UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Denkleiers • Leading Minds • Dikgopolo tša Dihlalefi

Surface-strip coal mine rehabilitation risk assessment: The development of an integrated rehabilitation risk assessment model for use in South Africa and Australia

PhD thesis for submission for a degree at the University of Pretoria

by

Vanessa Derryn Weyer

Submitted in fulfilment of the requirements for the degree
PhD Environmental Management

in the
Centre for Environmental Studies
Faculty of Natural and Agricultural Sciences
University of Pretoria
Pretoria, South Africa

February 2020

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Denkleiers • Leading Minds • Dikgopolo tša Dihlalefi

DECLARATION

I, Vanessa Derryn Weyer, declare that the thesis, which I hereby submit for the degree PhD (Environmental Management) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE:

12 FEBRUARY 2020

DATE:

ETHICS STATEMENT

The author, whose name appears on the title page of this thesis, has obtained, for the research described in this work, the applicable research ethics approval. The author declares that she has observed the ethical standards required in terms of the University of Pretoria's Code of ethics for researchers and the Policy guidelines for responsible research.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Denkleiers • Leading Minds • Dikgopolo tša Dihlalefi

ABSTRACT

Title: Surface-strip coal mine rehabilitation risk assessment: The development of an integrated rehabilitation risk assessment model for use in South Africa and Australia

Student name: Vanessa Derryn Weyer, Centre for Environmental Studies, Department of Geography, Geoinformatics and Meteorology, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa

Supervisor: Professor Wayne Frederick Truter, Department of Plant and Soil Sciences, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa

Co-supervisors: Professor David Mulligan, Sustainable Minerals Institute, Centre for Mined Land Rehabilitation, University of Queensland, Australia

Professor Timothy Gordon O'Connor, South African Environmental Observation Network, Pretoria, South Africa

Degree: PhD Environmental Management

<u>Key terms:</u>

Mine closure and rehabilitation; integrated multi-disciplinary risk assessment; rehabilitation maturity; Bayesian networks; integrated models and frameworks

Surface-strip coal mine rehabilitation planning in South Africa and Australia is immature. Rehabilitation risk assessment, despite being advocated by leading practice guidelines and in some instances by legislation, is conducted with minimum requirements often met by rehabilitation professionals. Specialist data is gathered during mine approval and for the environmental impact assessment process. However, the focus of this is toward assessing mining impacts and not for rehabilitation risk assessment. Quantitative, integrated, multi-disciplinary rehabilitation risk assessment is seldom undertaken. This thesis provides a methodology towards the development of a quantitative, integrative, multi-disciplinary rehabilitation risk assessment model. Its purpose being to 'profile' surface-strip coal mine sites, in terms of their rehabilitation risk and potential for rehabilitation failure, from the outset of mine operations, with adjustments possible progressively during mine operations. The methodology was developed by first reviewing techniques suitable for the development of the model, as well as techniques developed by others. Bayesian networks (BN) were found to be the most suited. A R^{2}AIN framework was then provided as a process towards developing several BN risk event models that can amalgamate to form a synthesis rehabilitation risk assessment model. A case study soil compaction BN model was used to demonstrate the framework in South Africa and Australia. The case study showed that it is possible to integrate and quantify rehabilitation risk, and most importantly to segregate risk into discrete contributing multi-disciplines for analysis. Risk percentages can be calculated per multi-discipline, per mine phase, per site, to aid site risk ‘profiling’. It is recommended that further risk event BN models be prioritised for development and that a rehabilitation risk assessment model be developed to synthesise these into one model. This will require continuous improvements in the method, to build confidence, including extensive risk event and synthesis BN model evaluation and testing; improved BN input node states and values; and simplification of the conditional probability table construction method. Adaptation to other mining types, development activities and other regions should be investigated, as well as spatial linkages to geographic information systems. This research contribution improves upfront mine rehabilitation planning and decision making, providing improved tools and techniques than what currently exist.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the following parties for supporting this study:

My Heavenly Father, who started this adventure and created a bridge between Australia and South Africa, you are the author and provider of my journey, you know no borders, I will go where you lead, I will trust in you and the plans that you have for my future.

Matt, the sunshine of my life, this is for you. Mark, thank-you for supporting this. Thank-you both for being passengers on this crazy journey.

David Mulligan. Thank-you for providing the initial opportunity in Australia and for being the first to believe in my abilities. Wayne Truter, a heavenly guardian angel, sent at the perfect time, when you were most needed when things looked bleak. Thank-you for your encouragement on so many seen and unseen levels. Tim O'Connor. Thank-you for keeping me grounded, for helping me to turn thoughts into reality and for showing me how to stand up for what I believe in and to believe in myself.

My Australian collaborators, who have become special friends and dear to my heart: Alex Lechner, Corinne Unger and Thomas Baumgartl. Alex you have helped me more than I can ever have imagined possible and I will always be indebted for this, thank-you for stepping in when I needed you. Corinne you have been there at my lowest moments and encouraged me so much – intuitively. Thomas thank-you for your technical guidance.

Roland Schulze, thank-you for your involvement and for believing in the project. Alta de Waal, it has been a privilege working with you and so much fun! Thank-you for sharing your incredible knowledge, particularly with the mysteries of Bayesian networks.

To my family: Roy, Belinda, Renay and all the Kneale clan, Megan Nowell, Federica Rosa, Viv Whiley, Natalie Way-Jones and Jeanne Pardey, also Mark for constantly affirming the 'Doc'. Thank-you for always encouraging me to keep my 'Little Red Hen' project going.

Lastly, Ed Granger, my first mentor. You are an example that age has no limitations if you love what you do and do it passionately. Thank-you for putting the idea in my head to start a PhD.

The University of Pretoria and the Coaltech Research Association are thanked for funding the research.

'Commit your works to the Lord and your thoughts will be established' Proverbs 16:3 – Jan 2015
and when the going gets tough know:
'That men ought always to pray and not to faint' Luke 18:1 – Dec 2018

DEDICATION

Dedicated to Matt

Never be afraid to have dreams and to follow them with all your heart and passion. You can achieve anything you set your mind to, with consistency, bit-by-bit, tenacity and hard work over time and above all faith. There are no limitations.

Always remember that you were uniquely and perfectly formed for a purpose, with God given gifts. Use these wisely for good, stay close to Him and above all believe in this ability that God has given to you before you were born – *Ephesians 2:10.*

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 2

CHAPTER 3

CHAPTER 4

LIST OF TABLES

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

LIST OF APPENDICES

CHAPTER 2

CHAPTER 4

LIST OF SYMBOLS AND ACRONYMS

Symbol or acronym	Definition
A-pan equivalent	Method used to measure mean annual potential evaporation
AMD	Acid Mine Drainage
AU	Australia
AUD	Australian dollar
AWC	Available Water Capacity
BN	Bayesian network
BNs	Bayesian networks
CAIR	Centre for Artificial Intelligence Research
cm	Centimetres
CPT	Conditional Probability Table
CPTs	Conditional Probability Tables
CRF	Closure Risk Factor
CV	Coefficient of variation, measurement used for precipitation variability
DAG	Directed Acyclic Graph
dS/cm	Decisiemens per centimetre, measurement used for salinity
EBQ	Experience-based Quantification
EC	Electrical conductivity, measurement used for salinity
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
ESP	Exchangeable Sodium Percentage, measurement used for sodicity
GIS	Geographic Information Systems
g/cm^3	Gram per cubic centimetre, measurement used for soil compaction measurement
ha	Hectare
H	High
ISO	International Organization for Standardization
KEBN	Knowledge Engineering for Bayesian Networks
kPa	Kilopascal, measurement used for Soil Water Content
L	Low
M	Medium
m	Metres
mbs	Metres below surface, depth to groundwater level
$MJ.m^{-2}.day^{-1}$	Megajoules per square metre per day, measurement used for solar radiation measurement

Symbol or acronym	Definition
mm	Millimetres
m/m	Measurement used for Soil Water Content
$mm.m^{-1}$	Millimetres per soil depth, measurement used for Plant Available Water
MPa	Megapascal, measurement used for soil compaction measurement
MPE	Most probable explanation
mS/m	Milliseimens per metre, measurement used for salinity
PAW	Plant Available Water
Penman-Monteith	Method used to measure mean annual potential evaporation
QRA	Quantitative Risk Assessment
R^2AIN	Rehabilitation risk assessment integrated network
RRC	Rehabilitation risk criteria
RUSLE	Revised Universal Soil Loss Equation
SA	South Africa
USLE	Universal Soil Loss Equation
%	Percentage
^{0}C	Degrees Celsius
3D	Three-dimensional

CHAPTER 1:
INTRODUCTION

> "Man's attitude toward nature is today critically important, simply because we have acquired a fateful power to alter and destroy nature. But man is a part of nature, and his war against nature is inevitably a war against himself? We are challenged as mankind has never been challenged before to prove our maturity and our mastery, not of nature, but of ourselves".
>
> **Rachel Carson (1907 – 1964)**

1.1 Background of the study

Although the length of time that humans have inhabited the earth is small, relative to the earth's geological time-scales, extensive land transformation has occurred. It is estimated that >50% of the Earth's land surface has been cleared by humans (Hooke et al., 2012). In Southern Africa, 16% of native vegetation was cleared by 2006 (Mucina and Rutherford, 2006). Australia, by 2004, had suffered a similar 12% clearance of native vegetation (Thackway et al., 2010).

Global change science has focused on the emergence of industrial processes over the past three centuries as the critical period within which anthropogenic processes became significant forces driving global changes in the Earth System (Ellis et al., 2013). Key influencing factors include the rise of agriculture, the industrial revolution and its need for minerals, the atomic age, technology advancement, the globalisation of the world economy and human population growth. Population has doubled in the past 40 years and is projected to again double in the next 40 years (Hooke et al., 2012). The world population was 7.3 billion people at mid-2015 and is expected to reach 9.7 billion by 2050 (United Nations Department of Economic and Social Affairs Population Division, 2015).

Shortages in resources, including water and food are expected, with climate change and natural events worsening circumstances. The top five global risks in terms of likelihood, for the next 10 years in order from highest to lowest likelihood are extreme weather events, failure of climate-change mitigation and adaptation, natural disasters, data fraud or theft and cyber-attacks (World Economic Forum, 2019). Water crisis is ranked 4th in terms of its impact. Technological advancements, including the 4th industrial revolution and the artificial intelligence age, agricultural intensification and implementation of sustainable development techniques are expected to help bridge the gap between the demand and supply of land and its resources, however this will likely not suffice to meet the needs of future generations. Immense pressure will be placed on land and the value of land as a commodity will increase. There will not be enough virgin land available to meet global needs. The science and practice of land rehabilitation and restoration will become critical for returning land into productive use.

