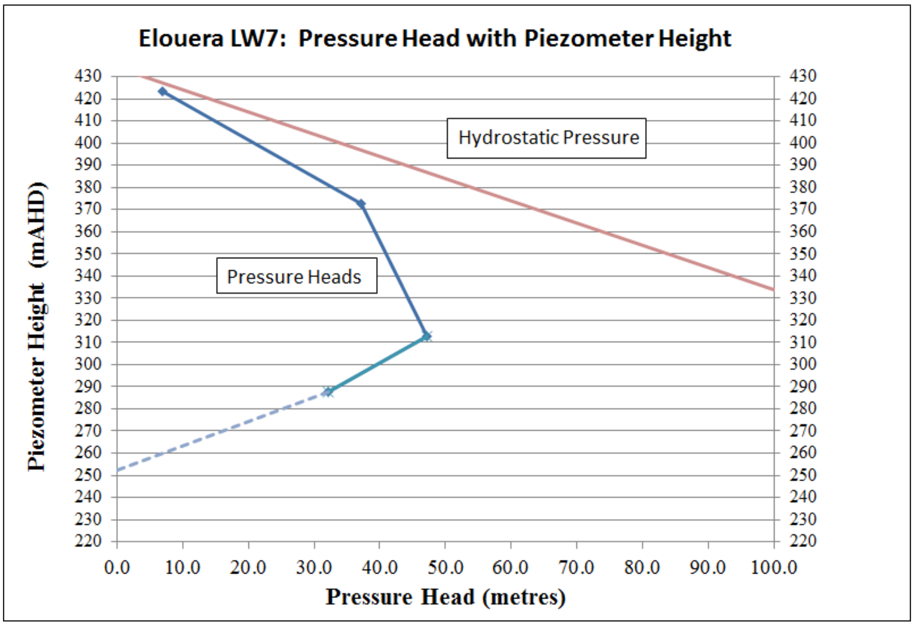
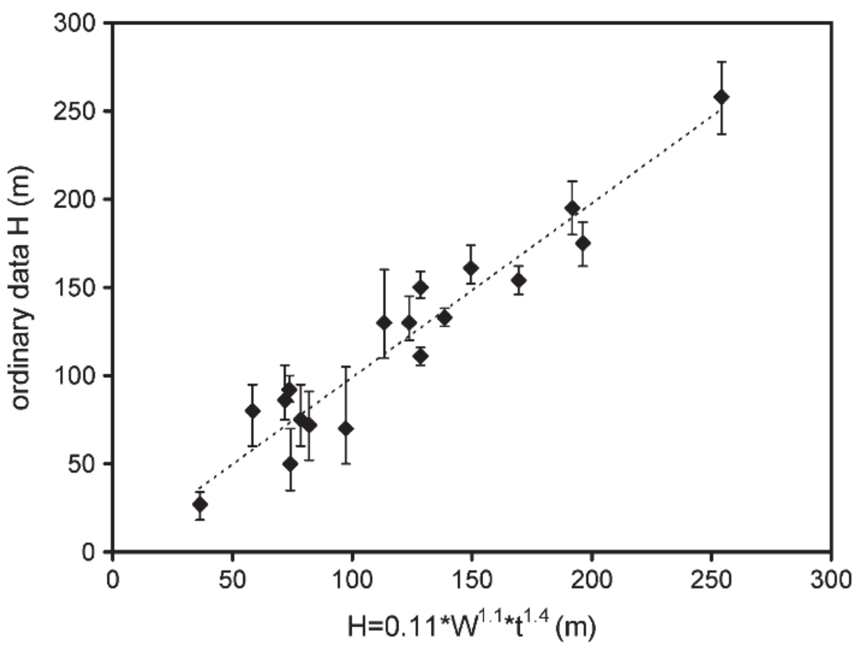
Some Comments on the 2017 PSM, Galvin and Mackie height of cracking reports for the Dendrobium coal mine





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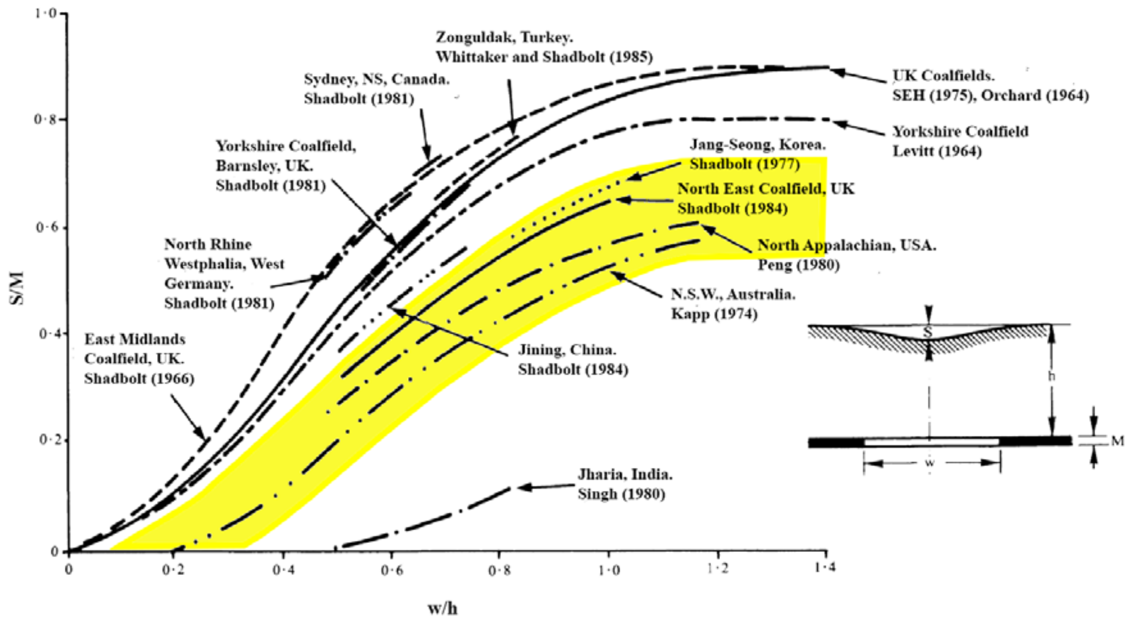

Above figure: The above figure is Figure 8 within and is a modification of Figure 199 in a 1989 coal mine subsidence book by Whittaker and Reddish. The yellow band added to the figure highlights locations with lithologies represented in Tammetta's primary database. The lithologies to the left and right are relatively unusual.

Cover figures: The upper figure is Figure 28 within and illustrates the determination of the height of the drainage zone above Longwall 7 in the Elouera domain of the Wongawilli Colliery. The lower figure is Figure 4 within and illustrates the fit of Mackie's simplified equation for estimating the height of the drainage zone with respect to primary Tammetta database, with error bars

General Disclaimer

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NATIONAL PARKS ASSOCIATION OF NSW
protecting nature through community action

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1. Introduction and summary

Comments are made herein on reports released by the NSW Department of Planning in September 2017 on impacts to the Schedule 1 Metropolitan Special Area arising from longwall coal extractions at the Dendrobium mine. These reports are comprised of a March 2017 impact assessment report[1] by civil and geotechnical engineers Mr Tim Sullivan and Dr Gareth Swarbrick from consultancy Pells Sullivan and Meynink (PSM; Tim Sullivan is the current head of PSM), a February 2017 review of the PSM work by hydrologist Dr Colin Mackie[2] and a second February 2017 review of the PSM work by mining and geotechnical consulting engineer and UNSW Emeritus Professor Dr Jim Galvin.[3] The Galvin and Mackie reviews appear to be of a November 2016 draft of the final PSM report. The release of the reports was accompanied by a June 2017 summary and explanation report[4] by Prof. Galvin.

In large part these reports stem from a July 2015 NPA letter[5] sent to the then Minister for Planning raising concerns regarding a key aspect of the impact of coal mining impacts on groundwater and, consequentially, surface water; the height of the drainage zone. The drainage zone is a zone formed over a coal extraction where water drains relatively freely towards the mine (see Figs. 1 and 16). Somewhat confusingly (see Section 13.1), this zone is also referred to as the connected or connective fracture zone, which identifies "*the zone of cracking above a longwall panel that is likely to result in a direct flow-path or hydraulic connection to the workings*".[6]

The importance of the drainage zone and of knowledge of its height was pointed out to the Minister in the NPA letter of July 2015. Prof. Galvin notes the central importance of the height of the drainage zone in his June 2017 summary and explanation of the findings and significance of the PSM report and the reviews of that report: "*The height above mine workings from which groundwater freely drains is a particularly important consideration when constructing the geometry of a numerical groundwater model and assigning values to the parameters that define groundwater flow in the model*."[4] As pointed out to the Minister in 2015, this height is most reliably determined with a string of piezometers (water pressure measuring devices) placed in a bore sunk over the centreline of an extraction (see Figs. 1 and 16).

The July 2015 NPA letter included the following recommendation made with respect to two empirical equations intended to provide at least a 'first pass' estimate the height of the drainage zone:

> " *Independent (non-industry related) expert panel review of the equations and databases used for the 2014 Springvale and Dendrobium Area 3B groundwater assessments and those used for the 2012 Dendrobium Area 3B assessment and published in the journal Groundwater. In the interim, given the available evidence and science journal publication, the latter to be recommended for groundwater assessments for mining proposals*."

The empirical equations and associated databases referred to are those of hydrologist Paul Tammetta and those of engineer Steven Ditton and his collaborator hydrologist Dr Noel Merrick. Tammetta developed his equation for the 2012 Dendrobium groundwater impact assessment[7]–[10] and the equation and its determination were published in 2013 in the international science journal Groundwater[11], which is a peer reviewed science journal of high standing. Closely related work was published in two further Groundwater papers[12], [13] in 2015 and 2016, that affirm the equation using two additional characterisation techniques. Of note, the journal editor for the 2013 paper was Prof. Colin Booth, a pioneer of the study of mining impacts on ground and surface waters (Section 2). The Ditton-Merrick equations were used for the 2014 assessments[6], [14] noted in the quote. The Ditton-Merrick empirical equations, introduced after that of Tammetta, have been presented at a conference[15], but have not been published in a peer reviewed science journal. A key task in the scope of works assigned to PSM was to undertake a review of the Tammetta and Ditton-Merrick databases. This report focuses on that aspect of the PSM report and the Mackie and Galvin reviews.

The supplementary material for Tammetta's 2013 Groundwater paper provides details, including source data references, for Tammetta's databases. Some of the underlying data is held by mining companies, or is otherwise not readily available. Distinguishing his work from that of Ditton, Tammetta separates geotechnical data (extensometer) from hydrological (piezometer) data in constructing his databases. This fundamentally important difference is not acknowledged in the PSM, Mackie and Galvin reports.

Further distinguishing his work, again not acknowledged in the PSM, Mackie and Galvin reports, Tammetta's primary database is comprised solely of piezometer data from bores over the centreline of coal extractions. Tammetta locates the boundary of the drainage zone between the deepest piezometer reporting a non-zero water pressure and the shallowest piezometer reporting no water pressure (see Fig. 1 and Fig. 24). The significance of piezometer data is noted in the PSM report and in Prof. Galvin's 2016 review[16] of the proposed SMP for Dendrobium Longwalls 14 to 18, Prof. Galvin highlights the limited utility of extensometer data and data not obtained from over the centreline of an extraction (see Section 12).

Characterised by Galvin and Mackie as a critical shortcoming of the PSM work, Sullivan and Swarbrick failed to review the Tammetta and Ditton-Merrick databases (see Section 17). Additionally, the consultants fundamentally misunderstand the hydrological implication of Tammetta's work (Section 18).

Currently the only assessment of the Tammetta database and the Ditton-Merrick databases appears to be that provided in a detailed NPA report[17] sent to the then Minister in December 2016; the report elaborates and expands upon the 2015 letter. The NPA report is available here:
https://drive.google.com/open?id=0BxrDWhFTAAvBaF9WUDhzMmQwX2c

While hampered by limited source data availability and/or access, a problem encountered by Sullivan and Swarbrick that is no fault of Tammetta's, the NPA report finds that the available data suggests that the database underpinning the work published in the journal Groundwater appears to be fit for purpose.

In contrast, the 2016 NPA report finds the database underpinning the Ditton-Merrick equations to be not fit for purpose, being a mixture of geotechnical and hydrological data from centre panel, side panel and off panel instrument bores. Ditton's database listing does not distinguish between centre, side and off-panel data (see Fig. 1). The 2016 NPA report finds the Dendrobium piezometer data are not in accord with the drainage zone height estimates provided by the Ditton-Merrick equations (see Section 19). For this and reasons given in some detail in the 2016 NPA report and within this report, and in the absence of further information suggesting otherwise (none is provided in the PSM, Galvin and Mackie reports), the Ditton-Merrick equations cannot be regarded as a credible means of estimating the height of the drainage zone.

In the absence of centreline piezometer data, the NPA report recognises that the large difference between the horizontal and vertical permeabilities of the rock over the Southern Coalfield offers a basis for using side and off-panel data to indirectly probe the height of the drainage zone (see Section 19) with respect to the heights estimates of the Tammetta equation and the Ditton Merrick equations. As Dr Mackie notes in his review of the PSM report; "*Since each equation generates a significantly different answer for Dendrobium conditions, logic dictates that one or the other is more representative*". The NPA report finds that piezometer data from key bores over the Dendrobium mine appears to be consistent with the estimates provided by the Tammetta equation (Section 19). The data are not consistent with the expectations of the Ditton-Merrick equations.

The Tammetta equation is an empirically determined hydrological equation; it calculates a hydrological observable and was obtained entirely from hydrological data; the equation has no direct knowledge of geology or geomechanics. Nonetheless, on the basis of the available information, including its Groundwater publication, the equation offers at least a first approximation estimate of the height above the centreline of a longwall coal extraction at which a piezometer would report zero pressure head as a consequence of relatively rapid drainage (see Fig. 1). That is, where a piezometer would report a zero groundwater pressure head and show no more than transient responses to rainfall/recharge. There is a physical limit to that height; the surface. Highlighted in the July 2015 NPA letter to the then Planning Minister, the Tammetta equation predicts the drainage zone will intersect the surface over parts of the Dendrobium mine (Section 23 and Fig. 33). The available evidence is consistent with that expectation (section 24).

To date there have been no reports, to the standard required of peer reviewed science journal publication, of data contradicting the Tammetta equation and no reports of fault being found in the database underpinning the Tammetta equation. The PSM, Galvin and Merrick reports provide no data to contradict Tammetta's work and nor do they examine or otherwise find fault with the database underpinning the equation. Discussed in Section 20 below, the 2016 NPA report illustrates the determination of the height of the drainage zone for Longwall 7 in the Elouera domain of the Wongawilli mine (see Fig. 28). Elouera adjoins the southern boundary of Dendrobium Area 3B. The data from Elouera data support the Tammetta equation and it appears to be represented in Tammetta's database.

Elouera Longwall 7 is not mentioned in the PSM, Mackie or Galvin reports and does not appear to be considered or referenced in any other reports, other than a 2005 report prepared by SCT and the October 2012 groundwater impact assessment for the then proposed Dendrobium Area 3B mining, undertaken by Tammetta on behalf of Coffey Geotechnics for the then Dendrobium mine operators BHP-Billiton. The SCT report was provided to BHP-Billiton following a request by the Dams Safety Committee. This report is not publicly available and, as discussed in the December 2016 NPA report, BHP-Billiton rejected Tammetta's 2012 assessments for the Dendrobium mine.

Tammetta's work finds that there is no need to explicitly incorporate geology and geomechanics in obtaining at least a first pass estimate of the height of the drainage zone (Section 6.2.4). The relative indifference, in general, of the Tammetta equation to lithology has caused consternation within some quarters of the coal mining community. In his first Groundwater paper, published in 2013, Tammetta himself expresses surprise in finding that his equation is relatively insensitive to lithology; "*The strength of the relationship is remarkable given the diverse range of lithologies and void geometries present.*" To date this has not been refuted.

Evidently finding no distinguishing merit in Tammetta's work, Prof. Galvin's reports dismiss both the Ditton-Merrick equations and the Tammetta equations as unsound. Suggesting a failure to consider geomechanics and trivialising Tammetta's work as "*simply drawing a line of best fit through a range of data points"*[4], Prof. Galvin implicitly characterises Tammetta's work as unscientific. This is not, however, suggested in the summary of Tammetta's work given in Galvin's 2016 book[18] on coal mine engineering (Ditton's work is not mentioned in the book). As discussed in Section 6.3, suggesting Tammetta's equation is unscientific because it lacks explicit recognition of the underlying geomechanics is not dissimilar to suggesting Kepler's laws of planetary motion are unscientific because they lack recognition of gravity.

Reflecting his considerable experience as a mining engineer, mine manager, academic and consulting specialist in coal mining geomechanics, Prof. Galvin commends Ditton's endeavours to explicitly incorporate allowance for geological circumstances in his equations. Prof. Galvin suggests in his review of the PSM report that, in principle, Ditton's approach in seeking to obtain a means of calculating an estimate of the height of the drainage zone is the more meritorious and "*represents a considerable advance on that of Tammetta*". This does not appear to be the case, however (Section 7).

Ditton presents the determination of his empirical equations as an outcome of a dimensional analysis based on Buckingham's method (Pi Theorem). However, variables carried over from his abandoned attempts to obtain an analytical equation based on beam theory are sequentially removed and little of substance is obtained from Ditton's dimensional analysis. Making his use of Buckingham's method essentially pointless, Ditton assumes a monomial relationship between the drainage zone height and extraction width, depth, depth of cover and, optionally a fourth term he characterises as and "*effective strata unit thickness*". As suggested in the July 2015 NPA letter to the then Planning Minister and indirectly suggested by Prof. Galvin[3] and WaterNSW[19], in practice the additional term serves as a back-analysis 'fudge factor' (Section 7.3). Ditton's work does not constitute a significant advance on that of Tammetta.

In contrast, in seeking a relationship Tammetta is guided by an evident relationship between extraction height and the ratio of the drainage zone height to extraction width, in ultimately identifying and refining a logarithmic function of a monomial product of extraction width, extraction height and depth of cover. Remarkably, the relationship exposed by Tammetta is that of a straight line (see Section 5).

Prof. Galvin is mistaken in at least implicitly suggesting that Tammetta gives no consideration to geology or geomechanics in developing his equation (Sections 6 and 14). He is likewise mistaken in implicitly suggesting a lack of awareness or understanding of the well-known characteristic surface subsidence curve. Prof. Galvin refers to a set of these curves (Fig, 8 below, with the central set highlighted) given in a 1989 book on subsidence by Whittaker and Reddish, in order to highlight the sensitivity of the overburden disturbance that follows coal extraction, to geology and geomechanics (Sections 6.2.1, 6.2.4, and 6.3). Galvin's reference to Whittaker and Reddish's surface subsidence curves overlooks, however, the relatively unusual lithologies represented to the left and right hand side of that set of curves (Fig. 8 and Section 6.2.5). Those to the right represent unusually strong and competent strata (see below), while those to the left appear to represent coal dominated settings found in parts of Europe (see Fig. 13 in the attached report).

In suggesting that the drainage zone height should show the same kind of geological sensitivity evident in these curves, Prof. Galvin doesn't distinguish the geomechanics of surface subsidence from the geomechanics of caving and collapse into the extraction void. Discussed in the attached, the two processes appear to be significantly different and would appear likely to have quite different sensitivities to mining depth (Section 6.2.1).

In the June 2014 subsidence assessment[20], undertaken by consultancy SCT on behalf of Wollongong Coal, for the proposed expansion of the Russell Vale Colliery, report author Dr Ken Mills applies the Tammetta equation and describes the analysis behind the equation as "*very good work*". Dr Mills has extensive experience in the assessment of underground coal mining impacts; including the sinking of centreline bores on behalf of coal mining companies and the Dams Safety Committee. Tammetta's work builds on that of Mills (Section 11).

Both Mills and Tammetta would appear to be well aware of the characteristic subsidence curves (Figs. 8, 9(a) and 10 and Sections 6.2.1, 6.2.4, and 6.3) that Prof. Galvin refers to, in arguing that there is need for the explicit representation of geomechanics in an equation intended to estimate the height of the drainage zone. Figure 9(a) below is from a 2014 knowledge report[21] prepared by Tammetta for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. Using the same data, essentially the same subsidence curve is provided in a conference paper[22] by Mills. Figure 10 is from a November 2012 revised data analysis[10] for the Coffey Geotechnics groundwater impact assessment for then proposed mining in Area 3B of the Dendrobium mine.

In his 2014 Russell Vale groundwater impact assessment report, responding to criticisms of his work from another consultant, Tammetta observes that anomalously high horizontal stress can delay the ultimate formation of the drainage zone (Section 6.2.5). Echoing this observation, Prof. Galvin highlights the role of horizontal stress in his 2016 book[18] on coal mine engineering and this includes commenting on its role in the collapse behaviour of the notably massive (in the geological sense of strength and spanning capacity[18]) dolerite sill in South Africa. Being much harder than the under- and over-lying sandstones and shales (see Fig. 12), these dolerite sills[23] form the flat-topped hills distinctive of the Karoo scenery in South Africa.

Discussed in in the supplementary material for his 2013 groundwater paper and again in a 2014 groundwater impact assessment for the expansion of the Russell Vale colliery, commissioned by the Department of Planning, this unusual formation constitutes one of the two locations found by Tammetta where the observed drainage zone height differs from the estimate of his equation. In the 2014 Russel Vale assessment Tammetta confirms that he has been unable to find further exceptions to his equation (see Sections 4, 6.2 and 8.5). Sullivan, Swarbrick, Mackie and Galvin may be unaware of Tammetta's discussion of the dolerite sill (see Section 6.2.5). They may also be unaware of the geomechanical discussion Tammetta provides in the supplementary material for his second Groundwater paper (see Section 14).

Prof. Galvin makes several comments and suggestions that may cause confusion, misunderstanding and the drawing of incorrect conclusions, particularly amongst those without a science background. For example:

(i) "*It is not a matter of which equation is correct …. Rather, it is a matter of which equation is the least incorrect*."[3]

(ii) The question of which is least incorrect "*cannot be answered from a technical perspective because each equation is based on a different set of data*".[3]

(iii) Referring to the Tammetta equation: "*Effectively, the equation was derived by simply drawing a line of best fit through a range of data points (each with its own considerable error band) without having any regard to geology or to the mechanics of rock behaviour*."[4]

(iv) "*Empirical approaches which disregard the mechanics of behaviour and, instead, rely on subjecting databases to simple statistical correlations such as linear regression are not scientific, regardless of the effort and care that has gone into collecting and plotting the data.*"[3], [18]

(v) *"Neither can be correct because neither properly and adequately accounts for geology, the mechanics of rock behaviour and time dependent hydrogeology processes*."[3]

These and other comments are discussed in Sections 6, 8 and 10.

Remarkably, PSM suggest "*Discussions over which model is more accurate or correct is somewhat distracting*." Discussed in Section 10, the question of which is more accurate is of central importance.

Prof. Galvin evidently anticipates a comprehensive equation, preferably derived from theory and not empirical analysis, capturing mining geometry, geology, geomechanics and time dependent processes, able to predict groundwater pressure changes in three dimensions within and beyond the drainage zone. The aspiration is currently unrealistic; notwithstanding the theoretical difficulties and vagaries of geology, the available data sets are notably coarse, patchy and limited in number.

Importantly, though not mentioned in the PSM, Galvin and Mackie reports, Tammetta's primary database is comprised of centreline piezometer data from bores over mines with extraction width to depth of cover ratios that span the range from subcritical, to critical to supercritical (see Figs. 2, 15(a) and 15(b) below). That is, the widths of the extractions represented in the database underpinning the Tammetta equation approach and pass the point at which the overburden fails to span the extraction void, resulting in complete collapse and maximum subsidence (see Figs. 3(a), 3(b), 8, 9(a), 9(b) and 10 and Section 6.2 and 7.1). This has been found to occur when the ratio is between 1.0 and 1.5, with 1.4 being regarded as representative.

To date, to the standard required of science journal publication, no data have been provided to refute Tammetta's finding that his equation applies (to within 10%) across a wide variety of lithologies (Section 16), stress fields and mining geometries(see Sections 2 and 6) and, to date, no fault has been found in the database underpinning Tammetta's work. Flaws in the limited underpinning database may subsequently be found or there may prove to be circumstances where the equation's estimates fail even as a first approximation (in addition to the two reported by Tammetta; see Section 6.2.5). The method may, for example, prove to be of limited immediate utility for the eastern part of Dendrobium Area 3B, which is known to have unusually high horizontal stress levels in the rock overlying the extractions that may, accordingly, delay the formation of the drainage zone.

Prof. Galvin concludes his comments on the Ditton-Merrick equations and the Tammetta equation in his June 2017 summary report with the following comment:

“*the reviews of the equations by Galvin (2016, 2017), Mackie (2017) and Sullivan and Swarbrick (2017) are consistent in concluding that neither equation is sound*.”

Any equation, whether empirical or analytically derived from first principles, is only as sound and robust as the data on which it rests. There is currently no evidence to suggest that the Tammetta equation does not provide a scientifically credible and useful representation of the coarse grained and patchy piezometer data currently available. Science progresses with the accumulation of data and evidence; more centreline groundwater pressure data from over a wide variety of past extractions are needed. This recognised by Tammetta[11]: “*Further field data will be required as an ongoing test of the derived equation, and to update the confidence limits*.”

While the PSM, Galvin and Merrick reports contain some prudent cautions, notably with respect to database extrapolation (see Section 9), the Tammetta equation stands as the only ‘fit for purpose’ science journal published equation offering a credible means of providing at least a ‘first pass’ estimate of the height of the drainage zone. The PSM, Galvin and Merrick reports provide no data to suggest otherwise. Though it might have been anticipated on the basis of the work of Gale and Mills (Section 11), the currently available information suggests Tammetta has made a significant discovery (Section 2); this is recognised by the publication of his work in Groundwater. It is neither recognised nor considered in the 2017 Dendrobium reports from Sullivan, Swarbrick, Mackie and Galvin.

Not mentioned in the PSM, Mackie or Galvin reports, in a November 2014 comment piece[23] published in Groundwater, Dr Colin Mackie makes the following comment:

“*The paper by Tammetta provides a useful empirical equation for predicting the height of complete drainage above longwall panels. Prior to this research effort, predictions in Australian coalfields often relied upon simple relationships*.”

Discussed in Section 3, below, Mackie’s positive comment of November 2014 is a prelude to suggesting a simplification of Tammetta’s equation. Of note, given the critical comments in his PSM review (Section 8.2 and 8.3), in empirically obtaining his simplified equation using regression, Mackie evidently uses the database content provided in the supplementary material published with Tammetta’s 2013 Groundwater paper (Section 8.3). Also of note, are Tammetta’s comments on the implicit capture of geomechanical stress in his informative reply to Mackie in the same issue of Groundwater (Section 6.2.3).

While it has weaknesses and mistakes are made, peer reviewed journal publication underpins scientific progress. Findings published in a peer reviewed science journal stand until relegated or refuted by the peer reviewed publication of new evidence and/or improved analysis, or the publication of fault in current data and/or analysis. Science journal publications are not relegated or refuted on the basis of ‘in-principle’ argument or opinion. Of note, Prof. Galvin was a member of a 2010 PAC panel that recognises the importance of journal publication (see Section 2). There is no such recognition on the PSM, Mackie and Galvin reports.

The comments within address significant omissions, errors, misdirection and misunderstanding in the PSM, Mackie and Galvin reports of 2017. Aspects of these reports suggest a fixed pre-conceived view. Prof Galvin for example, appears to hold a view that the drainage zone would not reach the surface before the critical mining width was reached (Section 7.1). Other than Mackie, none appear to consider the possibility that the Tammetta equation provides at least a ‘first pass’ estimator of the height of the drainage zone, yet this is supported by the available direct, indirect and circumstantial evidence.

2. Failure to recognise Tammetta's achievement

Prof. Galvin and Dr Mackie were members of the NSW Planning Assessment Commission (PAC) panel that undertook the 2010 Bulli Seam Operations (BSO) review. In commenting on a method for estimating swamp health, the review report[24] states:

> "*to the Panel's knowledge the technique has not been published in a reputable refereed scientific journal and, as such, the results must be treated with caution*".

The comment highlights the significance of science journal publication, notwithstanding its well-known limitations.

As pointed out in the July 2015 letter and December 2016 NPA report sent to the then Minister for Planning and the Department of Planning, Tammetta's 2013 Groundwater paper reports Tammetta's discovery that a knowledge of longwall extraction width (w) and extraction thickness/height (t) and mining depth (d) is sufficient to be capable of providing an estimate of the height (H) of the drainage zone (Fig. 1) to within 8%, across a range of mining geometries from subcritical to critical to supercritical (see Fig 2, 15(a) and 15(b)) and a variety of rock types comprised of:

> "*claystones, coarse-to-fine sandstones (lithic and quartzose), and limestones, in widely varying strengths, grain sizes, compositions, layer thicknesses, and recurrence patterns*".

Tammetta's discovery of a straight-line relationship involving a logarithmic function of just the three key mining geometry variables is remarkable in being relatively simple and, except where there are unusual circumstances (see Section 6.2.5), relatively indifferent to lithology and applicable across panel width to depth of cover ratios that span from subcritical to critical to supercritical (see Sections 6.2.1 and 6.2.2). The relative indifference to lithology surprised Tammetta but, as indicted in Section 1 and discussed in Section 6.2.5, he found[11], [25] only two locations for which the data deviate from the expectations of his equation; no other locations appear to have been reported.

The available information and evidence, including Tammetta's subsequent Groundwater publications, the supplementary material for the Groundwater publications, Appendix A of Tammetta's 2014 Russel Vale groundwater impact review, the December 2016 NPA report, the impacts reported in the March 2017 PSM report and the October 2017 HGEO review[26] of groundwater impacts to WC21 (see Section 24.3), argue that the equation is unlikely to be refuted. The equation may, however, at some point be relegated or subsumed in a more comprehensive equation should sufficient centreline piezometer data become available.

Early climate models were crude and of limited accuracy and precision. They were nonetheless useful and continue to evolve, becoming increasing sophisticated and powerful.

The Tammetta equation evidently captures, at the coarse-grained level of the available data, the underlying geomechanics sufficiently well (See Sections 4, 6.2.3, 11 and 14) to be able to represent the data with a straight line to within 8%. The equation accordingly offers a relatively simple and valuable means of gauging the impact of underground mining on groundwater regimes and surface waters.

It is then also remarkable that the comments on the Tammetta equation provided in the PSM report and the Mackie and Galvin reviews of that report are overwhelmingly negative; none find or consider merit in Tammetta's science journal published work. None accept, recognise or consider the possibility that the equation, a hydrological equation obtained from hydrological data, sufficiently captures geomechanics to allow at least a first pass estimate of the height of the drainage zone. None seek to consider or explore a geomechanical basis for Tammetta's discovery. On the contrary, Sullivan, Swarbrick, Mackie and Galvin effectively dismiss Tammetta's work. In being based on opinion, rather than data or other evidence, the manner of this dismissal is unscientific. Their comments are suggestive of a fixed pre-determined view and, discussed within, appear to be uninformed by significant aspects of Tammetta's work and its context.

In contrast, Prof. Galvin's 2016 book on coal mine engineering recognises the value of empirical equations, in enabling at least first pass estimates of measurable variables. The book includes several examples of equations that do not explicitly represent the underlying geology and geomechanics, including the Tammetta equation (the Ditton-Merrick equations are not mentioned), and none appear to be characterised as unscientific (see Section 6.3).

Recognition of the merits and significance of Tammetta's work is provided by its publication, three times, in Groundwater. Of note the journal's editor at the time of the publication of his 2013 paper was Professor Colin Booth. Now retired, Prof, Booth has been a pioneer in the study of the impact of coal mining on groundwater and surface waters. At the end of his 2013 paper Tammetta acknowledges constructive comments made by Prof. Booth, journal editor and hydrogeologist Dr Thomas Missimer and two anonymous referees.

No constructive comments are offered in the PSM, Mackie or Galvin reports; this is remarkable given the relevance of the Tammetta equation to the Schedule 1 Special Areas. The overwhelmingly negative nature of the comments of the PSM, Mackie and Galvin reports might have been balanced by acknowledging the originality of Tammetta's utilisation of centreline piezometer data, the beneficial aspects of the simplicity of his two zone hydrological model, acknowledging the resourcefulness exercised in gathering data from around the world, recognition of the range of lithologies and void geometries represented in Tammetta's database, consideration of the possibility and implications of Tammetta's interpretation of the data being correct, recognising the understanding displayed in Tammetta's careful data assessment and assembling appropriate databases, recognition that to date no contradictory data have been reported, highlighting the need for further centreline data, recognition of the geomechanical context provided in the supplementary material published with Tammetta's papers and in material provided to the Department of Planning, and exploring a geomechanical basis for the equation's limited sensitivity to lithology.

In the absence of confirmed contradictory data or unequivocal demonstration of fault in Tammetta's primary database, opinion or arguments of principle would not give sufficient cause for the editors of Groundwater to withdraw Tammetta's papers. In the absence of refutation, to the standard of science journal publication, there appears to be no scientific basis for suggesting other than that the Tammetta equation provides a simple, model independent, scientifically credible and valid representation of the available centreline piezometer data. It would be irresponsible not to heed its estimates of the height of the drainage zones over existing and proposed extractions in the Schedule 1 Special Areas.

3. Criticism of Tammetta in the journal Groundwater and other forums

Prof. Galvin advises in his summary and explanation report that "*Aspects of the Tammetta equation have been questioned by some in the peer reviewed journal in which it was first published in 2013 and in other forums.*" There appears to be only one comment piece published in the journal that questions Tammetta's work and that's by geotechnical engineer Dr Philip Pells[27], a now retired founding principal of PSM (his son is now a principal hydrologist with PSM). Dr Pells' comment is published in the May 2014 issue of the journal and, not mentioned by Prof. Galvin, Tammetta provides a comprehensive, informative (see Section 5) and compelling reply[28] in the same issue.

Prof. Galvin doesn't specify or otherwise elaborate on the "*other forums*". Tammetta comprehensively and informatively addresses public domain criticism (see also Section 4) in Appendix A of a September 2014 review[25], commissioned by the Department of Planning, of groundwater impacts for the proposed expansion of the Russell Vale Colliery. His detailed response highlights the role anomalously high horizontal stress may have in delaying the formation of the collapse zone (see Section 6.2.5). This is not discussed or mentioned by Prof. Galvin.

Also not mentioned by Prof Galvin, nor by Swarbrick, Sullivan and Mackie, is Dr Mackie's 2014 suggestion[27] in the journal Groundwater for a simplification of the Tammetta equation. As noted in Section 1, Dr Mackie suggests:

> "*The paper by Tammetta provides a useful empirical equation for predicting the height of complete drainage above longwall panels. Prior to this research effort, predictions in Australian coalfields often relied upon simple relationships*."

In obtaining his simplified equation, a monomial product of just the extraction width and height, Mackie evidently uses the Tammetta database content given in the supplementary material published with his 2013 Groundwater paper. Discussed in Section 6.2.3, Tammetta's reply suggests that overburden depth is required in implicitly capturing, to a first approximation, the role of stress in the underlying geomechanics.

4. Identification of the primary variables determining the height of the drainage zone

In his review of the PSM report[3], Prof. Gavin provides the following observation:

> "*in most instances in ground engineering for underground mining, it is not possible or practical to perform a sufficient number of experiments or to analyse a real engineering problem exhaustively in terms of all possible variables in order to obtain quantitative general solutions. This is addressed by adopting a scientific approach to empirical research that is focussed on only investigating the effects of the most important or primary variables*."

Mills[22], [29]–[31] and Tammetta[11] identify a zone of relatively large downward movement of rock towards and into the void created by the extraction of coal, that has a boundary shape essentially that of an inverted paraboloid (see Figs. 16 to and 20). Mills refers to this zone as Zone 2 of a six-zone model (See Fig 22) that reflects surface subsidence measurements, camera observations, packer testing, piezometer data, micro-seismic data, extensometer monitoring, and stress change monitoring. Tammetta refers to the zone as the collapsed zone and, in analysing an extensometer database he assembled from 21 sites around the world, finds that its height essentially coincides with that of the drainage zone (H):

"*A close relationship is apparent between the empirical equation for H derived from hydraulic head measurements, and the height where a large change in downward movement occurs. Given the equivalence between the two independent data bases, H is taken as being equal to the top of the zone of large downward movement. The desaturated zone and the zone of large downward movement are considered to be coincident.*"

Illustrated in Fig. 24 below, Tammetta locates the apex of the collapsed zone as a change in slope of a graph of centreline extensometer data, while that of the drainage zone is located between the shallowest centreline piezometer reporting a zero hydraulic pressure head and the deepest reporting a non-zero hydraulic pressure head.

Implicit in the overlapping and complementary geomechanical accounts of the response of the rock over and around a coal extraction provided by Galvin[18] (Section 6.2.1), Tammetta[32], [33] (Section 14) and Mills[34] is that the height of the collapsed zone is determined by the height at which a stable pressure arch (see Figs. 11 and 17) forms over the extraction. Step-wise pressure arch formation is suggested by the 'torn-edge' evident in the photograph shown in Figure 17 below and Tammetta's summary of the collapse process (Section 14). The geomechanical accounts provided by Galvin, Tammetta, Mills and others suggest the height of the pressure arch will be determined by the extraction geometry (extraction width, extraction height/thickness and overburden depth/height), geology and horizontal stresses.

4.1 Geology

In part, Appendix A of the September 2014 Department of Planning commissioned review of groundwater impacts for the proposed expansion of the Russell Vale Colliery, is a response to an assertion by consultancy Geoterra that the Tammetta equation assumes geology has a minor role in the formation of the drainage zone:

"*The Geoterra report (page 52) discusses the results of Tammetta (2013) (referencing the digital version of Tammetta 2013, dated 2012, which is identical to Tammetta 2013) and states that the "assumption" that the geology of the overburden strata plays a minor role in caving is questionable (referring to a personal communication from Seedsman RW, page 52). In Tammetta (2013) an analysis of piezometer water level data from 18 locations found that for those locations, observations of the maximum height of desaturation above the panel (at centre panel), referred to as H, could be reproduced to better than 8% RMS error without requiring knowledge of the lithology of the consolidated overburden, by use of a fitted empirical equation. Tammetta (2013) noted that this had been observed by other researchers in the literature. The finding is not an assumption, as stated in the Geoterra report, but is a result (of the analysis that relates to H over centre panel). Tammetta (2013) discussed super-strong dolerite sills in South Africa which showed H slightly lower than calculated using the equation. Despite a thorough search of the literature, no other published data could be found to show significant deviations from the equation.*"

That is, except in the unusual circumstances identified by Tammetta (Section 6.2.5) and on the basis of the available data, the Tammetta equation effectively demonstrates that geology plays no more than a secondary role in determining the height of the drainage zone. Tammetta's 2013 Groundwater paper reports that the key variables determining the height of the drainage zone were established in exploring the characteristics of the centreline piezometer data compiled from an exhaustive search of available reports from around the world.

Notwithstanding the publication of Tammetta's work in Groundwater, Prof. Galvin evidently does not accept Tammetta's published finding that geology has no more than a secondary role in determining the height of the drainage zone. This is demonstrated in several comments, including the following from his June 2017 summary and explanation report:

> "*the effects of mining on the subsurface and surface are governed primarily by the physical and mechanical properties of the geology, the ratio of excavation width, W, to the depth of the excavation, H (that is, by the W/H ratio), and by mining height, h*"

And:

> "*the equation was derived by simply drawing a line of best fit through a range of data points (each with its own considerable error band) without having any regard to geology or to the mechanics of rock behaviour*."

And, referring to Tammetta's equation and the Ditton-Merrick equations in his February 2017 PSM review:

> "*Neither can be correct because neither properly and adequately accounts for geology, the mechanics of rock behaviour and time dependent hydrogeology processes*."

Prof. Galvin's concerns are discussed in Section 6 and Section 8. Of note, Prof. Galvin's provides no data or direct evidence demonstrating a need to explicitly incorporate geology and geomechanics. As discussed in Section 6.2.5, in expressing his opinion, Prof. Galvin refers to the geology dependence of the characteristic subsidence curves given in Whittaker and Reddish's 1989 book on coal mine subsidence (see Fig. 8). Not noted however, is that the central set of curves are represented in Tammetta's primary database, while those to either side represent relatively unusual settings. The character of these settings is discussed in Section 6.2.5. Differences in the mechanisms of surface subsidence and of caving and collapse are discussed in Section 6.2.1.

Tammetta was not the first to find that extraction width, extraction height/thickness and depth of cover are, in general, the key variables that determine the height of the zone where water drains freely towards the mine. In his 2013 Groundwater paper Tammetta notes consistency with 1983 observations made by Garritty in studies of inrush in the Durham Coalfield in Britain.

The relative simplicity of Tammetta's equation is essentially anticipated by Gale in a 2008 report[35] for an ACARP funded study of inflows to longwall extractions:

> "*panel width typically controls the height of fracturing, the network connectivity and conductivity of fractures is controlled by the magnitude of strain and subsidence. Panel width, depth and seam thickness influence strain and subsidence. Geological factors also have an impact. It was found that the fracture connectivity was greater in stiff sandstone rich strata relative to strata having many coal and tuffaceous units. This was related to the ability of the overburden to flex and displace onto the goaf rather than fracture and rotate about the ribsides.*"

Tammetta's work suggests that geological factors are, in the absence of unusual circumstances (see Section 6.2.5), of no more than secondary importance. In his 2013 Groundwater paper Tammetta suggests that geology would primarily be expressed at the apex of the drainage zone:

“*Most of the uncertainty probably occurs at the apex of the desaturated zone, where the zone is thin (see the following) and variations in rock strength and fracture populations will affect bridging widths*.”

4.2 Mining height

A 2014 knowledge report[21] prepared for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining by Tammetta, includes a history of the study and evolving understanding of surface and subsurface changes caused by coal extraction. Tammetta notes that the identification of a paraboloidal or dome like “zone of falling” in 1882 by Rziha and mechanical aspects recorded by Fayol in 1885 are close to the current understanding of the mechanics of subsurface collapse.

Tammetta suggests that early attempts to understand caving, collapse and surface subsidence incorrectly focussed on the ‘bulking’ effect of the broken rock that falls and piles in the void left by coal extraction. Bulking was seen as the principal factor controlling the extent of caving and vertical dilation of the overburden and, accordingly, extraction height was believed to be the determining variable. Tammetta notes that in 1953 Grond pointed out this approach was defective in not taking the width of the extraction into account and would not have universal application. Tammetta then notes that in 1972 Kapp and Williams suggested that the height of the disturbed zone above a coal extraction is approximately equal to the extraction width.

