minerals

Article

A Geospatial Database for Effective Mine Rehabilitation in Australia

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Abstract: The Australian landscape is affected by abandoned mines that pose environmental, public health and safety risks. To promote the beneficial reuse, rehabilitation and/or remediation of these sites and understand their spatial arrangement, we compiled, classified and analysed a country-wide geospatial database of all known inactive hard rock mine sites. Following extensive review and classification of disparate records of such sites that have been terminated, neglected or classified as heritage, plus those under care and maintenance in Australia, we assessed state-by-state reporting and cross-border rehabilitation requirements. This was enabled by the development of the Mining Incidence Documentation & Assessment Scheme (MIDAS) that can be used to catalogue and compare active or inactive mine data regardless of reporting conventions. At a national level, and with four case studies, we performed GIS-based spatial analyses and environmental risk assessments to demonstrate potential uses of our database. Analyses considered the proximity of sites to factors such as infrastructure and sensitive environmental receptors. As Australia struggles to manage the ongoing technical, socioeconomic and environmental challenges of effective mine rehabilitation, the insights enabled by this national-level spatial database may be key to developing coordinated responses that extend beyond state boundaries. Our classification and methodology are easily transferable, thereby encouraging more formalized, systematic and widespread documentation of abandoned mines worldwide.

Keywords: mine rehabilitation; abandoned mines; Geographic Information Systems (GIS); spatial analysis; mine classification; sustainable landscape planning

1. Introduction

Mining has long been a key driver of Australia's economic development. Approximately AUD $15 billion in metal ores, minerals and coal products is exported every month, accounting for over half of the country's export revenue [1]. The economic contributions of mining are magnified for many remote parts of Australia that are almost entirely dependent on continued mine operation. However, by some estimates, such prolific development has come at the expense of at least 50,000 areas scarred by inactive mines over time [2]. These areas have no plans for rehabilitation and little prospect for future economic benefit. Inactive mine landscapes can be dramatically changed via waste disposal, polluted air, soil and water, and socioeconomic and/or cultural impacts. These impacts are not restricted to immediate mine areas, but can extend well beyond to surrounding environments and communities [3]. Recognising this, Australian states and territories have established a series of programs to assess the risks posed by abandoned mines and to prioritise funding for their management. These efforts have mainly been conducted independently, resulting in different reporting practices and classification schemes adopted between jurisdictions. Such variation means that cross-state comparisons are fraught with data inconsistencies, leading to uncertainty in attempts to form a national picture. Following recent recognition that the federal government has a distinct role to play in the management of abandoned mine sites, a unified national database is clearly needed.

In February 2017, the Australian Senate referred an inquiry into the 'rehabilitation of mining and resources projects as it relates to Commonwealth responsibilities' to the Environment and Communications References Committee for inquiry and report [4]. The terms of reference were later updated to further incorporate matters relating to the rehabilitation of power station ash dams. Commonwealth responsibilities are defined under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act, [5]). In the context of mine areas, this legislation may be triggered when matters of national environmental significance (e.g., world heritage areas, national parks, Ramsar wetlands, and areas of significant cultural heritage) are impacted. The cost of rehabilitation obligations, adequacy of existing regulations, effectiveness of current Australian rehabilitation practices in safeguarding human health and repairing and avoiding environmental damage (among a number of other issues) are considered relevant to the national inquiry [4].

Effective management of these issues requires comprehensive baseline data on the location and nature of Australia's inactive mines. In this endeavour, this study has sought to compile a comparative database that encompasses data on all such sites in Australia. It is a product of several preliminary studies conducted by the authors that investigated inactive mines in Australia. Past national-level databases of mining activity have been developed to assist in attracting mining exploration investment, to inform the public and industry analysts on resource endowments, and in some cases to assist in the reprocessing of mine wastes. An example is the ProMine database in Europe that seeks to enable the recovery of valuable materials from discarded mine wastes [6]. Yet, there is comparatively less research focussing on the development of national-level databases for tracking abandoned or inactive mine areas for purposes of remediation and/or rehabilitation. Such databases that provide data on mine location and nature have been demonstrated to provide key preliminary data for a range of potential GIS and remote sensing applications to assess mine impacts. At a local scale, studies such as Bao et al. [7] and Taylor et al. [8] use remote sensing and GIS to evaluate mine rehabilitation effectiveness, allow for adjudication of mining-related conflicts and to provide concrete recommendations for the management of health in towns adjacent to mines. At a sub-national scale, Lechner et al. [9] demonstrate the effectiveness of spatial methods in informing state and national government planning for costs of mine site rehabilitation. At a global scale, Sonter et al. [10] and Werner et al. [11] demonstrate the application of spatial methods to compare impacts between mines, to inform international policy, and to address issues affecting the mining industry overall. Northey et al. [12] also used mine location data to explore the exposure of base metal mines to water scarcity and climate change. Collectively, these underscore the breadth of spatial insights that could be derived from new knowledge of Australia's inactive mine locations. This study aims to enable and demonstrate some such insights. It is part of an ongoing research program led by Monash University that seeks broadly to facilitate more comprehensive and systematic spatial analyses of inactive mines globally.

In the following sections, we present an overview of our database and compilation strategies. We then conduct national-level spatial analyses of current spatial arrangements of all mapped inactive mines. While we note that mines interact with their surrounds in numerous and complex ways, this study considers only the broader impact themes of water, land, and society. Results and discussion focus on the effectiveness of our database structure and our classification scheme, which we adapt and update from an existing scheme, the distribution and potential impacts of inactive mines in Australia, and potential future steps needed for national responses to the challenges of effective mine rehabilitation in Australia.

2. Methodology and Data Sources

2.1. Data Sources and Evaluation

Multiple mine and quarry databases were consulted to quantify and classify mining occurrences in states and territories across Australia. The mining occurrence data were sourced using several datasets from the relevant state and federal government departments. Quality assurance of the data was conducted through validation of entries between sources, and the removal of irrelevant mineral occurrences, non-mining sites and repeated data. We broadly define accuracy in terms of our ability to (a) correctly identify and classify mine sites in Australia, (b) assign correct coordinates to each site, and (c) maintain consistency across the data sources assessed. Data collection focused primarily on hard rock mine sites, to the exclusion of petroleum, gas and some artisanal-scale projects, although our proposed methodology could be adopted to assess such sites further in future. Table 1 summarises the mining occurrence databases held by various states and territories and at the national level that were used to create a combined database along with notes on uncertainties.

2.2. Data Classification and Database Compilation

As a starting point, the Canadian National Orphaned/Abandoned Mines Initiative (NOAMI) framework was used as a basis for our classification system, which we termed the Mining Incidence Documentation and Assessment Scheme (MIDAS). The NOAMI framework has been used to map neglected sites across Canada within the publicly available NOAMI inventory [13]. The MIDAS framework was customised to include additional data types relevant to the reporting of inactive mines in Australia.

