Subsidence Advisory

Sinkhole risk study

April 2023

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Contents

1 Introduction

Subsidence Advisory New South Wales (SA NSW) is a state government body of Australia tasked with the management of compensation claims for mine subsidence damage to surface improvements as well as the regulation of development in areas prone to mine subsidence. These areas are termed mine subsidence districts. To regulate surface development, SA NSW categorises land within subsidence districts into development guidelines which state the requirements for a property such as size, height, materials and construction methods. Should an applicant submit a design which exceeds the guideline for the parcel of land, it is assessed on merit according to SA NSW's internal merit assessment policy (MAP).

Factors leading to mine subsidence and the way it manifests can vary depending on the type of mining (i.e. longwall, bord & pillar), depth, topography and geology. The three primary types of mine subsidence include trough subsidence (i.e. continuous subsidence), block failure (i.e. massive discontinuous subsidence) and pothole subsidence (Didier et al., 2009).

Trough subsidence, characterised by the large-scale sagging of overburden, can accompany longwall mining and bord and pillar mining, and in some cases are accompanied by tension cracks that delineate the subsided area where the gradual change in surface elevation slopes down to a central trough. When associated with bord and pillar mining, trough subsidence may result from secondary extraction (i.e. removal of pillars), with the failure of the mine pillars or by the punching of pillars into a soft roof or floor. Block failures, in contrast to trough subsidence, are areas where the central trough is bounded by open, subvertical cracks where given the rapid change in surface elevation can result in severe damage to property (Didier et al., 2009). Block failures are more commonly associated with pre-existing geological features such as dykes or faults, which act as lines of failure and exacerbate the rapid change in elevation at surface level (Didier et al., 2009).

Potholes remain one of the most prevalent and unpredictable forms of subsidence associated with shallow abandoned mine workings that SA NSW deals with and largely determines the conditions of development on parcels of land which are subject to shallow abandoned mine workings. Pothole mine subsidence is characterised by the localised and progressive roof failure within shallow underground bord and pillar mine workings. The progressive roof failure continues until a cavity reaches the surface. Though such failures are most likely to occur at the intersection of bords (see Canbulat et al., 2017), these events can occur anywhere a void is present below the surface, including along the bords themselves. This makes potholes both difficult to predict and makes them a significant hazard to both human life and built infrastructure. As a result, SA NSW may impose either rehabilitation (i.e. grouting of workings) or mitigation measures (i.e. structurally enhanced strip footings termed 'pothole footings') which often comes at considerable expense to the landowner.

To date, much of literature related to potholes focus on the dynamics of roof failure and the factors that contribute to the process (Price et al. 1969; Piggot and Eynon,1978; Dunrad, 1984, Whittaker and Reddish, 1989; Canbulat et al. 2017). Such studies made attempts to determine whether a pothole can or will occur at the surface by quantifying the relationship between the height of caving and depth of the resulting pothole. Such theoretical approaches generally utilise parameters such as the geometry of the mine workings, bulking factor of the overburden and angle of repose of the caved rock. Limitations of such approaches have been noted by Karfakis (1986), specifically with respect to assumptions of constant bulking, perfect geometries and no consideration given to the lateral movement of rubble. Further, whilst these approaches can determine possibility of occurrence for a given location in a binary sense, these insights are limited to a specific case by case bases and provide no insights into the broader rates or probability of occurrence over a wide area. One attempt by Johnston et al. (2017) was made to address this shortcoming by focussing on Depth of Cover (DoC) and its relationship to the frequency of pothole occurrence. This particular approach provides an avenue to develop it further into a probability model that can be applied to the estimation and management of the risk of pothole mine subsidence as is integral to the operations of SA NSW.

This study builds upon the approaches taken in previous work to provide a methodology to quantify the probabilities associated with pothole development and the likely size of the pothole across several coal seams that have been identified as problematic to surface development within the Hunter region of NSW, Australia.

2 Aims and Application

The overarching purpose of this study was to develop a probability model that is capable of assessing the likelihood of a pothole (i.e. only those arising from progressive roof failure) of a given design size developing for several coal seams. To achieve this, it was necessary to:

- Develop SA NSW's records of historical mine subsidence events into an interrogatable database focussing only on pothole subsidence events.
- From this database, develop a probability model able to assess the likelihood of occurrence of pothole/s given simple data inputs (area, time period, coal seam, depth of cover).
- Draw upon the distribution of pothole widths to determine the characteristics of potholes when they do occur;
- Develop a probability model to calculate both the likelihood that a pothole event will occur, and should it occur, the probability it will exceed a given size; and
- Use these exceedance criteria to support risk-based decision making as a part of SA NSW's Merit Assessment Policy.

This study is limited to potholes as the risk of these events largely determine the conditions applied to developments over shallow abandoned mine workings. SA NSW applies a DoC 'rule of thumb' of ten-times the seam thickness (typically equating to ~20m) for the most the most stringent remediation/mitigation conditions. This rule of thumb was based on a single coal seam in the Hunter region of NSW known as the 'Borehole seam'. Several seams are subject to underground mining in the same area and to date no detailed investigation of the suitability of this rule has been carried out. The outcomes from this work are intended to revise the way SA NSW regulates development over shallow abandoned mine workings, with emphasis on the assessment of applications over shallow workings that do not conform to current development guidelines that fall under the MAP.

SA NSW's MAP is designated as the assessment process for development applications that do not comply with the subsidence guidelines applied to each parcel of land. As such, the MAP will consider the following:

- Likelihood that mine subsidence will occur (all potential subsidence mechanisms)
- Consequence of mine subsidence events on surface infrastructure and public safety
- Reliability of information used to determine the above, including mine plans, assumed pillar and extraction dimensions, and assumptions regarding geotechnical modelling
- Risks arising from the proposed engineering controls.

The application of the probabilistic model presented here is to factor into the first point noted above; likelihood of mine subsidence. It is important to acknowledge, that this will only inform the potential for pothole mine subsidence, whilst other mechanisms will be will still be considered under current methods.

3 Data and Methodology

Figure 1 provides an overview of the three main stages employed in this study. Each stage can broadly be described as:

- Stage 1 – Database Development (Section 3.1)
- Stage 2 – Calculation of Potholing rates (Section 3.3)
- Stage 3 – Derivation of Probabilities (Section 3.4)

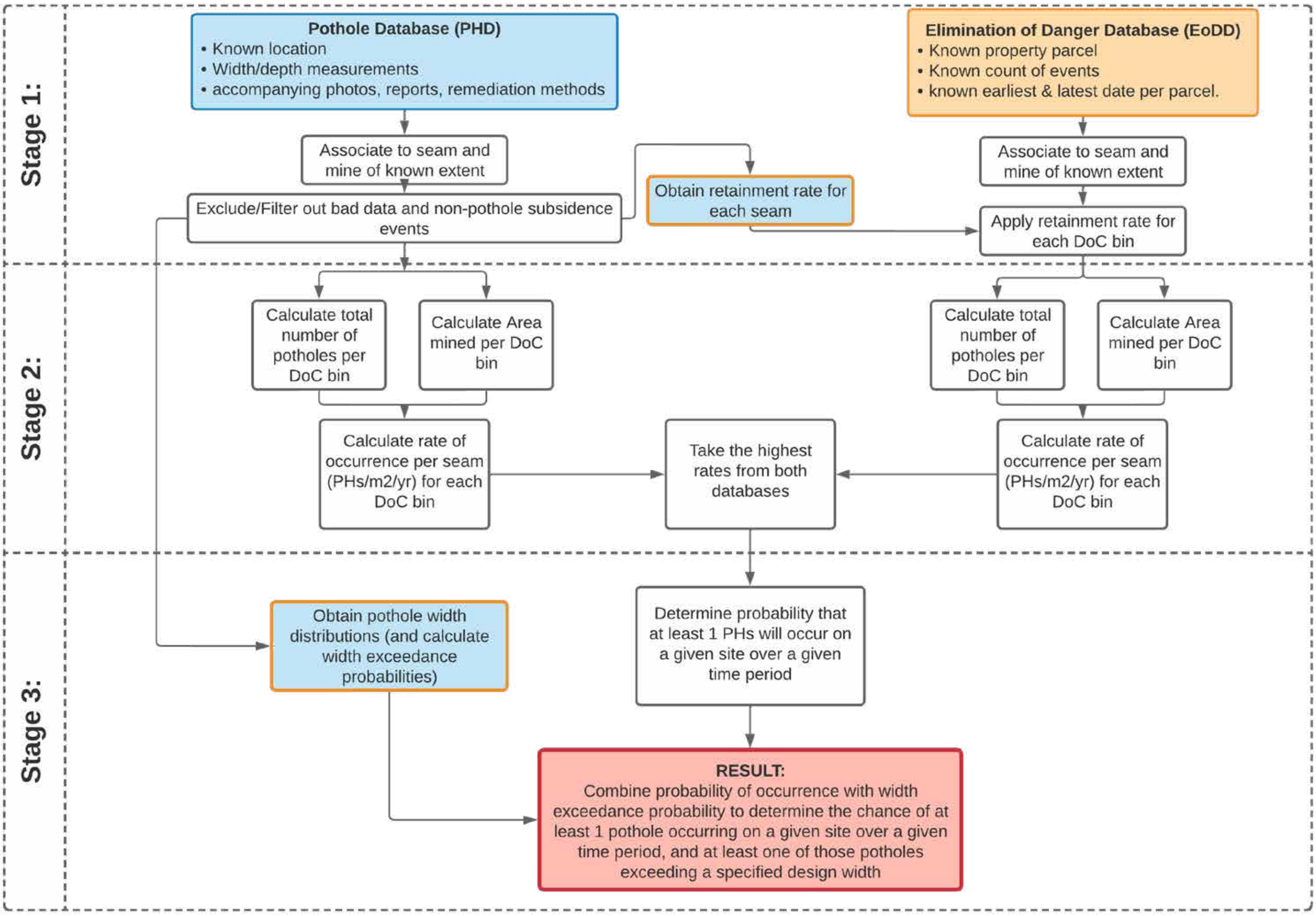

Figure 1: Flow chart detailing the three main stages of the data and methodology employed in this study.

3.1 Stage 1 - Database Development

As the first stage of the project, an assessment was made of the available sources of historical pothole data that could be used to support the study. From this, two large digital databases of mine subsidence events (predominately comprising records occurring within the last 30 years) were identified as suitable for analysis and sufficiently representative of recent pothole behaviour. These databases are described in sections 3.1.1 and 3.1.2 below.