A destructive landuse activity is surface-strip coal mining, which disturbs landscapes extensively, typically affecting ten times more land than that affected by underground coal mining (Tongway and Ludwig, 2011). Coal mining is also a highly competitive landuse type, competing predominately against agriculture in both South Africa and Australia (Bureau for Food and Agricultural Policy, 2012, Lechner et al., 2016). Surface-strip coal mining involves the use of walking draglines, which sit above the overburden (waste above coal seam) strip block, approximately 50 m wide, on the high-wall side. The dragline excavates the material in front of itself to uncover the top of the coal seam and then dumps the overburden on the low-wall or spoil side of the strip. Two long-walls are formed in the initial box-cut. The low-wall remains and is eventually covered by spoil. The high-wall is progressively excavated and occupies a new position with each strip. The maximum high-wall height is 45 - 50 m, whilst the strip length is approximately 2 km (Thompson, 2005). Once the overburden and then interburden (waste between coal seams) are removed, coal extraction occurs. This is done generally via blasting and by using the truck and shovel system, where loading units are typically wheel loaders, hydraulic excavators and rope excavators and trucks may include off-highway trucks, articulated dump trucks or coal haulers (Krause and Musingwini, 2007). Several box-cuts can occur simultaneously in various layouts within a mine site. The deposited spoil is rehabilitated, often progressively. The truck and shovel system may also be used instead of draglines to remove the overburden. Topsoil is removed and stored for reuse prior to the removal of the overburden, interburden and coal extraction.

It is estimated that there are over 869 billion tonnes of coal reserves worldwide, enough reserves for approximately the next 115 years at current production. In 2011, Australia ranked fourth and South Africa ninth out of the top countries, with proven recoverable coal reserves, whilst in terms of the top coal producers, Australia ranked fourth and South Africa seventh (World Energy Council, 2013). Australia and South Africa are therefore significant world coal suppliers.

In South Africa, the coal fields occur in the Mpumalanga, Gauteng, Limpopo and Kwazulu-Natal provinces and are spread over an area some 600 km from north to south and 500 km from east to west (Thompson, 2005). There are 19 principal coalfields. The Witbank coalfield, supplies more than 50% of South Africa's saleable coal (Hancox and Gotz, 2014). The Witbank and adjacent Highveld coalfields are nearing depletion and additional sources are sought, potentially from the Waterberg coalfield, located in the country's Northern Province (Jeffrey, 2005). The Waterberg coalfield contains between 40 to 50% of South Africa's remaining coal resources (Hancox and Gotz, 2014).

Coal occurs and is mined in all Australian states, with Queensland and New South Wales having the largest black coal resources and production, whereas Victoria hosts the largest resources and only production of brown coal. The principal coal producing basins are the Bowen in Queensland and the Sydney in New South Wales (Geoscience Australia and ABARE, 2010).

Coal accounts for some 40% of global electricity production and is the world's second largest source of primary energy, next to oil (World Energy Council, 2013). Its dominant position is due to coal being abundant and widely distributed across the globe and affordable (World Energy Council, 2013). Based on this need and availability, coal mining is likely to continue in the near future. However, as alternative energy sources compete and the threats to climate change increase, the use of coal is likely to gradually decline.

As surface-strip coal mines close, rehabilitation of these will be required. Mine rehabilitation knowledge, expertise and the tools to implement this are urgently required.

1.2 Problem statement

This study highlights immaturity in upfront surface-strip coal mine rehabilitation planning in South Africa and Australia. Rehabilitation risk assessment, despite being advocated by leading practice guidelines and in some instances by legislation, is conducted at a basic level by rehabilitation professionals. Minimum requirements are often met. A wealth of multi-disciplinary specialist data is gathered during the mine approval and environmental impact assessment processes. However, the focus of this data gathering is toward determining impacts from mining operations and there is limited focus on rehabilitation risk assessment. Quantitative, integrated multi-disciplinary rehabilitation risk assessment is generally not undertaken. A further difficulty is that rehabilitation risk assessment tools that are available for use to rehabilitation professionals are limited. Only a few have been developed via academic research works and these are often complex to understand and difficult to apply in-practice to mine planning applications. The need for the development of a model with capabilities to perform quantitative, integrative, multi-disciplinary rehabilitation risk assessment is identified, particularly for use in upfront mine rehabilitation planning, as well as progressively during other life of mine phases.

1.3 Research aim and objectives

1.3.1 Aim

The aim was to investigate how a rehabilitation risk assessment model could best be developed. The model should have the ability to integrate and quantify multi-disciplinary surface-strip coal mine rehabilitation risks, in order to calculate a mine site's risk profile for susceptibility to rehabilitation failure. The ability to include risk prevention and mitigation is an added benefit. The model should be designed to operate at a strategic level to aid upfront as well as progressive life of mine rehabilitation planning. It should be based on an understanding of risk, including natural and anthropogenic risk sources, which influence risk events.

1.3.2 Objectives

Objective 1: To set research foundations and confirm the need for the research.

Objective 2: To assess rehabilitation risk events of concern, associated with surface-strip coal mining.

Objective 3: To assess natural (geology, soils, topography, climate, hydrology, landcover and vegetation) and anthropogenic (as related to management actions) risk sources, which influence risk events.

Objective 4: To review techniques considered most suited for the development of a rehabilitation risk assessment model, in order to identify the best technique to use. To review relevant techniques developed by others.

Objective 5: To develop a framework and a methodology to integrate and quantify the relationships between rehabilitation risk sources and events.

Objective 6: To test the concept using a proof-of-concept case study based on a Bayesian network (BN) analysis of soil compaction risk.

Objective 7: To provide a research process for the future development of other risk event BN models, which can combine to form a composite rehabilitation risk assessment model.

1.4 Research hypothesis

This study is guided by the hypothesis that, a rehabilitation risk assessment model can calculate and profile a mine site’s susceptibility to rehabilitation failure, for all life of mine phases, based on the site’s inherent baseline characteristics and subsequent operational management actions taken and how these influence potential risk events.

This formulation could be supported by first developing a small proof-of-concept case study model and by testing this on mine sites.

1.5 Motivation, significance and focus of the study

This study is important for providing and then demonstrating a method to improve the current state of immature rehabilitation risk assessment planning in both South Africa and Australia.

There is a dire need for rehabilitation risk assessment tools and for a model capable of quantitatively integrating multi-disciplines to determine a site’s rehabilitation risk profile and its potential for rehabilitation failure. Very few such models have been developed by others, thus a research-gap has been identified. The outcomes from this study are of value to the surface-strip coal mining industry in both South Africa and Australia.

Surface-strip coal mining was chosen as the focus of the study, because this method of coal extraction tends to create a substantial level of surface disturbance; overburden is replaced back into the void; the filled void requires surface rehabilitation with the intention of re-use of the land; sequencing of mining operations and rehabilitation is possible; and as the mining method is highly cost effective it may likely continue to be used locally and internationally for many years, despite increasing competition from alternative energy sources and threats to climate change. This is a worst-case scenario. If a research process can be developed towards creating a rehabilitation risk assessment model for surface-strip coal mining, the process could be adapted for other coal mining methods, other mining types, as well as ultimately for other development activities.

1.6 The organisation of the thesis

This thesis consists of five chapters.

The three central chapters are written as stand-alone chapters, yet they function to provide a linked narrative, leading on from one another. These chapters are presented in the form of journal papers in various stages of preparation and publication. They have been written with international co-authors and have benefited from an extensive international peer-review process. Author contributions are stated in a preface located at the front of each paper, whilst a synopsis of the paper is provided at the end. High ranking international journals were selected for publication. Papers are formatted, with minimal changes, according to journal styles and requirements. References are provided at the end of each paper.

An introductory and conclusion chapter connects the three central chapters. References relevant to these chapters are provided at the end of these chapters. Figures and tables have been included within each chapter or paper. These have been numbered to match chapter numbering.

Chapter 1 provides the general introduction. This chapter provides a background of the study; states the problem to be addressed and the research aims and objectives; states the research hypothesis; provides motivation for and the significance and focus of the study; and provides an outline of the thesis structure.

Chapter 2 consists of the following published paper:

Weyer, V.D., Truter, W.F., Lechner, A.M., Unger, C.J., 2017. Surface-strip coal mine land rehabilitation planning in South Africa and Australia: Maturity and opportunities for improvement. Resources Policy 54, 117-129. http://dx.doi.org/10.1016/j.resourpol.2017.09.013

This paper sets the study foundations and substantiates the need for the research. This was achieved by developing a maturity model with objectives for mature upfront surface-strip coal mine rehabilitation planning, integration and rehabilitation risk determination. Mine approval consultant rehabilitation reports and the mine rehabilitation guidelines likely used by these consultants to prepare these, in South Africa and Australia, Queensland and New South Wales, were evaluated using the model to determine whether they addressed the maturity model's objectives. The need to determine upfront, a site's total rehabilitation failure risk, as an aid to improving rehabilitation planning was established.

Chapter 3 consists of the following paper, ‘in review’:

Weyer, V.D., Truter, W.F. (in review). Techniques suitable for surface-strip coal mine rehabilitation risk assessment: A review. Integrated Environmental Assessment and Management.

This paper reviews techniques potentially suitable for the development of a rehabilitation risk assessment model and investigates relevant risk assessment techniques developed by others. This paper functions as a supplementary literature review and position paper. It further locates the study in the body of similar research work conducted by others and confirms the research gap.

Chapter 4 consists of the following published paper:

Weyer, V.D., de Waal, A., Lechner, A.M., Unger, C.J., O’Connor, T.G., Baumgartl, T., Schulze, R. and Truter, W.F. 2019. Quantifying rehabilitation risks for surface-strip coal mines using a soil compaction Bayesian network in South Africa and Australia: To demonstrate the R^{2}AIN framework. Integrated Environmental Assessment and Management 15 (2), 190-208. http://dx.doi.org/10.1002/ieam.4128

This paper describes a framework as a process towards developing several BN risk event models that can amalgamate to form a composite rehabilitation risk assessment model. A case study soil compaction BN model is used to demonstrate the framework in South Africa and Australia.

The framework aligns with the ISO 31000 risk assessment process and principles. It includes: the identification of risk events and sources; the analysis of risk by the integration and quantification of the risk events and sources using Bayesian networks (BNs); and the evaluation and treatment of risk.

The soil compaction case study model involves: defining the model's structure (integration); parameterising the model (quantification); and validating the model by testing it on two mine sites: Kleinkopje, Witbank coalfield, South Africa and Caval Ridge, Bowen Basin, Australia.

Chapter 5 synthesizes the main findings of the study and discusses the integration of the thesis and its chapters. The research question is answered in relation to the problem statement, the research aim and objectives, the research hypothesis, prior research and the research gap. Limitations of the study are discussed, and recommendations are provided with a concluding summary.

An overview of thesis chapters, publication titles, publication status, their purpose and how these link to the objectives described in Section 1.3.2 is provided (Table 1.1). This is discussed further in Chapter 5.

Literature has been reviewed within individual chapters, the overall content of which is summarised in Table 1.2.

Table 1.1 Overview of thesis chapters

Ch.	Paper	Publication status	Purpose	Linked Objective
1	Introduction.	No paper. Chapter only.	Provides the general introduction.	No objectives linked.
2	Weyer, V.D., Truter, W.F., Lechner, A.M., Unger, C.J., 2017. Surface-strip coal mine land rehabilitation planning in South Africa and Australia: Maturity and opportunities for improvement. Resources Policy 54, 117-129. http://dx.doi.org/10.1016/j.resourpol.2017.09.013	Published.	To develop a maturity model with objectives for mature upfront surface-strip coal mine rehabilitation planning, integration and rehabilitation risk determination. To use the maturity model to evaluate mine approval consultant rehabilitation reports and the mine rehabilitation guidelines likely used by these consultants to prepare these, in South Africa and Australia, Queensland and New South Wales. To determine how mature these documents are and what is required to improve the situation.	**Objective 1:** To set research foundations and substantiate the need for the research.
3	Weyer, V.D., Truter, W.F. (in review). Techniques suitable for surface-strip coal mine rehabilitation risk assessment: A review. Integrated Environmental Assessment and Management.	In review.	Reviews techniques suitable for model development and techniques developed by others. This paper functions as a supplementary literature review and position paper. Locates the study in the body of similar research work conducted by others and confirms the research gap.	**Objective 1:** To set research foundations and substantiate the need for the research. **Objective 2:** To assess rehabilitation risk events of concern, associated with surface-strip coal mining.