In 1999 and 2000, stakeholders requested to Mines Ministers in Canada to establish a joint industry–government working group to investigate the issue of abandoned mines. Accordingly, the Ministers agreed to hold a multi stakeholder workshop on the 'Orphaned/Abandoned Mines in Canada' in June 2001 in Winnipeg. This workshop reviewed issues around orphaned/abandoned mine sites in Canadian jurisdictions and identified five themes for discussion, including (1) building a national inventory, (2) community perspectives, (3) setting standards and rational expectations, (4) ownership and liability issues, and (5) identification of funding models [14]. The NOAMI working group determined that 'orphaned or abandoned mines are those mines for which the owner cannot be found or for which the owner is financially unable or unwilling to carry out clean-up'. They pose environmental, health, safety and economic problems to communities, the mining industry and governments in many countries, including Canada.

A hierarchy of mining occurrences in Australia was created based on the NOAMI framework, shown in Table 1. Mines were initially separated according to their status as active or inactive sites, with several sub-categories for each status. Mineral occurrences were included as an indication of potential future mine rehabilitation requirements. Mining categories were subsequently differentiated through their commodity type, classified as a mine (mining license) or a pit and quarry (work authority) respectively. The NOAMI framework defines an abandoned site as an "Inactive mine or quarry site that has not been terminated and has no obvious owner" [14]. The term "neglected" was favoured for the description of such a site in this project, but can often be used interchangeably with "abandoned".

Definitions of what constitutes a neglected mine site have at times been unclear. A variety of terms are used to describe such areas, including "abandoned", "orphaned", and "legacy" mines. A mine can typically be described as neglected or abandoned if it has no current mining lease or clearly defined owner or operator at the site. However, definitions do vary [15]. Any mineral site used for extraction or exploration can be referred to as neglected if it has been inactive for at least one year, with no implementation or assurance of a plan for management or remediation, and with the mined land having been adversely affected by resource extraction. However, inconsistency in definitions has inhibited attempts to quantify the extent of issues derived from inactive mines [2]. The term "neglected" is used in this study (per Figure 1) to encompass other terms such as abandoned and legacy sites. This follows the same idea that Pepper, Roche, Mudd [16] and Worrall et al. [17] used, where they classified "mining legacies" as an umbrella term.

Table 1. Mining occurrence datasets that were used to create a combined database [18–27].

State	Dataset	Database Notes and Accuracy
Queensland (QLD)	QSpatial (Queensland Mineral Occurrence Data and Coal Resource Sites) [18]	■ Data portal operated by the Queensland Government. ■ Resource information separated into mineral resources (excluding coal) with all coal mine sites provided in the Coal Resource Sites dataset. ■ All data were recorded as point features and included information on commodity type and mine status, which was highly amenable for database integration.
Victoria (VIC)	VIC Open Data Repository [19,20]	■ Publicly available datasets from Victorian Government. ■ *Features of Interest (FOI)* and *Heritage* datasets were primarily used (all polygons converted to point coordinates). ■ *FOI* dataset: sub-categories were present and distinguishing between mines and quarries. ■ Heritage Dataset: no information to distinguish between a mine, quarry and other heritage sites; keywords, e.g., "mine", "shaft" and "quarry" used to filter out features of mining occurrence. ■ Duplicates (e.g., same name and location) removed to ensure single entry in the combined database.
Northern Territory (NT)	NT Wide Geoscience Datasets [21]	■ Publicly available datasets from Northern Territory Government Resources (NTGR) and Geoscience Australia. ■ NTGR data included more detailed and accurate information, e.g., mine location, status, name, commodities present and size. Therefore, this was the primary data source used.

Table 1. *Cont.*

State	Dataset	Database Notes and Accuracy
Tasmania (TAS)	Mineral Resources Tasmania [22]	■ Known as the 'LIST' database, i.e., Tasmanian Government Department of Primary Industries, Parks, Water and Environment's Land Information System Tasmania. ■ Shapefiles included mineral deposits and occurrences, address points and world heritage areas. ■ Some data discrepancies were identified (e.g., our data ultimately indicated 563 operating sites but the MRT website only indicated 15).
New South Wales (NSW)	MinView/NSW Geodata warehouse [23]	■ Publicly available resources from NSW Government. ■ Duplicates (by name and coordinates) removed. ■ Mining occurrences primarily sourced from MinView. ■ Sites related to clay, construction minerals, petroleum and gas were also removed.
South Australia (SA)	SARIG [24]	■ Database managed by the South Australian government. ■ Data were cross referenced with other sources such as the Australian Mine Atlas [25].
Western Australia (WA)	Department of Mines, Industry Regulation and Safety [26]	■ Database included various mining features, which were filtered for further analysis. ■ Mining occurrence database data were validated against data from MINEDEX and WA Department of Mines and Petroleum. ■ Duplicates with same name and location removed and unknown mine features double checked with online status.
National	Australian Mines Atlas [25]	■ Used to complement and check against state-level data.

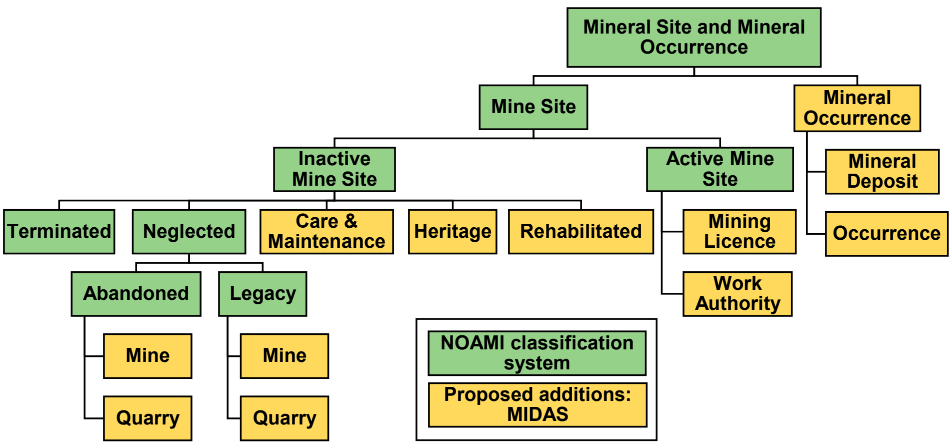

Figure 1. The NOAMI classification system [13] and proposed additions under MIDAS.

The NOAMI mining occurrence hierarchy [13] was also adapted to include terms like "Heritage" and "Care and Maintenance" (Figure 1). To create the combined database, each mine was classified per the following:

