orthogonal to each fault • Stochastic fault analysis can be used to assess the probability of juxtaposition • Distribution of aquifer juxtaposition areas, and thus distributions of likely cross-fault flow • Probabilistic analysis of across-fault flow should then be used to define fault transmissibility in groundwater flow models • While the existence of a cross-fault seal (membrane seal) provided by a fine-grained fault core material is possible, extensive evidence of the likely efficiency and character of any membrane seals should be presented • Pumping tests and/or environmental tracer tests should be done to support the conceptualisation and provide an analogue of possible drawdown changes caused by the development • If faults are identified as being material to the impact assessment, ensure any numerical groundwater modelling accounts for the repercussions of the fault presence, using information from the above assessments along with other hydrologic information. Stochastic or worst case numerical modelling approaches, including fit-for-purpose geomechanical models, would be required to allow uncertainty of impacts to be considered in the risk assessment
Scenario D: Differential subsidence may lead to increased flow along existing or new fractures	**Differential movement reactivates faults and fractures or develops new pathways in previously unfaulted or unfractured strata. This scenario is most likely to apply to underground mines but does occur in CSG and could also occur in open cut mining**	• Observable depletion of near surface aquifers (and potentially surface waters) through fracture or fault networks caused by project development	• Required for mines with significant differential subsidence • Characterisation of the geometry of near-surface faults and their associated damage zones as the first-order features • Surface and base aquitard structure contour maps illustrating the faults and their displacement • Analysis of in situ stress and the effect that excavation may have on stress and the change in stress required for fault reactivation • Water isotopes/tracers for conceptualisation of flow pathways • Geologically valid cross-sections that illustrate the linkage from the seam level to the surface	• Baseline studies of hydrogeological properties of faults are required to characterise their influence on hydrogeological systems • Stochastic modelling may be used to model the probability that an identified fault or a suspected fault provides a pathway that intersects an asset • In the case of a fault intersecting an asset, a stochastic modelling approach that includes discrete fracture flow can be used to derive distributions of the conservative estimates of flow from a source depressurisation effect • Field evidence, such as environmental monitoring, tracer and/or pumping tests, is required to support the conceptualisation • Combined geomechanical and groundwater flow modelling consistent with mine design is encouraged within the hydrogeological risk assessment to identify focus areas for specific assessment. Stochastic or worst case numerical modelling approaches would be required to allow uncertainty of impacts to be considered in the risk assessment

1. Introduction

This Explanatory Note is a guide to assist proponents preparing environmental impact assessments (EIAs) to address the risks posed to groundwater assets by geological faults acting as pathways or barriers. It contains tailored guidance and describes up-to-date, robust scientific methodologies for EIAs on CSG and LCM developments and includes example scenarios to demonstrate analysis and presentation techniques. It is designed to provide a 'line of sight' to support proponents' statements and assertions within an EIA. This Explanatory Note covers the types of geological, hydrogeological and modelling assessments needed to assess the risks posed by projects to groundwater assets due to faulting. While it is a guide, it is not a 'guideline' or a 'standard'. Completing such impact assessments requires professional judgement, and the level of assessment required will vary depending on the proposed development and the local setting.

Geological faults are displacements within otherwise intact rock material. They are normally described using their orientation, amount and sense of displacement, and the character of the rock materials they displace. The data that can be used to find and define faults can be sparse or have limited resolution. Because of this, there are usually significant uncertainties regarding their geometry, kinematics and displacement characteristics. Although inherently variable, faults have a significant commonality of features and characteristics which can help make interpretations and inferences about their influence on flow pathways more comparative when the data available for complete characterisation cannot be gathered. Faults are not perfectly planar or linear, and fault character may vary spatially and could change, or potentially reactivate, during a coal or CSG development project. Hence, the same fault may form a fluid flow barrier in some locations along its length while enabling or enhancing flow at other locations.

Technical terminology is needed to describe faults, how they can be investigated and their assessed hydrogeological significance. A glossary of terms is provided after the main body of the report to assist the reader, and the reference list provides details of key texts on structural geology and fault analysis.

1.1. Why do faults matter?

In addition to influencing the geotechnical stability of strata, characterising geological faults within and near CSG and LCM projects is important because the faults may potentially influence the groundwater flow connection between the extraction target and key assets such as aquifers, springs and GDEs. There are several mechanisms by which geological faults can influence connectivity (also see Figure 1):

- Flow can occur through the core of a fault, providing a pathway for groundwater movement and pressure propagation.
- The damage zone around the fault core may also provide preferential flows.
- Where sufficient offset exists, faults can directly connect aquifers across aquitards.
- Conversely, where there is a disconnect between aquifers, faults may be a barrier to groundwater flow.

Changes in pressure – for example, due to groundwater extraction during mining or gas extraction – can potentially activate or produce flow along pathways that were not active prior to development. There is also a possibility that fault movement and hydraulic head changes can connect and increase flows or, conversely, disconnect and isolate parts of groundwater systems. Ignoring the presence of a fault may also lead to significant errors in the estimates of drawdown impacts if the fault forms a barrier to areas of groundwater recharge.

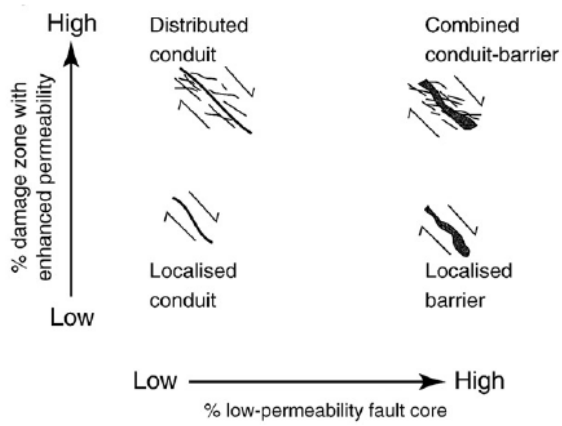


Figure 1: Influence of faults on preferential groundwater flow paths schematic (Bense et al. 2013, after Caine et al. 1996).

It is possible that faults could increase groundwater flows in a particular direction and propagate drawdown. Conversely, it may be shown that the risk of significant changes to the pre-development recharge, discharge and flow for groundwater assets is minimal or at an acceptable level. Risks are negligible, for example, where there is evidence that groundwater assets and the receptor sites (i.e. GDEs) are separated by thick aquitards that limit significant flow. The risks may also be negligible when the displacement on faults is too small to cross flow barriers (e.g. aquitards), thus not providing a significant flow pathway linking the assets to the coal seams or excavations.

Some types of mining and site conditions can be associated with significant disruption to natural groundwater systems, and in some cases these disruptions are permanent or will persist long after a project's closure and rehabilitation. An example of a high-risk case is a large underground coal mine that has a high probability of ground movement and subsidence. If ground movement such as subsidence causes reactivation of nearby faults, the flow through these faults could increase by orders of magnitude and thus provide new pathways that connect different aquifer systems, potentially leading to degradation of groundwater sources for GDEs. Changes in groundwater flow and storage could potentially be permanent or long-lasting, particularly if shallow, relatively small, perched surface aquifers and or zones of surface discharge are compromised.

1.2. Aquitard integrity

Evaluation of aquitard integrity along with fault analysis is important, as aquitards are often a controlling factor in groundwater flow pathways. There are many geological and hydrogeological aspects of aquitard integrity to consider in combination with fault zone analysis for CSG and coal mine projects (Timms et al. 2012; Bouzalakos et al. 2013). An ideal aquitard can be characterised as having a high degree of integrity if it has the following attributes:

- It is a regionally extensive stratigraphic layer without 'windows' or flow paths due to faults, depositional discontinuities, or leaky boreholes through the aquitard
- It is a thick stratigraphic layer, or series of multiple thin layers, that significantly limits vertical flow, where transport of solutes or salts can only occur by diffusion (i.e. a chemical concentration gradient)
- It is hydraulically tight, with low hydraulic conductivity at both core testing scale (i.e. matrix permeability) and site scale (i.e. no macropores or fractures that form discrete flow paths)
- It maintains integrity during ground deformation – for example, by plastic rather than brittle deformation or by swelling clay mineralogy that reduces the effects of fracturing.

1.3. Assessing the potential risks due to faults

When assessing the potential risks of fault systems on connectivity between CSG or LCM development and environmental assets, the repercussions of the presence of a fault on the groundwater flow system before, during and post development should be considered. The presence of a fault may influence the way a development perturbs the pre-development groundwater system and may lead to impacts on groundwater-dependent assets. Different methods and variable levels of complexity can be used by proponents to assess and present the risks related to geological faults, their identification and early discussion of the methods and presentation with the relevant regulator is encouraged when planning and conducting an assessment.

Assessing the groundwater impacts related to geological faults involves three main steps: static conceptualisation and characterisation of the fault system; dynamic simulation of the groundwater system; and risk assessment of fault behaviour and potential for reactivation and damage to groundwater assets and GDEs. Both static and dynamic data are required about the geology and geotechnical behaviour of the strata, the nature of the faults and the hydraulic parameters assigned to them, which can vary through time in response to development and require monitoring. Fault characterisation and conceptualisation is the focus of this Explanatory Note, with some discussion of how faults can be incorporated into dynamic simulation models, with a view to assessing their influence on flow pathways. A general process is shown schematically in Figure 2, and described here:

- First, the characterisation of the geological framework and the aquifer flow properties, particularly around known faults, is required. This includes the relative position of any aquitards and fault offsets and their relationships to the proposed development and any groundwater assets and GDEs. Typical sources for this information are discussed in section 2. The characterisation should also define or describe any uncertainties salient to fault flow pathways and potential connectivity to environmental receptors. Collectively this allows an initial conceptual-model assessment of whether there is a plausible risk that a fault or fracture induced pathway exists between the coal seam and a groundwater-dependent asset. In some cases, based on this initial system conceptualisation the risk can be assessed as unlikely and can be dismissed, while in others a detailed analysis of the likely groundwater flow upon development will need to be completed to fully assess risk. Examples of assessment methods are introduced in section 3.

- Second, based on the conceptual model, dynamic groundwater simulation models are designed and built to support the assessment of potential impacts on groundwater assets and GDEs resulting from the proposed development. These models represent transient groundwater flow (i.e. changing groundwater pressures over time) for key stages before, during and after project development. Coupled geomechanical and flow modelling may also be feasible (Zhang et al. 2018). Faults may be represented in the model as connected fractures in fault damage zones using a DFN (Cook 2003). Alternatively, EPM methods may be adopted so that faults are represented as altered hydraulic property values along the fault, albeit with some limitations. Other methods of representing faults in groundwater models include dual porosity models, which may be used when considering contaminant transport in fractured rock associated with faulting (Ward et al. 2017). While there is no single correct representation of faults in models, if a fault-related groundwater flow pathway or barrier is possible then it must be represented within the model in a way that gives a numerical expression to the possible influence of the fault on transient groundwater flow and potentially transport. A currently accepted approach is 'pilot point methodology' (Doherty 2003; 2015). The adopted model must also be capable of exploring the uncertainty of the simulated outputs. Some models may also need to account for changing fault zone properties if these are likely to change during or post the development period (Wang et al. 2016; Newman et al. 2017; Doherty and Moore 2020).

- Third, the models are used to assess the likelihood and significance of consequences for groundwater assets or GDEs related to the potential development scenarios. In some cases, the presence of faults may not be a significant factor in the simulated changes to groundwater flow paths and environmental consequences. In others, detailed analysis of the likely groundwater flow and storage changes that occur in relation to geological faults at key stages of development may be required and this may include evaluation of changes in the magnitude of permeability around faults or fractures due to depressurisation. The scope of this Explanatory Note considers the hydrogeological domain; it does not extend to detailed consideration of potential consequences for groundwater assets and GDEs.

Formal risk management assesses risk as a function of the probability of an event occurring and the consequence of the event. This Explanatory Note is primarily focused on the probability that the presence and nature of faults leads to an adverse 'event', such as drawdown propagating through an aquitard. The consequence of an event is highly dependent on the characteristics of the receptor, a landholder bore being very different to a GDE. The overall assessment of risk needs to take account of receptors, consequences to them, and any regulatory thresholds. This is addressed further in section 5.

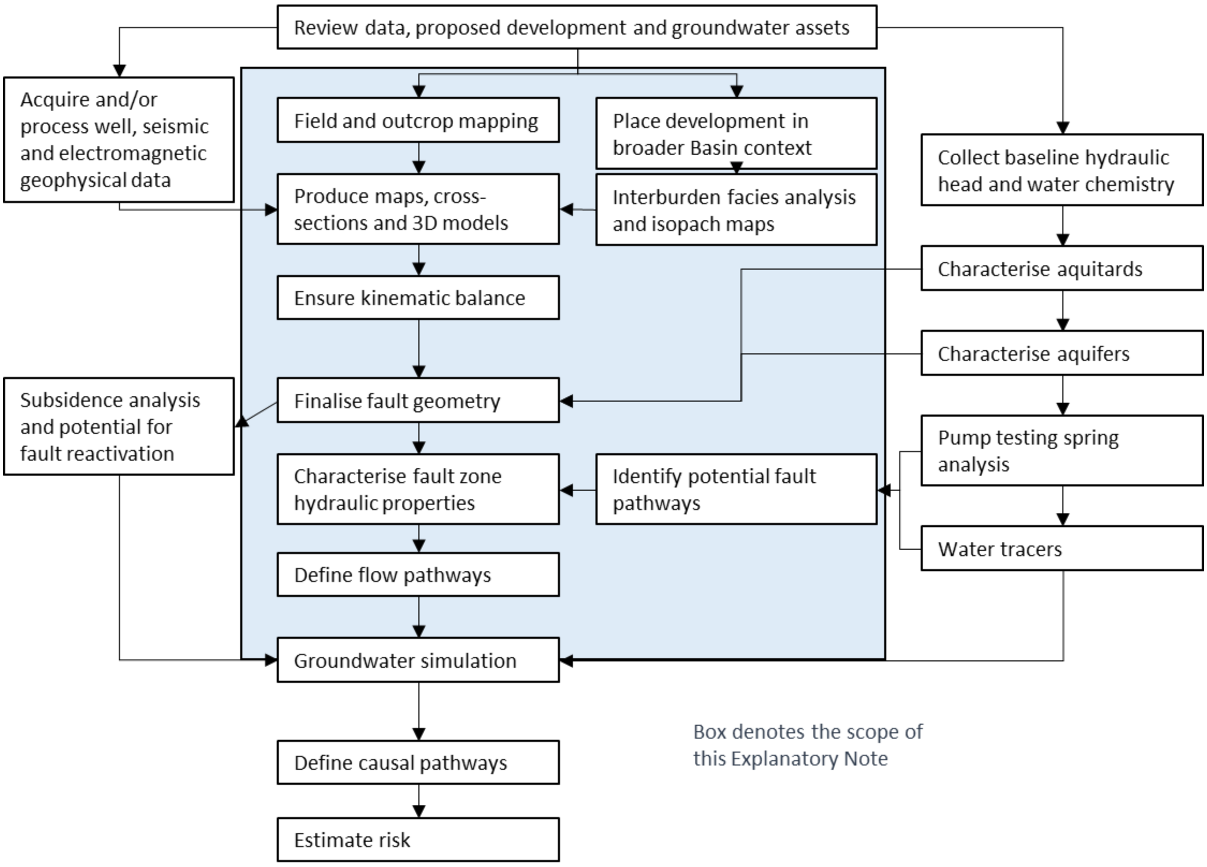


Figure 2: Flow diagram for the geological assessment and the geological/hydrological assessment of fault related flow for a CSG or LCM development. Note: This Explanatory Note focuses on the areas within the highlighted box.

1.4. Objectives of this Explanatory Note

The overall aim of this Explanatory Note is to assist proponents preparing EIAs to address the risks posed to groundwater assets by geological faults acting as pathways or barriers. To achieve that, the objectives of this Explanatory Note are to:

- highlight the types of investigations and data that can be used to help characterise faults
- present an overview of fault definitions and techniques that can be used to help visualise displacement
- present general steps that can be taken to conceptualise the hydrogeological role of fault(s) and to identify risk pathways
- provide an outline of methods for numerical simulation of groundwater flow, including faults, to aid in assessment
- illustrate application of risk assessment using example scenarios that consider different project and geological settings.

In publishing this Explanatory Note, the IESC is setting out the evidence required to support statements made within EIAs.

In terms of its scope, this Explanatory Note is not intended to be a textbook and is not a step-by-step instruction manual. A single preferred assessment approach cannot apply to all development scenarios due to the inherent diversity of sites and risk assessment requirements for individual projects. The scope of this Explanatory Note is to consider groundwater assets; it does not extend to considering surface water or the consideration of ecosystem consequences for groundwater assets and GDEs.

1.5. Structure of this Explanatory Note

The main body of this Explanatory Note consists of four further sections accompanied by appendices that present example scenarios. In the main body, section 2 considers relevant data sources for identifying and assessing faults together with basic definitions of structural geology and faults. In section 3 the conceptualisation of faults and identification of pathways is described, along with an introduction to the example scenarios. Section 4 considers the assessment of how the presence of faults may influence the hydrogeological regime and how this may be assessed using numerical simulations. The example scenarios presented in the appendices are hypothetical cases of proposed project and groundwater assets, informed by Australian experience. The examples include workflows for different levels of impact due to faults, from essentially no faults or impact to more complex investigations.

