Spatial context in the calculation of gas emissions for underground coal mines

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A B S T R A C T

The prediction of gas emissions arising from underground coal mining has been the subject of extensive research for several decades, however calculation techniques remain empirically based and are hence limited to the origin of calculation in both application and resolution. Quantification and management of risk associated with sudden gas release during mining (outbursts) and accumulation of noxious or combustible gases within the mining environment is reliant on such predictions, and unexplained variation correctly requires conservative management practices in response to risk. Over 2500 gas core samples from two southern Sydney basin mines producing metallurgical coal from the Bulli seam have been analysed in various geospatial context including relationships to hydrological features and geological structures. The results suggest variability and limitations associated with the present traditional approaches to gas emission prediction and design of gas management practices may be addressed using predictions derived from improved spatial datasets, and analysis techniques incorporating fundamental physical and energy related principles.

1. Introduction

Underground mining methods account for approximately 20% of total black coal and a proportionally higher amount of metallurgical coal production in Australia [1]. In NSW, hard metallurgical coal is exclusively mined from the Illawarra coal measures in the southern region of the Sydney Basin. Co-located with these coal reserves are significant quantities of methane (CH₄) and carbon dioxide (CO₂) gas [2].

Fugitive emissions of gas from mining via ventilation air not only contribute towards greenhouse gas (GHG) inventory, but in the case of methane, also represent a lost opportunity for energy recovery. Gas reserves are not limited to economically recoverable coal seams, but also include coal measures and other porous stratigraphy both above and below the working seam [3].

Emission predictions are essential for the quantification and management of risk associated with sudden gas release during mining (outbursts), and accumulation of noxious or combustible gases within the mining environment. Unexplained variation in gas character rightly requires conservative mining practices to manage such risks [4].

In many cases, risks are identified later in the mining cycle where remedial action is typically more expensive and is more likely to incur production delay or loss. Over 2500 gas core samples from three southern Sydney Basin mines producing from the Bulli seam have been analysed in various geospatial context including relationships to hydrological features and geological structures. Improved spatial datasets, particularly those containing a vertical dimension and derivatives thereof, may be applied to prediction and management of gas emission using fundamental principles. The application of the physical and spatial techniques described enhance the potential future use of high volume and high resolution real time measurement data for proactive management of gas emission risk much earlier in both the gas and mining life cycle.

The improved resolution and definition in the prediction of site specific transient gas emission character, in terms of source location, quantity, composition, flow path and timing is acknowledged by several authors as critical for maintaining current production rates in higher gas content environments [3,5,6].

Gas emissions will increase well beyond the practical management capacity of ventilation and current pre and post drainage systems at several Australian underground coal mines [4]. Hence the traditional approach of increasing ventilation quantity is unlikely
to be sustainable due to practical constraints such as roadway area and maximum air velocity therein.

Only a step change improvement in gas drainage, capture and utilisation practices will allow coal to remain a sustainable source of energy in a low emission world [3]. The identification and use of gas management controls which are fundamentally based and incorporate improved spatial and time resolution will not only make mining safer, delivery of this outcome will reduce interruptions for reasons of safety management and lift both coal and overall energy productivity.

2. Historical gas emission prediction

The prediction of methane emissions arising from underground coal mining has been the subject of extensive research for several decades and techniques range from simple geometric models to modern finite element models [7–12]. Despite improvement in computation processing power and speed over this time period, calculation techniques remain empirically based and are hence limited to the origin of information in both application and resolution.

Gas emissions due to mining extraction are transient and a complex function of the in-situ resource character, the space where in-situ character and gas equilibrium is affected by extraction, the degree to which character and equilibrium is affected, and the system response [9].

In order to simplify the calculation process of most current prediction techniques, key inputs for gas content, material properties and spatial attributes are generally either (1) provided as input variables at low resolution, (2) held constant, or (3) neglected altogether.

Of the many prediction techniques available, the Flügge technique continues to be used for the purpose of total specific gas emission calculation at many Australian mines [13,14]. However, limitations in describing spatial and time based gas emission character with any resolution renders this technique ineffective for design of gas drainage programs. Evidence provided through finite element analysis and micro seismic observations suggest the triangular prism representation is only valid in specific geological conditions and does not cater well for changes in either geology or operational practices [15].