- **Mining site:** The definition of a mining site was left relatively broad to ensure comprehensiveness, but only included site types of significant size or potential impact (such that they are reported at a state level), to reduce the chance of overestimation and the dilution of database significance. Hence, for practicality purposes, our database excludes mines that are operated at very small scales (e.g., some clay and sand mining operations), such that their environmental or socioeconomic impacts do not warrant significant consideration for national rehabilitation efforts.
- **Active mine:** Defined as a site on which mineral exploration, mining or processing is ongoing with regulatory approvals in place. Active mineral exploration sites are those sites included in the approved work program of the current mineral tenure holder, those sites covered by the appropriate mining permissions and those sites involved in the ongoing process of beneficiating mine commodities. An active mine incorporates the following two classifications depending on its mined resource and regulatory approvals required:
    - **Work authority license** sites are delineated for the extractive/quarry industries. An extractive work authority license gives quarry operators the right to extract stone (e.g., sand, gravel and hard rock) from land with the landholder's consent. Australian states and territories may have different terms for a work authority license such as an extractive industry license.
    - **Mining license** sites have appropriate approvals in place to mine for specified minerals (e.g., zinc, copper, coal, gold and mineral sands).
- **Inactive mine:** All mineral sites that are not considered active mineral sites were ultimately assigned under this umbrella term. Inactive sites may be inactive for many reasons including (a) completion of the exploration, mining or processing project; (b) standby status of exploration, mining or processing projects awaiting better market conditions; and (c) loss of owner/operator capability for any number of reasons. For any of these reasons, inactive mines can be further classified as:
    - **Terminated/Ceased:** Where operations have ceased, with there being little to no prospects for rehabilitation.
    - **Care and maintenance:** A closed mine site where there is potential to recommence operations at a later date. During the care and maintenance phase, production is ceased although is managed to ensure it remains in a safe and stable condition.
    - **Heritage sites:** Located within World Heritage, National Heritage, or state or local government heritage sites. A site may also be classified as a heritage site due its historical importance. Active heritage sites are defined similar to an inactive heritage mine site although are currently active and operational in mineral extraction, mining or processing. Some active mines may have partial areas that may be considered heritage.
    - **Neglected (Abandoned/Legacy) sites:** Sites that have been inactive for at least one year, with no implementation or assurance of a plan for management or remediation and with the mined land having been adversely affected by resource extraction. Further, an abandoned site can be classified as a mine site that lies on Crown Land whilst a legacy site is one that lies on Private Land. We note that VIC was the only state where we had adequate information to distinguish between abandoned and legacy sites. Similar sites in all other states were simply classified as neglected. For comparative purposes, we summarise all mines in this category as neglected in later sections.

- **Mineral occurrences:** Undeveloped sites were also considered for purposes of developing an indication of the potential number of sites for future mining, and hence longer-term rehabilitation requirements.
- **Rehabilitated sites:** Inactive mine sites that have successfully completed remediation objectives. Upon remediation, this type of site has a defined post-mining land use (e.g., agriculture, forestry and lakes) with no further mining care and maintenance required from authorities.

2.3. Spatial and Site-Specific Analyses

2.3.1. National and State-Level Analysis

To demonstrate some of the spatial insights enabled by the MIDAS national database, we performed spatial analyses using ArcMap Version 10.6. These analyses sought to explore spatial relationships between inactive mine locations and potential environmental or community receptors that may be impacted by these sites. We further explored accessibility by examining the proximity of mines to road and rail infrastructure. Such infrastructure may be important for removing waste, or delivering resources required for rehabilitation. For impact assessment, we identified the proportion of abandoned mines within protected areas such as national parks and national heritage areas and Indigenous heritage sites, as well as those near or within urban centres. Potential hazards were identified considering regions of high acid sulphate soil occurrence, complemented by high average annual rainfall volumes and proximity to major watercourses and lakes. The acid sulphate soil database prescribes three probability classes encompassing high, low, or extremely low probabilities of occurrence. Although we looked at the distribution of mines across all three categories, we also placed greater focus on the high and low occurrence categories in further analyses. Table 2 summarises all spatial layers used and the rationale for their inclusion.

Datasets were sourced in a range of geographic formats including shapefiles and rasters (sources included in Table 2). All abandoned mines within our spatial database were overlaid and intersected with the various datasets and analysed using a 'Near' function in ArcMap. Outputs were analysed at a national level, but we also conducted a state-by-state comparison (considering six of the seven states; the ACT was not considered as only 30 abandoned occurrences were present within its boundary, which was negligible when compared with other states). Outputs are presented as frequency plots and nationwide spatial plots (see Section 3.2).

To better compare all abandoned mines and identify potential priority rehabilitation candidates, we also analysed potential 'hotspots' in the geographic distribution of mines across the country by calculating the average distance of occurrences from the nearest road or railway and by calculating the *average proximity to sensitive areas* (d_{sen}) as:

$$d_{sen} = w_w d_w + w_h d_h + w_p d_p + w_u d_u \tag{1}$$

where d_w, d_h, d_p and d_u are the Euclidean distances of an abandoned occurrence to the nearest water, heritage, national park and urban centre feature, respectively [km] and w_w, w_h, w_p, w_u are their corresponding normalised weights ranging from 0 (not considered) to 1 (only factor considered). We equally weighted all four distances as 0.25 in this case, thereby making $d_{sensitive}$ simply an average of the four distances. Depending on the context of rehabilitation, sets of weights can be varied in a deliberative process with stakeholders. Although simplistic, the indicator serves as a proxy for rapidly identifying potential regions of interest within the large dataset.

Table 2. Spatial overlays assessed against inactive mine locations.

Overlay Category	Rationale	Format Source(s)
Major Urban Centres	Proximity to major urban centres has a twofold implication: on the one hand, access to populous areas will create employment opportunities during rehabilitation; conversely, adverse impacts on urban areas may be felt from legacy issues.	Polygons [28]
Major Road and Rail Infrastructure	Proximity to road and rail infrastructure determines accessibility for resources required to conduct mine site rehabilitation, to remove waste materials, or to transport products, should the sites be deemed economically viable in future.	Lines [29]
Major Waterways and Lakes	Proximity to major waterways and lakes allows us to understand the potential environmental impact of rehabilitation measures on downstream natural aquatic environments.	Lines and Polygons [30]
Heritage and Indigenous Areas	Contain areas of international and Indigenous significance, relevant to the EPBC Act (1999) and within the scope of effects relevant to Commonwealth intervention.	Polygons [31]
National parks	Contain areas of national environmental significance, also relevant to the EPBC Act (1999) and within the scope of effects relevant to Commonwealth intervention.	Polygons [32]
Acid Sulphate Soils	Acid and metalliferous drainage (AMD) is a key environmental challenge induced by the exposure of sulphate rocks to rainfall, areas highlight the likelihood of acid sulphate soil prevalence.	Polygons [33]
Average Annual Rainfall	To establish potential interactions with receiving watercourses and lakes and with regions of high acid sulphate soil prevalence, we used long-term spatial average annual rainfall.	Raster [34]

2.3.2. Site-Specific Environmental Risk Assessment—Queensland Case Studies

In recognising that mine areas can extend across a range of scales, and can be highly heterogenous in form, we note that point data have limited capacity to represent the profile of risks posed by abandoned sites. To reflect on this source of uncertainty, we performed preliminary, comparative environmental risk analyses on four abandoned mine case studies using satellite imagery in the state of Queensland. These sites are shown in Figure 2. Mines were selected for their spatial variability and differing commodities to demonstrate the effectiveness of this method broadly across sites in the database. Using the most recent cloud-free composite imagery available in Google Earth Pro, we delineated approximate boundaries of former extraction and waste disposal areas using visual inspection methods as described in [11].

A method of determining an environmental risk score for each mine was created, utilising areas of assumed environmental significance from the Major Watercourse Lines—Queensland, Ramsar sites—Queensland, and data from the Collaborative Australian Protected Area Database (CAPAD). Areas of each mine are considered as an indication of the relative extent of vegetation and soil disturbance at each site. Ramsar sites are wetlands or waterbodies of international environmental significance listed under the Ramsar Convention on Wetlands 1971, and thus were included as their potential degradation along with major watercourses is of serious environmental concern [35]. Protected areas (PAs) as contained in the CAPAD dataset were included due to their significant environmental value. Each site was given a point score out of 5 for impact area, and score out of 3 for each of the three proximity categories (distance to watercourse, distance to Ramsar, and distance to PAs), making for a maximum score of 14. Mines with a higher score were classified as having a higher relative environmental risk. It is noted that given the visual uncertainties associated with the processes of image delineation, this approach serves primarily to highlight the differential risks arising between mine sites in our database by virtue of their scale and form. It does not represent absolute environmental harm induced, and does not consider other aspects, e.g., mining depth or groundwater interference, that would ideally be factored into a more robust assessment of mine impact.