3.1.1 The Pothole Database (PHD)

The pothole database is a spatial database of mine subsidence events reported to SA NSW (or Mine Subsidence Board NSW) that led to the expression of a hole or localised depression at the ground surface. It contains a relatively consistent record of events, their coordinates and their dimensions from approximately the year 2003 onwards. As a part of SA NSW's operations, some work has been carried by the GIS team out to augment the pothole database based on subsidence events from historical records and as such includes sparsely populated events as far back as 1964. These efforts by the GIS team were done so to further support internal SA NSW's processes for the assessment of claims and further risk of occurrence. Prior to screening, this database had 1508 subsidence events, ranging from potholes, tension cracks, piping failures, shaft failures and block failures.

As the standardised recording of subsidence events into a spatial database did not begin until around the year 2000, it was acknowledged that as a part of scoping this study, the database did not contain a full record of all potholes that have occurred throughout SA

NSW operational existence. However, the benefit of the PHD is that detailed records of the event dimensions (width, length and depth which is available for one half to two thirds of all records), positional data (typically in GDA Coordinates taken from either handheld GPS or back calculated from taped site measurements) and summary reports with accompanying photographs of a large number of potholes were typically available.

Given its higher data quality, this database was used to develop both a rate of rejection/acceptance of potholes arising from progressive roof failure, as well as a characterisation of pothole dimensions linked to seam and depth of cover.

3.1.2 The EOD Database (EoDD)

An additional database containing a more comprehensive number of pothole events was also available for analysis. This database, typically noted as the 'Elimination of Danger' (EoD) database (EoDD) has records of emergency pothole subsidence events from 1962 onwards, with a stable annual rate (excluding any natural interannual variability) commencing in 1986 to the present. The stabilisation of annual rates post 1986 is a result of mandatory financial reporting which was introduced into SA NSW's practices.

Unfortunately, the EoDD simply records the location of each event limited to the resolution of the size of the property parcel on which it occurred with no specific position or pothole dimensions available. The EoDD has only the date of occurrence and the property address, and therefore can provides only total number of EoD events per property along with the first and last date of occurrence for each property.

As the recording of EoD's has been maintained with relative consistency from 1986 onwards, and the PHD spatial database from ~2003 onwards, there is overlap between these databases towards later years as both became maintained simultaneously. Prior to analysis, a methodology (detailed in Section 3.1.3) was therefore developed to examine and screen the PHD to include only genuine pothole events, and use the rejection ratio (or conversely the retainment ratio) to pro-rata the EoD database so that an extended record could be used to draw rates of potholing per year, area, depth of cover and coal seam.

3.1.3 Data Screening

Due to the nature of the two datasets, only the PHD contained sufficient accompanying information to allow it to be accurately screened for potential events that were specifically related to progressive roof failure. At the time of analysis, the PHD contained approximately 1508 subsidence events. The screening process removed 604 events which ensured that only genuine pothole occurrences were retained. During the screening, all documentation associated with the event, including descriptions and photographs (where available) were reviewed. Events which were excluded include:

- Tension cracks in the bedrock as described by the assessing officer or visible in the accompanying photographs. This also included any piping failures as inferred from hole dimensions and concrete/grout takes from remediation;
- Subsidence events associated with mine shafts;
- Block failures, pillar failures or creeps of standing workings;
- Failures that were associated with faulty sewer, water mains or drainage infrastructure that may have contributed significantly to any void being created;
- Events in areas where the associated coal seam was known to have been, or still is, on fire;
- Events that occurred immediately following the undermining of a subsequent (deeper) seam using either longwall or total pillar extraction techniques.
- Events that occurred more than 20m outside the recorded extent in any known mining records.

The removal of the instances described above ensured that the resulting database consisted of potholes which developed by the typical process of localised and progressive roof failure to the surface (such as those described in Gray et al., 1977; McNally, 2000; Johnston et al., 2017).

During the screening of subsidence events, GIS scripts were employed to ensure that each event was attributed to the most likely colliery and coal seam. Typically, potholes were attributed to the most shallowly mined coal seam. More details on this process can be found in the supporting material under Section 7.1.

3.2 Key Mines as Case studies

The reporting of pothole and emergency events by the public is generally assumed to contain a reporting bias towards those areas that have been subjected to urban or commercial development, are readily accessible and frequently visited, or are within close proximity to developed land (subsidence in areas of bushland reserve may go unnoticed or unreported for indefinite periods). In order to mitigate the variation and effects of reporting bias in the PHD and EoDD, a subset of undermined land within or in close proximity to residential or developed land was used as the focus of this study. These areas are depicted in **Figure 2.** Although the mines in the Cessnock/Kurri Kurri area which operated in the Greta and Homeville Top Split coal are primarily located in bushland, they are adjacent to residential settings and are extensively frequented by members of the public for recreational use.

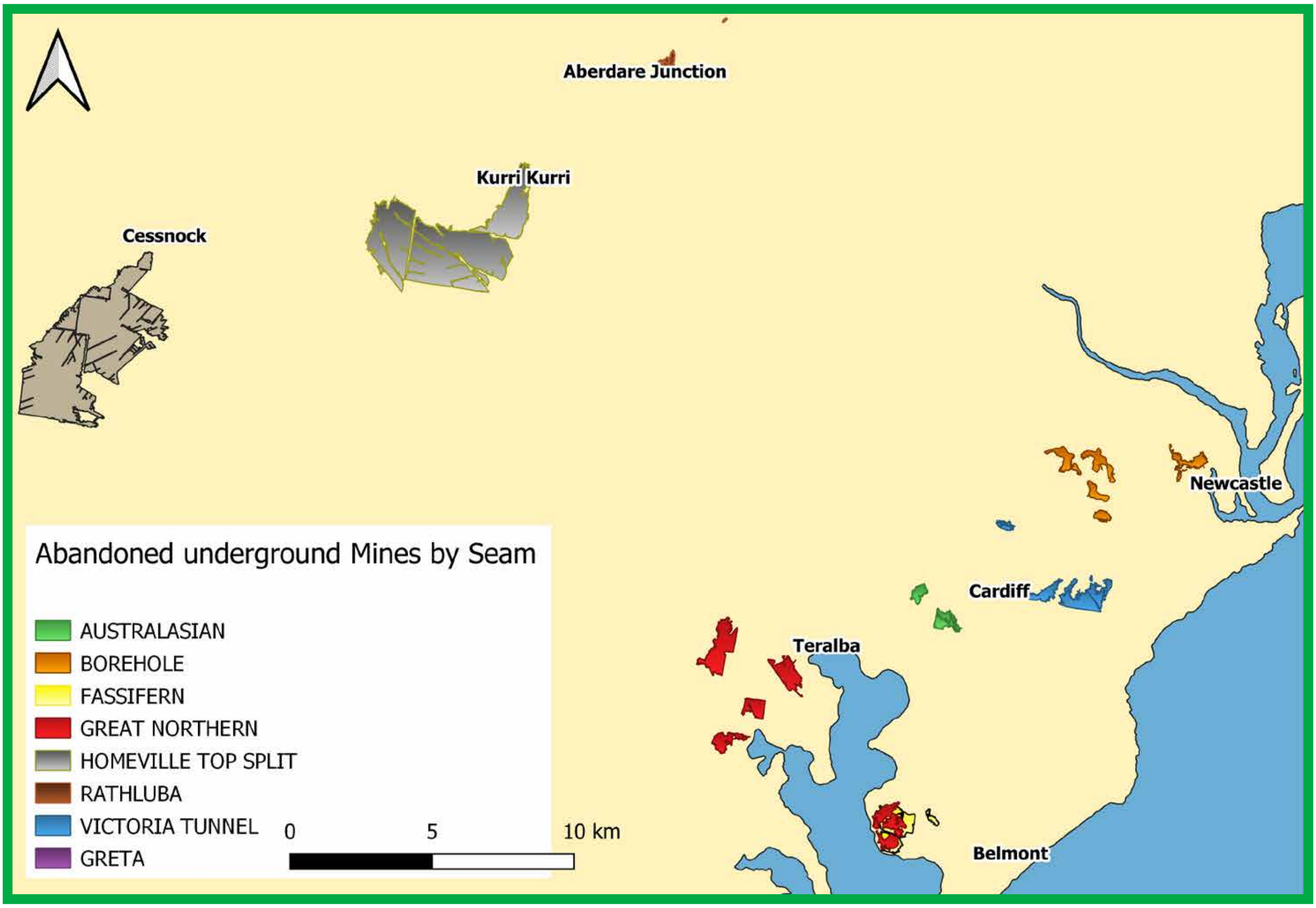

Figure 2: Location of mines used in case-study by coal seam.

Table 1 details the mines shown in Figure 2 that were studied in this analysis including the coal seam, their overall areal extent and the approximate years in which they operated. Those in the Borehole (BH) seam are typically the oldest recorded workings in this study, operating from the late 1800s to the early 1900s. The workings in the remaining seams have operations beginning ~1930s and generally cease during the 1950s. These are assumed to have a relatively consistent residual pothole development rate.

Table 1: Case study mines from which statistics were derived

Coal Seam	Mine	Area (m2)	Opened	Closed
Borehole	Waratah Old	410056	1863	1933
	Waratah + 6 Others	392133	1873	1874
	Lambton Commonage	214084	1861	1884
	Dunkirk New Duckenfield	160634	1883	1912
	Pride Ferndale + Adjacent	390540	1877	1913
Victoria Tunnel	St George, Ayrvale, Belvue	342147	1933	1934
	Lambton Central No3, Kirkdale	103075	1920/1946	1956
	Westwood, Ayreview	1066669	1932	1940
Great Northern	Newstan (South Pacific, Olstan, Northumberland)	767340	1931/1954/1949	1995
	Belmont No.3 & Northern No2	874233	1932	1956
	Pacific	678252		1967
Fassifern	Belmont, Belmont No.2, Belltop	1504199	1932	1941
Australasian	Ajax	210853	1937	1956
	Cardiff Evelien	345387		
Greta	Bellbird, Cessnock No.2, Aberdare	13799286	<1937,<1929,<1930	1976,1955,1961
Homeville Top Split	Pelaw Main, Hebburn, Stanford Main	11669773		
Rathluba	Fernwood, Maitland Greta	236728	1930	1943,1974

3.3 Statistical analysis

The analysis presented in this paper first aimed to resolve the probability of pothole occurrence on a given area of land within a given time frame. The second component of the analysis was to determine the likely outcome (i.e. dimension of the pothole) of that event. As such, the probabilities of occurrence and consequence were combined so that SA NSW can determine the likelihood of a pothole occurring and exceeding a certain size.