Ch.	Paper	Publication status	Purpose	Linked Objective
				Objective 3: To assess natural (geology, soils, topography, climate, hydrology, landcover and vegetation) and anthropogenic (as related to management actions) risk sources, which influence risk events. **Objective 4:** To review techniques considered most suited for the development of a rehabilitation risk assessment model, in order to identify the best technique to use. To review applicable techniques developed by others.
4	Weyer, V.D., de Waal, A., Lechner, A.M., Unger, C.J., O'Connor, T.G., Baumgartl, T., Schulze, R. and Truter, W.F. 2019. Quantifying rehabilitation risks for surface-strip coal mines using a soil compaction Bayesian network in South Africa and Australia: To demonstrate the R^{2}AIN framework. Integrated Environmental Assessment and Management 15 (2), 190-208. http://dx.doi.org/10.1002/ieam.4128	Published.	Describes a framework for developing several BN risk event models that can amalgamate to form a composite rehabilitation risk assessment model. A case study soil compaction BN model is used to demonstrate the framework in South Africa and Australia.	**Objective 2:** To assess rehabilitation risk events of concern, associated with surface-strip coal mining. **Objective 3:** To assess natural (geology, soils, topography, climate, hydrology, landcover and vegetation) and anthropogenic (as related to management actions) risk sources, which influence risk events. **Objective 5:** To develop a framework and a methodology to integrate and quantify the relationships between rehabilitation risk sources and events.

Ch.	Paper	Publication status	Purpose	Linked Objective
				Objective 6: To test the concept using a proof-of-concept case study based on a BN analysis of soil compaction risk. **Objective 7:** To provide a research process for the future development of other risk event BN models, which can combine to form a composite rehabilitation risk assessment model.
5	Conclusion and recommendations	No paper. Chapter only.	Synthesizes the main findings of the study. Discusses the integration of the thesis and its chapters. Answers research question. Discusses study limitations and provides recommendations including a concluding summary.	**Objective 7:** To provide a research process for the future development of other risk event BN models, which can combine to form a composite rehabilitation risk assessment model.

Table 1.2 Summary of literature reviewed throughout the thesis

Topic	**Ch. 1**	**Ch. 2**	**Ch. 3**	**Ch. 4**	**Ch. 5**
Land transformation	X	X			
Global risks	X				
Surface-strip coal mining	X	X		X	
Coal reserves and usage	X	X			
Coal and agricultural competition		X			
Life of mine phases			X		
Mine closure and rehabilitation planning		X		X	
Progressive rehabilitation		X	X		
Post-closure landuses			X		
Sustainable development and mining		X			
South African and Australian mine rehabilitation legislation and processes		X			
Financial provisions		X			
Negative mine legacies in South Africa and Australia		X	X		
Costs of rehabilitation		X	X		
Upfront rehabilitation planning		X	X	X	
Mine rehabilitation and related definitions		X			

Topic	**Ch. 1**	**Ch. 2**	**Ch. 3**	**Ch. 4**	**Ch. 5**
Rehabilitation completion criteria and performance indicators				X	
Mine rehabilitation guidelines and mine approval consultant rehabilitation reports: South Africa, Australia, United States and Canada		X			
Maturity models		X	X		
Risk assessment and the ISO 31000 process and principles		X	X	X	X
Rehabilitation failure and risk events		X	X	X	
Rehabilitation risk sources		X	X	X	
Integrated modelling and assessment		X	X	X	
Qualitative, semi-quantitative and quantitative risk assessment			X		
Temporal and spatial modelling			X		X
Expert knowledge			X		
Criteria weighting			X		
Fault-tree analysis			X		
Bow-tie analysis			X		
Bayesian networks			X		X
Risk assessment techniques developed by others			X		X
Soil compaction				X	
Cumulative impacts				X	
Integrated frameworks				X	

Topic	**Ch. 1**	**Ch. 2**	**Ch. 3**	**Ch. 4**	**Ch. 5**
South Africa and Australia baseline conditions				X	X

1.7 References

BUREAU FOR FOOD AND AGRICULTURAL POLICY 2012. Evaluating the impact of coal mining on agriculture in the Delmas, Ogies and Leandra districts: A focus on maize production. *BFAP Reports 279783.* Johannesburg, (ZA): Bureau for Food and Agricultural Policy.

ELLIS, E. C., KAPLAN, J. O., FULLER, D. Q., VAVRUS, S., KLEIN GOLDEWIJK, K. & VERBURG, P. H. 2013. Used planet: A global history. *Proceedings of the National Academy of Sciences,* 110**,** 7978-7985.

GEOSCIENCE AUSTRALIA & ABARE 2010. Australian energy resource assessment. *Report No. 70142.* Canberra, (AU): Commonwealth of Australia.

HANCOX, P. J. & GOTZ, A. E. 2014. South Africa's coalfields - a 2014 perspective. *International Journal of Coal Geology,* 132**,** 170-254.

HOOKE, R., MARTIN-DUQUE, J. & PEDRAZA, J. 2012. Land transformation by humans: A review. *GSA Today,* 22**,** 4-10.

JEFFREY, L. S. 2005. Characterization of the coal resources of South Africa. *The Journal of the South African Institute of Mining and Metallurgy,* 105**,** 95-102.

KRAUSE, A. & MUSINGWINI, C. 2007. Modelling open pit shovel-truck systems using the Machine Repair Model. *The Journal of the South African Institute of Mining and Metallurgy,* 107**,** 469 - 476.

LECHNER, A. M., BAUMGARTL, T., MATTHEW, P. & GLENN, V. 2016. The impact of underground longwall mining on prime agricultural land: A review and research agenda. *Land Degradation & Development,* 27**,** 1650-1663.

MUCINA, L. & RUTHERFORD, M. C. (eds.) 2006. *The vegetation of South Africa, Lesotho and Swaziland,* Pretoria, (ZA): South African National Biodiversity Institute.

THACKWAY, R., WILSON, P., HNATIUK, R., BORDAS, V. & DAWSON, S. 2010. Establishing an interim national baseline 2004 to assess change in native vegetation extent. *Report* Canberra, (AU): Bureau of Rural Sciences.

THOMPSON, R. J. 2005. Surface strip coal mining handbook. *Report No. SACMA 01/03.* Johannesburg, (ZA): South African Colliery Managers Association.

TONGWAY, D. J. & LUDWIG, J. A. 2011. *Restoring disturbed landscapes: Putting principles into practice*, Washington, (DC), Island Pr.

UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS POPULATION DIVISION 2015. World population prospectus: The 2015 revision, key findings and advance tables. *Working paper No. ESA/P/WP.241*. New York, (US): United Nations.

WORLD ECONOMIC FORUM 2019. The global risks report 2019 14th edition. *Report* 14 ed. Geneva, (CH): World Economic Forum.

WORLD ENERGY COUNCIL 2013. World energy resources: 2013 survey. *Report* London, (UK): World Energy Council.

CHAPTER 2:

SURFACE-STRIP COAL MINE LAND REHABILITATION PLANNING IN SOUTH AFRICA AND AUSTRALIA: MATURITY AND OPPORTUNITIES FOR IMPROVEMENT

Vanessa D. Weyer[a,□], Wayne F. Truter[b], Alex M. Lechner[c,d], Corinne J. Unger[e,f]

*Corresponding first author: Vanessa D. Weyer; vweyer@global.co.za

[a] Centre for Environmental Studies, University of Pretoria, P.O. Box 1456, Kloof, 3640, South Africa
[b] Department of Plant and Soil Sciences, University of Pretoria, Private bag X20,
Hatfield, Pretoria 0028, South Africa
[c] Centre for Water in the Minerals Industry, Sustainable Minerals Institute, University of Queensland,
St Lucia, Brisbane, Queensland 4072, Australia
[d] School of Environmental and Geographical Sciences, University of Nottingham Malaysia Campus, Semenyih, Selangor 43500, Malaysia
[e] Centre for Mined Land Rehabilitation, Sustainable Minerals Institute, University of Queensland,
St Lucia, Brisbane, Queensland 4072, Australia
[f] University of Queensland Business School, University of Queensland,
St Lucia, Brisbane, Queensland 4072, Australia

Published in: *Resources Policy* (2017) 54:117-129

Preface

This chapter consists of a published paper and is cited as follows:

Weyer, V.D., Truter, W.F., Lechner, A.M., Unger, C.J., 2017. Surface-strip coal mine land rehabilitation planning in South Africa and Australia: Maturity and opportunities for improvement. Resources Policy 54, 117-129.
http://dx.doi.org/10.1016/j.resourpol.2017.09.013

This paper sets the study foundations and substantiates the need for the research. This was achieved by developing a maturity model with objectives for mature upfront surface-strip coal mine rehabilitation planning, integration and rehabilitation risk determination. Mine approval consultant rehabilitation reports and the mine rehabilitation guidelines likely used by these consultants to prepare these, in South Africa and Australia, Queensland and New South Wales, were evaluated using the model to determine whether they addressed the maturity model's objectives. The need to determine upfront, a site's total rehabilitation failure risk, as an aid to improving rehabilitation planning was established.

The paper was co-authored with Wayne F. Truter, Alex M. Lechner and Corinne J. Unger. The conceptualisation of the paper, the data analysis and the actual article writing was conducted by me. Corinne J. Unger proposed the method which could be adapted for the maturity model’s development. Wayne F. Truter, Alex M. Lechner and Corinne J. Unger assisted with developing the paper’s structure and with reviewing the paper.

2.1 Abstract

At the mine approval phase, there is logically a focus on mine start-up and operational requirements, however, insufficient attention is given to rehabilitation planning aspects. To evaluate how rehabilitation planning is addressed upfront, we proposed a maturity model, which consists of three maturity performance indicators measured for seven environmental domain evaluative criteria. The maturity model was applied to mine rehabilitation guidelines and mine approval consultant rehabilitation reports in South Africa and Australia, Queensland and New South Wales. We found that these documents were vulnerable to adequate, but not yet resilient, i.e. rehabilitation information was gathered, but seldom analysed, with limited integration and rehabilitation risk determination. Legislation, as well as the temporary and dynamic nature of mining, may inadvertently be contributing to immaturity. We conclude by discussing ways forward and the need to determine upfront, a site's total rehabilitation failure risk, as an aid to improving rehabilitation planning.