4.3 Mining width

Tammetta highlights the importance of extraction width in noting earlier work in his comprehensive reply[28] to critical comments[27] made by Dr Philip Pells in Groundwater (see also Section 5):

“*Another example of an empirical approach is the derivation by Singh and Kendorski (1981) for the height of the water-conducting fissured zone above caved longwall panels. Unfortunately, this relationship omitted the critical independent variable w, and so poorly reproduces observations from wider panels (Tammetta 2013). However, the dataset of entities used by Singh and Kendorski (1981) had little variation in w at the time, so the effect of w was masked. It is only recently that w has increased significantly in mining worldwide, allowing more detailed identification of the governing processes.*”

Figure 9 in Tammetta’s 2013 Groundwater paper compares the effectiveness of his empirical equation with earlier endeavours.

Discussed in Section 11, Tammetta’s work may be regarded as building on the work of Gale and Mills. This is, in effect, implied in Prof. Galvin’s 2016 book on coal mine engineering, where the summary of the works of Gale and Mills is followed by a summary of Tammetta’s work (Ditton’s work is not mentioned in the book). Mills identifies six overburden impact zones (see Fig. 22) above a coal extraction and in this model Zone 2 is a zone of significant downward movement and fracturing of the overburden. Mills finds that, for the mining geometries studied, the height of Zone 2 approximately corresponds to the extraction width[29]:

“*field observations indicate that the height of Zone 2 is equal to about the panel width in most geological settings*”

Mills concludes[29] that groundwater depressurisation in this zone is likely. As discussed in Section 11, a 2006 study[36] by Gale finds that surface water inflow occurs when the width to depth ratio is greater than 1. Gale characterises a ratio of 0.75 as transitional, with seam to surface connection increasingly likely above that value.

In the detailed summary of caving and subsidence included in his 2014 knowledge report[21] prepared for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, Tammetta notes that others had also found that the height of significant disturbance over a coal extraction corresponded approximately to the width of the extraction:

> "*Reynolds (1977) observed significant fracturing to a height above the mining horizon of slightly less than the panel width*."

And:

> "*Byrnes (1999) reported interconnected fracturing to a height approximately equal to panel width. These reported zones correlate closely with zone 2*."

Where zone 2 is a reference to Zone 2 of Mills' six zone model (Fig. 22 and Section 11). Tammetta refers to the zone of relatively large downward movement as the collapsed zone (Section 14).

Highlighting the role of width, Tammetta's 2013 paper notes that in India limiting the drainage zone height to extraction width ratio to between 1 and 1.5, based on physical models, limited in-rush problems. The same ratio was likewise found for the Wistow Colliery in Britain. Both observations are in accord with the 2006 study[36] by Gale noted above, that found panels with a width to depth ratio greater than one typically resulted in inflow's arising from seam to surface hydraulic connections (see Section 11 and Fig. 23).

In his first Groundwater paper Tammetta finds, from an extensometer database of 21 worldwide locations, that the zone of significant downward movement, the collapsed zone, appears to correspond to the drainage zone:

> "*A close relationship is apparent between the empirical equation for H derived from hydraulic head measurements, and the height where a large change in downward movement occurs. Given the equivalence between the two independent data bases, H is taken as being equal to the top of the zone of large downward movement. The desaturated zone and the zone of large downward movement are considered to be coincident. Extensometer results have a larger scatter than hydraulic head results, because of the more chaotic nature of seismic energy release and the disproportionate effects of localized, unrepresentative defects or structural features*."

Mills' rule of thumb is then an over-simplification. For modest extraction heights/thicknesses, consistent with the work of Mills, the Tammetta equation finds that the height of the drainage zone corresponds to the mining width; this is evident in Figures 14(a), 14(b) and Figs. 6(a) to 6(c) below. These graphs illustrate the variation of the drainage zone height with extraction width, height/thickness and depth of cover. These graphs also find that the Mills rule of thumb may underestimate the height of the drainage zone for aggressive extractions of the kind used at Dendrobium (Section 4.5).

4.4 Mining depth – and the Mackie equation

Though the Tammetta equation is itself surprisingly simple, as noted in Section 3 Mackie provides the following comment as a preface to suggesting a simplification of the Tammetta equation:

> "*The paper by Tammetta provides a useful empirical equation for predicting the height of complete drainage above longwall panels. Prior to this research effort, predictions in Australian coalfields often relied upon simple relationships*."

Mackie discards extraction depth as a variable, with the following explanation:

> "*The depth of cover could arguably be viewed as the least important variable in Tammetta's equation because it does not directly contribute to the mined void that initiates subsidence and strata cracking*."

He then uses Tammetta's primary database to fit a simple monomial containing just extraction width (w) and height/thickness (t), as a means of estimating the drainage zone height (H):

$$H = 0.11 \times w^{1.1} \times t^{1.4}$$

Figure 4 below, from Mackie's Groundwater contribution, shows that this simple equation fits Tammetta's data remarkably well, with a high correlation (coefficient of determination = 0. 92, compared to 0.93 for Tammetta's equation) and low fitting error (root mean square error = 8%[37], compared to 7.3% for Tammetta's equation).

Nonetheless, as noted in Section 6.2.3, Tammetta provides the following caution:

> "*Simplification of the equation in Tammetta (2013), by eliminating d, is discouraged, as the role played by d in the equation of Tammetta (2013) is believed to incorporate the significant effect of high horizontal stresses in the upper crust*."

Manifesting the Poisson effect[18] and adding to tectonic stresses, horizontal stress increases with depth as a fraction of the vertical stress imposed by the weight of the overburden (lithostatic stress). Discussed in Section 6.2.1, loss of confinement results in the redirection of vertical stress to the sides of the extraction. The formation of the collapsed zone, characterised as a zone of relatively large downward movement (see Section 14), is then driven by horizontal compression, tensile failure and gravity. That is, the formation of the collapsed zone would be expected to have a degree of depth dependence.

The need to include depth as a variable is suggested in Figures 5(a) and 5(b), which graph Tammetta, Mackie and Mills drainage zone height estimates with respect to extraction depth, for extraction heights of 3, 4, 4.5 and 6 metres and widths of 300 and 150 metres respectively. An extraction width of 300 metres corresponds to the width used in Dendrobium Area 3B, while a width of 150 metres is much the same as that used at the Metropolitan Colliery.

4.5 The primary variables and the Metropolitan and Dendrobium coal mines

Figures 6(a) to 6(c) below graph Tammetta, Mackie and Mills drainage zone height estimates with respect to extraction width, for extraction heights of 3, 4, 4.5 and 6 metres at depths of 200, 300 and 400 metres. Figure 6(c) finds that at a depth of 400 metres and an extraction height of 3.0 metres, the Tammetta, Mackie and Mills drainage zone height estimates are very similar, up to the point of intersection with the surface. The Tammetta and Mackie estimates are slightly lower than those of the Mills estimate.

A mining depth of 400 metres is similar to the mining depth at Dendrobium Area 3B and somewhat shallower than the Longwall 23 to 302 depths at the Metropolitan Colliery (420 to 500 metres), An extraction height of 3.0 metres is similar to the 2.8 to 3.2 metres used at the Metropolitan Colliery, whereas extraction heights in Dendrobium Area 3B range from 3.7 to 4.5 metres.

Figure 6(c) shows that for a depth of cover of 400 metres the Tammetta and Mackie estimates remain very similar at greater extraction heights and both increasingly rise above the extraction height independent Mills estimate. Reflecting the influence of the Tammetta equation's representation of depth, depth is absent from Mackie's equation, a comparison of Figures 6(a), 6(b) and 6(c) finds that the Mackie estimate increases above that of the Tammetta estimate as the depth of cover reduces.

Figure 4(a) demonstrates that for an extraction width of 300 metres, the Tammetta, Mackie and Mills drainage zone height estimates converge with increasing depth. Figure 4(b) shows, however, that this is not the case for an extraction width of 150 metres. At shallow depths the Tammetta estimates are lower than the Mackie estimates, however as depth increases the estimate approach and rise above the Mackie estimates.

Figure 4(b) suggests that the Tammetta and Mills estimates are much the same for the geometry of the Longwall 23 to 303 extractions at Metropolitan, whereas the Mackie estimate is lower. The modest nature of the mining is reflected in the low drainage zone height relative to the mining depth.

Replacing past use of the Ditton-Merrick equations by HydroSimulations in providing groundwater impact assessments for the Dendrobium mine, a HGEO report of October 2017 uses Mills' rule of thumb in gauging the height of the drainage zone in the vicinity of Wongawilli Creek tributary WC21. The Tammetta equation warns in Figure 6(c), that while the rule of thumb would be applicable for 3.0 metre cutting heights, it would significantly under estimate the drainage zone heights for the 3.7 to 4.5 metre cutting heights used in Area 3B. That is, the Tammetta equation warns that Mill's rule of thumb fails for the notably aggressive mining approved and carried out at Dendrobium.

Perhaps recognising this, HydroSimulations use the Tammetta equation in their March 2018 groundwater modelling in support of the proposed mining of Dendrobium Longwalls 14, 15 and 16. This is noteworthy, given their past endeavours to discredit the Tammetta equation, some of which are discussed in the December 2016 NPA report.[17]

5. Tammetta's composite variable and scientific determination of his equation

Tammetta's 2013 Groundwater paper reports that the formulation of his equation was facilitated with the introduction of a composite variable (u) containing the key mining parameters (width w, extraction height/thickness t and depth of cover d). The introduction of the composite variable was prompted by the discovery that plotting the ratio (H/w) of the height of the observed drainage zone (H) to the extraction width (w) with respect to the extraction thickness (t) for the extractions represented in centreline piezometer database suggested a simple relationship (Figure 7(a) below and Figure 3a in his 2013 paper) between these variables. As noted earlier, Tammetta comments on the discovery in his 2013 paper: "*The strength of the relationship is remarkable given the diverse range of lithologies and void geometries present*". This is not mentioned in the PSM, Mackie or Galvin reports. Importantly, as noted earlier, discussed below and pointed out in the December 2016 NPA report, the range of void geometries in the underpinning database spans from subcritical to critical to supercritical (Figs. 2 and 15(a) and 15(b)). Again, this is not mentioned in the PSM, Mackie or Galvin reports.

Remarkably, not acknowledged in any of the reports, Tammetta then obtained a form of the composite parameter that suggested a linear relationship between the height (H) of the drainage zone and a logarithmic function of the composite parameter (u). Computational fitting of the two parameters that define a straight line (slope and intercept), to the data (H and u) then gave the final form of the Tammetta equation. Surprisingly, given the range of lithologies and mining geometries, the root mean square error in the fit between the data and the equation is just 7.3% (not 9.8% as suggested in the PSM report; the consultants appear to be referring to Tammetta's initial exploration with an exponential integral function).

In replying to critical comments made Dr Philip Pells in the journal Groundwater, a now retired founding member of consultancy PSM, Tammetta makes the following comments:

> "*Pells (2014) states that there is no physical basis for the u parameter in Tammetta (2013), and that it is mathematically inappropriate to combine independent variables. This is incorrect. Empirical models are based entirely on observation. The selection of independent variables for an empirical model is completely arbitrary, and there are no limitations imposed on input formulation. The variables can comprise any physical characteristic(s) of an entity. The physical characteristic(s) of one entity must not have been influenced by another entity in the group, but only by a common governing process (or processes) acting on each entity. The choice of dependent variable(s) is also completely arbitrary. However, the validity of an empirical model depends entirely on a statistically valid reproduction of the defined dependent variable(s), using the defined independent variable(s). This can only be achieved by a judicious choice of variables, and observance of the logic of cause and effect. Identification of independent and dependent characteristics of the entities in a system is obvious in most, but not all, cases in scientific endeavor. A valid empirical model, therefore, is ultimately enslaved to the unknown number of governing processes that define the relationship between entities in a dataset*."

Tammetta finds, scientifically, that the three key mining parameters are sufficient to mathematically reproduce his primary drainage zone height data to within 8%, with the exception of unusual circumstances identified by Tammetta (see Section 6.2.5). To date, this has not been refuted.

Tammetta's Groundwater papers, their supplementary material and material provided to the Department of Planning make it clear that Tammetta's work satisfies Prof. Galvin's requirement of a "*scientific approach to empirical research that is focussed on only investigating the effects of the most important or primary variables.*"[3], [18] Importantly, it satisfied the requirements of peer reviewed publication in the highly regarded science journal Groundwater.

6. Prof. Galvin's advice that the Tammetta equation is neither sound, robust nor scientific

Prof. Galvin characterises Tammetta's equation as being neither sound nor robust, in being an equation that:

(i) "*was derived by simply drawing a line of best fit through a range of data points*" and
(ii) was derived "*without having any regard to geology or to the mechanics of rock behaviour*"

Taken from his 2016 book on coal mine engineering, Prof. Galvin also provides the following comments on empirical equations in his review of the PSM report:

> "*Empirical approaches which disregard the mechanics of behaviour and, instead, rely on subjecting databases to simple statistical correlations such as linear regression are not scientific, regardless of the effort and care that has gone into collecting and plotting the data*."

In dismissively trivialising Tammetta's work as 'simply drawing a line' without regard for geology or geomechanics, Galvin's comments accordingly characterise Tammetta's work as unscientific. These comments are incorrect, highly misleading and do Tammetta a considerable professional disservice. Prof. Galvin's comments appear to be uninformed by the knowledge report[21] prepared by Tammetta for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, the supplementary material for his 2013 and 2015 Groundwater papers and Appendix A of the 2014 Russell Vale groundwater impact assessment[25] commissioned by the Department of Planning.

Prof. Galvin's states[18] that the development of a sound empirical equation requires "*a scientific approach to empirical research that is focussed on only investigating the effects of the most important or primary variables*". Effectively extending the work of Gale and Mills before him (Section 11), Tammetta finds that the primary variables are the extraction width, extraction height/thickness and depth of cover (Sections 4 and 5).

In reviewing empirical design in mining ground control, Christopher observes;

> "*Salamon wrote that empirical methods were a "very powerful, and to an engineer, very satisfying technique to solve strata control problems. . .the main advantage of this approach is its firm links to actual experience. Thus, if it is judiciously applied, it can hardly result in a totally wrong answer". Salamon did, however, caution that the developer of an empirical method must start with "a reasonably clear understanding of the physical phenomenon in question. This is a feature which distinguishes it from ordinary regression used in statistics"*".

In his 2016 coal mine engineering book Prof. Galvin also refers to the late Prof. Salamon, who was a highly distinguished pioneer of rock mechanics and mine engineering and a visiting academic at UNSW. In his PSM review comments Prof. Galvin quotes from his 2016 book on coal mine engineering in referring to University of New South Wales colleague Suorineni[38];

> "*To properly use empirical methods, one must understand the underlying assumptions and the databases used for their development (Suorineni, 2014). Given this and a reasonably clear understanding of the underlying physical phenomenon, empirical models can form the bases of valuable design tools*."

Tammetta's papers[11]–[13], their accompanying supplementary material[32], [39], replies to comments made by Pells[28] and Mackie[37] in Groundwater, Appendix A of the 2014 Russell Vale groundwater impact assessment[25] commissioned by the Department of Planning (se Section 14) and his account of subsidence in his 2014 knowledge report[21] for the Commonwealth Interim

Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, make it clear that Tammetta has a deep knowledge and understanding of the geomechanics of subsidence, understands the importance of properly constructed databases (described in the December 2016 NPA report), identifies the important variables, recognises limitations the limitations of the available data and understands the geomechanical context and assumptions underlying his equation.

Perhaps unaware of the material, the PSM, Mackie and Galvin reports do not discuss or mention the supplementary material published with Tammetta's papers, nor the replies to Pells and Mackie, nor Appendix A of the 2014 Russell Vale groundwater impact assessment and nor the 2014 knowledge report.

With cautions discussed in Section 6.2.5, in his 2016 book Prof Galvin makes the following observation:

> "*Empirically deduced models of sub-surface behaviour zones are very useful for conceptualising the development of subsidence effects and their impacts and, in many cases, may prove to be quite accurate predictors*."

6.1 Tammetta simply drew a line of best fit through a range of data points

Prof. Galvin's characterisation of Tammetta's work as "*simply drawing a line of best fit through a range of data points*" is highly misleading. A particularly troubling aspect of this dismissive and diminishing misrepresentation is that it's made in Galvin's summary and explanation document[4] that's presumably intended for a general audience. Prof. Galvin's trivialisation neither correctly nor reasonably represents Tammetta's work and is unhelpful in an explanatory document intended for a non-scientific/non-technical audience.

Tammetta discovered a linear relationship on introducing a composite variable (u) that comprised of a product of powers of the key mining parameters; extraction width, thickness/height and depth (w, t and d). The linear relationship then being exposed by a logarithmic function of the composite variable. Prior to adopting a logarithmic function, prompted by the data, Tammetta had explored an exponential integral function.

That there might be such a relatively simple relationship is remarkable and this is marked by the publication of Tammetta's work in Groundwater. The significance of leading journal publication as the measure of scientific credibility is recognised in the BSO PAC review quote given in Section 2; Prof. Galvin was a member of the panel that undertook that review.

The discovery made by Tammetta could have been made at any point since at least 2007, when the possibility is effectively suggested explicitly in a discussion report[40] on subsidence MSEC:

> "*The effect of mining geometry on the heights of the collapse and fractured zones is not well documented. Theory would suggest that the height of the collapse zone would be directly related to the width of the extraction, the height of extraction, the depth of cover and the nature of the rocks in the overburden*."

Tammetta appears to have been the first to recognise the importance of centreline piezometer data and undertake a global search to assemble as much data as possible.

Tammetta finds that in general there is no need to explicitly include geology or geomechanics (see Section 6.2.5). As discussed in Section 11, the possibility of a relationship of the kind discovered by Tammetta was also anticipated by Gale, whose work is summarised in Prof. Galvin's 2016 book on coal mine engineering:

> "*Gale (2008) also concluded from the modelling that while panel width typically controlled the height of fracturing, the network connectivity and conductivity of fractures was controlled by the magnitude of strain and vertical surface displacement as determined by panel width, panel depth and seam thickness*."

Four years later, in preparing the Coffey groundwater impact assessment for Area 3B of the Dendrobium mine, Tammetta found a linear relationship between the drainage zone height, obtained from centre-line piezometer data, and a logarithmic function of a composite variable embodying the key mining parameters; extraction width, thickness/height and depth. Tammetta also identified unusual geological circumstances where his equation might fail (Section 6.2.5).

As noted in Section 2, in suggesting a simpler equation in a November 2014 comment piece[41] published in Groundwater, Dr Colin Mackie makes the following comment:

> "*The paper by Tammetta provides a useful empirical equation for predicting the height of complete drainage above longwall panels. Prior to this research effort, predictions in Australian coalfields often relied upon simple relationships*."

In contrast, without providing contradictory data or finding fault with the underpinning database, Galvin instead flippantly dismisses Tammetta's discovery. While the Tammetta equation is relatively simple in character, it was not found by "*simply drawing a line of best fit through a range of data points*". The seemingly unlikely possibility of a linear relationship was exposed, not imposed, by a logarithmic function found in a scientific manner by Tammetta.

6.2 Tammetta disregards geology and geomechanics

Prof. Galvin's assessment that the Tammetta equation is neither robust, sound nor scientific is evidently centred on a concern that it lacks "*any regard to geology or to the mechanics of rock behaviour*".[4] Yet, on the basis of the available data and in the absence of contradictory data, it would appear that Tammetta has scientifically demonstrated that, to within 8% across the variety of rock types and void parameters represented in his primary database, there is no need to explicitly incorporate geology and the mechanics of rock behaviour in his equation. Tammetta expresses surprise in his 2013 Groundwater paper, commenting that "*The strength of the relationship is remarkable given the diverse range of lithologies and void geometries present*".[11] As noted above, in a September 2014 Russell Vale impact assessment report[25] commissioned by the Department, Tammetta comments "*Despite a thorough search of the literature, no other published data could be found to show significant deviations from the equation*". The exception referred to in the quote is that of a massive dolerite formation found in South Africa, which is discussed in Section 6.2.5.

Galvin provides no data or evidence to contradict or refute Tammetta's work and nor does he review Tammetta's databases. Instead he offers a geotechnical argument that explicit representation of geology and geomechanics is needed; no direct demonstration of need is provided. Science neither rests nor progresses on opinion or arguments of principle; it is supported and driven by data, evidence, analysis, peer reviewed journal publication and peer reviewed refutation. Opinion or arguments of principle would not be sufficient cause for the editors of Groundwater to withdraw Tammetta's papers.

In expressing his concern, Prof. Galvin refers to a graph (Fig. 8 below) from the 1989 book[42] on subsidence by Whittaker and Reddish. The graph illustrates variability in the extent of *surface* subsidence, relative to extraction height (or thickness), for a given extraction width to extraction depth ratio. This variability is attributed[4], [18] to location specific geology and geomechanics. Though Prof. Galvin's comments might suggest otherwise, Tammetta is clearly well aware of these effects and their well-known graphical representation. This is evident for example in the description of subsidence included in a 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, prepared by Tammetta. Figure 9(a) below is Figure 5.4 from the 2014 knowledge report (essentially the same graph appears in 2011[22] and 2012[29] conference papers by Mills). Figure 10 is Figure 39 from the November 2012 revised data analysis[10] for the Coffey Geotechnics groundwater impact assessment for the then proposed mining in Area 3B of the Dendrobium mine; the assessment was undertaken by Tammetta on behalf of Coffey Geotechnics. The quote given in Section 6.3 further illustrates Tammetta's awareness of the significance of the characteristic subsidence curve.

Tammetta's work finds that the location dependent sensitivity evident in the Whittaker and Reddish surface subsidence curves highlighted by Prof. Galvin, is not manifested in the height of the drainage zone, to within 8% of that height, over the wide range of lithologies represented in his primary database. The Whittaker and Reddish curves are discussed in Section 6.2.4.

The Tammetta equation is a hydrological equation; its prediction is hydrological and it was obtained exclusively from data provided by hydrological instruments (piezometers) installed over the centreline of a longwall coal extraction. In focussing on identifying the highest point at which piezometers report no water pressure, it side steps the distraction and confusion inherent in attempting to characterise fracture types and densities.

The available evidence suggests that the Tammetta equation implicitly captures at least coarse-grained rock behaviour and geomechanical effects across a wide range of rock types (Section 16) sufficiently to allow a drainage zone height estimate to within 8%. Importantly, Tammetta's database spans subcritical, critical and supercritical extractions (see Figs. 2, 15(a) & 15(b)) and would then traverse the "*critical influence of the W/H ratio*".

6.2.1 The critical influence of the panel width to depth ratio

Prof. Galvin suggests the Tammetta equation is scientifically flawed in not explicitly incorporating geomechanics and, in particular, in not explicitly allowing for changes in the nature of overburden failure that occur with increasing mining width to depth ratios (W/H for Ditton, w/d for Tammetta). Galvin illustrates these changes in his PSM review by referring to four graphical representations of overburden response, including surface subsidence, to extraction (Figs, 1 to 4 in his PSM review; Figs 1 to 3 are respectively Figs. 3.30, 3.31 3.14, and 3.19(a) in Galvin's 2016 book on coal mine engineering). Prof. Galvin provides the following comment in his review of the PSM report:

"*the inclusion of the variables 'W' and 'H' in an equation intended to predict rock behaviour above an excavation is not sufficient to take account of the critical influence of the W/H ratio on the mechanics of behaviour of that rock mass if the data on which the equation is based relate to excavations of various width and/or depth*" (H: depth of cover; W: extraction width).

Other than in-principle argument however, Prof. Galvin does not establish or demonstrate a need to explicitly accommodate changes in the nature of overburden behaviour with increasing mining width to depth ratios, as expressed in the characteristic surface subsidence curve in particular[4], in an equation representing the currently available drainage zone height data. Tammetta's data finds no need, to within 10%.

Puzzlingly, Prof. Galvin does not distinguish the geomechanics of subsidence and spanning failure from the geomechanics of caving and the formation of the collapsed zone (zone of relatively large downward movement; Section 14). Yet the accounts given by Galvin[18], Tammetta[32], [33] and Mills and Blacka[34] suggest they are quite different.

Figure 3.3 in Prof. Galvin's book illustrates (Fig. 11 below) that 'loss of confinement' on the removal of coal results in the redirection of vertical stress to the sides of the extraction, as it dilates, sags, fractures, spalls and fails as a consequence of tensile stress (stretching and shear) arising from horizontal compression. Prof Galvin comments in his book of 2016:

"*The strata within the pressure arch effectively constitute a decoupled immediate roof for the excavation, being vertically destressed and loaded transversely by only its own weight and axially by lateral forces*."

In the absence of vertical stress, rock failure and spall formation are driven by horizontal compression and gravity.[18], [34] Prof. Galvin summarises[18] the determinants of vertical and horizontal stress:

"In summary, the induced vertical stresses in the immediate roof of an excavation are independent of the size and shape of the excavation and are only a function of depth of mining. The induced horizontal stresses are a function of the shape and size of the excavation, the depth of mining, and the nature and behaviour of the immediate roof, the upper roof and the coal seam."

As noted in Section 4.4, while extraction redirects the vertical stress (lithostatic; overburden weight) to the sides of the void, it fractionally contributes to the horizontal stress as a consequence of the Poisson effect. Though not explicitly noted by Prof. Galvin, this then imparts a degree of depth dependence to the horizontal stress.

The rock surrounding a coal extraction is usually sedimentary and contains bedding planes. Prof Galvin further comments:

"*bedding planes constitute potential slippage planes and can effectively divide the roof strata into an assembly of thin rock beams, thereby permitting the immediate roof to sag under its own weight. The sense of slip causes inward displacement towards the centreline of the span and decreases with height into the roof, so that there is a tendency for the beds to delaminate, or decouple, in both the immediate roof and the immediate floor. In the case of the immediate roof strata, bed separation results in a loss of load sharing with upper beds and the transfer of horizontal stress to higher horizons in the roof as shown on the right-hand half of Fig. 3.3*." (Fig. 3.3 is Fig 11 below).

In noting the role of gravity in these comments, Prof. Galvin appears to overlook explicit mention of the key role of horizontal compression in causing tensile deformation and roof failure over the extraction. Spall forming fracturing and the development of the collapsed zone (see Section 14) continues upwards until a point is reached, for subcritical extractions, where the rock no longer fails to span the extraction. Mills and Blacka comment:

> "*Above the top of the zone of fracture formation, the horizontal stresses are concentrated in the zone where the rock is yet to fail in horizontal compression*."

The apex of the collapsed zone is determined by the height at which a stable pressure arch is established. The incremental nature of the pressure arch is suggested by the 'torn edge' character of the collapsed roadway roof in Figure 19 of Whittaker and Reddish's 1989 book on coal mine subsidence (Fig. 17 below).

As noted above, Tammetta suggests that lithology may be expressed at this point:

> "*Most of the uncertainty probably occurs at the apex of the desaturated zone, where the zone is thin (see the following) and variations in rock strength and fracture populations will affect bridging widths*" (Tammetta finds that the collapsed zone, the zone of significant downward movement, coincides with the drainage zone; see Section 4.3).

Discussed in Section 4.4 and 6.2.3, Dr Mackie's suggestion that mining depth need not be included in the Tammetta equation would appear to implicitly recognise the key role of horizontal stress in the development of the collapsed zone and the more limited role of depth. However, as noted above and in Section 4.4, the Poisson effect impacts a degree of depth dependence through a fractional transfer of vertical (lithostatic) stress to horizontal stress.

Described in Prof. Galvin's 2016 book, overburden subsidence reflects compression, flexing, shear and, when the extraction width becomes supercritical, overburden bridge abutment failure and full collapse of the overburden onto the goaf. In the absence of abutment failure, complementing the upward growth of the collapsed zone, the subsiding rock above the collapsed zone arcs downwards in response to the depth dependent vertical stress of the overburden. Adding to this downward deformation, described as 'sag' subsidence, the deflection of the vertical stress from the roof of the collapsed zone to the sides of the extraction compresses the rock around the void.

Give the differences between the mechanics of subsidence and of the formation of the collapsed zone, there would appear to be no reason to expect them to have the same dependence on the width to depth ratio. On the contrary, it would seem reasonable to expect them to have quite different responses to varying width to depth ratios. In particular, the role of depth would appear to be quite different.

Referring to the characteristic surface subsidence curves compiled and presented Figure 199 of Whittaker and Reddish's 1989 book[42] on coal mine subsidence (Fig. 8 below), Prof. Galvin makes the following observation in his 2016 coal mine engineering book:

> "*The shape of curves showing panel width-to-depth ratio, W/H, plotted against vertical surface displacement for isolated panels, such as those shown in Fig. 3.14, reflect the fact that there is a transition rather than a step change between subcritical and supercritical caving behaviour*."

The database underpinning the Tammetta equation spans subcritical to supercritical width to depth ratios and a variety of rock types. To the extent that there may be need, Tammetta's work suggests that his equation sufficiently captures the apparently smooth transition in overburden behaviour (see Fig. 8) across subcritical to supercritical mining to allow drainage zone height estimates to within 10%. Prof. Galvin provides no data or evidence that would refute or challenge Tammetta's data. Tammetta's work, and that of Mills, (see Section 11) also suggests that the drainage zone can reach the surface at or before the onset of abutment failure (see Figs. 14(a), 14(b) and 6(a) to 6(c)).

The characteristic subsidence curves referred to by Galvin are further discussed in Sections 6.2.4 and 6.2.5.

6.2.2 Exceeding the limit of maximum subsidence

Prof. Galvin appears to be particularly concerned that the Tammetta equation doesn't explicitly allow for the onset of spanning failure as the critical width to depth ratio is approached. That this is a key concern is suggested by the following comment in his PSM review:

> "*As the width, W, of an excavation of fixed depth, H, is increased, a point is reached where further increases in panel width do not increase the extent of disturbance*."

He commends Ditton's equations for their recognition of "*a limiting value of W/H ratio above which the level of disturbance of the overburden does not increase*" (Ditton's flawed work is discussed in Section 7). Prof. Galvin doesn't point out that this reflects failure of the overburden to span the extraction void (see Figs. 3(a) and 3(b)), with the onset of abutment failure. Nor does Prof. Galvin point out in his PSM review or his summary report, that abutment failure would be expected to result in connected seam to surface fracturing (Fig. 3(a)). This is however briefly noted[18], albeit somewhat obliquely, in discussing abutment failure in his 2016 book on coal mine engineering:

> "*any further increase in span results in full overburden load being transmitted through the goaf to the floor of the excavation. Therefore, the daylight span should correspond to the critical span at which full surface subsidence, or vertical surface displacement, develops (ignoring additional time-dependent compaction and settlement, which typically makes up about 10 % of the final vertical displacement*).

Connected seam to surface fracturing as a consequence of abutment failure is indicated by the reference to the "daylight span" (see Figs 3(a) and 3(b)). Further mining beyond this point can not result in significant additional subsidence.

That does not necessarily mean, however, that there would be no further increase in the extent of the disturbance of the overburden. Where spanning failure results in seam to surface connected fracturing, continued collapse as mining proceeds and the width of extraction increases beyond the point of spanning failure and maximum subsidence, could result in lateral broadening of the extent of seam to surface fracturing.

Discussed in Section 7 in the context of the Ditton-Merrick equations, Prof. Galvin's concern appears to be predicated on an assumption that the drainage zone would not reach the surface before abutment failure occurred. Discussed in Section 11, Tammetta's work is consistent with that of Mills, who finds that the height of the collapsed zone, the zone of significant downward movement, is approximately equal to the height of the extraction width, for the mining geometries studied. That is, Mills' work suggests that the drainage zone would reach the surface as the point of abutment failure was approached. Tammetta's work further finds that for more aggressive mining geometries, such as those of Dendrobium Area 3B, the drainage one can reach the surface before abutment failure commences (see Figs. 14(a), 14(b) and 6(a) to 6(c)). It also suggests there are geometries, such as those at Tahmoor (Section 21), where the height of the drainage zone is less than the width of the extraction.

Increasing the mining width beyond the point that the Tammetta equation estimates that the drainage zone will reach the surface, would result in an increase in the area of the surface 'foot print' of the drainage zone. That is, while the surface physically 'caps' the maximum height of the drainage zone, the physical implication of a drainage zone height estimate that's above the surface is a corresponding area over the surface where the drainage zone intersects the surface.

This is indirectly recognised by Prof. Galvin in briefly commenting on Tammetta's work in his December 2016 review of the Subsidence Management Plan (SMP) proposed for Longwalls 14 to 18, commissioned by the Department of Planning. Prof. Galvin observes: "*As this model already predicts that the height of connective fracturing will reach the surface, the effect of increasing mining height is to increase the lateral extent of this zone of fracturing*." This would also be the case for increased mining width.

As noted above, Tammetta's database spans the range of subcritical to critical to supercritical mining parameters (see Figs. 2, 15(a) and 15(b) below). Accordingly, for conservative extractions where the Tammetta equation would not expect the drainage zone to reach the surface before abutment failure, the "*critical influence of the W/H ratio"* across the incremental subcritical to supercritical transition highlighted by Prof. Galvin (Section 6.2.1), would appear to be implicitly incorporated sufficiently to allow a drainage zone height estimate to within 10%.

6.2.3 Implicit capture of geomechanical stress

Published in the same issue of Groundwater, Tammetta's comments in reply[37] to Dr Mackie's simplified equation suggestion[41] (see Section 4.4) are noteworthy, particularly with respect to critical comments made by Prof. Galvin:

> "*Simplification of the equation in Tammetta (2013), by eliminating d, is discouraged, as the role played by d in the equation of Tammetta (2013) is believed to incorporate the significant effect of high horizontal stresses in the upper crust*."

And

> "*The logarithmic equation of Tammetta (2013) has embedded within it some part of the role played by a complex stress field in the creation of a collapsed zone of a longwall panel, via the d parameter. Removal of the d parameter would result in the confounding of the action of horizontal stress (in the physical caving process) into the remaining two parameters.*"

Tammetta's comments implicitly recognise the redirection of vertical stress to the sides of an extraction, as discussed in Chapter 3 of Prof. Galvin's 2016 book on coal mine engineering (see Fig. 11 below).

The PSM, Mackie and Galvin reports neither recognise nor consider the possibility that Tammetta's empirical equation implicitly captures the underlying geomechanics sufficiently to be capable of providing a drainage zone height estimate to within 10%. Nor do they explore or consider a geomechanical basis for Tammetta's discovery. Tammetta discusses the geomechanics in the supplementary material[32] for his 2015 Groundwater paper (Section 14). He notes that hydraulic conductivity changes

> "*are the direct result of changes to defect void space caused by the redistribution of the mined void into overlying (and underlying) strata through the process of subsidence. This is in turn dependent on the post-mining three-dimensional stress field, which is itself dependent on mining geometry and depth. Thus, at any point in the subsurface, the post-mining void space will depend on H (and A), and varies with mine void geometry and mining depth*."

Sullivan, Swarbrick, Mackie and Galvin may not have read this material.

6.2.4 Insensitivity to lithology

Implicitly suggesting an order with respect to significance, Prof. Galvin's 2017 summary and explanation report states the following:

> "*the effects of mining on the subsurface and surface are governed primarily by the physical and mechanical properties of the geology, the ratio of excavation width, W, to the depth of the excavation, H (that is, by the W/H ratio), and by mining height, h*"

Prof. Galvin's comments implicitly reject Tammetta's observation that his drainage zone height equation applies across a wide range of lithologies, without need for an explicit representation of geomechanics.

In emphasising a need to explicitly include geology and geomechanics in an equation representing the impact of a coal extraction on the overlying rock, Prof. Galvin refers to the characteristic surface subsidence curves in Figure 199 of Whittaker and Reddish's 1989 book[42] on subsidence (see Fig. 8 below; provided as Fig. 3.14 in Prof. Galvin's 2016 book, Fig. 3 in his February 2017 PSM review and Fig. 4 in in his June 2017 summary and explanation report). These curves are graphs of surface subsidence to extraction height ratios with respect to the extraction width to depth of cover ratios. Galvin's expectations with respect to width to depth of cover ratio are discussed in Section 6.2.1 and 6.2.5.

Prof. Galvin's annotation of the Whittaker and Reddish subsidence curves highlights variability as geological circumstances change with geographical location, illustrating the sensitivity of surface subsidence to geology and geomechanics. Subsidence is measurable manifestation of overburden disturbance, as is the height of the drainage zone.

Prof. Galvin's comments argue that the height of the drainage zone would have the sensitivity to geology represented in the surface subsidence curves of Whittaker and Reddish. Galvin accordingly requires explicit representation of geology in an equation representing the key variables determining the height of the drainage zone. He does not however demonstrate that the height of the drainage zone is sensitive to geology and nor does he find fault with Tammetta's data.

Tammetta finds that the drainage zone at least approximately coincides with the collapsed zone (see Section 4.3 and the Elouera example in Section 20). Tammetta and Mills (see Section 11) identify the collapsed zone as a zone of significant downward movement of rock (Fig. 2 in Tammetta's 2013 paper), with an approximately parabolic cross section.

As discussed in Section 6.2.1, the formation of the collapsed zone proceeds by a different mechanism to that of surface subsidence. Post extraction, the rock immediately over the resultant void fails under tensile stress as it deforms into the void under horizontal compression from the surrounding stress field (see Fig. 11). In the account of caving provided by Tammetta in the supplementary material for his 2015 paper, the formation of the collapsed zone and, accordingly, drainage zone progresses upwards through the strata with episodic fracturing and spall formation in response to the tensile (flexing) stresses. Bed separation and rock failure progressively transfers horizontal stress to the rock above, until this dissipation reaches a point that the rock is able to span the extraction, with the formation of a pressure arch. As noted in 6.2.1, in his first Groundwater paper Tammetta suggests that geology may become evident at the apex of the collapsed zone:

> "*Most of the uncertainty probably occurs at the apex of the desaturated zone, where the zone is thin (see the following) and variations in rock strength and fracture populations will affect bridging widths.*"

While geology would accordingly have a lesser role than that of extraction width, extraction height/thickness and depth of cover, Tammetta suggests that it may dominate the 8% uncertainty found with respect to his primary database.

Tammetta finds that the height of the drainage zone, with the two exceptions reported by him (Section 6.2.5) and a third suggested below, is primarily determined by the three key mining geometry parameters and that geology and geomechanics are of no more than secondary importance. Of note, discussed in Section 6.2.5, Tammetta finds that his equation significantly, with respect to the 8% fit for his underpinning database, underestimates the drainage zone height for extractions beneath the massive South African dolerite sills.

6.2.5 Consideration of unusual geological circumstances

In his 2016 book on coal mine engineering Prof. Galvin offers cautionary comments on empirical equations representing subsurface behaviour:

> "*Empirically deduced models of sub-surface behaviour zones are very useful for conceptualising the development of subsidence effects and their impacts and, in many cases, may prove to be quite accurate predictors. However, the end-user needs to be alert to a range of limitations associated with these models, the more important being*:
>
> *(i) None have regard to the effect of horizontal-to-vertical stress ratio on strata behaviour, even though, as evident in preceding chapters, this parameter is important when considering excavation performance. It is an important consideration because it can impact on permeability, conductivity and the formation of a constrained zone.*
>
> *(ii) None have regard to discontinuous subsidence associated with bridging strata. Should a constrained zone develop as a result of caving and fracturing being interrupted by the*

presence of a particularly competent bed that spans the excavation, extrapolation of the corresponding derived zone thicknesses to different geological settings is fraught with risk? This is complicated by the fact that the capacity for bridging is also a function of the horizontal-to-vertical stress ratio which, as noted already, is not taken into account by the models."

Prof. Galvin's cautions immediately follow his book's summary of Tammetta's work. The two potential complications overlap. In his book Galvin identifies and discusses two geological settings that evidently prompt these cautionary comments; a massive (in the geological sense) dolerite sill over a mine in South Africa and conglomerate-sandstone strata in parts of the Newcastle Coalfield. Tammetta discusses the same locations in 2013[39] and 2014[25], however Tammetta's discussion of these locations is not mentioned in either Prof. Galvin's 2016 book or his 2017 PSM reports. This suggests he was not aware that his observations echo those made by Tammetta.

As indicted in Sections 1and 4, but not noted in the PSM, Mackie or Galvin reports, Tammetta finds[11], [25] only two locations for which the data deviate from the expectations of his equation. One of these locations is the South African sill discussed by Prof. Galvin:

"*These data strongly support the derived equation for H. Only the determination for the Port Hood Mine (u = 3340 and H > 272 m) falls significantly outside its boundary. This site was at a location with steep strata dip and significant structural features. Anecdotal information suggested a downward inrush of surface water; however, an inquiry failed to identify the inrush pathway (John and Mckinnon 1947). Apart from the Port Hood Mine, only one specific location was found in the literature where the behaviour of H deviated significantly from calculations using the derived equation for H. This was a sedimentary sequence interspersed with thick massive dolerite sills in some South African coal mines. This unique location is discussed further in the on-line Supporting Information for this study. "*

Being much harder than the under- and over-lying sandstones and shales (see Fig. 12), these dolerite sills[23] form the flat-topped hills distinctive of the Karoo scenery in South Africa.

The supplementary material[39] for the paper provides a detailed discussion of these dolerite sills, for which Tammetta observes:

"*The effect of super-strong massive rock, as observed in South Africa, is unusual, and is worth exploring by analysis of field observations as a rare case where rock type is known to impact H. Sweby (1997) provides observations from several locations of continuously-sheared and pillar extraction mining underneath massive dolerite sills in South Africa. These observations are summarised in Table 1. Monitoring information comes exclusively from MPBX installations over centre panel at each location*" (MPBX is a reference to the use of extensometers).

And, referring to his Groundwater paper:

"*This is a unique situation not observed at any other location in the databases of the paper. Field measurements and theoretical studies have shown that strong dolerite sills behave like elastic plates close to the point of failure (Salamon et al., 1972, in Wagner and Schumann, 1991), a most remarkable property*."

And:

"*The results in Table 1 show that with the right conditions, maximum observed H (from extensometer movements) can be smaller than H calculated by the derived empirical equation.*

Where the sill has failed (e.g., the Springfield mine), H is very similar to the calculated value. The measurements from the Durban mine suggest that in that environment, increasing the mined height had a more significant impact on H than increasing the panel width, for the same sill."

Table 1 is reproduced below and Figure 12 is taken from Tammetta's supplementary material and depicts the strength of the dolerite sill relative to other common rock types.