2. Faults: data sources, definitions and geometry

To assess the risks posed by LCM or CSG developments to groundwater assets and the role that faults play, information about faults is required. This section considers data sources for that information. The definitions of faults and their attributes are then considered together with methods to display the geometry of faults and the degree of juxtaposition of geological units that faults cause.

2.1. Data sources

A variety of pre-existing public domain data and private or confidential data will be available to project proponents for any proposed LCM or CSG development. Data types, coverage and availability will vary between greenfield and brownfield development areas, and it is important to address the potential for cumulative impacts.

In many cases, proposed LCM or CSG developments will be placed in close proximity to existing, similar projects and there will be substantial structural and geotechnical assessment work available. This work can be a valuable contribution to the characterisation and assessment of the faulting relative to the stratigraphy and distribution of aquifers and aquitards and their geomechanical and hydrological properties in the area. Mature projects in which numerical models have achieved good calibration and reproducibility of water levels and inflows may provide analogues for nearby mines of similar geology.

Proponents should outline and summarise the relevant data types and how they were used; assess their applicability or shortcomings; and describe a plan for the collection of new data if or as exploration for the development proceeds. Planning for data acquisition and/or presentation of the area of investigation should extend beyond the target coals (coal seams or excavations) and include the regions of the main environmental assets (aquifers, GDEs), as well as any intervening region between the assets and aquifers that may contain important faults, coal seams or excavations.

This section discusses the main data types for characterising a fault or fault network and assessing its potential influence on the groundwater system response. Because of the diversity of projects, it is not possible to comment on all the types of data that may be useful. As shown in Figure 3, different data types provide fault information at different scales. There is significant variability in fault properties at the small scale, and approaches that aim to measure large-scale properties that integrate the small-scale variability are more likely to be successful than those that aim to characterise the small-scale variation (Cook 2003). In keeping with this observation, field approaches that integrate aquifer properties at a similar scale and in a similar manner to the risks being considered are recommended for use (Cook 2003; Doherty 2015), and useful examples of these types of analyses are provided in the literature by Mallants et al. (2018) and Underschultz et al. (2018).

2.1.1. Geologic stratigraphy and mappable rock units

Understanding of the host lithology units that are present, how they are sequenced or layered stratigraphically, and if they are laterally continuous is of primary importance in the development of a geological model of faults, aquitards and aquifers. The mapping of key stratigraphic horizons in 3D and their displacement is used to identify faults, and the distribution and character of aquitards and aquifers is best determined directly from geological data.

Superposition and sequence stratigraphy are key tenets of geology, which provide the basis for mapping of time correlative horizons across a project area. Correlations of rock layers deposited during the same time periods are typically based on basin-wide time horizons and, in some cases, these can be constrained in absolute time using high-resolution biostratigraphy and radiometric dating. Volcanic ejecta (tuff) can be assessed with radiometric dating and assist correlation, as they tend to be deposited broadly and during a short interval of time. These time-specific stratigraphic markers can be used with historical sea level curves to correlate sequence boundaries. With these tools, it is possible to define sediment unit thicknesses and time of deposition with accuracy. More importantly, stratigraphy allows correlation between sedimentary facies defined by the texture, composition and bedding characteristics (for example, coarse-grained sandstones and fine-grained shales or siltstones) that influence the interpretation of units as aquifers or aquitards and their lateral continuity. A time-based sequence stratigraphic interpretation places importance on sequence boundaries as stratigraphic markers and, in particular, maximum flooding surfaces that comprise the regionally extensive, fine-grained units that discriminate the aquitards. Depositional discontinuities or strata pinch-outs that provide even a relatively small window in an aquitard can provide a flow pathway in addition to the possibility of fault-related flow pathways. Similar information on overburden lithological heterogeneity can also inform geomechanical and subsidence modelling.

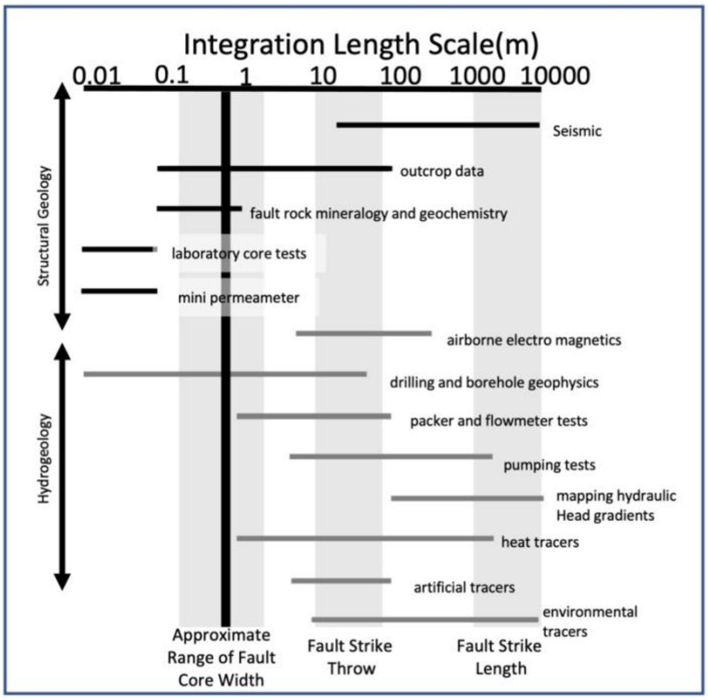


Figure 3: Length scales of methods used for fault investigation (partly after Bense et al. 2013). The approximate scales for geophysical techniques and for fault juxtaposition analysis, as well as the typical dimensions for faults common to coal projects, have been added to the diagram.

Outcrop analogues can provide detailed sedimentary facies information for stratigraphic and hydrostratigraphic units that are defined using sub-surface data, but caution is required to understand how and where they fit in the sequence. Depending on the scale of the outcrop, marker horizons or sequence boundaries may not be obvious mappable units in the outcrop. Similarly, faults or elements of a fault system can also be observed and characterised in outcrop and must be placed in context of the regional to local models developed for the site. A logical hierarchy of investigation is:

1. concentrate on lithologies and their lateral continuity in a sequence stratigraphic context
2. identify and characterise the faults, relative to stratigraphy

3. characterise the aquitards and aquifers, their spatial continuity and juxtaposition relative to the target coal measures.

To strengthen the clarity and transparency of interpretation for aquifers and aquitards, development proposals should include or specifically reference the data used to develop the geological model(s) and constrain rock character and stratigraphy, such as mineralogy and petrography, measured porosity and permeability, and the stratigraphic and facies models or interpretations, determined by a combination of drilling and seismic survey.

2.1.2. Regional-scale geological mapping and interpretation and public domain data

In Australia, organisations such as Geoscience Australia, CSIRO, state geological surveys and universities, as well as industry – for example, Seebase (Geognostics 2021) – have conducted regional-scale studies which can aid the development of resource projects. Accessing these studies and, where possible, the data that underpin them is an important first step in developing an initial interpretation. Exploration and development data that companies are required to file (as part of their leasing of exploration or development rights) contain many types of data from drilling data and mapping, as well as detailed geological assessment and review of that data. General library searches can also reveal key information provided in scientific journals and conference proceedings. Regional to local studies specific to Australian coal measures can also be found in literature such as reports by the Australian Coal Association Research Program (ACARP) (e.g. Sliwa et al. 2017) and its predecessor, NERDCC.

Due to the differences in mechanical properties of coal versus clastic rocks, considerable differences in fault and fracture character may be observed in the overburden (aquitards and aquifers) compared with that observed in the mining environment close to the coal. These differences must be carefully considered when using various sources of data to assign properties to the aquitards and aquifers.

2.1.3. Aerial photography, topography and LiDAR

Analysis of lineaments and drainage networks (Hodgkinson 2009) in remote sensing datasets can assist in revealing surface expressions of faults. The geology of an exploration region is often obscured by vegetation or there are landholder issues that can limit surface access. Modern LiDAR and aerial imagery can help with interpretation of faults, even in regions of very low topographic relief. The use of detrended and light shaded topographic models is a starting point. Detrending is the process of removing the gross topographic tilting. With the appropriate analysis it is often possible to see linear anomalies that may represent the strike of faults. There is also a series of Geoscience Australia products, including Water Observations from Space, that can be used to review how flash flooding may be controlled by faults. The NSW Geological Survey bedrock exposure product provides a regional surface from which to evaluate structural features in the bedrock that might be inherited in the overlying stratigraphic sequence (SEED 2019). Topographic analysis and the production of lineament maps is a possible preliminary starting point for fault analysis.

2.1.4. Outcrop geological mapping

Of key importance and often neglected is the constraint provided by geological mapping. This information can be a valuable asset that improves the understanding and also aids the generation of a geological model. Geological mapping takes time but is relatively inexpensive in comparison to drilling. Mapping may provide constraints on where faults come to the surface, or constrain fault orientation. Even if faults cannot be found through geological mapping, the mapping can be used to document where faults are *not* present or to constrain the strike and dip of key stratigraphic horizons.

Faults are very hard to identify in some rock types (for example, in the Hawkesbury Sandstone of the Sydney Basin). Often it is easier to identify faults in interbedded or heterolithic successions, more common in marine depositional settings. Categorical fault throw information will seldom be derived from a single outcrop, but it is often the case that repeat visits to field exposures can help direct and inform an ongoing project design, analysis or risk assessment.

2.1.5. Pit and underground mapping

In LCM developments, ongoing mining typically generates detailed records of production, including (for example) data on coal quality, major and minor faulting, degassing and dewatering behaviour of the strata and faulted ground. Significant amounts of geotechnical data are often also collected. These data are useful in developing planning and proposals for either extensions to existing projects (i.e. brownfields sites) or for new projects. In particular, these data can be used to constrain the statistical and probabilistic character of faulting. A sample list of data of these types for open pit mining might include floor maps with noted locations and throws of faults, maps of the distribution of dilution which might constrain faulting locations, and the boundaries of excavated panels (commonly designed to avoid faults and stress related discontinuities). In underground environments these data might include mapping and characterisation of underground access roads, records from drilling conducted to de-gas the coal, or planning and reconciliation between dilution and production.

2.1.6. Borehole core, wireline and image log interpretation

Borehole geophysical logs (e.g. natural gamma, caliper, acoustic imaging, nuclear magnetic resonance) and core and drill chips are used to identify lithologies and stratigraphic sequences but can also be used to determine the mechanical stratigraphy and the distribution of fractures relative to lithology in the sequence, and stress via borehole breakout methods. Direct observation of faults and fractures, and the nature of the fault plane in core – for example, the presence of fault gouge or precipitates – assists with the interpretation of discrete flow pathways and hydrogeological properties of porous rock. Measurement while drilling data can also provide information about rock strength, loss of downhole pressures or returns.

2.1.7. Seismic surveys

Reflection seismic surveys are a relatively mature technology that can be used to generate robust 2-dimensional (2D) profiles and 3D volumes, particularly in layered horizontal or nearly horizontal rock sequences. 3D seismic data is one of the best ways to constrain fault throw and is considerably cheaper than drilling a fine grid of bore holes. 3D seismic can be used to visualise the displacement of target coal seams and map the architecture of the fault system(s) and its variation through the stratigraphy within the proposed development area. It is also important to collect seismic data over larger regional faults that may juxtapose coal seams with shallow aquifers.

Commonly the data is presented in two-way travel time but, with appropriate pre-stack depth migration (PSDM), relatively accurate 3D volumes can be produced. Seismic data always has an inherent resolution limit that depends on the acquisition parameters; these can be tailored to improve the quality and utility of the final structural interpretations. Archival data, such as scanned paper records, should also be used in addition to electronic forms.

2.1.8. Electromagnetic surveys

Ground-based transient electromagnetics (TEM), airborne electromagnetics (AEM) and magnetic surveys determine electrical properties of sub-surface material and fluids and can identify changes in lithology and reveal structure. TEM is a well-established method, with AEM a maturing technology that requires substantial processing or inversion to adequately image faults and aquifers. AEM can be flown by helicopter with relatively narrow line spacing, without the need for ground access. Strictly speaking, AEM is a 2D dataset, but with appropriate rock type parameterisation and geologically motivated inversion (i.e. integration with multiple datasets) it can provide sufficient resolution for near 3D constraint on shallow aquifer and fault geometry. Geoscience Australia has successfully applied this technique to identify multiple faults in shallow sediments – for example, along the Darling River at Menindee Lakes (Lawrie et al. 2012).

2.1.9. Fault inferences in sparse data situations

In some situations, faults are inferred from the interrelation of other aspects of geology, as faults may not be geophysically imaged or intersected in drilling. For example, if a distinct step in level is observed in the sub-surface, a fault is inferred. It is common at preliminary planning stages to identify large faults and avoid them, to eliminate or reduce risk to development and production. Even if these larger faults are outside the proposed development plan, changes in the stress or pressure during development could cause reactivation and lead to communication with local or regional aquifers. In areas where the existence of faults, acting as conduits or barriers, could change the outcome of the groundwater risk assessment, they need consideration and characterisation. In areas of sparse data, fault statistics of the relationship between length and throw are often employed. If the number and location of smaller faults within a region relative to aquifers and aquitards can be estimated, it may be able to predict the probability of larger faults of similar character and form the basis for further exploration (Bailey et al. 2005; Barnett et al. 1987; Delogkos et al. 2018).

2.1.10. Hydrogeological testing and groundwater-level data

Hydraulic head (expressed as mAHD) can be mapped either side of a possible fault zone, identifying possible connected or disconnected zones within an aquifer. Dissimilar measurements either side of a fault are a line of evidence that a fault zone is a potential barrier, or partial barrier, to groundwater flow across the fault zone and, similarly, consistent measurements either side of a fault are a line of evidence of continuity of the aquifer across the fault zone. Potentiometric mapping could, however, be misleading if measurements are allocated to the incorrect aquifer or aquitard across either side of the fault zone. The influence of discrete flow (e.g. through fault-related chimneys) on groundwater pressures should also be considered (Mallants et al. 2018).

Hydrogeological characterisation near and within fault zones needs to be part of a multidisciplinary analyses involving geology, geophysics and other essential lines of evidence (see, for example, Bense et al. 2013). Examples of integrated multi-scale methods for evaluating the integrity of aquitards for coal projects in a risk-based framework, including the possibility of flow pathways through aquitards associated with faults, was presented by Timms et al. (2012). Hydrogeological testing of aquifers and aquitards can be conducted at a number of scales using various methods as shown in Figure 3. The design, operation and reporting of pumping tests should follow industry standard practice, with careful consideration of the likely aquifer volume to be analysed. An aquifer test program needs to consider heterogeneity of the strata to determine an appropriate number of tests and observations points and the duration of testing that is required (e.g. short test periods may not accurately reflect lateral drawdown extents where a highly conductive fault is present). Other common methods for measuring hydraulic properties range from core scale tests (e.g. of aquitards and fine-grained fault gouge) to packer and flow meter testing in open rock boreholes and slug testing of monitoring bores. Alternative methods for measuring in situ hydraulic properties can also be applied – for example, use of groundwater level changes in response to rainfall recharge or passive pore pressure response to small natural stresses (McMillan et al. 2019).

Downhole flow logging, either during drilling or pumping or in static water columns within wells, can reveal where in a well transmissive fractures occur, and this can be used in conjunction with other downhole methods. Lo et al. (2014) describe use of televiewer, packer testing and heat pulse flow metering to estimate fracture transmissivity and hydraulic connections through fractures.

A large range of techniques for borehole geophysics can also provide valuable hydrogeological information, particularly through fault damage zones. Although indirect geophysical measurement of rock properties does have limitations, multiple geophysical logs within a borehole (e.g. natural gamma, caliper, acoustic imaging, nuclear magnetic resonance) are important to identify discrete flow pathways; and hydrogeological properties of porous rock.

2.1.11. Water chemistry and environmental tracer studies

A range of environmental tracer techniques, including water chemistry data, temperature and isotope data, can be used to provide another line of evidence to define a geological and hydrogeological model of faults (OWS 2020). In some cases, these data can also be used to constrain fault location and behaviour, and the monitoring of changes in water chemistry or isotopic composition through a project may provide further evidence for faults acting as conduits or barriers.

The use of multiple lines of evidence, including geological, geophysical and hydrogeological information and water chemistry and tracer data, is particularly important when testing conceptual models and conditioning groundwater models. Mixing (i.e. across aquitards) of waters of differing salinities can be used to infer the existence of faults (Tan et al. 2012). Seepage of methane and other gases are common in hydrocarbon and coal bearing basins and can be enhanced during subsidence where fracturing occurs. If data on coal-related gases are available, they are clearly relevant to fluid flow and can provide valuable constraint information on the current or possible future groundwater flow (Iverach et al. 2015).

Observations of other gases not directly related to coal basins may be useful (Iverach et al. 2019). For example, studies in uranium provinces and basement terrains show that helium and radon gas may be associated with faults (Pereira et al. 2010; Sun et al. 2018). Other studies have inferred inter-aquifer flow via faults from anomalies in temperature or ion chemistry (Bense et al. 2008; Gumm et al. 2016; Batlle-Aguilar et al. 2017).

In the broader realm of oil and gas development and production, the integration of production geochemistry data with flow and faults is now an established part of studies. The beginnings of these efforts to integrate data can be found in the foundations of fault flow analysis (Allan 1989).

Although environmental tracer data are useful, it is essential to combine these data with appropriate geometric and geological analysis of the fault(s) in 3D. In particular, the production of Allan Maps (Allan 1989) enables the development of a comprehensive model and understanding of the 3D network of flow pathways, and this network, integrated with the geochemistry, temperature and tracer data, provides the most complete and comprehensive understanding of the flow characteristics. These data inform the conceptual model and can also potentially be used to validate the numerical model.