2.2 Highlights

- A maturity model for surface-strip coal mine land rehabilitation planning is presented
- The model was applied to mine rehabilitation guidelines and approval reports
- Guidelines and approval reports are vulnerable to adequate, but not yet resilient
- Legislation may be contributing to immaturity for some aspects of planning
- Upfront planning and analysis in dynamic mining environments are discussed

2.3 Keywords

Mine closure and rehabilitation; Mineral legislation; Risk assessment; Environmental planning; Multi-discipline; Integrated modelling; Maturity models; Cumulative impacts

2.4 Introduction

It is estimated that >50% of the Earth’s land surface has been cleared by humans (Hooke et al., 2012). In Southern Africa, 16% of native vegetation was cleared by 2006 (Mucina and Rutherford, 2006). Australia, by 2004, suffered a similar 12% clearance of native vegetation (Thackway et al., 2010). In both these countries mining has claimed large tracts of high potential agricultural land, resulting in competition between agriculture and mining. This is especially true for coal mining, due to its geological formations, which extend over large areas. 1.5% of South Africa has high potential arable soils, with half occurring in the province of Mpumalanga. At current mining rates, approximately 12% of this will be lost, while a further 13.6% is under prospecting rights (Bureau for Food and Agricultural Policy, 2012). Lechner et al. (2016a) reported approximately 61% of good quality strategic cropping land coincides with coal mining exploration permits

Land use degradation from coal mining is likely to continue into the foreseeable future with South Africa and Australia playing pivotal roles in coal supply, despite increasing market competition from alternative energy sources (Hancox and Gotz, 2014). Coal accounts for some 40% of global electricity production, is abundant, widely distributed across the globe, affordable and it is estimated that there are enough reserves for approximately 115 years at current production (World Energy Council, 2013). In 2011, South Africa ranked ninth and Australia fourth, in terms of countries, with largest proven recoverable coal reserves (World Energy Council, 2013). Given the ongoing threat to high productivity potential agricultural land and impacts on biodiversity, the science and practice of land rehabilitation is critical for meeting global and national environmental sustainability objectives and achieving future food security.

Our paper's geographical focus is on the Southern Hemisphere countries of South Africa and Australia, specifically Queensland and New South Wales. These countries and jurisdictions were chosen as they share similarities in climate, geology and vegetation. Also, many of the large mining companies are present in both countries and Australia provides an international bench-mark for comparison with South Africa.

Surface-strip coal mining can disturb landscapes extensively, typically affecting ten times more land than that affected by underground coal mining (Tongway and Ludwig, 2011). Surface mines have a disturbance potential that is unmatched by any other human activity, except for urban development. Surface-strip coal mining may involve the use of walking draglines which can excavate pits 2 km long, 50 m wide and 50 m high, thus potentially disturbing 5 million m^3 of soil per pit (Thompson, 2005).

Following coal extraction, disturbed lands require rehabilitation. Failure to rehabilitate mined land effectively may result in the occurrence of negative rehabilitation risks such as soil erosion and loss of valuable soil resources, soil and water contamination, soil compaction, ponding, surface cracking, spontaneous combustion and subsidence, which could lead ultimately to site rehabilitation failure (Australian Government et al., 2016b; Gauteng Department of Agriculture Environment and Conservation, 2008; Limpitlaw et al., 2005; Rethman, 2006). Site rehabilitation failure may include weed infestation and unproductive land with the substrate unable to support sustainable end landuses such as grazing and cropping. Withdrawal of social license may also result from poor rehabilitation performance, as well as company reputational damage and heightened community opposition to new and expansion mining applications and public campaigning for stronger regulatory controls, with added costs to mining companies. Mined landscapes are highly-disturbed (Erskine and Fletcher, 2013). Doley et al. (2012) state within the post-mining context, the inability to achieve true restoration, in terms of the ‘pure restoration’ definition, is due primarily to the radical differences between the physiochemical and biological characteristics of the original vs. rehabilitated mine environments. Rehabilitation may only be achieved in-part through a multi-disciplinary approach and restoration in its pure definition is seldom achievable.

Rehabilitation falls within mine closure planning, exerting an influence throughout the mine life-cycle (Australian Government et al., 2016a). The rehabilitation process is conceptualised as five stages of planning and implementation by Australian Government et al. (2016b): Stage 1. Defining rehabilitation objectives and targets; Stage 2. Conducting rehabilitation planning; Stage 3. Implementing rehabilitation techniques, which is split into five categories, i) Landform design and construction; ii) Reconstruction of the soil profile; iii) Selection of suitable species; iv)

Establishment of vegetation and v) Fauna recolonization; Stage 4. Setting completion criteria; and Stage 5. Undertaking rehabilitation management and monitoring.

Sustainable development principles are of importance for rehabilitation planning. Sustainable development was first defined by the World Commission on Environment and Development as, ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (Brundtland, 1987). The 1992 and 2002 World Summits on Sustainable Development were further key milestones. Sustainable development principles have evolved with applicability to mine closure and rehabilitation in South Africa and Australia (Australian Government et al., 2011, 2016a, b; Australian Government and Department of Industry Tourism and Resources, 2006; International Council on Mining and Metals, 2003, 2008; International Institute for Environment and Development and World Business Council for Sustainable Development, 2002; Minerals Council of Australia, 2005). Sustainable development principles are not static, are often not universally agreed upon and have different compliance standards depending on local policy and legislation requirements. Sustainable development as applied to the Australian context means that investments in minerals projects should be financially profitable, technically appropriate, environmentally sound and socially responsible (Australian Government et al., 2011, 2016a). In South Africa, sustainable development is defined as the integration of social, economic and environmental factors into planning, implementation and decision making so as to ensure that mineral and petroleum resources development serves present and future generations (Department of Minerals and Energy, 2002).

Mine rehabilitation legislation in both South Africa and Australia has developed in response to the sustainable development movement. In South Africa, prior to 1956, no mine closure and rehabilitation legislation existed (Limpitlaw et al., 2005). The first voluntary rehabilitation guideline document was compiled in 1981 (Chamber of Mines of South Africa, 1981). At this time rehabilitation was approved simultaneously with mining applications by the Department of Water Affairs & Forestry and the Government Mining Engineer (Wells, 1986).

Legislation promulgated thereafter included: Minerals Act, Act No. 50 of 1991; Environmental Impact Assessment Regulations of 1997 in terms of the Environmental Conservation Act, Act

No. 73 of 1989; National Environmental Management Act, Act No. 107 of 1998, National Water Act, Act No. 36 of 1998; Minerals and Petroleum Resources Development Act, Act No. 28 of 2002 and its 2004 Regulations (GNR No. 527); and National Environmental Management: Waste Act, Act No. 59 of 2008 (Supplementary material, Table 2). The Environmental Impact Assessment Regulations has had four amendments, the most recent in 2017. More recently the 2015, Financial Provisions Regulations were promulgated (Department of Environmental Affairs, 2015). These operate in conjunction with the Environmental Impact Assessment Regulations of 2014 and their 2017 amendments (Department of Environmental Affairs, 2017).

Queensland, Australia was one of the first states to introduce Environmental Impact Assessment procedures, with the State Development and Public Works Organisation Act, 1971 (Elliott and Thomas, 2009). The Mineral Resources Act, 1989; Environmental Protection Act, 1994; Integrated Planning Act, 1997; and the Environmental Protection Regulations, 2008, followed (Supplementary material, Table 2). Currently, mined land rehabilitation is regulated by Sections 125 (1) (l) (i) (E); 264; 268; and 318Z of the Environmental Protection Act, 1994 (Department of Environment and Heritage Protection, 2014; State of Queensland Australia, 1994).

In New South Wales, the Environmental Planning and Assessment Act, 1979 was the first protective environmental legislation promulgated (Elliott and Thomas, 2009). The Mining Act, 1992 and the Protection of the Environmental Operations Act followed (Supplementary material, Table 2).

Despite the good intentions of guiding policy and legislation, sustainability objectives are rarely achieved, with rehabilitation failures often evident. A worst-case failure example is negative mining legacies. It is acknowledged that many of these legacy mines are historic and the mining activity most certainly was initiated and likely ceased before environmental or sustainable development legislation- so there was much less emphasis on stakeholder interests and long-term environmental impacts. Negative mine legacies are indeed a grave reminder of what can result from inadequate environmental responsibility. Negative mine legacies include approximately 6000 abandoned mines in South Africa and more than 50,000 in Australia, with 15,380 situated in Queensland and 410 in New South Wales (Auditor-General South Africa, 2009; Department of Mineral Resources, 2009; Unger et al., 2012). Unger et al. (2012) note inconsistency and the ambiguity in the category definitions describing mine characteristics for the Australian data sets. Further, only a percentage of these are surface-strip coal mines and mine site size varies. Therefore, mine numbers may be over representative. The contingent liability to rehabilitate the 15,000 abandoned mines in Queensland is estimated in excess of $1B AUD (Queensland Government, 2012). It is estimated that it would cost almost $3B AUD to rehabilitate the 6,000 abandoned mines in South Africa (Auditor-General South Africa, 2009). The long-term treatment of acid mine drainage and the construction and operating fees of plants was excluded in the cost calculation for South Africa. In addition, reputational costs, which are difficult to quantify and end land-use specification have likely too not been included in either calculation.

End land-use rehabilitation costs vary considerably, with ‘native ecosystems’ costing almost double that for ‘permanent pasture’ establishment (Department of Environment and Heritage Protection, 2017). Lechner et al. (2016b), using spatial data and the Queensland financial assurance calculator, estimated the rehabilitation financial liability for operating surface coal mines in the Fitzroy Basin, Australia, to be more than $4.349 and $5.461B AUD, with some rehabilitation liabilities omitted due to the spatial data method applied. Financial assurance is a type of financial security provided to the Queensland Government by the holder of an environmental authority. It covers any costs or expenses incurred to prevent or minimise environmental harm or rehabilitate or restore the environment, should the holder fail to meet their environmental obligations in the environmental authority. To facilitate financial assurance calculation the Queensland Department of Environment and Heritage Protection developed financial assurance calculators to help streamline the assessment of the environmental authority financial assurance requirement (Department of Environment and Heritage Protection, 2017). These rehabilitation costs, although seemingly exorbitant, in comparison to the profits derived from mining are minimal. To put rehabilitation liabilities in context, Australia’s exports of black coal from 2007 to 2008, were valued at $24.4B AUD (Geoscience Australia and ABARE, 2010).

An attribute of negative mine legacies is incomplete remediation, with responsibility by default relegated to governments and communities (Unger et al., 2015). Unger et al. (2015) note that incomplete remediation may be due to premature cessation of operations, inadequate regulatory requirements, insufficient funds, or inadequate community engagement to agree upon and meet closure expectations. A deeper cause may however be due to the lack of legislation and sustainable responsibility being applied to these early mines. Mine planning most likely would not have taken environmental considerations seriously and critical rehabilitation risks and their interactions may not have been adequately considered.

While it is recognised in good practice guidance that early upfront rehabilitation planning reduces the potential risk of rehabilitation failure, this practice seldom occurs (Lechner et al., 2017; Limpitlaw and Mitchell, 2013; McCullough, 2016; Minerals Policy Institute, 2016). Authorities emphasise developing the necessary skills, equipment and technical knowledge over time during progressive rehabilitation actions so as to achieve successful rehabilitation (Australian Government et al., 2016b). In project planning, it is accepted that the earlier planning is initiated and the greater the analysis and attention to detail, the higher the project success rate, with minimal failures, associated costs and damage to the environment (Australian Government et al., 2016b; Ireland, 2008). There is the added potential for rehabilitation failures to compound exponentially during the mine life-cycle, making later rectification difficult and expensive.