Prof. Galvin discusses the effect of the South African dolerite sill on collapse and subsidence over an unnamed South African mine in his 2016 book on coal mine engineering (the mine may be one of those listed in Table 1 below). He points to the role anomalously high horizontal stress may have played in the unusual subsidence progression observed over the mine, where subsidence halts at the base of the sill before progressing through the sill in two distinct steps. As a consequence, the amount of surface subsidence is small until the onset of the final collapse:

"*It has been suggested that the behaviour may be associated with the redistribution of horizontal stress as failure progresses through the massive strata, with the increased lateral stress improving the structural stability of the remaining jointed material (Galvin 1983)*."

Prof. Galvin finds similar behaviour is associated with total extraction beneath massive conglomerate-sandstone strata in the Newcastle Coalfield. Tammetta discusses what appears to be the same setting in Appendix A of a Department of Planning commissioned 2014 groundwater impact review[25] for a proposal to expand the Russell Vale mine. The appendix is a detailed response to suggestions that the Mandalong mine in the Newcastle Coalfield demonstrates a failure of his equation.

Tammetta concludes instead that unusually high horizontal stress delayed the formation of the drainage zone, but that it eventually reached a final height consistent with the equation as this stress was relieved. He comments as follows:

"*This stress field does not eliminate caving but does retard it, creating difficulties in forecasting roof falls (Iannacchione et al. 2005). These horizontal stress magnitudes are far in excess of those commonly seen in the near surface around the world (where the horizontal stress is commonly about 2 to 3 times the vertical stress). This stress regime is a phenomenon of the near surface (from ground surface to depths nearing 1000m, depending on topographic relief). It is common in hilly terrain and is prominent in the eastern USA and eastern Australia*."

And:

"*The Teralba and Munmorah Conglomerates are frequently reported as the units which, in the Lake Macquarie area, have the capability to create spans larger than seen elsewhere, immediately after caving. The uniaxial compressive strength (UCS) of these units is unremarkable, ranging between about 40 and 80MPa (McNally 1995) (typical UCS of sandstones and shales range between 10 and 70 MPa, and rarely to 120MPa). The spanning creates a highly unstable stress state which may seek to redistribute itself at even the smallest opportunity offered by small-scale seismic activity. This is probably the main reason for the difficulty in forecasting roof falls. The area is seismically active. The horizontal stress regime likely plays a significant role in allowing transient spanning. Super-strong dolerite sills in South Africa (UCS ranging between 250 and 390MPa) are known to create larger than normal spans following caving of pillar extraction and longwall panels, however eventual failure occurs, with the same difficulty of forecasting span failure (Wagner and Schumann 1991).*"

After examining the data Tammetta concludes:

> "*The example of the Mandalong water level database highlights the necessity of undertaking adequate review of estimates made by proponents of heights of desaturation for underground mining projects, so that unrepresentative or erroneous results are not incorporated into impact assessments. Despite the anomalous stress regime near Lake Macquarie, the behaviour of the groundwater system to longwall caving accords well with results from Tammetta (2013). This will be relevant for coal developments in the southern Newcastle Coalfield.*"

Tammetta's observations are not mentioned in the PSM, Mackie or Galvin reports.

Taken from a 2014 knowledge report by Tammetta report[21] for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, Figure 9(a) below includes the effects of anomalous horizontal stress on the characteristic surface subsidence curve. Mills suggests that high horizontal stress results in an increase in the height of the height of the drainage zone. The final height at Mandalong, however, is consistent with the estimate provided by the Tammetta equation.

Prof. Galvin makes the following observations on mining beneath exceptionally strong or massive strata in his 2016 book:

> "*From an operational perspective, it is desirable to make a panel sufficiently wide to induce failure of massive strata as soon as possible after the commencement of mining. Alternatively, the panel span needs to be restricted so that caving does not occur and abutment stresses are not excessive. A situation to be avoided is where the panel span is only marginally less than the critical span, such that mining operations are subjected to high abutment stress for the operational life of a panel and prone to a small change in geology triggering the collapse of a large area of strata within the goaf. This latter situation creates the potential for the ingress of flammable and noxious gases into the workplace and for windblast.*"

Accordingly, except where mine design ignores or is unaware of this advice, the Tammetta equation may reasonably be expected to provide an informative estimate of the drainage zone height in the presence of massive or exceptionally competent strata, though attainment of that height may be unpredictably delayed. Tammetta describes[32] the intermittent nature of the collapse process in the supplementary material for his second Groundwater paper (Section 14).

As discussed in Section 6.2.4, in arguing that Tammetta's equation is unscientific in not including explicit representation of geology in his equation, Prof. Galvin refers to the surface subsidence curves in Fig 199 of Whittaker and Reddish's 1989 book on subsidence. This figure is provided in Figure 8 below, with the addition of a central yellow band intended to highlight the locations, and associated lithologies, represented in Tammetta's primary database. Centreline piezometer data for the locations beyond this band are presumably not available, given Tammetta's global search for such data.

Reference to Whittaker and Reddish's book suggests that the locations to the left of this band may represent a second lithological exception to his equation, but at the opposite end of the spectrum represented by the South African dolerite sill. Figure 13 below is Figure 50 from Whittaker and Reddish and it shows that the overburden in the Yorkshire coalfield is dominated by coal measures; in some cases it would appear to be made up entirely of coal. Referring to Figure 199 in the book (Fig.8 below), the authors provide the following observations:

“*European coalfields frequently experience maximum subsidence of the order of 90% of the extracted seam height, particularly where the cover rocks consist mainly of typical Coal Measures strata. However, increasing amounts of more massive strata such as limestones and sandstones tend to reduce the maximum amount of subsidence experienced above longwall extractions.*

Examples of different cover rock conditions are presented in Figure 199 which clearly show how subsidence arising from longwall mining differs in respect of the case history data used for various countries. The examples from India, Australia and North America have substantially stronger cover rocks, in addition to being shallower, than the European examples shown. The data for India and Australia show that the strata do not subside at low values of w/h.”

These observations are not noted by Prof. Galvin. While European coalfields may record maximum subsidence of up to 90% of the extraction height, in NSW its limited to 55 to 65% for supercritical extractions.[43] Reflecting coal being considerably weaker and more friable than sandstone and other rocks, at least in part this large difference will reflect a greater degree of compaction as the overburden settles onto the goaf. In part then, the separation in Whittaker and Reddish’s Figure 199 between the central band of lithologies represented in the Tammetta database, highlighted in yellow in Fig. 8 below, and those to the left will reflect compaction differences.

Given the considerable difference between the character of the lithology of the locations in the central band and those to the left in Whittaker and Reddish’s Figure 199 (Fig. 8 below), represented by the difference between coal and sandstone, the Tammetta equation may underestimate the height of the drainage zone in locations of the kind typified by the Yorkshire coalfields (Fig. 13 below). Given the apparent absence of data, this cannot currently be tested.

Irrespective of whether or not the lithological character represented by the Yorkshire coalfield might constitute a counterpoint to the South African dolerite sills, the sandstone dominated character of the lithology over the Dendrobium mine is represented in Tammetta’s primary database (see Section 20 and Figure 25). This is not noted in the PSM, Mackie or Galvin reports.

6.3 Tammetta’s equation is unscientific

As noted above, Prof. Galvin quotes from his 2016 book in stating the following in his February 2017 review of the PSM report:

“*Empirical approaches which disregard the mechanics of behaviour and, instead, rely on subjecting databases to simple statistical correlations such as linear regression are not scientific, regardless of the effort and care that has gone into collecting and plotting the data.*”

In his June 2017 summary and explanation report he dismissively characterises Tammetta’s work as:

“*simply drawing a line of best fit through a range of data points (each with its own considerable error band) without having any regard to geology or to the mechanics of rock behaviour*.”

Prof. Galvin’s comments at least implicitly suggest that, in not explicitly incorporating geomechanics and geology, the Tammetta equation is unscientific (the error band is discussed in Section 8.3). Galvin’s 2016 book on coal mining engineering provides examples of empirical equations that do not explicitly incorporate geomechanics or allow for local geology, including the

Tammetta equation. While the book reasonably cautions the reader in noting their known and potential limitations, none are explicitly or implicitly characterised as unscientific.

In responding in detail to criticism of his use of a composite variable by Dr Philip Pells in the journal Groundwater, Tammetta provides[28] another example of an empirical relationship:

> "*A well-known empirical relationship is presented in Holla and Barclay (2000) for predicting the magnitude of maximum surface subsidence above mined longwall panels. The derivation not only uses convolved independent variables, but also uses a dependent variable convolved with an independent variable, to form a hybrid dependent variable. The empirical model comprises a graphical correlation between w/h as the independent variable and S max/t as the hybrid dependent variable (where S max = maximum surface subsidence, t = mined thickness, w = panel width, and h = overburden thickness). The distribution of observations follows a pattern that can be validly reproduced with various mathematical functions such as the inverse tan function and has been frequently used for impact assessment by geotechnical consultants.*"

The graphical correlation Tammetta highlights is the characteristic subsidence curve that Prof. Galvin refers to in suggesting the Tammetta equation is scientifically flawed in not explicitly accommodating changes in the nature of overburden failure that occur with increasing mining width to depth ratios (Figs. 8, 9(a), 9(b) and 10 and Section 6.2.1 and 6.2.2).

Prof. Galvin's suggestion that an empirically determined relationship that lacks explicit recognition or incorporation of the underlying phenomenon is unscientific would not be shared by the science community. Science is the practice of organising and then rationalising observations of the physical world. An empirical equation specifies a testable relationship between a set of observations and one or more variables that determine those observations. Such an equation does not require a priori knowledge or explicit recognition of the underlying phenomenon (see below and Section 10). Tammetta's equation was derived entirely from hydrological data (centreline piezometer data) and estimates a hydrological observable; the height of the drainage zone. The equation does not seek to (explicitly) represent (or predict) the underlying geomechanics and, to within 8%, apparently has no need.

Tammetta's papers and their supplementary material contradict Prof. Galvin's suggestion the equation was obtained by disregarding geomechanics and thoughtlessly applying regression analysis (see also Sections 4, 5, 11 and 14). In replying to critical comments made Dr Philip Pells, a now retired founding member of consultancy PSM, Tammetta makes the following comments:

> "*the validity of an empirical model depends entirely on a statistically valid reproduction of the defined dependent variable(s), using the defined independent variable(s). This can only be achieved by a judicious choice of variables, and observance of the logic of cause and effect. Identification of independent and dependent characteristics of the entities in a system is obvious in most, but not all, cases in scientific endeavour.*"

All scientific equations, empirical or otherwise, are only as sound, robust, accurate and precise as the data from or against which they're derived and subsequently tested. Given the available data, Tammetta appears to have enacted the best possible scientific practice from limited, patchy and coarse-grained data. That he appears to have done so is recognised by the publication of his work, three times, in Groundwater. This is not recognised in the PSM, Mackie or Galvin reports.

Suggesting Tammetta's hydrological equation is inadequate in not being explicitly geomechanically comprehensive, is not dissimilar to suggesting that Kepler's laws of planetary motion should explicitly express Newton's laws of gravity or should incorporate Einstein's General Relativity. Deduced from observations, Kepler's simple but effective laws provide a description of planetary motion but provide no explanation for that motion. Nor are they able to describe the motion of the Moon around the Earth and nor do they capture the anomalous character of Mercury's orbit, for which rationalisation requires General Relativity. Yet as a first approximation 'coarse grained' representation of the dynamics of the solar system, they are remarkable. The available evidence and information suggests Tammetta has made a noteworthy and useful discovery.

As discussed in Section 4 and 5, Tammetta's work is consistent with Prof. Galvin's expectation[3], [18] of:

> "*a scientific approach to empirical research that is focussed on only investigating the effects of the most important or primary variables. Success is dependent on identifying all of these variables and having a database which contains sufficient relevant information to evaluate the influence of them (Salamon 1992b, 1993)*".

The late Prof. Miklos Salamon was a world leader and pioneer of rock mechanics and mine engineering. Tammetta's work also satisfies the requirements Prof. Galvin highlights in his 2016 book[18] and 2017 PSM review[3], where he refers to another distinguished University of New South Wales colleague, Prof. Fidelis Suorineni[38];

> "*To properly use empirical methods, one must understand the underlying assumptions and the databases used for their development (Suorineni, 2014). Given this and a reasonably clear understanding of the underlying physical phenomenon, empirical models can form the bases of valuable design tools*."

Tammetta's publications, their supplementary information and reports provided to the Department of Planning provide no support for the suggestion that he lacks understanding of the nature of his databases and the underlying geology and geomechanics.

7. Ditton's approach represents a considerable advance on that of Tammetta?

Prof. Galvin makes the following comments in his review of the PSM report:

> "*The PSM report gives no consideration to the basic differences in how the Tammetta and Ditton equations have been derived. For the record and to facilitate discussion, Ditton's approach is distinguished by having some regard to the influence of the panel width-to-depth ratio, W/H, on overburden behaviour; to the variation in failure mode with W/H ratio; and to there being a limiting value of W/H ratio above which the level of disturbance of the overburden does not increase.*
>
> *Ditton has attempted to take these factors into account by applying mechanics based on simple beam theory to derive three sets of equations, each describing a particular type of ground behaviour that has been assumed to be linked to ranges in W/H ratio (0 to 0.7, >0.7 to 1.4, >1.4).* ***In principal, the approach represents a considerable advance on that of Tammetta because of its attempted foundation in mechanics and improved conceptualisation of how the overburden may behave***." Emphasis added here.

While it captures the nature of Ditton's work, this concise summary falls short in the following respects:

(i) While they are presented in the context of abandoned efforts to obtain 'analytical' equations from the application of beam theory mechanics, Ditton's empirical equations are not themselves derived from the application of beam theory mechanics (Section 7.2).
(ii) Ditton doesn't provide three sets of drainage zone height equations describing ground behaviour across three W/H ratio ranges (Section 7.4).
(iii) Ditton's equations exclude extractions widths greater than 1.4 times the mining depth. While this recognises there is a limit to the extent of sag subsidence, determined by overburden spanning failure, it precludes recognition that the lateral spread of the drainage zone effectively increases as extraction width increases beyond the critical width (Section 7.1).
(iv) The suggestion that representation of geology and geomechanics in an empirical equation constitutes a considerable advance on the Tammetta equation, in turn suggests geomechanics is known to be an important determinant of the height of the drainage zone. Other than the unusual circumstances noted by Tammetta, to date this has not been demonstrated or established. The available centreline piezometer data, as compiled by Tammetta, suggest the contrary.

7.1 Reaching the limit of maximum subsidence

The character of the Ditton-Merrick equations is such that it does not admit drainage zone height estimates that would reach the surface. Prof. Galvin commends Ditton's equations for their recognition of "*a limiting value of W/H ratio above which the level of disturbance of the overburden does not increase*". The comment is implicitly predicated on an assumption that the drainage zone would not reach the surface before this limiting value, the critical width at which overburden spanning fails (see Fig. 3(a) and 3(b)), is reached.

Tammetta's work suggests, however, that the drainage zone can reach the surface before or as spanning failure (abutment failure) commences (see Figs. 14(a), 14(b), 6(a) to 6(c) and Section 11). The available evidence suggests that this is the case (Section 24) in Area 3B of the Dendrobium mine.

Discussed in Sections 4.3 and 11, Mills finds that, for the extractions studied, the height of Zone 2 of his six-zone model of overburden disturbance corresponds approximately to the width of the extraction. Zone 2 is identified as the zone of relatively large downward movement of the subsurface over an extraction. Tammetta refers to this zone as the collapsed zone and he finds that the zone corresponds to the drainage zone. Mills' rule of thumb then suggests that the drainage zone would reach the surface as spanning failure begins to occur. The work of Mills and Tammetta then suggests there is no need to impose a limiting W/H value; the ground surface caps the drainage zone.

A key concern with Ditton's equations, noted by the NPA, WaterNSW and Prof. Galvin, is that their mathematical character is such that their drainage zone height estimates are notably insensitive to increases in extraction width and height (see Fig. 14(a) and 14(b)). As a consequence, the imposed height estimate limit for which Prof. Galvin commends Ditton is such that the equation's estimates are capped well below the distance from the extraction to the surface (see Fig. 14(b)). This is consistent with Ditton's view[6], [44] that "*fracturing to the surface can only occur in the critical to supercritical panel width range*". That is, according to Ditton, connected mine to surface fracturing can only occur at or beyond the point at which the extraction width is 1.0 to 1.4 or more times the mining depth and only occurs as a direct consequence of overburden spanning failure. Prof. Galvin's commendation of Ditton's cap suggests he shares this view.

The Ditton equations incorporate recognition of the maximum subsidence limit referred to by Prof. Galvin, by representing the extraction panel width (W) as an "*effective panel width*" (W'). In application, this means the actual extraction width (W) is replaced in the equations by 1.4 times the mining depth (H), when it's greater than 1.4 times that depth (H). That is, Ditton 'caps' the value of his effective panel width parameter (W') when the actual extraction width exceeds the critical width of 1.4 times the mining depth (see Fig. 14(b)), which is regarded as the width at which spanning failure and maximum subsidence typically occur. That Prof. Galvin commends Ditton for imposing a limit of this kind suggests that he shares Ditton's view. The available evidence from the Dendrobium mine suggests that, depending on the mining geometry, the drainage zone can reach the surface before the onset of spanning failure.

As discussed in Section 6.2.2, Prof. Galvin doesn't point out in his PSM reports that there is a limit to the extent of sag subsidence because a point is reached, as extraction width increases, where the overburden is no longer able to span the extraction void. When this critical extraction width is reached, the full weight of the overburden collapses onto the rubble of the goaf and there would then be significant 'connected fracturing' between the extraction and the surface. The lateral extent of this connected fracturing would continue to increase as extraction proceeds beyond the critical width. That is, while the extent of subsidence reaches a limit, the overburden continues to be disturbed as extraction proceeds beyond the critical width. In that perspective, whether or not the drainage zone height estimate is capped with respect to the critical width may be regarded as an academic consideration rather than of practical 'catchment impact' significance.

The means used by Ditton to cap drainage zone height estimate at the critical width could be used in applying the Tammetta equation, in circumstances where the mining geometry is such that the equation does not suggest the drainage zone would reach the surface before or at the critical width. However, as noted, at this point seam to surface cracking would be expected to have occurred as a consequence of abutment failure.

As Fig. 14(b) suggests, the Tammetta equation can provide drainage zone height estimates that exceed the distance between the mining and the surface. While the surface limits the 'real world' vertical extent of the drainage zone, the horizontal extent of the drainage zone can continue to increase with increasing mining width and/or increasing extraction thickness/height. There is then a real world 'physical' benefit in not capping a drainage zone height estimate when it exceeds the distance to the surface, as it would provide a basis for gauging the lateral extent of the intersection of the drainage zone with the surface. This is not noted by his Prof. Galvin in either his PSM review or his summary report. It is however, in part, recognised in his brief comments[16] on Tammetta's work in a December 2016 review of the Subsidence Management Plan (SMP) proposed for Longwalls 14 to 18 commissioned by the Department of Planning: "*As this model already predicts* *that the height of connective fracturing will reach the surface, the effect of increasing mining height is to increase the lateral extent of this zone of fracturing*."

In summary, while the extent of subsidence reaches a maximum value at the point of overburden spanning failure, it would be incorrect to suggest there is then no further disturbance of the overburden. The lateral extent of connected seam to surface fracturing would be expected to continue to increase as the extraction width increases. While a drainage height estimate greater than the height of the surface above the extraction would be physically meaningless, it has physically meaningful utility in offering a means of gauging the lateral spread of the drainage zone. While this is possible, at least in principle, in applying the Tammetta equation, it is excluded in the Ditton equations.

7.2 Formulation of Ditton's empirical equations

In commenting[3] on the approach taken by Ditton's in deriving his empirical equations, Prof. Gavin advises; "*In practice, however, it pushes the limits of simple beam theory and is subject to the limitations associated with applying beam theory to complex 3-dimensional situations.*" Ditton used beam theory in endeavouring to obtain 'analytical' fracture zone height equations from first principles. This approach was abandoned however, with Ditton noting "*difficulties involved with using analytical or numerical techniques v. empirical methods*".[6], [45] The variables identified in his abandoned application of beam theory were then used in obtaining an empirical equation.

As Prof. Galvin notes in his December 2016 review[16] of the Subsidence Management Plan for Dendrobium Longwalls 14 to 18, Ditton comments;[6] "*considering the complexity of the resulting analytical equations and uncertainty in the assumptions made, the physical relationship between the variables may also be assessed practically with Dimensional Analysis*." Ditton's use of dimensional analysis in obtaining and empirical equation is, however, limited.

After presenting the variables carried over from attempts to obtain an analytical equation in a general functional representation, Ditton immediately specifies a form in which each variable is raised to an undetermined exponent. This suggests Rayleigh's method for dimensional analysis, in which the determination of the exponents, using simultaneous equations, and subsequent gathering together of dimensionless groups with like exponents may identify or suggest the form of the relationship between the variables.

Rayleigh's method is limited in assuming a monomial relationship (product of positive integer powers) of the variables and is increasingly difficult to use as the number of variables increases. In Ditton's dimensional analysis formulation there are initially 10 variables before two are discarded, leaving eight. Ditton then follow's Buckingham's method (a generalisation of Rayleigh's method) in obtaining five dimensionless groups of the variables and then, without justification, simply inserts them into a monomial relationship.

While Ditton's use of Buckingham's method demonstrates dimensional consistency (homogeneity) it does not vindicate or test the original assumption of a monomial relationship between the variables identified in his abandoned application of beam theory. That is, Ditton's use of dimensional analysis does not identify or suggest "*the physical relationship between the variables*" and, as Prof. Galvin indirectly suggests[16], the dimensional homogeneity of the assumed monomial relationship can be checked by inspection without recourse to Buckingham's method.

Having recast the assumed monomial equation for the height of the drainage zone with dimensionless groups of the remaining variables, Ditton then discards the only term in the equation that contains variables with more than one base unit and the resulting equation then only has variables with units of length. So, while he presents the determination of his empirical equations as an application of dimensional analysis, Ditton in fact simply assumes that the drainage zone height has a monomial dependence on extraction width, height, depth of cover and, optionally, a parameter that he refers to as an *effective strata unit thickness* (see Section 7.3). That is, nothing of substance appears to have been achieved with his application of dimensional analysis.

In commenting on Ditton's work Prof. Galvin concludes that "*In practice, however, it pushes the limits of simple beam theory and is subject to the limitations associated with applying beam theory to complex 3-dimensional situations.*" It's not clear whether Galvin is referring to Ditton's abandoned attempts to obtain an analytical equation or his subsequent work to obtain an empirical equation. While they are initially presented with respect to 10 variables identified in the abandoned work, Ditton's empirical equations were not obtained from the application of beam theory. Instead they are the outcome of an assumed monomial equation of three variables in one case (geometry equation) and four in the second (geology equation).

In contrast, Tammetta determined the form of his equation in a scientific manner, utilising observed characteristics of centreline piezometer data to identify a functional form. Remarkably, Tammetta found that the use of a logarithmic function exposed a straight-line clustering of the data for which regression techniques provided a fit to with an error of just 7.3%. In their 2017 reports, Sullivan, Swarbrick, Mackie and Galvin offer no recognition of merit in this expected finding.

7.3 Ditton's effective strata unit thickness – a fudge factor

As described in Section 7.2, Ditton presents two monomial equations, with the product of powers of three variables (extraction width, thickness and depth of cover; the same variables used by Tammetta) and a second additionally including a fourth variable that refers to as an "*effective strata unit thickness*". This fourth term is intended to accommodate the possibility that local lithology might determine the drainage zone height. Ditton refers to the regression optimised monomial equation with four variables as the "geology", while that with three variables is referred to as the "geometry" equation.

As Ditton points out[6], in practice it's not possible to reliably estimate or otherwise determine an apriori value for the '*effective strata unit thickness*':

> "*It should be understood that the vagaries of the rock mass do not usually allow the strata unit thickness term to be assessed directly from borehole data without back analysis of overburden performance measurements*."

In practice then, as pointed out to Minister Stokes in July 2015, and indirectly suggested by Prof. Galvin[3] and WaterNSW[19], the additional term serves as a back-analysis 'fudge factor'. In his PSM review, Prof. Galvin comments:

> "*the effective thickness is not based on any actual assessment of geology but is apparently derived by manipulating the value of 't' to obtain the closest agreement between predicted and locally measured outcomes (ignoring the fact that the veracity of the measured outcomes is an issue that also needs careful consideration).*"

Ditton's additional term does not offer a significant advance on the work of Tammetta.

As pointed out to the then Minister for Planning[5], [17], the problems with Ditton's empirical equations stem primarily not from having pushed beam theory too far or the assumption of a monomial relationship, but instead from the ill-suited nature of the database used for their determination (see Sections 8.5. 10 and 12).

7.4 Three error estimates, but not three equations for the drainage zone height

In his PSM review Prof. Galvin suggests Ditton's approach is superior to that of Tammetta:

> "*For the record and to facilitate discussion, Ditton's approach is distinguished by having some regard to the influence of the panel width-to-depth ratio, W/H, on overburden behaviour; to the variation in failure mode with W/H ratio; and to there being a limiting value of W/H ratio above which the level of disturbance of the overburden does not increase. Ditton has attempted to take these factors into account by applying mechanics based on simple beam theory to derive three sets of equations, each describing a particular type of ground behaviour that has been assumed to be linked to ranges in W/H ratio (0 to 0.7, >0.7 to 1.4, >1.4).*"

If not read in conjunction with Ditton's own account, Prof. Galvin's summary might suggest Ditton provides three beam theory derived empirical equations, for mining scenarios in which the extraction width to depth ratio has the ranges of 0 to 0.7 (subcritical range), greater than 0.7 to 1.4 (critical range), and greater than 1.4 (super-critical range). Instead however, for both his empirical geometry equation and his empirical geology equation, Ditton specifies error estimates (95% confidence limits) for each of the three mining scenarios; the height estimates themselves are not calculated with respect to the three scenarios.

That is, the Ditton equations don't provide different drainage zone height estimate formulations for each of the three scenarios, as Prof. Galvin's summary might suggest, but his formulation of the error estimate differs according to the mining type (subcritical, critical and supercritical).

8. Other puzzling criticisms of the Tammetta equation

8.1 Lack of provision for time dependent drainage

Evidently suggesting a deficiency, Prof. Galvin comments

> "*The equation does not include provision for drainage (seepage) and depressurisation in the longer term. Depending on porosity and permeability, complete drainage may take many years*."

The comment is puzzling, particularly given Galvin's recognition[4] of the importance of the mining impact the Tammetta equation seeks to estimate:

"*The height above mine workings from which groundwater freely drains is a particularly important consideration when constructing the geometry of a numerical groundwater model and assigning values to the parameters that define groundwater flow in the model*."

The intended application of the Tammetta equation is no more than to provide at least a first order estimate of the height of the drainage zone. That is, an estimate of the height over the centreline of an extraction where a piezometer would report a zero pressure head and show no more than transient responses to rainfall/recharge. The equations says nothing about the hydrology of the disturbed zone that surrounds the drainage zone; that's not its intent. It nonetheless provides a valuable tool in gauging mining impacts. This is not acknowledged by Swarbrick, Sullivan, Mackie or Galvin.

Reaffirming his equation, though not mentioned by Galvin, Mackie or Sullivan and Swarbrick, Tammetta's second Groundwater paper[12] analyses hydraulic conductivity changes within and beyond the drainage zone. The equation is further affirmed in Tammetta's third Groundwater paper.[13]

8.2 The equation is one dimensional and does not provide a profile

Summarising Sullivan and Swarbrick in agreement, Dr Mackie comments:

"*The equations are regarded as one dimensional in that they only apply to the centre line of a panel. The inverted parabolic shape of the desaturation interface described by Tammetta (2013) and the dome shape implied by Ditton-Merrick, cannot be calculated*."

Again, the criticism is bewildering; as Prof. Galvin notes, knowledge of the height of the drainage zone is a particularly important in understanding and modelling the groundwater impacts of underground coal mining:

"*The height above mine workings from which groundwater freely drains is a particularly important consideration when constructing the geometry of a numerical groundwater model and assigning values to the parameters that define groundwater flow in the model*."[4]

Given the available data, the comprehensive equation expectations of Swarbrick, Sullivan, Mackie and Galvin are unrealistic. The Tammetta equation, in the absence of refutation, is useful in being capable of providing an estimate of the height of the drainage zone to within 10%.

As Prof. Galvin points out in his review of the PSM report, the work of Mills and O'Grady finds the profile of the collapsed zone to be parabolic. Tammetta additionally notes a 1968 study by Dowdell that finds the shape is parabolic. Tammetta explores the profile in some detail in his 2015 Groundwater paper, further affirming the essentially parabolic character of the drainage zone profile. As discussed in Section 6.2.1 and noted elsewhere in this report, the parabolic profile reflects the post extraction formation of a pressure arch. The character of the pressure arch is suggested in the photograph of Figure 17 below.

Tammetta cannot be criticised for failing to use data that doesn't exist. As noted earlier, the need for more data is recognised by Tammetta[11]: "*Further field data will be required as an ongoing test of the derived equation, and to update the confidence limits*." The July 2015 NPA letter to the then Planning Minister included the following recommendations:

“*(v) Review and expand, with new industry funded piezometer bores, the database of reliable piezometer measurements of the height of the drainage above coal extractions. This should include overlapping multiple extractions, such as has those at Russell Vale.*

(vi) Industry funded research programme to sink bores and gather piezometer data from a set of representative longwall extractions, selected in agreement with the agencies and public, in order to obtain a set of cross-section profiles of the drainage zone above longwall extractions.”

Further recommendations were offered in the December 2016 NPA report, including:

“*(iii) At least three bores, each with closely spaced piezometers, to be sunk in a line across a suitable location in the western half of LW10 in order to determine the drainage zone height and profile. One bore to be placed centre-panel, one midway between centre panel and the side and one over the side-pillars.*

The vicinity of existing bore S1908 would appear to be a suitable location (see Fig. 31(b)). The terrain in the western half is comparatively flat (see Figs. 31(b) and 52) and does not appear to have the stress conditions found in the eastern half of Area 3B. The extraction height in the western half of LW10 is such that the drainage zone is expected to be generally less than 30 metres from the surface, the exception being between 1140 and 1040 metres from the western end, where the extraction height was 4.5 metres and the drainage zone would be expected to have intersected the surface.

The bores should be drilled as soon as possible, with a first report provided within three months of sinking and piezometer commissioning. Data collection to continue for at least a year and the data reports to be owned by the State of NSW and publically available.

(iv) Sinking of multi-piezometer bores on the centre-line of overlapping double and triple seam extractions at the Russell Vale Colliery. Remarkably, this has not been done. As pointed out in the Sydney Morning Herald in December[1], the drainage zone may intersect a shear plane bearing water from Cataract Reservoir (Section 25 within). Currently there is insufficient data from overlapping coal extractions to allow the development of an equation for the estimation of the drainage height over multi-seam extractions.”

Following evidently similar recommendations for Dendrobium from WaterNSW in 2017, a centreline bore is to be installed over each of Longwalls 13, 14 and to 15, and three bores will be installed in a line across LW 12. Of concern to the NPA, the bores over Longwall 12 are in the eastern area of Area 3B; this area has anomalously high horizontal stress. As discussed in Section 6.2.5, both Prof. Galvin and Tammetta observe that high horizontal stress can hinder the collapse process and, accordingly, the formation of the drainage zone. This is recognised in recommendation (iii) of the December 2016 NPA report. The report suggests that the ambiguous results from the centreline bores over the eastern end of Longwall 9 may reflect the effects of the high horizontal stress.

8.3. The predictive error is large

Using an absolute rather than relative error measure, Sullivan and Swarbrick comment that “*The predictive error is significant considering the small sample size giving rise to large standard* *deviations, these being 20 to 50 m*". Prof Galvin is similarly critical in the parenthetical observation included in his dismissal of Tammetta's work; "*the equation was derived by simply drawing a line of best fit through a range of data points (each with its own considerable error band)*". Similarly Mackie suggests "*the empirical nature of both models and the errors associated with fitting equations to the data sets, detract from their usefulness*". Reference to Figure 3 in Tammetta's 2013 Groundwater paper finds, however, that the error estimates are generally relatively small (see Figs. 7 and 4 below).

No fault of Tammetta's, the noted error band in part reflects the coarse grained and patchy nature of the available data. Tammetta suggests[11] that site specific geological effects at the apex of the drainage zone make a greater contribution to the error band. Tammetta makes the following comments in his 2013 paper:

> "*Further field data will be required as an ongoing test of the derived equation, and to update the confidence limits. There is more uncertainty created by variations between H determinations, than the uncertainty within an individual determination. Most of the uncertainty probably occurs at the apex of the desaturated zone, where the zone is thin (see the following) and variations in rock strength and fracture populations will affect bridging widths. Uncertainty is also generated by locations not being precisely on panel centerlines*."

The coarse grained and patchy nature of the available data reflects inadequacies of the monitoring networks, which often have large intervals between instruments. The 2016 NPA report sent to the then Minister includes the following recommendation:

> *(xvii) Piezometers to be installed at underground mines in NSW at height intervals that allow a sufficiently precise gauging of the drainage zone height.*

As far as we are aware, the recommendation has not been acted on.

Nonetheless, Tammetta finds[11] the uncertainty (root mean square error) in the fit of his equation across a wide range of rock types and mining geometries is 7.3%. Of note, the PSM report incorrectly suggests the Tammetta equation error is 9.8%; the consultants appear to be referring to Tammetta's initial attempts to find an equation, where he used an exponential integral function. A fit to within 8% (or indeed 10%) is clearly useful in obtaining at least a first-pass estimate in the context of mining to depths of 400 metres; this is not acknowledged or considered by Sullivan, Swarbrick, Mackie or Galvin in their 2017 reports. The perspective of these reports in commenting on Tammetta's work is notably negative. There is no recognition of Tammetta's achievement, which makes the most of the coarse and limited data currently available in revealing an unexpected relationship. Recognition is however provided in the publication of his work in Groundwater.

As noted earlier, in suggesting a simpler equation to that of Tammetta in a November 2014 comment piece[41] published in Groundwater, Dr Colin Mackie makes the following comment:

> "*The paper by Tammetta provides a useful empirical equation for predicting the height of complete drainage above longwall panels. Prior to this research effort, predictions in Australian coalfields often relied upon simple relationships*."

The comment precedes a suggested simplification of the Tammetta equation, in which Mackie removes overburden depth as a variable in obtaining a drainage zone height estimator that's a simple monomial function of extraction width and depth (not dissimilar to that of Ditton, but without the inclusion of the depth). Tammetta's reply is discussed in Section 6.2.3. Of note here is that Mackie used Tammetta's database entries, as provide in the supplementary material for his 2013 paper, in empirically determining his equation using regression methods. Mackie makes no comment on the database error bands and his graphical representation of the fit of his equation shows that in general the errors are modest.

Any equation, whether derived from theory or empirical analysis, is only as precise as the data on which it rests. Assuming a comprehensive equation could be obtained from first principles, its validation would likewise be constrained.

8.4 The Tammetta's database doesn't account for incremental subsidence

In his review of the Tammetta equation Prof. Galvin asks, "*Do the data points adequately reflect incremental subsidence*?" This question and other comments addressed in this report suggest Prof. Galvin expects a comprehensive equation, preferably derived from theory and not empirical analysis, capturing mining geometry, geology, geomechanics and time dependent processes, able to predict groundwater pressure changes in three dimensions within and beyond the drainage zone The aspiration is currently unrealistic; notwithstanding the theoretical difficulties and vagaries of geology, the available data sets are notably coarse, patchy and limited in number.

A reading of the supplementary material provided with Tammetta's first Groundwater paper, that of 2013, makes it clear that his database cannot provide a time dependent equation sensitive to incremental subsidence. This reflects of the limited availability and limited vertical resolution of centreline piezometer data. The equation is nonetheless fit for purpose in providing a first approximation estimate of the height of the drainage zone.

Prof. Galvin also appears to be unaware of Tammetta's discussion of the time dependent development of the collapsed zone in the supplementary material for his second Groundwater paper, published in 2015 (see Section 14). He may also be unaware of Tammetta's observation of the anomalous horizontal stress delayed progression of the formation of a collapsed zone at the Mandalong mine (see Section 6.2.5) in a 2014 report[25] commissioned by the Department of Planning.

In a 2014 review of subsidence around Cataract Reservoir, the Dams Safety Committee's Ziegler and Middleton report[46] that "*Residual subsidence has added 25% to the initial subsidence in this area, a figure that is much higher than the typical 5% to 10%*". An increase of 25% is exceptional.

8.5 Is the Tammetta equation based on representative data points?

Prof. Galvin asks, "*Is the Tammetta equation based on representative data points?*" As noted earlier, Tammetta's database content represents a wide variety of rock types and includes subcritical to critical to supercritical void parameters (see Fig. 2, 15(a) and 15(b)). As noted earlier, this is not mentioned in any of the recently released reports.

Similarly the PSM, Mackie and Galvin reports do not mention that, in contrast to Ditton, Tammetta obtained his equation for estimating the height of the drainage zone entirely from centreline piezometer data. In his 2016 book on coal mine engineering Prof. Galvin incorrectly suggests Tammetta used extensometer data to obtain his equation. Tammetta's use of centreline piezometer data is parenthetically noted in Prof. Galvin's PSM review, however its significance is not pointed out and nor does Prof. Galvin note the distinction with respect to the data used by Ditton. Similarly, the significance of Tammetta's use of centreline data is not noted in Prof. Galvin's summary and review report.

As the PSM report notes (see Section 12), and pointed out in the NPA letter of July 2015 to the then Minister for Planning, "*The real measure of connection are the piezometric profiles over time, they are the best available means for quantifying the impact of mining on the hydrogeological regime.*" Unreasonably negative in their perspective, the 2017 PSM, Mackie and Galvin reports do not acknowledge Tammetta's global search and gathering together of suitable data.

In contrast, as pointed out to the Minster in July 2015, Ditton uses a mixture of piezometer and extensometer data, most of which is not centreline data (see Section 12 for comments on the use of extensometer data). Problematic aspects of Ditton's database are identified in the July 2015 NPA letter to the then Minister for Planning and expanded upon in the December 2016 NPA report. The NPA's concerns and related concerns raised by WaterNSW in their April 2016 submission to the Department of Planning for the proposed SMP for Longwalls 14 to 18 are noted by Prof. Galvin in his December 2016 review of the SMP material comments:

> "*A number of submissions, notably those of WaterNSW and the NSW National Parks Association, raise concerns about the accuracy and processing of data used in developing and calibrating the model. I have not been through every specific concern but at least some have merit.*"

This is not noted in Prof. Galvin's review of the PSM report, yet he regards PSM's failure to review the Tammetta and Ditton databases as a critical shortcoming.

9. Extrapolation beyond the Tammetta database

Perhaps the most significant caution Prof. Galvin provides with respect to the Tammetta equation is in noting[4] the following:

> "*In the case of Dendrobium Mine, the equation has been applied to mining geometries that fall outside the range of data used to derive the equation. This increases the potential for unreliable predictions*".

As discussed above, the Tammetta equation was empirically obtained with respect to a composite variable (u) for which the largest value in the Tammetta database is 4,367 for an extraction at Springvale. The values of u for parts of the Dendrobium extractions are considerably greater than those of the database; around 50% greater for Area 3B. As is well known, the reliability (consistency) or otherwise of an empirical equation used beyond its underpinning database cannot be gauged in advance with certainty. As Prof. Galvin points out[3] however, extrapolation is not doomed to failure; "*this does not automatically mean that the accuracy and standard deviation of the fit will decay*". Discussed in Sections 22 and 23, there are good grounds for expecting that the Tammetta equation does provide informative and useful first order drainage zone height estimates for Area 3B, at least in the areas where the horizontal stress is not anomalously high.

Importantly, from a geomechanical perspective, the extraction width to depth ratios of the Area 3B longwalls are within the range spanned by the Tammetta's primary database (see Fig. 15(b) below).

The importance of this is signalled in Prof. Galvin's comment on Sullivan and Swarbrick's 'scatter plot' assessment of the relationship of the Tammetta database geometries to those of Area 3B:

> "*The PSM analysis of the data would be more meaningful if it was also undertaken on the basis of panel width-to-depth ratio, W/H*."

Figures 15(a) and 15(b) provides the scatter plot recommended by Prof. Galvin; the width to depth ratios of the Area 3B longwalls are well within the range of values represented in the Tammetta database. The large drainage zone height estimates shown in the graph highlight the aggressive nature of the Area 3B longwalls.

10. *"It is not a matter of which equation is correct …"*

In his February 2017 PSM review Prof. Galvin makes the following comments on the Tammetta equation and the Ditton-Merrick equations:

(i) "*It is not a matter of which equation is correct …. Rather, it is a matter of which equation is the least incorrect*."

Prof. Galvin further advises that the question of which is least incorrect "*cannot be answered from a technical perspective because each equation is based on a different set of data*".

(ii) "*Neither can be correct because neither properly and adequately accounts for geology, the mechanics of rock behaviour and time dependent hydrogeology processes*."

These comments are incorrect, misleading and may cause confusion. One the basis of these comments, a reader might reasonably, but incorrectly, conclude that both the Tammetta equation and the Ditton-Merrick equations are inadequate and of little or no utility. Prof. Galvin's comments equivalently and unreasonably characterise both equations in a negative manner.

The question Prof. Galvin poses, with clearly negative connotations, is itself incorrectly framed from a scientific perspective; there are no 'correct' models of physical phenomena. All that can be asked is; which model/equation is the most useful in a given context? As noted in Section 6.3, Kepler's laws are not regarded as incorrect because they lack explicit recognition of gravity; they are a useful approximation in their context, as are Newtonian's law of gravity and Einstein's General Relativity. In the context of groundwater impact assessments, the appropriate question to ask of the Tammetta equation and the Ditton-Merrick equations is; which of the two alternatives provides the better estimate of the height of the zone where water drains relatively freely towards the goaf? This is clearly an important question.

Notwithstanding the importance of the question, Prof. Galvin quotes and agrees with the following remarkable PSM statement:

> "*Discussions over which model is more accurate or correct is somewhat distracting*."

The statement opens the following paragraph in the PSM report:

> "*Discussions over which model is more accurate or correct is somewhat distracting. All these models are trying to predict the same effects. Hence the differences between the models and predictions discussed above should really be taken as fundamentally a measure of the possible degree of accuracy that results from using empirical models like these. The underlying fundamental problem with both Tammetta (2013) and Ditton and Merrick (2014)*

for this study is that the basis upon which they have been developed is not supported by the data at Dendrobium."

That is, the statement quoted by Prof. Galvin is predicated on PSM's fundamental misunderstanding of Tammetta's work (see Section 18); Dr Mackie and Prof. Galvin recognise this critical flaw in their reviews of the PSM report. Compounding this fundamental misunderstanding. The quoted paragraph fails to recognise that the difference in the predictions offered by the Tammetta and Ditton-Merrick equations reflects their underlying databases.