2.2. Fault definition

2.2.1. Definition

Geological faults are approximately planar discontinuity surfaces in the earth's crust, across which a relative displacement in a direction parallel to the surface can be observed (Figure 4). Fractures should not be confused with faults; fractures are cracks in rocks with no significant measurable displacement and can range in spacing and length from very small (mm scale) to very large (see, for example, Schultz and Fossen 2008; Fossen 2016). Faults often have an associated network of fractures.

It is important to characterise the geometry of faults, beyond a 'line on a map' to a representation of the 3D displacement. The type of fault is part of a basic definition – for example, a normal or reverse (defined in the glossary) fault that can be readily depicted by standard geological symbols on maps of a project site. Other key features of fault architecture and anatomy, such as fault core and damage zones, are also important within the characterisation process, as it will relate to the flow behaviour.

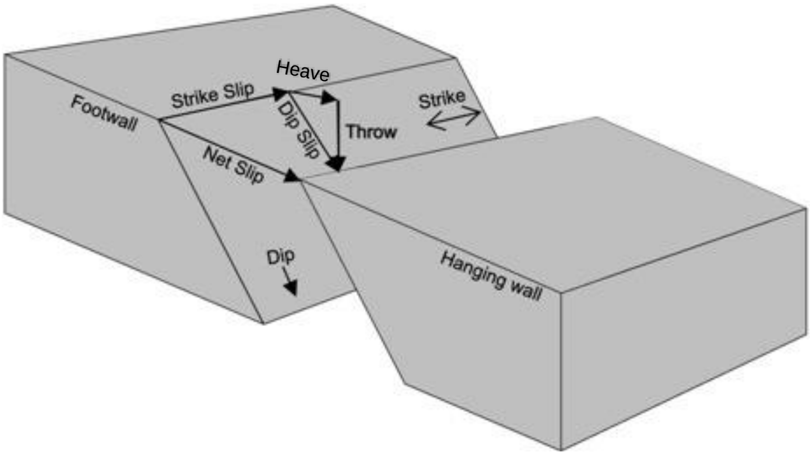


Figure 4: Fault displacement schematic. Major aspects of displacement that may influence groundwater movement are indicated (see definitions in the glossary).

2.2.2. Strike and dip

The approximate fault surface and fault zone can be averaged (or best-fit plane in 3D identified), despite faults having surface irregularities and roughness that arise from many different mechanisms. Thus, a fault is often described using an 'average plane', the orientation of which is described using either 'strike and dip' or 'dip and dip-direction'. The strike is a vector that is horizontal in the average plane of the fault. The strike is traditionally measured with a bearing or angle measured clockwise from north (e.g. an east strike is 90° and a northwest strike is approximately 315°). For more detail see McClay (1987).

2.2.3. Strike and separation / heave and throw

In some cases, it is possible to identify corresponding features on the opposing sides of a fault, which allows the total relative displacement to be directly measured. This is a vector quantity, which is usually referred to as fault slip. Formally, slip describes the full movement history, including faults which move one way then move backwards, i.e. change direction of displacement. Consequently, slip may be a complex, non-linear vector.

Because it is usually difficult to determine the full history of the fault, it is common to consider only the pre-faulting and current-day geometry, and it is preferred to use the term 'separation' to describe the difference between the original and the post-faulting state. Separation can thus be described as a single linear vector connecting two points on the opposing sides of a fault, which were formerly adjacent to each other. It is then common to resolve the total separation into two or three components, with the vertical component being the throw (vertical separation) and the horizontal separation being divided into two components, one parallel to the strike and one perpendicular to the strike. The component perpendicular to the strike is also called the heave. For more background and detail see Fossen (2016).

2.2.4. Slip/separation variability

While it is convenient to describe a fault's geometry as a plane with separation resolved as a single vector, in reality the slip and separation vectors vary over the fault surface, and with the available data and normal observation methods it is not always possible to determine where the maximum separation point or points are. This is partly because observation methods and data have an intrinsic resolution limit. However, despite the uncertainty, separation, where it can be summarised in detail, is found to vary in a predictable fashion across the fault surface. Typically, there is a maximum value near the central part of the fault surface, which then rapidly decreases to zero as the fault surface tip or edges are approached (Fossen 2016). It is also important to consider that faults do not always occur independently and they can interact, conserve or transfer displacement from one fault to another (Fossen 2016). Understanding the variation across and between faults, in addition to their location, can reduce uncertainty when modelling their influence on flow pathways.

2.2.5. Fault architecture

Fault architecture refers to the general style of faulting, typically at the regional scale, and faulting extent. In particular, larger structures can influence or cause the generation of smaller faults. Conversely, the evolution and growth of large fault zones through the linkup of smaller fractures or faults can also result in geometrical complexity. Further information is available at Fossen (2016), particularly chapters 17, 18, and 19.

2.2.6. Fault anatomy

It is common to refer to the outcrop or local-scale character of fault zones as fault anatomy (Fossen 2016). This Explanatory Note uses the following key terminology for three aspects of fault zones:

- Principal slip surfaces: These are discrete surfaces that are the main location where most of the relative displacement of the two sides of the fault occur. They commonly have clear evidence of frictional wear processes, including friction striations and polishing.
- Fault core: Near the principal slip surfaces it is common, although not universal, for there to be a zone of pulverised and ground rock material (also known as gouge or cataclastic material) derived from the surrounding rock, with a smaller grain size and possibly reduced permeability to fluid flow.
- Fault damage zone: Surrounding the fault core and principal slip surfaces there may be a zone of increased fracture density in comparison to the broader host rock material.

The thickness and character of damage zones and fault core materials is of key importance to hydrogeology. These aspects determine whether the faults will act as preferential fluid flow conduits (for example, enhanced flow through fractures in the fault damage zones) or as flow barriers (reduced flow because of fine-grained fault core materials).

In the absence of the ability to make direct, site-specific measurements of fault anatomy, it is appropriate to consider references to outcrop studies for conceptualisation. Outcrop studies of faults demonstrate that fault zones are exceedingly complex, and because of this it is difficult to estimate the dimensions and properties of the principal slip surface, the fault core(s) and the damage zone using sub-surface data. As such, it is appropriate to include large uncertainties or error ranges when performing calculations and simulations that might be incorporated into groundwater flow predictions.

There are a number of studies that can be used as starting points for the hydrological conceptualisation of faults, including, but not limited to:

- scale and fault zones in interbedded clastic rocks: Fossen (2016), Davatzes and Aydin (2005), Shipton and Cowie (2001), Schultz (2019), Sosio de Rosa et al. (2018) and Walsh and Watterson (1988) among others
- fault transmissibility: Manzocchi et al. (2010) and Sperrevik et al. (2002)
- potential biases in conceptual models of fault zone character and anatomy: Scibek et al. (2016) and Shipton et al. (2019).

Some studies of groundwater flow around faults tend to propose singular fault behaviour and frequently reference Caine et al. (1996), Bense et al. (2013) and Caine and Tomasiuk (2003). Cain et al. (1996) concentrate dominantly on fault zones in crystalline basement rocks, whereas Bense et al. (2013) provide a broad overview of faults in a wide range of rock types. Figure 3 provides an overview of the relative scales of observation and testing. It provides a starting point when planning geological and hydrogeological investigations. Of particular note is that the key geometric features related to faults can be inferred using geophysical and outcrop mapping.

2.3. Graphical representations of fault juxtaposition

It is important to assess the potential effects of individual faults, particularly where stratigraphic and hydrological units (stratigraphic layers / aquifers / aquitards) are juxtaposed across the faults. Juxtaposition area can provide an estimate for across fault leakage potential. As a first step, Allan Maps can provide a useful tool for this purpose and were first proposed or described by Allan (1989).

An Allan Map is made by projecting the intersection of footwall geologic layers onto the fault surface, followed by projecting the intersection of the hanging wall traces onto the fault plane (Figure 5). This workflow can be done in 3D software working with triangulations or grids of fault surfaces. In this case the Allan Map consists of a long section for the footwall superimposed (to be coplanar) with a long section of the hanging wall. This process can readily be conducted in most mine planning and or geologic modelling software packages. Alternatively, an Allan Map can be generated by hand using a depth structure contour map and graph paper.

Another aid to visualisation of juxtaposition is the triangle diagram that plots stratigraphic thickness of individual units against the fault displacement. This method is described and illustrated by Fossen (2016). Triangle diagrams are also referred to as 'clay-smear type panels', 'triangle plots' or 'juxtaposition diagrams' and have been used to represent fault sealing in reservoir simulations (e.g. Bentley and Barry 1991; Knipe 1997).

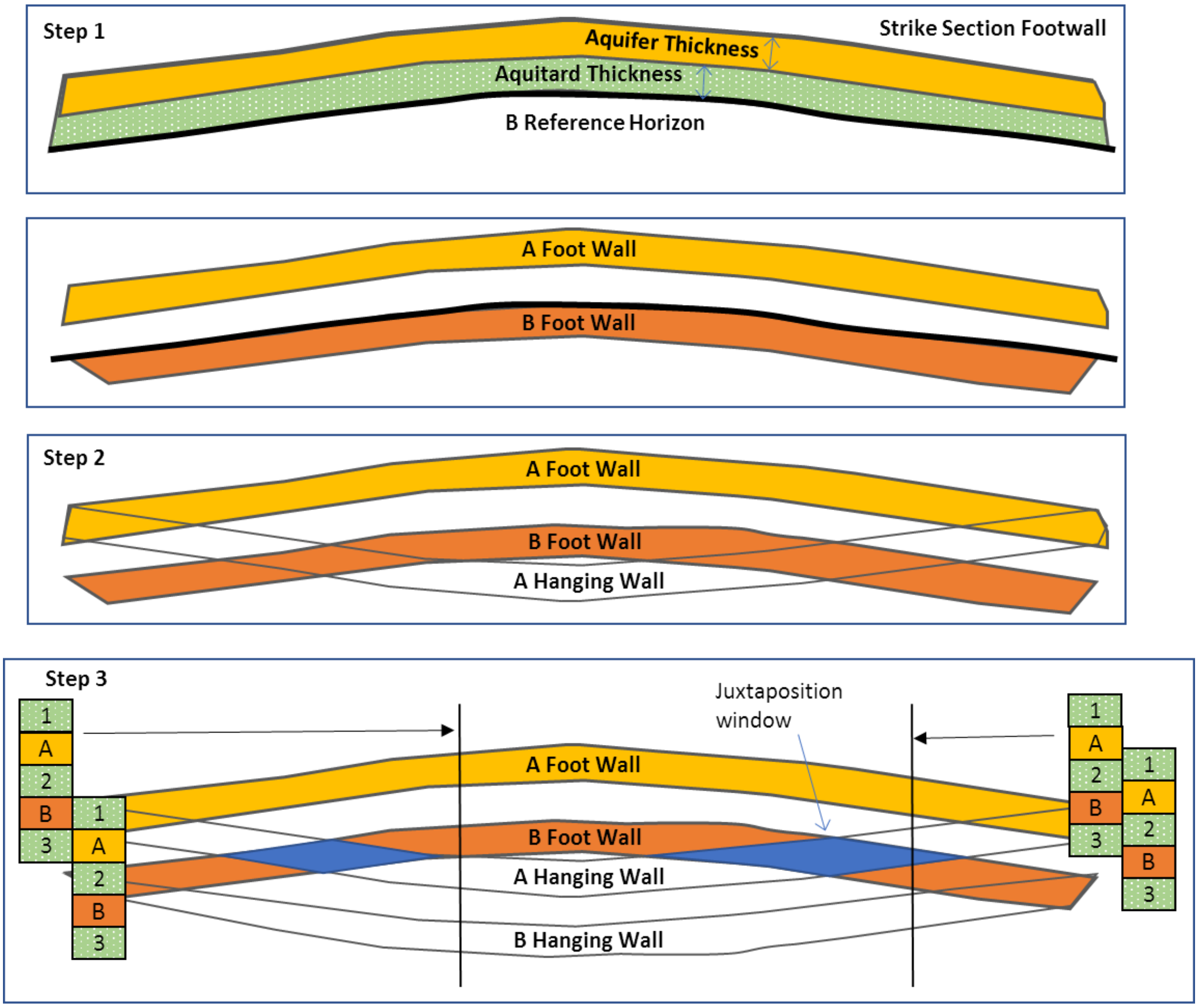


Figure 5: Example of an Allan Map. Construction can be broken down into three steps: identify the formation foot wall, identify the hanging wall and then identify the overlap.

3. Fault conceptualisation and identification of risk pathways

This section considers the general steps that may be taken to conceptualise faults and the risks they pose to groundwater assets with project development. Several example scenarios are then introduced to help contextualise workflows to assess fault risks.

3.1. The hydrogeological role of faults

While investigations may be targeted at determining the role of faults as conduits and preferential flow paths, the influence of faults as barriers on broader groundwater flow dynamics should not be discounted. Faults can provide a barrier to groundwater flow both within the site and regionally – for example, causing greater groundwater drawdown from extraction at the location of the boundary. This drawdown also has the potential to activate other faults within the area (Carreón-Freyre et al. 2016; Hadley et al. 2019; Marshall et al. 2019).

3.2. General steps

A large and growing number of approaches, methods and tools are available for investigating faults. Within the context of the site and proposed project, the following steps are suggested to analyse the potential influence of a fault or faults on a groundwater asset:

1. Develop a geometrical understanding of the geological setting of the development study area, including the major lithologies and their lateral continuity, the stratigraphy and the interpreted faults or fault zones.
2. Where necessary, expand the area or depth of geological investigation to include key groundwater assets, coal seams, existing mines or CSG developments and nearby faults.
3. Use a geological model to define, estimate or otherwise constrain the properties of the aquifers and intervening aquitards within the development area.
4. Assess the potential that any faults may connect assets, the coal seams or excavations, and any pre-development flow pathways.
5. Using the 3D geometry, enumerate potential pathways between the groundwater assets and the coal seams or excavations, including those that involve flow either across or along fault zones within a given stress regime, and the potential for reactivation.

Once an initial assessment has been undertaken, the following further assessments *may* be required:

1. Estimate or constrain the pre-development hydrogeological character, including the flow pathways and the rates and magnitudes of recharge and discharge for the key assets.
2. For each flow pathway, estimate the rate and magnitude of both pre-development and post-development flow.
3. Calculate the probability of each potential flow pathway to extract water from the asset(s), which may be qualitative.
4. Produce a summary of the rate and magnitude of the post-development and the pre-development groundwater flows through the life cycle of the development and use this summary to determine if any of the fault-related pathways are possible causal pathways.

5. Finally, assess the probability or likelihood that the development-related flow has an adverse impact on the asset or assets through the life cycle of the development.

3.3. Conceptual scenarios

A number of conceptual scenarios are now introduced to contextualise workflows for assessing fault-related risk in different development settings. The scenarios illustrating differing situations and degrees of risk posed by faults to groundwater assets are:

- Scenario A-1: Faults are unlikely to affect groundwater flow:
  - There are no faults.
- Scenario A-2: Faults are unlikely to affect groundwater flow and impact assessment due to an aquitard:
  - There is a regional aquitard separating the groundwater asset or aquifer from the coal seam or excavation, and this aquitard is not breached by faults. No primary juxtaposition of flow units across the faults is present.
- Scenario B: Faults are potentially relevant to impact assessment within aquifer systems:
  - There are no regional aquitards in the development region that segregate the groundwater asset or aquifer from the coal seam or excavation.
- Scenario C: Faults are important to impact assessment within aquifer–aquitard systems:
  - Faulting displaces regional aquitards, thus connecting the asset or aquifer to the coal seam by generating primary juxtaposition.
- Scenario D: Differential subsidence may lead to increased flow along existing or new fractures:
  - Differential movement as a result of mine subsidence reactivates faults and fractures or develops new faults and fractures in previously unfaulted or unfractured strata. This scenario is most applicable to underground mines and might be mitigated through mine design, but it could also occur in open cut mining or gas operations.

Table 1 (below and in the executive summary) sets out features that may cause connection, analyses that a proponent may consider and suggested approaches for characterisation of uncertainty and risk. The table presents, at the highest level, a range of available approaches.

To further contextualise assessment of fault-related risk, the conceptual scenarios presented in Table 1 are further developed into case-study-like examples presented in the appendices. Proponents are encouraged to consider the scenarios in Table 1 and the case-study-like examples in the appendices when planning environmental impact assessments. It should be recognised that specific proposed developments may present complexities that are not considered in this Explanatory Note and that items listed in Table 1 may be pertinent to several scenarios.

In some cases, it may be possible for proponents to show that faults are not a risk factor for groundwater assets and GDEs. This could be done either by providing evidence that there are no faults or by demonstrating that faulting does not compromise a regional aquitard with high integrity that isolates the asset from the coal seam or any planned excavations or extractions; or by demonstrating that the risk of rapid flow in faults parallel to groundwater flow is negligible.