Initial analysis presents the distribution of potholes versus DoC for each coal seam; both in total for all mines in that seam including mines that were not used as case studies, as well as separately for each of the case-study mines detailed in ***Table 1.***

To demonstrate that the case study mines are an adequate representation of mining in the greater coal seam, cumulative distribution functions (CDFs) are presented and non-parametric, two-sample Kolmogorov-Smirnov tests were conducted against each pair of distributions for each coal seam. The test statistics and p-values were then used to identify whether the distribution of DoC values from all potholes in that seam, and the distribution of DoC values from each case-study colliery in that seam, were significantly different; where they were not, this justified their use as being representative of pothole behaviour in the greater coal seam.

Initially rates of pothole occurrence were calculated on a per colliery basis using the area mined and the number of pothole and emergency events associated with each colliery. Based on the robust relationship between DoC and pothole development illustrated in Johnston et al. (2017), the area mined, and the frequency of pothole development was further stratified according to 2.5m DoC increments. These increments were also calculated using overlapping bins to account for any sensitivities associated with the upper and lower bounds of each bin: ie, 0 to 2.5m; >2.5m to 5m; >5m to 7.5m; >7.5m to 10m, and so on. The second set of bins which overlap the first were offset by 1.25m, resulting in 0-1.25, >1.25 to 3.75m, >3.75m to 6.25m, >6.25m to 8.75m, >8.75m to 11.25m, and so on.

As detailed in **Section 3.1.2**, retainment ratios (RRs) from the PHD were also calculated on a per seam, per mine and per DoC basis. These RRs were then used to pro-rata the frequency of EoD events for the same stratifications. Two possible approaches were considered for the calculation and application of the RR:

1. Calculate RRs based on seam per DoC bin to account for any relationship between RR and DoC (i.e. rejection of events over deeper workings as the result block failures, tension cracks, etc). Apply each unique RR to the equivalent DoC bin for the EoDD.
2. Calculate RRs based on a seam-wide basis and apply that same RR to each DoC bin for the EoDD.

Further, an upper DoC limit was enforced on EoD events, taken as the maximum DoC of a retained PH in a given seam plus 5m. As such, any EoD parcel, and therefore event, which exceeded the upper DoC limit as derived from the PHD was also excluded. Using the pro-rated EoDD, rates were then calculated for 0-10m, >10 to 20m and >20 to 30m DoC intervals.

Given that the events were drawn from a pool that covered the last 30 years, the resulting rates were recalculated to represent the number of events per square metre per year. The rate of occurrence (being the most conservative for the purpose of risk assessments) was calculated from both PHD and EODD datasets separately, with the highest rate used in the next step (see Stage 2 in **Figure 1**).

3.4 Derivation of Probabilities

Once the rates of potholes (PH/m^2/yr) for each seam have been established, the Poisson probability mass function can be employed to derive the probability of pothole occurrence on different land parcel areas within a specified time period, at various depths and for each coal seam. The Poisson probability mass function is as follows:

$$P(k) = \frac{(\lambda^k e^{-\lambda})}{k!} \quad \text{(Equation 1)}$$

In this expression, *k* is the variable representing the number of events (in this case the number of potholes) occurring in a specified time period and area; λ is the expected value (average) of *k*, and *e* is Euler's number.

λ is calculated as the product of

- the area of land under investigation,
- the defined period of assessment divided by the 30-year baseline and
- rate of potholing within the specified seam for the particular depth of cover.

For SA NSW's purposes, the probability of n potholes occurring on a site for the defined time period is given as;

$$P(k = n) = \frac{(\lambda^n e^{-\lambda})}{n!} \quad \text{(Equation 2)}$$

Hence, the probability of zero potholes occurring on a site for the defined time period is given as;

$$P(k = 0) = \frac{(\lambda^0 e^{-\lambda})}{0!} \quad \text{(Equation 3)}$$

And conversely, the probability of any potholes (i.e. more than 0 potholes) occurring on a site for the same defined time period is given as;

$$P(k > 0) = 1 - \frac{(\lambda^0 e^{-\lambda})}{0!} \quad \text{(Equation 4)}$$

From this equation and the derived values of λ, the probability of any pothole events occurring *P(k>0)* on a site of given size (e.g. 500m^2) over a given design life (e.g. 50 or 100 years) may be calculated.

As an alternative to the above expression for calculating the likelihood of at least one pothole, the likelihoods of 1 or 2 or 3 or 4 etc potholes could instead be calculated. In calculating the probability of a number of events (as many as n potholes) occurring on a single property, the following equation may be used.

$$P(0 < k \leq n) = \sum_{k=1}^{n} \frac{(\lambda^k e^{-\lambda})}{k!} = \frac{(\lambda^1 e^{-\lambda})}{1!} + \frac{(\lambda^2 e^{-\lambda})}{2!} + \frac{(\lambda^3 e^{-\lambda})}{3!} + \cdots + \frac{(\lambda^n e^{-\lambda})}{n!} \quad \text{(Equation 5)}$$

This alternative approach to calculate the probability of at least one or more events on a site allows for a comparison between an arbitrary number of discrete events (*n* number of events) and the > 0 events to be undertaken, and a % total error may be calculated using the following equation;

$$\frac{P(k>0) - P(k=1\ to\ n)}{P(k>0)} \quad \text{(Equation 6)}$$

To determine the joint likelihood of one or more potholes occurring *P(k>0)* and that any (one or more) of them exceed a design value of Wc, is a complicated calculation of joint probabilities requiring the summation of partial probabilities of 1, 2, 3, 4, ... potholes occurring, and of any one or several of them exceeding the width Wc. This can be simplified by considering instead the likelihood that one or more potholes occurs, but in each case, none of them exceed width Wc.

Consider the case of only one pothole occurring. The chance that it will exceed Wc is P(W>Wc) = 1 – P(W<Wc).

Consider now the case that two potholes occur. The chance that either one or both of them exceed Wc is 1 minus the chance that neither of them exceed Wc, and the chance that neither of them exceed Wc is $(P(W<Wc))^2$. Hence, the chance that one or both exceed Wc is $1 - (P(W<Wc))^2$. By similar argument, for k potholes, that chance that one or more of them will exceed Wc is $1 - (P(W<Wc))^k$

This can now be combined with the previously derived expression for the probability that n potholes occur.

$$P(k = n) = \frac{(\lambda^{n} e^{-\lambda})}{\mathrm{n!}} \qquad \text{(Equation 7)}$$

The resulting joint probability that n potholes occur, and at least one of them exceeds Wc is given by

$$P((k = n) \cap (\mathrm{W} > \ \mathrm{Wc})) \ = \frac{(\lambda^{n} e^{-\lambda})}{\mathrm{n!}} \times [1 - P(W < Wc)^{n}] \qquad \text{(Equation 8)}$$

where *P(W<Wc)* is the percentage value of potholes recorded up to width Wc determined using the cumulative distribution function for pothole widths in a given seam.

To calculate the probability of up to n potholes occurring on a given site with one of them wider than Wc the following equation may be used;

$$\textit{P (one or more potholes occur \& at least one exceeds Wc)} \quad = \sum_{k=1}^{n} \frac{(\lambda^{k} e^{-\lambda})}{\mathrm{k!}} \times [1 - P(W < Wc)^{k}] \qquad \text{(Equation 9)}$$

The derivation of probabilities outlined here in **Section 3.4** provide the methodology which is employed in the results of this study, and presented in **Section 4.3**.

4 Results

4.1 Distributions of DoC and Pothole dimensions

Figure 3 illustrates the cumulative distribution of DoC values for each seam as derived from the full PHD and full EoDD. Note that the red and blue lines in the PHD data represent the distribution of DoC values pre and post screening, respectively. The results drawn from land parcels in the EoDD were derived using the mean DOC for the parcel (solid black line) as well as the minimum and maximum DoC (dashed black and green lines, respectively) of each undermined portion from each property parcel. Note, that in implementing an upper DoC threshold on EoD events (based upon the maximum DoC in the screened PHD plus 5m), there is a decreasing number of EoD samples when using the maximum DoC of the parcel than when using the mean or minimum DoC. The number of samples are shown in the title of the subplots, which are described in the caption of **Figure 3**.

From **Figure 3**, the rejection of PHD samples following screening, ranges from uniform across all DoC bins (GN seam), to a tendency to reject samples from the upper bins (BH, VT, FASS, HMTS and RATH seams) and those with no distinct relationship between rejection and DoC (AUS, GRETA). The minimum and maximum DoC CDFs for the EoDD illustrate that there is little variation in DoC over affected properties in most seams. The exception to this are those parcels located above mining in the GRETA and HMTS. These characteristics are primarily the result of location and land parcel size. Whilst events in the GRETA and HMTS are adjacent to residential and developed land, they are typically located in bush and parkland and cover large aerial extents. Conversely, EoD parcels located above other seams are situated within residential areas themselves, and the area of these parcels places a limit on the surface elevation range and subsequently the DoC.

Table 2 provides a summary of the upper tail of the DoC distributions, from the 80th to 100th percentiles. Note at this stage, the RR has not been applied to the EoDD and as such the distribution of DoC values are in most cases heavily skewed to higher values compared to those in the screened PHD.