The question would best be answered by testing each against centreline piezometer data sets that are not represented in either of the databases against which the alternative equations were developed. Currently doing so would be a problematic, because of the very limited number of centreline piezometer bores. In his review of the PSM report Dr Mackie highlights this problem in the specific context of the Dendrobium mine:

"*These equations attempt to predict the height of connected cracking and free drainage within the subsidence zone. Since each equation generates a significantly different answer for Dendrobium conditions, logic dictates that one or the other is more representative. A sensible approach to address this issue is to validate the equation(s) using local piezometric observations. Unfortunately there is not a single piezometer at Dendrobium that provides continuous pore pressure observations before, during and after mining and is located centrally within a panel*."

While desirable, centreline piezometer data collected before, during and after mining is not essential; reliable post mining centreline data is sufficient to determine the height of the drainage zone.

A candidate validation data set not represented in either the Tammetta or the Ditton-Merrick databases is that of the piezometer data obtained by consultants SCT in 2014 from the centreline of Longwall 10A at the Tahmoor mine. Published at a conference in 2017[34], SCT found a drainage zone height of 140 metres (see Fig. 31) and note close agreement with the 147 metre estimate provided by the Tammetta equation. Discussed in Section 21 below, the Tahmoor data however provide only weak support for the Tammetta equation. As noted in the 2016 NPA report, the Tammetta and Ditton-Merrick equations give similar estimates for modest mining geometries (see Fig. 5 in the 2016 NPA report).

Contrary to Prof. Galvin's suggestion otherwise, however, even a superficial a comparison of the two databases is sufficient to gauge which of the two equations is likely to be the most useful. In contrast to Tammetta, Ditton provides limited information about the nature and location of the bore sites used for his database. It's clear from the information that is provided, that the database is comprised of a mixture of piezometer and extensometer data from bores that appear primarily to be either located over the side of a panel (side-panel) or are not over the panel (off-panel). As pointed out in the July 2015 NPA letter to the then Minister for Planning, in Prof. Galvin's December 2016 review of the LW 14-18 SMP material, in the February 2017 Mackie and Galvin review's and in the March 2017 PSM report, the height of the drainage zone is (currently) most reliably determined from centreline piezometer data (see Sections 8.5 and 12). Extensometer data do not provide an appropriate means of gauging the height of the drainage zone (Section 12).

The Ditton database then does not provide a suitable basis for obtaining an equation, empirical or otherwise, to estimate the height of the drainage zone. This is reflected in the following comment from Prof. Galvin's comment from his review of the LW 14-18 SMP:

> "*The insensitivity of the Ditton model to mining height suggests to me that the prediction equation does not adequately reflect physical and mechanical principles*."

This observation and other critical comments of the nature of the data used by Ditton are not repeated or referred to in Prof. Galvin's subsequent review of the PSM report or his summary and explanation document. In contrast to Ditton-Merrick, Tammetta's equation is derived from centreline piezometer data and is consistent with the observations of Mills (Section 11). While Tammetta's use of centreline piezometer data is parenthetically noted in Prof. Galvin's, PSM review, its significance is not noted and nor is it contrasted with the data used by Ditton.

The December 2016 NPA report[17] reviews the side and off-panel piezometer data from key bore sites over the Dendrobium mine. In the absence of a predominance of unusual geological conditions and recognising the well known large difference in vertical and horizontal hydraulic conductivities, the NPA report finds the data are not in accord with the Ditton-Merrick equations. The data appear to be consistent with the Tammetta equation and long-range depressurisation effects, also noted in the March 2017 PSM report, are rationalised by the Tammetta equation.

As noted by Mackie, the evidence of seam to surface cracking at Dendrobium reported by Sullivan and Swarbrick and more recently by HGEO (see Section 24.3) is consistent with the Tammetta equation; it is not however consistent with the Ditton-Merrick equations. Also consistent with the Tammetta equation is the observation by Sullivan and Swarbrick of depressurisation throughout the vertical profile and that is extends well beyond the longwall panel. This is noted and explained in the NPA report of December 2016; the observation is consistent with a drainage zone height of the kind estimated by the Tammetta equation. The 'disconnect' between the available evidence and the critical comments made on the Tammetta equation in the Galvin and the Sullivan and Swarbrick reports is puzzling.

11. Consistency with the work of Whittaker and Reddish, Kelly, Gale, Mills and others

Suggesting limited directly relevant experience and background knowledge, the PSM comment has the following criticism of Tammetta's work:

> "*The Tammetta (2014) HoF model assumes associated changes to hydraulic conductivity and storativity within an idealised parabolic area of influence above the collapse zone. There is a limited basis for this assumption given the lack of data, in particular data located away from the longwall centreline. This lack of data is due to lack of measurements in these areas.*" (HoF abbreviates 'height of fracture').

Of note in considering the geomechanical credibility of the Tammetta's work, is that it is consistent with modelling studies of Whittaker and Reddish, seismic studies by Kelly and others, extensometer studies by Mills and O'Grady and numerical simulations and observations by Gale. These studies find the collapsed zone profile has the shape approximating that of an inverted parabola (see Figs. 16 to 22). In his 2013 Groundwater paper Tammetta also refers to a 1968 study by Dowdell[47] that finds a parabolic profile for the collapsed zone.

Referring to Whittaker and Reddish[42], his 2014 report[21] for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining traces the observation of a paraboloid profile to Rziha in 1882. Provided as Figure 6.8 in Tammetta's 2014 knowledge report, Figure 17 below is Figure 19 in Whittaker and Reddish's 1989 book[42] on subsidence. The roadway roof has collapsed, exposing a pressure arch. Tammetta comments:

> "*The overhang of the strata on the sides of the excavation is consistent with Hausse's (1907, cited in Whittaker & Reddish 1989) 'main break', and the central shape of the zone of deformation is consistent with the paraboloid shape proposed during the early stages of subsidence by Rziha (1882), including the zone of tearing around the edges*."

In accord with Mills, Tammetta characterises the collapsed zone[11] as a zone of significant downward movement over a coal extraction (Tammetta's 2013 paper highlights a sharp change in the extent of downward movement; see Fig. 24). In his first Groundwater paper[11] Tammetta refers to the work of Mills and O'Grady in finding that the height of the collapsed zone found from his extensometer database coincides with the height of the drainage zone found from his piezometer database (see Section 4.3). Discussed in Section 20, this is demonstrated by data collected from a centreline bore above Longwall 7 of the Elouera domain of the Wongawilli coal mine, which adjoins Area 3B of the Dendrobium mine (Figs. 26 and 27).

Summarised in Section 14, Tammetta provides a geomechanical context for his work in the supplementary material accompanying his second Groundwater paper, published in 2015. This follows a comprehensive account of subsidence included in a 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, prepared by Tammetta on behalf of Coffey Geotechnics. The descriptions overlap and compliment coverage in Prof. Galvin's 2016 book on coal mine engineering. Drawing on a year 2000 CSIRO extensometer study by Michael Kelly at a coal mine in Queensland, Tammetta's 2015 summary describes spall formation, a consequence of flexing and tensile failure[18], and the evolution of the collapsed zone (Figs. 19 and 20 below).

Suggestive of a progression, Prof. Galvin summarises the work of Forster and Enever, Guo, Gale, Mills and Tammetta in his 2016 coal mine engineering book, with a summary of simulation work by Gale (see Fig. 21; discussed below) and an account and depiction of the six zone sub-surface subsidence model (see Fig. 22) proposed by Mills[22], [29] being immediately followed by a description of the work of Tammetta.

Mills developed his six zone geotechnical model of overburden disturbance on the basis of surface subsidence measurements, camera observations, packer testing, piezometer data, micro-seismic data, extensometer monitoring, and stress change monitoring. The extractions studied by Mills include Longwalls 4 and 5 at the Clarence Colliery (Section 14.1), Longwall 7 at the Elouera mine (Section 20) and Longwall 10A at the Tahmoor Colliery (Section 21). Zone 2 in Mills' model is characterised as "*A zone of large downward movement from seam level to a height above the mining horizon approximately equal to the panel width.*" Zone 2 would then correspond to Tammetta's collapsed zone.

A consequence of flexing and tensile failure, this zone has "*extensive conjugate shear fracturing with numerous open fractures, particularly around the margins of this zone, and numerous inclined fractures throughout*". Mills also notes[29]:

"*field observations indicate that the height of Zone 2 is equal to about the panel width in most geological settings*"

And:

"*The interface between the zone of large downward movement and the less disturbed strata above and to the sides of this zone accommodates some relatively large differential movements for rock strata within a short distance. This interface zone is characterised by open shear fractures and fractures between rotated blocks of intact material.*"

Mills illustrates Zone 2 with a model of strata collapse over a longwall extraction ((Fig. 16(b) below) presented in 1989 by Whittaker and Reddish (in the same book used by Galvin for Fig. 4 below). On the basis of this modelling, as Prof. Galvin notes in his 20016 book, for hydrogeological purposes Whittaker and Reddish (1989) identify just two disturbance zones, with one being a zone of continuous cracking and the other a zone of discontinuous cracking. Commenting with respect to Whittaker and Reddish's physical model, Mills suggests:

"*the level of disturbance illustrated by this model clearly shows that there is likely to be significant disturbance to the overburden strata in Zone 2 with depressurisation of the groundwater system in this zone likely*."

Whittaker and Reddish's zone of continuous cracking (Figs. 19 and 16), Zone 2 in the model of Mills (Fig. 22), would correspond to Tammetta's drainage zone (Fig. 1).

Mills finds that:

"*Panel width controls the height of fracturing. Panel width, overburden depth to the mining horizon, and seam thickness collectively influence the magnitude of strain and subsidence and so influence the aperture of fractures, the overall network connectivity, and thus the hydraulic conductivity of the overburden strata*".

Referring[29] to a 1999 piezometer study at what was then South Bulli Colliery, Mills makes the following observations:

"*This work and other similar studies demonstrate that there is significant interaction with the groundwater within a distance above the mining horizon equal to the longwall panel width.* ***A zone of large downward movement from the mining horizon to a height above the mining horizon equal to the longwall panel width typically shows significant hydraulic depressurisation because of the fracture network that is created by mining****. Above this zone, there is typically a zone of slight depressurisation below hydrostatic consistent with low level flow in a downward direction. Recharge from rainfall is sometimes sufficient to substantially maintain groundwater levels in the upper levels of the overburden strata.*" Bold emphasis added here.

Tammetta comments on the study in his 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining:

"*The study included installation of multiple piezometers directly above the longwall panels. These piezometers provide one of the first vertical profiles of pore pressure directly above a longwall goaf. They indicated that the maximum height of interconnected fractures, as indicated by complete drawdown in the piezometric profile, was approximately 120 m and therefore approximately equal to the width of the longwall panels.*"

Data from South Bulli are included in his primary database[39], where the mine is listed with respect to its 1997 name of Bellambi West. Tammetta's interpretation of the piezometer data finds a drainage zone height of 92 metres for extraction with a width of 110 metres and a height of 2.6 metres and depth of cover of 421 metres. The Tammetta equations suggests a drainage zone height of 86 metres. Mills' rule of thumb would suggest 110 metres.

Section 4.5 above discusses differences between the estimates of the Mills rule of thumb and the Tammetta and Mackie equations. While Mills finds that height of Zone 2 corresponds to the width of the extraction, Tammetta's extensometer database finds that the height of the collapsed zone corresponds to that given by his extraction width, extraction height and depth of cover dependent equation for height of the drainage zone:

> "*A close relationship is apparent between the empirical equation for H derived from hydraulic head measurements, and the height where a large change in downward movement occurs. Given the equivalence between the two independent data bases, H is taken as being equal to the top of the zone of large downward movement. The desaturated zone and the zone of large downward movement are considered to be coincident.*"

Mills rule of thumb is a guide with an accuracy that depends on the geometry of the mine; the height of the drainage zone is not determined solely by the extraction width and there would appear to be no reason to expect it to be fixed at the mining width. Mills' rule of thumb works well at Clarence (Section 14.1) and Elouera (Section 20), but appears likely to be less effective at Tahmoor (Section 21) and Dendrobium (Sections 22 and 23).

Figure 14(a) below shows that for an extraction height of 3.5 metres and depth of 400 metres the Tammetta equation drainage zone height estimate corresponds approximately to the extraction width. The Tammetta equation representation in Figure 14(b) suggests Mills' rule of thumb would apply for extractions heights of between 3 and 4 metres, at a depth of cover of 400 metres. In contrast, the Ditton-Merrick equation is inconsistent with the work of Mills and Gale. Figures 6(a) to 6(c) compare Tammetta equation estimates with those of the Mackie equation (Section 4.4) and the Mills rule of thumb with respect to mining width for several extraction heights and cover depths.

The observation by Mills of two principal hydrological zones in the quote above, echoes the 1989 identification of two such zones by Whittaker and Reddish in 1989[42], based on their physical modelling studies. Tammetta likewise identifies just two zones of hydrological significance (see Section 15) and finds that the height of the zone of significant downward movement identified by extensometer data, the collapsed zone, essentially coincides with the height of the drainage zone (Section 4.3). This is demonstrated by data from above Longwall 7 of the Elouera domain of the Wongawilli mine (Section 20).

Figure 3.1 in Holla and Barclay's June 2000 book on subsidence in the Southern Coalfield depicts a two zone model, with a zone of large downward movement arching over a coal extraction. Tammetta's depictions are based on this figure, as he notes in his first Groundwater paper.

Numerical simulation work undertaken by Gale[35] (see Fig. 21), described by Prof. Galvin in his 2016 coal mine engineering book, is consistent with the work of Mills and that of Tammetta. Gale comments in his 2008 ACARP funded review[35]:

“*panel width typically controls the height of fracturing, the network connectivity and conductivity of fractures is controlled by the magnitude of strain and subsidence. Panel width, depth and seam thickness influence strain and subsidence. Geological factors also have an impact. It was found that the fracture connectivity was greater in stiff sandstone rich strata relative to strata having many coal and tuffaceous units. This was related to the ability of the overburden to flex and displace onto the goaf rather than fracture and rotate about the ribsides*.”

Gales’ work finds an inverted-parabolic zone of fracturing and elevated hydraulic conductivity forms over a longwall panel as a consequence of subsidence. As Figures 1 and 21 suggest, Tammetta’s two zone model is consistent with Gale’s numerical simulation work.

In a 2006 study of surface water inflows, Gale finds the following (see Fig. 23):

“*The results show that for situations of normal rock head, without significant aquacludes, panels with a width to depth ratio greater than one typically show confirmed connection. One site shows connection with a width to depth ratio of approximately 0.75. Panels with a width to depth ratio of less than 0.4 show no connection*.”

Gale characterises a ratio of 0.75 as transitional, with seam to surface connection increasingly likely above that value.

The available evidence argues that the height of the drainage zone, Zone 2 in the work of Mills, is determined primarily by the extraction width, extraction thickness/height and extraction depth. Other than in the kinds of exceptional circumstances identified by Tammetta and Galvin, local geology and geomechanics appear to be of no more than secondary importance.

As discussed in Sections 5 and 6, in obtaining his equation Tammetta followed “*a scientific approach to empirical research that is focussed on only investigating the effects of the most important or primary variables*”.[3], [18]

Tammetta’s work also satisfies the requirements Prof. Galvin highlights in his 2016 book[18] and 2017 PSM review[3], where he refers to University of New South Wales colleague Prof. Fidelis Suorineni[38];

“*To properly use empirical methods, one must understand the underlying assumptions and the databases used for their development (Suorineni, 2014). Given this and a reasonably clear understanding of the underlying physical phenomenon, empirical models can form the bases of valuable design tools*.”

The available evidence advises that the Tammetta equation offers a valuable design tool.

12. Use of piezometer and extensometer data

In both his peer review and his summary and explanation report Prof. Galvin refers to his 2016 book[18] ‘Ground Engineering - Principles and Practices for Underground Coal Mining’. The book has the following erroneous description of the Tammetta equation:

“*was derived by regression analysis of ground movement detected by multi-point borehole extensometers at 18 mines from nine coalfields in five countries*.”

Importantly, in contrast to Ditton and Merrick, Tammetta obtained his equation exclusively from centreline piezometer data. Prof. Galvin’s mistake is not repeated in his 2017 Dendrobium reports.

The book further comments:

> "*The relationship is not accepted universally, with a number of aspects warranting further research. These include the reliability of determining the horizon of zero pressure on the basis of extensometer data; the capacity to distinguish between depressurisation and zero flow; and how to also account for the effect of time on groundwater drainage height.*"

The comment alludes to the difficulty of using extensometers to locate the drainage zone. As noted in the July 2015 letter to the then Planning Minister and the follow-up report sent to the Minister in 2016, Tammetta comments on this limitation in his first Groundwater paper:

> "*Extensometer results have a larger scatter than hydraulic head results, because of the more chaotic nature of seismic energy release and the disproportionate effects of localized, unrepresentative defects or structural features*."

Prof. Galvin highlights the hydrological inadequacy of extensometer data in his December 2016 review of the SMP material for Dendrobium Longwalls 14 to 18:

> "*extensometers installed in vertical boreholes do not detect or measure the height of connective or continuous vertical fracturing. Rather, they measure vertical displacement associated with the opening of horizontal and inclined partings and fractures. These may or may not form part of a connective fracture network to the mining horizon*."

The NPA letter and report point out that Tammetta constructs his databases by discriminating between and separating centre-panel data, side-panel data, inadequate data and piezometer data from extensometer data. In contrast Ditton, obtained his equation from a mix of piezometer and extensometer data, most of which was from side-panel or off-panel instruments. Neither Galvin and Mackie nor Sullivan and Swarbrick note this important distinction between the work of Tammetta and that of Ditton and Merrick. Yet in his December 2016 review[16] of the then proposed SMP for Dendrobium Longwalls 14 to 18, Prof. Galvin comments:

> "*I question how information obtained from boreholes located off the centreline of a longwall panel and, in particular, over chain pillars and abutment pillars, as on this occasion can be utilized reliably to test the veracity of the Ditton & Merrick (2014) model for predicting the height of (connective) fracturing*."

Though they evidently misunderstand Tammetta's work, in discussing the hydrological significance of fracture connectivity, Swarbrick and Sullivan point out the advantage of piezometer data:

> "*The real measure of connection are the piezometric profiles over time, they are the best available means for quantifying the impact of mining on the hydrogeological regime, because they are a direct large scale measurement of any changes in the hydrogeological system. As such they are also a measure of hydraulic connectivity*."

And

> "*The most relevant direct evidence were the piezometer records due to their spatial and temporal coverage, the high reliability of the predominant instrument used (vibrating wire piezometer) and the response of groundwater pressures to interconnected fracturing, which is the basis of permeability*."

While Tammetta doesn't use extensometer data in obtaining his equation, he does in exploring the relationship between the drainage zone and the zone of relatively large downward movement of rock referred to as the collapsed zone. Tammetta finds that, within the limits of the available data, the two zones coincide. As discussed in Section 11, Mills uses extensometer data in identifying Zone 2 of his six zone model; Zone 2 would appear to correspond to Tammetta's drainage zone.

13. Zone boundaries

Prof. Galvin's 2016 book on coal mine engineering makes the following comment on the conceptual partitioning of rock into zones when considering the impact of mining;

> "*Although it is convenient to divide sub-surface behaviour into a series of zones with distinct physical and/or hydrogeological characteristics, in reality behaviour types, permeability and the lateral extent of affected areas change gradationally as depth of mining increases relative to panel width*."

Dr Mackie likewise comments in his review of the PSM report:

> "*I concur that fracture connectivity is best perceived as a continuum migrating from highly connected pathways in lower parts of the fractured zone to weakly connected and disconnected pathways in upper parts of the zone*."

In a recent review of impacts at Dendrobium (Section 25.2), Prof. Bruce Hebblewhite comments:

> " *these relatively simplistic conceptual models, while having a role to understand the overburden behaviour, should not be assigned too much importance. It is far more important to interpret the monitored, or modelled results directly to determine the nature of the effects and impacts of mining within the strata*."

These comments lack recognition of the extensometer studies reported by Mills[29], who observes the following:

> "*The interface between the zone of large downward movement and the less disturbed strata above and to the sides of this zone accommodates some relatively large differential movements for rock strata within a short distance. This interface zone is characterised by open shear fractures and fractures between rotated blocks of intact material*."

That is, Mills' extensometer data point to a relatively sharp physical boundary. A relatively sharp boundary is also suggested by the marked change in slope in the extensometer data graph of Figure 2 in Tammetta's 2013 paper (see Fig. 24). Physical models also point to a relatively sharp boundary (see Fig. 16). Tammetta refers to the zone of relatively large downward movement as the collapsed zone, while the rock beyond is referred to as the disturbed zone. Discussed in Section 6.2.1, within the collapsed zone the vertically 'destressed' rock has failed under horizontal (deviator) stress, while beyond the zone the rock is able to span the extraction void. The zone boundary manifests a pressure arch.[19]

In in his 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, Tammetta adopts Mills' six zone model of mining induced overburden disturbance. He suggests

> "*The transition between zone 2 and the overlying zone of bedding plane separation (zone 3) appears to be quite sharp in some geological settings. This transition can be an open void where a bridging unit in the overburden strata coincides with the top of zone 2*."

Zone 2 corresponds to the zone Tammetta identifies as the collapsed zone. In noting the 1998 Mills and O'Grady study at Clarence Colliery, Tammetta comments:

> “*The study also showed that there must be large, open voids created within the overburden strata around the sides of the zone of large downward movement and potentially also at the top of it (in the sandstone strata at this site)*.”

Tammetta locates the drainage zone boundary between the highest piezometer that reports no pressure head and the lowest that reports a positive pressure head (see Fig. 1 and Fig. 24). The zone highlighted by Tammetta, the drainage/depressurised/desaturated zone, is a physically detectable zone and is then more than a convenient notional concept. That is, at some depth below the surface over an extraction, there will be a point where a piezometer is unable to report a pressure head above zero (within its uncertainty envelope).

As noted in Section 4.3, within the limits of the coarse-grained nature of the available data, imposed by instrument placement intervals, Tammetta finds the drainage zone coincides with the collapsed zone:

> “*A close relationship is apparent between the empirical equation for H derived from hydraulic head measurements, and the height where a large change in downward movement occurs. Given the equivalence between the two independent data bases, H is taken as being equal to the top of the zone of large downward movement. The desaturated zone and the zone of large downward movement are considered to be coincident. Extensometer results have a larger scatter than hydraulic head results, because of the more chaotic nature of seismic energy release and the disproportionate effects of localized, unrepresentative defects or structural features*.”

Discussed in Section 11, this is consistent with the following suggestion[29] from Mills:

> “*there is likely to be significant disturbance to the overburden strata in Zone 2 with depressurisation of the groundwater system in this zone likely*.”

Zone 2 corresponds to the zone of relatively large downward movement; the collapsed zone. That is, the hydrological drainage zone and the geotechnical collapsed zone are physically locatable zones with identifiable and, it seems, at least approximately coincident boundaries. Tammetta refers to the zone beyond this boundary, where a pressure head is maintained, as the ‘disturbed zone’ (see Fig. 1).

Not discussed by PSM, Mackie, Galvin or Hebblewhite, Tammetta’s 2015 Groundwater paper[12] finds a sharp transition in hydraulic conductivity along the depth profile over an extraction, that corresponds to the boundary of the collapsed zone. The paper assesses evidently gradational changes in hydraulic conductivity within the zone.

The PSM, Mackie and Galvin reports do not consider Tammetta’s two zone model. Yet in commenting on the traditional multi-zone geotechnical model PSM recognised that “*The important elements of this conceptual model for this study are related to two zones:*” (see Section 15). Nor do the PSM, Mackie and Galvin reports note the correspondence between Tammetta’s model and the two zone model of Whittaker and Reddish (see Section 11), nor the similarity to the depiction of the zone of large downward movement in Fig. 3.1 of Holla and Barclay’s 2001 subsidence book[48] for the NSW Government, or the boundary correspondence with Mills’ Zone 2 (Section 11).

13.1 Confusion by terminology

In his review of the PSM review Prof. Galvin draws attention to the confusion that may arise when reference is made to the 'height of fracturing' over a coal extraction. He comments as follows;

> "*To a geologist, this is likely to mean the height to which any fracturing of rock is observed, irrespective of the nature of the fracture network that it may be associated with. An underground coal geotechnical engineer, on the other hand, may take it for granted that the term refers to the 'height of connective fracturing', with the understanding that there is no connected fracture network to the surface above this height. Some hydrogeologists experienced in underground mining adopt the same model of ground behaviour as coal geotechnical engineers but conceptualise the 'height of connective fracturing' as the 'height of free drainage' that is then overlain by a zone of drainage through a 'tortuous connective fracturing network'*."

Prof. Galvin recognises that will be a point at which water drains relatively freely towards the mine and acknowledges the central importance of the height of the drainage zone:

> "*The height above mine workings from which groundwater freely drains is a particularly important consideration when constructing the geometry of a numerical groundwater model and assigning values to the parameters that define groundwater flow in the model*."

Understanding how mining impacts a catchment area is primarily a question of hydrology and central to that understanding is the height of the drainage zone. The mechanism of the formation of the drainage zone and the characterisation of fractures within and beyond that zone is of less importance in this context. The use of geomechanical terminology causes distraction and confusion and would seem best avoided. Tammetta's hydrological identification of the 'drainage zone' avoids the confusion inherent in referring to the 'fracture zone' and the 'height of fracturing', when discussing mining impacts on groundwater. In other contexts reference to the 'collapsed zone' would assist in avoiding confusion.

14. Tammetta's description of rock behaviour over a coal extraction

Tammetta provides a detailed summary of caving and collapse in his 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining Tammetta. The account includes an historical summary and is framed with respect to Mills' six zone model (Section 11). Further detail is provided in the supplementary material[32] for his second Groundwater paper, published in 2015. The accounts overlap and complement descriptions provided in Prof. Galvin's 2016 book on coal mine engineering.

In his third Groundwater paper[13], published in 2016, Tammetta provides the following brief summary of caving over a coal extraction:

> "*When a longwall or pillar extraction panel is mined, a void is created, having approximate dimensions of the mined thickness by the panel width, in section. This void poses an unstable state for the system, and caving ensues to allow redistribution of the empty void into the surrounding strata*".

And:

"*The goaf occurs between the mined floor and the overlying collapsed zone (see the following discussion). It is characterized by rotation and translation of rock blocks with respect to each other, where the layered pattern of the rock mass is lost and the resultant material forms a rubble with a broad range in fragment size (up to several meters or more). At some distance behind the longwall face, overburden pressure reestablishes and compacts the goaf from its initial thickness at the face. The resulting shape of the goaf is squat in cross-section with vertically extended lobes near the panel edges, with the greatest compaction along panel center (Xu et al. 2010; Bai and Elsworth 1989; see also Wachel, 2012).*"

Tammetta identifies the collapsed zone as a zone of relatively large downward movement, the apex of which is located by a sharp change in slope in a graph of centreline extensometer data. This is illustrated in Figure 2 of his first Groundwater paper (Fig. 24 below).

As noted above and in the December 2016 NPA report, a detailed summary of caving and the he formation of the collapsed zone is provided in the supplementary material[32] for the second Groundwater papers, published in 2015. This account of subsidence and the evolution of the collapsed zone given in the supplementary material draws in particular on a CSIRO extensometer study at a mine in Queensland, reported by Michael Kelly in 2000 (see Figs. 19 and 20). Involving the formation of ill-fitting and fractured spalls (Fig. 19, which is Fig. A1(c) from the supplementary material for Tammetta's second Groundwater paper[32]), the process is quasi-discrete with variable intervals between events:

"*As a longwall advances, caving occurs as quasi-discrete events. At some mines, the first caving event may occur when the distance of advance is comparable to the panel width (depending on structural features and rock strength). The first collapsed block frequently has a pseudo conical shape. The shapes of subsequent collapsed blocks are concave-down spalls whose upper surfaces resemble a part of a pseudo cone and whose lower surfaces have the shape of the upper surface of a preceding block. The shape of a spall is similar to a longitudinal portion of a conical tube. Figure A1a illustrates this process using the results of a numerical simulation, showing the evolution of the collapsed zone in three dimensions (Abouzar et al. 2010). The lower surface of a spall will not easily mate with the upper surface of the preceding spall or block. These surfaces are likely to be sub-vertical in the interior of the collapsed zone, along most of the length of the panel. At longwall start-up initial spall surfaces may be more sub-horizontal (see the example below). The body of a spall will be highly fractured, and the spall is unlikely to act as a rigid body. The aperture of the poorly mated surfaces of adjacent spalls is likely to be significantly larger than intra-spall fracture apertures, at a given depth.*"

And:

"*the collapse process is not just dimensionally-based (that is, according to void size), but that part of the process is time-dependent (that is, there occurs a gradual weakening or relaxation of strata prior to a collapse).*"

And:

"*The main zones created by the caving process are interpreted from previous work to be the collapsed zone (immediately above the mined seam) and the overlying disturbed zone*"

Tammetta suggests a transition, rather than a distinct boundary, in the character of the rock disturbance between the floor of the extraction and the top of the collapsed zone. Referring to Zones

1 and 2 identified by Mills (Section 11), in his 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining Tammetta comments:

> "*The chaotic zone (zone 1) extends to a height generally indicated in the literature as being about 10–15 times the seam thickness, although the boundaries of this zone with zone 2 are likely to be transitional*."

Tammetta's accounts of caving and collapse provide a geomechanical basis for his finding that the collapsed zone (identified by geotechnical data) appears to coincide with the drainage zone (identified by hydrological data). Sullivan, Swarbrick, Mackie and Galvin appear to be unaware of Tammetta's accounts. Their reports also lack recognition of Tammetta's two zone hydrogeological model (see Fig. 1 and Sections 13 and 15), comprised of the drainage zone and the continuum of the disturbed zone.

The geomechanical context provided in Tammetta's summaries draws on the extensometer work of Mills and O'Grady[30] and the numerical work of Gale.[35] The work of Mills and O'Grady is referred to in Tammetta's first Groundwater paper. Mills and O'Grady find an inverted parabolic collapsed zone (see Fig. 18) and this is supported by Gale's numerical simulation work (see Fig. 21). Tammetta also refers to a 1968 study by Dowdell[47] that finds a parabolic profile for the collapsed zone.

At the coarse grained level of the patchy available data and in the absence of refutation, the Tammetta equation evidently captures the hydrological consequences of the rock behaviour documented by Kelly, Gale, Mills and O'Grady and others.

14.1 Mills and O'Grady's study of collapse over Longwalls 4 and 5 at Clarence Colliery

As mentioned above, in his first Groundwater paper Tammetta refers to a 1998 paper by Mills and O'Grady in discussing the shape of the collapsed zone, which corresponds to Zone 2 of Mills' six zone model (see Fig. 22). Informing the development of Mills' model, the 1998 paper reports a detailed extensometer study of overburden collapse over Longwalls 4 and 5 at the Clarence Colliery. As shown in Figure 18 below, the study finds that the cross-section profile of the collapsed zone, the zone of significant downward movement, approximates that of an inverted parabola.

The paper reports that the coal seam is level and has a thickness of 3.6 to 3.8 metres. The depth of cover is 240 metres over the 160 metre wide Longwall 4 (width to depth ratio of 0.67) and 260 metres over the 200 metre wide Longwall 5 (width to depth ratio of 0.77). The overburden includes two massive sandstone units.

Referring to the zone of large downward movement, the paper includes the following observations:

> "*The zone of movement extended through the overburden strata to a height of approximately 1.0-1.1 times the panel width. The height of movement was greatest in the centre of the panel decreasing on each side nearer to the chain pillars. Movements within the overburden strata occurred as downward movements of discrete blocks. Separation was concentrated at horizons 20 m, 50 m, 100 m and 130 m above the coal seam*."

And:

"*The progression observed was cyclical. Initial movements were concentrated below a series of parting horizons. The magnitude of movement below each horizon continued to increase until a point when there was downward movement "en masse". At some stage during the latter stages of this process, a new separation horizon developed higher up in the sequence and the cycle was repeated*."

And, referring to Longwall 5:

"*The longwall panels were not wide enough for large downward movements to extend through to the surface. The upper 40 m or so of overburden strata bridged across the panel. The downward subsidence in the centre of the panel was 185 mm when the longwall face was 250 m past. Approximately half of this subsidence was associated with elastic compression of the chain pillar between Longwalls 4 and 5 and the immediate roof and floor strata. The remaining 80-90 mm was associated with downward sag deflection of the overburden*."

Notwithstanding their differences in widths and seam depths, in both cases the top 40 m or so of the overburden strata remained relatively unaffected by the deeper subsurface movements and both were found to have much the same small sag subsidence. The differences in widths is however reflected in the height of their respective collapsed zones:

For the 160m wide longwall, the top of the zone was 170-180 m above the coal seam. For the 200 m wide longwall panel, the top of the zone was 200-210 m above the coal seam."

As discussed in Section 20 below, extensometer studies over Longwall 7 at Elouera undertaken by Mills also find that the height of the collapsed zone is approximately equivalent to the extraction width (width to depth ration of 0.51 and an extraction height of 3.4 metres).

15. Failure to recognise Tammetta's two zone hydrogeological model

In their report for PSM, Sullivan and Swarbrick make the following observations in presenting the traditional multi-zone geotechnical view of caving and collapse:

"*The important elements of this conceptual model for this study are related to two zones:*

1. The Constrained Zone is where deformations of the rock mass are sufficiently low as to cause little depressurisation and pre-mining groundwater pressures are essentially maintained.

2. The Caved and Fractured Zones, where deformations to the rock mass are sufficient to cause full depressurisation. The rock mass becomes desaturated or fully (100%) depressurised.

The Sullivan and Swarbrick report offers two key findings:

1. *There is no widespread evidence of a Constrained Zone limiting effects of mining and impacts on the more shallow ground and surface water systems.*

2. There is no evidence of desaturation, rather the data shows the rocks remain saturated but with very significantly depressurisation.

Discussed in Section 18, the second finding reflects a fundamental misunderstanding of Tammetta's work that negates many of their criticisms of the Tammetta equation and undermines much of the value of their report more generally.

The first finding effectively demonstrates the hydrological utility of Tammetta's two zone model (Fig. 1), which is comprised of the drainage zone and the surrounding 'disturbed zone'. Sullivan and Swarbrick fail to equate their summary of the "*important elements*" of the traditional model and their first "*key fining*" observations to Tammetta's model.

16. Critical omission - the wide range of rock types represented in the Tammetta database

None of the recently released reports acknowledge that Tammetta's database covers a diverse range of rock types. As pointed out in the 2016 NPA report and noted above, Tammetta's 2013 Groundwater paper (one of three) effectively demonstrates, in the absence of refutation and the coarse grained nature of the available data, that a knowledge of longwall extraction width and height and mining depth is sufficient to provide an estimate the height of the drainage zone to within 8%, across a variety of rock types comprised of:

> "*claystones, coarse-to-fine sandstones (lithic and quartzose), and limestones, in widely varying strengths, grain sizes, compositions, layer thicknesses, and recurrence patterns*".

Contradicting Tammetta, is his June 2017 summary and explanation report Prof. Galvin advises:

> "*It is also important to appreciate that the behaviour being described is sensitive to geology and can be modified in the presence of strong and massive stratum*."

Tammetta's work suggests that, to within 8%, these effects are not significant. Neither Sullivan and Swarbrick nor Mackie and Galvin fault Tammetta's database or provide contradictory data. Not noted by Sullivan and Swarbrick or Mackie and Galvin, in his global search Tammetta finds two locations representing exceptional circumstances.

As discussed in Section 6.2.5 and in the December 2016 NPA report, in the supplementary[39] material for his first Groundwater paper Tammetta discusses super-strong dolerite sills in South Africa, that have an observed drainage zone height lower than calculated using the equation. Tammetta comments:

> "*The effect of super-strong massive rock, as observed in South Africa, is unusual, and is worth exploring by analysis of field observations as a rare case where rock type is known to impact H*."
>
> "*This is a unique situation not observed at any other location in the databases of the paper. Field measurements and theoretical studies have shown that strong dolerite sills behave like elastic plates close to the point of failure (Salamon et al., 1972, in Wagner and Schumann, 1991), a most remarkable property*."

The supplementary material may not have been read by the authors of the recent reports. The South African dolerite sills are pointed out as an exceptional location in Prof. Galvin's 2016 book on coal mine engineering. That Tammetta refers to the same location is not mentioned in Prof. Galvin/s February 2017 PSM review or his June 2017 summary and explanation document.

Also pointed out in the December 2016 NPA report, as mentioned earlier, in a September 2014 Russell Vale impact assessment report[25] commissioned by the Department, Tammetta comments:

"*Despite a thorough search of the literature, no other published data could be found to show significant deviations from the equation*".

None of the recently released reports present or point to data contradicting the equation.

Of note, as discussed in the NPA report, in the discussion in the Russell Vale report noted above, Tammetta attributes delays in the formation of the drainage zone over a longwall at Mandalong to anomalously high horizontal stress. The NPA report suggests that this effect may account for the inconclusive data from the centreline bores over Dendrobium Longwall 9.

17. Critical PSM shortcoming - no database assessment

Recommendation (vii) in the July 2015 letter to the then Minister for Planning includes, in part, the following:

"*Independent (non-industry related) expert panel review of the equations and databases used for the 2014 Springvale and Dendrobium Area 3B groundwater assessments and those used for the 2012 Dendrobium Area 3B assessment and published in the journal Groundwater*."

It's understood this recommendation was included in the scope of work assigned to PSM in April 2016 and then undertaken by Sullivan and Swarbrick for PSM. The database underpinning the 2012 Dendrobium assessment is that of hydrologist Paul Tammetta, while that for the 2014 Springvale and Dendrobium assessments is that of mining company consulting engineer Steven Ditton and mining company consulting hydrologist Dr Noel Merrick, founder of consultancies Heritage Computing and HydroSimulations.

The final report returned by Sullivan and Swarbrick in March 2017, which presumably reflects their response to the February 2017 review reports from Galvin and Mackie and earlier advice from these consultants, has at least two critical flaws:

(i) It fails to assess the Ditton-Merrick and Tammetta databases.

(ii) It fundamentally fails to understand Tammetta's work and the later work of Ditton and Merrick (see Section 18).

In his February report Galvin comments on the first shortcoming as follows:

"*The report does not analyse the evidentiary databases and provides only a cursory assessment of the reliability of data points and statistical methods used by Tammetta and the potential sources of uncertainty. I consider these to be critical shortcomings, especially the failure to establish the veracity of the Tammetta database*."

And

"*In summary, the analysis presented in the PSM report does not go to the heart of the SOW pertaining to this height of fracturing model and, hence, is of limited assistance in resolving the issues surrounding the technical integrity of the Tammetta equation and its application to Dendrobium Mine*."

The comments highlights the significance of the Tammetta equation.

Given PSM's failure to assess the Tammetta and the Ditton-Merrick databases, the July 2015 letter to Minister Stokes and its elaboration and expansion in the December 2016 NPA report provided to the then Minister for Planning and the Department remain the only reviews of the databases. While hampered by lack of access to data and information held by mining companies, the NPA finds the

Ditton-Merrick database ill-suited (Sections 8.5. 10 and 12 in this report and Section 6 and other sections in the NPA report), while that of Tammetta is well suited and carefully constructed (Section 7 and other sections in the NPA report). Though requested by the NPA, the Department of Planning did not refer the December 2016 report to the consultants.

Tammetta's carefully constructed databases reflect Prof Galvin's expectations of empirical equation determination:

> "*in most instances in ground engineering for underground mining, it is not possible or practical to perform a sufficient number of experiments or to analyse a real engineering problem exhaustively in terms of all possible variables in order to obtain quantitative general solutions. This is addressed by adopting a scientific approach to empirical research that is focussed on only investigating the effects of the most important or primary variables. Success is dependent on identifying all of these variables and having a database which contains sufficient relevant information to evaluate the influence of them (Salamon, 1992; 1993).*"

Of note, PSM and Galvin note data access difficulties. Galvin for example comments "*I have also had to rely on information contained in consulting reports by DgS that are in the public domain*." Lack of access to data and information held by mining companies was highlighted in the May 2014 report of the NSW Chief Scientist on cumulative impacts in the Sydney Catchment. None of the recommendations of that report appear to have been acted upon.

Entries in the Ditton-Merrick and the Tammetta databases are considered in Sections 6 and 8 to 12 of the December 2016 NPA report.[17] Of direct relevance to Dendrobium, sections 5 and 12 in the NPA report find, for example, that the centreline piezometer data from nearby Longwall 7 at the adjacent Elouera mine (Figs. 26 and 27) support the Tammetta equation. Figure 28 below (Fig. 16 in the NPA report) demonstrates how the piezometer data provide the drainage height; see Section 20.

Of relevance, the Elouera bore was one of two drilled to provide field data to inform concerns raised by the Dams Safety Committee prior to their approval for mining in Dendrobium Area 1. The drilling was undertaken by consultancy Strata Control Technology (SCT), for which Dr Kenneth Mills is a director and principal geotechnical engineer. Mills' six zone overburden disturbance model is discussed in Section 11.

As an example illustrating the problematic nature of the Ditton-Merrick database, Section 11 in the NPA report notes that the March 2014 HydroSimulations report introducing the Dendrobium groundwater model that, belatedly, replaced Tammetta's model states:

> "*The Ditton (2012) height of fracturing estimate is near-perfectly matched with the observed height of fracturing data for Longwall 5*".

Echoing this, their October 2015 height of connected fracturing report[49] for Area 3B states:

> "*This is further confirmed with the Ditton (2013) method for calculating the height of fracturing found by HydroSimulations (2014) to be a good match with observed data from Longwall 5*".

Longwall 5 lacks a centreline piezometer bore. In Section 15.1.4, the NPA report seeks and fails to identify which monitoring site(s) would have provided the referred to data. As noted in the 2015 NPA letter and in Section 18 of the 2016 NPA report, clarification was sought and denied from HydroSimulations.

18. Critical PSM shortcoming – lack of understanding of Tammetta

A second critical flaw is evident in the following comment in the PSM report:

> "*It is a key finding of this report that the groundwater response at Dendrobium has not exhibited full depressurisation at any height apart from the near surface zone (as defined generally and not specifically by depth or related to conventional subsidence model zones) in any piezometer. In all cases pore pressure profiles exhibit a gradual change in depth and do not exhibit discontinuities as suggested by Tammetta (2013)*".

Of significance, this comment is made in the final PSM report, which followed the Mackie and Galvin reviews of the earlier drafts. PSM puzzlingly fail to respond to the comments made Mackie and Galvin, who point out that full depressurisation would only be expected over the extraction (see Fig. 1).