Table 1: Case studies/scenarios that illustrate differing situations and fault risk character

Case studies	Diagnostic for scenario	Fault flow groundwater phenomena	Site-based evidence and geological products to justify the choice of this scenario	Suggested approaches for characterisation of uncertainty for risk
Scenario A-1: Faults are unlikely to affect groundwater flow	**There are no faults**	• No faults and/or few faults with negligible displacement	• Documentation of flat-lying or essentially undeformed stratigraphy, represented by a series of cross-sections parallel and perpendicular to strike, that illustrate the relative lack of faults • Provide complementary data (e.g. potentiometric maps that display presence or absence of anomalies)	• Assess the likelihood that faults exist that have not been observed • Explore alternative interpretations, then use one of the following scenarios to characterise the probability of critical repercussions of an unobserved fault on predicted impacts to environmental receptors
Scenario A-2: Faults are unlikely to affect groundwater flow and impact assessment due to an aquitard	**There is a regional aquitard separating the groundwater asset or aquifer from the coal seam or excavation, and this aquitard is not breached by faults. No primary juxtaposition of flow units across the faults is present**	• An aquitard separates the groundwater asset from the coal seam or excavation • Vertical fault offset (throw) is smaller than the thickness of aquitards and any slip along strike is minimal • Faults are therefore unlikely to form vertical *causal pathways*	• Geological, hydrogeological and geochemical evidence for a regionally extensive valid aquitard • A set of regional cross-sections showing faulting that is geometrically and kinematically consistent • A comprehensive description of the aquitard, including, if possible, a description of the depositional environment • Fault statistics, including length and throw ratios/distributions • Systematic analysis of fault displacement profiles, stress regime • Structure contour maps for the top and base of the aquitard • Isopach map of all regional aquitards	• Risk assessment of potential aquitard breach through analysis of the likely range of fault offset relative to aquitard thickness. A range of 1D, 2D and 3D techniques can be used to assess the probability that the aquitard has, or has not, been breached • Should a significant probability of this be shown then an uncertainty analysis based on scenario C would be required • Baseline geochemistry and pressure data from above and below aquitard
Scenario B: Faults are potentially relevant to impact assessment within aquifer systems	**There are no regional aquitards in the development region that segregate the groundwater asset or aquifer from the coal seam or excavation**	• Flow parallel to faults may be enhanced laterally and vertically in fault damage zones that contain fractures • Drawdown impacts may be greater or lesser in the presence of a fault barrier, depending on the relative placement of the development compared to the fault	• Site-based hydrogeological characterisation of damage zones with multiple lines of evidence • Displacement analysis assessing lateral continuity of faults • Analysis of the significant uncertainties that arise from the character of the fault damage zone(s), including the thickness and continuity of the damage zones, fracture density and effective fracture transmissivity within given stress regime • Analog studies of similar faults in outcrop, documenting damage zone architecture, fracturing and any fault rocks • Characterisation of the mechanical stratigraphy of the aquifers and thus their propensity to fracture during dewatering/depressuring	• Stochastic modelling may be used to model the probability that an identified fault or an unidentified fault intersects an asset • In the case of a fault intersecting an asset, a stochastic modelling approach that represents the potential repercussions of the fault on the groundwater flow system, potentially based on Cubic Law assumptions, can be used to derive distributions of the conservative estimates of flow from a source depressurisation effect, as an initial check on the potential significance of the fault(s) on an impact assessment • Ideally this approach would be validated through monitoring of a long-term pumping testing in the vicinity of key groundwater assets • If faults are identified as being material to the impact assessment, ensure any numerical groundwater modelling accounts for the repercussions of the fault presence, using information from the above assessments along with other hydrologic information. Stochastic or worst case numerical modelling approaches would be required to allow uncertainty of impacts to be considered in the risk assessment
Scenario C: Faults are important to impact assessment within aquifer–aquitard systems	**Faulting displaces regional aquitards, thus connecting the asset or aquifer to the coal seam by generating primary juxtaposition**	• Flow may occur across faults between aquifers through juxtaposition windows • Depressurisation at the coal seam or excavation may draw down shallower aquifers that would otherwise be separated by aquitards • Aquifers may be fully juxtaposed with aquitards to form primary juxtaposition/no-flow barriers	• A set of regional cross-sections showing geologically consistent faulting kinematics, architecture and the deposition environment of the aquitard • Depth structure contour maps for the top and base of aquitards • Isopach map for the aquifers and aquitards • As with scenario A-2, description and assessment of all aquitards. Quantitative juxtaposition analysis of aquifers, seams and aquitards across faults should document the locations of juxtapositions and then estimate the areas of these juxtapositions • For the case of 'no-flow' fault barriers, juxtaposition analysis and extensive site-specific pumping tests from both sides of the fault and along strike of the fault. Studies using hydrochemistry and water tracers (e.g. helium and radon) may be useful • Baseline geochemistry and pressure data	• Fault juxtaposition occurrence and area are the key uncertainties in this scenario. The construction of Allan Maps for key faults is encouraged, or else generating a series of cross-sections orthogonal to each fault • Stochastic fault analysis can be used to assess the probability of juxtaposition • Distribution of aquifer juxtaposition areas, and thus distributions of likely cross-fault flow • Probabilistic analysis of across-fault flow should then be used to define fault transmissibility in groundwater flow models • While the existence of a cross-fault seal (membrane seal) provided by a fine-grained fault core material is possible, extensive evidence of the likely efficiency and character of any membrane seals should be presented • Pumping tests and/or environmental tracer tests should be done to support the conceptualisation and provide an analogue of possible drawdown changes caused by the development • If faults are identified as being material to the impact assessment, ensure any numerical groundwater modelling accounts for the repercussions of the fault presence, using information from the above assessments along with other hydrologic information. Stochastic or worst case numerical modelling approaches, including fit-for-purpose geomechanical models, would be required to allow uncertainty of impacts to be considered in the risk assessment
Scenario D: Differential subsidence may lead to increased flow along existing or new fractures	**Differential movement reactivates faults and fractures or develops new pathways in previously unfaulted or unfractured strata. This scenario is most likely to apply to underground mines but does occur in CSG and could also occur in open cut mining**	• Observable depletion of near surface aquifers (and potentially surface waters) through fracture or fault networks caused by project development	• Required for mines with significant differential subsidence • Characterisation of the geometry of near-surface faults and their associated damage zones as the first-order features • Surface and base aquitard structure contour maps illustrating the faults and their displacement • Analysis of in situ stress and the effect that excavation may have on stress and the change in stress required for fault reactivation • Water isotopes/tracers for conceptualisation of flow pathways • Geologically valid cross-sections that illustrate the linkage from the seam level to the surface	• Baseline studies of hydrogeological properties of faults are required to characterise their influence on hydrogeological systems • Stochastic modelling may be used to model the probability that an identified fault or a suspected fault provides a pathway that intersects an asset • In the case of a fault intersecting an asset, a stochastic modelling approach that includes discrete fracture flow can be used to derive distributions of the conservative estimates of flow from a source depressurisation effect • Field evidence, such as environmental monitoring, tracer and/or pumping tests, is required to support the conceptualisation • Combined geomechanical and groundwater flow modelling consistent with mine design is encouraged within the hydrogeological risk assessment to identify focus areas for specific assessment. Stochastic or worst case numerical modelling approaches would be required to allow uncertainty of impacts to be considered in the risk assessment

4. Numerical simulation of groundwater flow systems with faults

Groundwater modelling is a tool that is frequently used to support the assessments of risks to groundwater assets and GDEs caused by LCM and CSG developments by simulating changes to groundwater levels, flows and spatial distributions of groundwater quality that may occur as a result of the development (Barnett et al. 2012). Numerical groundwater models are adopted for this purpose because of the complexity of the relationship between a groundwater system and LCM and CSG developments. In the implementation of these numerical models, analytical models may be adopted to analyse data at a local scale to support both the conceptualisation of the behaviour of the groundwater system in the presence of faults; and the estimation of fault parameters that will be used in the numerical models.

Most of the industry standard numerical groundwater modelling codes, such as MODFLOW (Harbaugh 2005; Langevin et al. 2017) or FEFLOW (Diersch 2014), represent sub-surface hydraulic properties by modelling the material as a porous media. The hydraulic properties of this porous media are represented in the model by spatially distributed permeability, storage and porosity model parameters. The model implements solutions of the equations of groundwater flow to calculate changes in groundwater levels, flows and concentrations under changing stresses that may result from the development.

Where the hydraulic parameters of sub-surface strata differ significantly adjacent to or on opposite sides of a fault, the impact and risks must be considered conceptually and in the groundwater model. The following impacts on groundwater flow are possible:

- A fault may present a barrier to horizontal water movement, or it may provide a conduit for rapid water movement or it may act as both a barrier and a conduit.
- Fault zones may provide flow paths between upper and lower layers through aquitards that otherwise are of high integrity.

4.1. Representing faults in groundwater models

The representation of faults in groundwater models ranges from the simple to the very complex. Faults may be represented simply via the adjustment of model parameter values at fault locations, to represent the altered hydraulic properties of the fault relative to the adjacent strata. Alternatively, faults may be represented explicitly within model meshes by offsetting and connecting layers, pinching out layers or including boundary conditions that represent fault connectivity or barriers to flow. These methods are 'single continuum' or 'equivalent porous media' approaches to modelling the fault. Alternatively, depending on the nature and scale of the groundwater impact under consideration, faults may be represented using a 'dual continuum' modelling approach. A dual continuum approach represents the sub-surface as a combination of fractures and a matrix. These fractures may be represented either explicitly or implicitly, e.g. using a DFN or dual porosity approach respectively.

There are pros and cons to adopting either a single or dual continuum approach and in the selection of various parameter discretisation options. These pros and cons are of varying importance in different groundwater modelling contexts. Hadgu et al. (2017), in a study that compares EPM and DFN representations, discuss factors to be considered in selecting between approaches, including the size of the modelling domain; the availability of data; the anisotropy in permeability; and whether diffusion or sorption of contaminants is required. As the distance between the project site and faults increases, the approximations introduced by the EPM approach may become less important (Reynolds 1977). Selection of modelling approach can be limited by data availability and the ability to extrapolate properties from smaller scale tests to larger regions of interest.

In the context of modelling to support impact risk assessments, the overriding consideration in the model design and development must be that the model is capable of supporting the quantification of risk associated with the fault. This then ensures that the assessment of risk posed to groundwater assets and GDEs is possible and that the modelling meets its objectives. Multiple models may be needed to assess different risks (Doherty 2015; Doherty and Moore 2020). Cook (2003) also notes that the model design adopted should be prediction specific, and grouped prediction types based on three key factors:

- whether the study is concerned with bulk hydraulic (flow) or solute transport
- the steady-state or transient nature of the problem
- the scale of the prediction of interest (near-well, local or regional).

Figure 3 presents the length scale of various field investigation methods. The scale that field data represents must also be considered when designing the model. The model should be designed to extract optimum information from available data and to use the information to constrain estimation of parameter values. However, data may have been collected at very different scales to the prediction of interest, and these scale differences may cause significant disparities between modelled and observed water levels and flows. Field and model estimates of parameter values may be found to be different. OGIA (2019) presents field data scales and parameter estimates compared with modelled values for the Surat Cumulative Management Area, illustrating that small-scale data, such as individual core plug permeability, may differ significantly from history matched values representing much larger volumes of rock.

When history matching and assessing the uncertainty of predictions, it is important to establish credible bounds on the fault parameters and estimate the pre-history matching (prior) distributions of these parameters. These parameter assessments provide the basis of the estimated modelled parameter values and their distributions which underpin uncertainty quantification and risk assessments. In the case of a mature project where a numerical model with a strong history match exists, the influence of faults may already be assimilated by the model's hydraulic properties. Whether additional fault representation in such as model is required in such as case would depend on the nature of new information and the potential impacts and pathways.

Sections 4.2 to 4.5 describe the methods currently used in groundwater modelling practice to parameterise and represent faults and outline the pros and cons associated with them. Because the representation of faults in groundwater models is an area of active research, these methods are evolving. Therefore, the modelling methods described briefly in the following sections represent the current state of modelling of groundwater flow systems with faults, and it is also possible that alternative approaches may be developed.

4.2. Deriving prior estimates of fault and fracture parameters

Modelled fault parameters are based on identifying and quantifying uncertainties in the fault geometry and fault properties (such as damage zone and core zone thicknesses) and in the aquitard and aquifer thicknesses and flow properties (e.g. see Cook 2003; McCallum et al. 2018). These fault properties are then translated to either EPM parameters of permeability and porosity or to discrete fracture flow parameters which describe flow through a connected pipe network or to implicit parameter representations of fracture flow in combination with flow through an EPM matrix.

Parameter values can be estimated on the basis of history matching to field data, using models that simulate flow through a fault core and fault damage zones or fractured aquitards. These models can be based on EPM, dual porosity and DFN approaches as described in sections 4.3 to 4.5. Parameter estimates can also be supported using analytical approaches.

For flow through fractured media which is represented as an EPM, bulk fault properties can be estimated based on relationships such as described by Bense and Person (2006), and flow can be calculated using Darcy's Law. This allows the fault properties to be calculated based on the assumption that they represent an alteration of the host rock, given a fault throw, and fault zone thickness (both a fault core and fault damaged zone) and a fault zone permeability based on integration of the combined damage zone and fault core.

The Cubic Law is an analytical approach for flow through fractures, where fracture flow is more analogous to flow through a pipe network (assuming that fractures are open and relatively smooth) than it is to flow in a porous medium.

An approximation for fracture flow is given by the Cubic Law, attributed to Snow (1968):

$$Fracture\ flow = -\left(\frac{\rho g}{12\mu}\right) Aperture^3.\Delta P.Fracture\ Height$$

For a given fluid pressure gradient ΔP, fluid density ρ, gravity g, and fluid viscosity μ, the flow is controlled by the fracture height and the cube of fracture aperture. Depending on the stress state, changes in fluid pressure (injection or recharge) can change the fracture aperture and, due to cubic relationship, the flow rate may change substantially.

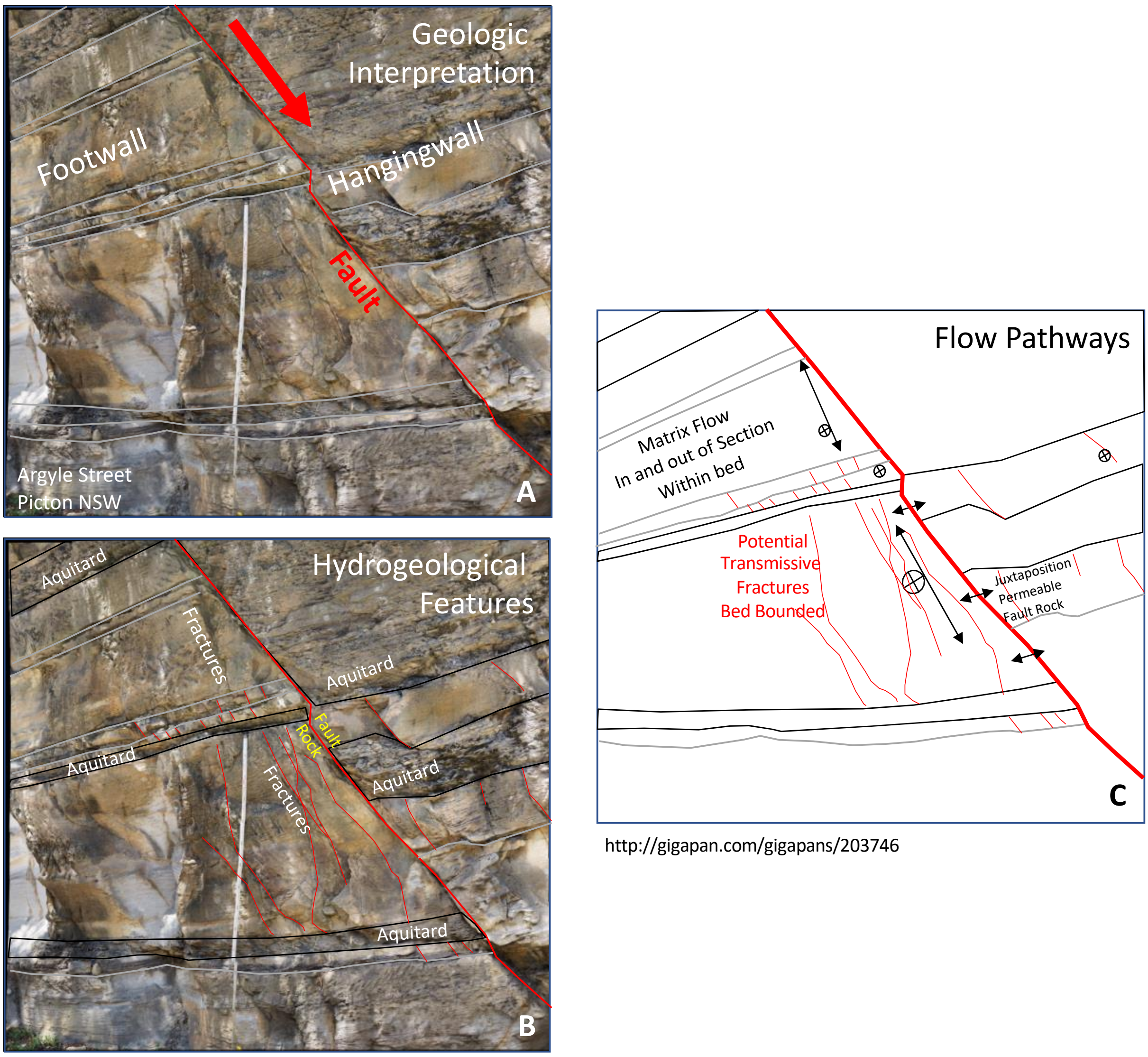
It is important to recognise that the Cubic Law is an approximation based on a parallel plate model. Fracture surfaces have irregularities; thus the flow is highly tortuous. Nonetheless, the model provides a useful way to calculate, estimate or understand the flow. The Cubic Law has been extended to consider lateral continuity of fractures and tortuosity of connected fractures (Zoorabadi 2014) and ensure estimated flow rates are realistic by accounting for losses of energy due to turbulent flow (e.g. see Zoorabadi et al. 2015).