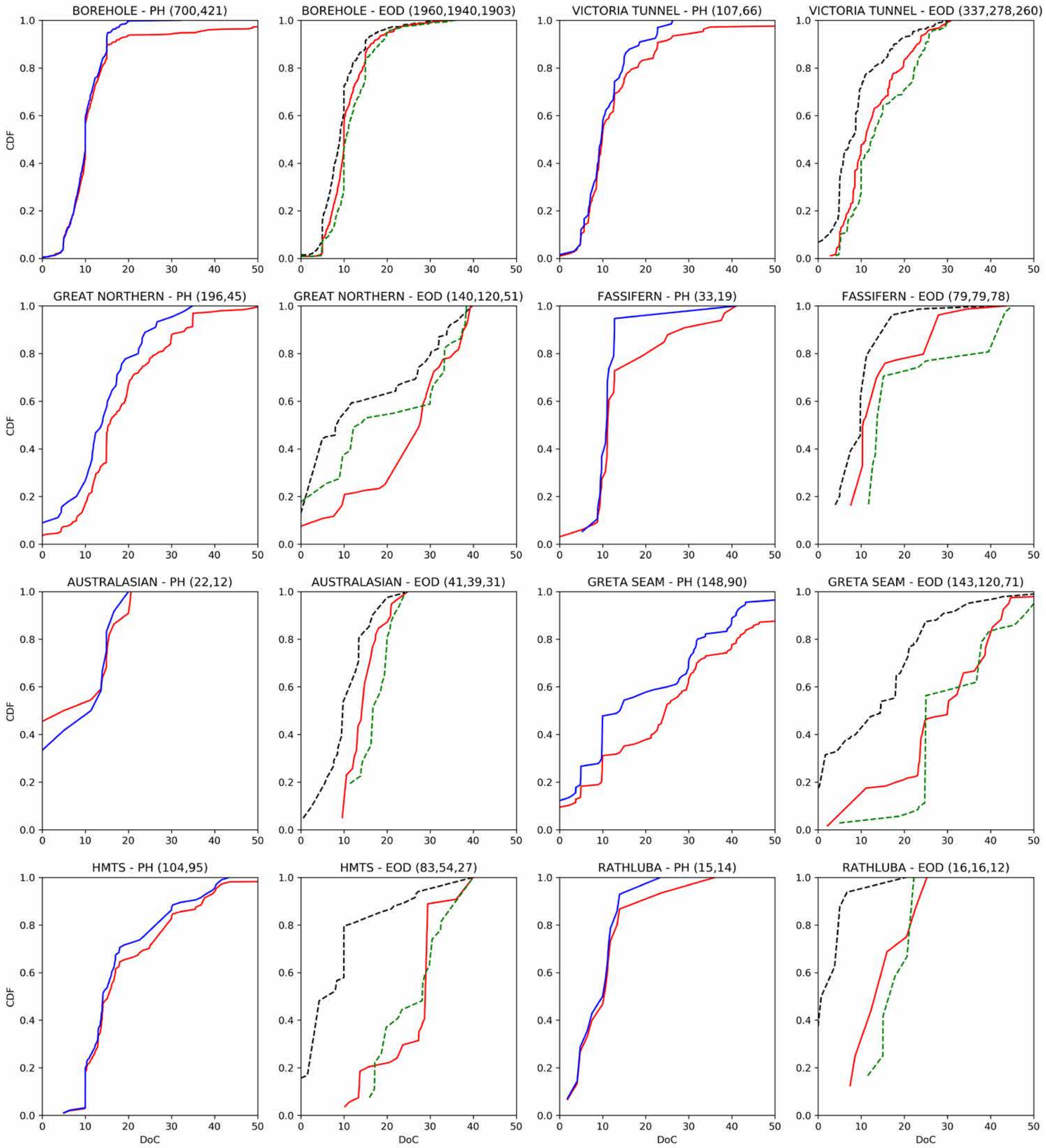

Figure 3: CDFs of DoC for each coal seam. Red and blue lines depict the CDF pre and post screening of the PHD, respectively. The solid red lines in the EoD plots depict the CDF for the mean DoC from the EODs, while the dashed black and green lines are derived from the minimum and maximum DoC values from the EoD parcels. Subplot titles include the number of PHD events (pre and post-screened, respectively) and EoD events (based on min, mean and max DoC). Note, EOD cases have been limited by the maximum DoC registered in the equivalent seam's screened PHD.

Table 2: Percentile DoC value per seam and database

Seam	Database	80th	85th	90th	95th	100th
Borehole	PHD pre	13.8	15	15.9	35.9	285.84
	PHD post	13.4	14.5	15	15.9	32
	EOD Min	13	15	17.2	27.9	285
	EOD Mean	15	16.28	21.6	35.2	291.6
	EOD Max	16.7	19.2	23.5	56.2	298.2
Victoria Tunnel	PHD pre	18	21.8	22.8	32.4	87.1
	PHD post	14.7	15.1	18.5	22.7	26.3
	EOD Min	21.1	28.7	43.6	86.9	125
	EOD Mean	42.1	55.7	60.4	91.1	132
	EOD Max	79.9	85.5	105.5	121.6	150
Great Northern	PHD pre	26.7	30	33.2	35	56.3
	PHD post	22.3	23.2	25.3	29.5	34.9
	EOD Min	159	172.8	176.2	179.1	192.1
	EOD Mean	159.3	174.6	178.6	180.4	193.2
	EOD Max	159.6	176.4	180.4	184.3	194.1
Fassifern	PHD pre	23.2	24.6	28.7	37.9	40.9
	PHD post	12.6	12.7	12.7	15.6	20
	EOD Min	13.7	17.1	17.1	17.1	40.26
	EOD Mean	25.9	27.9	27.9	27.9	43.5
	EOD Max	41.1	43.4	43.4	43.4	46.1
Australasian	PHD pre	15.5	16.5	19.7	20.4	20.6
	PHD post	14.9	15.5	16.5	18.2	20
	EOD Min	16.2	18.3	20	26.6	38.4
	EOD Mean	21	24.8	26.2	27.6	39
	EOD Max	27.3	29.9	35	40.2	40.6
Greta	PHD pre	41.2	44.9	53.6	63.6	121.5
	PHD post	32.4	39.4	40.9	43.1	51.7
	EOD Min	64.2	73.8	114.7	301.9	348.8
	EOD Mean	101.3	109.7	117.4	308.2	374.2
	EOD Max	174.4	180.2	224.3	314.4	413.2
HMTS	PHD pre	30	31.3	37.6	40.3	117.6
	PHD post	30	30	34.2	39.8	43.4
	EOD Min	129.9	129.9	129.9	141.2	141.2
	EOD Mean	142.5	142.5	175.1	175.1	175.1
	EOD Max	150.7	150.7	400.2	400.2	400.2
Rathluba	PHD pre	13.5	13.9	19.6	27.3	36.1
	PHD post	12.4	13.4	13.8	17.3	23.5
	EOD Min	5	5.1	6.2	6.7	6.7
	EOD Mean	16	16	16	16	16
	EOD Max	22.2	22.2	22.2	22.2	22.2

Figure 4 illustrates the CDFs of pothole dimensions in the different seams, based on the entire PHD data, both pre (red) and post (blue) screening. The solid lines reflect the mean width dimension, while the minimum and maximum width dimensions of each pothole are represented by the dashed lines. Note, that for most seams there are considerably fewer samples than those detailed in the DoC CDFs (**Figure 3**) as dimensional recordings were not available for all events in the PHD.

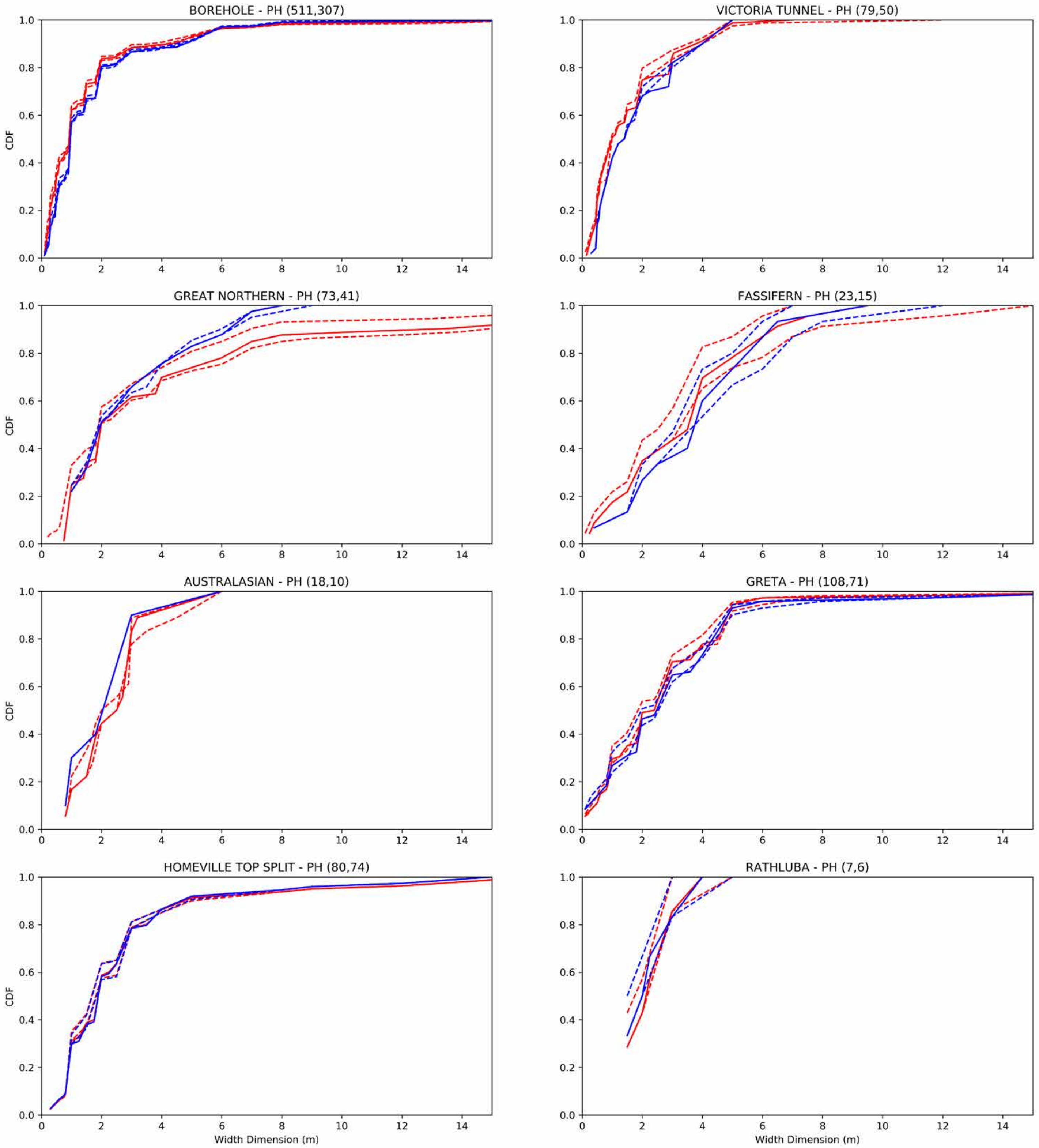

Figure 4: CDFs of PH width for each coal seam. Note solid red and blue lines depict the CDF for the average width pre and post screening of the PHD, respectively. The dashed lines of equivalent colour represent the CDF for the minimum and maximum widths.