Research by Lama in the 1990s led to the significant reduction of risk associated with gas outburst through the development of composition dependent gas content threshold levels for the Bulli seam [16]. These thresholds or derivations thereof largely remain in place in the Australian coal industry to the present day due to the principles based methodology used. Further research during the latter part of the decade also focussed on developing an understanding of fundamental mechanisms driving gas emission behaviour from coal and surrounding strata [16–18]. The importance of cleat and joint geometry and net effective stress in the control of fluid movement was highlighted.

A detailed description of the process for measurement of gas content and its’ contributing components may be found in Australian Standard AS 3980 [19]. Limitations of some of the measurement techniques used, specifically including assumptions of the timing of initial desorption and the lost gas component Qd, are discussed further by Saghafi [20].

Other factors considered in emission prediction include differential sorption properties of coal under the effect of a shear structure, and gas pressure measurements which change as a result of changes in the permeability of the structure. Significantly, the fracture density and sorption properties may change up to 20 m away from the shear structure, but gas pressure changes can occur up to 100 m away from the structure.

The GeoGAS Longwall “pore pressure” model described by Ashelford took account of many gas reservoir and geological parameters of coal seams and allowed variation of mining operations in arriving at a gas emission value [11]. The model relies upon measured gas reservoir properties for the determination of gas release such as; measured gas content (Qm), gas desorption rate, gas composition, gas sorption capacity, seam thickness and mineral matter above and below the working section, pore pressure and coal and sandstone porosity. The model parameters and how they are measured are described by Williams et al. [21].

The advantage of this model over prior techniques was its’ ability to accurately predict the magnitude of gas emission from the floor seams below the Bulli seam in the southern Sydney Basin. This was due to the significant deformation and order of magnitude changes in horizontal and vertical stress in the floor strata recognised and displayed by finite element software. Whilst the pore pressure model remains the most adaptive and fundamentally based calculation of gas emission for longwall operations, the input assumptions limit the application of this technique to the increasing spatial and time resolution required for design of gas drainage programs.

The availability of increasing computational processing capability has enabled the management of the increased size and complexity of the data available for gas emission analysis in recent years. Studies including those by Karacan used statistical, principle component analysis (PCA) and artificial neural network (ANN) based approaches to predict the ventilation methane emission rates of U.S. longwall mines [10,22,23].

Critically, all techniques which involve the use of large historical data sets for gas emission prediction by analysis using statistical, PCA or ANN approaches rely on a fundamental assumption that input conditions will not materially change. Model outputs are based in fundamental scientific principles however the model design and structure limits the ability for its use in locations where input conditions change rapidly.

Comparison of the output of various prediction models is difficult due to lack of a common gas, material and spatial datum reference and also for the reasons discussed in Jensen et al. [24].

3. Relevant gas fundamentals used

3.1. Gas generation

Coalbed or coal seam gas are general terms used to describe gases contained within coal measures that are generated as part of coalification and other geological and hydrogeological processes [25]. Similar to the creation of coal itself, coal bed gas generation pathways are also dependent on fundamental physical and chemical character and changes in both level and form of energy within the environment. Coal bed methane can be classified as either biogenic or thermogenic in origin [26].

Biogenic methane is generated at low temperature by anaerobic microbes (methanogens) when coal beds are exposed to groundwater recharge after basin deformation. The dominant biological processes involved in the generation of biogenic methane include carbon dioxide reduction and acetate reduction or fermentation which are described in chemical Eqs. (1)–(3). Two significant factors must be carefully considered in the characterisation of the origin of biogenic gas. Firstly, for carbon dioxide reduction to methane, hydrogen must be present. Secondly, in addition to the methane, the two-part acetate fermentation process also produces CO₂ [27].

\[
\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \quad (1)
\]

\[
\text{CH}_3\text{COO}^- + \text{H}^+ \rightarrow \text{H}_4 + \text{CO}_2 \quad (2)
\]
\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CH}_4 + \text{HCO}_3^- \]  

Availability of hydrogen ions is increased via groundwater flow and recharge in subterranean aquifers. Such aquifers may include seawater sources, noting that sea water is under saturated with respect to its salts, except for calcium carbonate which may occur in saturated or near-saturated state. The flow pathway of water is therefore an important factor in characterising gas reservoir conditions. The relative rate of change of coal seam gradient and orientation hence provide information on available potential energy under the influence of gravity. The effect of gravity on hydrogeological and material deposition character has remained constant over geological time.