The definition of fault parameters and their distributions is problematic, as fault zone and fracture flow parameters are difficult to measure in the field. Experience from historical fault investigations may assist in constraining factors such as fault core and damage zone thicknesses based on fault displacement (for example, see Fossen 2016). The schematic in Figure 6 is illustrative of the complexity and range of flow paths caused by faulting. Defining fault parameter distributions to use within the model is also challenging because the modelled fault parameters will likely represent a significantly upscaled volume compared to the field fault measurements. These 'upscaled' or 'effective' parameters represent a complex stress and scale dependent integration of the heterogeneous hydraulic properties that can be measured in field tests and that is difficult to define without supporting numerical experiments.

Adhikary et al. (2017) report on numerical predictions using geomechanical modelling of fracture propagation above LCM operations with comparison to two Australian mines. A modelling method or workflow for predicting fracture growth above longwalls is presented. This work also includes methods for estimation of the increased permeability (hydraulic conductivity) above longwalls due to fracturing and how this varies with height above the mined seam. Results show increases of 1 to 8 orders of magnitude, depending on fracture aperture, intensity and connectivity.

Upscaled estimated parameter values can also depend on the flow pathways being considered. Additionally, the general disposition of the fault compared to the groundwater flow direction is a key factor in decisions on fault representation in a model, which must accommodate either or both of the following flow regimes:

1. flows across faults (from one side of the fault to the other), typically where flow units such as aquifers or coal seams are juxtaposed against one another across the fault
2. flow parallel to faults, typically through fracture networks that develop in a tabular zone generally parallel to the faults.



http://gigapan.com/gigapans/203746

Figure 6: Photo showing flow paths related to faulting and fracturing. Panel A shows the basic geology. Panel B shows the hydrogeologically important features. Panel C shows an interpretation of the potential flow pathways.

There are a few important points to mention:

- For a juxtaposition flow path, if the fault rock thickness tends to zero anywhere along the fault zone (this appears to be common according to recent studies, including Sosio de Rosa et al. 2018) then there is no fault core. The permeability term for cross-fault flow therefore reverts to the matrix permeability of the material to either side of the fault.

- When Darcy's Law is applied to cross-fault flow through a crushed rock material, the hydraulic conductivity within and along the fault path is heterogeneous and the hydraulic conductivity employed in applying Darcy's Law is scale dependent. In general, the juxtaposition area term is far more important than the fault thickness because for typical faults around coal developments the areas are often very large (hundreds to thousands of m2) in comparison to the thickness or the core zones (frequently less than 1 m). The choice of flow calculations between Darcy's Law and the Cubic Law should be based on conservative assumptions from the perspective of influence on groundwater assets and GDEs. A relevant discussion of the potential pitfalls in different approaches is outlined in the Explanatory Note for groundwater modelling (Middlemis and Peeters 2018, particularly chapters 4, 5 and 6). Discussions of the relevance of the Cubic Law and its applicability, limitations and possible modifications are discussed in more detail (for example) by Zoorabadi et al. (2015).

4.3. Single continuum or EPM models

Single continuum, or EPM approaches, rely on representing the bulk properties of faults as EPM hydraulic properties and assume Darcian flow. This approach can be adopted for large regional or subregional scale models (e.g. a model domain extending tens of kilometres), where the investigation scale is much greater than the scale of the sub-surface heterogeneities (Bense et al. 2013).

4.3.1. Parameterisation devices

Groundwater models cannot replicate the full geological detail of a groundwater system with or without faulting. When faults are present, their representation must enable the repercussions of the fault on the simulated changes to the groundwater flow system to be determined. This may require a somewhat abstract representation of the fault and its parameterisation. The modelling methods available to represent faults in EPM models include the following:

- The conductance between neighbouring model cells can be modified in order to represent barriers or conduits to flow. An example is the horizontal flow barriers or HFB package in MODFLOW (Hsieh and Freckleton 1993) that can be used to represent faults which serve as a barrier in a relatively straightforward manner. A disadvantage of these methods is that they do not account for more complex fault geometries, particularly those where the fault may serve as both a barrier to flow in one direction and as a conduit to flow up and along the fault.
- Another method used in reservoir simulation, described by Manzochhi et al. (2010), relies on the introduction of so-called 'transmissibility multipliers' to cell connections which cross fault planes. This allows representation of faults serving as both a barrier and conduit to groundwater flow. Calculation of these multiples often follows estimation of fault permeability. A modified Manzochhi approach was presented by McCallum et al. (2018) to allow for more complex geometries where there may be significant offset of strata, but this method requires that the geometry is well known. This method could be implemented using MODFLOW6 capabilities. Note that calculation of multipliers is a complex matter where multiple cells linkages take place along a fault.
- Regional model grid cell properties can also be adjusted so that the horizontal permeability and vertical permeabilities represent a fault which represents both a barrier and a conduit. This requires initially calculating the fault parameters – for example, using the method as outlined in Bense and Person (2006) – and then adjusting the regional model cells to accommodate the fault zone permeability within the host rock. The horizontal and vertical permeabilities of the fault-affected cell are then modified in order to accommodate the presence of the core zone, taking into account the fraction of the cell that this zone occupies, as dictated by its thickness. This was used in Cui et al. (2018) and OGIA (2019) using a methodology reported by Watermark Numerical Computing.
- Finally, faults can be represented explicitly by actual cells in an EPM model. The main advantages of this method are that conduit flow behaviour can be accurately represented while also allowing for horizontal bypass of less permeable layers along fault planes. The drawback is that the explicit representation of the fault or faults increases the number of cells in the model significantly, resulting in greater computational burdens. The resulting computational load is often not practicable to work with in history matching or uncertainty quantification procedures which require many model runs.

All of these parameterisation devices can be represented using spatially distributed parameters to allow the heterogeneity of the fault to be expressed, such as pilot points (Doherty 2015) or grid-cell-based parameters.

4.3.2. History matching and uncertainty quantification

History matching compares model outputs to observed data including groundwater pressure heads, changes in head, derived data such as gradients and, where available, measured flows and water production. The EPM parameter devices described above have the advantage of being able to be conditioned with history matching and uncertainty quantification procedures implemented via the widely adopted continuously differentiable methods such as found in PEST and PEST++ (Doherty 2015; Doherty 2018; White et al. 2020). However, the determination of aquifer and fault parameters at EPM scales to underpin uncertainty quantification can be difficult. As mentioned above, numerical experiments can be used to support the estimation of such upscaled or abstract parameter values and their stochastic distribution, but this represents a significant computational commitment. Alternatively, where there is sufficient data that is of a similar type to the prediction and collected under similar stress regimes as in the past then history matching with a conservative allowance for the upscaled parameter uncertainty may be sufficient. Another alternative is to use a very small parameter discretisation that is commensurate with the hydraulic property heterogeneity; however, this is not practicable computationally for large-scale problems. Cook (2003) recommends adopting site and parameter characterisation field methods that correspond to the scale of the risk the model being used to assess (e.g. Figure 3). As with fault modelling methods in general, estimating upscaled parameter distributions remains an area of current research that is evolving.

4.4. Dual continuum models

Dual continuum models rely on representing dual flow regimes, one through a fracture network and the other through a matrix. One flow regime represents the rock matrix, which has a small hydraulic conductivity and a large porosity (diffuse flow regime); the other regime has a large hydraulic conductivity and small porosity to represent the higher velocity flow (conduit or pipe flow) through fractures (assuming they are open). Fractures may be represented explicitly in space, e.g. using a DFN. Alternatively, fractures may be represented implicitly using a dual porosity representation. Reservoir simulators such as Eclipse, Schlumberger (2020) and CMG-GEM, CGM (2020) used by the oil and gas industry are examples of dual continuum models. These approaches can be useful where the impact predictions are sensitive to the processes occurring in the fracture and matrix flow regimes.

4.4.1. Parameterisation devices

The methods available to represent faults in dual continuum models include the following:

- DFN models, such as FracMan (Golder Associates 2019), explicitly represent fracture flow as through connected conduits or pipe networks. These methods require fracture to be described either discretely or stochastically with properties including aperture, orientation and length (i.e. continuity) to be parameterised. Flow through each fracture can then be treated as being equivalent to flow between two uniform plates with separation equivalent to the aperture of the fracture. Application of this approach is generally limited by the data available on fractures as well as the ability to extrapolate properties from smaller scale tests to larger regions of interest. DFN models can be used in numerical studies to derive representative 3D EPM parameters that are then applied to simulate the effects of fractures without representing individual discrete features. For example, Oda (1985) presents an upscaling method to estimate the permeability tensor in fractured rocks that is implemented in some DFN modelling codes.

- Dual porosity models consider the movement of fluids in the matrix and fracture separately, coupling the two sets of flow equations via terms representing the rate of mass transfer between the two domains. This method is simpler to set up and implement than DFNs and is able to represent a rapid flow through the fractures, as well as the lag in water released from the matrix under a forcing pressure gradient. The dual porosity method is most widely used in solute transport. The application of the method can be limited by its simplicity, as complex spatially varying fracture geometries are unable to be represented. It is also difficult to determine reasonable parameter estimates for these abstract representations of fracture and matrix flow. Some public domain or commercial codes that have dual porosity/permeability capability are Tough2, HYDRUS2/3D, MODFLOW-2005, MODFLOW-USG and MT3DMS for mass transport.

4.4.2. History matching and uncertainty quantification

Dual porosity model parameters and predictions are able to be conditioned with history matching and uncertainty quantification procedures implemented via continuously differentiable parameter estimation methods such as PEST and PEST++ (Doherty 2015; Doherty 2018; White et al. 2020). As with EPM model parameters, the derivation of reasonable parameter bounds and distributions to underpin uncertainty quantification is difficult, and similar methods to ameliorate this difficulty can be adopted for dual porosity models.

History matching and uncertainty quantification with discrete fracture models is not likely to be practicable using the continuum-based methods in PEST and PEST++, where multiple (stochastic) realisations of fracture networks need to be represented. This is because each discrete fracture realisation requires a new model grid specific to the disposition of the fractures. History matching and uncertainty analysis, coupled with the need to build a new model grid for each realisation, represents a substantial computational burden. Instead, history matching and uncertainty quantification methods that rely more on rejection sampling rather than parameter adjustment are often more useful in this context.

If DFN models are used in numerical permeameter studies to derive EPM properties then history matching can be undertaken using continuum approaches. It is important to remember when selecting a modelling approach that representing fault details is not the same as representing the effects of the fault, and hardwiring of imperfectly known geological fault detail can impede rather than enable the flow of information from data and reduce the ability to express the uncertainty of predictions.

4.5. Poro-elastic modelling approaches

As noted in section 4.2, changes in pressure, potentially from a LCM or CSG development, could alter the geomechanical stress state, causing changes in the aperture and permeability of fractures or faults. A review of studies of geomechanics effects of mining to help improve impact prediction can be found in Mills (2020) with fracturing and subsidence due to mining explored in Adhikary et al. (2017) and Waddington (2020).

The reservoir simulators mentioned in section 4.4 can approximate stress and permeability changes, as can some DFN models. Fully coupled poro-elastic simulation lies beyond groundwater modelling codes and is an area of continued research. Geomechanical effects from CSG are explored via modelling by Zhang et al. (2018).

5. Summary and project evaluation checklist

5.1. Summary

CSG and LCM developments have the potential to disrupt hydrological systems, resulting in potentially significant impacts to groundwater-related features such as springs, well fields, GDEs, wetlands, streams and rivers. Significant changes could occur due to depressurisation of either coal seams or of excavations (e.g. open pits, underground drives and stopes) and groundwater flow along pathways that are related to geological faults. An EIA for CSG and LCM developments should specifically assess the likelihood that faults could be a connective flow pathway and assess the potential consequences on groundwater assets and GDEs. In most cases, the pre-development and post-development geometry and character of the faults will be the same, but in some cases ground movement, including subsidence, could change fracture apertures or reactivate geological faults and influence groundwater flow and storage.

To realistically assess the risk of coal and CSG developments, it is important to characterise the pre-development hydrological system, as well as the potential changes that may occur from development. The whole system should be considered to provide a realistic and comprehensive risk assessment, including faults in the context of other risk factors. Groundwater flow can be defined and described using field tests, analyses and modelling approaches that are long established in hydrogeology. However, there is a growing realisation that in some cases multidisciplinary analyses involving geology, hydrogeology, geomechanics and other lines of evidence are essential (see, for example, Bense et al. 2013).

This section should be read in conjunction with the IESC's Information Guidelines (2018). It provides a short checklist of items which can be included or submitted by proponents. The use of a structured program to compile information on geological faults as they relate to groundwater assets may be used. There is no single workflow or method applicable to all projects, and use of a structured risk assessment tailored to the hydrogeological-fault risk context is encouraged (Figure 2). It is highly recommended that proposals provide key information and analysis for each of the three main sections outlined in section 5.2.

5.2. Project evaluation checklist

5.2.1. Geology

Proposals should clearly explain a geological model of the host rock types, stratigraphy and fault geometry; the location of the mining resource (coal seam or gas location); and the location and character of the key assets (aquifers, GDEs, wells, springs). Key items for this part of the submission might include:

1. an outline of the regional geology, geological history and the regional structures, including an evaluation of the parts of the history that influence or provide insight to more local concepts
2. a summary of the data that are available and that were used to develop the project-scale geological model, including both the rock types and stratigraphy, and the fault geometry
3. maps at the regional and project scale to illustrate faulting, including:
   - outcrop geology maps with faults projected to surface where applicable; alternatively, a map that illustrates which strata are displaced

- structure maps with posted standard fault markings (lines, polygons, tick marks, displacement)
- isopach maps of key strata, particularly aquifers and aquitards.

4. fault displacement profiles that are derived from and consistent with the structure maps, showing if and how the throw (vertical displacement) for each fault varies along the length of the fault.

5.2.2. Hydrogeology

Proponents should present a description of the hydrogeology using a conceptual model that specifically addresses structure based on available information including the geometrical and geological information. The conceptual understanding is then the basis for designing any numerical models for impact prediction. The reader is also referred to the Explanatory Note for groundwater modelling (Middlemis and Peeters 2018). Key parts of this section may include:

1. a summary of the type and character of the data that were used to constrain the thicknesses and properties of the aquitards and aquifers in the hydrogeological model, including hydraulic conductivity, transmissivity and storativity of the hydrological units and fault(s)
2. maps and potentiometric/isopach maps of key hydrological units (aquitards and aquifers) and how they are offset by the faults in the inferred fault geometry
3. representative fault triangle diagrams for each region of differing aquitard and aquifer thickness to illustrate the potential fault juxtaposition scenarios
4. Allan Maps (Allan 1989) showing the main juxtapositions of coal seams, aquitards and aquifers which are constructed and presented to document and assess cross-fault and parallel to fault flow
5. a table of geologic units designated as aquifers or and aquitards, enumerating distribution of thicknesses and hydraulic conductivity. Hydrogeological evidence for high-integrity aquitards could include significant hydraulic head differences across aquitards, hydrochemistry and isotopes and tests at core and site scale
6. tabulated details of predevelopment groundwater pressures and aquifer pumping test data near and across fault zones. Water chemistry and tracer data adjacent to and distant from identified faults could also provide evidence of the possibility of discrete flow paths or a lack of flow through aquitards
7. a summary listing of the potential flow pathways between assets and coal seams or excavations (both pre-development and development related) that were considered
8. an assessment of any possible changes in the hydrogeology or water flow pathways that may be induced by development through depressurisation and or subsidence. For some projects the chance of subsidence will be minimal and does not require a detailed analysis. Where greater subsidence is possible, a detailed assessment, preferably with groundwater monitoring data, across the faulted area should be undertaken
9. estimated rates of flow, drawdown and transport along the key flow pathways based on groundwater flow models; and quantification of the uncertainty surrounding these estimates to underpin risk assessments.

5.2.3. Risk assessment

The risk assessment section of an EIA should specifically address the uncertainties and the relative risks that may be associated with the development. Regarding faults, the main goal is to assess and document the risks that faults provide a causal pathway between an asset (aquifer, GDE, etc.) and a depressurised zone such as a coal seam or excavation. Environmental impact studies for CSG and LCM developments should specifically assess the likelihood of faults that could be a flow pathway and assess the potential consequences on groundwater assets and GDEs.

The exact scope of the risk assessment will be project specific, so here we outline some steps likely to be required. In assessing risk, stochastic or probabilistic assessment is highly recommended. Further detail on these techniques is provided in the Explanatory Note on uncertainty analysis (Middlemis and Peeters 2018).