The aim of this paper is to review rehabilitation maturity in mine rehabilitation guidelines and mine approval consultant rehabilitation reports, with comparison between all South Africa's coal bearing Provinces and Australia, specifically the states of Queensland and New South Wales. We first define rehabilitation and the rehabilitation end-product. We then develop a maturity model with objectives for mature upfront surface-strip coal mine rehabilitation planning, integration and rehabilitation risk determination. Using the maturity model, we systematically review mine approval consultant rehabilitation reports and the mine rehabilitation guidelines likely used by these consultants to prepare these. We evaluate these documents on whether they address the maturity model's objectives. We then explore legislation as a driver of immaturity. We discuss the nature of mining operations and whether it is possible to include a high level of detail and analysis upfront in planning for mining projects, which are temporal and dynamic and when progressive rehabilitation methods are favoured. We conclude by suggesting ways forward and the need to develop a tool to determine a site's rehabilitation failure risk, thereby identifying opportunities for improvement in upfront rehabilitation planning. This paper focuses on environmental issues pertaining to rehabilitation however, we acknowledge that there are also associated socio-economic and management issues that need to be addressed.

2.5 Method

2.5.1 Defining rehabilitation and the rehabilitation end-product

The first step to developing a rehabilitation maturity model is to define rehabilitation and what the rehabilitation end-product should look like. These definitions are necessary for clarity and as they provide an indication of what the rehabilitation maturity model should strive to include as a bench-mark for the evaluation of rehabilitation planning documents, to lead towards an improved rehabilitation end-product.

Several terms exist which are synonymous with mined land rehabilitation. These are used interchangeably and are seldom defined by rehabilitation professionals. They include: ecological restoration, restoration, rehabilitation, reclamation, revegetation, reforestation, remediation and closure. This lack of clarity can be problematic, as the failure to define the rehabilitation end-product can create legal disputes at closure, when rehabilitation outcomes show disparity to the expectations of regulatory authorities, mining companies and local communities.

The authors offer their definition for rehabilitation, which they see as comprising of three sequential phases, from remediation, to revegetation/ reforestation to a final stage of reclamation (Table 2.1). This definition attempts to attain a balance between theory definitions such as ‘ecological restoration’ and ‘restoration’ and practice-based definitions used in the mining industry, including ‘reclamation’, ‘rehabilitation’ and ‘remediation’. These have been adapted from work by others (Australian Government et al., 2016b; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 2007; Clewell and Aronson, 2013; Howell et al., 2012; Principles and Standards Reference Group and Society for Ecological Restoration Australasia, 2016; Society for Ecological Restoration International Science & Policy Working Group, 2004).

Table 2.1 Mined land rehabilitation author definitions

Term	Definition
Rehabilitation	Encompasses three phases: Phase 1- Remediation, Phase 2- Revegetation/ Reforestation and Phase 3-Reclamation, which may be present singularly or in combination, within portions or the whole of disturbed mine sites. These form a trajectory towards an improved ecosystem from least to moderate ecological value. They are phases of ‘succession’, along time-lines, leading to ‘rehabilitation’. The re-establishment of pre-existing biotic integrity in terms of species composition and community structure is excluded. Final rehabilitation includes repaired ecosystem processes, productivity and services with indigenous vegetation of a moderate ecological value. Detailed scientific restoration ecology principles do not apply, rehabilitation is practice based.
Phase 1: Remediation	Involves eliminating or reducing contaminants from a place where they are not wanted. Geohydrological changes due to mining activity primarily dictate remediation requirements.
Phase 2: Revegetation/ Reforestation	Includes the establishment of one or several quick growing stabilising indigenous or non-indigenous plants species. This may include: commercial cropping or pastures; native grasslands; timber plantations; or native forests.
Phase 3: Reclamation	The land is returned to a useful purpose, which may include: non-indigenous plantings (commercial cropping, pastures or timber plantations) or indigenous vegetation of low to moderate ecological value. Non-indigenous plantings are permissible as they act as ‘nurse’ species, making the site favourable for later indigenous species introduction. Reclamation also includes the process of making favourable the ‘soil foundation’ for plant establishment. Public safety and aesthetics are included. Reclamation allows for the ‘rehabilitation’ end-product to be attained.

2.5.2 Rehabilitation maturity model

Our rehabilitation maturity model includes objectives for mature upfront surface-strip coal mine rehabilitation planning, integration and risk determination with indicators of what is the ideal mature rehabilitation state and the steps required to attain this (Table 2.2). Specifically, it serves as a bench-mark for the evaluation of maturity in rehabilitation planning documents.

The model is based on the Culture Ladder by Hudson (2007) developed for Health, Safety and Environment in the oil and gas industry and as adapted by Unger et al. (2015) for the evaluation of abandoned mine rehabilitation programs. The Hudson Ladder defines a pathway from less to more advanced cultures, with five ‘categories of advancement’ including: pathological, reactive, calculative, proactive to generative. The adaption by Unger et al. (2015) also uses five ‘categories of advancement’ but terms these ‘performance indicators’, which include vulnerable, reactive, compliant, proactive and resilient. The Hudson Ladder uses an instrument of measurement for characterisations which define how an organisation’s culture is currently best defined and provides advanced targets toward which it can evolve (Hudson et al., 2002). Information is presented in table format with a vertical column of ‘dimensions’ and horizontal rows of ‘categories of advancement’. Descriptions of behaviour are provided for each of the levels of ‘categories of advancement’ across all ‘dimensions’.

Our rehabilitation maturity model uses seven environmental domain evaluative criteria: geology, soils, topography, hydrology, climate, vegetation and landuse. These evaluative criteria are foundation rehabilitation factors that influence the potential for rehabilitation failures as well as opportunities, they determine the long-term viability of land for sufficient ecosystem restoration and are important for building a landscape from the bottom-up. They have their origin in the ecological concept of environmental and anthropogenic determinants of vegetation distribution and therefore may too dictate what can be achieved during rehabilitation by offering trends for vegetation establishment and suitable species choices (Greve et al., 2011; Mucina and Rutherford, 2006). The environmental domain evaluative criteria are representative of the multi-disciplines that are involved during the mine rehabilitation process. They include key factors that should be considered as a minimum for any operation, to assist with closure planning and to identify which elements need to be monitored or investigated during the mine life-cycle (Australian Government et al., 2016a).

Each environmental domain evaluative criteria was measured for their maturity using only three of the five performance indicators as described by Unger et al. (2015): vulnerable, compliant and resilient, with compliant reworded to adequate. The remaining two intermediate performance indicators of reactive and proactive were omitted. These adaptations were made for simplification and so as to apply the maturity model by Unger et al. (2015) to our maturity model's specific needs. There is significant quantity of information in our three performance indicators and having five would make the model impractical. In our model, 'vulnerable' implies inadequate consideration, with no data gathered at all, e.g. in the topography environmental domain evaluative criteria category, this would imply not including or requesting the consideration of elevation or aspect issues among other; 'adequate' implies suitable consideration, with data as required gathered, e.g. includes/ requests specific information on: upland or lowland elevation; and north, south, east or west facing slopes; and 'resilient' implies full consideration, in addition to complying with the criteria for adequate, showing full maturity where data gathered has been used for 'intelligent' rehabilitation planning, e.g. elevation and aspect topographic information has been used/ requested to inform rehabilitation planning decisions; integration has been undertaken/ requested to indicate potential rehabilitation failure and risk; and rehabilitation failure risk has been determined/ requested.

The key undertakings required to attain resilience include rehabilitation planning, integration and risk determination. Planning refers to whether data has informed rehabilitation decisions. While, integration is based on the 'integrated modelling' concept, whereby different components of the natural and other systems are modelled in a linked way, ideally with representation of feedbacks, loops, responses, thresholds and other features of system behaviour (Argent, 2004; Hamilton et al., 2015). Integration in the context of our maturity model, is therefore important within and across the environmental domain evaluative criteria, to go beyond linear relationships with a focus on linked network relationships, their analysis and potential contribution to rehabilitation failure risk. Risk is defined as, the overall process of risk identification, analysis and evaluation by Council of Standards Australia & New Zealand (2009). Where risk identification is the process of finding, recognising and describing risks, including their sources and events; risk analysis is the process to comprehend the nature of risk and to determine the level of risk; and risk evaluation is the process of comparing the results of risk analysis with risk criteria to determine whether the risk and/ or its magnitude is acceptable or tolerable. Risk treatment, the process to modify a risk is also included, i.e. controls of prevention and mitigation. Our maturity model's resilient status therefore aims to ensure that these risk parameters are adequately met.

Table 2.2 Rehabilitation maturity model for evaluation of mine rehabilitation guidelines and mine approval consultant rehabilitation reports with emphasis on a) rehabilitation planning, integration and risk determination and b) regulatory approval requirements Adaptation of (Hudson, 2007; Unger et al., 2015))

Performance Indicators	**Vulnerable (1)[1]**	**Adequate (2)**	**Resilient (3)**
Environmental Domain Evaluative Criteria	Inadequate consideration, with no data gathered at all	Suitable consideration, with data gathered	Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
Geology	Does not include/ request geological information on substrates for new landforms. Does not include/ request geological characterisation of wastes. Does not include/ request consideration of acid rock drainage and toxicity development potential.	Includes/ requests specific information on unstable geological formations. Includes/ requests specific information on physical behaviour, chemical reactivity and geochemical characterisation of mine waste material under the conditions in which it is stored, the constituent elements present and their likely future speciation and mobility. Includes/ requests specific information on presence of sulphide minerals, water and	Geological information has been used/ requested to inform rehabilitation planning decisions. Integration has been undertaken/ requested within the geology domain to indicate potential rehabilitation failure and risk, e.g. are there any ore bodies, such as nickel that could cause toxicity, when combined with other geological conditions? Integration has also been undertaken/ requested with linkage to other domains, e.g. high water table (hydrology domain), high rainfall area (climate domain), increases potential for acid rock drainage. Rehabilitation failure risk has been determined/ requested, involving identification, analysis, evaluation and treatment of risk, e.g. the potential risk of acid rock drainage has been identified;

---

[1] A score of (1) is awarded for vulnerable, (2) for adequate and (3) for resilient. Intermediate scores are awarded for when documents do not fall definitively within these three main performance indicators. A score of (1.5) is awarded for falling between vulnerable and adequate and (2.5) for falling between adequate and resilient.