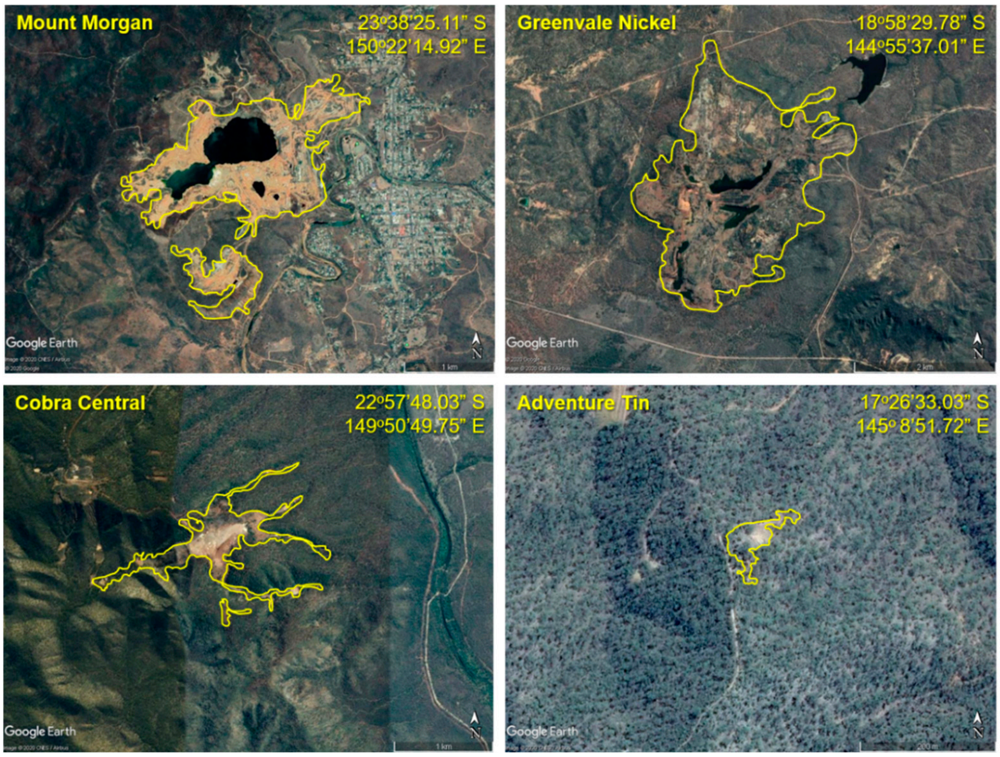

Figure 2. Selected mine sites in the state of Queensland for environmental risk analysis. Imagery derived from the most recent cloud-free composites available in Google Earth Pro. Areas in yellow were delineated by visual inspection per Werner et al. [11].

Although this analysis used proximity to sensitive environmental receptors as integrated into the previous geographic analysis outlined in Section 2.3.1, this method looked to integrate the spatial form and extent of each mine into the determination of potential environmental risk. This ensured that effects such as the extent of vegetation disturbance for mineral extraction were able to be estimated. It was assumed that this would increase the relative environmental risk score for neglected sites of larger size. The distance to the closest sensitive receptor was also measured from the perimeter of each impact area, as opposed to point data. This was assumed to decrease the distance between mines and sensitive receptors, particularly for larger mines. Euclidean distances are an approximate representation of risk that are valid for the demonstrative purposes of this case study, but it should be noted that factors such as surrounding topography can significantly alter the direction and extent of mine's impacts on surrounding areas, e.g., via surface runoff. Such factors are assessed for mining in studies such as Yenilmez et al. [36] and Tiwari et al. [37].

3. Results and Discussion

3.1. National Mine Classification and Database Summary

A summary of the number of sites assigned to each classification for each state is provided in Table 3. Overall, 95,320 active and inactive mines were identified, classified and georeferenced, with full datasets available as Supplementary Information. Inactive mines constituted the vast majority (89%) of these in number, nearly 70% more than were identified by Unger et al. [2]. Among the inactive mines, the majority are classified as neglected (68%). Only 4% of inactive mines have been noted as rehabilitated, signalling a clear need for continued national rehabilitation efforts. Of those that are not neglected, 75% are noted as terminated mines, with little prospect for rehabilitation. Combined, these figures suggest that ~82% of Australian mines may require rehabilitation, presenting an enormous economic, environmental and social challenge moving forward. This challenge will be disproportionately felt between the states and territories. The NT was found to possess the fewest (~1%) mine sites, while NSW hosted the greatest number (26,953 inactive mines, comprising 28.27%). It is important to note that these numbers are based on reported and recorded sites across states, and hence reporting practices may distort the state-by-state representation in the national database. NT and TAS (with five and three classes respectively) were found to have the weakest documentation system for recording mining activity. The dataset from the NT is currently undergoing reclassification with the abandoned mine category being separated into 'ceased', 'historical workings' and 'abandoned'. The mines currently listed under these categories were not included in the neglected mine database, and it is understood that a significant number of sites in the Northern Territory still need to be added to their database at the time of writing. In Tasmania, it was found that mining data were comprehensive in number, yet limited in detail on mine activities and conditions for each site. It was unclear whether neglected/abandoned mines in this state were subject to care and maintenance, or to what extent rehabilitation had been conducted.

Conversely, WA and QLD were found to highly detailed systems for classification and documentation. VIC has seven classes, although there is no record on the "rehabilitated" and "active heritage" mines in this state. The "rehabilitated" mines are so far recorded in only two states, QLD and WA. Other states, although having a suitable record of the extent of sites, do not provide any information on such factors. For instance, VIC and NSW appear to have near comprehensive records of different mining activities, but no record on rehabilitation or no detailed classification on the active mines are provided. QLD is the only state that exhibited reporting across all categories in our database, reflecting its relative action in enacting mine rehabilitation programs.

Table 3. Australian mine sites and mineral occurrences within the developed national database.

State/Territory			**VIC**	**NSW**	**WA**	**SA**	**QLD**	**TAS**	**NT**	**TOTAL**
Inactive	Terminated/Ceased		1	19,728	N/A	132	N/A	112	118	20,091
	Neglected	Mines	18,171	7183	20,303	3759	2820	4266	738	58,017
		Quarries			559		218			
	Care and Maintenance		1	42	671	148	104	N/A	28	994
	Rehabilitated		N/A	N/A	3068	13	N/A	N/A	N/A	3081
	Heritage		2175	N/A	N/A	N/A	394	N/A	42	2611
Active	Mining License		2070	3447	1098	957	711	1305	11	10,526
	Work Authority		750		888					
	Heritage		N/A		N/A					
TOTAL			23,168	30,400	26,587	5009	3536	5683	937	95,320

3.2. Spatial Distribution of Inactive Mines

The spatial distribution of entries (both active and inactive occurrences) in the national database is illustrated in Figure 3. This map again highlights the uneven distribution of inactive mines between states. It also shows that clusters of inactive mines do not necessarily adhere to state boundaries, potentially suggesting a need for cross-jurisdictional coordination of responses. The largest density of occurrences can be found along the south-eastern region, covering the states of SA, VIC and NSW, which has been illustrated in Figure 4 within the extent of four major Australian cities. In the northern region, sites are concentrated primarily along the QLD coastline. However, a cluster of occurrences appears at the border between QLD and the NT. Along with the distribution in the south-east (Figure 4), these illustrate the potential cross-border interactions that may need to be considered. TAS and WA appear to have a fairly uniform distribution of mines across their landscapes.