Thermogenic gas is generated at high temperature during late stage coalification and generally contains heavier carbon isotopes than biogenic gas. The results described by Moore indicate that the first gas generated via thermogenic processes is CO\(_2\) at approximately 50 °C [26]. Above this temperature, increasing amounts of hydrocarbons (methane, ethane and higher) and nitrogen are produced at maximum volume at approximately 150 °C. At higher temperature, gas generation reduces, producing a parabolic maximum gas volume trend with temperature and/or rank. Such parabolic gas content trends have been reported from a number of Australian Basins including the southern Sydney Basin which is the subject location of this research [28].

3.2. Gas storage

Over 90% of gas storage in coal occurs by physical adsorption to the surface of the coal matrix, including the surfaces of all internal pores and cleats or fractures [25]. The remaining is free gas, which may also reside within internal pores depending on pore geometry, and also within cleats or fractures. It is the physical adsorption process which differentiates coal bed reservoirs from conventional gas reservoirs. Conventional gas reservoirs may contain only one-sixth to one-seventh of the equivalent coal bed reservoir by rock volume, as the gas is free within porous spaces and not held to surfaces via adsorption.

Adsorption concepts between gas and a solid surface are usually described in terms of isotherms, where the amount of adsorbate on adsorption is depicted for three gases (CO\(_2\), CH\(_4\) and N\(_2\)) at one of the study sites as shown in Fig. 1. The movement of gas molecules through either other gases, fluids or solids is described by Fick’s Laws [20]. The key point for the diffusive behaviour of gas described by these laws is that the energy driving the diffusion process is atomic energy, and molecular vibration motion in response to this energy [34]. The gas concentration gradient is a proxy term for a molecular energy density per unit volume gradient across three-dimensional space. This is relatively small in total available energy terms, in the absence of other forces (e.g. pressure gradients). The critical point being that on reducing spatial component of the denominator of both of Fick’s equations (dx), it becomes more probable that molecules will be subject to much larger external energy forces (e.g. pressure gradients) in shorter time frames.

Darcy’s law is an expression of conservation of momentum and describes a proportional relationship between the instantaneous discharge rate through a porous medium, viscosity of the fluid and pressure drop over a given distance. This equation can also be solved for permeability, allowing for relative permeability to be calculated. In practice, this measurement is difficult and expen-

![Image](image_url)
sive to complete in-situ, but is the only method of obtaining a true permeability result which reflects the reservoir conditions [17].

In case of coal, permeability is a complex, multi-dimensional function of several influences such as width, length, height, aperture spacing, frequency or density, and connectivity of cleats or fractures [25]. Many of these influence functions are non-linear, however, have components that can be either readily measured directly or indirectly or otherwise grouped without affecting materially affecting calculation results. Changes in permeability in coal may be summarised into two main components; the effective stress effects, and the shrink and swell strain effects on the coal matrix with desorption or adsorption which may increase or decrease relative permeability [35,36].

In case of coal, permeability is a complex, multi-dimensional function of several influences such as width, length, height, aperture spacing, frequency or density, and connectivity of cleats or fractures [25]. Many of these influence functions are non-linear, however, have components that can be either readily measured directly or indirectly or otherwise grouped without affecting materially affecting calculation results. Coal composition hence controls a broad range of gas reservoir properties including gas adsorption capacity, gas content, porosity, permeability and gas transport.

4. Calculation of relevant spatial properties

The fundamental nature of the physical and chemical interactions between the principal components of coal, coal seam gases and other substances found in the mining environment have remained constant over geological time. These interactions are significantly influenced by the various forms of energy applied over time, however the potential energy involved in sedimentary deposition, gas generation and flow is of particular relevance to analysis of gas emission at higher resolution. An overview of the process for calculation of the relevant spatial properties is depicted in Fig. 2. In the absence of vertical dimension data specific to the location of gas core samples, alternate sources of vertical information or interpolation can be used to inform predictive modelling of gas emissions.

4.1. Derivation of the elevation surface

The goal of the first stage of model development is to obtain the best possible representation of the relative level (RL) of the floor of the coal seam in the subject area using a common datum. To achieve this, original sources of data included but were not limited to, manual survey, drilling records and seismic interpretation. Ideally, all input data is provided in the form of three-dimensional points. However, this is not always available.