Performance Indicators **Environmental Domain Evaluative Criteria**	**Vulnerable (1)**[1] Inadequate consideration, with no data gathered at all	**Adequate (2)** Suitable consideration, with data gathered	**Resilient (3)** Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
		exposure to atmosphere; and on salinity and metal toxicities.	analysis has included determining the level of risk based on the integration of parameters from the geology, hydrology and climate domains; evaluation has included comparison to known acid rock drainage severity parameters; and treatment has included among other considering lowering of the water table and capping of the site to prevent atmospheric exposure and exposure to high rainfall conditions.
Soils	Does not include/ request soil information for new landforms. Does not include/ request baseline soils data for topsoil and subsoil in the context of future use of soils. Does not include/ request consideration of: soil chemical, physical and biological properties.	Includes/ requests specific information on soil chemical properties of: pH; salinity; sodicity; exchangeable cations and anions; electrical conductivity of saturation extract; and plant nutrient availability. Includes/ requests specific information on soil physical properties of: texture; aggregation; soil cohesion; bulk density; topsoil depth; permeability; erodibility; water retention; infiltration and dispersive ability; rockiness;	Soil information has been used/ requested to inform rehabilitation planning decisions. Integration has been undertaken/ requested within the soil domain to indicate potential rehabilitation failure and risk, e.g. which soil parameter combinations (texture/ particle size, bulk density, top soil depth, water retention capacity, known problem soils, and organic carbon content) may contribute to soil compaction? Integration is also undertaken/ requested with linkage to other domains, e.g. for compaction risk to increase are other parameters also present e.g. flat slopes (topography domain), highwater table (hydrology domain) and high rainfall (climate domain)? Rehabilitation failure risk has been determined/

Performance Indicators **Environmental Domain Evaluative Criteria**	**Vulnerable (1)[1]** Inadequate consideration, with no data gathered at all	**Adequate (2)** Suitable consideration, with data gathered	**Resilient (3)** Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
		and known problem soils. Includes/ requests specific information on soil biological properties of: litter cover; organic carbon content; nitrogen fixation; Mycorrhizal fungi; and soil seedbanks.	requested involving identification, analysis, evaluation and treatment of risk, e.g. the potential risk of compaction has been identified; analysis has included determining the level of risk based on the integration of parameters from the soil, topography, hydrology and climate domains; evaluation has included comparison to known compaction severity parameters; and treatment has included among other considering slope alterations and implementation of controls of soil handling methods and machinery use.
Topography	Does not include/ request topographical information as a baseline for geomorphic design of landforms. No inclusion or request for consideration of elevation and aspect. No inclusion or request for consideration of slope categories.	Includes/ requests specific information to aid the design of landforms. Includes/ requests specific information on: upland or lowland elevation; and north, south, east or west facing slopes Includes/ requests specific information on slope stability, drainage, length, shape and roughness.	Topographical information has been used/ requested to inform rehabilitation planning decisions. Integration has been undertaken/ requested within the topography domain to indicate potential rehabilitation failure and risk, e.g. which topographic parameter combinations (slope drainage, length, shape and roughness) may contribute to slope instability? Integration is also undertaken/ requested with linkage to other domains, e.g. for slope instability risk to increase are other parameters also present e.g. faults/ fissures (geology domain); coarse sandy textured soils, low cohesion soils, shallow soil depth, and

Performance Indicators	**Vulnerable (1)**[1]	**Adequate (2)**	**Resilient (3)**
Environmental Domain Evaluative Criteria	Inadequate consideration, with no data gathered at all	Suitable consideration, with data gathered	Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
			low litter cover and organic carbon content (soil domain); high surface runoff intensity and high velocity of flow (hydrology domain); low vegetation cover (vegetation domain); and high rainfall area (climate domain)? Rehabilitation failure risk has been determined/ requested involving identification, analysis, evaluation and treatment of risk, e.g. the potential risk of slope instability has been identified; analysis has included determining the level of risk based on the integration of topography, soil, hydrology, climate and vegetation domain parameters; evaluation has included comparison to known slope stability severity parameters; and treatment has included among other considering altering slope angle, length, shape etc.
Hydrology	Does not include/ request hydrological information in a manner which could inform new landform design. No inclusion or request for consideration of ground or surface water	Includes/ requests specific information on: groundwater table depth; underground streams; aquifers; boreholes; and on: surface water runoff intensity, velocity of flow, depth, frequency, water quantity and quality.	Hydrological information has been used/ requested to inform rehabilitation planning decisions. Integration has been undertaken/ requested within the hydrology domain to indicate potential rehabilitation failure and risk, e.g. which hydrological parameter combinations (high water table, low runoff intensity and low flow velocity)

Performance Indicators **Environmental Domain Evaluative Criteria**	**Vulnerable (1)**[1] Inadequate consideration, with no data gathered at all	**Adequate (2)** Suitable consideration, with data gathered	**Resilient (3)** Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
	information. No inclusion or request for consideration of wetlands and 1:100 year floodlines nor water regimes.	Includes/ requests specific information on: wetlands and 1:100 year floodline inundation, frequency, duration, depth and depth to groundwater in the growing season; Includes/ requests specific information on: presence of water reducing dams and vegetation, potential for irrigation from natural water and decant sources.	may contribute to water retention? Integration is also undertaken/ requested with linkage to other domains, e.g. for water retention risk to increase are other parameters also present e.g. high clay content soils (soil domain), wet south gentle concave slopes (topography domain) and high rainfall (climate domain)? Rehabilitation failure risk has been determined/ requested involving identification, analysis, evaluation and treatment of risk, e.g. the potential risk of water retention has been identified; analysis has included determining the level of risk based on the integration of parameters from the hydrology, soil, topography and climate domains; evaluation has included comparison to known water retention severity parameters; and treatment has included considering slope alterations and soil amendments among other.
Vegetation	Does not include/ request vegetation information in a manner which can be used to inform re-vegetation.	Includes/ requests information to inform vegetation establishment. Includes/ requests specific information on: past vegetation	Vegetation information has been used/ requested to inform rehabilitation planning decisions. Integration has been undertaken/ requested within the vegetation domain to indicate potential rehabilitation failure and risk, e.g. which

Performance Indicators **Environmental Domain Evaluative Criteria**	**Vulnerable (1)**[1] Inadequate consideration, with no data gathered at all	**Adequate (2)** Suitable consideration, with data gathered	**Resilient (3)** Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
	No inclusion of past vegetation types, resilience nor succession status. No inclusion of: vegetation biodiversity potential for linkage etc., suitable plant species and propagative material, nor of potential threats to vegetation establishment, i.e. alien vegetation presence and influence of fauna and humans.	types; frequency and magnitude of natural disturbances, i.e. site resilience; succession status; biodiversity potential; potential nurse and vegetation establishment species; and availability of seed and vegetative plant propagation material. Includes/ requests specific information on: resistance ability to invasion from alien plant species, proximity to alien vegetation seed banks; extreme fire events/ fire regimes; and anthropogenic perturbations, i.e. restricted or open access types allowing human/ animal impacts.	vegetation parameter combinations (poor species selection and planting of climax vegetation in a pioneer environment) may contribute to vegetation failure? Integration is also undertaken/ requested with linkage to other domains, e.g. for vegetation failure risk to increase are other parameters also present e.g. negative soil states (soil domain), steep slopes (topography domain) shallow water table (hydrology domain) and low infrequent rainfall (climate domain)? Rehabilitation failure risk has been determined/ requested involving identification, analysis, evaluation and treatment of risk, e.g. the potential risk of vegetation failure has been identified; analysis has included determining the level of risk based on the integration of vegetation, soil, hydrology, climate and topography domain parameters; evaluation has included comparison to known vegetation failure severity parameters; and treatment has included considering soil amendments, use of decant for irrigation and correct choice of species among other.

Performance Indicators	**Vulnerable (1)[1]**	**Adequate (2)**	**Resilient (3)**
Environmental Domain Evaluative Criteria	Inadequate consideration, with no data gathered at all	Suitable consideration, with data gathered	Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
Climate	Does not include/ request climate information. No inclusion or request for consideration of precipitation nor temperature. No inclusion or request for consideration of humidity, evaporation, wind factor, micro-climates and season length	Includes/ requests specific information in a manner which provides partial insight into influencing factors on rehabilitation. Includes/ requests specific information on: mean annual precipitation, seasonality, annual deviation, intensity and frequency; and mean annual temperature and winter and summer maximums. Includes/ requests specific information on: high, medium or low humidity and evaporation; strong/ constant/ weak/ seldom wind factors; microclimates including valleys (sheltered/ cooler), hillslopes and plateaus (exposed/ hot and dry); extremes of climates i.e. droughts, frost, snow; and season length.	Climate information has been used/ requested to inform rehabilitation planning decisions. Integration has been undertaken/ requested within the climate domain to indicate potential rehabilitation failure and risk, e.g. which climate parameter combinations (low rainfall and hot temperatures) may contribute to surface cracking? Integration is also undertaken/ requested with linkage to other domains, e.g. for surface cracking risk to increase are other parameters also present e.g. problem soils (soil domain), low water table (hydrology domain) and minimal vegetation cover (vegetation domain)? Rehabilitation failure risk has been determined/ requested involving identification, analysis, evaluation and treatment of risk, e.g. the potential risk of surface cracking has been identified; analysis has included determining the level of risk based on the integration of parameters from the climate, soil, hydrology and vegetation domains; evaluation has included comparison to known surface cracking parameters; and treatment has included considering soil amendments among other.

Performance Indicators	**Vulnerable (1)**[1]	**Adequate (2)**	**Resilient (3)**
Environmental Domain Evaluative Criteria	Inadequate consideration, with no data gathered at all	Suitable consideration, with data gathered	Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
Landuse	Does not include/ request landuse information. No inclusion or request for consideration of historical and existing landuse. No consideration has been undertaken of opportunities, threats and needs for future landuse establishment.	Landuse information included, but only superficially. Includes/ requests specific information on: historical, existing and potential landuses. Include a mechanism for regular review of landuse suitability and an analysis of requirements to progressively attain end landuse goals and objectives.	Landuse information has been used/ requested to inform rehabilitation planning decisions from the outset. Limitations on land use are clearly understood. Opportunities for beneficial landuses identified early and studies planned for during operations. Integration has been undertaken/ requested within the landuse domain to indicate potential rehabilitation failure and risk, e.g. what past site landuses have occurred that could restrict future landuse options? Integration is also undertaken/ requested with linkage to other domains, e.g. for agricultural crop cultivation to be successful you require good soil fertility (soil domain), high rainfall (climate domain), gentle slopes (topography domain) and water available for irrigation (hydrology domain). Rehabilitation failure risk has been determined/ requested involving identification, analysis, evaluation and treatment of risk, e.g. agricultural crop production may fail; analysis has included determining the level of risk based on the integration of parameters form the landuse, soil, climate, topography and hydrology domains; evaluation has included comparison to known

Performance Indicators	**Vulnerable (1)**[1]	**Adequate (2)**	**Resilient (3)**
Environmental Domain Evaluative Criteria	Inadequate consideration, with no data gathered at all	Suitable consideration, with data gathered	Full consideration, in addition to Adequate (2), with rehabilitation planning, integration and risk determination
			agricultural crop failure severity parameters; and treatment has included considering soil amendments, irrigation from decant and slope treatments among other.

2.5.3 The systematic review process and study limitations

Using our rehabilitation maturity model (Table 2.2) we systematically reviewed surface-strip coal mine related rehabilitation documents. These documents consisted of mine approval and after mine approval consultant rehabilitation reports and mine rehabilitation guidelines from South Africa and Australia, Queensland and New South Wales (Supplementary material, Table 1).

Fourteen mine approval consultant rehabilitation reports were reviewed: seven from South Africa and seven from Australia, four of these being from Queensland and three from New South Wales. Six after mine approval consultant rehabilitation reports were reviewed from Australia, one from Queensland and five from New South Wales. Equivalent reports in this category, from South Africa could not be found for review. Ten mine rehabilitation guidelines were reviewed: five from South Africa comprising of two leading practice guidelines, one company and two technical guidelines and five from Australia comprising of one technical and four leading practice guidelines.

The mine approval phase was the primary focus, as this period can substantially influence rehabilitation success or failure outcomes. After mine approval consultant rehabilitation reports were included for comparison and to determine if maturity improves progressively. Rehabilitation guidelines are of importance as they influence the content of mine approval consultant rehabilitation reports.

Documents were acquired via an internet web-search, hence only documents in the public domain were used. Mine approval and post mine approval consultant rehabilitation reports were found difficult to attain online due to mining company confidentiality constraints. Mostly only reports forming part of the public participation process were found uploaded. Therefore, assessed reports may be under-representative, with potential errors in results possible. An added challenge is that the format and content of these reports varied widely among consultants and jurisdictions, making document comparison difficult. Although mine rehabilitation guidelines were easily attainable online, a potential error could be that the sample size of 10 is small, as few guidelines have been prepared to date, that could be reviewed, due to their wider application. However, even with this small sample size, valuable observation could be drawn.