Key items in a probabilistic risk assessment may include:

1. a summary, preferably probabilistic, of fault presence/absence and of the chances that faults intersect key assets. For some systems, the juxtaposition of key assets with coal seams or possible depletion zones (for example, shallower or deeper aquifers) could be included
2. a temporal analysis of the likelihood of faults providing a flow pathway, including at localised points along a fault system, over the life of the project
3. a summary of the hydrological character of the pre-development water and ecological asset(s), including estimated or known rates and magnitudes of recharge, discharge and extraction (as applicable)
4. a summary of the estimated or modelled flow rates for potential flow pathways that have been identified in the fault analysis
5. quantitative estimates of the parameter uncertainty and the probabilistic description of the flow rates and magnitudes for the key flow pathways that were identified
6. a comparison of the pre-development and post-development flow pathways and flow rates, leading to the delineation of any causal pathways, and potential changes spatially and over time
7. a summary assessment of the potential consequences if flow pathways through a fault or fault system were to result in relevant changes to a groundwater asset or GDE.

Glossary

Term	Description and explanation
Allan Map	A fault plan profile view. A cross-section where the view direction is essentially normal to the fault plane. Features such as juxtapositions across the fault are easiest to portray in these views, and it is easy to measure areas of juxtaposition. Areas of juxtaposition are a key input to hydrogeological modelling. For more information or a complete description, consult Allan (1989).
Aperture	The open width or space between the two walls or sides of a fracture discontinuity. This aperture is measured in a direction approximately normal to the fracture surfaces and is difficult to accurately predict.
Assets	In this document, 'asset' or 'assets' is used to refer collectively to groundwater assets or related ecological assets. 'Assets' refers to an extensive list, including but not limited to springs, groundwater dependent ecosystems, aquifers, well fields, wetlands, rivers, streams and lakes.
Balanced cross-section	A cross-section that has been checked to ensure that the changes in shape, and the changes in horizontal length, of the major stratigraphic surfaces as depicted in 2D are reasonable. There is not extensive difference between the different layers. This strategy for validating a cross-section drawing is appropriate for most coal mining or CSG scenarios, because it works in relatively shallow levels in the earth's crust where ductile changes in shape are minimal.
Cataclasis/cataclastic	A mechanism that results in grain size reduction of the rock material due to crushing and deformation. This frequently occurs in a fault zone. 'Cataclastic' is the adjective used to describe material that has developed through cataclasis.
Causal pathway	Defined in other Explanatory Notes as 'a logical chain of events either planned or unplanned that link coal resource development and potential impacts on water resources and water-dependent assets' (see Middlemis and Peeters 2018; Doody et al. 2019). In this Explanatory Note, the terms 'pathway', 'flow pathway' and 'causal pathway' are used in specific ways, and each term has specific implications. 'Pathway' alone is used to denote a possible or potential pathway (along a linear or 3D path) from one location to another (for example, between a groundwater asset and a coal seam). 'Flow pathway' is used to denote a pathway in 3D which has been assessed as likely to allow water flow at a rate or magnitude that is significant in the overall hydrogeological system. A causal pathway is not defined as a path in 3D, although it may include or imply such a path. 'Causal pathway' implies a sequence of events which has an impact on a groundwater asset.
Damage zone or Fault Damage zone	The name given to the fractured or otherwise disrupted rock to one or both sides of the fault principal slip surfaces or the fault core.
Dip	The angle of inclination of a planar feature. A horizontal plane has a dip of 0 degrees, while a vertical plane has a dip of 90 degrees.
Dip-direction	The direction of the dip or, alternatively, the direction perpendicular to the strike (see 'Strike' below) and in the direction downwards (not upwards) on the inclined plane.
Fault core	The name given to the fine-grained rock material in a fault zone that has been reduced in grain size due to frictional processes or cataclasis. Usually, the fault core is adjacent to the fault principal slip surfaces, although this is not always the case. Since the fault core materials are normally of finer grain size than the rock to either side of the fault, fault core zones can inhibit flow.
Fault triangle diagram	A 2D plot showing typically depth on the vertical axis and increasing fault displacement on the horizontal axis. A triangle diagram can be used to display

Term	Description and explanation
	the vertical extent of juxtaposition between stratigraphic or hydrogeological units.
Flow pathway	A potential or likely pathway in 3D along which water or other fluid may flow. In this Explanatory Note, the terms 'pathway', 'flow pathway' and 'causal pathway' are used in specific ways, and each term has specific implications. 'Pathway' alone is used to denote a possible or potential pathway (along a linear or 3D path) from one location to another (for example, between a groundwater asset and a coal seam or between a rainwater source region and an aquifer). 'Flow pathway' is used to denote a pathway in 3D which has been assessed as likely to allow water flow at a rate or magnitude that is significant in the overall hydrogeological system. A 'causal pathway' is defined in other Explanatory Notes as 'a logical chain of events either planned or unplanned that link coal resource development and potential impacts on water resources and water-dependent assets' (see Middlemis and Peeters 2018; Doody et al. 2019).
Inversion	A process whereby earth forces or tectonic forces change, causing faults to be reactivated with a new slip / displacement vector. For example, a fault might form in an extensional setting as a normal fault, but later the forces and stresses change and it reactivates as a reverse fault.
Isopach, isopach map	A map showing the thickness of a stratigraphic horizon or of an aquifer or aquitard. Isopach maps are usually presented as colour-coded maps or with contours that trace along paths of constant thickness. An isopach could refer to a single contour line on an isopach map.
Mechanical stratigraphy	The varying mechanical material properties of rock strata (properties like Young's modulus, compressive and tensile strengths), the nature and frictional properties of boundaries between mechanical layers and mechanical layer thicknesses.
Normal fault	A fault where the hanging wall has moved downwards over the footwall (see Figure 4).
Pathway	A path in 3D xyz space which connects two points or locations – for example, a trace along a fault zone between an excavation and an asset or between a GDE and a CSG development. In this Explanatory Note, the terms 'pathway', 'flow pathway' and 'causal pathway' are used in specific ways, and each term has specific implications. 'Pathway' alone is used to denote a possible or potential pathway (along a linear or 3D path) from one location to another (for example, between a groundwater asset and a coal seam or between a rainwater source region and an aquifer). 'Flow pathway' is used to denote a pathway in 3D which has been assessed as likely to allow water flow at a rate or magnitude that is significant in the overall hydrogeological system. A 'causal pathway' is defined in other Explanatory Notes as 'a logical chain of events either planned or unplanned that link coal resource development and potential impacts on water resources and water-dependent assets' (see Middlemis and Peeters 2018; Doody et al. 2019).
Principal slip surface or fault principal slip surface	Frictional sliding surface in a fault zone.
Relay ramp	Relay ramps, often referred as stepover ramps, are a type of displacement transfer structure between overlapping normal fault segments that can have enhanced fracturing.
Reverse fault	A fault where the hanging wall has moved upwards over the footwall (see Figure 4)
Strata	Layers of sedimentary rock or soil, or igneous rock, that were formed at the earth's surface with internally consistent characteristics that can distinguish them from other layers. An individual layer can be referred to as a 'stratum', and this is the fundamental unit in a stratigraphic column and forms the basis of the study of stratigraphy.

Term	Description and explanation
Stratigraphy	The study of rock layers (strata) and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks.
Sequence stratigraphy	A branch of geology that attempts to subdivide and link sedimentary deposits into unconformity bound units on a variety of scales and explain these stratigraphic units in terms of variations in sediment supply and variations in the rate of change in accommodation space (relative sea level, the combination of eustatic sea level and tectonic subsidence). The essence of the method is mapping of strata based on identification of surfaces which are assumed to represent time lines (e.g. subaerial unconformities, maximum flooding surfaces) and therefore placing stratigraphy in chronostratigraphic framework. Sequence stratigraphy is a useful alternative to a lithostratigraphic approach, which emphasises similarity of the lithology of rock units rather than time significance.
Sequence boundary	The most significant surfaces in sequence stratigraphy. They are defined as unconformities or their correlative conformities. Sequence boundaries are formed due to the sea level fall.
Stope	Open space left behind from underground mining.
Strike	For an inclined plane, measures the compass direction of a horizontal line in that plane, relative to north. If the horizontal line trends exactly north–south then the strike is 0 degrees; if it trends east–west, the strike is 90 degrees.
Strike-slip fault	A fault where the dominant slip or displacement direction is horizontal.
Superposition	An axiom that forms one of the bases of geological stratigraphy. It is a form of relative dating. It states that, in undeformed stratigraphic sequences, the oldest strata will be at the bottom of the sequence.

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Appendices

Example scenarios

- Scenario A-1: Faults are unlikely to affect groundwater flow.
- Scenario A-2: Faults are unlikely to affect groundwater flow and impact assessment due to an aquitard.
- Scenario B: Faults are potentially relevant to impact assessment within aquifer systems.
- Scenario C: Faults are important to impact assessment within aquifer–aquitard systems.
- Scenario D: Differential subsidence may leading to increased flow along existing or new fractures.

Example scenario A-1
Faults are unlikely to affect groundwater flow

In this scenario we consider situations where there are no faults evident.

Initial risk profile given geology and groundwater conditions

- There are either few faults or no faults with negligible displacement/throw and thus no significant fault-related flow pathways.

Site-based evidence

- Documentation of relatively flat-laying or undeformed stratigraphy.
- Development and presentation of a regional geological model as a series of cross-sections that include the target coal seams and illustrate the general lack of faults in the region.
- Analysis and presentation of geologic illustrations indicating that the system is relatively flat-laying – for example, structure contour maps or cross-sections that are constrained by interpreted seismic data, extensive drilling data or other data.
- Analysis of gravity and/or magnetics data to illustrate that there are no basement faults.
- Analysis of geophysical surveys, such as airborne electromagnetics (AEM) and/or seismic, to demonstrate there are no faults in the study area.

Characterisation of uncertainty required for risk assessment in this context

- In this circumstance, uncertainty characterisation is concerned only with the confidence that there is an absence of faults, rather than the disposition of the fault. Assess the possibility or likelihood that faults are present but could not be observed or inferred with the existing data.
- If there is some possibility that faults which have not been observed or inferred are actually present then one of the following scenarios can be used to estimate the probability of critical fault behaviour.

Fault-related risk assessment – potential repercussions of the fault

- Not required because there is an absence of faults thus the risk of fault-related groundwater flow does not exist.

Example scenario A-2
Faults are unlikely to affect groundwater flow and impact assessment due to an aquitard

In this scenario we consider situations where a regional aquitard that is not compromised by faults isolates the groundwater asset from the coal seam or excavation.

Initial risk profile given geology and groundwater conditions

- A regionally extensive aquitard with high integrity separates groundwater assets from the coal seam, extraction area, or excavation. For example, the coal measures are overlain by a regionally contiguous, fine-grained unit interpreted to have formed in a deep marine or lacustrine setting.
- Vertical fault offset (throw) is less than the thickness of the aquitard and thus does not compromise the integrity of the aquitard.
- Faults are therefore unlikely to form vertical flow pathways.

Site-based evidence

- Analysis and presentation of geological and hydrogeological evidence for a regionally extensive aquitard of high integrity that has not been compromised by any discrete flow pathways.
- Documentation of data leading to the interpretation of the depositional environment of the aquitard and its lateral continuity.
- Presentation of a series of regional cross-sections showing faulting and illustrating that it is geometrically and kinematically consistent.
- Analysis and presentation of fault statistics, including length and throw ratios/distributions for the site and the region.
- Systematic analysis of fault displacement profiles.
- Presentation of structure contour maps for the top and base of the aquitard.
- Analysis and presentation of isopach maps of significant regional aquitards.

Characterisation of uncertainty required for risk assessment in this context

- Stochastic analysis of aquitard thickness combined with fault length-throw.
- An assessment of the probability that the aquitard has/has not been breached, using a range of 1D, 2D and 3D techniques.
- Should a relevant probability of this breach be shown then an uncertainty analysis based on scenario C would be required.

In this scenario, an aquitard that is laterally extensive and of high integrity is thoroughly characterised. It is important to characterise the full spatial nature of the aquitard to ensure that there are no poor-quality aquifers and or fractured rocks within the aquitard. Presentation of a well constrained depositional model for the aquitard and detailed petrophysical observations of the mechanical and hydraulic properties at suitable scales of testing would be highly recommended as supporting data. It is particularly important to measure at core scale (i.e. evidence of low matrix permeability) and also at larger scales to determine if the aquitard is potentially leaky due to macropores and fractures.

The aquitard needs to be documented using isopach maps which should include appropriate probabilistic thickness distribution maps (P10, P50, P90). A validation of the integrity of the aquitard can be included – for example, using water chemistry and tracer data to indicate whether the dominant transport mechanism within the aquitard is limited to diffusion (i.e. a chemical gradient) in the absence of significant groundwater flow. Also, tracer data may indicate a unique water chemistry in aquifers above and below an aquitard that is further evidence of an effective barrier to flow.

Clear evidence of the character of any faulting (or evidence that faulting is not present) is essential. Ideally the key interpretations would be derived from high-quality 3D seismic data, preferably depth converted. Faults should be documented with throw profiles for reflectors above and at seam level, and for the top of the aquitard. If possible, fault throw profiles for strata below the seam should also be provided. If the faults have relatively small throw, it may be evident in the data that faults cannot be traced through the coal and upwards through the aquitard.

Distributions that describe the uncertainty of fault throw for the fault population should also be provided. These distributions should account for the vertical resolution of the seismic data or the vertical resolution afforded by surface geological mapping or drilling.

Fault statistical data may be used to illustrate that the fault population has been adequately described. Provision of a fault length versus throw relationship, based on regional and prospect scale mapping, is recommended. The definition of a robust power-law population of faults may be used to show that the interpretation of the smaller displacement faults is reasonable. Using fault statistics and seismic modelling it may be possible to illustrate that a fault of enough size to compromise the integrity of the aquitard would have to be seismically visible and or too large to fit within the development area.

The assertion that the fault throw is consistently smaller than the aquitard thickness could be tested using stochastic modelling that simulates the effects of varying fault throws and aquitard thicknesses. The aquitard thickness estimates could come from a probabilistic isopach for the aquitard, and the fault throws could come from a fault population statistical model that fits the site data.

Fault-related risk assessment – potential repercussions of the fault

It is necessary to account for the possibility that the faults could breach the aquitard with enough throw to juxtapose the coal measures against the aquifer, across the faults. Uncertainty analysis for the fault throw and the aquitard thickness can be used to estimate a combined or derived probability for coal measures to aquifer juxtaposition.

For example, the aquitard thickness in the project area has been estimated as between about 95 and 125 m, depending on location, with thinner or smaller estimated thicknesses located in the north. This is clear from the isopach thicknesses (Figure 7, parts c and e). An uncertainty can be assigned based on the vertical resolution of the seismic reflection data, perhaps guided by sub-surface drilling information and any relevant surface mapping data.

A plot of fault throws versus fault length with a horizontal band showing the aquitard thickness and the thickness uncertainty is shown in Figure 7, part f. This suggests that the chance of a coal seam to aquifer juxtaposition is nil to very small for faults F-1, F-2, F-3, F-4 and F-Bound.

For rigour, one should assess the possibility of undetected or 'missed' faults by estimating the chances that a fault large enough to breach the aquitard could be hidden in the project area, immediately above the proposed development target. To make this assessment, we consider how large a fault could be if it were not detectable in the existing seismic data (e.g. with 10–20 m shallow 3D seismic fault resolution) or the detailed water and coal/gas resource definition drilling.

The irrigation asset (the area outlined in the red rectangle in Figure 6, part e) has very poor seismic coverage. It has a dimension of about 3 x 7 km, and there are seismic lines immediately to the north and south of this area. If these seismic lines did not detect a fault, it is reasonable to conclude that the largest fault would have a total length of circa 7,000 m. Using the throw versus length plot (Figure 6, part d), the largest credible maximum throw for a fault 'hidden' within the development area would thus be about 70–80 m.

We can then assess the probability that a hidden fault might breach the aquitard within the irrigation area, and this analysis is shown in the plot of throw versus length in Figure 6, part f. The likely throw and uncertainty is shown as the small triangle which is labelled and to the left of the plot showing maximum fault throw versus fault length. The aquitard thickness and the possible maximum throw distribution overlap slightly (with the largest credible maximum throw overlapping with the smallest credible aquitard thickness); therefore, it is possible to calculate the probability that the largest possible 'hidden fault' could breach the aquitard and provide a cross-fault juxtaposition between the aquifer and the coal measures.

As the chance of the largest credible hidden fault breaching the aquitard is relatively small, it can be argued that for this proposed development the faults do not breach the regional aquitard. There does appear, however, to be a small chance (perhaps 5%) that a fault could breach the aquitard. If this were shown by further investigation then the development should be considered as one of the more complex examples, perhaps scenario C.

Flow calculations, simulations and flow pathways: If we assess the fault character and uncertainties as outlined above and demonstrate that the possibility of breach of the aquitard is very small, it can be argued that there are no flow pathways and, because of this, conclude that detailed flow modelling and calculations are not needed for assessing risk from faults. It is thus fair to conclude that the risk to assets from development is very low and that no causal pathways that are related to faults are likely. Detailed flow modelling and calculations may still be required to address risks other than those presented by faults.

Risk mitigation and knowledge gaps: This scenario illustrates that there are no pathways, thus there can be no causal pathways. Risk mitigation is related to the conceptual uncertainty of whether or not this development lies within this scenario.

The key elements of this scenario are the thickness of the aquitard and the throw of the fault. An obvious knowledge gap is the uncertainty related to faults and aquitards. As coal developments occur in distinct basins, it is possible to develop regional aquitard and quantitative fault framework models and statistics, and these can be used to assess whether or not this scenario has been correctly applied.

Example case study

This scenario considers a proposed coal seam gas (CSG) development near two groundwater-dependent ecosystems (GDEs) – a river and an aquifer used for irrigation. The scenario is summarised in Figure 7. Part 1 of the attachment shows the location and setting of the proposed development, part 2 shows the aquitard isopach and the faults and part 3 shows the analysis of the aquitard in relation to the faulting.