4.2 Pothole Occurrence in Case Study coal mines and seams

Figure 5 re-examines the distribution of pothole occurrences by DoC, using only those contained within the key case-study collieries. Note, EoD distributions have been pro-rated in these CDFs and as such include values beyond the upper DoC limit outlined in Section 3.3. In order to justify that of the selected case-study collieries are representative of the wider workings in the same coal seams, a two-sample Kolmogorov-Smirnov test was conducted on the post-screened PHD, as well as the minimum, mean, and maximum EoDD DoC distributions (excluding values beyond the DoC limit) with these results tabulated in **Table 3**. Note, the test statistic and p-values in parentheses for the EoD distributions follow testing of EoD counts using a second set of bin limits shifted 1.25m (ie, 1.25 to 3.75m; >3.75m to 6.25m; >6.25m to 8.75m; >8.75m to 11.25m, and so on) to account for any sensitivity arising from the chosen bin definitions.

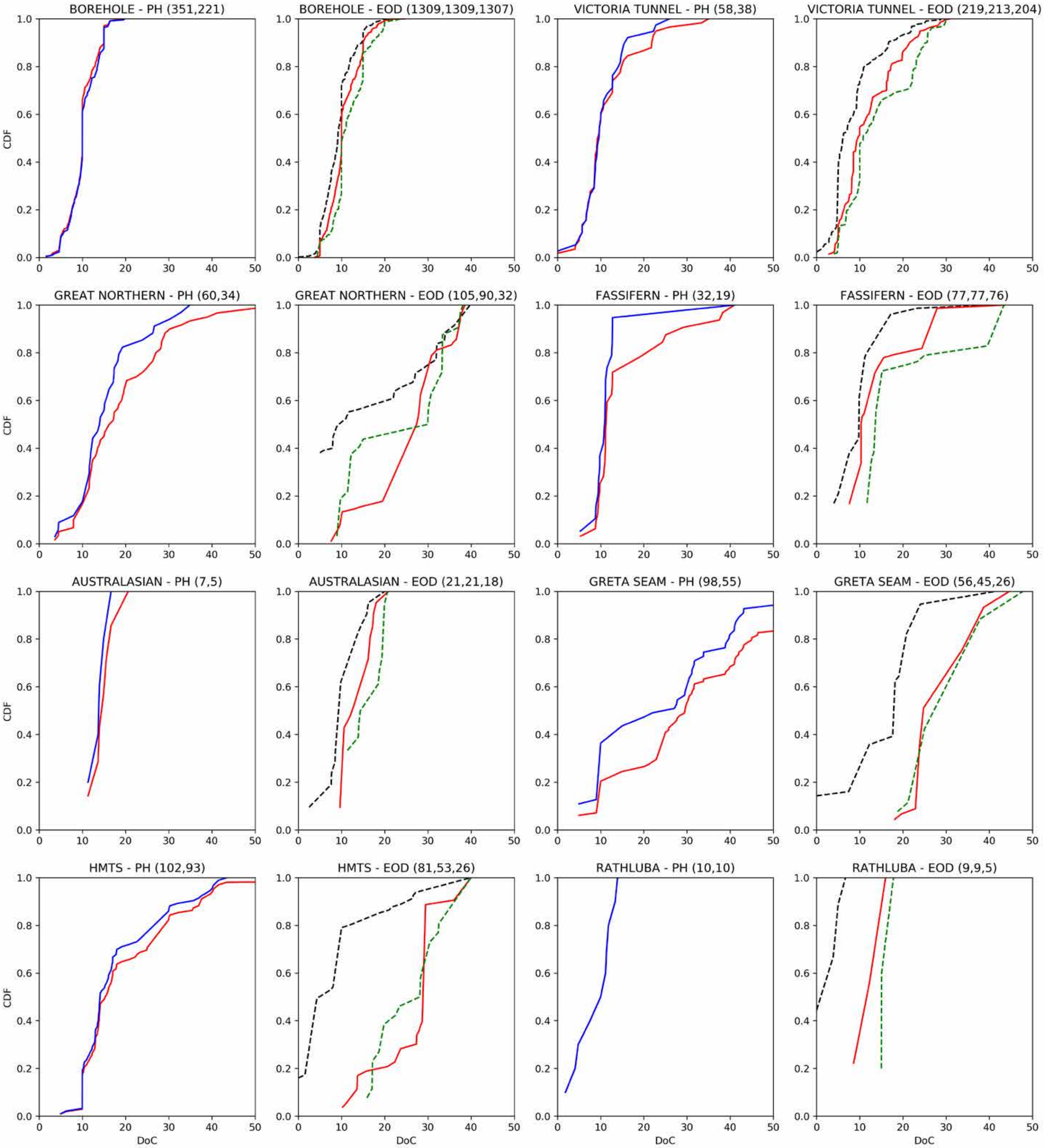

Figure 5: CDFs of DoC as per Figure 2, but only with data from the case-study collieries. Subplot titles include the number of PHD events (pre and post-screened, respectively) and EoD events (based on min, mean and max DoC). Note, EOD cases have been limited by the maximum DoC registered in the equivalent seam's screened PHD.

Table 3: Two Sample KS test results for comparison between the overall seam DoC distributions and the subset distributions of the case-study mines. Significance at the 95% level are depicted with bold red text.

Seam	**PHD post-screening**		**EoDD (Min)**		**EoDD (Mean)**		**EoDD (Max)**	
	KS Test Statistic	p-value	KS Test Statistic	p-value	KS Test Statistic	p-value	KS Test Statistic	p-value
BH	0.07	0.55	0.04	0.13	**0.05**	**0.07**	0.03	0.36
VT	0.06	1.0	0.08	0.38	0.08	0.37	0.08	0.46
GN	0.09	1.0	0.13	0.26	0.11	0.56	0.25	0.13
FASS	0.0	1.0	0.02	1.0	0.02	1.0	0.02	1.0
AUS	0.42	0.45	0.12	0.97	0.22	0.47	0.21	0.64
GRETA	0.19	0.16	**0.24**	**0.02**	0.2	0.13	0.2	0.41
HMTS	0.01	1.0	0.01	1.0	0.02	1.0	0.02	1.0
RATH	0.07	1.0	0.08	1.0	0.31	0.54	0.42	0.45

The results of the KS tests reveal that the case-study collieries are an adequate representation of what can be expected to occur more widely in the workings in the coal seams that they represent. All p-values resulting from paired tests using the PHD show two instances of significance at the 5% level. Only two instances of significance were found using the EoDD. This occurred in the GRETA seam workings using the minimum DoC distribution and in the BH seam using the mean DoC distribution. The CDFs for both distributions have been provided in **Figure 6**.

From **Figure 6**, the very small KS-statistics (0.05) which was deemed significant with respect to the BH seam is associated with the different DoC limit arising from the PHD across all mines (1,940 samples) in the BH seam versus the case-study mines (1,309 samples). Up until ~15m DoC the two CDFs are very similar and diverge thereon. This suggests caution should be taken for results within the deeper portions of the BH seam when based on the subset of collieries. For the Greta seam illustrated in the right-hand subplot of **Figure 6** there is again a different upper DoC limit for the minimum DoC distribution and a considerable difference in the number of samples (143 overall versus 54 in the subset collieries). However, the main area of divergence occurs from ~20-25m DoC with a higher proportion of events occurring in this DoC range as opposed to the wider Greta seam.

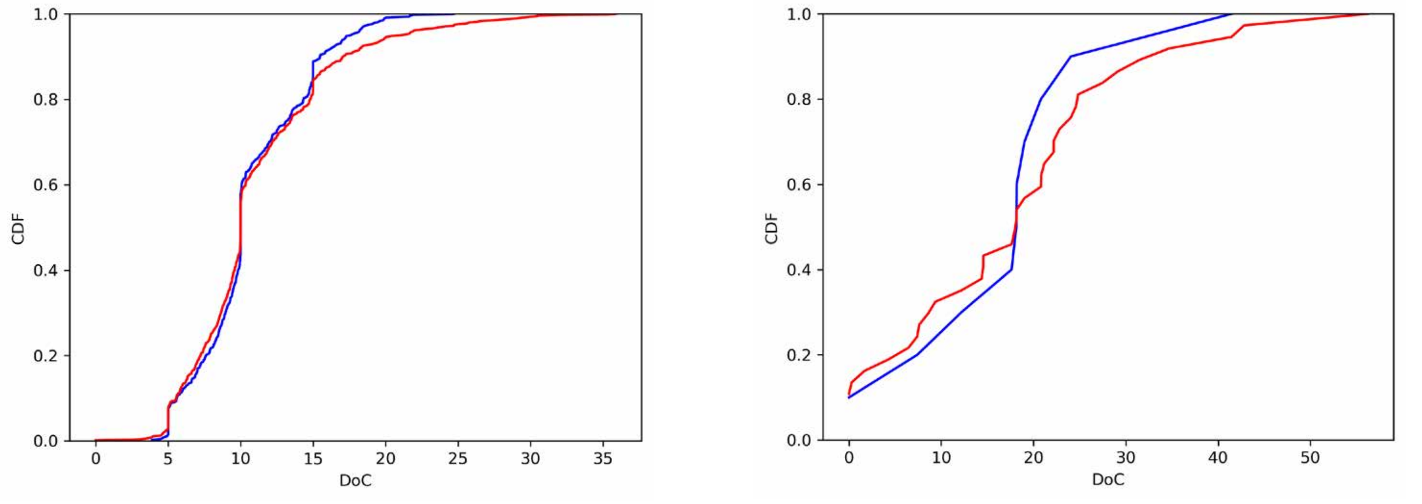

Figure 6: CDF for the mean DoC BH (left) and minimum DoC Greta (right) EoDD distributions. The blue line represents the distribution from areas above the case-study collieries, whilst the red line is representative of data from all mined areas in the same seam.