4.1.1. Location (point) data sources

Care must be taken to ensure the use of a common reference datum for all available location and level measurements entered as input data. The Map Grid of Australia (MGA) Zone 56 and Australian Height Datum (AHD) were selected as the common reference datum for all location and level information used, and several data sources required conversion to this datum initially. The dimensional convention used throughout this study is X related to longitudinal co-ordinates, Y related to latitudinal co-ordinates, and Z related to height or RL co-ordinates.

Although sources of RL data may include contours, these are generally previous interpolations of X, Y, and Z point data sources. To allow for future model prediction, development and improvement in real time location measurement technology, all RL input data sources were converted to X, Y and Z point data before proceeding to the next stage.

4.1.2. Interpolation technique selection and output

Selection of the interpolation technique suitable for creation of the elevation surface used in this study considered a range of selection criteria. Input data and processing constraints and future use of the interpolation outputs in later model processes received higher weighting in the assessment process. Of the many techniques described and compared in the literature, the spline with barriers interpolation was selected due to the use of exact measured point data as input data, the ability of the technique to manage known abrupt changes in level (e.g. geological faults), the maintainability of the interpolation process with updated input data, and the ability to balance competing requirements for processing time and output resolution.

The result of the interpolation is a raster surface of configurable grid cell size, using barriers, from measured points using a minimum curvature spline technique. The barriers are entered as polyline features, and the resulting smooth surface is constrained by the input barrier features. Input datasets may also have several points with the same x and y coordinates. An important feature of this technique is that if the values of the points at the common

**Table 1**

Range of coal properties within the Bulli seam–Mine A.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Proximate analysis (% by weight)</th>
<th>Coal grain density (kg/m³)</th>
<th>Intraparticle porosity (%)</th>
<th>Surface area (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moisture</td>
<td>Ash</td>
<td>Volatiles</td>
<td>Fixed Carbon</td>
</tr>
<tr>
<td>Top</td>
<td>1.35</td>
<td>12.53</td>
<td>17.98</td>
<td>68.14</td>
</tr>
<tr>
<td>Middle</td>
<td>1.00</td>
<td>10.53</td>
<td>23.55</td>
<td>64.92</td>
</tr>
<tr>
<td>Bottom</td>
<td>1.15</td>
<td>25.88</td>
<td>15.06</td>
<td>57.91</td>
</tr>
</tbody>
</table>

Note: all proximate analysis on percentage by weight air dried basis; and surface area data is calculated based on the pores whose diameter above 30 nm.
location are the same, they are considered duplicates and have no effect on the output.

Several tests were undertaken of total surface calculation area versus raster resolution (individual cell size) and processing time. The final selected digital elevation model (DEM) configuration for the two study sites covered an area of approximately 200 km² each, contained multiple barrier features of both two and three-dimensional data types, at a 1 m × 1 m resolution and processed in approximately 10 min.

This configuration was deemed acceptable for future use and maintainability of the modelling process, and considering eventual development to multi-stratum environments.

Fig. 3 provides an example three-dimensional DEM representation of the Illawarra coal measures viewed from the north looking south. The Bulli seam is the uppermost seam in the sequence displayed in light grey, conformably overlying up to 5 other seams. Surface elevations appear in green, generally above the AHD zero reference shown in blue. The study area is shown in light tan with relevant geological structures shown in red.

4.2. Spatial parameters derived from elevation surface

Spatial parameters deemed essential for the eventual calculation of gas emission character across the mining environment and calculated at the required higher resolution (i.e. each 1 m × 1 m cell) are the vertical dimension Z in metres (AHD), the maximum slope in degrees (0–90°), the aspect in degrees (0–360°), and the curvature in metres per metre, overall and then separately in plan and in profile.

Calculation of the above italicised terms all involve the evaluation of the cell in consideration against each of up to eight of its neighbouring cells in the horizontal X-Y plane. The slope is a representation of the maximum rate of change of elevation (Z) with respect to both X and Y. The aspect represents the orientation of the slope, where values near 0° and 360° indicate a north facing area, 90° an easterly facing, 180° a south facing, and 270° a west facing area.

The calculation of curvature is the derivative of the slope (i.e. \( \frac{d^2 z}{dy^2} \)) using a similar process to the slope calculation, but using the slope value for each cell as the input to the curvature calculation. By definition, the curvature at a point with zero slope (flat) will also be zero. This phenomenon may be used to determine areas likely to retain fluid, also known as sinks. Curvature may be further defined into profile and plan curvatures, which are useful for describing the acceleration or deceleration of flow paths in the case of the profile curvature, or convergence or divergence of flows in the case of plan.