Geological setting: The coal measures are overlain by two regionally extensive aquifers and an intervening aquitard (Figure 7, part b). There are five faults in and near the project region (Figure 7, part c). A large throw normal fault from geologic survey maps in the south is known as the 'F-Bound', and four smaller faults (F-1, F-2, F-3 and F-4) are normal and reverse faults (Figure 7, part c), which are derived from outcrop and regional 2D seismic analysis. At the development scale, a 3D seismic survey has been used to plan a series of horizontal wells. A structure contour map with consistently annotated faults has been prepared (inset in Figure 7, part c).

Key supporting data:

- regional geological studies, including depositional environments and character of the stratigraphic succession, including the depositional environments of the regional aquifers and aquitard units
- coal resource definition drilling

- seismic lines (Figure 7, parts a, c and e)
- surface geological mapping, including some excellent exposures of the aquitard and aquifer in nearby areas.

Fault character: The seismic data, surface geological mapping, and resource drilling, coupled with the other data can be used to define a top coal structure contour map, as well as a top aquitard structure contour map. These, in turn, can be used to develop fault throw profiles for the five faults. A local plot of maximum fault throw versus fault length is shown in Figure 7, part d. This plot shows the five named faults as labelled red points. Other smaller faults identified in the surface geological mapping are included in the fault throw versus length plot as orange data points.

Fault F-Bound appears to be the biggest fault in the area, with a strike length of ~25 km (the full length of this fault is not shown in Figure 7). The F-Bound fault has a maximum throw in the project area of circa 500 m. Faults F-1 and F-2 are normal faults which dip eastwards and have strike lengths of 4,000 and 5,000 m respectively. These faults have maximum throw of 30–40 m. Two reverse faults in the far east (F-3 and F-4) dip westwards and have strike lengths of ~4,500 and 4,000 m respectively, with maximum throw of circa 50 and 60 m. The ratios of fault throw to total fault length for all the faults shown lie between approximately 0.1 and 0.001, which is in line with most fault data (see, for example, Shultz and Fossen 2008 or Fossen 2016). These data are shown in the top right of Figure 7, part d. The comparison with other general fault data provides confidence in the fault interpretation. The fact that the smaller faults observed in mapping have similar character lends confidence in the interpretation of these larger faults from the seismic and mapping data.

Evaluation of pathways: To consider the possible fault-related pathways, consider the possibility of flow both parallel to the faults and flow across the faults, including any potential for fracturing and connecting faults (e.g. strike slip or relay ramps). Lack of flow may be supported by additional hydrogeochemical data.

Fault parallel flow: Flow can be up and down (parallel to the dip direction) or horizontal (parallel to the fault strike direction). Due to the mechanical stratigraphy and the documented composition of the regional aquitard, it is unlikely that well-developed damage zones occur in the aquitard. Any fractures that do form are likely to heal and seal, as observed in many oil and gas wells. Flow up and down along the fault through damage zones within the aquitard is unlikely. Note that fault parallel flow may be more prevalent shallower in the sub-surface.

Cross-fault flow: Since the faults do not breach the aquitard, providing juxtapositions of the coal development with the aquifer/asset, there is essentially little chance of cross-fault flow, because juxtaposition of the aquitard against either the aquifer or the coal seam will produce an effective no-flow fault boundary.

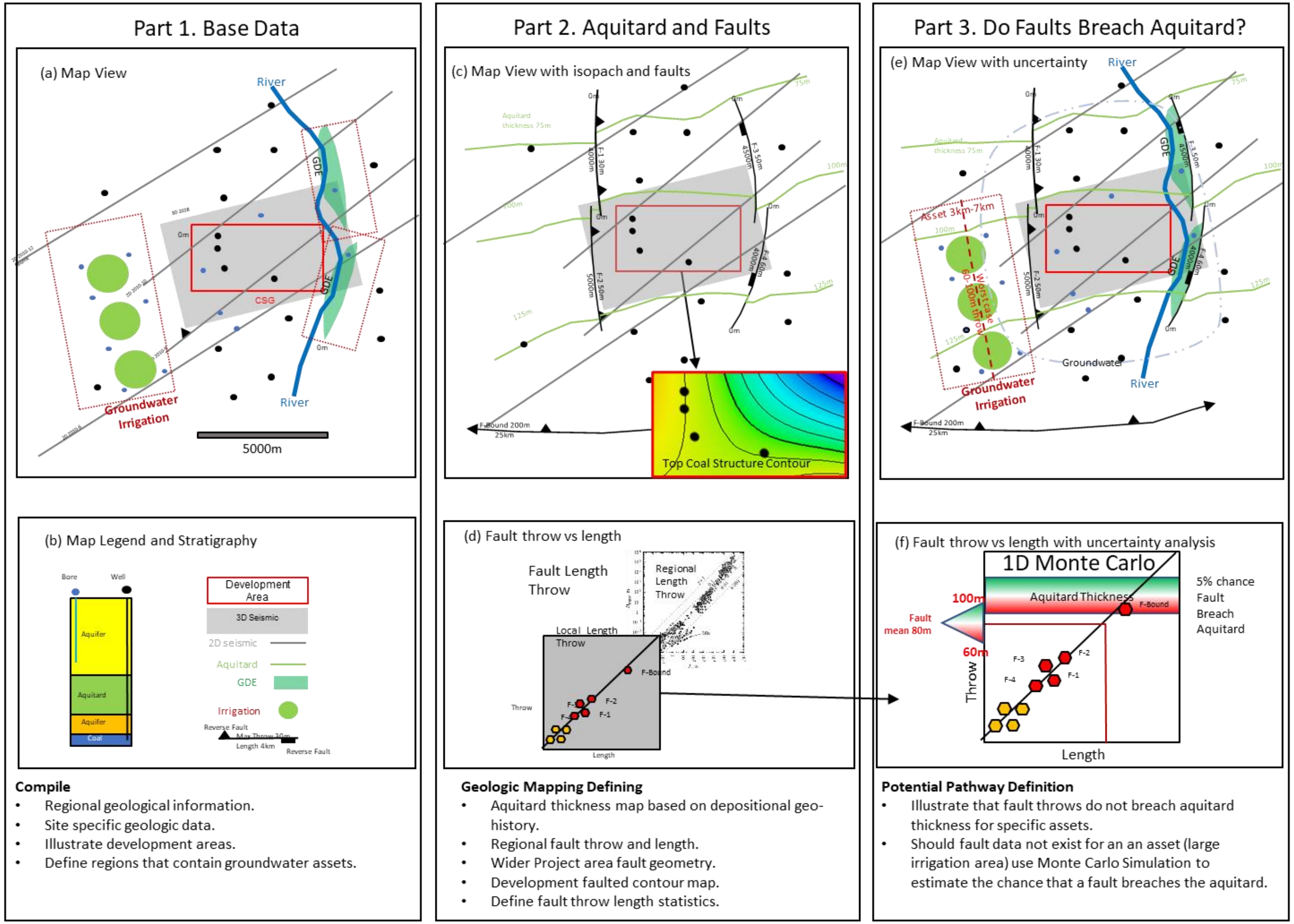

Figure 7: Example workflow that addresses Scenario A-2 for a ‘regional aquitard with a high integrity’.

Example scenario B
Faults are potentially relevant to impact assessment within aquifer systems

In this scenario we consider situations where there are no regional aquitards in the development region that segregate the groundwater asset or aquifer from the coal seam or excavation and where faults are potentially relevant in the risk assessment.

Initial risk profile given geology and groundwater conditions

- Flow parallel to faults may be enhanced in fault damage zones that contain fractures.
- The relative importance of flow within the aquifer and flow along fault zones must be assessed.

Site-based evidence

- Documentation, analysis and presentation of geological and hydrostratigraphic model, using cross-sections and isopach maps.
- Analysis and presentation of hydrogeological characterisation of damage zones (including hydraulic conductivity, transmissivity and storativity), preferably with multiple lines of evidence.
- Analysis of displacement profiles to assess lateral continuity of faults.
- Analysis of the uncertainties that arise from the character of the fault damage zone(s), including the thickness and continuity of the damage zones, fracture density and effective fracture transmissivity.
- Analysis of outcrop studies of nearby fault zones or of fault zones from analogous geological settings, documenting damage zone architecture, fracturing and any fault rocks.
- Characterisation of the mechanical stratigraphy of the aquifers and thus their propensity to fracture.
- Analysis of aquifer pumping tests designed to characterize fault flow parallel to the fault zones (for example, within fractures/fault damage zones), including hydrogeochemical and tracer data.

Characterisation of uncertainty required for risk assessment in this context

- Stochastic modelling may be used to estimate the probability that an identified fault or an unidentified fault intersects an asset and to assess the repercussions of estimated impacts on the groundwater flow regime.
- The resulting probability and flow distribution could then be used in groundwater modelling to evaluate the drawdown effect on an asset.
- Ideally, uncertainty in the fault zone properties could be constrained with appropriate aquifer pumping tests, or tracer analyses, that measured flow along the fault zone (rather than across it).

Worst case approach to uncertainty assessment

Stochastic analysis is the preferred method of uncertainty analysis in this Explanatory Note. However, early (and sometimes sufficient) insights about the behaviour of faults, and how their presence influences groundwater impacts, can be determined and quantified by considering the worst case outcomes.

In assessing the risk posed by a fault to either a water asset or a GDE, the level of effort should be commensurate with the risk.

Fault-related risk assessment – potential repercussions of the fault

Mechanical stratigraphy, and the anatomy and nature of fault damage zones, remain key elements of uncertainty in this scenario. Given that many developments in Australia are contiguous within a given basin, research to develop regional fault statistics is recommended. In many cases small faults in aquifers are mined through as waste rock or overburden, yet useful data on the faults and characteristics of aquifers and aquitards can be obtained during exploration and mining. As many proposed projects are in active mining areas, there is considerable scope to test the hydraulic behaviour of fault damage zones using pre-existing data. For example, automated groundwater level logging may be used to observe long-term mine dewatering and or planned maintenance shut in.

It is expected that newly activated flow pathways resulting from coal or gas extraction can be identified so that effects can, if possible, be managed. For example, a single extraction bore that is over-producing because it is connected to a damage zone can be shut down to reduce flows through the fracture networks. Discrete fractures that occur at rock outcrops and rock bars that are related to fault movement can be targeted for remediation. Natural remediation with sediment filling fractures, and active remediation using grout and polyurethanes, could reduce flows through fractures. However, there is a lack of detailed scientific studies over the long term to demonstrate that groundwater assets and GDEs have been protected (Commonwealth of Australia 2014). Where fault-related ground movement causes fractures in rocks that are covered by sediments or wetlands, it is not possible to readily identify damage, and thus remediation of flow paths in the underlying rock may not be possible.

Example case study

For this scenario we consider a proposed large coal mining (LCM) project which consists of two phases:

- Phase 1 is an open cut development.
- Phase 2 is an underground extension which accesses the same coal seam using a longwall method.

The complete scenario is shown in Figure 8:

- Part 1 shows the pre-development geometry and geology.
- Part 2 shows the open cut development.
- Part 3 shows the underground longwall development.

Geological setting: The local stratigraphic section consists of two different sandstone aquifers, one above the coal and one below. Aquifer A (above the coal) is relatively homogenous and much more uniform in character. Aquifer B (below the coal) has discontinuous silty to shaly lenses, which impede fracture development and impede groundwater flow. A regional shale (aquitard) unconformably overlies the two sandstones and the coal measures. The key resource (coal measures) is both folded and faulted, as shown in the cross-sections in Figure 8. Two faults pass through the proposed development. The East Fault is a normal fault, whilst the West Fault is a reverse fault.

Groundwater assets: Two key groundwater assets have been identified in the region. These are an aquifer used for irrigation and a GDE (e.g. riparian vegetation). The aquifer and the GDE occur to the south of both the proposed open cut and the underground development. The GDE occurs near the surface trace of the East Fault, and the aquifer used for irrigation occurs near the West Fault.

Key supporting data:

- regional geological mapping and summary data from the state geological survey
- surface geological mapping
- three seismic lines
- water bore drilling records from the state government and groundwater drawdown and usage information
- drilling data which define the coal thickness and continuity (coal resource assessment drilling)
- stratigraphic/structural drilling (drilling performed to constrain the faults and stratigraphy)
- drill logs for the coal resource and stratigraphical/structural drilling, which include geological and geotechnical information.

Fault character – general: Both faults appear to be segmented, with small relay ramps. This is evident in the surface geological mapping, but difficult to see in the seismic lines, which are at oblique angles to the surface traces of the faults. The proposed open cut lies just to the north of relay ramps in both faults. Surface observations and mapping enabled the creation of a relatively detailed local stratigraphy for Aquifer B, and this can be used to infer the distribution of throw on the three segments of the East Fault (Figure 8). The throw distribution for the West Fault is more difficult to determine, because the total throw is significantly larger, and the detailed stratigraphy of Aquifer A is much more uniform, thus providing less constraint.

Mechanical stratigraphy: Aquifer A has a significantly different mechanical stratigraphy to Aquifer B, based on the lack of interbedded shale units in Aquifer A. Bed bounded fractures in Aquifer A could span from the surface to the coal measures, while in Aquifer B shale lenses will impede fracture propagation. Fracture networks form where there is a greater chance of individual fractures intersecting one another. Thus, a wide damage zone and tall fractures (Aquifer A) have a greater chance of connecting.

East Fault – fault zone geometry: Using the throw distribution, a likely damage zone width for the East Fault can be estimated using published relationships. In this case we show the damage zone width estimates from Shipton (2001) as a function of total throw (Figure 8, part e).

West Fault – fault zone geometry: Using the throw distribution for the West Fault, an estimated damage zone width can be obtained. Because this fault has greater throw and passes through Aquifer A, which is known to generate more connected fracturing, it appears likely that the damage zone width on this fault is substantially greater.

Pathways general: For both the open cut and the underground development, there are potential pathways both along the fault zones (horizontally) and up-dip/down-dip (vertically). Conventional flow within Aquifer A and Aquifer B is also possible. Based on the mechanical stratigraphy information from Aquifer B, it appears that fracturing in the silty and shale rich portions of Aquifer B will be much less prevalent than within the sandier portions. In Aquifer A (in the footwall of the West Fault) damage zone width and fracturing might be much more extensive because this sandstone is more massive and continuous.

Pathways for open cut development: For the initial open cut development, the pit exposes the East Fault and mines up to the West Fault (Figure 8, parts c and d). When providing hydraulic properties to groundwater modellers, consideration of fracture connectivity within the damage zone is essential. Connectivity to the GDE is possible along the strike of the East Fault. Connectivity is also possible along the West Fault, but the path would be longer. The drawdown and thus head difference for the open cut would be modest with little differential pressure along the fault. A stochastic modelling approach that includes discrete fracture flow could be used to assess the probability of pressure connectivity.

Pathways for underground development: For the underground development, the damage zones in the footwall of the fault zone in Aquifer A might become much more important (Figure 8, parts f and g). With the underground development there is potential for connected fractures to the surface. With dewatering at the seam level there is the potential to generate very significant head and thus pressure differences, within the fault zone. Thus, it seems likely that flow along the West Fault will be the most significant pathway.

Pathways summary: Importantly, even when considering the same fault, the analysis of potential flow pathways is different for the open cut and for the underground development (Figure 8, parts d and g). The driving force or groundwater pressure differences will also vary substantially for the two project phases. This highlights the need to clearly define the geometry of the fault network in relationship to the assets and developments, prior to assessing pathways.

Flow modelling and risk assessment: In this scenario the western fault static hydrogeological character remains the same for both the open cut and the underground development. Despite this, the fault could be expected to have a very different risk for the open cut versus the underground extension. Flow modelling which accounts for the identified fault-related flow pathways and the uncertainties associated with them, followed by a comparative risk analysis, would enable the identification of causal pathways.