Figure 7 illustrates the rates of PH occurrence per coal seam using the PHD and pro-rated EoDD, based on the key case-study collieries. The pro-rated rates of occurrence in Figure 7 have been based on the mean DoC per property parcel, whilst Figure 10 and Figure 11 in the supplementary material employ the minimum and maximum DoC per property parcel, respectively. For these figures PH's per Hectare (Ha) has been used for the purpose of visualising more meaningful numbers.

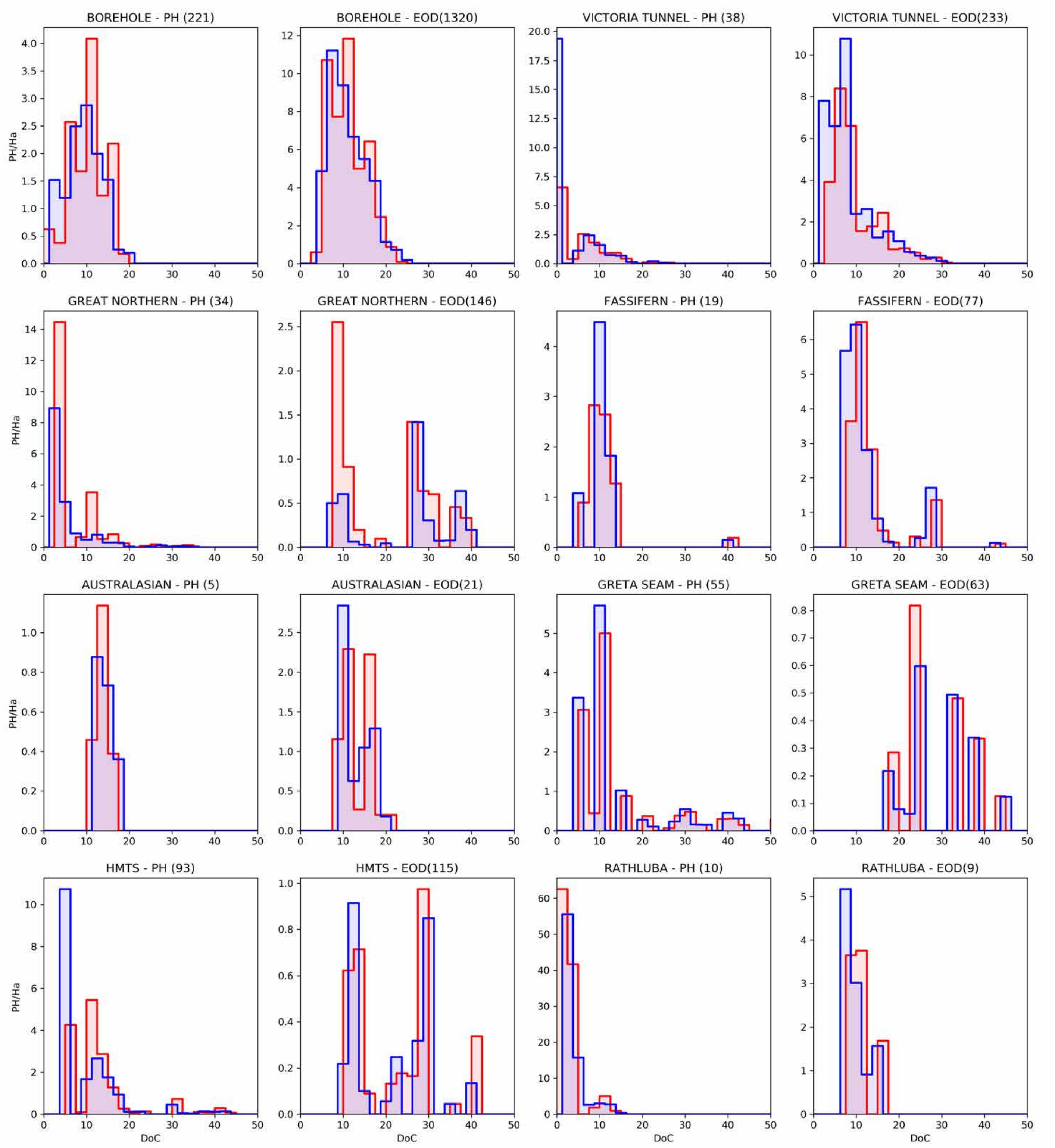

Figure 7: Bar chart showing the rates of occurrence of PHs per hectare per seam based on case-study collieries data from the PHD, and the pro-rated data from the same collieries from the EoDD using the mean DoC values. Red bar charts represent rates using the first set of bin limits, whilst the blue bar charts use bin limits offset by 1.25m.

4.3 Probability of Pothole Occurrence in Case Study coal mines and seams

The rates of pothole occurrence (originally illustrated in **Figure 7**) were calculated into 10m DoC bins with the resulting rates defined as the number of potholes per square metre per year (PHs/m²/yr). These rates are tabulated in **Table 4**.

Table 4: Pothole rates for various seams at various depth of cover intervals, calculated over a year (PHs/m²/30 years).

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	2.298E-05	2.119E-05	5.914E-06	6.974E-06	2.507E-06	3.430E-06	8.546E-07	1.578E-05
>10-20	2.256E-05	5.242E-06	2.722E-06	6.800E-06	3.674E-06	3.457E-06	5.624E-06	2.802E-06
>20-30	8.110E-07	1.395E-06	1.696E-06	1.741E-06	1.646E-07	7.383E-07	1.541E-06	NA

To demonstrate how these rates would then be employed in the MAP, the following scenarios were considered for each seam, for DoCs of 0-10m, >10-20 and >20-30m:

- 500m² parcel of land, with the intention to build a structure with a 50-year design life
- 500m² parcel of land, with the intention to build a structure with a 100-year design life

As outlined in Section 3.4, λ is calculated as the product of:

- the area of land under investigation (in these examples 500m²),
- the defined period of assessment (i.e. design life) divided by the 1-year baseline rate and
- rate of potholing within the specified seam for the particular depth of cover.

As a result, the values of λ corresponding to a 50-and 100-year design life are contained respectively in **Table 5** and **Table 6** below;

Table 5: Values of λ calculated for a 50-year design life and a 500m² land area.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	0.57	0.53	0.15	0.17	0.06	0.09	0.02	0.39
>10-20	0.56	0.13	0.07	0.17	0.09	0.09	0.14	0.07
>20-30	0.02	0.03	0.04	0.04	0.00	0.02	0.04	NA

Table 6: Values of λ calculated for a 100-year design life and a 500m² land area.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	1.15	1.06	0.30	0.35	0.13	0.17	0.04	0.79
>10-20	1.13	0.26	0.14	0.34	0.18	0.17	0.28	0.14
>20-30	0.04	0.07	0.08	0.09	0.01	0.04	0.08	NA

To determine the probability of any potholes (i.e. more than 0 potholes) occurring on a site for the same defined time period, Equation 4 is used. From this equation and given the derived values of λ provided in **Table 5** and **Table 6**, the probability of any pothole events occurring P(k>0) on a 500m² site over a 50-and 100-year design life may be calculated. The values are shown in **Table 7** and **Table 8** below.

Table 7: Probability of more than 0 potholes occurring on a 500m² site for a 50-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	44%	41%	14%	16%	6%	8%	2%	33%
>10-20	43%	12%	7%	16%	9%	8%	13%	7%
>20-30	2%	3%	4%	4%	0%	2%	4%	NA

Table 8: Probability of more than 0 potholes occurring on a 500m^2 site for a 100-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	68%	65%	26%	29%	12%	16%	4%	55%
>10-20	68%	23%	13%	29%	17%	16%	25%	13%
>20-30	4%	7%	8%	8%	1%	4%	7%	NA

As outlined in **Section 3.4**, the alternative approach to calculate the probability of at least one or more events on a site allows for a comparison between an arbitrary number of discrete events (*n* number of events) and the > 0 events to be undertaken, and a % total error may be calculated using Equation 6. The results are presented in **Table 9** and **Table 10** below. It was determined that there was no material increase in the cumulative probability of occurrence after n = 5. The calculated error for *P(k=1 to 5)* when compared to *P(k>0)*. The result effectively confirms that there is a very small likelihood of having 6 or more potholes on a site during its design life.

Table 9: Percentage error between P (1 to 5 potholes) compared to P (more than zero potholes) for a 50-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	0.007%	0.005%	0.000%	0.000%	0.000%	0.000%	0.000%	0.001%
>10-20	0.006%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
>20-30	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	NA

Table 10: Percentage error between P (1 to 5 potholes) compared to P (more than zero potholes) for a 100-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	0.177%	0.122%	0.000%	0.001%	0.000%	0.000%	0.000%	0.031%
>10-20	0.163%	0.000%	0.000%	0.001%	0.000%	0.000%	0.000%	0.000%
>20-30	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	NA

For SA NSW's purposes, knowing the likelihood of there being more than 0 potholes is not sufficient for a meaningful assessment of risk. In order to be able to assess the risks of a pothole to a structure, the consequence, in terms of pothole dimensions, must be included in the assessment.

Table 11 presents the cumulative percentage of average and maximum PH width W smaller than a nominated critical width, Wc, for workings in each of the important local coal seams. The right-hand column details the 90th percentile width dimension for all recorded potholes. The likelihood that a pothole will be smaller than a nominated size Wc P(W≤Wc) is given by the cumulative percentage of widths smaller than Wc, which can be determined from the graphs in Figure 3, as per **Table 11**. The likelihood that a pothole will exceed a nominated size Wc is given by 1-P(W ≤ Wc) and represented by the following term;

$$P(W>Wc)$$

Based previous assessments by engineering consultants who were commissioned by SA NSW to carry out the analysis, pothole design widths of 3m and 5m were selected as appropriate design values which can be reasonably catered for through appropriate design measures.

Table 11: Cumulative percentages of PHs smaller than nominated average and maximum PH dimensions Wc (P(W≤Wc)), according to coal seam; PH width for which 90% of PHs are smaller (right hand column).