Documents were qualitatively scored, in a single round, per category, by the corresponding first author, who has over 20 years of consulting environmental impact assessment experience. Scoring was done by only one author to ensure consistency in scoring across the performance indicators. A score was awarded depending on which maturity performance indicator each environmental domain evaluative criteria fell within. A score of (1) was awarded for vulnerable, (2) for adequate and (3) for resilient. A score of (1.5) was awarded for falling between vulnerable and adequate and (2.5) for falling between adequate and resilient. These intermediate scores were awarded for when the documents did not fall definitively within the three main performance indicators and to increase the scoring range. Average scores were calculated for all document categories across each environmental domain evaluative criterion. A comparative analysis of the various document types was conducted using Microsoft Office™ Excel 2016 Radar Charts (Fig. 2.1 - 2.5).

2.6 Results and discussion

Mine approval consultant rehabilitation reports for South Africa and Australia, (Queensland and New South Wales), showed low levels of maturity, falling between vulnerable and adequate, but not yet resilient. The average score for South Africa (1.74) was slightly higher than that of Australia (1.60) (Fig. 2.1 and Supplementary material, Table 1). The highest scoring environmental domain evaluative criteria taken from the average scores for all these reports from South Africa showed a focus on geology, soils and hydrology, suggesting attention to contamination prevention/ remediation. This was followed by a focus on end landuse. Reports for Australia focused mostly only on contamination prevention. These observations appear to correlate to our rehabilitation definition in Table 2.1, showing that there is firstly a focus on Phase 1: Remediation followed thereafter by Phase 2: Revegetation/ Reforestation. The highest score was attained for the New Vaal Colliery (2.14), in South Africa, for its suite of mine approval consultant rehabilitation reports which consisted of an Environmental Impact Assessment and Environmental Management Programme report. This included financial provisions, specialist studies, a risk assessment and a preliminary closure plan. Here, the preliminary closure plan is one of the few documents found that attempts rehabilitation planning, integration and risk determination, although further detail and analysis could still be provided. The second highest score was attained for the Cavel Ridge mine (1.93) in Australia, Queensland, for its Environmental Impact Statement and Environmental Management Plan report, with specialist studies.

Scores were higher for when the full suite of documents were included in the evaluation. Environmental Impact Assessment/ Environmental Impact Statement, Environmental Management Programme/ Environmental Management Plan and their specialist study reports contained the most detail, whereas stand-alone documents were found lacking in detail. Despite the value of all these documents, their focus is toward the assessment of impacts from mining on the environment and not on the rehabilitation risks that are imposed by the environmental domain. Rehabilitation when described in these documents is management, objective and target based. There is little attention paid to rehabilitation planning, integration and risk determination.

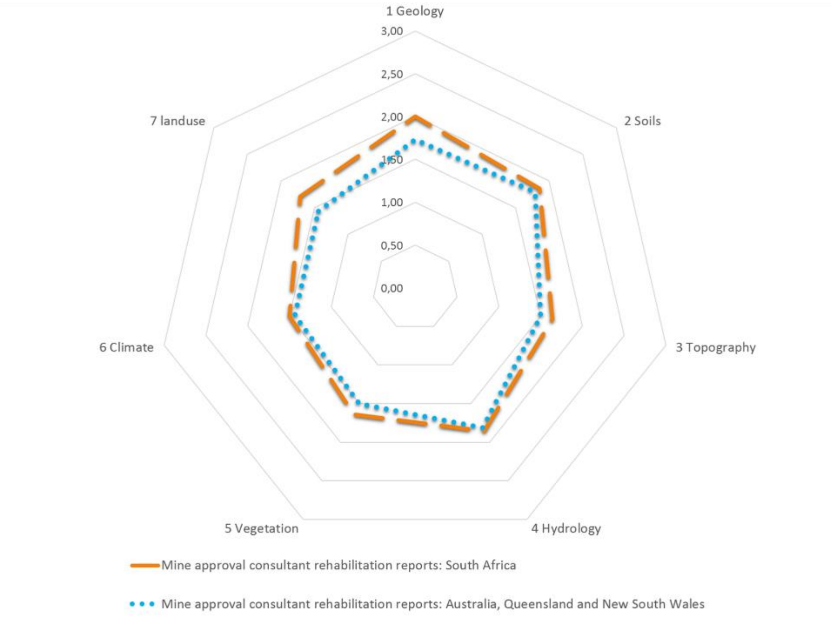


Fig. 2.1 Radar chart of maturity model rankings, of mine approval consultant rehabilitation reports for South Africa (7) and Australia (7), Queensland and New South Wales, showing averaging categorical scores.

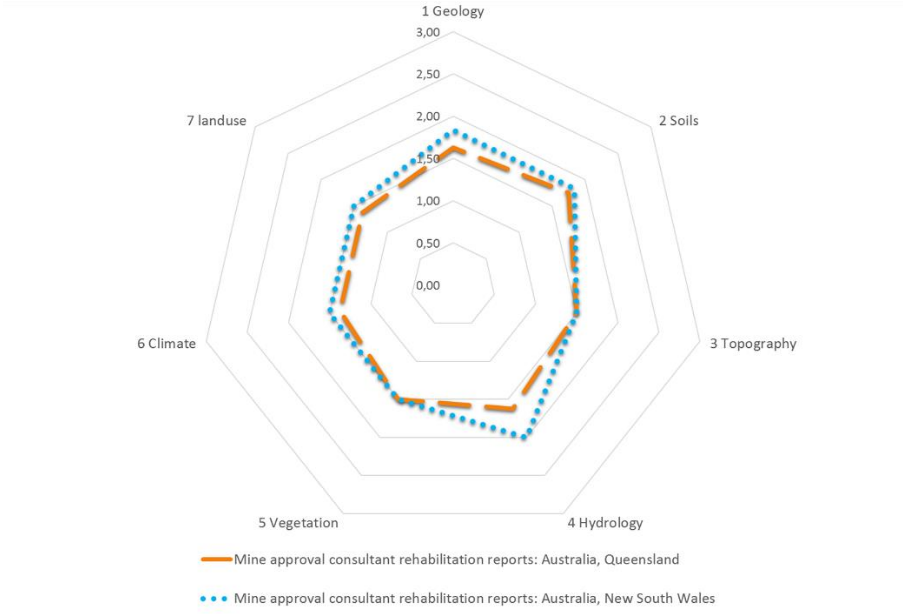


Fig. 2.2 Radar chart of maturity model rankings, of mine approval consultant rehabilitation reports for Australia, Queensland (4) and New South Wales (3), showing averaging categorical scores.

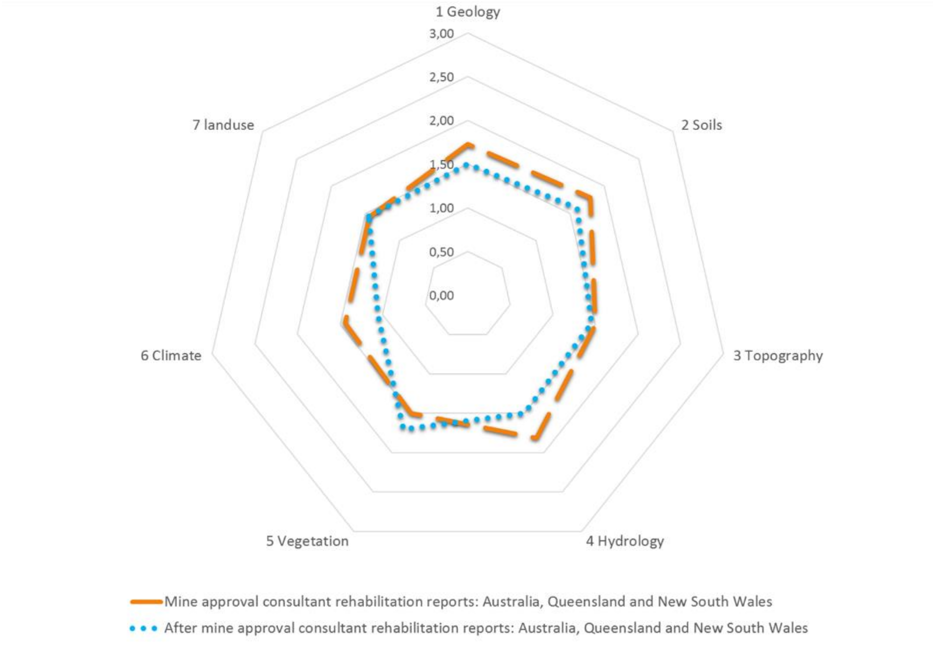


Fig. 2.3 Radar chart of maturity model rankings, of comparison of mine approval (7) and after mine approval (6) consultant rehabilitation reports for Australia, Queensland and New South Wales, showing averaging categorical scores.

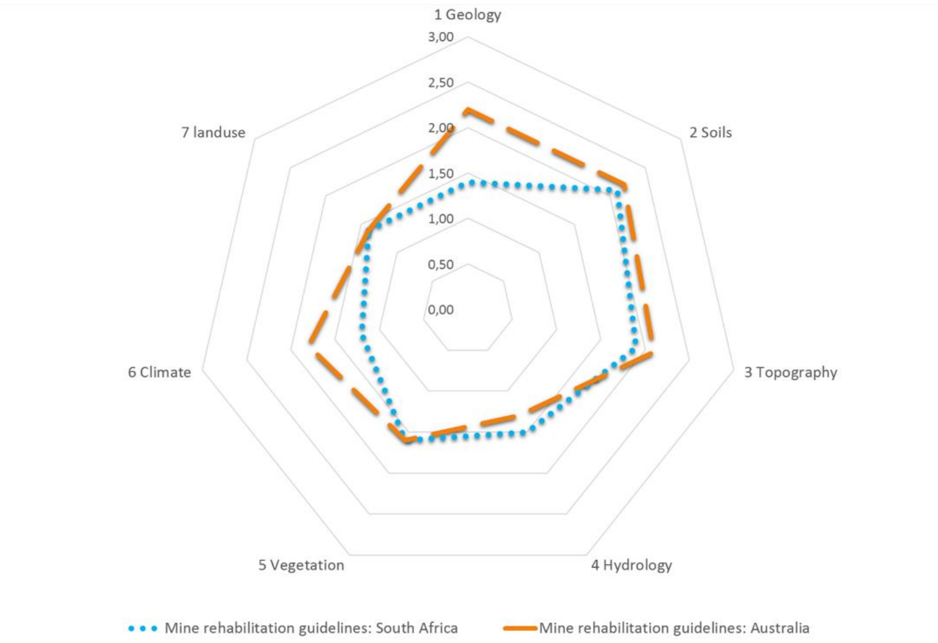


Fig. 2.4 Radar chart of maturity model rankings, of mine rehabilitation guidelines for South Africa (5) and Australia (5), showing averaging categorical scores.