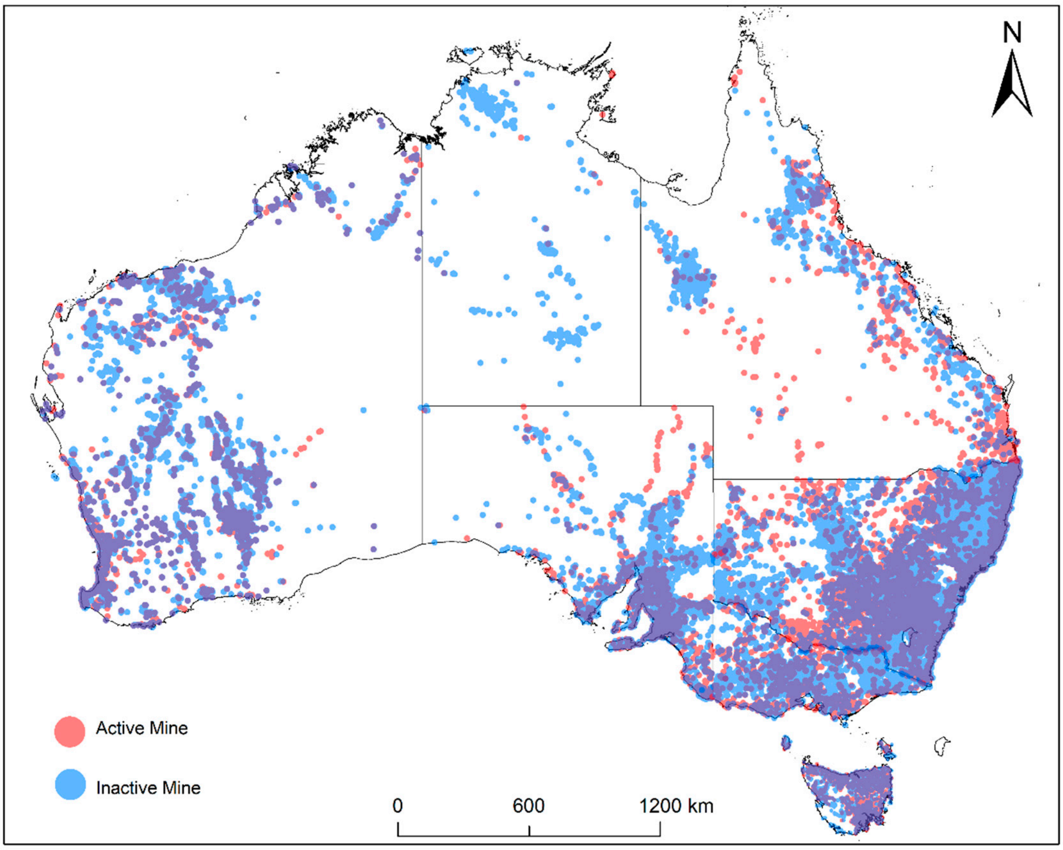

Figure 3. National overview of active and inactive mines across Australia, as identified within our database.

When considering their proximity to major infrastructure and environmental receptors, Figures 5 and 6 show nationwide similarities between categories, but clear contrasts between some states. Urban centres and national parks, for example, are important features to consider in TAS, with a high proportion of mines situated in close proximity (approximately 50% near national parks). This may be explained by TAS's smaller land mass compared to continental Australia and broad coverage of national parks, but also a potential concentration of economic mineral deposits based on factors such as cover thickness [38]. Heritage areas are relevant for abandoned mines in both SA and the NT as many Indigenous heritage sites are located along this central continental region. VIC and NSW share the Australian Alps, a large national park which is also visible in Figure 4. This again highlights the potential need to consider cross-border interactions and, therefore, what governance arrangements may best facilitate mine rehabilitation.

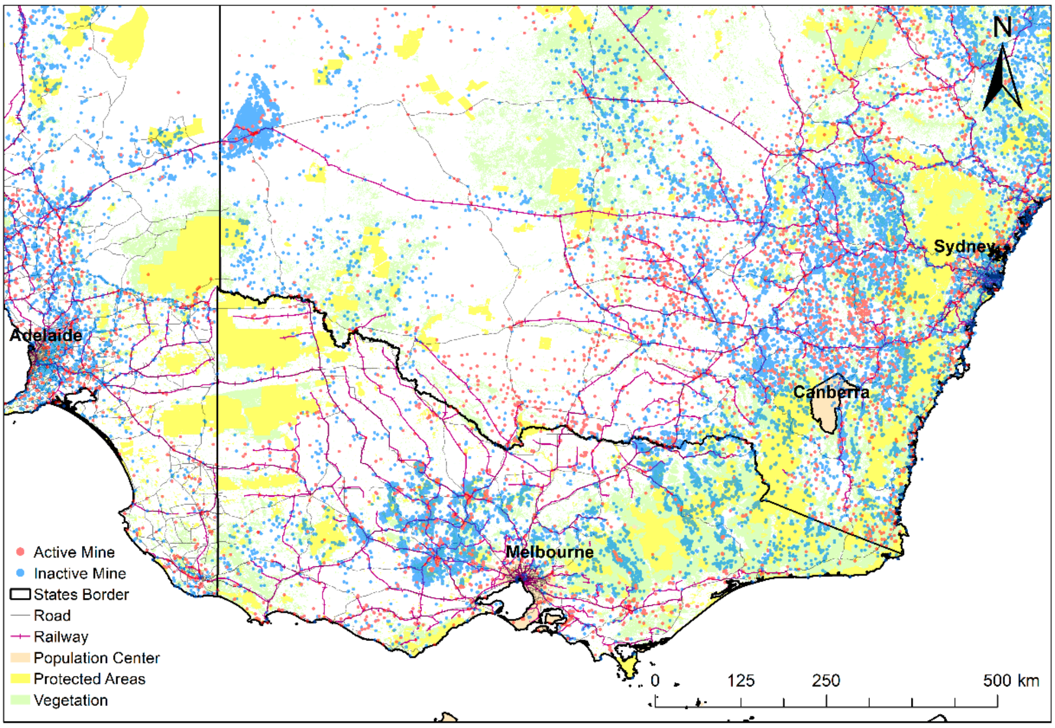

Figure 4. Cross-border spatial distribution of active and inactive mines alongside major transport corridors, urban centres, protected areas and vegetation in south-east Australia.