5. Application of spatial parameters to gas samples

Over 2500 gas core sample locations from two mine sites were initially provided in the form of AutoCAD drawing files, complete with two-dimensional X and Y co-ordinates. Drilling trajectories to obtain the core samples were also provided in most cases. Laboratory sample analysis results containing a range of gas properties were provided in the form of MS Excel spreadsheets. Gas parameters included gas content, gas composition and concentration, and desorption characteristics with a unique reference to a sample or core identification number. An overview of the collation process and gas property information contained in the dataset is depicted in Fig. 4.

5.1. Gas sample location referencing

The first stage of assessment of spatial parameters involved referencing AutoCAD two-dimensional location information for each unique sample to the laboratory analysis results. Significantly, this process revealed a 5%–10% mismatch error rate, which was identified using standard database tools.

Errors appeared to be caused by either incorrect data entry into spreadsheet or incorrect placement of sample location or sample number within the AutoCAD drawing. Such errors were resolved by manually reconfirming sample results and locations with drilling records.

5.2. Allocation of spatial parameter data to gas samples

Once gas core sample locations were confirmed as two-dimensional X, Y points, the next stage of assessment involved the allocation of all previously calculated values for elevation, slope, aspect, and curvature to each of the gas samples. The output of these previously calculated spatial parameters was, in each case, a raster surface of 1 m × 1 m resolution. As each of the gas sample locations were specified as unique points, the process of extracting the relevant spatial parameters from the raster surfaces and allocating the value to the gas sample point was completed in less than 5 min.

The final stage of spatial data allocation involved the calculation of the distance and direction to the nearest geological structure. Structures may include faults, dykes or other anomalies which may be represented as either a two or three dimensional features. For initial assessment, a simple two-dimensional planar distance and direction was selected, although the software is capable of full three-dimensional calculation.

6. Initial observations and results

A range of two and three-dimensional representations of the dataset were prepared for preliminary interpretation and visual trend observation. As existing mining threshold limits are determined primarily by measured gas content and gas composition, these dependent variables were considered initially.

Assessment of the full dataset’s gas content result using simple scatter distribution analysis by X, Y and Z location did not reveal any significant first order linear trend.

Whilst the magnitude of observations in Fig. 5 might suggest linear trends with respect to the vertical Z dimension, this is a function of the greater sampling density within the mining horizons of the subject mines.

Assessment of gas composition using scatter distribution analysis of CO₂ concentration by X, Y and Z dimensions revealed a localised trend with respect to the Z dimension at each individual mine as shown in Fig. 6.

Analysing the dataset collectively, a distinct layering of gas composition and concentration is observed with respect to the vertical dimension as shown in Fig. 7.

Localised trends appeared at each mine with increasing CO₂ concentrations being observed downslope of higher CH₄ concentrations and geological features. Increasing observed gas content...
with CO₂ concentration shown in Fig. 8 is primarily accounted for by comparison to the experimentally determined isotherms for the mine (Fig. 1), recognising that coal structural properties and hence sorption capacity is also likely to vary relative to many spatial parameters. Difference in localised seam hydrostatic pressure may also account for such observations, however in the absence of in-situ pressure measurement, this could not be confirmed.

Of significance in Fig. 8 is the apparent single outlier having a CO₂ concentration of approximately 10% and measured gas content of 20 m³/t. On further investigation, it was found that this core sample was actually taken from a cross-measure drill hole from the Bulli seam to the underlying Wongawilli seam and had a CH₄ concentration of approximately 85%. Such display demonstrates the potential ability of the spatial techniques used for easy anomaly detection within large datasets.

The introduction of further independent spatial variables for slope, aspect, curvature and geological structures visually suggested a strong dependence between higher gas content and areas where localised fluid accumulation or flow restriction was likely to occur. The number of core samples taken in these areas over an extended time period, combined with the number of gas drainage holes drilled in the immediate area, suggests that these areas were also difficult to drain.

An example of these areas within Mine A is depicted in Fig. 9. The gas composition of this particular area was greater than ninety percent CO₂, however the dependence between areas of likely fluid accumulation and higher gas content appeared to be independent of gas composition. Other areas of Mine A with higher CH₄ composition also demonstrated a similar relationship. The seam reservoir gas pressure for this area was estimated to be in the order of 3 MPa.