Wc (m)	**<1.0**	**<2.0**	**<3.0**	**<4.0**	**<5.0**	**90th Percentile width (m)**
BH Avg	36.8%	67.8%	81.8%	87.6%	88.6%	4.8
BH Max	35.5%	67.1%	81.1%	87.3%	87.9%	4.7
VT Avg	22.0%	54.0%	72.0%	82.0%	90.0%	4.0
VT Max	22.0%	54.0%	68.0%	80.0%	90.0%	4.0
GN Avg	0.0%	31.7%	53.7%	65.9%	75.6%	6.2
GN Max	0.0%	31.7%	51.2%	65.9%	75.6%	6.3
FAS Avg	6.7%	13.3%	33.3%	40.0%	60.0%	6.3
FAS Max	6.7%	13.3%	33.3%	33.3%	53.3%	7.5
AUS Avg	10.0%	40.0%	40.0%	90.0%	90.0%	3.0
AUS Max	10.0%	40.0%	40.0%	90.0%	90.0%	3.0
GRETA Avg	21.1%	32.4%	50.7%	66.2%	73.2%	4.9
GRETA Max	18.3%	29.6%	46.5%	62.0%	71.8%	5.0
HMTS Avg	9.5%	39.2%	63.5%	79.7%	86.5%	4.6
HMTS Max	9.5%	36.5%	58.1%	78.4%	85.1%	4.9
RATH Avg	0.0%	33.3%	66.7%	83.3%	100.0%	3.4
RATH Max	0.0%	33.3%	50.0%	83.3%	83.3%	3.8

As shown in **Table 9** and **Table 10**, the error values associated with assuming that the number of potholes occurring on a given site is limited to 5, when compared to the total probability up to infinite potholes is negligible. It is expected therefore that n=5 is a reasonable upper bound limit of potholes occurring on any given site and thus *P(k>0)*≈*P*(1 to 5).

Using this approach detailed in Equation 8, the percentage likelihood of a pothole exceeding 3m for a 500m^2 block for both a 50-and 100-year design life is given in **Table 12** and **Table 13** below;

Table 12: Cumulative Probability of exceedance of a pothole >3m occurring on a 500m^2 site for a 50-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	9.9%	13.8%	6.6%	11.0%	3.7%	4.1%	0.8%	12.3%
>10-20	9.8%	3.6%	3.1%	10.7%	5.4%	4.2%	5.0%	2.3%
>20-30	0.4%	1.0%	1.9%	2.9%	0.2%	0.9%	1.4%	NA

Table 13: Cumulative Probability of exceedance of a pothole >3m occurring on a 500m^2 site for a 100-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	18.8%	25.6%	12.8%	20.7%	7.2%	8.1%	1.5%	23.1%
>10-20	18.5%	7.1%	6.1%	20.3%	10.4%	8.2%	9.8%	4.6%
>20-30	0.7%	1.9%	3.9%	5.6%	0.5%	1.8%	2.8%	NA

The percentage likelihood of a pothole exceeding 5m for a 500m^2 block for both a 50-and 100-year design life is given in Table 14 and Table 15 below;

Table 14: Cumulative Probability of exceedance of a pothole >5m occurring on a 500m^2 site for a 50-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	6%	5%	4%	7%	1%	2%	0%	0%
>10-20	6%	1%	2%	7%	1%	2%	2%	0%
>20-30	0%	0%	1%	2%	0%	0%	1%	NA

Table 15: Cumulative Probability of exceedance of a pothole >5m occurring on a 500m^2 site for a 100-year design life.

DoC (m)	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
0-10	10%	8%	7%	13%	1%	5%	1%	0%
>10-20	10%	3%	3%	13%	2%	5%	4%	0%
>20-30	0%	1%	2%	3%	0%	1%	1%	NA

5 Application of probability of exceedance to the Management of Risk

An example application of using exceedance probabilities for the assessment of risk when assigning development controls has been performed using the following criteria:

- Risk of exceedance ≤ 1% = Low Risk (1)
- Risk of exceedance of between 1 and 5% = Medium Risk (2)
- Risk of exceedance >5% = High risk (3)

When assigning development controls for varying structures, it is appropriate to consider the type, scale and design life of the structure. **Table 16** and **Table 17** show the comparative risk of exceedance using a combination of 50/100 year design life for a 5m pothole size and a variety of proposed building/lot envelopes in m^2. This is to provide indicative values for the assessment of guideline 1 properties as properties not considered guideline 1, 1A or 7 are considered to have low to negligible risk of pothole subsidence.

Table 16: Risk of pothole subsidence with 50-year design life and a 5m design pothole

Block size	DoC	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
250	10	2	2	2	2	1	2	1	1
250	20	2	1	1	2	1	2	1	1
250	30	1	1	1	1	1	1	1	NA
500	10	3	2	2	3	1	2	1	1
500	20	3	2	2	3	1	2	2	1
500	30	1	1	2	2	1	1	1	NA
750	10	3	3	3	3	1	2	1	1
750	20	3	2	2	3	2	2	2	1
750	30	1	1	2	2	1	1	1	NA

Table 17: Risk of pothole subsidence with 100-year design life and a 5m design pothole

Block size	DoC	BH	VT	GN	FASS	AUS	GRETA	HMTS	RATH
250	10	3	2	2	3	1	2	1	1
250	20	3	2	2	3	1	2	2	1
250	30	1	1	2	2	1	1	1	NA
500	10	3	3	3	3	2	2	1	1
500	20	3	2	2	3	2	2	2	1
500	30	1	1	2	2	1	1	2	NA
750	10	3	3	3	3	2	3	1	1
750	20	3	2	2	3	2	3	3	1
750	30	1	2	2	3	1	2	2	NA

By way of example, a B1 structure located within a guideline 1 500m^2 site at 0-10m DoC over the borehole coal seam is considered to have a design life of 50-years , and therefore a high risk of experiencing a pothole of 5m within the design-life of the structure. Similarly, an identical structure would be considered to have a medium risk when located over identical workings within the Victoria Tunnel Coal Seam and a low risk if located over workings in the Rathluba coal seam. Further, if a B3 structure with a 100-year design life is considered for the same site and influenced by mining in the Victoria Tunnel seam, the risk of a 5m pothole developing during the design life is now considered high.

6. References

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7 Supplementary Material

7.1 Event attribution to Mine and Coal Seam

Pothole occurrence has both spatial and temporal aspects, and the spatial analysis of data lends itself well to the application of GIS tools. In the majority of events recorded potholes occurred directly within the extent of an underground coal mine in a particular seam. The positioning of the coal mine outlines themselves are subject to variable accuracy, with more recent mining typically more reliable than earlier mining. As such, there were instances where the position of a pothole event occurred close to, but outside of the recorded mine outline. Additionally, there were frequent instances where the pothole and/or EoD events were underlain by multiple underground coal mines, each operated in a different coal seam. As such, the following automated scripted procedure in GIS was used to attribute each pothole and/or EoD to the most likely underground mine and coal seam:

- Looping through each mine in each coal seam from shallowest to deepest, if an event fell within the extent of a mine worked in the iteration's current coal seam, it was attributed to that mine and seam. As EoD's were polygons representative of the parcel of land where an event occurred, if the parcel was only partially undermined, the polygon was clipped to the area common to both the parcel and the mine outline, with the undermined portion retained and the non-undermined portion discarded.
- For the remaining events that were not captured in the initial loop, a secondary loop was initiated, allowing for a buffer of up to 15m (outside the recorded extent of workings) and the event was attributed to a coal mine and seam if it fell within the extent of the buffer. Events beyond this extent remained unassigned.
- A manual quality assurance check was completed to verify that the associated coal mine and seam was correct. In complex scenarios where (resulting from the second loop's iteration) a pothole was attributed to the next closest mine (within 15m distance), but was significantly deeper (i.e. >20m depth of cover difference) than a mine within 20m distance, the pothole was reassessed as occurring in the shallower mine despite it being further away.
- Depth of Cover (DoC) to the roof of the mine workings were then assigned to each event. For pothole events with defined location, this was simply based on the DoC at the centre of the positioned pothole. For the EoD events where to location is a parcel of land, DoC statistics were drawn systematically from the portion of the property parcel that was undermined. As such the maximum, minimum, average and standard deviation of DoC for the undermined area of each parcel of land in the EoDD was calculated. Based on the frequency of accepted events for that parcel of land, the DoC statistics were replicated to populate the EoD DoC distribution.
- Events that were not within the buffers of known mine workings remained unassigned and were not used in any analysis.