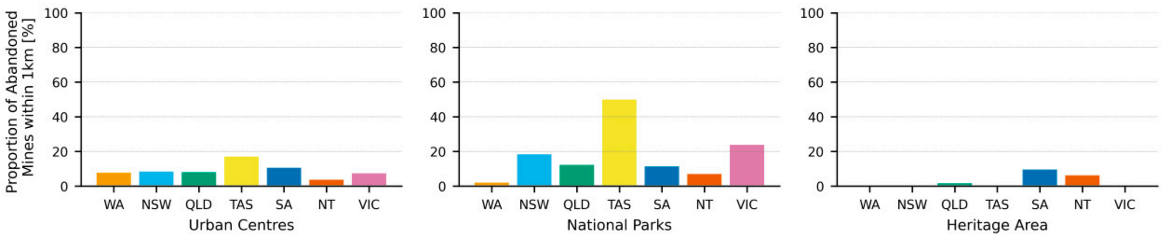

Figure 5. State-by-state breakdown of abandoned mines located within 1 km of urban areas, national parks, national heritage and Indigenous heritage areas.

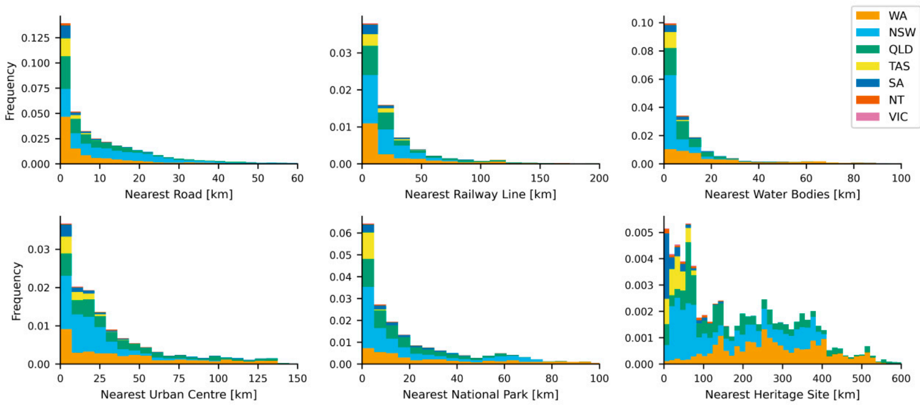

Figure 6. Frequency distribution of abandoned mine proximity to major transport routes, waterways and lakes, urban centres, national parks and heritage sites. Stacked plots show both national and state-level proportions, distance value limit on the *x*-axis encompasses up to 90% of mine features.

The majority of inactive mines are located within shorter distances to key transport infrastructure and environmental receptors. Figure 6 shows that a dominant portion of the dataset is located within 50 km of many of these features. Major roads are more prominent than railways, indicating that any planning of rehabilitation measures would need to consider this infrastructure as the primary means of access. For purposes of simplification, we assessed Euclidean distances to road and rail infrastructure, but not distances or directions of travel along these paths to link mines to potential endpoints. This would be a valuable avenue for further research that establishes possible costs of rehabilitating sites in our database.

Audet et al. [39] noted that several climatic factors such as water availability, seasonality and precipitation intensity can interact to influence rehabilitation success, suggesting a more detailed evaluation of climatic variables is necessary when allocating resources towards rehabilitation efforts. Here, we consider only average annual rainfall in relation to acid sulphate soils as an indication of AMD potential. Inactive mines are in a variety of rainfall regions (see Figure 7-left). Two major groups are prevalent: those within lower rainfall areas and a significant proportion within regions of approximately 800 mm rainfall/year (located along the eastern coastline as shown in Figure 8c). The overall potential for inactive mines to contribute to AMD appears limited, as a majority of inactive mines are in extremely low acid sulphate prevalence regions. The state-by-state comparison (Figure 7-right) reflects this issue being predominant in WA, VIC and SA. The proportion of abandoned mines within high acid sulphate soil regions, however, remains low and evenly distributed across the country (visible in Figure 8d), highlighting that this issue is one to investigate on a case-by-case basis.

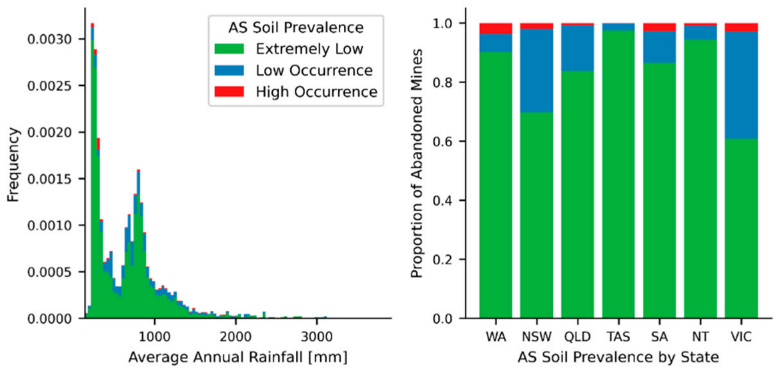

Figure 7. Relationship between average annual rainfall and acid sulphate (AS) soil prevalence of abandoned mines across Australia, overall national perspective (**left**) and state-by-state breakdown (**right**) of the proportion of mines within high, low and extremely low occurrence areas.

A side-by-side comparison of the average proximity to sensitive areas d_{sen} and the average distance to road and rail infrastructure is shown for the entire country in Figure 8a,b. Major hotspots (i.e., close proximity, low d_{sen} values) are visible in south-east Australia, and parts of the eastern coastline near the border between NSW and QLD and in northern QLD. Interestingly, the largest density of abandoned mines in NSW do not appear as a hotspot. South Australia's hotspots are concentrated around the Greater Adelaide region that has a high concentration of urban areas, heritage areas and national parks. Good accessibility within this region may provide cost effective opportunities for prioritising this region in rehabilitation efforts. Compared to this region, hotspots at the borders between VIC and NSW and between NSW and QLD would ideally require cross-border collaboration in their effective rehabilitation, once again highlighting the importance of forming a national-level perspective. Both regions have reasonable accessibility, while some mines, such as those in remote parts of WA that are primarily serviced by airports, clearly present accessibility challenges.