The December 2016 NPA report notes (e.g. Section 15.1) comments similar to those of PSM, made by HydroSimulations in their flawed and misleading October 2015 height of connected fracturing assessment[49] and March 2016 groundwater impact assessment[50] for the then proposed SMP for Dendrobium Longwalls 14 to 18. In the 2016 assessment HydroSimulations comment "*There are numerous 'little or no depressurisation' points below the calculated Tammetta H level, which is conceptualised as the height of complete groundwater drainage.*"

Like HydroSimulations before them, Sullivan and Swarbrick evidently misunderstand Tammetta (and Ditton). As Figure 1 below indicates, the Tammetta's drainage zone is largely contained within the extraction panel(s). With the puzzling exception of Longwall 9 (December 2016 NPA report Section 16.7) there are currently no post-mining functioning centreline piezometers over the Dendrobium mine, as also noted by Galvin and Mackie. That is, with the noted exception, there are currently no functioning instruments that would expected to show zero pressure to the height predicted by the Tammetta equation. Beyond the drainage zone, which is located over the extractions, the rock remains saturated.

The PSM report has the following incorrect advice; "*The Tammetta (2014) HoF model assumes associated changes to hydraulic conductivity and storativity within an idealised parabolic area of influence above the collapse zone.*" The cross-section profile depicted in Tammetta's is based on the available evidence and represents a conclusion, not an assumption.

The work of Mills and O'Grady and others finds that the profile of the collapsed zone across the width of a longwall extraction approximates that of an 'upside down' parabola centred over the longwall and 'sitting' on the coal pillars that form the sides of the extraction and support the overlying strata.[11], [12], [30], [51] The work of Gale and that of Holla and Barclay[48] finds no significant lateral extension beyond the pillars. Gale finds;

> "*The zones of significantly enhanced conductivity about a longwall panel are contained inside the panel, and slope inward to the panel*".[35]

And;

> "*The results of the study indicated that the conductivity of the overburden is not significantly impacted adjacent to the panel edge. In the cases studied, the conductivity of the ground was not impacted 50m from the ribline. The flow networks created adjacent to longwall panels are*

> *typically related to conductive coal seams which depressurise and induce seepage through the overburden. The conductivity of the overburden is essentially unchanged from the in situ state, however the pore pressure distribution may be modified*."

The PSM report conclusion that "*the entire premise upon which the Tammetta (2013) and Ditton and Merrick (2014) models are based is not applicable to Dendrobium*" is fundamentally incorrect. This critical misunderstanding may also be the origin of the following criticism of both the Tammetta and the Ditton-Merrick equations:

> "*They ignore any site specific geological conditions, which have a significant effect on HoF estimates at Dendrobium*."

In the absence of reliable centreline data, there is no basis for this suggestion. Further, the comment ignores or is unaware of the centreline piezometer data over Longwall 7 at the adjacent Elouera domain of what is now the Wongawilli mine (see Section 20). As noted in the December 2016 NPA report, the stratigraphy above the mining in the Southern Coalfield is dominated by sandstone, with essentially the same repeat pattern (see Fig. 25).

Also overlooked by PSM is that Tammetta's database spans a variety of rock types comprised of "*claystones, coarse-to-fine sandstones (lithic and quartzose), and limestones, in widely varying strengths, grain sizes, compositions, layer thicknesses, and recurrence patterns*" (Section 16).

19. Critical shortcoming – missed validation opportunity

Recognising the importance of centreline piezometer data, Dr Mackie's review comments include the following observations on the Tammetta and the Ditton-Merrick equations:

> "*These equations attempt to predict the height of connected cracking and free drainage within the subsidence zone. Since each equation generates a significantly different answer for Dendrobium conditions, logic dictates that one or the other is more representative. A sensible approach to address this issue is to validate the equation(s) using local piezometric observations. Unfortunately there is not a single piezometer at Dendrobium that provides continuous pore pressure observations before, during and after mining and is located centrally within a panel*."

The quoted comments highlight a missed opportunity for PSM, in part because they fundamentally misunderstand Tammetta's work in not appreciating the importance of centreline piezometer data and in expecting full depressurisation beyond the drainage zone (see Section 18 and Fig. 1).

The height estimates provided by the Tammetta equations are much greater than those of the Ditton-Merrick equations. Accordingly, in the absence of unusual geological circumstances, large difference in off-panel horizontal and vertical hydraulic conductivities admit the use of side-panel and off-panel piezometer data to indicatively probe the drainage zone height, albeit indirectly, and test the estimates returned by the Tammetta and Ditton-Merrick equations (see Fig. 1).

This is recognised and utilized in the December 2016 NPA report, which finds the Dendrobium piezometer data consistent with the estimates of the Tammetta equation. Of note, as discussed in the December 2016 NPA report, the notably large distances over which drawdowns are observed at Dendrobium are readily rationalised by drainage zones with the heights suggested by the Tammetta equation.

The December 2016 NPA report is currently the only report that comparatively assess the Tammetta and Ditton-Merrick databases. Though requested by the NPA, the Department of Planning did not refer the report to the consultants.

20. Elouera Longwall 7

Elouera Longwall 7 is discussed in Section 12 of the December 2016 NPA report and much of that discussion is reproduced here. The Dendrobium mine is effectively an extension of the Elouera mine, which adjoins the southern boundary of Dendrobium (see Figs. 26 and 27) and is now part of the current Wongawilli mine. Elouera Longwall 7 has a depth of cover of 368 metres, an extraction height of 3.4 metres (up to 1.1 metres less than the extraction heights of Dendrobium Area 3B) and an extraction width of 190 metres (115 metres less than the mining width of Area 3B).

As noted in Section 5 of the December 2016 NPA report, there are no unusual geological structures over the Elouera longwalls. Figure 27 below shows that a nephaline syenite intrusion slightly protrudes into the south eastern corner of Area 3B, but has minimal overlap with the Area 3B longwall extractions.

Sunk at the request of the Dams Safety Committee (DSC), Longwall 7 has a centreline bore referred to as DDH9 that hosts four vibrating wire instruments. Figure 6 of the October 2012 Coffey groundwater impact assessment[7] for Dendrobium Area 3B represents and interprets 2009 piezometer data from this bore and a second evidently located over the northern pillars of the northern most Elouera longwall, Longwall 8, referred to as DDH8. Reference to this figure suggests that Elouera Longwall 7 correspond to the Mine A entry in Tammetta's database.[39]

Figure 28 below was obtained by digitising the Coffey figure, extracting the represented pressure heads and graphing these pressures with respect to the measurement depth. All of the instruments are located above the depressurised zone, the drainage zone. The pressure heads increasingly deviate from the hydrostatic pressure line, with the lowest instrument recording a pressure head of 32 metres at approximately 146 metres below the surface.

It's possible that the hydraulic pressure then increases, rather than continues to decrease below this depth, before then again falling with depth until the underlying drainage zone is reached. Requiring a second sink located above and independent of the drainage zone over the longwall extraction, this seems unlikely. The profile in the graph of Figure 28 instead indicates an inverted water table perched at the drainage zone interface. The profile suggests the 'half tear-drop' profile highlighted by Tammetta in a June 2013 groundwater impact assessment review[52] commissioned by the Department of Planning for the proposed expansion of the Russell Vale Colliery:

> "*The profile shape resembles a half tear-drop, commonly seen above collapsed workings prior to, or at, equilibration throughout the profile. The base of the tear represents a significant downward gradient, with vertical flow dependent on the vertical hydraulic conductivity, not the lateral conductivity measured by the packer tests*."

Tammetta notes this profile is seen elsewhere in the Southern Coalfield and around the world; examples are found in his November 2012 revised groundwater impact assessment data analysis report for then proposed mining in Area 3B of the Dendrobium mine.

Conservatively extrapolating the profile to a pressure head of zero provides a drainage zone elevation estimate of 252 metres, corresponding to a height above the seam of 186 meters. In assuming a constant hydraulic pressure loss with depth towards the drainage zone, this is more likely to be an underestimate than an overestimate. The Tammetta database records an interpreted drainage zone height of 195 metres and this presumably assumes a half tear-drop profile, rather than the one to one gradient assumed in Fig. 28.

As noted in Section 14.1 above, extensometer measurements over Longwall 7 of the former Elouera mine undertaken by SCT and assessed by SCT director and principal geotechnical engineer Dr Ken Mills as part of the study requested by the DSC, found that the height of Zone 2 of the Mills model (see Fig. 22 and Section 11) corresponds approximately to the extraction width. That is, the 190 metre height of the collapsed zone found from the extensometer data corresponds to the drainage zone height estimate found from the piezometer data. This is consistent with Tammetta's published[11] finding that the heights of the collapsed zone and drainage zone essentially coincide. Of significance, Tammetta notes[10] the following:

> "*It is understood that great difficulty was encountered during the drilling of DDH09 below a depth that was coincident with the predicted H, precluding installation of VWP units in the collapsed zone*."

The height estimate returned[8] by the Tammetta equation for Elouera Longwall 7 is 198 metres.

In contrast, the height estimate returned by the Ditton geometry equation is 112 metres, while that from the Ditton geology equation with an adjustment term of 32 is 128 metres and 131 metres with an adjustment parameter of 30. An adjustment term of 12.5 is needed in order for the Ditton geology equation to provide a fracture zone height estimate that matches the height obtained from the centreline piezometer data from Elouera Longwall 7.

The Elouera Longwall 7 piezometer and extensometer data are not included in Ditton's database and are not mentioned in either the 2014 or the 2016 HydroSimulations or 2017 HGEO groundwater assessments[14], [26], [50] for Dendrobium Area 3B. The Elouera Longwall 7 results are not mentioned in the March 2015 Parsons Brinckerhoff connected fracture report for Dendrobium Area 3B Longwall 9 and nor are they mentioned in the PSM, Mackie and Galvin reports.

As noted in Section 4.5, replacing past use of the Ditton-Merrick equations by HydroSimulations in providing groundwater impact assessments for the Dendrobium mine, the HGEO report of October 2017 uses Mills' rule of thumb in gauging the height of the drainage zone in the vicinity of Wongawilli Creek tributary WC21. The report concludes that the zone would approach and, in some parts, reach the catchment surface above the mine (see Section 24.3). The SCT report[31] assessing the Elouera Longwall 7 extensometer data was provided to BHP-Billiton in 2005.

Consistent with the findings by Mills, a 2006 study[36] by Gale finds the likelihood of seam to surface connections increases as the depth of cover to extraction width ratio increases beyond a 'transitional' value of 0.75 (see Section 11 and Fig. 23). The Tammetta equation suggests the Mills rule would underestimate the drainage zone height over the extractions of Dendrobium Area 3B (see Section 4.5).

As noted in Section 4.5, HydroSimulations use the Tammetta equation in their March 2018 groundwater modelling in support of the proposed mining of Dendrobium Longwalls 14, 15 and 16.

Earlier reports and assessment by the consultants for various mines in NSW have endeavoured to discredit the Tammetta equation.[17]

The author of the HGEO report contributed to HydroSimulations groundwater impact assessment of March 2016, that was provided as part of the SMP proposed for Dendrobium Area 3B longwalls 14 to 18 (discussed in the December 2016 NPA report). The March 2016 assessment partnered an October 2015 height of connected fracturing assessment from HydroSimulations. Discussed in the December 2016 NPA report, both of the HydroSimulations reports purport to represent evidence that the Dendrobium piezometer data are consistent with the Ditton-Merrick equations. The NPA report finds otherwise. The recent use of Mills' rule of thumb, some 12 years after the SCT report of 2005, and the Tammetta equation implicitly acknowledges the contradiction between past assessments provided by HydroSimulations and the weight of the accumulating evidence.

20.1. GHD's interpretation of Elouera Longwall 7

A 2007 GHD hydrogeology assessment[53] for a then proposed Area 3 consent modification discusses the 2005 SCT assessment[31] of extensometer data from two bores sunk over and beside a longwall at the Elouera Colliery. Identified as DSC12 and DSC13, they are likely to be the same bores subsequently used to house piezometers and relabelled DDH8 and DDH9. GHD report that the SCT study finds, like their earlier Clarence Colliery study (Section 14.1), that the zone of large downward movement develops in an arch shape, or perhaps flat-topped triangular shape (in recognition of horizontally bedded stratigraphy) above a longwall extraction (see Fig. 22 below; the SCT report does not appear to be publically available). As noted in Section 14.1, the height of the arch is found to be approximately equal to the panel width, which is 190 metres for Longwall 7; essentially the same height as found from the DDH9 piezometer data. As noted above, this is consistent with Tammetta's published[11] finding that the heights of the collapsed zone and drainage zone coincide.

GHD attempt to combine the SCT findings with conclusions from a 1992 study of Central Coast data by Forster and Enever[54] that relate subsidence zones to mining height (see Fig. 29); width and depth are excluded. Remarkably, in doing so, GHD implicitly suggest that the zone of large downward movement identified by SCT, Zone 2 in Mills' model (Section 11), would not result in depressurisation. Accordingly, GHD place the upper 60% of the collapsed zone in a constrained zone defined by GHD, following Forster and Enever, as follows:

> "*A Constrained Zone will exist above the Fractured Zone, probably in an arch shape, up to a height of 1.5 m or to within 15 to 30 metres of the ground surface within which little variation in vertical permeability exists, but increases in horizontal permeability occur through shearing and limited bed separation*." (Note: "1.5 m" appears to be a typographical error and should perhaps instead be '1.5 W')

The stark contradiction inherent in suggesting that 60% of the zone of large downward movement, Mills' Zone 2, is within the constrained zone is overlooked or ignored by GHD.

In contrast, accommodating the evidence reported by Mills, in a 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, prepared on behalf of Coffey Geotechnics, Tammetta instead extends the 'distressed zone' of the Forster and Enever Central Coast based model to match Zone 2 of the Mills model (see Figs. 29 and 30).

In an October 2015 height of connected fracture assessment[49] for the subsidence management plan (SMP) proposed for Dendrobium Area 3B longwalls 14 to 18, discussed in Section 16 of the 2016 NPA report, consultants HydroSimulations present a summary of the GHD assessment and its account of the SCT extensometer study of longwall subsidence at the Elouera mine. The summary doesn't mention, however, that SCT find the zone of large downward movement above the longwall to be at a height equivalent to the longwall width, or that SCT found likewise at Clarence Colliery. Nor does the report mention Mills' conclusion that Zone 2 is a zone of depressurisation. The 2015 HydroSimulations report asserts that the Dendrobium piezometer evidence is consistent with the drainage zone height estimates provided by the Ditton-Merrick equations. The December 2016 NPA report finds that this is not the case.

The Elouera and Clarence studies are not mentioned in the PSM or Mackie reports, nor Prof. Galvin's summary and explanation report. While the Clarence study is referred to in Galvin's PSM review, the Elouera study is not mentioned.

21. Tahmoor Longwall 10A

A candidate validation data set not represented in either the Tammetta or the Ditton-Merrick databases is that of the piezometer data obtained by consultants SCT from the centreline of Longwall 10A at the Tahmoor mine. The bore drilling, instrument installation and data assessment project undertaken by SCT was commissioned in 2012 by the mine operators in preparation for the proposed Tahmoor South expansion. At a depth of 420 metres, Longwall 10A has a modest geometry in being 235 metres wide and having an extraction height of 2.25 metres.

In June 2014 the Community Consultative Committee for the Tahmoor mine was advised[55] that the data were in good agreement with the estimated drainage zone height returned by the Tammetta equation. However, though requested, the results were not made publically available by the mine operator and did not become available until presented[34] by SCT at a conference in November 2017. The SCT data find a drainage zone height of approximately 140 metres and the consultants note that the Tammetta equation provides a height estimate of 147 metres, in close agreement with the value obtained from the piezometer data (see Fig. 31).

The SCT conference paper doesn't mention or refer to the Ditton-Merrick equations and doesn't provide a comparison with the height estimates obtained from the equations. A comparison is, however, of relevance in the context of this report. Ditton's geometry equation provides a drainage zone height estimate of 108 metres and, with the "*effective strata unit thickness*" adjustment factor value of 30 used by Ditton and Merrick for the Dendrobium mine, the geology equation returns an estimate of 128 metres. An adjustment factor of 24 is needed for the geology equation estimate to match the height found by SCT. The uncertainty estimates provided for each equation suggest that the Tahmoor data provide only weak support for the Tammetta equation. As noted in the 2016 NPA report, the Tammetta and Ditton-Merrick equations give similar estimates for modest mining geometries (see Fig. 5 in the 2016 NPA report). As discussed in Section 20, the Tammetta and the Ditton-Merrick equations return significantly different estimates for Elouera Longwall 7, located immediately to the south of the Dendrobium mine. Their respective estimates for Area 3B of the

Dendrobium mine are very different, with those of the Tammetta equation being around twice those of the Ditton-Merrick equations.

The SCT report does not include extensometer and, accordingly, the height of the collapsed zone, Zone 2, is not determined. The paper observes that downward flow to the mine and groundwater pressure draw down from hydrostatic begins at a height equivalent to the extraction width. While the paper assumes this corresponds to the apex of Zone 2, the Tammetta equation suggests that this point would be located in Zone 3 of Mills' model.

22. Application of the Tammetta equation to the Dendrobium mine

Notwithstanding the critical comments of Galvin and those of Sullivan and Swarbrick in their 2017 reports, the Tammetta equation may reasonably be expected to provide a scientifically credible and informative estimate of the height of the drainage zone over extractions at the Dendrobium mine for the following reasons:

(i) Other than the exceptional circumstances discussed by Tammetta (see Sections 6.2.5), to date no contradictory data have been reported.

(ii) To date no errors, misinterpretations or other faults have been found in the Tammetta database. While constrained by the limited data readily available in the public domain, the December 2016 NPA report remains the only report to have assessed the Tammetta database (the NPA report was not referred by the Department to PSM or Galvin and Mackie). PSM failed to review the Tammetta database - a critical aspect of the work they were assigned by the Department of Planning. The lack of access to data encountered by the NPA, PSM and Galvin highlights the need for reform.

(iii) The December 2016 NPA report found the piezometer data available from a number of key piezometer bore sites at Dendrobium to be consistent with the predictions of the Tammetta equation. The data contradict the Ditton-Merrick equations. While Sullivan and Swarbrick fundamentally misunderstood Tammetta's work and failed to comparatively review the Dendrobium piezometer data with respect to the drainage zone height estimates provided by the Tammetta equation, other impact evidence reported by Sullivan and Swarbrick is consistent with the Tammetta equation. As Dr Mackie notes, the rainfall sensitive inflows are consistent with the predictions of the Tammetta equation.

(iv) Prof. Galvin highlights the geomechanical importance of the width to depth ratio of longwall extractions. Not pointed out by Sullivan and Swarbrick, Mackie or Galvin, the Tammetta database spans the range of subcritical to critical to supercritical extraction width to depth ratios (see Figs. 2, 15(a) and 15(b)). The Area 3B ratios range ranges from 0.74 to 1.1 and are well within the range spanned by the Tammetta database. This is illustrated in Fig. 15(b) below.

(v) Not mentioned by Sullivan and Swarbrick, Mackie or Galvin, the Tammetta database spans a variety of rock types comprised of "*claystones, coarse-to-fine sandstones (lithic and quartzose), and limestones, in widely varying strengths, grain sizes, compositions, layer thicknesses, and recurrence patterns*".[11]

(vi) The lithology across most of the Dendrobium mine does not vary significantly, with the notable exception being small areas overlain by a nephaline syenite formation (a map is provided in the December 2016 NPA report).

(vii) The Dendrobium lithology is much the same as that over the Elouera domain of the adjacent Wongawilli mine (Section 20). Dendrobium is effectively an extension of Elouera. As demonstrated in the December 2016 NPA report (Fig. 16 in the NPA report; Fig. 28 below), which was not referred to PSM, Galvin or Mackie by the Department, the data from the centreline bore over Elouera LW7 support the Tammetta equation. The Elouera data are not noted or otherwise considered by Galvin, Mackie or Sullivan and Swarbrick.

(viii) In the absence of refutation and within the constraints of the available data, to within 8% the science journal peer reviewed Tammetta equation evidently has no need to explicitly incorporate local geology and rock mechanics. Other than the exceptional circumstances noted by Tammetta, such effects appear to be no more than secondary and not significant in the data compiled by Tammetta. Tammetta's work is consistent with that of Gale and Mills (see Section 11) and Appendix A of the Supplementary Material to his 2015 Groundwater paper (see Section 14) provides a geotechnical account of the collapse process (Galvin, Mackie, Sullivan and Swarbrick may be unware of this material).

(ix) Prof. Galvin observes in his review comments: "*The PSM report goes on to conclude on the basis of the matrix scatter plots, that application of the Tammetta model at Dendrobium Mine results in an over extrapolation of the data that will see the accuracy and standard deviation of the fit decay significantly. This is attributed to the Dendrobium panel widths and extraction thickness being well beyond the limits of the database. However, reference to PSM Figure 25 indicates that the Dendrobium mining heights are within the upper range of those used to derive the Tammetta equation (especially when the mining height for LW10 is corrected). Furthermore, although the empirically derived equation is being extrapolated beyond the range of the database used to derive the equation, this does not automatically mean that the accuracy and standard deviation of the fit will decay.*"

The equation may fail if it is tested with data obtained from bores in areas of anomalously high horizontal stress, such as the eastern area of Area 3B (e.g. centreline bores over Longwall 9 and this planned for Longwall 12). Tammetta and Galvin both observe that high horizontal to vertical stress ratio will unpredictably delay full collapse and drainage zone formation (see Section 6.2.5).

23. Tammetta equation predictions for Area 3B

Prof. Galvin provides the following comments in his summary and explanation report:

> "*Since the commencement of longwall mining at Dendrobium Mine, longwall panel widths have increased from 245 to 305 m while mining height has increased from 3.4 to 4.5 m. The minimum excavation width-to-depth ratio, W/H, for Longwall Panels 1 to 11 ranges from 0.6 to 0.98 and the maximum ranges from 0.86 to 1.56. Based on Figure 4, it can be expected that there are*

areas above most of these longwall panels that will have experienced maximum possible vertical displacement. Field measurements generally confirm that this is the case."

Not explicitly mentioned is that as the width to depth ratio approaches 1, the ability of the overburden to span the extraction void begins to fail. When the ratio reaches or exceeds 1.4, complete failure is likely to have occurred. The ratio of 1.4 is characterised as critical, with lower ratios being regarded as subcritical and greater ratios regarded as supercritical (Figure 3 in the Galvin review has 1.4 as the limiting width to depth ratio; see Fig. 8 below). Subsidence is 'capped' by spanning failure, as noted by Prof. Galvin:

"*As the width, W, of an excavation of fixed depth, H, is increased, a point is reached where further increases in panel width do not increase the extent of disturbance*."

Not mentioned by Prof. Galvin, failure would be expected to result in significant seam to surface connected fractures. This is illustrated in Figure A2(b) in Appendix 1 of the supplementary material for Tammetta's 2015 Groundwater paper (Fig. 3(a) below and Figure 4(c) in the December 2016 NPA report) and Fig. 3.27 in Prof Galvin's 2016 book (Fig. 3(b) below). As Prof. Galvin's comments indirectly suggest, the Dendrobium mining spans the range of subcritical to supercritical geometries. That such mining was approved in a Schedule 1 Special Area is of itself cause for concern.

The width to depth ratios of the Area 3B extractions ranges from 0.7 to 1.1 (Fig. 32 depicts variations in depth of cover at Dendrobium); they approach the range where spanning failure would be expected to commence, irrespective of the extraction height (thickness). As noted by Prof. Galvin in his 2016 book on coal mine engineering, the work of Gale and that of Mills finds that while extraction width is the primary determinant of the height of the zone of significant collapse and fracturing (the drainage zone), its character also determined by depth and extraction thickness.

Consistent with this work (see Section 11), Figure. 14(a) below shows that for a depth of cover of 400 metres and an extraction height of 3.5 metres, the Tammetta equation drainage zone height estimate corresponds approximately to the extraction width. The Tammetta equation representation in Figure 14(b) suggests Mills' rule of thumb would apply for extractions heights of between 3 and 4 metres, at a depth of cover of 400 metres. These mining parameters correspond approximately to those of the mining in Area 3B. Fig. 6(b) and 6(c) graph the width dependence of the drainage zone estimates provided by the Tammetta and Mackie equations at 300 and 400 metres respectively, for extraction heights of 3.0, 4.0, 4.5 and 6.0 metres.

Reference to Figs 6(b) and 6(c) finds that the Tammetta equation suggests that the rule of thumb suggested by Mills will underestimate the height of the drainage zone of the aggressive Area 3B mining. Abandoning past use of the Ditton-Merrick equations, but making no mention of the Tammetta equation, HGEO use Mills' rule of thumb to gauge the height of the drainage zone in their October 2017 groundwater impact report[26] for the mine.

The Tammetta equation warns that the drainage zone could, depending on the extraction height/thickness, interest the surface for subcritical Area 3B extractions - even though the mining width is generally less than the depth of cover over the Area 3B mining. The Tammetta equation predicts that for the originally planned 4.6 metre high extractions, the drainage zones would intersect the surface over most of Area 3B. In February 2013 the Department of Planning approved extraction to a height of 3.9 metres for Longwall 9 and 4.6 metres for Longwalls 10 to 13. In December 2016 extraction to 3.9 metres was approved for Longwalls 14 and 15 and again for

Longwall 16 in May 2016. Characterised by the Department as precautionary, the reduction in height for Longwalls 14 onwards makes little difference; the drainage zone either reaches the surface or gets to within 25 metres of the surface and would join the surface fracture network (see Fig. 33 below). This would be in addition to any connected fracturing arising from abutment failure (to the side of the extractions), should that occur over those extractions approaching the critical width to depth ratio.

Affirming the concerns raised in the NPA letter to the then Planning Minister in July 2015, the accumulating evidence is consistent with the Area 3B expectations of the Tammetta equation. In 2012 the Department of Planning accepted BHP-Billiton's rejection of the Dendrobium Area 3B modelling undertaken by Tammetta on behalf of Coffey Geotechnics. In March 2014 HydroSimulations provided replacement modelling based on the Ditton equations. The modelling provided by HydroSimulations in March 2018 in support of the mining of Longwalls 14, 15 and 16 uses the Tammetta equation. The available information suggests this modelling is inferior to Tammetta's modelling of November 2012.

In the interim between 2012 and 2018, reports by HydroSimulations for a number of mines in NSW have misleadingly and, it would appear, deceptively asserted that the evidence favoured the Ditton-Merrick equations. Examples are noted in the December 2016 NPA report.

24. Manifestation of the Tammetta equation at the Dendrobium coal mine

24.1. Rainfall dependence of mine inflows

As discussed in Section 19, the PSM failed to utilise the available Dendrobium piezometer data to probe the predictions of the Tammetta and Ditton-Merrick equations. Mackie, however, recognises in his PSM review that the 'spikey' rainfall dependent Dendrobium mine inflows are consistent with the predictions of the Tammetta equation (see Fig. 33 below):

> "*An alternate pointer to the extent of crack connectivity and associated drainage characteristics is the presence of rainfall recharge contributions to mine water inflows. Reported weak correlations between rainfall events and mine water inflows in Area 1, strong correlations in Areas 2 and 3A, and weak but potentially increasing correlations in Area 3B infer the presence of fracture flow pathways from seam to surface in these areas. It could be argued that these observations favour Tammetta's model*."

Mackie qualifies that recognition with the following comment:

> "*However the empirical nature of both models and the errors associated with fitting equations to the data sets, detract from their usefulness. Critical review and assessment of the underlying data sets may resolve this question*."

The puzzling nature of this comment is highlighted by his November 2014 comments in Groundwater (Section 3 and 4.3) and proposed simplification of the Tammetta equation:

> "*The paper by Tammetta provides a useful empirical equation for predicting the height of complete drainage above longwall panels. Prior to this research effort, predictions in Australian coalfields often relied upon simple relationships*."

The utility of empirical equations is recognised and, evidently regarding the error band (see Fig. 4) as acceptable, Dr Mackie uses Tammetta's database is in obtaining his simplified empirical equation (using regression methods or, in Prof Galvin's view, "*simply drawing a line of best fit*"). The significance of the error band is discussed in Section 8.3 and Dr Mackie's equation is discussed in Section 4.4. Figure 4 below is from Mackie's Groundwater contribution and it shows that the errors bands are relatively modest and decrease with increasing extraction width; at 305 metres, the Dendrobium Area 3B extractions are notably wide.

Clearly an equation that predicts that the drainage zone could reach the surface of a Schedule 1 Special Area is of considerable value. As Dr Mackie reluctantly observes in his PSM review, the available evidence is consistent with the Tammetta equations predictions for the Dendrobium mine.

As discussed in Section 8.3, the large error band suggested by Dr Mackie's comments (see Fig. 4), which echo those of the PSM report, at least in part reflects the coarse grained nature of the available data and they in turn reflect the placement of piezometers by the mining companies - with government approval.

In the absence of contradictory data or establishing fault with the underlying database the Tammetta equation provides a valuable 'fit for purpose' first order estimate of the drainage zone height. That it is an empirical equation does detract not from its value, particularly since there are no *ab-initio* or numerical alternatives and no prospect of better alternatives in at least the short to medium term.

Dr Mackie recognises the implications of the rainfall dependence of the mine inflows:

> "*Clearly if rainfall related contributions are present in the mine water system (and the data suggests they are) then it could be reasonably inferred that seam to surface fracture flow pathways are present and that the height of connected fracturing therefore extends to surface*."

Puzzlingly, he does not relate this observation to the Tammetta equation predictions.

In his PSM review, Prof. Galvin notes that Mackie's assessment for the Longwall 14 to 18 SMP indicates that there is *"direct association between rainfall and water inflow in all four mining areas at Dendrobium Mine"*. He does not relate this observation to the predictions of the Tammetta equation.

The drainage zone reaching the surface, or to a height that joins the surface facture network, may not explain all of the mine's rainfall sensitivity. Seam to surface fracturing arising from areas with near critical and supercritical extractions and geological discontinuities would also contribute to the mine inflow behaviour. The relative significance of these contributions will vary across the mine.

24.2. Extensive depressurisation and swamp impacts at significant distances

The December 2016 NPA report finds of a significant disruption of the groundwater regime between the Avon and Cordeaux reservoirs, and this is confirmed by the PSM report. The NPA report notes a relatively rapid horizontal propagation of pressure head falls reported by some of the Dendrobium piezometers at significant distances from the causal extraction. Reflecting much greater horizontal hydraulic conductivity, including shear effects, than vertical hydraulic conductivity, these observations are readily rationalised by drainage zone heights consistent with the estimates provided by the Tammetta equation. While the PSM report records impacts at considerable distances from extractions, this explanation does not appear to have been considered by any of the consultants.

Recognising the importance of horizontal transmission, the NPA report accordingly recommended that any further mining in Area 3B should be restricted such that the height of the consequential drainage zone, as estimated by the Tammetta equation, would be kept at a prudent distance below the base of the reservoirs. The report quoted advice[56], [57] from Geoterra:

> "*A minimum thickness of unfractured overburden is required to maintain hydraulic separation between a mine and saturated aquifers, with the critical value depending on lithology, structure and topography. The minimum separation has been established through observation and research in NSW mines as ranging from less than 90m up to 150m*."

The NPA report assumed the mining company had flexibility in setting the mining cutting height, but that that the width was 'locked in' as a result of first workings. It was subsequently learned that the equipment being used was such that the height could not be reduced sufficiently. The Department of Planning's approval of Longwalls 14 and 15 did not require a corresponding reduction in extraction width.

24.3 More recent observations at Dendrobium

An October 2017 review[26] by HEGO on behalf of South32 of groundwater impact monitoring at Wongawilli Creek tributary WC21, affirms and deepens the concerns of seam to surface fracturing raised in the July 2015 letter to the then Planning Minister. The report also affirms and deepens the concerns of considerable disruption to the groundwater regime between Avon and Cordeaux Reservoirs, raised in the NPA report of December 2016. Referring to graphical representations of the geology and piezometer bore placement, the HGEO report advises the following:

> "*An approximation of the expected height of connected vertical fracturing, based on the generalised model presented by (Mills, 2011), is shown for reference. It is evident from this, and the observations from the WC21 bores (SCT, 2016), that longwall related fracturing most likely extends to the depths intersected by the piezometers, and possibly to the surface along WC21*."

As discussed in Section 4.5, the Tammetta equation suggests Mills' rule of thumb will underestimate the height of the drainage zone for the aggressive extractions at Dendrobium.

Discussed in Section 25, the March 2018 groundwater modelling provided by HydroSimulations in support of the then proposed SMP for Longwall 16 replaces the consultancy's past use of the Ditton-Merrick equations with the Tammetta equation. Figure 33 depicts the height of the drainage zone with respect to the catchment surface for the extraction heights approved by the Department of Planning for Area 3B. The drainage zone will either reach the surface or reach to between 25 metres below the surface and the surface.

The HGEO report includes the following summary:

> "*In summary, potentiometric head at the base of the Hawkesbury Sandstone, beneath the ridge, was variable but tended to be at or above the level of Wongawilli Creek bed, prior to mining at Area 3A (but below the level of WC21). Mining at Area 3B has resulted in depressurisation in all strata, including the lower parts of the Hawkesbury Sandstone such that potentiometric heads are below the Wongawilli Creek bed at S1930 and S1931. It is likely that a hydraulic gradient with a downward component exists between Wongawilli Creek and WC21 in the direction of Area 3B*."

Mining has caused considerable drawdown extending across and beyond Area 3B and this is impacting the watercourses, suggesting a change in character from being gaining to being losing streams. The large drawdowns tabulated in the December 2016 NPA report (Table 2 below) will have continued and point to a more than negligible decline in groundwater supply to at least the southern side of Cordeaux Reservoir. It would seem likely that the mine's approval conditions have been breached. As the groundwater decline continues, at some point a tipping pint will be reached and passed, with the reservoir losing more water to the groundwater system than it gains.

25. Recent comments and observations regarding or related to the Tammetta equation

25.1 Prof. Galvin

In providing expert advice in November 2017 to the Planning Assessment Commission, now the Independent Planning Commission, with respect to the then proposed Wallarah 2 coal project, Prof. Galvin makes the following comments:

> "*The methodology relied upon to asses the height of fracturing in the 2010 EIS for the Wallarah 2 project continues to find application, being a component of two conference papers in the last week, namely Gale (2017) and Mills and Blacka (2017). The latest findings presented by Mills have been adopted for the purpose of preparing this advice.*
>
> *Since 2010 two empirical equations have also been developed for predicting the height of connective fracturing above longwall panels. These are referred to as the Tammetta equation (Tammetta, 2013) and the Ditton and Merrick equation (Ditton & Merrick, 2014). Both equations have their strengths and weaknesses and neither are universally accepted. The Tammetta equation tends to be more conservative than the Ditton and Merrick equation in many situations. That is, it predicts greater heights of fracturing. This is the case for the Wallarah 2 project.*"

The Mills and Blacka reference refers to the Tahmoor study discussed in Section 21. Reflecting the modest nature of the mining geometry, the Tahmoor study provides weak support for the Tammetta equation with respect to the Ditton-Merrick equations.

Having made the quoted comments, Prof. Galvin then suggests a panel width for which the Tammetta equation suggests a 90% probability that the drainage zone will not reach the surface.

Of concern, however, is that Prof. Galvin characterises the Tammetta estimate as being "conservative", implicitly suggesting that the Tammetta equation underestimates the height of the drainage zone. There is no evidence to support this implicit suggestion. The available evidence suggests that the Tammetta equation is currently the only scientifically credible means of estimating the drainage zone height.

Also of concern, Prof. Galvin's comments make no distinction between the scientific credibility of the Tammetta equation and the Ditton-Merrick equations. The December 2016 NPA report[17] finds that the Ditton-Merrick equations are derived from inappropriate data and do not provide realistic drainage zone height estimates; they are not scientifically credible. This is recognised by Prof. Galvin in his December 2016 comments on the them proposed SMP for Longwalls 14 and 15 at the Dendrobium mine:

"*The insensitivity of the Ditton model to mining height suggests to me that the prediction equation does not adequately reflect physical and mechanical principles*."

The unsuitable nature of the Ditton-Merrick database is indirectly recognised by Prof. Galvin, who makes no comment on that database, in the following comment:

"*I question how information obtained from boreholes located off the centreline of a longwall panel and, in particular, over chain pillars and abutment pillars, as on this occasion can be utilized reliably to test the veracity of the Ditton & Merrick (2014) model for predicting the height of (connective) fracturing*."

The comments effectively echo the concerns raised in the July 2015 NPA letter to the then Planning Minister and the December 2016 report. In contrast to Tammetta's database, the Ditton-Merrick database is an admixture of centreline, side-panel and off-panel piezometer and extensometer data. Galvin comments on the unsuitable character of extensometer data:

"*extensometers installed in vertical boreholes do not detect or measure the height of connective or continuous vertical fracturing. Rather, they measure vertical displacement associated with the opening of horizontal and inclined partings and fractures. These may or may not form part of a connective fracture network to the mining horizon*."

In his review of the PSM report, Prof. Galvin comments on Dittons "*effective strata unit thickness*":

"*the effective thickness is not based on any actual assessment of geology but is apparently derived by manipulating the value of 't' to obtain the closest agreement between predicted and locally measured outcomes (ignoring the fact that the veracity of the measured outcomes is an issue that also needs careful consideration).*"

That is, the term amounts to a fudge factor.

Prof. Galvin's reference to the Ditton-Merrick equations in the Wallarah 2 advice lends credibility to a set of equations that are fundamentally flawed and unscientific. That this is problematic is reflected in the following comments from HydroSimulations in their March 2018 groundwater modelling update:

"*While PSM (2017) indicated that neither of these empirical models was robust, no alternative method was suggested. The result is that while they are not universally accepted, these methods still provide useful estimates (Galvin, 2018b*)."

The Galvin reference refers to the Wallarah 2 advice quoted above. The HydroSimulations comments are made with respect to the Tammetta and Ditton-Merrick equations. The suggestion that the Ditton-Merrick equations provides useful estimates lacks a scientific basis and is not credible.

25.2 Prof. Hebblewhite

Like Prof. Galvin, Prof. Bruce Hebblewhite is a consultant mining engineer with expertise in subsidence from the School of Mining Engineering at the University of New South Wales. The following comment from a March 2018 review[58] of fracturing at the Dendrobium recognises the flawed nature of the Ditton-Merrick equations:

"*It is clear from this data, based on the previously discussed link between borehole water pressure loss and height of fracturing, that the Tammetta and SCT models are the only ones that are close to the height indicated by the monitoring data, with both versions of the Ditton predictive model (with and without a geological adjustment) seriously under-predicting the fracturing height*."

The following comment, however, finds limited knowledge of Tammetta's work (no papers or reports are included in the report's references) and of the response of piezometers over and around coal extractions:

"*What is agreed is that there is enhanced vertical permeability such that the groundwater pressure levels will be reduced. However, this may occur over some considerable time, and certainly not instantly, such that 100% depressurisation may take many years to occur*."

Similarly:

"*total depressurisation may take some time to occur (could be years or tens of years in some strata), but this should not be regarded as being in conflict with the concept of a fractured zone existing. PSM has adopted a definition that included total depressurisation, which has led to the apparent contradiction of the data, but this has ignored the time factor, for gradual depressurisation, and so the data is not considered to be in conflict with the models*."

While Swarbrick and Sullivan fail to recognise that total depressurisation would not be expected beyond the drainage zone, Hebblewhite is evidently unaware that relatively rapid drainage and depressurisation occurs within the drainage zone.

References

[1] T. Sullivan and G. Swarbrick, "Height of Cracking – Dendrobium area 3B," Pells Sullivan and Meynink (PSM), Prepared for the NSW Department of Planning PSM3021-002R, Mar. 2017.

[2] C. Mackie, "Height of fracturing at Dendrobium Mine – Peer review of PSM report," Mackie Environmental Research Pty. Ltd, Prepared for NSW Department of Planning 906/17, Feb. 2017.

[3] J. Galvin, "Review of PSM Report on Height of Fracturing – Dendrobium Area 3B," Galvin & Associates, Prepared for NSW Department of Planning, Feb. 2017.

[4] J. Galvin, "Summary and Explanation of Height of Fracturing Issues at Dendrobium Mine," Galvin & Associates, Prepared for NSW Department of Planning 1716–11/1b, Jun. 2017.

[5] P. Turner, "Concerns arising from flawed groundwater impact assessments in NSW," NSW National Parks Association, Letter to NSW Minister for Planning, Jul. 2015.

[6] S. Ditton, "Subsurface Fracture Zone Assessment above the Proposed Springvale and Angus Place Mine Extension Project Area Longwalls," Ditton Geotechnical Services Pty Ltd, SPV-003/7b, Sep. 2014.

[7] P. Tammetta, "Groundwater Study Area 3B Dendrobium Coal Mine - Numerical Modelling," Coffey Geotechnics Pty Ltd, Groundwater assessment prepared for BHP Billiton GEOTLCOV24507AA-AB2, Oct. 2012.

[8] P. Tammetta, "Groundwater Study Area 3B Dendrobium Coal Mine Revised Numerical Modelling.," Coffey Geotechnics Pty Ltd, Groundwater assessment prepared for BHP Billiton GEOTLCOV24507AB-AB2, Nov. 2012.

[9] P. Tammetta, "Groundwater Study, Area 3B Dendrobium Coal Mine, Data Analysis," Coffey Geotechnics Pty Ltd, Groundwater assessment prepared for BHP Billiton GEOTLCOV24507AA-AB1, Oct. 2012.

[10] P. Tammetta, "Groundwater Study, Area 3B Dendrobium Coal Mine, Data Analysis (2nd Edition)," Coffey Geotechnics Pty Ltd, Prepared for BHP Billiton GEOTLCOV24507AB-AB1, Nov. 2012.

[11] P. Tammetta, "Estimation of the height of complete groundwater drainage above mined longwall panels," *Ground Water*, vol. 5, pp. 723–34, Oct. 2013.

[12] P. Tammetta, "Estimation of the Change in Hydraulic Conductivity Above Mined Longwall Panels," *Groundwater*, vol. 53, no. 1, pp. 122–129, 2015.

[13] P. Tammetta, "Estimation of the Change in Storage Capacity above Mined Longwall Panels," *Ground Water*, vol. Epub ahead of print, p. Online, Jan. 2016.

[14] C. N. Nicol and N. P. Merrick, "Dendrobium Area 3B Groundwater Model Revision: Swamps, Stream Flows and Shallow Groundwater Data," HydroSimulations, HC2014/4, Mar. 2014.

[15] S. Ditton and N. Merrick, "A New Sub-Surface Fracture Height Prediction Model for Longwall Mines in the NSW Coalfields," in *Abstract Proceedings of Australian Earth Sciences Convention*, Newcastle., NSW, Australia, 2014, vol. 136.