Although not finalised, datasets collected from each mine include attributes which will allow calculation of gas drainage quantities and timing. Due to the configuration of the database, spatial relationships between various attributes may be assessed using the same process as described in Section 4.2.

Data from Mine B also suggests a similar strong relationship between spatial characteristics and higher gas content. At this mine, such spatial relationships also appeared to be independent of gas composition. Areas dominated by higher CO₂ concentration were laterally separated from areas of higher CH₄ concentration by over 2000 m. However, a similar localised trend of higher CO₂ concentrations downslope of geological features and higher CH₄ concentrations was observed.

In summary, each observed high gas content sample location exhibited one or more the following spatial characteristics;

1. Immediately adjacent to and upslope from structures forming flow barriers or restrictions to the general trend of within seam flow,
2. An adjacent high rate of change of slope (curvature) tending to localised minima where both slope and curvature tends to zero,
(3) A coincident or immediately adjacent change in aspect from the general aspect trend.

In general, very localised areas featuring all of the above characteristics tended to exhibit higher gas content towards the upper extreme of the sample range. As these gas content observations also approached the sorption capacities displayed on the experimentally derived gas isotherm, it is suggested these areas are at or near saturation for the given seam reservoir pressure.

7. Preliminary multivariate statistical analysis of spatial parameters

A preliminary ordinary least squares linear regression test was undertaken, using gas content as the dependent variable, in order to statistically confirm the observations made visually. The statistical significance of the input candidate variables, with the contributing direction of the relationship is shown in Table 2.

As expected, due to the form of the input candidate variables for aspect, slope and near angle in degrees, the adjusted $R^2$ of any preliminary linear predictive model tested was poor. However, the results demonstrate that predictive models incorporating derivatives of the candidate spatial variables are worthy of further investigation. Furthermore, due to the use of two-dimensional planar proximity calculations for preliminary derivation of the proximity candidate variable, it is expected that a three-dimensional proximity assessment yielding full three-dimensional magnitude and bearing values to near structures will significantly improve the predictive model fit and eventual results.

8. Conclusions and future directions

Over 2500 gas core samples from two southern Sydney basin mines producing metallurgical coal from the Bulli seam have been analysed in various geospatial context. A robust foundation for the process to obtain, prepare and load the relevant spatial input datasets into a predictive model has been described.

Spatial relationships between measured gas content, gas composition, and spatial parameters such as RL, slope, aspect and curvature have been determined. The relevance and importance of determining these relationships at a localised or site-specific, rather than regional level have been demonstrated.

Statistically significant determining factors, including those influenced by hydrological features and geological structures have been identified and will be investigated further.

Further development of the predictive model to include time and material property dimensions, full three-dimensional assessment of proximity to adjacent structures and gas drainage holes, techniques to normalise input datasets to improve calculation speed, and incorporation of hydrological assessment tools, will significantly improve model outcomes. This will allow further application of the model to site specific and more complex geology including multi-seam mining environments.

The results suggest variability and limitations associated with the present traditional approaches to gas emission prediction and design of gas management practices may be addressed using predictions derived from improved spatial datasets, and analysis techniques incorporating fundamental physical and energy related principles. This foundation will allow increasingly complex factors, such as strata material properties, and stress directions and magnitude to be incorporated into predictive models.

The application of the physical and spatial techniques described enhances the potential for use of high volume and high resolution real time measurement data in management of gas emission risk. By proactively addressing such risks earlier in both the gas and mining life cycle, material reduction of costs and improvement

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Table 2

Summary of variable statistical significance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Significant (%)</th>
<th>Negative (%)</th>
<th>Positive (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (longitude)</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Y (latitude)</td>
<td>96.93</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CO₂ (%)</td>
<td>87.12</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Aspect (°)</td>
<td>60.12</td>
<td>66.87</td>
<td>33.13</td>
</tr>
<tr>
<td>Near angle (°)</td>
<td>53.37</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Z (RL metres)</td>
<td>49.09</td>
<td>44.79</td>
<td>55.21</td>
</tr>
<tr>
<td>Proximity (m)</td>
<td>25.77</td>
<td>80.37</td>
<td>19.63</td>
</tr>
<tr>
<td>Slope (°)</td>
<td>1.84</td>
<td>83.44</td>
<td>16.56</td>
</tr>
</tbody>
</table>
production and environmental outcomes are more likely to be obtained.

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