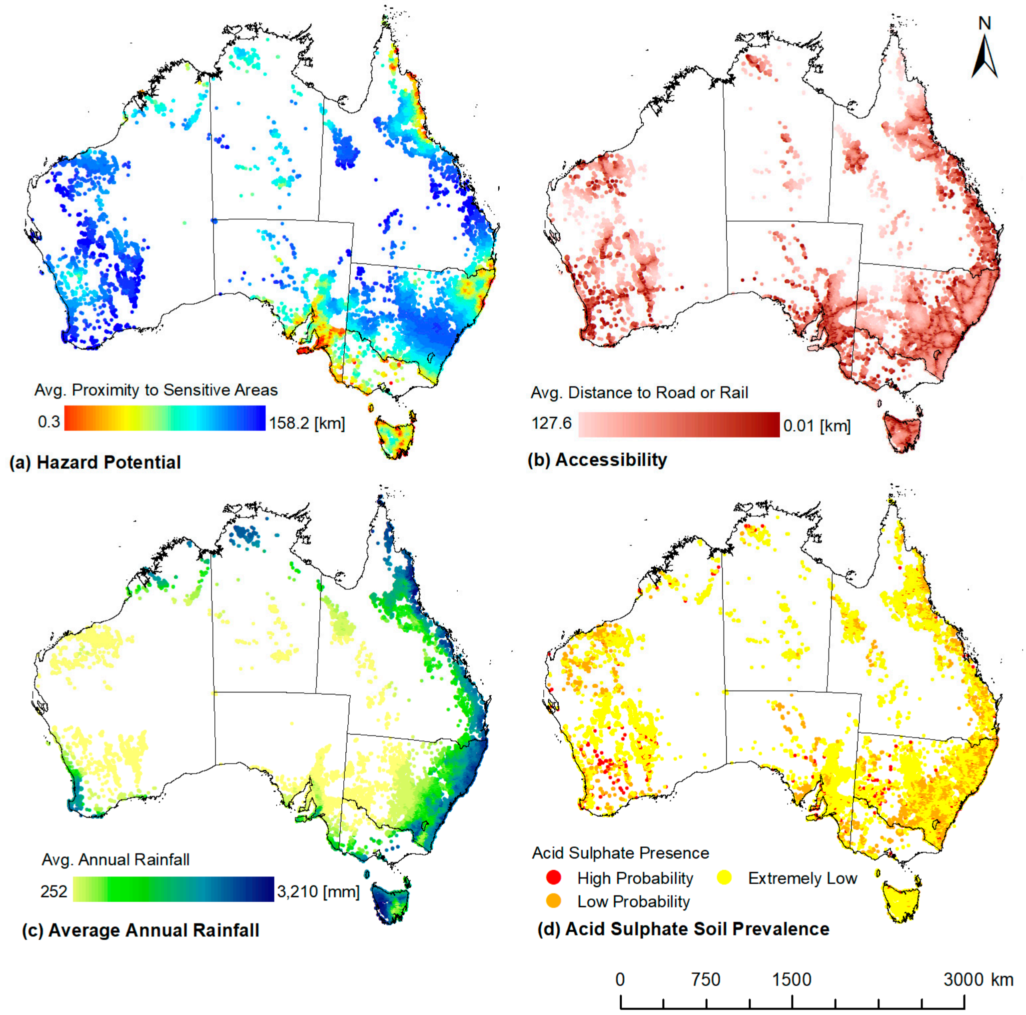

Figure 8. Spatial plots of inactive mines showing the distribution of (**a**) hazard potential, indicated by average proximity to sensitive areas d_{sen}; (**b**) accessibility, indicated by the average distance to nearest road and railway infrastructure; (**c**) average annual rainfall distribution; and (**d**) prevalence of acid sulphate soil.

3.3. Site-Specific Comparative Environmental Risk Assessments

A summary of the environmental risk analysis scores and overall risk classification for the four case study mines is provided in Table 4. The environmental risk scores varied significantly across the four case study sites. The risk score calculated for Mount Morgan was 11, correlating with a "high" risk to the environment. This represented the highest risk mine of the four case studies in this report according to this methodology. Whilst Greenvale Nickel has an impact area more than twice the size of Mount Morgan, it was categorized as a lower risk to the environment ("medium") due to its significant distance from the closest environmentally sensitive PAs or Ramsar wetlands. Integrating area into this risk evaluation gave the smallest Mine Impact Area sub-score to Adventure Tin (sub-score of 3), which was classified as having the lowest overall Environmental Risk out of the four cases studies, but would have had the same overall score as Greenvale Nickel if area was not integrated.

Table 4. Summary of environmental risk analysis for four neglected mine sites in Queensland, Australia. Each site is assigned a score for area, distance to closest water course, distance to closest protected area, and distance to closest Ramsar site, with a total risk score and Environmental Risk Category.

	 **Mount Morgan**	 **Greenvale Nickel**	 **Cobra Central**	 **Adventure Tin**
Mine impact area [km^2]	3.07	6.93	0.71	0.37
Area score [-]	5	5	5	3
Distance to closest water course [km]	0.07	6.54	1.27	2.27
Watercourse score [-]	3	2	2	2
Distance to closest protected area [km]	7.74	46.5	8.41	10.8
Protected area score [-]	2	1	2	1
Distance to closest Ramsar site [km]	86.6	225	81.7	299
Ramsar score [-]	1	1	1	1
Total Risk Score [-]	11	9	10	7
Environmental Risk Category	High	Medium	High	Medium

The estimation of the areal impact of neglected mines provides an indication of the local extent of vegetation clearing or habitat deterioration. Clearing is integrated into the environmental risk score method through the inclusion of the mine impact area, with larger areas assumed to correlate with higher vegetation disturbances. Spatial analysis techniques such as this have been used widely to estimate the area of impact of open-cut mines. Lechner et al. [9] used a GIS method to map mine disturbance and progressive rehabilitation, and to provide an estimate of rehabilitation cost, for coal mines in the Fitzroy River Basin in central Queensland. However, it should be noted that optical mapping of neglected sites is potentially more difficult due to vegetation growth making impact perimeters less visible in satellite imagery. This is especially evident for smaller, older sites such as Adventure Tin (see [40]). Other approaches, e.g., using LiDAR or hyperspectral image processing, can help to reveal features obscured by vegetation [3].

Recording sites as individual points allows for broader spatial analysis as previously detailed. However, our analysis shows that not assessing the impact area or size of each site distorts our understanding of risk. Detailed site-specific spatial analysis as shown in Table 4 allows for the calculation of the mine impact area, as well as more in-depth proximity analysis to sensitive receptors taking the distance from the perimeter of the mine (as opposed to a single data location point) into account. One of the case study mines, Mount Morgan, is a neglected mining site located in central Queensland, 38 km inland of Rockhampton, operating to extract gold, silver, and copper from 1882–1990 [41]. There is a particularly short distance between this mine site and the closest watercourse, the Dee River, with the perimeter of the tailings pile only 71 m away from the river (Figure 2 and Table 4). The relatively large extraction and waste disposal area (approximately 3.1 km^2) means that using a point location for proximity analysis has the potential to underestimate potential environmental risk, as the perimeter of the open-cut mine may be significantly closer to a receptor than the single data point may indicate. In this example, arbitrarily placing a single set of coordinates on a far side of the total mine area could have the potential to decrease the mine's calculated proximity, and associated risk, to watercourses such as the Dee River. This highlights the strengths of integrating impact area into environmental risk scores when assessing the risk of neglected mining sites. The ideal dataset would incorporate polygons of all mining occurrences into the large national database, which is a significant logistical endeavour, but a worthy avenue for future research.

4. Evaluation and Implications

4.1. Accuracy and Data Limitations

Differing jurisdictions, reporting practices and the sheer scale of abandoned mines in Australia are key factors that have inhibited the past development of a national database of Australia's inactive mines. In turn, this has limited our understanding of the potential risks posed by these mines. Poor rehabilitation rates and standards are often cited as being influenced by (a) limited knowledge to justify or rank the potential threats posed by each site and (b) unclear definitions of the status of each site [42]. Addressing this, we have developed MIDAS, extending from NOAMI classifications to foster clearer classification of Australia's disparate inactive mine data.