7.2 Additional results

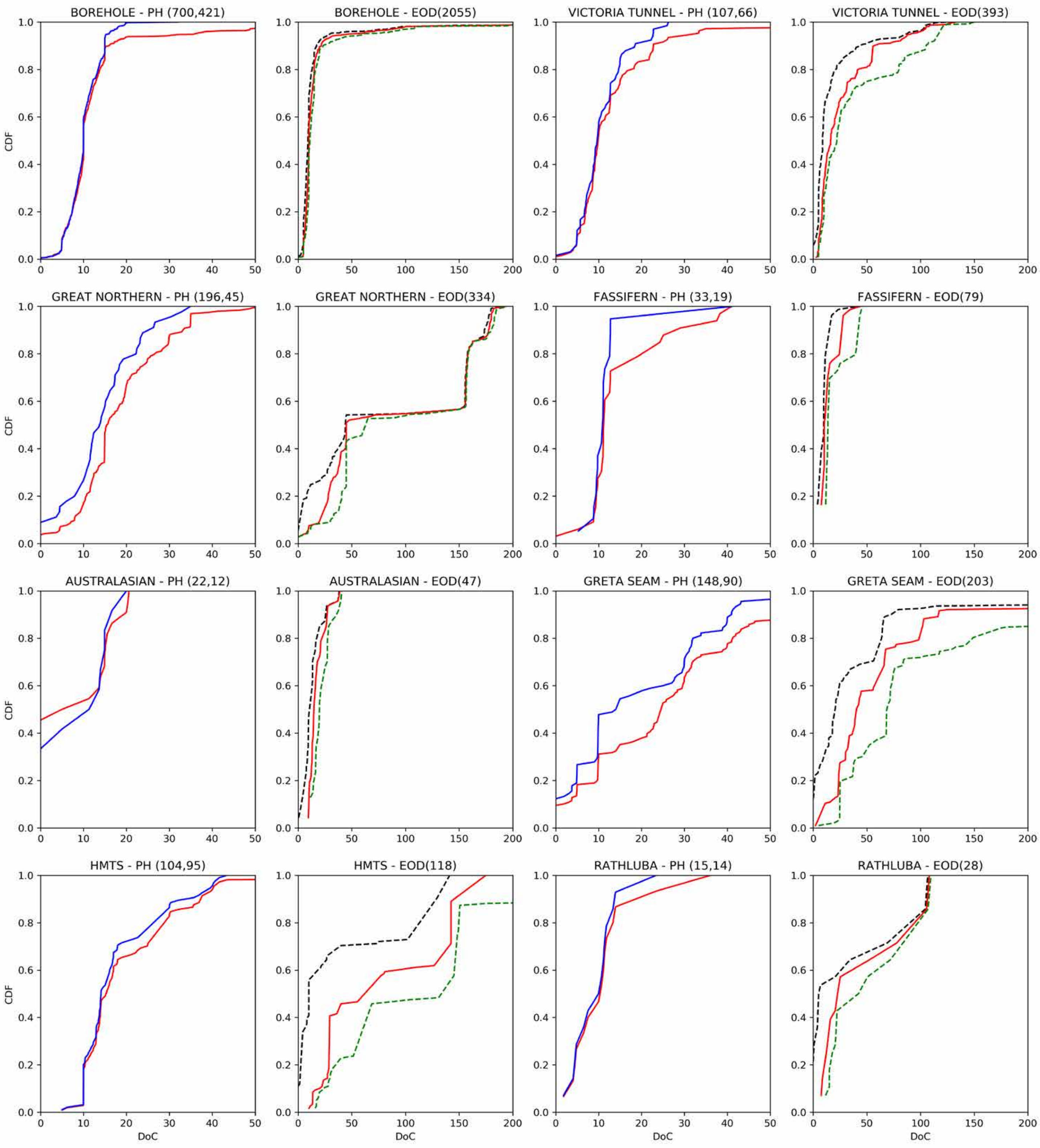

Figure 8: CDFs of DoC for each coal seam. Red and blue lines depict the CDF pre and post screening of the PHD, respectively. The solid red lines in the EoD plots depict the CDF for the mean DoC from the EODs (not pro-rated), while the dashed black and green lines are derived from the minimum and maximum DoC values from the EoD parcels. Subplot titles include the number of PHD and EoD events in parentheses (PHD pre and post-screened, respectively)

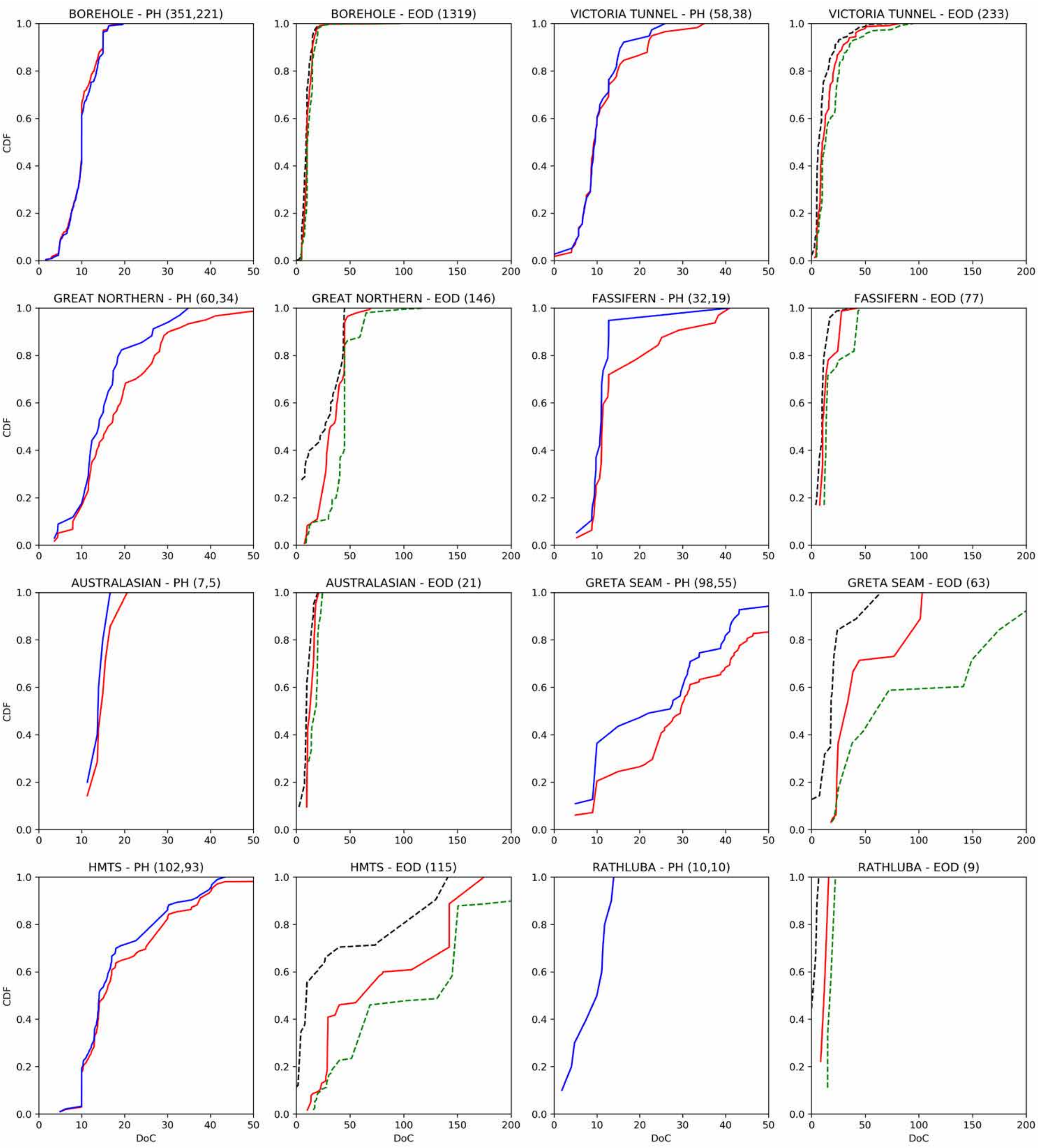

Figure 9: CDFs of DoC as per **Figure 8**, but only with data from the case-study collieries. Subplot titles include the number of PHD and EoD events in parentheses (PHD pre and post-screened, respectively).

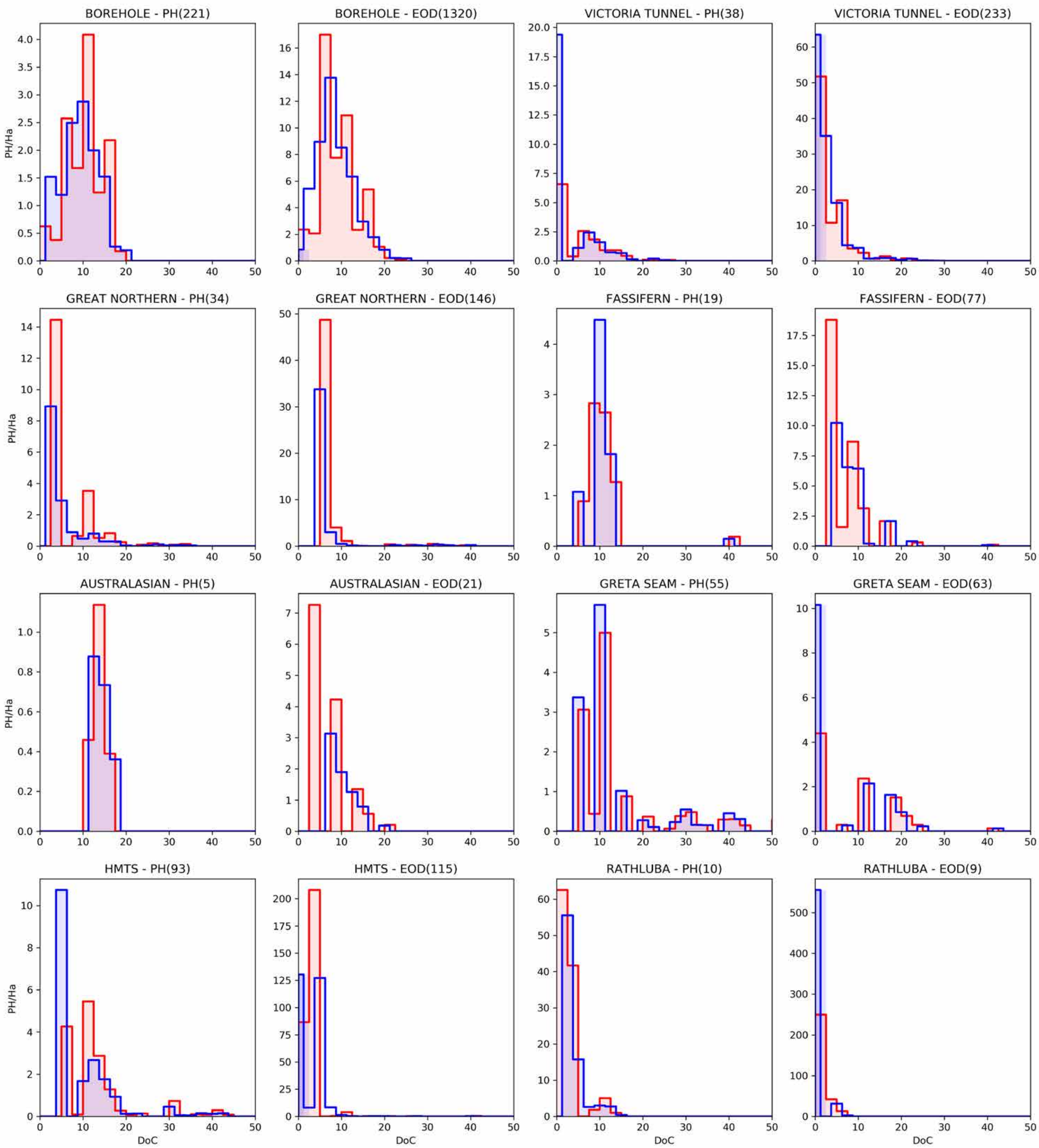

Figure 10: Bar chart showing the rates of occurrence of PHs per hectare per seam based on case-study collieries data from the PHD, and the pro-rated data from the same collieries from the EoDD using the minimum DoC values. Red bar charts represent rates using the first set of bin limits, whilst the blue bar charts use bin limits offset by 1.25m.

Figure 11: Bar chart showing the rates of occurrence of PHs per hectare per seam based on case-study collieries data from the PHD, and the pro-rated data from the same collieries from the EoDD using the maximum DoC values. Red bar charts represent rates using the first set of bin limits, whilst the blue bar charts use bin limits offset by 1.25m.

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