[16] J. Galvin, “Review of Dendrobium Subsidence Management Plan – LW 14 to 18,” Galvin and Associates, Prepared for NSW Department of Planning, Dec. 2016.

[17] P. Turner, “Some Concerns Regarding Groundwater Impact Assessments for Coal Mines in NSW,” NSW National Parks Association, Dec. 2016.

[18] J. Galvin, *Ground Engineering - Principles and Practices for Underground Coal Mining*. Springer International Publishing Switzerland, 2016.

[19] F. Smith, “Dendrobium Area 3B - Application for Approval to Extract Longwalls 14-18,” WaterNSW, 02016/32556, Apr. 2016.

[20] K. Mills, “Update to Subsidence Assessment of Wollongong Coal Preferred Project Report Russell Vale No 1 Colliery - Appendix B of the Underground Expansion Project Residual Matters Report,” Strata Control Technology (SCT) Pty, WCRV4263, Jun. 2014.

[21] Commonwealth of Australia 2014, “Temperate Highland Peat Swamps on Sandstone: longwall mining engineering design—subsidence prediction, buffer distances and mine design options, Knowledge Report,” prepared by Coffey Geotechnics for the Department of the Environment, Commonwealth of Australia., Aug. 2014.

[22] K. W. Mills, “Developments in Understanding Subsidence with Improved Monitoring,” in *Proceedings of the 8th Triennial Conference on Mine Subsidence, 2011*, Pokolbin, N.S.W, 2011.

[23] G. Cawthorn, “Unpacking the secrets of South Africa’s dolerite sills,” *The Conversation*, Jul. 2015.

[24] N. Shepherd, J. Bennett, J. Galvin, C. Mackie, and J. Tilleard, “Review of the Bulli Seam Operations Project.” NSW Planning Assessment Commission (PAC), Jul-2010.

[25] P. Tammetta, “Russell Vale Colliery (formerly the NRE No. 1 Mine) Underground Expansion Project Groundwater Review,” Coffey Geotechnics Pty Ltd for the NSW Department of Planning, GEOTLCOV24840AC-AB, Sep. 2014.

[26] S. Brown, “Review of groundwater monitoring at WC21 – Update October 2017,” HGEO Pty Ltd, Pepared for South32 D17280, Nov. 2017.

[27] P. Pells, “Estimation of the Height of Complete Groundwater Drainage above Mined Longwall Panels - Comment by Philip Pells,” *Groundwater*, vol. 52, no. 3, pp. 338–339, May 2014.

[28] P. Tammetta, “Estimation of the Height of Complete Groundwater Drainage above Mined Longwall Panels - Authors Reply to Philip Pells,” *Groundwater*, vol. 52, no. 3, pp. 339–342, Jun. 2014.

[29] K. W. Mills, “Observations of Ground Movements Within the Overburden Strata Above Longwall Panels and Implications for Groundwater Impacts,” in *Proceedings of 38th Symposium on the Advances in the Study of the Sydney Basin*, Hunter Valley, NSW, 2012.

[30] K. Mills and P. O’Grady, “Impact of longwall width on overburden behaviour,” presented at the Coal 98 Conference, Wollongong, 1998.

[31] K. W. Mills, “Interpretation of results from Boreholes DSC12 and DSC13 at Elouera Colliery,” Prepared for BHP Billiton DEN2947, Dec. 2005.

[32] P. Tammetta, “Estimation of the Change in Hydraulic Conductivity Above Mined Longwall Panels. Supporting Information.,” *Groundwater,* vol. 53, no. 1, pp. 122–129, 2015.

[33] P. Tammetta, “Temperate Highland Peat Swamps on Sandstone: longwall mining engineering design—subsidence prediction, buffer distances and mine design options, Knowledge report,” Coffey Geotechnics for the Department of the Environment, Commonwealth of Australia, Aug. 2014.

[34] K. W. Mills and B. G. Blacka, “Experience of Monitoring the Interaction between Ground Deformations and Groundwater above an Extracted Longwall Panel,” in *Proceedings of the 10th Triennial Conference on Mine Subsidence*, Kirkton Park, Pokolbin, NSW, 2017.

[35] W. Gale, “Aquifer Inflow Prediction Above Longwall Panels,” ACARP Project C13013, 2008.

[36] W. Gale, “Water Inflow Issues above Longwall Panels,” in *Aziz, N (ed), Coal 2006: Coal Operators’ Conference,* 2006, pp. 175–179.

[37] P. Tammetta, “Estimation of the Height of Complete Groundwater Drainage above Mined Longwall Panels - Reply to Mackie,” *Groundwater*, vol. 52, no. 6, p. 826, Nov. 2014.

[38] F. T. Suorineni, “Reflections on Empirical Methods in Geomechanics - The Unmentionables and Hidden Risks,” presented at the AusRock 2014: Third Australasian Ground Control in Mining Conference, Sydney, N.S.W., 2014, pp. 143–156.

[39] P. Tammetta, “Estimation of the height of complete groundwater drainage above mined longwall panels - Supplementary Material,” *Ground Water*, vol. 5, pp. 723–34, Oct. 2013.

[40] Mine Subsidence Engineering Consultants (MSEC), “General Discussion on Systematic and Non Systematic Mine Subsidence Ground Movements.” Aug-2007.

[41] C. Mackie, “Estimation of the Height of Complete Groundwater Drainage above Mined Longwall Panels - Comment,” *Groundwater*, vol. 52, no. 6, p. 825, Nov. 2014.

[42] B. N. Whittaker and D. J. Reddish, *Subsidence: occurrence, prediction, and control*. 1989.

[43] “Introduction to Longwall Mining and Subsidence.” Mine Subsidence Engineering Consultants (MSEC), Aug-2007.

[44] S. Ditton, “North Wambo Underground Mine Extraction Plan Longwalls 8 To 10; DGS Alluvium Impact Management Options Report NWU-001/7, Attachment A - Sub-Surface Fracturing Prediction Model Details (Extract from Subsidence Prediction Models, DgS, 2013),” Prepared for Peabody Energy DgS-001/2, Aug. 2013.

[45] S. Ditton, “Subsidence Predictions and General Impact Assessment for the Tasman Extension Project,” Ditton Geotechnical Services Pty Ltd, DGS Report No. TAS-005/1, Jun. 2012.

[46] W. Ziegler and H. Middleton, “Is there a 4th Dimension to Subsidence Monitoring?,” in *Proceedings of the 9th Triennial Conference on Mine Subsidence*, 2014.

[47] R. S. Dowdell, "Response to Wardell and Eynon, in Wardell, K. and Eynon P. 1968. Structural concept of strata control and mine design.," *Trans. Inst. Min. Metall.*, vol. 77, no. Section A, pp. A125–A150, 1968.

[48] L. Holla and E. Barclay, "Mine Subsidence in the Southern Coalfield, NSW, Australia." New South Wales Department of Mineral Resources, Jun-2000.

[49] A. Skorulis and W. Minchin, "Estimated Height of Connected Fracturing above Dendrobium longwalls," HydroSimulations, Report for Illawarra Coal / South32 BHP008-HC2015-27f, Oct. 2015.

[50] W. Minchin, S. Brown, and C. Turvey, "Dendrobium Area 3B Groundwater Assessment," HydroSimulations, Dendrobium LW14 - LW18 Groundwater Assessment for Illawarra Coal - South32 HC2016/02, Mar. 2016.

[51] K. Wardell and P. Eynon, "Structural concept of strata control and mine design," *Trans. Inst. Inst. Min. Metall.*, vol. 77, no. Section A, pp. A125–A150, 1968.

[52] P. Tammetta, "Gujarat NRE No.1 Colliery Major Expansion Project Part 3A Application: Review of the Groundwater Component of the Preferred Project Report - June 2013," Coffey Geotechnics Pty Ltd for the NSW Department of Planning, GEOTLCOV24840AB-AB, Jun. 2013.

[53] GHD Geotechnics, "Dendrobium Area 3 - Predicted Hydrogeologic Performance." GHD Pty Ltd 2007, Nov-2007.

[54] I. Forster and J. Enever, "Hydrological response of overburden strata to underground mining," Office of Energy Report Vol 1, 1992.

[55] J. Sheppard, "Advice to the June 12th 2014 Tahmoor Community Consultative Committee Meeting," *Pers. Commun.*

[56] GeoTerra Pty Ltd, "Gujarat NRE Coking Coal Ltd Preliminary Works Surface Water & Groundwater Assessment Bellambi, NSW," GUJ3-R1C, Sep. 2010.

[57] A. Dawkins, "Appin Area 7 Longwalls 705 to 710 Groundwater Assessment," Geoterra Pty Ltd on behalf of BHP-Billiton Illawarra Coal Pty Ltd, BHP41-R1B, Jun. 2008.

[58] B. K. Hebblewhite, "Dendrobium Mine – Longwalls 14-18 Independent Review – Height of Fracturing (Stage 1)," Consultants report provided to the NSW Department of Planning 1708/03.1 (V2.0), Mar. 2018.

[59] D. P. Olsen, "Environmental Assessment Illawarra Coal Seam Gas Exploration Drilling & Gas Monitoring Program," Olsen Consulting Group Pty Ltd, for APEX Energy NL, Mar. 2009.

[60] Mine Subsidence Engineering Consultants (MSEC), "Dendrobium Area 3B – Longwalls 9 to 18 Subsidence Predictions and Impact Assessments for Natural Features and Surface Infrastructure in Support of the SMP Application," Mine Subsidence Engineering Consultants Pty Ltd (MSEC), MSEC459 Revision B, Sep. 2012.

[61] Mine Subsidence Engineering Consultants (MSEC), "Dendrobium Area 3B – Longwalls 12 to 18: Review of the Subsidence Predictions and Impact Assessments for Natural and Built Features in Dendrobium Area 3B based on Observed Movements and Impacts during

Longwalls 9 and 10," Mine Subsidence Engineering Consultants Pty Ltd (MSEC), MSEC792 Revision C, Dec. 2015.

Table 1

Mine	Panel	t (m)	w (m)	d (m)	Sill interval (m above mined seam)	Sill thickness (m)	Height of collapsed zone (m above mined seam)	Calculated H (m above mined seam)
Durham	410		220	230	90 to 163	73	97 (7m into sill)	
Sigma	1	2.25	100	95	24 to 57	33	25 (1m into sill)	48
Sigma	2	2.25	100	96	24 to 57	33	30 (6m into sill)	48
Sigma	4, I, II	2.3	200	93	24 to 57	32	>93 (to surface) *	97
Highveld			220	195	130 to 190	60	>195 (to surface)	
Springfield^		3.5	126	175	115 to 120	5	125 (sill had no effect)	124
Durban^		3.3	250	183	110 to 180	70	>183 (to surface)	221
Durban^		1.65	400	183	110 to 180	70	110 (base of sill)	138

Table 1
Analysis of the Height of the Collapsed Zone underneath Super-Strong Dolerite Sills in South African Coal Mines (data from Sweby, 1997)

w denotes void width (panel width plus heading widths), t denotes mined thickness, d denotes overburden thickness. H denotes the height of the desaturated zone. ^ Pillar extraction in room and pillar workings. *The face had advanced by between 166m and 180m when the sill failed.

Table 1 is from Appendix A of the supplementary material for Tammetta's 2013 Groundwater paper.[39]

Figures

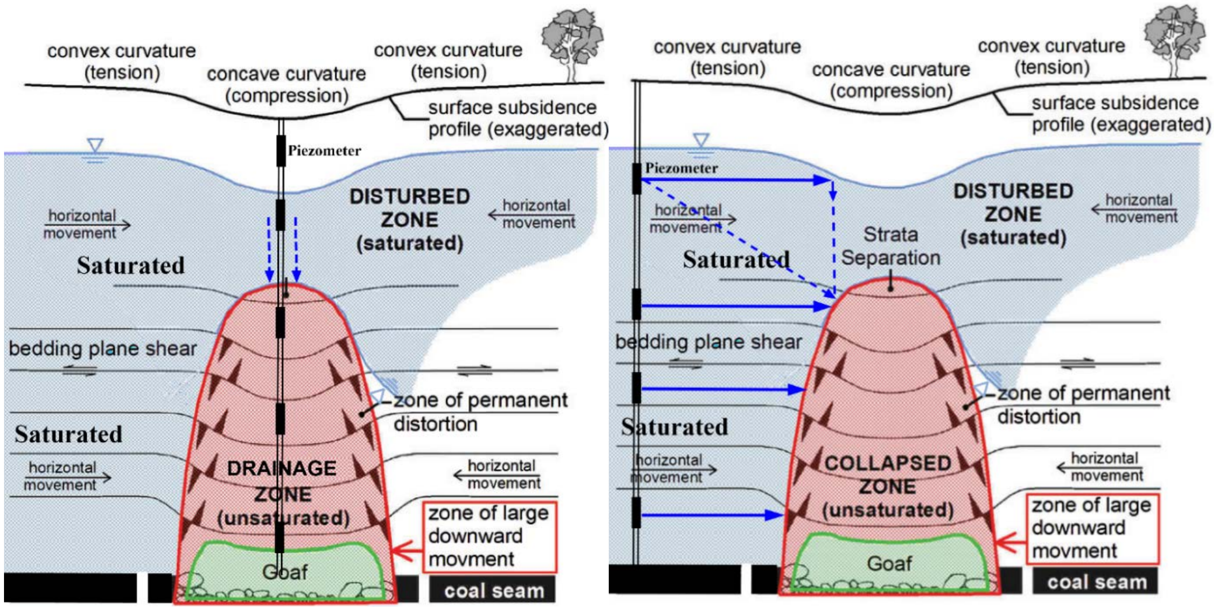


Figure 1. Depiction of a centreline piezometer and off-panel bore with respect to Tammetta's drainage zone

Taken from Figure 3 in the 2016 NPA report, the depictions above are adapted from that given by Tammetta[32], showing a longwall coal extraction with and an adjacent extraction to the right. Tammetta notes in Fig. 10 of his 2013 paper that his depiction adapts the original given in Holla and Barclay's book[48] of June 2000 on mine subsidence in the Southern Coalfield. The original depiction appears as Fig. 3.1 in Holla and Barclay and demarks a zone of large downward movement; the collapsed zone.

The one to two or more order of magnitude difference between horizontal and vertical hydraulic conductivity is represented by the use of solid (horizontal) and dashed (vertical) arrows. As pointed out in the December 2016 NPA report, depending on distance and elevation, off-panel piezometers horizontally in line with the drainage (collapsed) zone would be expected to report greater rates of pressure loss than those located above the drainage zone. Centreline piezometer bores provide the most reliable means of determining the height of the drainage zone.

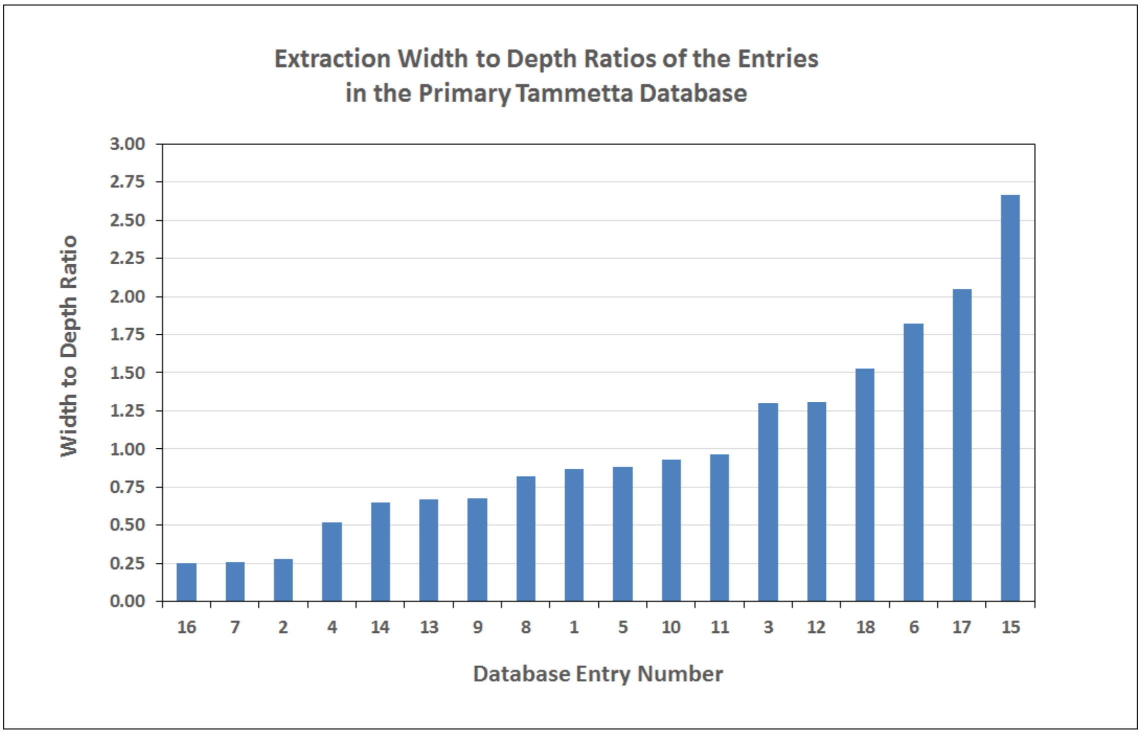


Figure 2. Extraction width to depth ratios of the entries in the primary Tammetta database**.**

Extractions with width to depth ratios less than 1.0 are generally regarded as sub-critical, those with a ratio of 1.0 to 1.4 are characterised as critical and those with a ratio greater than 1.4 are regarded as supercritical. The critical to supercritical threshold ratio of 1.4 appears to be largely independent of lithology (see Fig. 8).

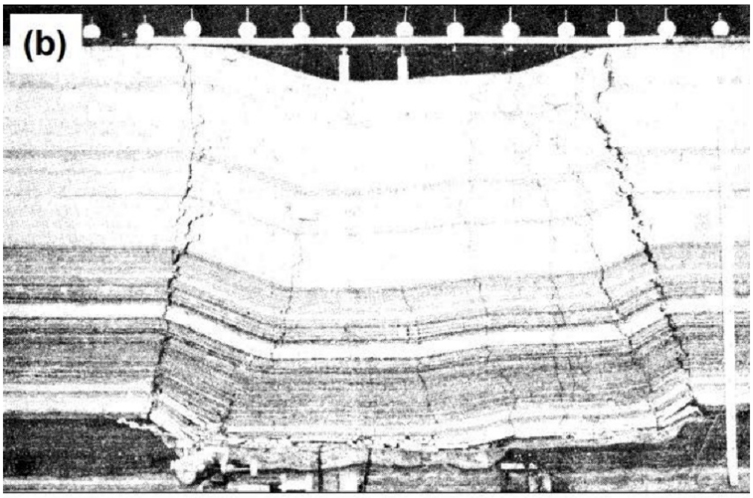
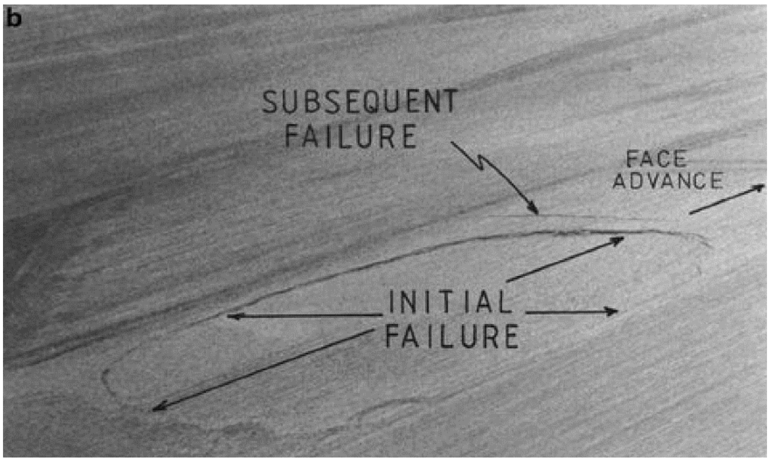


Figure 3(a). Physical model of supercritical collapse and a collapsed zone that has reached and extended over the surface.

Physical model of supercritical collapse and a collapsed zone that has reached and extended over the surface above an extraction where the extraction width is greater than the critical width. See also Fig. 3(b). The image is Figure A2(b) from the supplementary material for Tammetta's second Groundwater paper.[32]

(i)



(ii)

Figure 3(b). Supercritical collapse over a mine in South Africa.

Taken from Prof. Galvin's 2016 book on coal mine engineering, the photographs show the surface manifestation of collapse over a supercritical extraction beneath a massive dolerite sill in South Africa. The upper photograph shows abutment failure (see Fig. 3(a)) 'daylighting' at the surface, while the lower photograph shows the perimeter of the collapse.

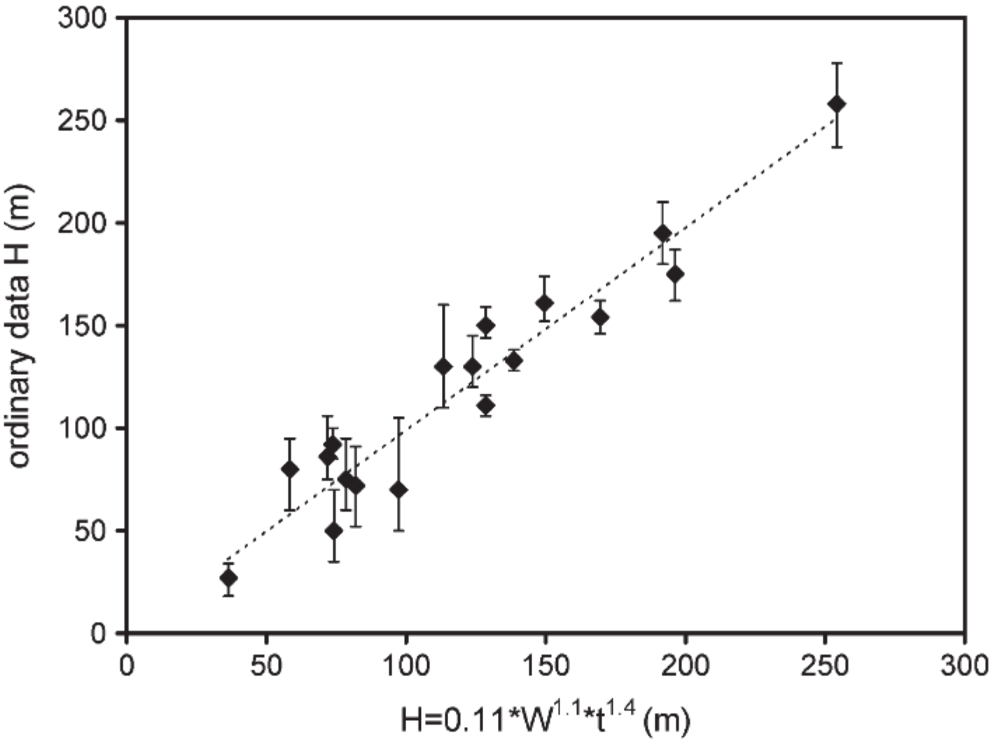


Figure 4. Mackie's simplified equation with respect to primary Tammetta database and error bars.

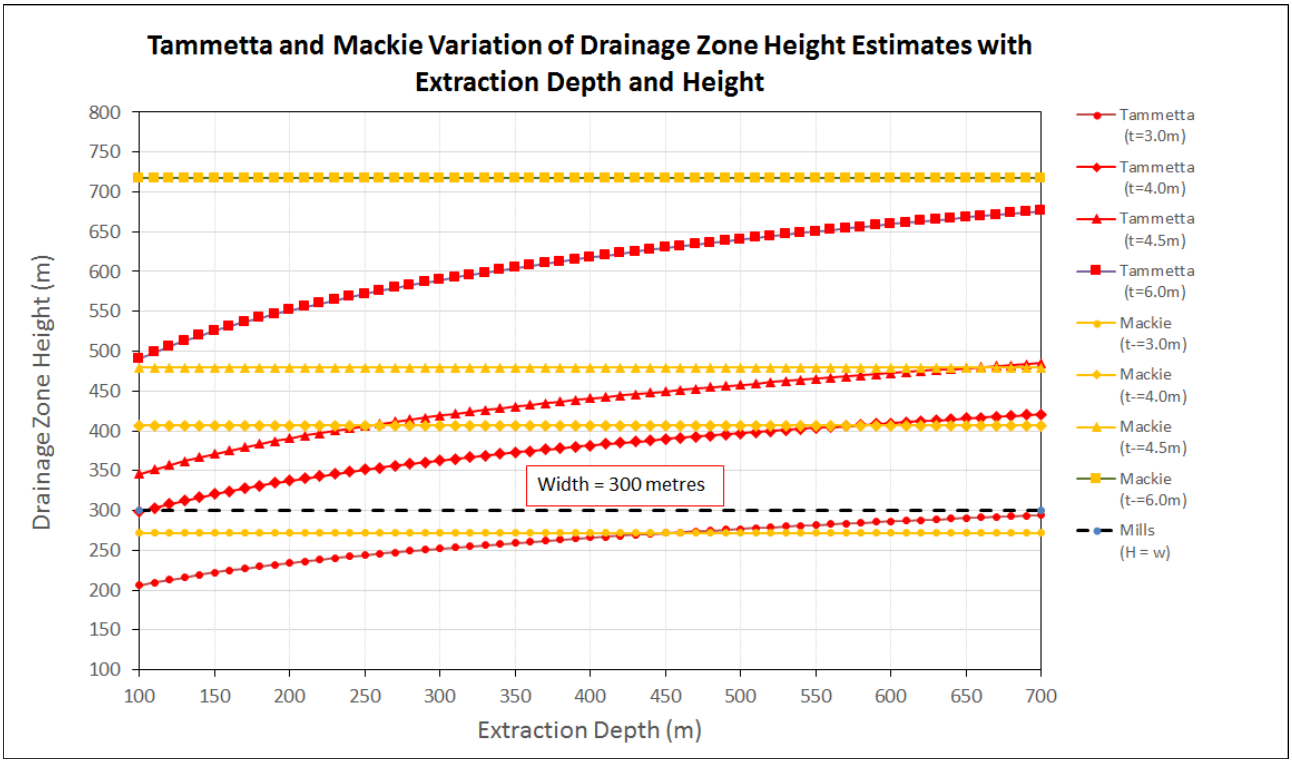


Figure 5(a) Graph of Tammetta, Mackie and Mills equations with respect to extraction depth and height for a width of 300 metres.

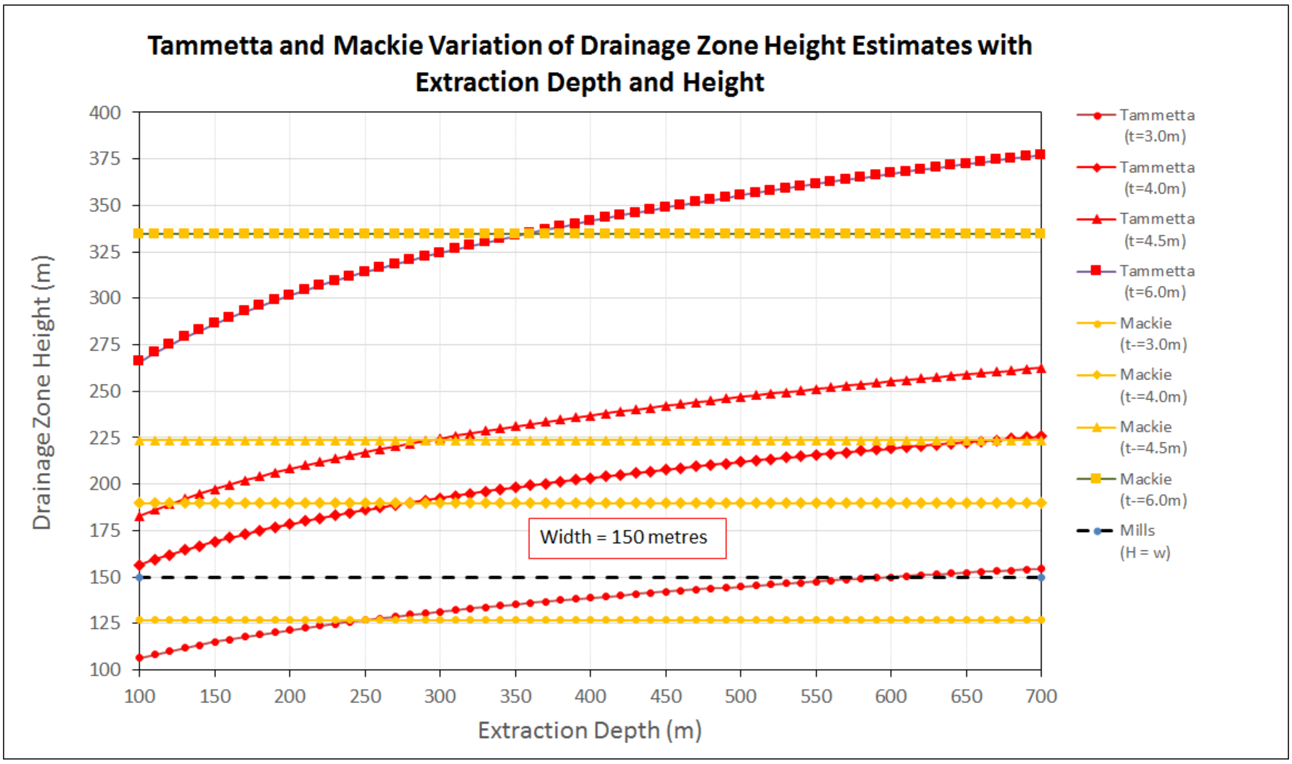


Figure 5(b) Graph of Tammetta, Mackie and Mills equations with respect to extraction depth and height for a width of 150 metres.

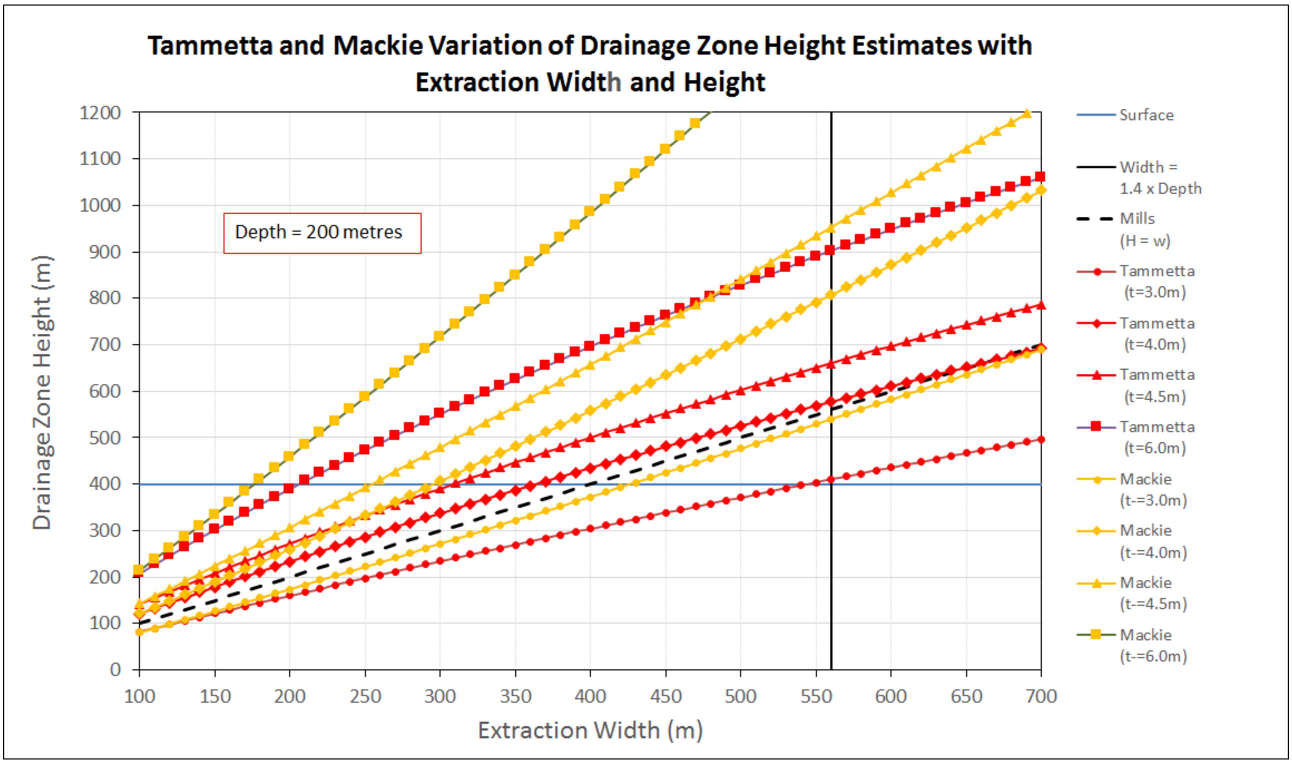


Figure 6(a). Graph of Tammetta, Mackie and Mills equations with respect to extraction width and height at a depth of cover of 200 metres.

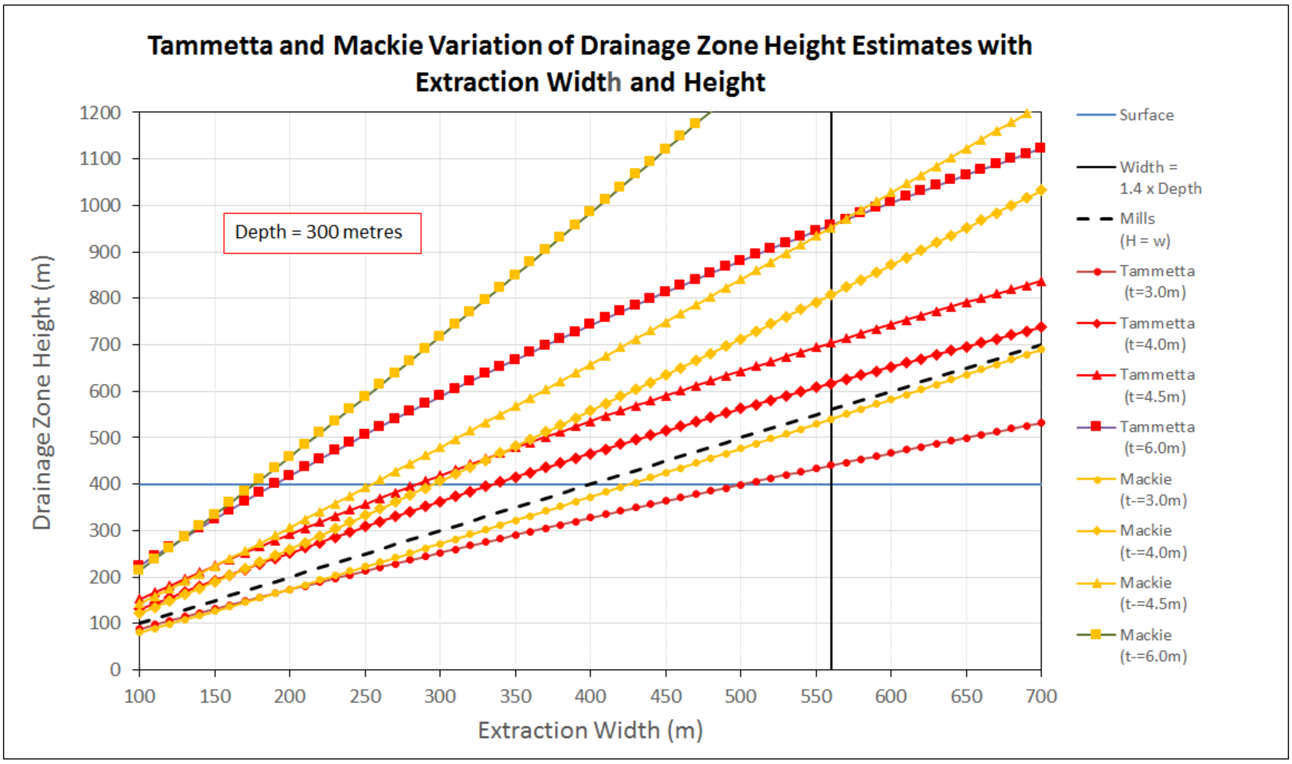


Figure 6(b). Graph of Tammetta, Mackie and Mills equations with respect to extraction width and height at a depth of cover of 300 metres.

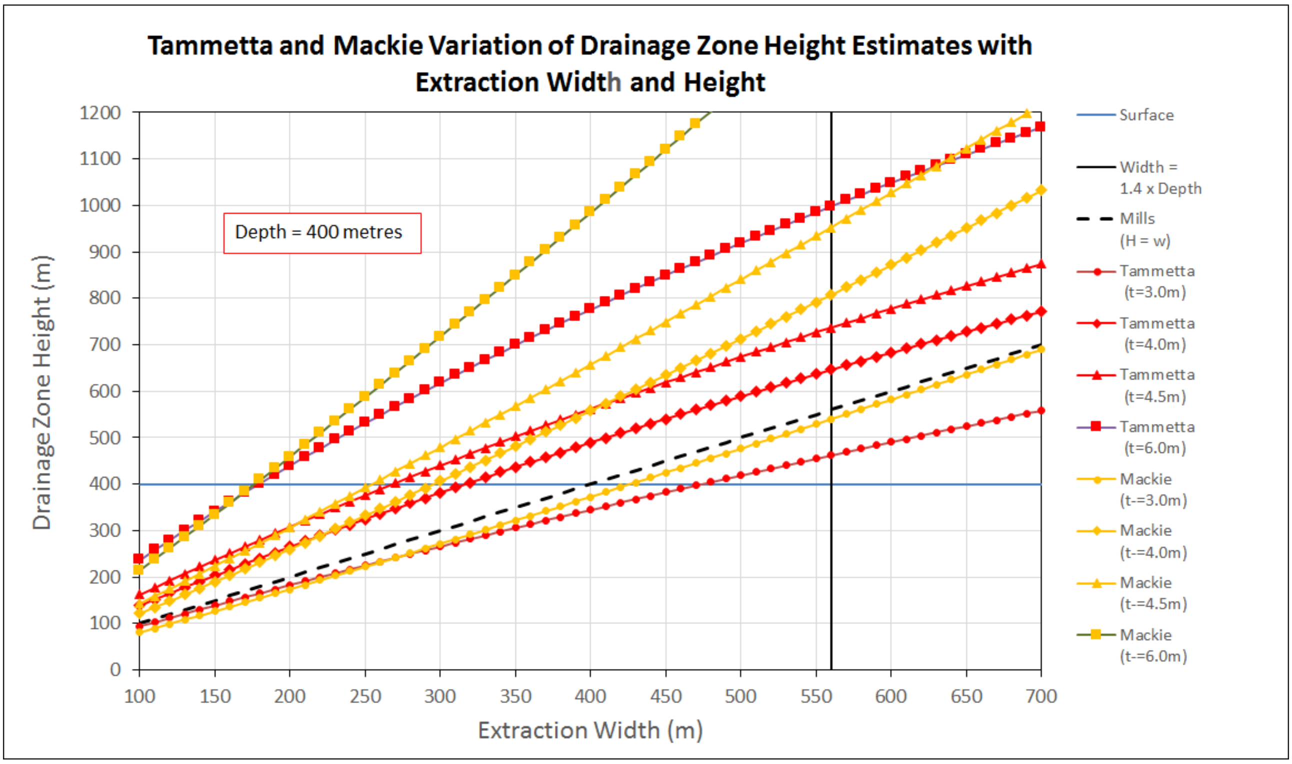


Figure 6(c). Graph of Tammetta, Mackie and Mills equations with respect to extraction width and height at a depth of cover of 400 metres.

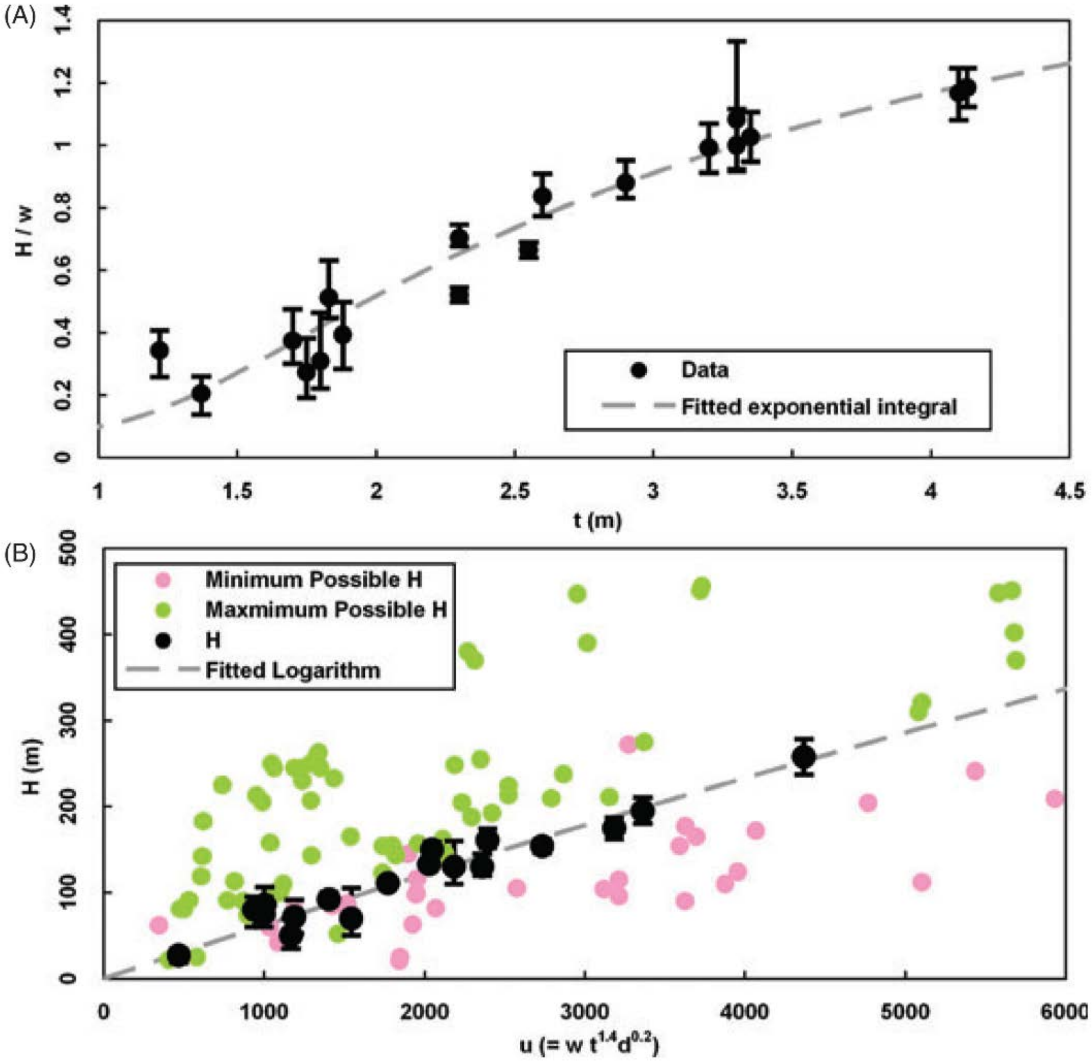


Figure 7. Graphical representations of Tammetta's primary database and equation with error bars.