Nonetheless, while our study represents an advancement in classification methods, reporting issues still affected our ability to identify sites and to assign classifications. This comes despite recognition of the need for a coordinated national approach to mine rehabilitation since at least 2010 [43]. The exact number of neglected mines or mining occurrences in each state and the relative accuracies of the databases available remains difficult to independently validate due to few alternative data sources available and limited resources available for field-based assessments of the many thousands of sites across Australia. Further, as each database is updated periodically by the states and territories depending on the resources available to them, there is an additional element of temporal uncertainty. Limited resources also inhibit the abilities of these governments to uphold spatial data quality standards (described by Devillers and Jeansoulin [44]) that help to facilitate compatibility and interpretation.

Only 3081 sites have been reported as being rehabilitated. Given the positive public perceptions usually attributed to rehabilitation efforts, this is likely a reflection of limited rehabilitation work having actually been conducted, yet it does remain a possibility that such works are also underreported, as nearly all of these are just from WA.

The Mines and Mineral Occurrences dataset (VIC) showed the largest variation in accuracy and proved to be the most problematic for analysis. Mining occurrence points that had poor spatial accuracy had a higher chance of obtaining an inaccurate site status. Although we used multiple datasets where possible to compare the accuracy of location data, it should be noted that duplicate data increases the calculated density of mines in an area. The Heritage Datasets overlapped with the other datasets most frequently, with heritage sites in the Bendigo region (western VIC) overlapping with the other datasets by up to 60%.

4.2. Local Impacts and Challenges of Inactive Mines

Visualising the spatial variability of inactive mines (Figure 2), provides insights into the local extent of vegetation clearing or habitat deterioration. For example, the environmental impacts of Mount Morgan on the adjacent Dee River have been well documented, including by Edraki et al. [45], who found highly acidic effluent with high concentrations of heavy metals, specifically iron (Fe) and aluminium (Al) hydroxides, draining into the river. This was despite a water management system existing at the mine. Figure 2 highlights the short distance between the mine site and the Dee River, with the perimeter of the tailings pile only 71 m from the watercourse.

A range of risks are presented at all sites, yet these vary considerably depending on the scale, nature and context of each mine. As noted earlier, local topography (i.e., slope and elevation of areas immediately surrounding a mine) can substantially influence the direction and extent of mine risks and impacts (see [11]). However, this was not considered in our spatial assessments. Risks can also vary greatly over time, as evidenced broadly by the Latrobe Valley region (eastern VIC) which has had to contend with the 'Black Saturday' bushfires of 2009, the collapse of a wall in the Yallourn coal mine during the 2007/2008 drought, and subsidence and damage to batters at the Hazelwood mine due to heavy rain in 2011, leaving the adjacent Princes Highway (a major transport corridor) around the nearby town of Morwell closed for seven months. The Hazelwood coal mine, now closed and undertaking decommissioning, was also the site of fires in 2014 that carried on for 45 days. The fire came within 200 m of the power station requiring an enormous emergency effort and affected air quality to townships in the region. The Victorian government held an Inquiry into the Hazelwood Mine Fire, which concluded in 2016, instigating a regional rehabilitation strategy that enabled the creation the Mined Land Rehabilitation Authority—an independent body to work with community, industry and government to oversee the rehabilitation planning of declared mine land to ensure the transition to safe, stable and sustainable post-mining land uses in Victoria [46].

Even if considerable resources and expertise are allocated to prioritise and conduct rehabilitation efforts, there are no guarantees of successful, or long-lasting outcomes. This is exemplified by Australia's uranium mines that have posed such significant technical and economic challenges for rehabilitation that despite several hundred million $AUD spent, rehabilitation efforts at Rum Jungle, Mary Kathleen and Ranger have not been successful [47]. The purposeful destruction of 46,000-year-old cultural sites at Juukan Gorge, WA [48] also highlighted to many Australians that knowledge of sensitive areas, plus the presence of well-resourced operating companies may not even guarantee the protection of areas surrounding active mines, let alone those that are no longer profitable.

4.3. Towards a Unified Approach: Meeting the Needs of the Senate Inquiry

At present, only four states have established broader public mine rehabilitation programs: WA, NSW, QLD and TAS. Such programs have had limited success, given so few instances recorded of successful mine rehabilitation and unclear standards as to the level of rehabilitation required [49]. Following the senate inquiry into mine rehabilitation, national consistency has been the subject of much consideration. In a report produced from this inquiry, the establishment of federal bodies (e.g., a Commonwealth Environmental Protection Authority and National Abandoned Mines Commission) was noted as key to overseeing mine rehabilitation in Australia. This inquiry also noted the need for the creation of a nationwide inactive mine database, based on the NOAMI classification system, and the establishment of a National Mine Rehabilitation Commission [4]. Our study has conducted several key steps in these endeavours, yet successful mine rehabilitation outcomes across Australia require many other efforts to be conducted in parallel. These include the development of enforceable national standards on mine rehabilitation and bond amounts. To ensure such bonds are robust, they should be verified by open and transparent means, including by an independent audit. This is supported by a recent audit of mine rehabilitation regulations for VIC that highlighted systemic regulatory failures in rehabilitation cost estimates, bond management, auditing of rehabilitation plans and review of on-site practices [50].

Continuous updates to our MIDAS database are also warranted, requiring ongoing field work at abandoned mine sites (particularly those near wetlands and other sensitive receptors). Amendments to EPBC Act have also been recommended as a way to ensure that a progressive rehabilitation plan; closure cost estimate; and approved final landform be determined during approvals processes to ensure the lowest possible impact on matters of national environmental significance [4].

4.4. Environmental Challenge or Economic Opportunity?

Australia's abandoned mines are largely considered liabilities, but many have the potential to be valuable assets if properly managed. Conducting proper management requires strategic planning across governments, proper allocation of resources, and technical expertise. Policy frameworks have previously recommended 'valuing abandoned mines' in Australia [15,51]. Deriving value from inactive sites can come via further mineral extraction, waste reprocessing for remnant metals (e.g., critical metals), industrial archaeological heritage conservation and tourism, and developing unique habitats for biodiversity enhancement. Collaborative research into innovative solutions to contamination problems can further guide the broader mining industry and offer employment and training opportunities for regional Australia. The potential opportunities for local industry diversification through the development of rehabilitation-based businesses include:

- Construction works (restoration and rehabilitation) [52];
- Tourism potential to rehabilitated sites (e.g., bike paths and recreational lakes) [53];
- Carbon farming opportunities (e.g., via *Eucalyptus* plantation on rehabilitated lands);
- Overburden waste for making building bricks and ceramic products to support regional construction industry [54];
- Potential to use rehabilitation areas for renewable energy generation;
- Nursery to supply plants, blending of waste streams to develop artificial soils that are used as capping material on the coal slopes, re-forestation [55,56];
- Consulting practice through the monitoring of rehabilitated conditions (geotechnical and environmental).

While the mining industry has undoubtedly made significant contributions to the Australian economy over time, at least 80,000 sites remain inactive and unrehabilitated, posing a range of environmental, public health and safety risks. Efforts to ensure progressive rehabilitation throughout the life of mining operations and to promote an effective transition to post-mining landscapes are critical for Australia to achieve its goals of being a world leader in environmental stewardship and mineral resource governance.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-163X/10/9/745/s1. A database consisting of seven CSV files for Australian states and territories that show active and inactive mining sites classified under the MIDAS system.

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