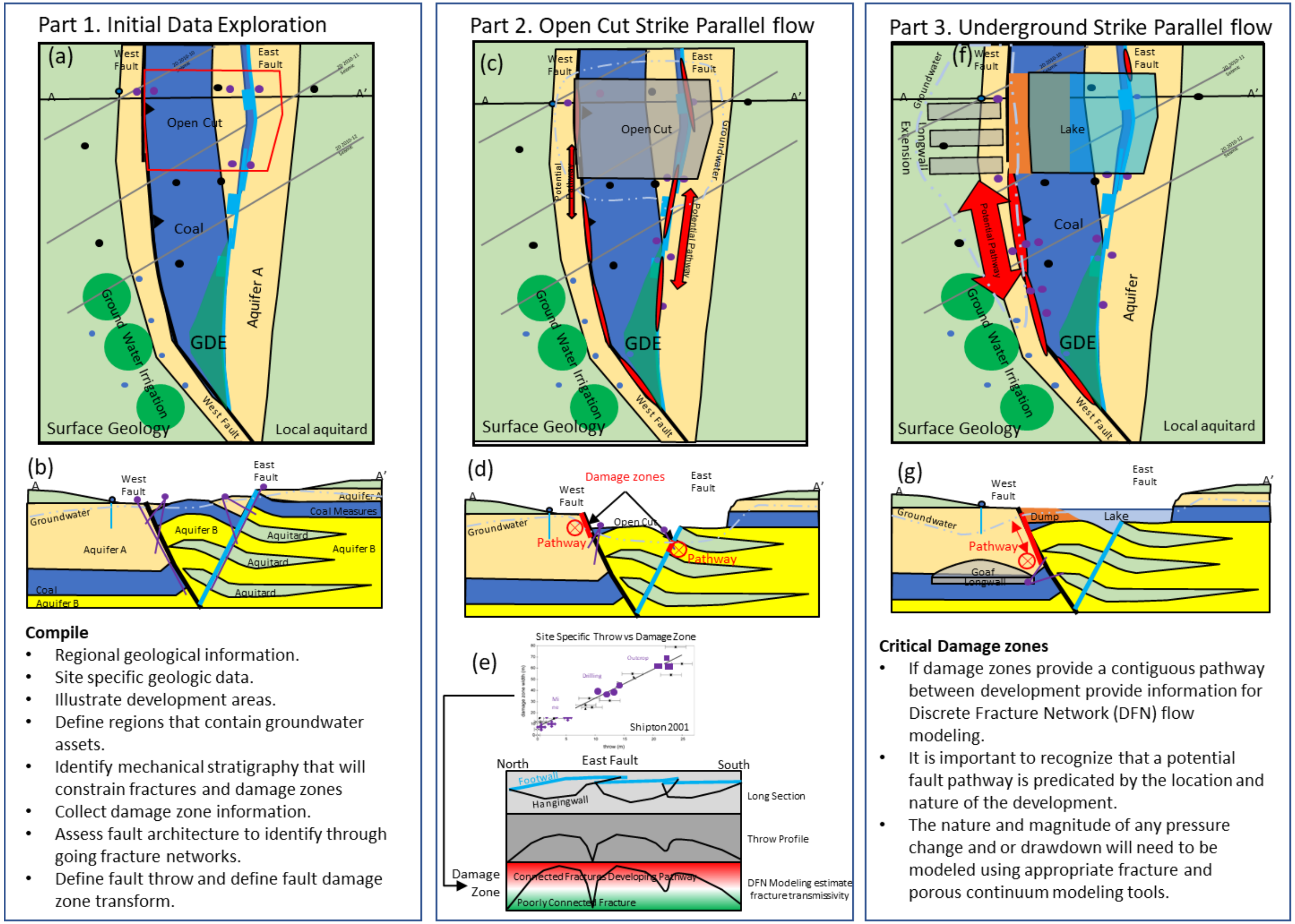

Figure 8: Conceptual diagram of a 'no regional aquitard' scenario.

Example scenario C
Faults are important to impact assessment within aquifer–aquitard systems

In this scenario multiple aquifers and aquitards that are truncated by faults are considered. Throw, on at least one of the faults, is large enough that one or more of the aquitards are breached, and cross-fault juxtapositions become important flow pathways. For this scenario, a stack of semi-confined aquifers requires consideration of groundwater flow downwards through a series of aquifers and across or along faults. It may be that a deeper aquifer is supporting a shallower aquifer via a fault juxtaposition window between the two aquifers. In this scenario the macro-scale geometry of the faults, aquitards, aquifers and coal may all have a primary influence on flow through the system.

Initial risk profile given geology and groundwater conditions

- Flow may occur across faults between aquifers through juxtaposition windows.
- Flow pathways between the asset and the coal may include combinations of:
  - matrix flow through the aquifer(s)
  - matrix flow across faults
  - fracture flow along fault damage zones.
- Propagation of depressurisation upwards along complex flow pathways involving faults may draw down shallower aquifers that would otherwise be isolated by aquitards.
- Conversely, some of the aquifers may remain isolated because the faults do not juxtapose them against other flow units.
- In some cases, fine-grained fault zone material (fault gouge or cataclastic material) may result in flow reductions across the faults.

Site-based evidence

- Analysis of local and regional cross-sections and maps that document a geologically consistent stratigraphy, fault architecture and the temporal deposition environments for the aquitards and aquifers.
- At project scale, coherent and consistent structure contour maps, cross-sections and a well-documented local stratigraphy (summary of aquitard/aquifer thicknesses) are essential. These could include:
  - multiple depth structure contour maps for the top and base of key horizons/levels
  - isopach maps for the aquifers and aquitards
  - description and assessment of the aquitards and aquifers.
- Given that fault juxtapositions and their areas are important in this scenario, the construction of Allan Maps (Figure 9, part c) for representative of key faults (or a series of cross-sections orthogonal to each fault) is strongly encouraged. Fault triangle diagrams (Figure 9, part d) and cross-sections can also be used to illustrate the juxtapositions that are likely to occur.
- In cases where 'no-flow' fault barriers are possible, juxtaposition analysis and extensive site-specific aquifer pumping tests from both sides of the fault and along strike of the fault are recommended. In addition, characterisation of the fault zone materials, including characterisation of the fault core (fine-grained gouge or fault rock) and the character of any damage zones are essential to predict potential impacts of a development.
- Analysis of environmental water tracers (e.g. helium and radon).

Characterisation of uncertainty required for risk assessment in this context

- Quantitative analysis of the uncertainty of juxtaposition occurrence and juxtaposition area would be useful, particularly uncertainty analysis that accounts for fault throw and stratigraphic thicknesses. This analysis could examine possible ranges of juxtaposition area across faults, aquifers and coal seams, and also the possible range of fault rock character.
- Probability distributions for the likely thicknesses and character of fault zone materials may be useful, such as through extrapolation from outcrop mapping or borehole televiewers of fractures.
- Uncertainty in the cross-fault transmissivity may be inferred from the uncertainties in the juxtaposition areas and the host rock properties either side of the fault.

Fault-related risk assessment – potential repercussions of the fault

In this scenario, the delineation and assessment of potential pathways is complex. Pathways may involve multiple segments of differing character – for example, starting with flow through the porous matrix of an aquifer, then along a fault damage zone, then across a fault into a different aquifer and finally into the depressurised coal seam or excavation. Given the likely complexity of flow paths, 3D visualisation and presentation may be useful for the development of a transient 3D groundwater model, evaluating changes in flow over time.

The assessment of whether an asset is connected to a coal seam or excavation is easiest if Allan Maps are generated for each fault. It is possible to provide an indication of connectivity using a series of cross-sections. However, any flow simulation will require the calculation of juxtaposition areas, and this process is more complex and difficult with a series of cross-sections than with Allan Maps. To generate either Allan Maps or a series of cross-sections, a fault framework that is kinematically consistent and that fits within a coherent fault architecture is required.

Additionally, environmental tracer data may help analyse and constrain scenarios of flow pathways. For example, saline or fresh water recharge could help identify fault-related flows that are induced by depressurization from neighbouring developments. A detailed analysis of groundwater pressure and tracer information (i.e. physio-chemical properties, major and trace ions and/or environmental isotopes) for all aquifers associated with the proposed development could thus be useful. With multiple aquifers it may be important to define the pre-development connections and the possibility of aquifer interference.

For this scenario it is necessary to assess structural (i.e. conceptual) uncertainty and to quantify parameter uncertainty. Structural uncertainty could consider, for example, the possibility of additional faults of relevance or geometry and the possibility of various aquifer–aquitard systems. Quantifying parameter uncertainty could include an analysis of the resolution limits of the seismic data and how these could influence the structural interpretations (cross-sections and structure contour maps). Thus, there are several uncertainties in developing Allan Maps that show the most likely juxtapositions and fault characters. The interactions of these uncertainties are frequently non-linear, and with some fault or aquitard geometries the stratigraphic thicknesses are most important in determining juxtaposition area, while in other situations the fault throw is much more important.

However, with this scenario, the key uncertainties relate to the gross fault and aquitard geometry which can in many cases be derived with a relatively high level of confidence. To provide this confidence, both (a) aquifer and aquitard thicknesses and properties; and (b) fault throw profiles should be estimated using distributions. These uncertainties should then be used to derive a combined analysis of the ranges of across fault aquifer / seam juxtaposition areas and of the fault rock character. With well-defined estimates of the key parameters for the flow pathways, the results can be implemented into a groundwater model.

Ultimately, the flow calculations are based on the estimation of juxtaposition areas or assessment of fault parallel flow. The calculation of these areas from the basic data (fault throw and aquitard / aquifer thicknesses) have strongly nonlinear character. Thus, it is difficult to predict results without these calculations.

The final steps in the fault analysis that are not fully described in this Explanatory Note are the calculation of rates for the potential flow pathways and selection of the ranked causal pathways for a comparative risk assessment.

Example case study

For this scenario we present a case study which describes a proposed underground longwall coal mine in the vicinity of a surface reservoir or lake (Figure 9). Part 1 shows the location of the proposed longwall development in relation to the stratigraphic horizon and the reservoir. Part 2 shows the analysis of potential flow paths.

Geological setting: The coal measures are overlain by a sequence of regionally consistent aquifers and aquitards, and the area is cut by five NNW trending faults (labelled F1 through F5 in Figure 9, part a). The uppermost aquifer (Aquifer A) is thicker than the other aquifers and is of greater areal extent (200 km^2) than the other stratigraphically lower aquifers (Aquifers B and C, which have areas of 10 km^2 and 25 km^2 respectively). Aquifer A also contains local horizons of finer grained, clay/shale rich material that are less permeable. The general stratigraphic thicknesses are illustrated in the cross-section (Figure 9, part b). Fault F1 is a reverse fault, while Faults F2 through F5 are normal faults.

Key supporting data:

- regional geological studies that characterise the heterogeneity and lateral continuity of regional aquifers and aquitards and their host stratigraphic units
- surface geological mapping and topography (Digital Elevation Models)
- coal resource definition drilling
- geophysical survey such as sub-surface seismic data, ground and/or aeromagnetics, transient electromagnetics, electrical resistivity tomography, and microseismics
- additional deeper drilling which constrains the stratigraphic and structural character of the area
- isopach maps of the aquifers and aquitards, some from regional studies and some that are derived from the local data
- structure contour maps showing the key horizons including the aquitards and the coal measures
- illustrative cross-sections.

Fault character: The network of faults and intersected aquifers and aquitards is complex. For each fault, plots showing throw versus distance along the fault were produced. Each fault was individually validated by comparing the throw profiles on at least two different levels. The throw profiles were then used to develop Allan Maps (Figure 9, part c) for each fault that show/delineate the character of the cross-fault juxtapositions. A triangle map is also shown (Figure 9, part d).

Pathways: In order to illustrate the possible complexity of the flow paths, we show a cross-section (Figure 9, part e) with a number of possible flow paths. Showing these pathways on a cross-section simplifies the presentation but also hides the complexity; it must be emphasised that flow in and out of the section plane is possible, and in many ways finding and presenting potential pathways in 3D is difficult. It is only by using an integrated groundwater simulator that the multiple potential pathways can be identified, and this is an area of ongoing research.

Uncertainty analysis: As described above, for scenarios of this type it is wise to assess structural/conceptual uncertainty as well as parameter/measurement uncertainty. Perhaps the most important uncertainty relates to the probability of juxtaposition and the derived fault juxtaposition areas.

Flow simulation and risk assessment: After a comprehensive list of potential pathways has been developed, the normal procedure would be to perform flow simulations or calculations for the various potential pathways and then proceed to the determination of causal pathways and the final risk assessment. Flow modelling which accounts for the identified fault-related flow pathways and the uncertainties associated with them, followed by a comparative risk analysis, would enable the identification of causal pathways and potential risks.

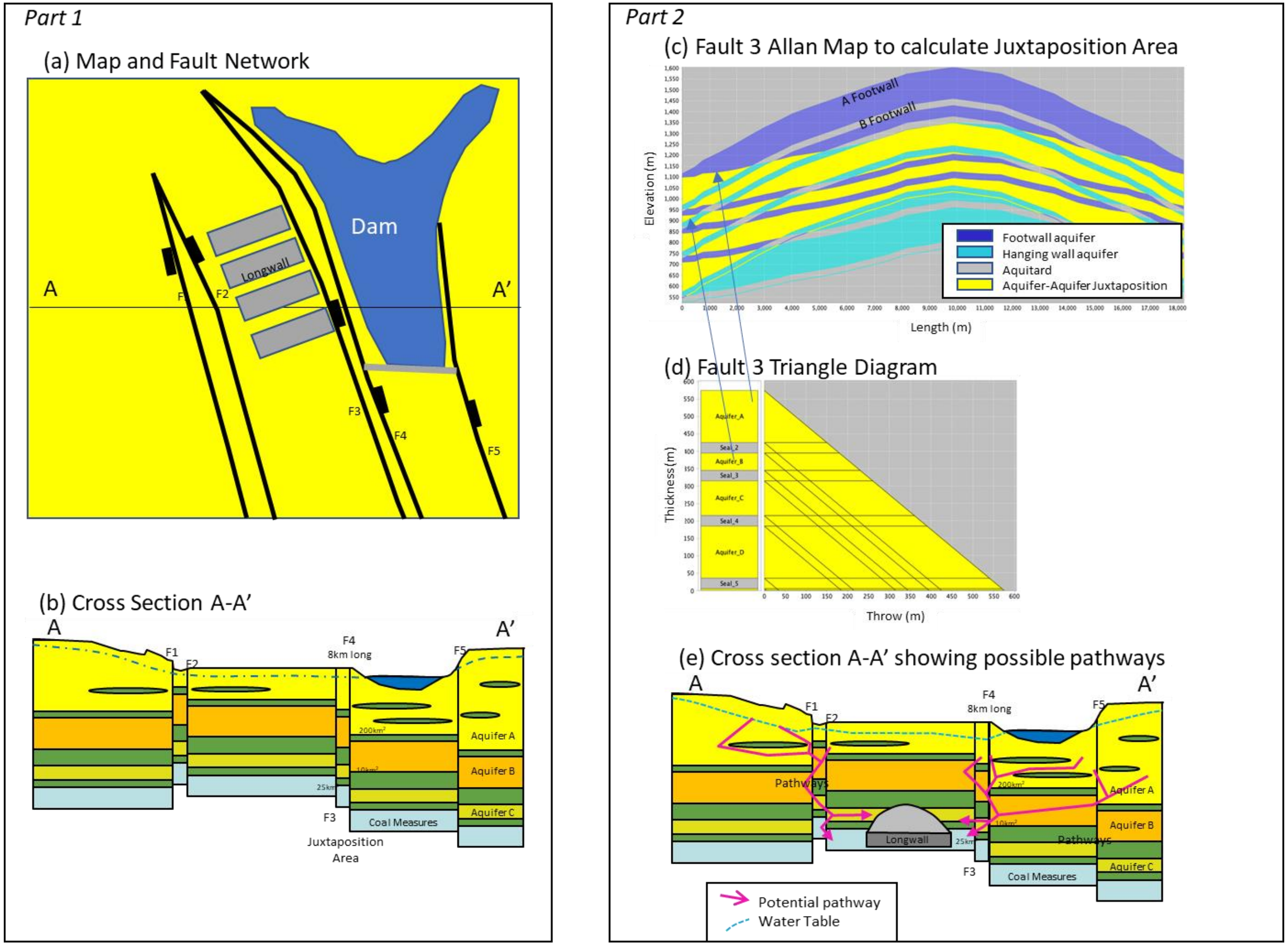

Figure 9: Conceptual diagram of an 'aquifer-aquitard system' scenario.

Example scenario D
Differential subsidence may lead to increased flow along existing or new fractures

The fourth scenario in Table 1, where ground movement, including subsidence, occurs due to changing stress fields associated with underground mining or near open cut mines and in CSG production fields where reservoir compaction and pore pressure depletion occur. Ground movement results in reactivation of faults or causes the development of mining-induced fracturing. The extent of fracture propagation above the mining horizon depends on a range of factors, including the thickness and strength of the overlying strata and the mine design (ratio of mining void width to depth of cover, thickness of the coal seam mined, support pillar dimensions). Ground movement will take advantage of fault planes, which has the potential to enhance the flow rates through existing faults and mining induced fractures (potentially by many orders of magnitude). Where groundwater assets or GDEs are nearby, this situation is of concern and requires baseline, predictive simulation and ongoing monitoring studies as part of a hydrogeological risk assessment.

When considering fault reactivation potential, the assessment should consider the fault zone orientation, mechanical strength of the fault, the in-situ stress and the pore pressure to identify areas of highest risk (e.g. Underschultz et al. 2018), integrated with geotechnical assessment of the overburden mechanical stratigraphy and mine design. This assessment should yield a risk of reactivation and the range of hydraulic connection the reactivated fault or mining induced fracturing may cause, that can then be incorporated into a groundwater model.

Scenario D may require relatively extensive study and documentation of the possible flow paths, including the likelihood of mining-induced changes. Careful assessment of the fault geometry, and how the known faults would be expected to respond to changes in the in-situ stress, would therefore form a key part of the fault analysis. Fault reactivation could change the aperture of fractures in fault damage zones and may also create new flow pathways along the main failure surface of frictional sliding.

Evaluating possible changes in potential flow pathways with ground movement including subsidence is important, though technically challenging, and is an area of active research in geomechanics and groundwater modelling (see, for example, CSIRO 2021). Given the complexity of scenario D, a quantitative assessment of uncertainty and risk for fault-related flow paths may not be possible, and instead a worst case assessment could be adopted, and with reference to relevant empirical data and case studies in similar hydrogeological settings with similar mine design. This is an area of active research and requires diligent environmental monitoring from baseline through post extraction response of the hydrogeological system to inform and enhance the accuracy of predictive numerical models. It might then be possible to establish mine design guidelines to provide acceptable outcomes for environmental receptors and increased certainty of environmental compliance.

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