Figure 7 is Figure 3 from Tammetta's first Groundwater paper[39], published in 2013. The upper graph (a) shows the fit of an exponential integral function to his primary database and, representing his final equation, the lower shows the fit of a logarithmic function of Tammetta's composite variable to the primary database. The both cases the error bars are relatively small.

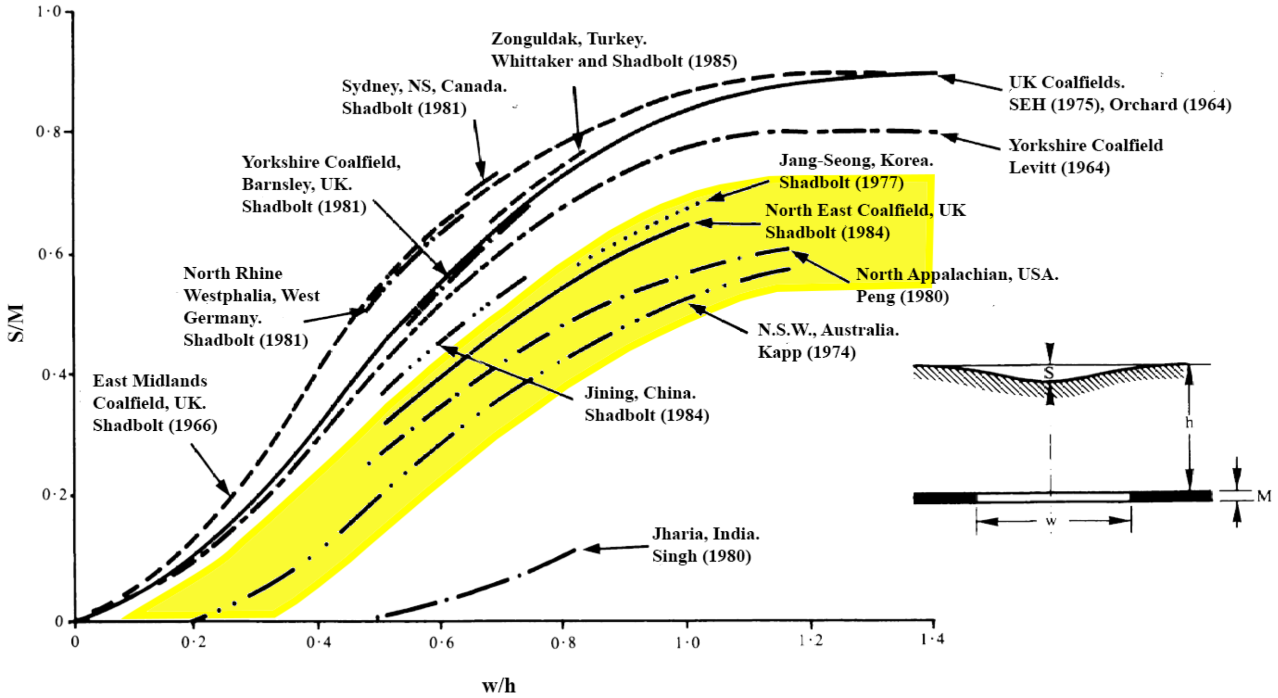


Figure 8. The characteristic surface subsidence curve.

Figure 8 is adapted from Figure 199 in a 1989 subsidence book by Whittaker and Reddish. The Whittaker and Reddish figure appears as Figure 3.14 in Prof. Galvin's 2016 book[18] on coal mine engineering, Figure 3 in his February 2017 review[3] of the PSM report and Figure 4 in his June 2017 summary and explanation report.[4] The surface subsidence curve is obtained as a graph of the ratio of surface subsidence to mining height and the extraction panel width to depth ratio, for isolated extractions at various locations. Pillar compression effects become evident when adjacent panels are extracted; see Figure 9(b).

Discussed in Section 6.2.5, the yellow band highlights regions with lithologies with representation in Tammetta's primary database. Those to either side of the yellow band represent relatively unusual circumstances.

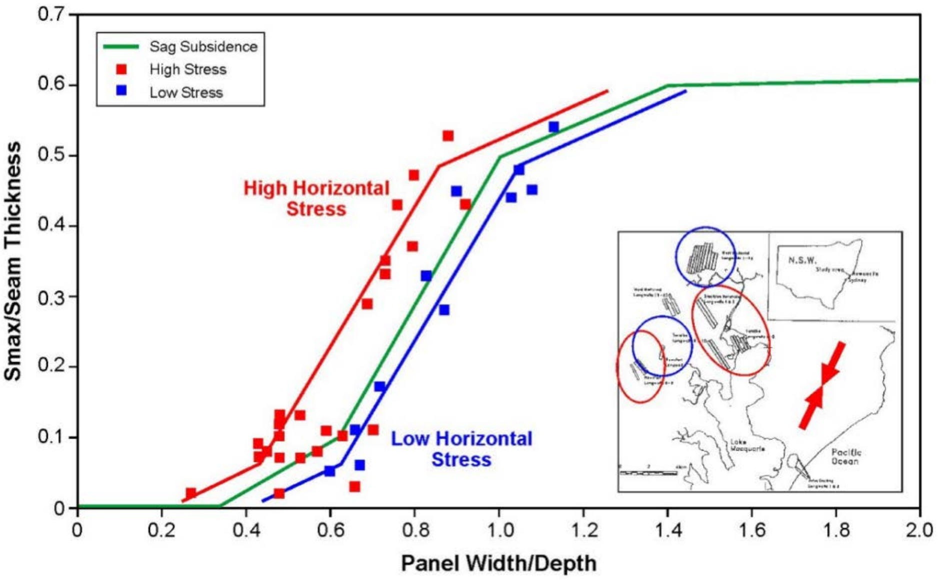


Figure 9(a). Characteristic surface subsidence curve variation with horizontal stress.

Attributed by Tammetta to Tobin, Figure 9(a) is Figure 5.4 from Tammetta's 2014 knowledge report[21] for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. The graph depicts the sensitivity of the characteristic surface subsidence curve to horizontal stress variations.

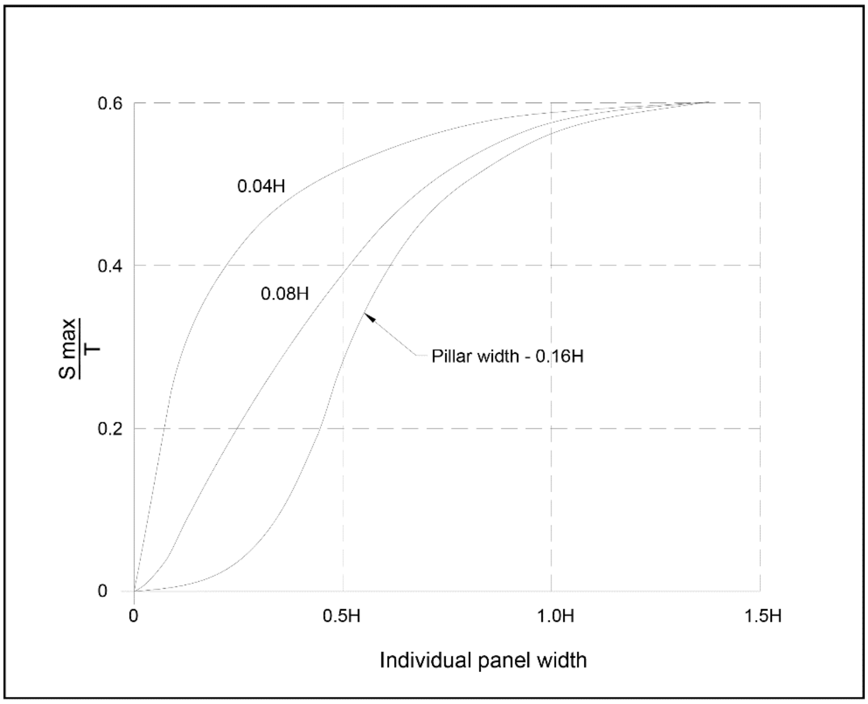


Figure 9(b). Characteristic surface subsidence curve variation with pillar width to depth ratio.

Figure 9(b) is Fig. 1.1 in a 2007 subsidence discussion paper[40] by consultants MSEC and depicts the sensitivity of the characteristic surface subsidence curve to pillar width.

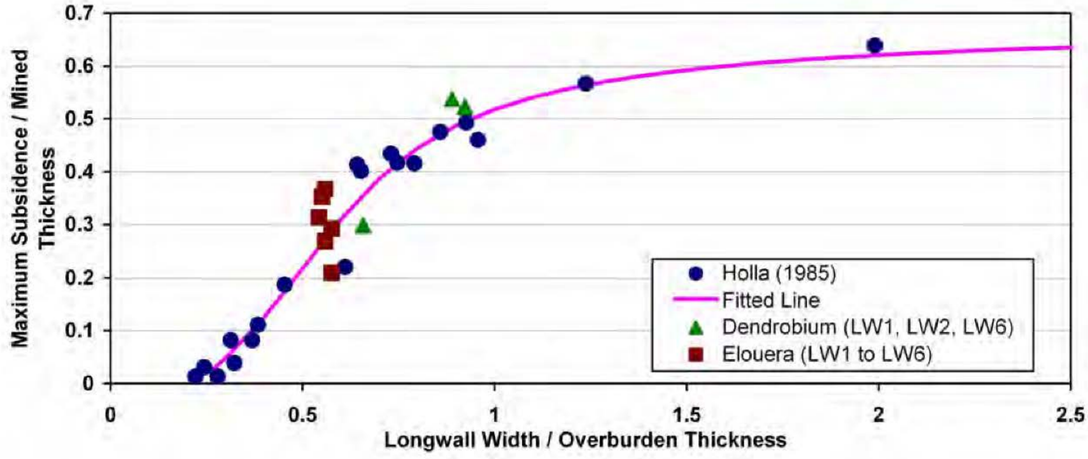


Figure 10. Fitted curve for surface subsidence data from longwalls in the Southern Coalfield and at the Dendrobium and Elouera mines.

Figure 10 is Figure 39 from the November 2012 revised data analysis[10] for the Coffey Geotechnics groundwater impact assessment for then proposed mining in Area 3B of the Dendrobium mine. The assessment was undertaken by Tammetta on behalf of Coffey Geotechnics. The spread evident for the Elouera longwalls presumably reflects pillar compression variations (see Fig 9(b)) and possibly horizontal stress variations (see Fig 9(a)). The data analysis report was released in 2016; the mining company has refused to release numerical analysis report which partnered the data analysis report. The numerical analysis report includes groundwater impact estimates.

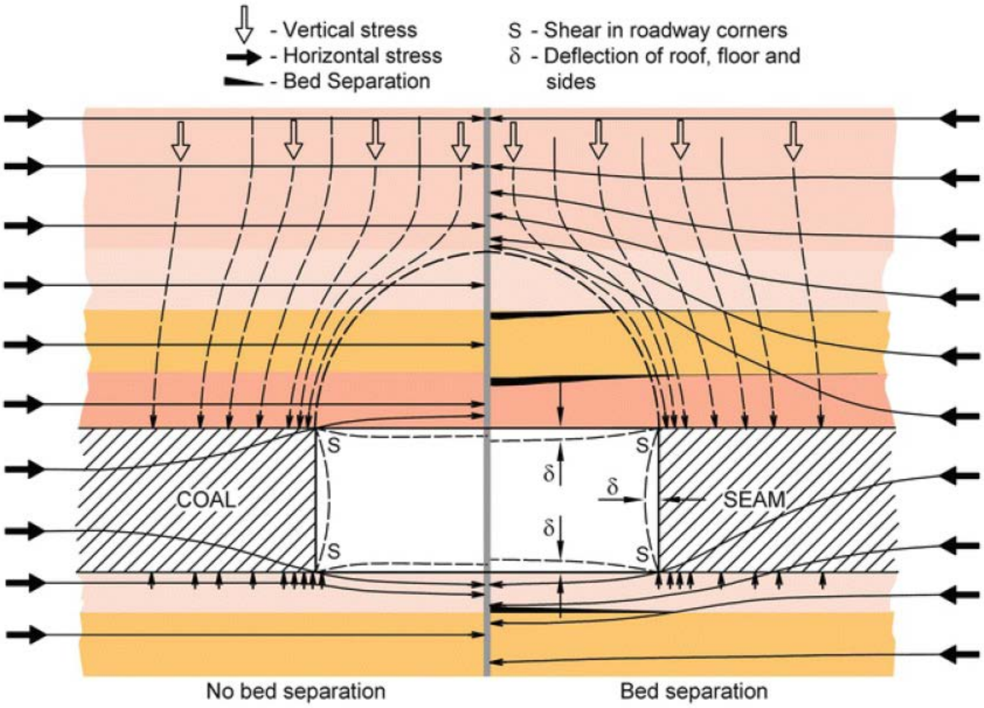


Figure 11. Depiction of stress redistribution around a pressure arch formed over a coal extraction.

Depicting the redistribution of vertical stress over a coal excavation, Fig. 11 is Fig. 3.3 from Prof. Galvin's 2016 book[18] on coal mine engineering. The collapse process that follows coal removal redirects vertical stress to the sides of the extraction, with the 'roof' becoming vertically 'de-stressed'. Imparting a degree of depth dependence, some fraction of the vertical (lithostatic) stress contributes to the horizontal stress via the Poisson effect (Section 6.2.1). A pressure arch is clearly evident in the photograph shown in Fig. 17 below.

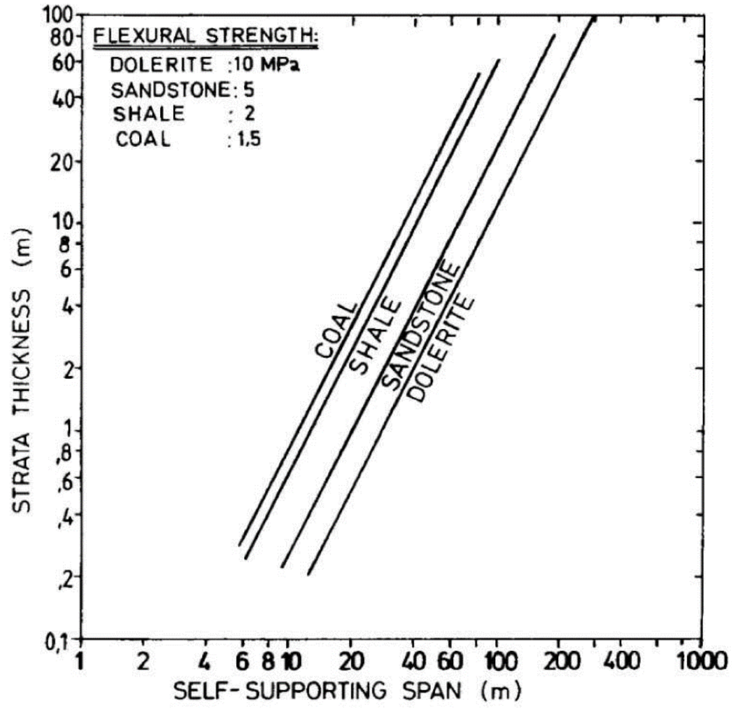


Figure 12. The spanning capacity of dolerite with respect to other formations.

Discussed in Section 6.2.5, Figure 12 is Figure 1 in the supplementary material[39] for Tammetta's first Groundwater paper. The lithology of the Southern Coalfield is dominated by sandstone, notably the Bulgo Sandstone (see Fig. 25; Fig. 11 in the December 2016 NPA report).

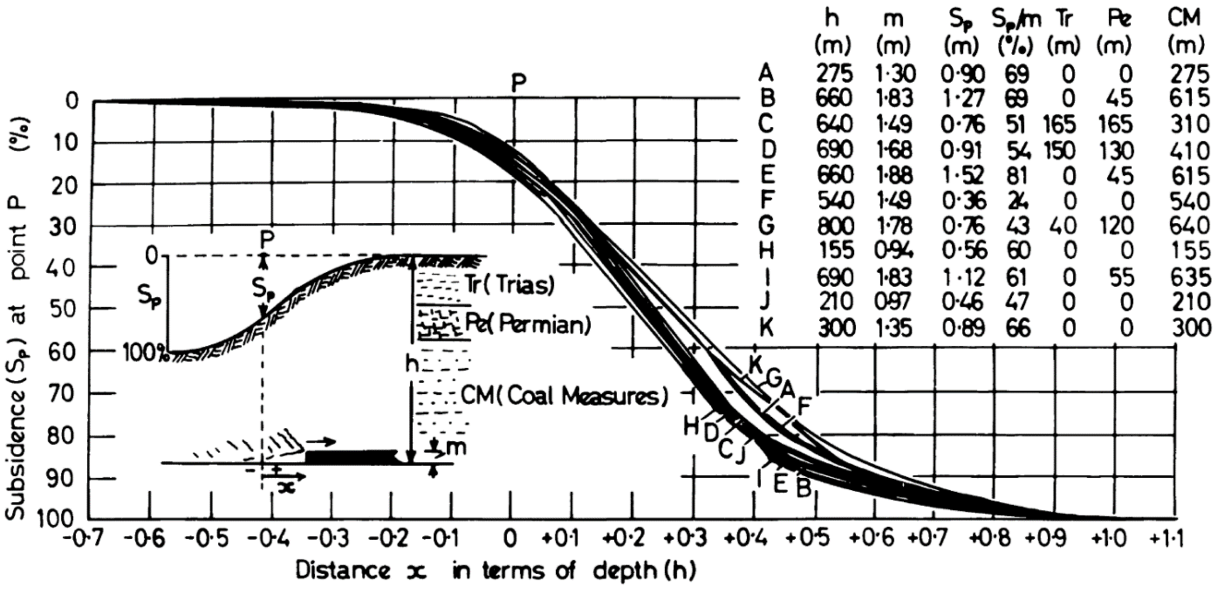


Figure 13. Whittaker and Reddish representation of subsidence progress in Yorkshire

Depicting the development of subsidence over mines in Yorkshire, Fig. 13 is Fig. 50 in Whittaker and Reddish's 1989 book[42] on coal mine subsidence. The graphic suggests coal dominates the lithology at the represented mines. This type of lithology is represented to the left of the yellow central band in Fig. 8 above.

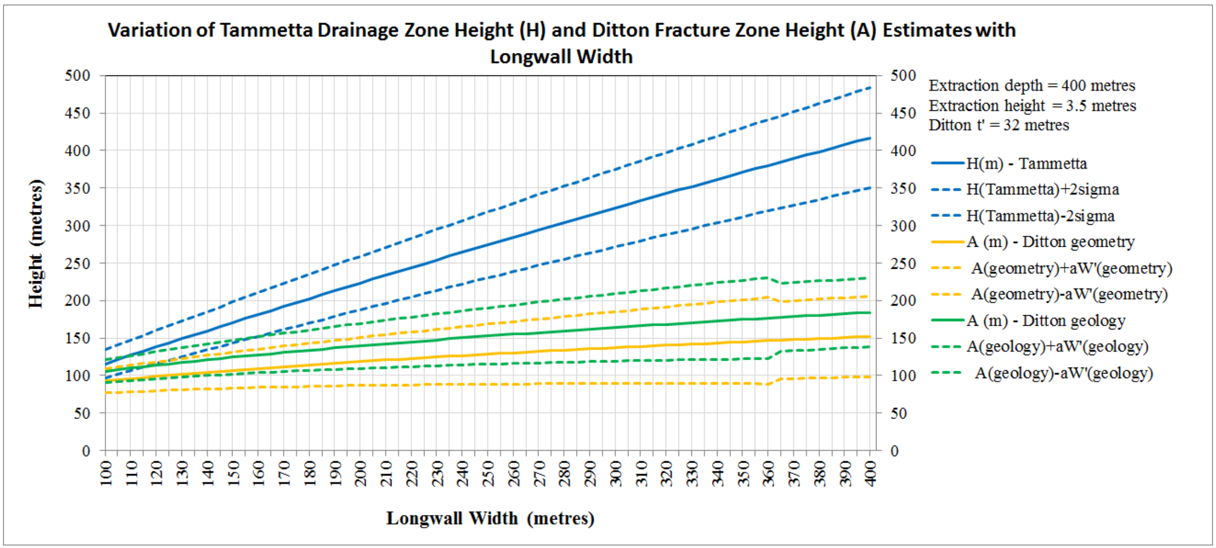


Figure 14(a). Tammetta and Ditton equation height estimate variation with longwall width

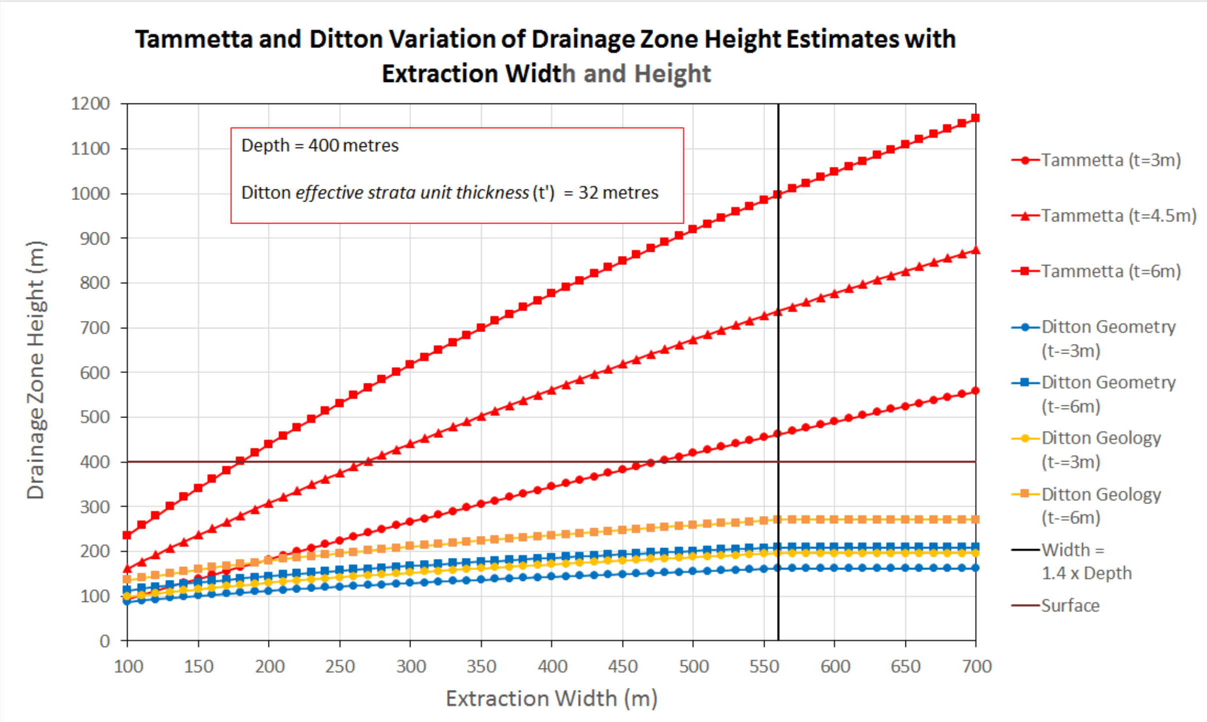


Figure 14(b). Tammetta and Ditton equation height estimate variation with longwall width and height.

The horizontal line represents the surface over extractions with a depth of cover of 400 metres and the vertical line represents the critical extraction width (1.4 times the depth). The work of Mills and Gale suggests, for the extractions studied, that the zone of significant downward movement (see Figs. 16 and 22), referred to by Tammetta as the collapsed zone, has a height approximately equivalent to the height of the extraction width. The Tammetta equation suggests that for a mining depth of 400 metres, this is the case when the extraction height is between 3 and 4 metres.

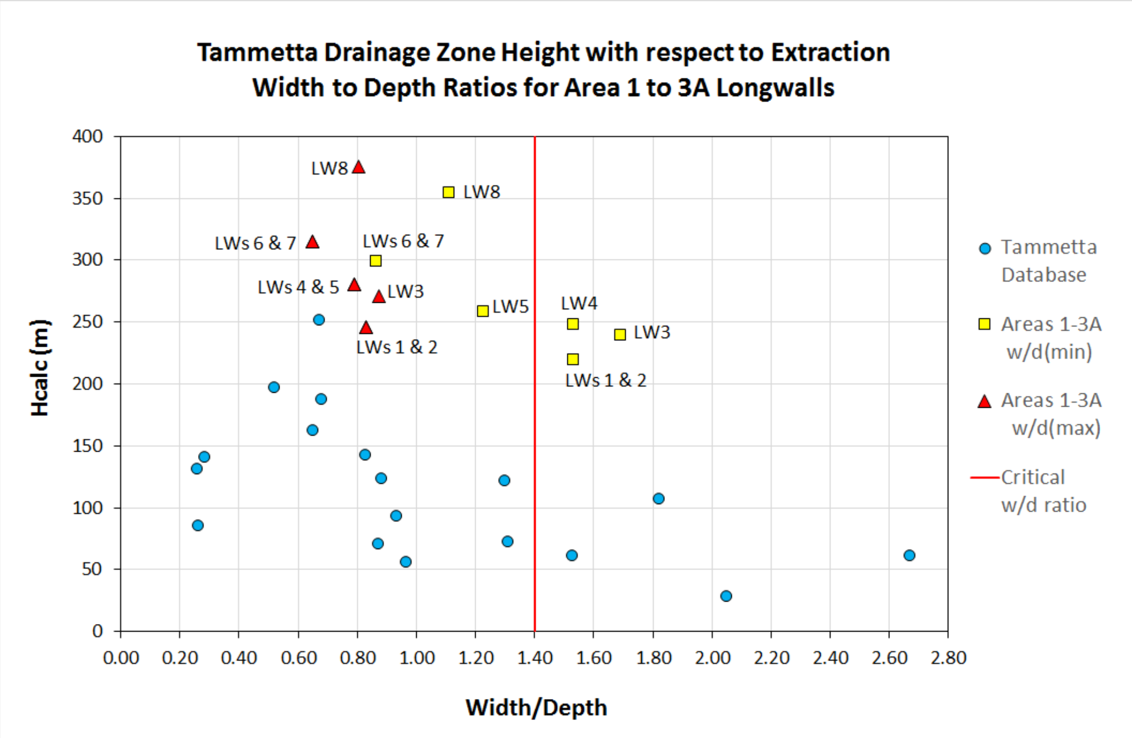


Figure 15(a). Tammetta equation drainage zone height estimates with respect to extraction width to depth ratios for Area 1 to 3A longwalls and Tammetta's database.

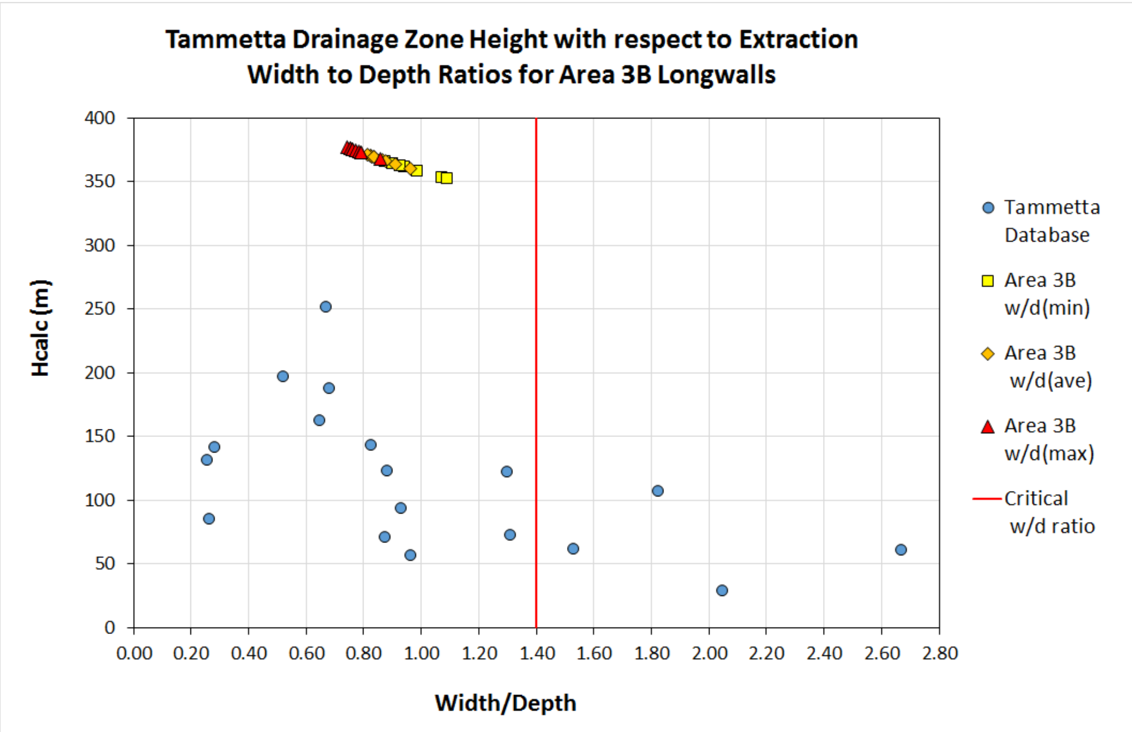
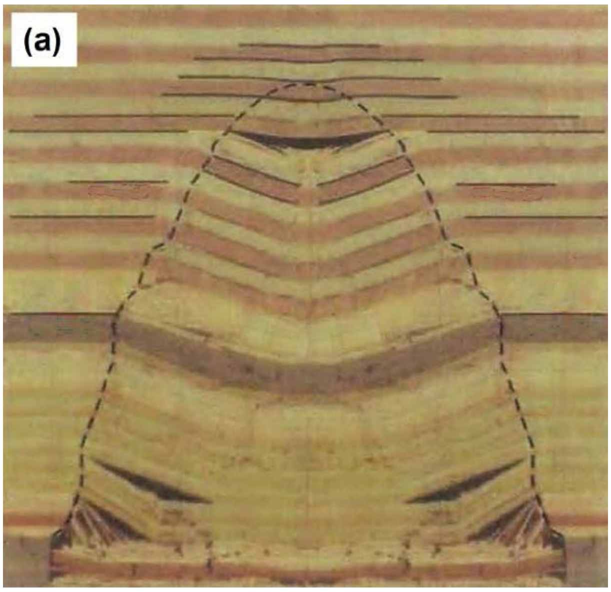
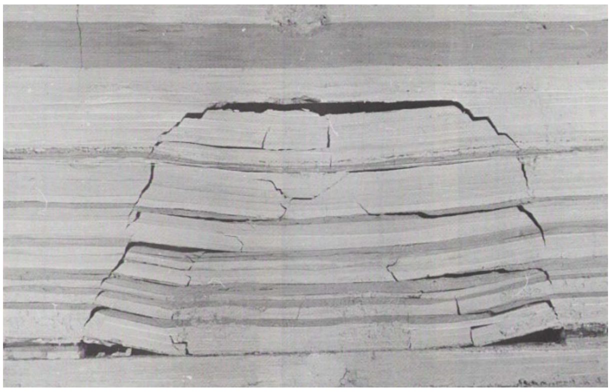


Figure 15(b). Tammetta equation drainage zone height estimates with respect to extraction width to depth ratios for Area 3B longwalls and Tammetta's database.



(a)



(b)

Figure 16. Models of the collapsed zone.

Figure 16 is from a 2007 GHD assessment[53] for Dendrobium Area 3A, where its attributed to a 2005 study by Dr Ken Mills of consultancy SCT, of Longwall 7 in the adjacent Elouera domain of what is now the Wongawilli coal mine (see Fig. 26). Figure 16(a) is also Fig. A2(a) from the supplementary material for Tammetta’s second Groundwater paper[32] and also appears in Fig. 22 below. Figure 16(b) is Fig. 6 in a 2012 conference paper[29] by Mills and is from a 1989 publication[42] by Whittaker and Reddish. Mills makes the following comments with respect to 14(b):

> “*The zone of large downward movement (Zone 2) is clearly evident in this model. The shear constraints associated with the glass side panels in a physical model reduce the height of Zone 2 to less than the full panel width, whereas field observations indicate that the height of Zone 2 is equal to about the panel width in most geological settings. Nevertheless, the level of disturbance illustrated by this model clearly shows that there is likely to be significant disturbance to the overburden strata in Zone 2 with depressurisation of the groundwater system in this zone likely.*

Tammetta finds the collapsed zone coincides with the drainage zone (Section 4.3) and this is demonstrated by data from Elouera Longwall 7 (see Section 20).

Figure 17. Parabolic profile over a roof collapse onto a roadway into a mining highwall.

Figure 17 is Figure 6.8 in a 2014 knowledge report[21] to the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining, prepared by Tammetta on behalf of Coffey Geotechnics. Discussed in Section 11, the image appears as Figure 19 in Whittaker and Reddish's 1989 book[42] on subsidence. Highlighting a pressure arch (see Fig. 11), the original roof has collapsed onto the roadway. Step-wise formation of the pressure arch is suggested by the 'torn-edge' evident in the photograph and Tammetta's summary of the collapse process (Section 14).

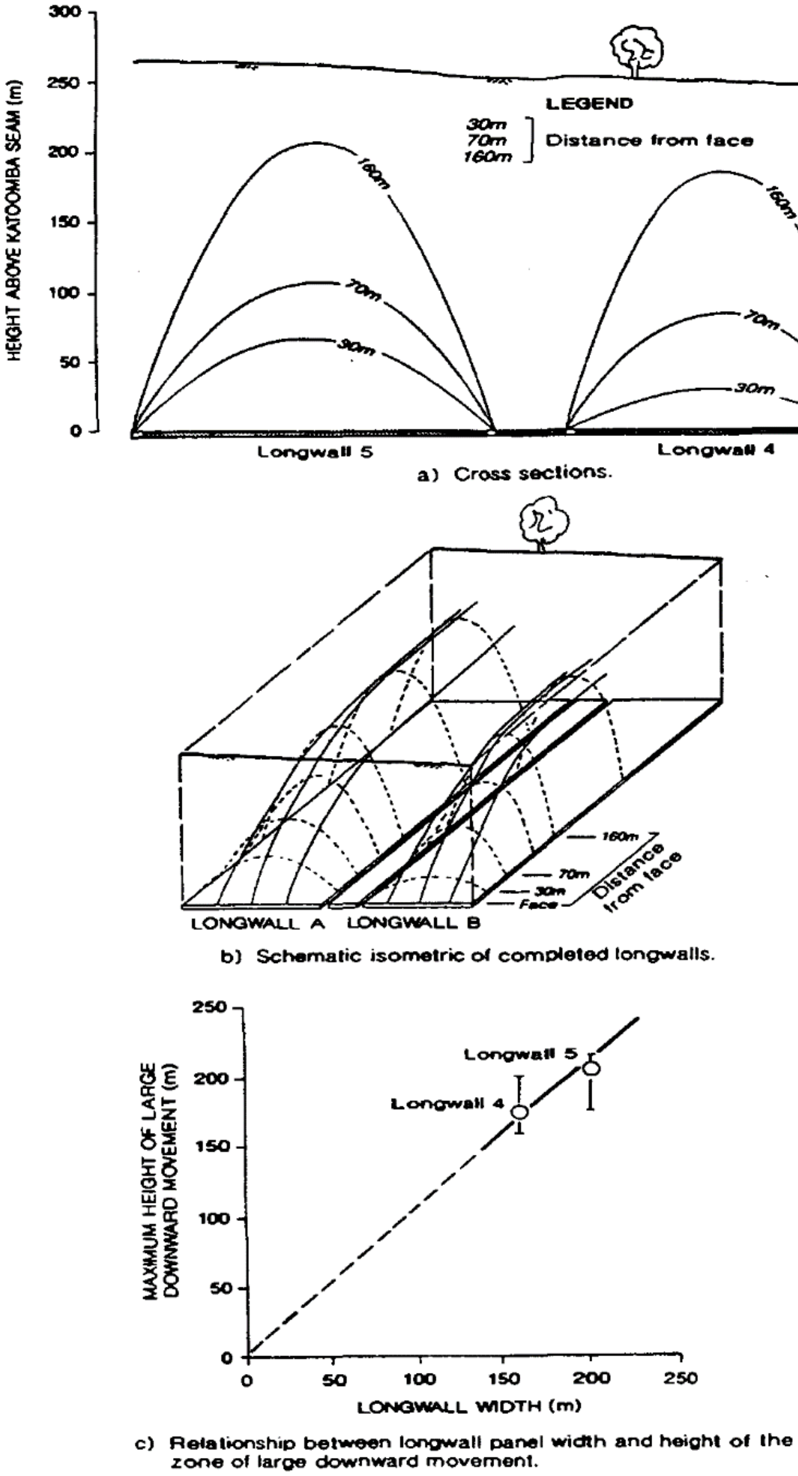


Figure 18. Collapsed zone profile found by Mills and O'Grady at Clarence Colliery.

Discussed in Section 14.1, Figure 18 is Figure 7 from a 1998 paper by Mills and O'Grady reporting an extensometer study over the centreline of Longwalls 4and 5 at the Clarence colliery in the Blue Mountains. The height of the collapsed zone, the zone of significant downward movement, is found to correspond to the width of the extractions. The profile shape suggests a pressure arch.

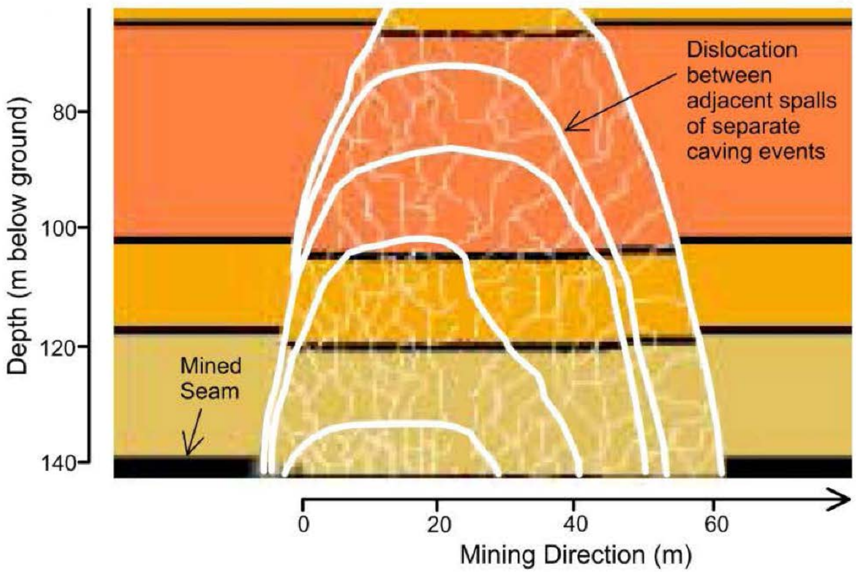


Figure 19. Development of the formation of the collapsed zone.**[32]**

Tammetta finds the collapsed zone coincides with the drainage zone (section 4.3).

Figure 20. Cut-away view of the developing collapsed zone

Cut-away view[32] of the developing collapsed zone over a completed longwall extraction and over the early stage of a second extraction.

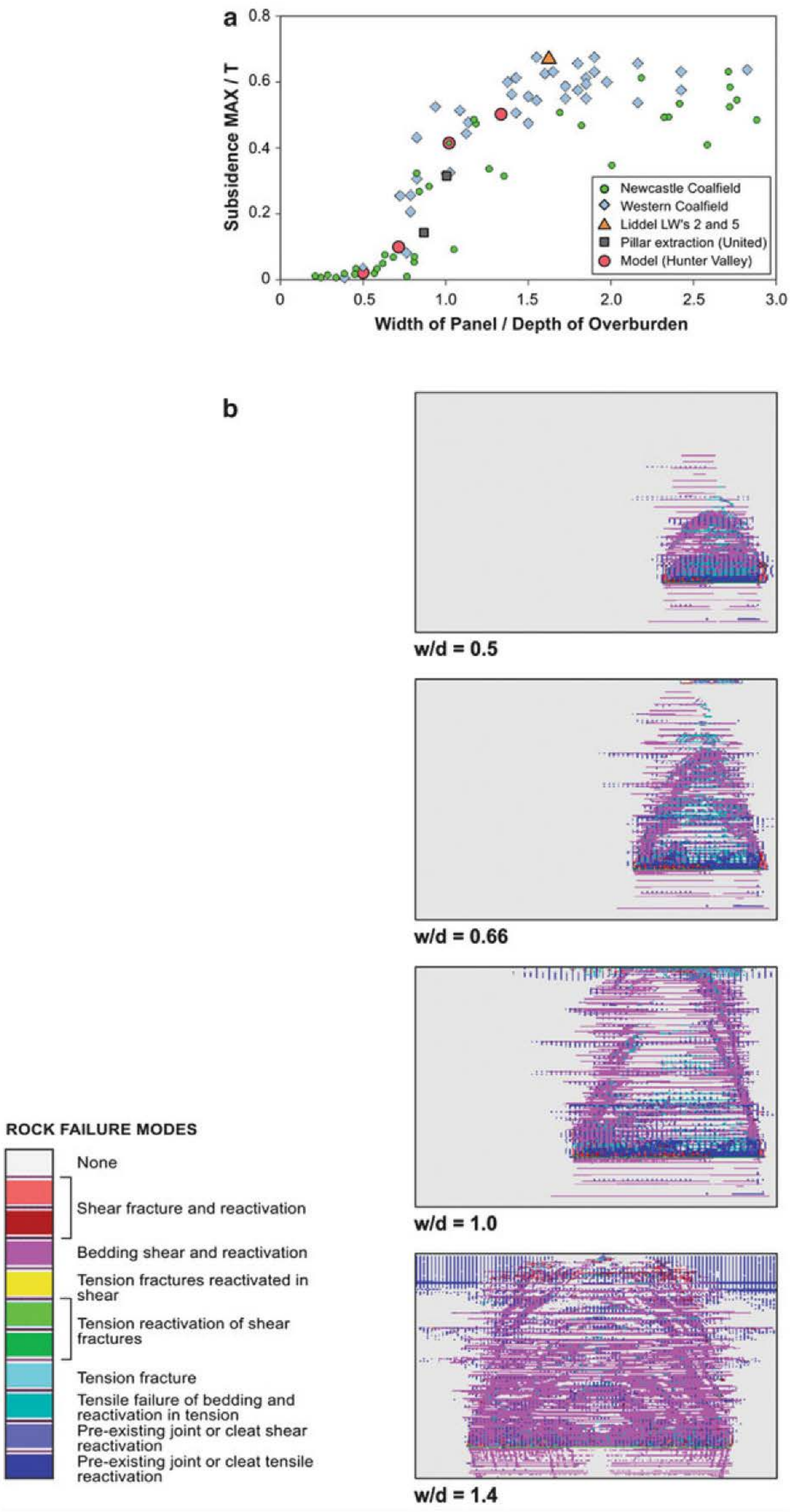


Figure 21. Gale's simulation of fracturing over extractions with varying width to depth ratios.

Figure 21 is provided as Fig. 10.8 in Prof. Galvin's 2016 book on coal mine engineering, which reproduces Fig. 14 in Gale's 2008 ACARP project report.[35] Part (a) shows the characteristic surface subsidence curve for some extractions in NSW (see also Figs. 8, 9(a) and 10).

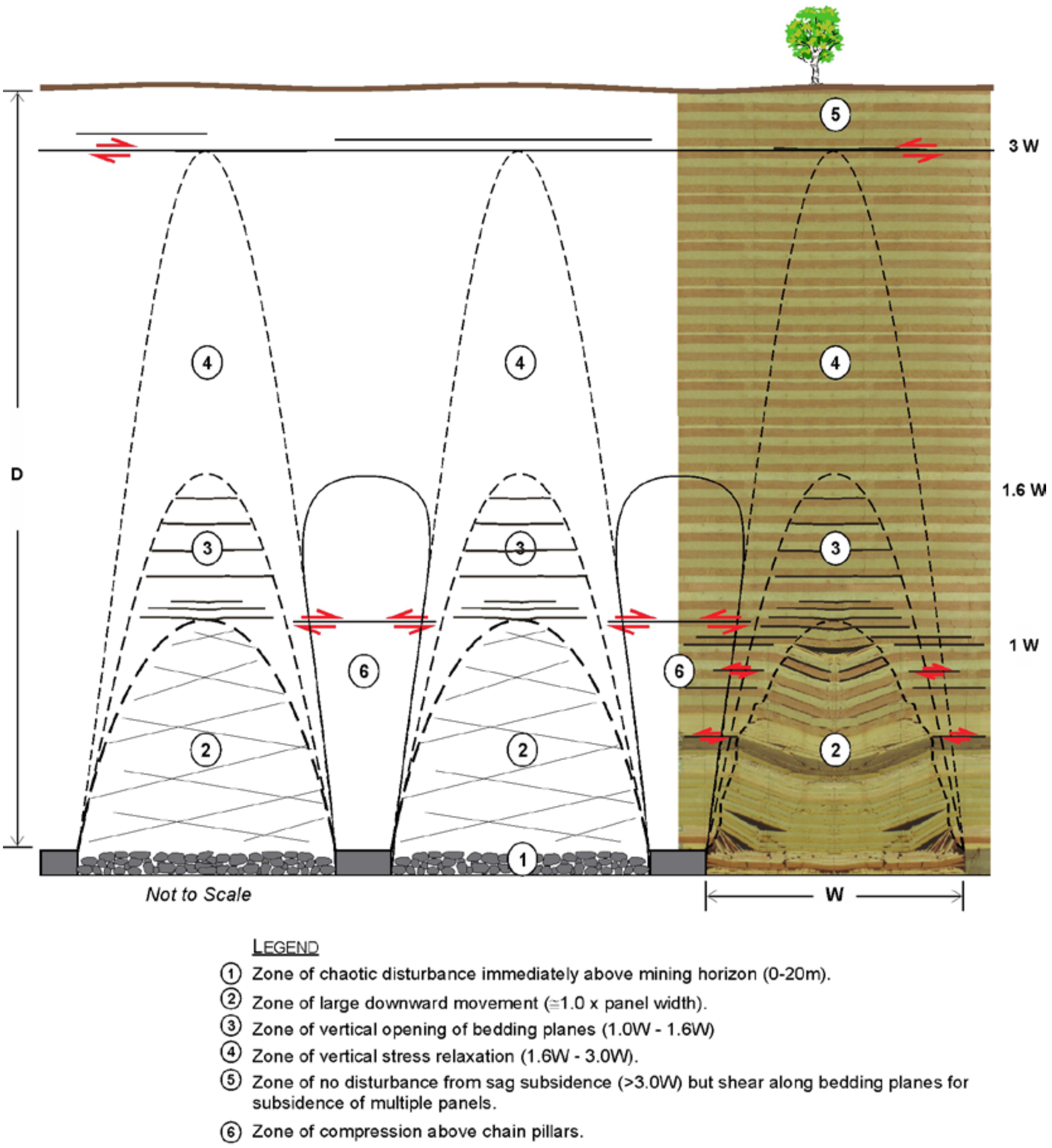


Figure 22. Six zone overburden subsidence model proposed by Mills

Figure 22 is Fig. 5 in a 2012 conference paper by Mills and is provided as Fig. 10.11 in Prof. Gavin's 2016 coal mine engineering book. Based on subsidence measurements, camera observations, packer testing, piezometer data, micro-seismic data, extensometer monitoring, and stress change monitoring, the graphic highlights six overburden disturbance zones. Zone 2 is a zone of significant downward movement that Tammetta finds coincides with the drainage zone. Mills finds that, for the set of extractions studied, the height of Zone 2 is approximately the same as the extraction width. The Tammetta equation suggests that this depends on the depth and extraction height (see Fig. 14(b), Figs 6(a) to 6(c) and Figs. 5(a) and 5(b)). Tammetta regards the zones beyond Zone 2 as a hydrological continuum of non-zero water pressure that he refers to as the 'disturbed zone'.

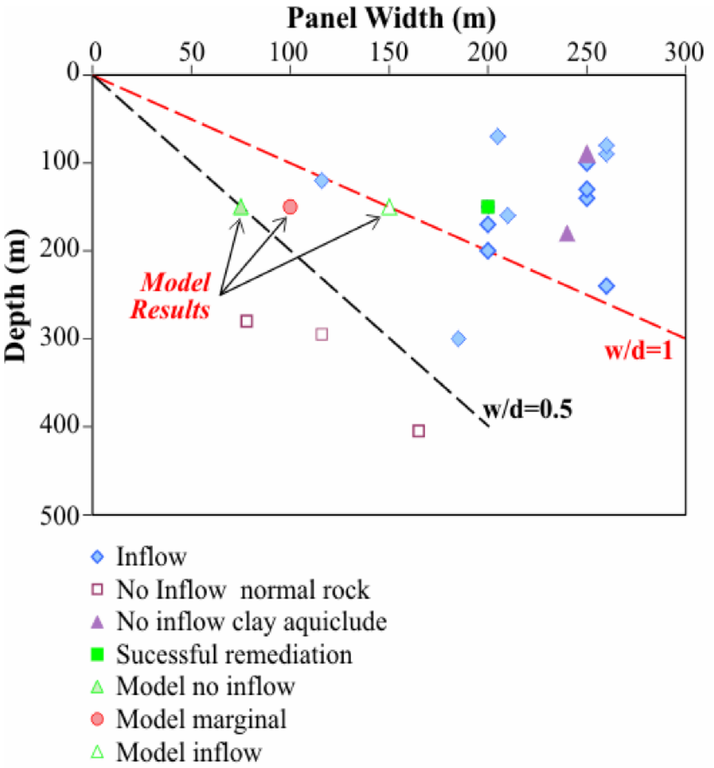


Figure 23. Gale's 2006 graph of mine inflow with respect to extraction width to depth ratio.

Figure 23 is Figure 4 from a 2006 conference paper[36] by Gale on surface water inflow to mines through the fractured overburden above longwall panels. Gale reports that "*panels with a width to depth ratio greater than one typically show confirmed connection. One site shows connection with a width to depth ratio of approximately 0.75. Panels with a width to depth ratio of less than 0.4 show no connection*." Gale suggests 0.75 ratio marks a transition from no connection to increasingly likely connection to the surface.

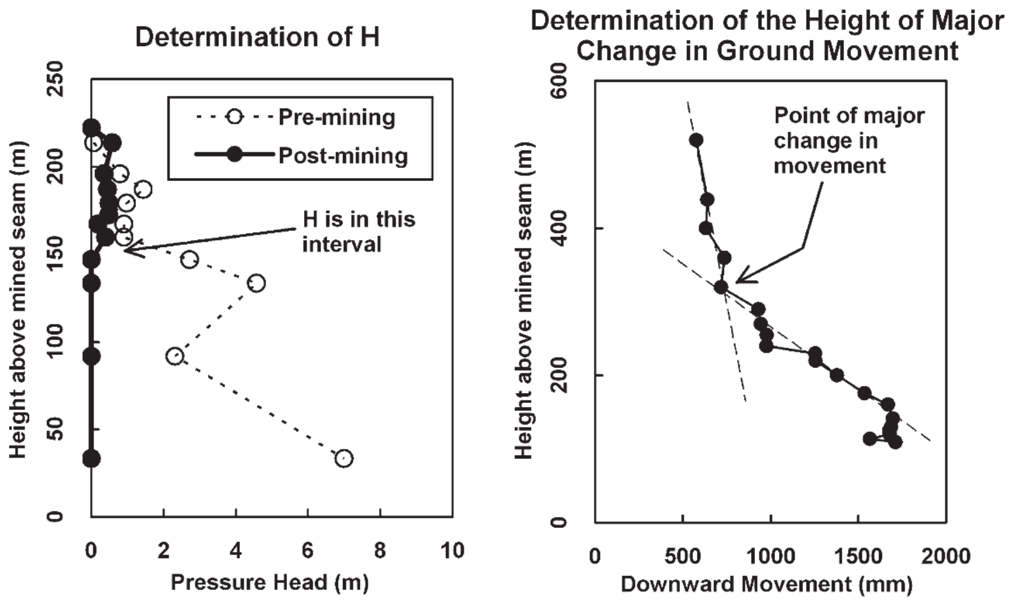


Figure 24. Examples of the determination of the drainage and collapsed zone heights from Tammetta's 2013 Groundwater paper

Figure 24 is Figure 2 from Tammetta's first Groundwater paper[11], published in 2013. The left-hand side illustrates the determination of the drainage zone height using data from the Beech Fork mine in Appalachia in the US. Illustrating the determination of the height of the collapsed zone, the righthand side shows a relatively sharp change in slope through extensometer data from the Westcliff Colliery in the Southern Coalfield of NSW. Tammetta finds the heights of the drainage zone and the collapsed zone essentially coincide.

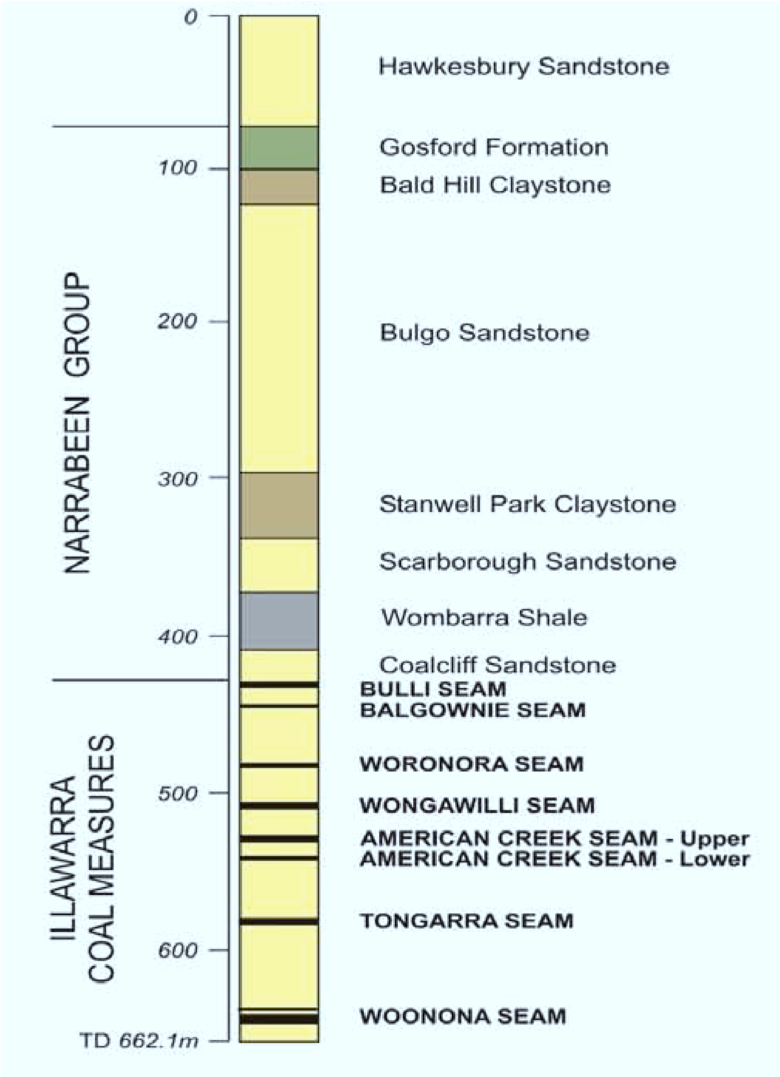


Figure 25. Representative stratigraphy of the Woronora Plateau.**[59]**

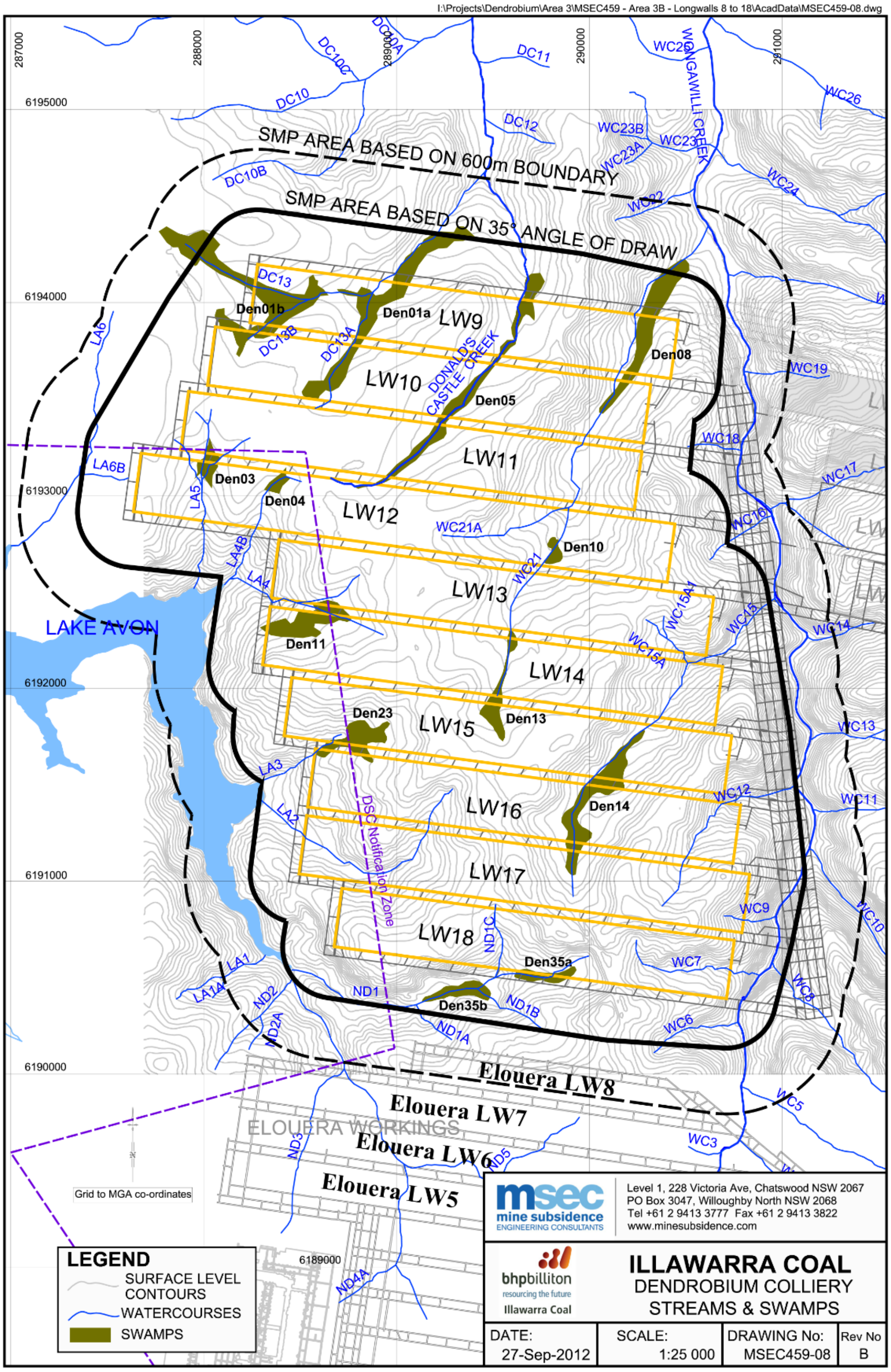


Figure 26. Proximity of Elouera domain and swamps and streams over Area 3B.

Numbers for the longwalls in the Elouera domain immediately to the south of Area 3B have been added to the MSEC depiction of Area 3B.[60] Fig. 26 is Fig. 56 in the December 216 NPA report.

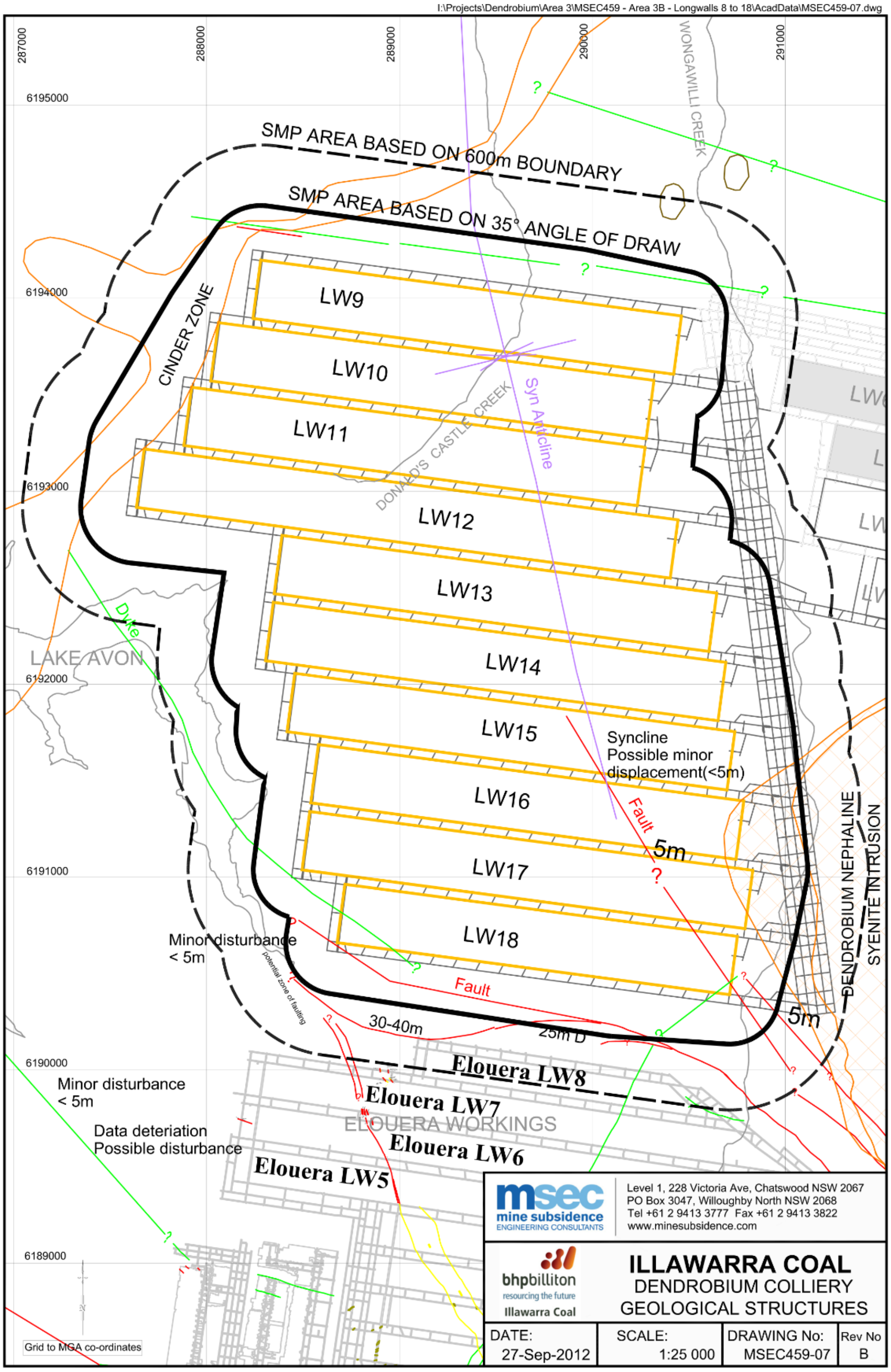


Figure 27. Geological structures over the Area 3B and proximity of Elouera Longwalls.

MSEC[60] depiction of geological structures over the Area 3B longwalls. An unusual nephaline syenite formation slightly intrudes in to the south eastern corner of Area 3B. There are no other noteworthy Area 3B deviations from the stratigraphy typical of the Woronora Plateau (see Fig. 25). Labels for the Elouera longwalls adjacent to Area 3B have been added to the MSEC map.

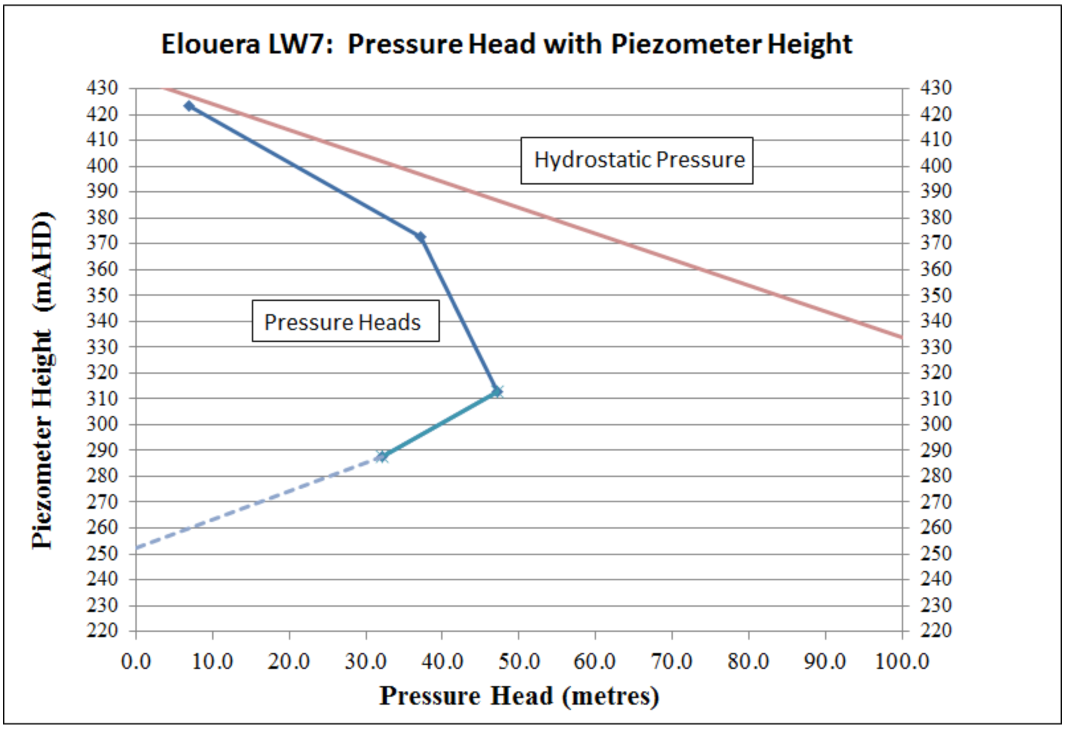


Figure 28. Height of the drainage zone obtained from Elouera LW7 piezometer data.

Discussed in the December 2016 NPA report, the data in Fig.28 (Fig. 16 in the 2016 NPA report) were obtained by digitising Fig. 6 from the October 2012 Coffey (Tammetta) groundwater impact assessment for Area3B (Fig. 15 in the December 2016 NPA report).[7] The blue line links the pressure heads at each piezometer in the centre-line bore over Elouera Longwall 7 (LW7; see Figs. 26 and 27). In each case the pressure head was obtained by subtracting the piezometer height given in Fig. 6 of the Coffey report from the hydraulic pressure given in that figure.

The grey line in the above figure depicts the change in groundwater pressure head with depth that would be expected under 'artesian' conditions in the absence of mining impacts (hydrostatic pressure). The pressure recorded by the piezometers deviates from this hydrostatic pressure as the distance between a piezometer and the drainage zone decreases.

The height of the drainage zone is obtained extrapolating to a pressure head of zero, conservatively assuming a 'hydrostatic' (1:1) rate of change of pressure between the deepest piezometer and the top of the drainage zone, which identified in having no measurable water pressure. The height of zero pressure head is accordingly estimated to be 252 mAHD (Australian Height Datum in metres; effectively the height above sea level). Coffey Fig. 6 suggests the coal seam is 66 mAHD and the peak height of zero pressure head, the height of the drainage zone, above the coal seam is then 186 metres. Given the conservative nature of the extrapolation, the height is likely to be slightly underestimated. The profile is seen above longwall extractions at other locations in the Southern Coalfield, such as Russell Vale.

The height estimate returned by the Tammetta equation is 198 metres. The height estimate returned by the Ditton geometry equation is 112 metres, while that from the Ditton geology equation, with t'=32 (as suggested by Ditton[6] and used by HydroSimulations[14]), is 128 metres.

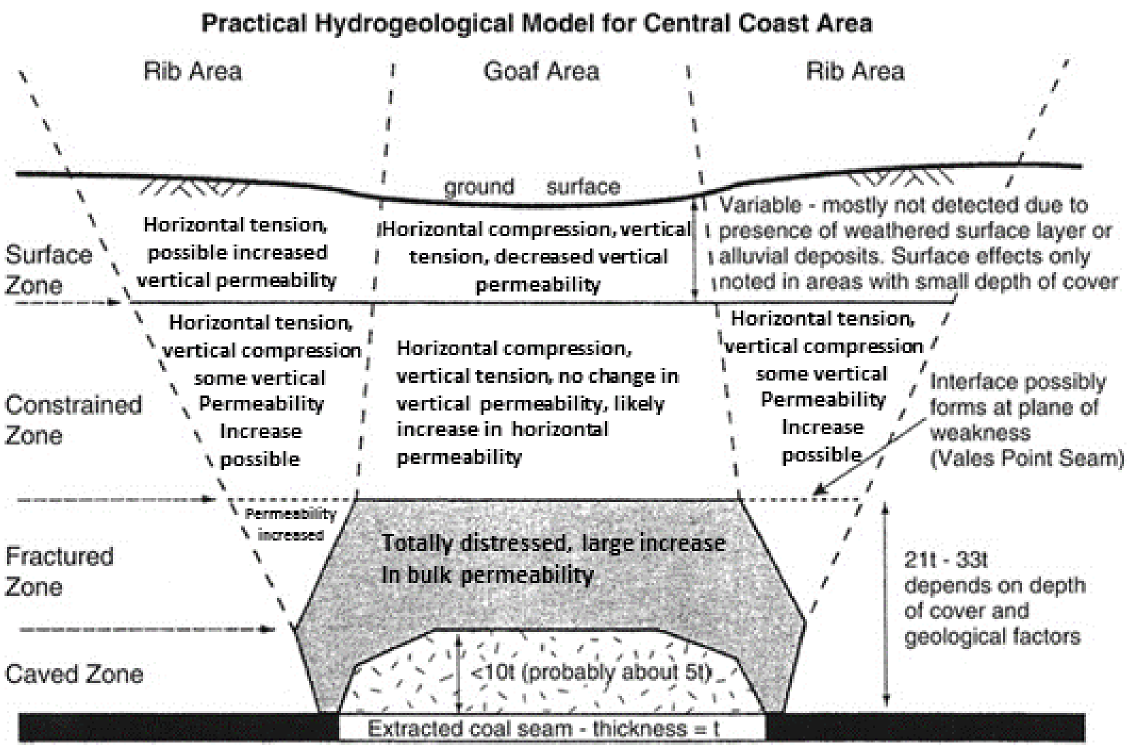


Figure 29. 1992 Forster and Enever conceptualisation of overburden disturbance based on data from the Central Coast region of NSW.

Figure 29 is an amalgam of Figs. 10.3 and 10.4 of Prof. Galvin's 2016 book on coal mine engineering. The thickness ranges assigned to the zones reflect field measurements over a supercritical mining layout. The model does not then include mining width as a determining parameter.

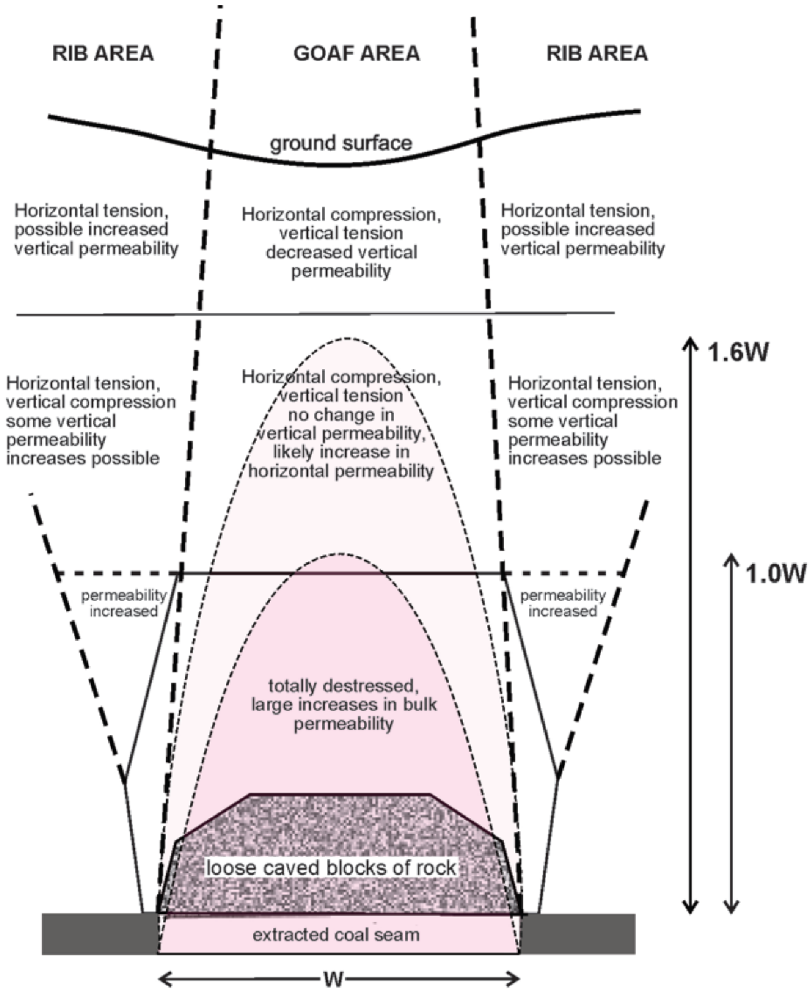


Figure 30. Tammetta's 2014 modification to the 1992 Forster and Enever conceptualisation of overburden disturbance.

Figue 30 is Figure 6.12 from a 2014 knowledge report[21] for the Commonwealth Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining prepared by Tammetta on behalf of Coffey Geotechnics. The figure shows the 1992 Forster and Enever (see Fig. 29) representation of the key subsidence zones, based on data from the Central Coast of NSW. Tammetta has modifed the depiction to incorporate the current understanding represented by Mill's model (see Fig. 22). The zone described as 'totally destressed' by Forster and Enever is 'stretched' vertically by Tammetta to correspond to the top of Mills' Zone 2. In Tammetta's words, "*A strong correlation then exists between the zones described by Forster and Enever and the various zones inferred from generalised subsidence monitoring and other information.*" This zone corresponds to the drainage zone of Tammetta's hydrological model.

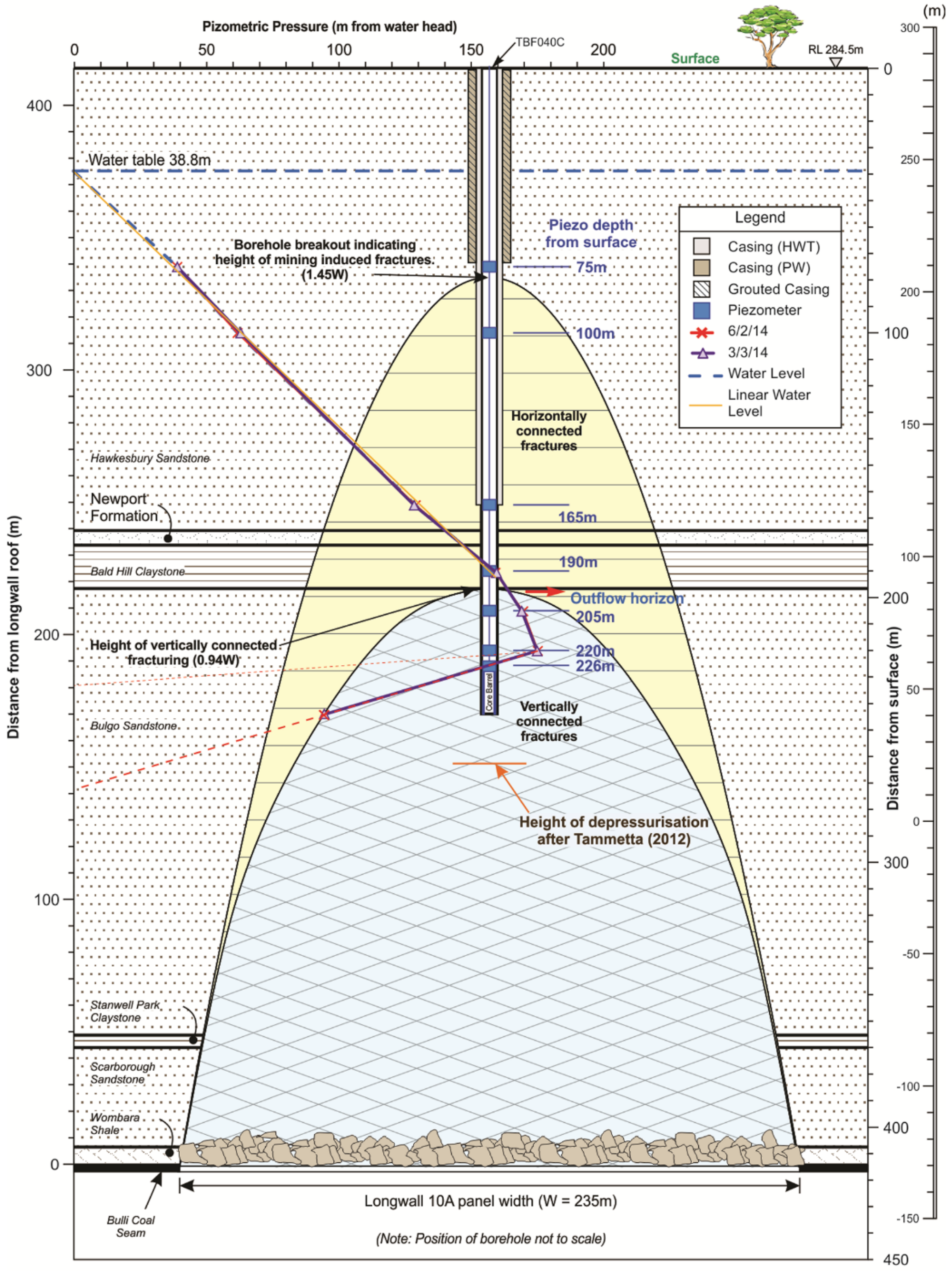


Figure 31. SCT representation of their results from Longwall 10A at the Tahmoor Colliery

Figure 31 is Figure 7 from a 2017 conference paper by Dr Ken Mills of consultancy SCT. The conference paper reporting the Tahmoor Colliery results (Section 21) does not include extensometer data, suggesting the height of the collapsed zone was not determined. Tammetta finds that the height of the drainage zone and the collapsed zone coincide and this is supported by SCT's 2005 study of Longwall 7 in the Elouera domain of the Wongawilli Colliery (Section 20).

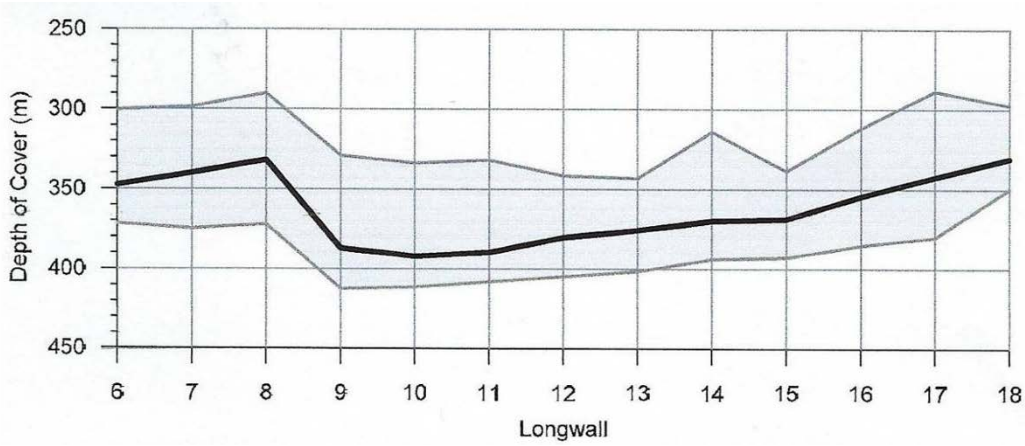


Figure 32. Variation of depth of cover over Dendrobium Longwalls 6 to 18

Fig. 32 is Fig. 7 from Hebblewhite's 2018 review of the assessment of the height of fracturing over the Dendrobium mine. The black line represents the average depth of cover for each longwall, while the upper and lower lines represent the maximum and minimum respectively.

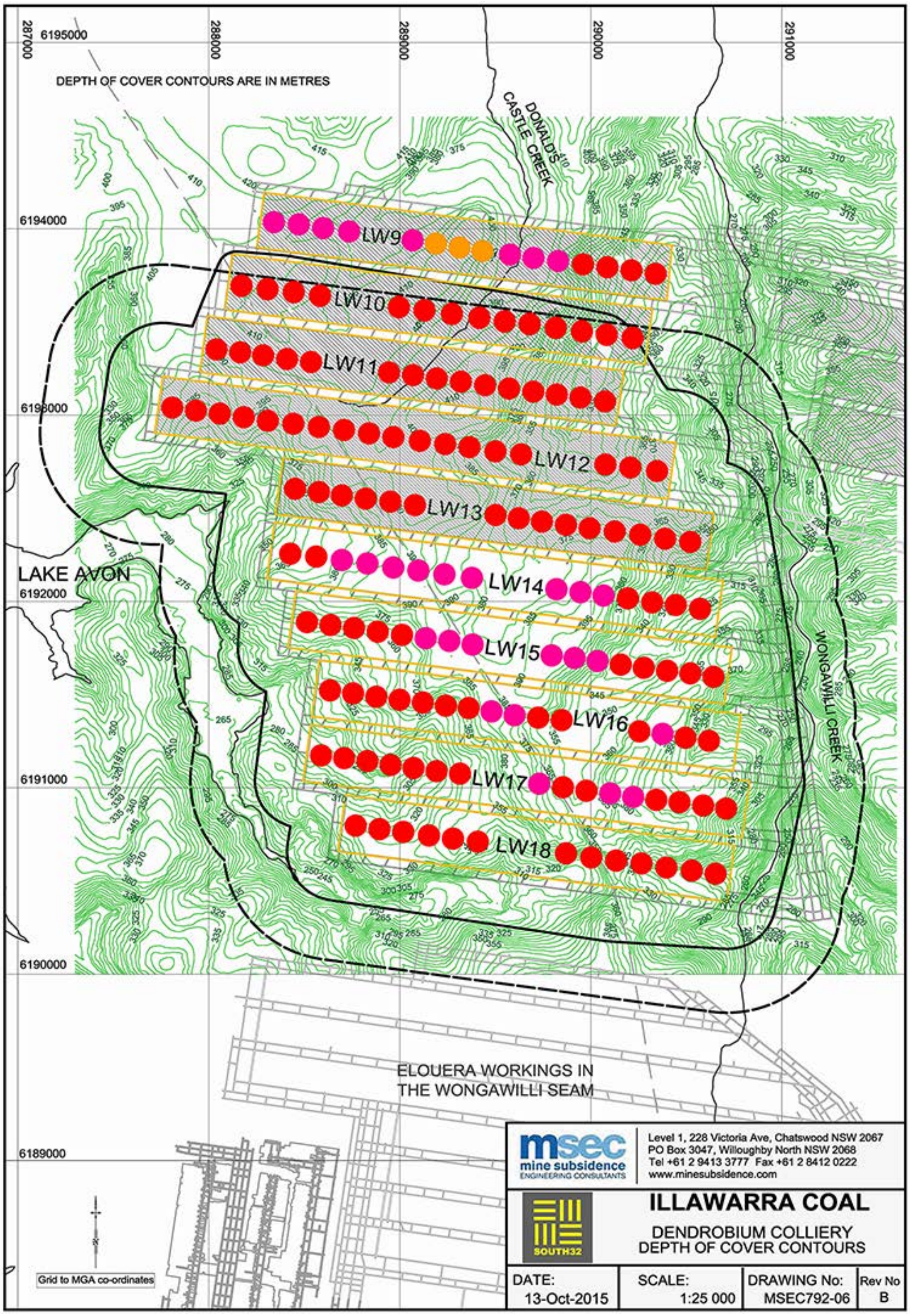


Figure 33. Depiction of the Tammetta equation estimates for the drainage zones over Area 3B extractions with extraction heights approved by the Department of Planning.

Coloured circles have been added to the MSEC representation[61] of the depth of cover over the Area 3B longwalls, to indicate the Tammetta equation[11] estimates of the height of the drainage zone for 3.9 high extractions (LWS 9 and 14 to 18) and 4.6 metre high extractions (LWs 10 to 13). Pink indicates a height between 25 metres from the surface and the surface, and red indicates intersection with the surface. The shaded longwalls have been extracted and Longwall 14 commenced in May 2018.