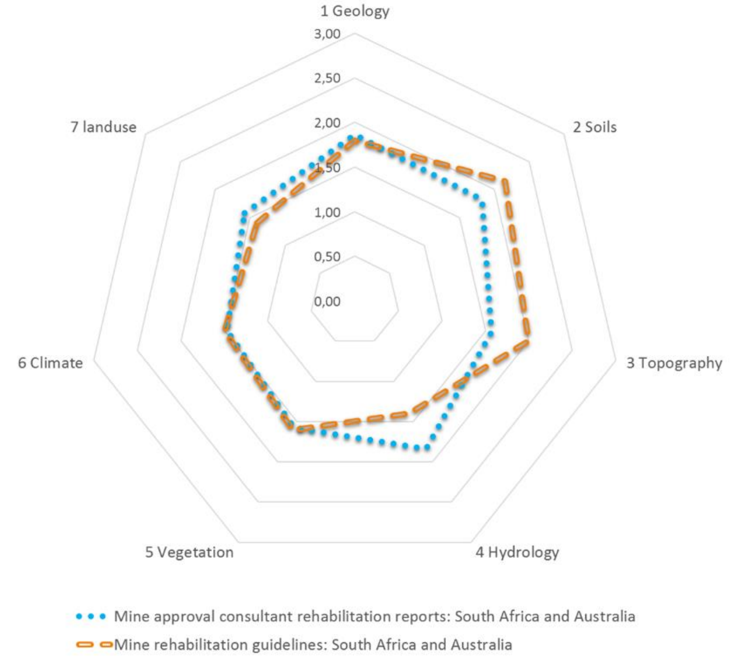


Fig. 2.5 Radar chart of maturity model rankings, of comparison of mine approval consultant rehabilitation reports (14) and rehabilitation guidelines (10) for South Africa and Australia, showing averaging categorical scores.

A comparative assessment was made between Queensland and New South Wales, Australia for mine approval consultant rehabilitation reports (Fig. 2.2 and Supplementary material, Table 1). New South Wales' (1.67) average score was higher than that of Queensland (1.54). The Queensland reports focused on contamination prevention, followed by landform and substrate establishment, whereas the New South Wales reports focused on mostly contamination prevention.

A further comparison was made between mine approval and after mine approval consultant rehabilitation reports for Queensland and New South Wales, Australia (Fig. 2.3 and Supplementary material, Table 1), i.e. progressive rehabilitation management documents, as produced after mine approval has been granted, to ascertain if rehabilitation planning improves following mine approval, during the operational phase. Mine approval documents tended to focus on contamination prevention, whilst after mine approval documents were mainly concerned with landform and substrate establishment. The average score for the mine approval documents (1.60) was higher than that of the average score for the after mine approval documents (1.46). This was surprising, as it was theorised that by progressive rehabilitation, the after mine approval rehabilitation reports would become more detailed over time. The low scoring could be due to documents having a management, objective and target-based approach, with attention on criteria and indicators and again not so much on rehabilitation planning, integration and risk determination.

Mine rehabilitation guidelines showed similar low levels of maturity, falling between vulnerable and adequate, but not yet resilient (Fig. 2.4 and Supplementary material, Table 1). The average score for Australia (1.80) was higher than that for South Africa (1.59). The South African guidelines focused on landform and substrate establishment, containing detail on soils, topography and vegetation, whilst the Australian guidelines focused firstly on contamination prevention and only then on landform and substrate establishment. The highest scoring document was an Australian technical guideline (Department of Minerals and Energy, 1995), which scored 2.14. This document contains useful detailed technical data sheets; however; the focus is more on mining than on rehabilitation. This was followed by a South African leading practice guideline which scored 1.86, the high score may be attributed to the inclusion of detailed appendices and that this document was prepared voluntary and not in response to legislation (Chamber of Mines of South Africa, 1981). Two Australian leading practice guidelines were ranked after these, with scores of 1.79 each (Australian Government and Department of Industry Tourism and Resources, 2006; Minerals Council of Australia, 1998). These early leading practice guidelines attained high scores, despite being dated and that more recent versions have since been produced to include Chamber of Mines of South Africa (2007), which scored 1.57 and Australian Government et al. (2016b), which scored 1.71. Detail in leading practice guidelines appears to have declined, inadvertently legislation driven, which is discussed further in a subsequent section and possibly in response to the increasing use of progressive rehabilitation and that detail is only expected to be added during the mine operational and closure phases and not at the planning phase. Liability may also be a contributory factor, with regulators being reluctant to stipulate prescriptive detail, fearing legal accountability, should failures arise from information misuse.

It is unknown what terms of reference were used in the updating of guidelines in South Africa and Australia nor what the focus issues were. Revised or new guidelines appear to be the modernisation of earlier versions or adaptations of existing jurisdiction guidelines, with local content or company specifics simply added e.g. Anglo Coal Environmental Rehabilitation Improvement Group (2009) is based on Chamber of Mines of South Africa (2007). Another example of this includes Chamber of Mines of South Africa (2007), which is based on Chamber of Mines of South Africa (1981).

Resilient maturity was rarely observed in mine rehabilitation guidelines. Guidelines emphasised management actions, such as how to create a landform or establish vegetation, with little focus on rehabilitation risk determination and on understanding how the environmental domain integrates to determine rehabilitation opportunities or failure outcomes.

The reviewed guidelines differed in their mining type focus. Only three guidelines were found to be coal mining specific. The remaining seven guidelines have application to other mining types, including metalliferous mining, as well as to coal, over several geographical areas. This wide focus could be to satisfy government, state and private sector mine industry bodies with diverse membership and needs. Such an approach can prove problematic, as issues relevant to specific mining types may be overlooked, leading to poor rehabilitation planning decisions and ultimately rehabilitation failure. The format of rehabilitation guidelines differed too. Guidelines were found to be formatted mostly according to mine life-cycle phases. Occasionally guidelines followed an environmental domain structure. Structuring guidelines toward mine life-cycle phases, may be beneficial for general mining decisions, however an environmental domain structure may be more suited for rehabilitation decisions, as this allows similar information to be grouped to aid rehabilitation planning, integration and risk determination.

An additional web-search was undertaken to include other mining countries in an attempt to acquire an example of a resilient or near resilient rehabilitation guideline, that could be used as a bench-mark of what a resilient guideline should look like. A detailed guideline by Newton and Claassen (2003), for the rehabilitation of disturbed lands in California, United States of America was found and this scored 2.21. The guideline is not mining specific, but has value in its attention to environmental domain criteria and their integration to form rehabilitation failure risks, such as soil erosion, compaction etc.

A final comparative assessment was made between mine approval consultant rehabilitation reports and mine rehabilitation guidelines for South Africa and Australia (Fig. 2.5 and Supplementary material, Table 1). Mine approval consultant rehabilitation reports were found to focus on contamination prevention, whilst mine rehabilitation guidelines focused more on landform and substrate establishment. The focus toward contamination prevention in consultant reports could be attributed to geohydrological legal liability issues, particularly those linked to acid mine drainage. Mine rehabilitation guidelines (1.69) scored very close to mine approval consultant rehabilitation reports (1.67), both however fall between vulnerable and adequate and are not yet resilient. This lack of resilience, apart from reflecting poor rehabilitation planning and integration also reflects the lack of inclusion of risk in rehabilitation planning.

2.7 Legislation as a driver of immaturity

Although there have been some improvements in some jurisdictions, legislation in South Africa and Australia, Queensland and New South Wales, may inadvertently be driving immaturity in rehabilitation documents.

In South Africa, rehabilitation, from 1997 to 2015, was specified within a stand-alone Mine Rehabilitation Plan, as appended to a Basic Assessment or Scoping and Environmental Impact Assessment, Environmental Management Programme, Closure Plan or Environmental Risk Assessment (Supplementary material, Table 2). Alternatively, rehabilitation specifications were included as sub-sections within all or some of these reports. These documents formed part of the mine approval process (Department of Environmental Affairs, 2014). Broad document content, including rehabilitation requirements was stipulated in the Environmental Impact Assessment and Minerals and Petroleum Resources Development Act Regulations (Department of Environmental Affairs, 2014; Department of Minerals and Energy, 2004). Only as mines moved into their operational and closure phases was greater detail requested (Department of Minerals and Energy, 2004).

To address this oversight, as well as insufficient financial provisions and the need to integrate Environmental Impact Assessment, waste, water and mineral legislation, the 2015 Financial Provisions Regulations were promulgated (Department of Environmental Affairs, 2015). These regulations require that an Annual Rehabilitation Plan; Final Rehabilitation, Decommissioning and Mine Closure Plan; Environmental Risk Assessment; and Financial Provisions be included within the Environmental Management Programme and hence the upfront mining application approval process (Supplementary material, Table 2). Provision is made for the annual updating and auditing of the Annual Rehabilitation Plan, allowing for continual improvement. The Final Rehabilitation, Decommissioning and Mine Closure Plan, Environmental Risk Assessment and Financial Provisions are required to be updated progressively and finalised at closure. Few mine applications have been submitted in terms of the 2015 regulations, hence limiting our assessment thereof. Based on a review of those that we could acquire, document content was found to be broad, with detail only increasing marginally during the operational and closure phases. The 2015 Financial Provisions Regulations, however provide a mechanism for promoting improved rehabilitation planning and enforcement. Risk assessment techniques, mitigation and controls are also emphasised.

In Australia, a similar situation exists, where the legislative process in Queensland includes the preparation of an Environmental Impact Statement to attain an Environmental Authority, which includes a Mine Rehabilitation Plan. The Mine Rehabilitation Plan later transitions into a Progressive Rehabilitation report during the operational phase and a Final Rehabilitation report, with residual risk calculations and a risk assessment at closure. Prior to construction commencement, a Plan of Operations is required detailing how the applicant intends meeting Environmental Authority conditions including rehabilitation and financial assurances (Supplementary material, Table 2). There is overlap between the Mine Rehabilitation Plan and the Plan of Operations. At closure, application is made for the surrender of the Environmental Authority.

In New South Wales, once the Environmental Impact Statement has been submitted and the Environmental Authority issued, prior to construction, a Mining Operations Plan must be prepared (Supplementary material, Table 2). This includes cost estimates for rehabilitation, an Environmental Risk Assessment, risks specific to rehabilitation and adaptive management responses.

Requirements for Plan of Operations and Mining Operations Plans stipulate more detail than that required for approval documentation in both states, whilst Mining Operations Plans call for more detail than Plan of Operations. There is no legislative requirement for a closure plan in either state, in contrast to Western Australia, which requires this (Government of Western Australia et al., 2015).

In both South Africa and Australia, Queensland and New South Wales, detail is not prescribed for mine approval. Only after mine approval, during the operational and closure phases, with progressive rehabilitation, are detailed rehabilitation methodologies prescribed. Mine rehabilitation guidelines and thereafter mine approval consultant rehabilitation reports are formatted based on legislation, therefore if legislation prescriptions are broad these documents too will be broad. Legislation may therefore inadvertently be contributing to immaturity in these rehabilitation documents.

2.8 The temporal and dynamic nature of mining and progressive rehabilitation

Mining is a temporary activity, spanning between 15 to 50 years. It is also dynamic, and constantly adapting in response to environmental, socio-economic and political circumstances (Laurence, 2006, 2011). This temporal-dynamic nature makes it difficult to plan for rehabilitation at the mine approval phase, with progressive rehabilitation favoured, after mine approval. Monitoring from progressive rehabilitation provides knowledge of what constitutes closure risk and whether management actions will be successful (McCullough, 2016). Successful rehabilitation requires continuous improvement, as afforded by progressive rehabilitation and is reliant on the site personnel developing the skills, equipment and necessary technical knowledge to carry out rehabilitation, which may not be available at the time of mine approval planning (Australian Government et al., 2016b).

Given the temporal-dynamic nature of mining and the benefits of progressive rehabilitation mine authorities, owners and their consultants are understandably reluctant to include detailed planning and analysis during the mine approval phase. The lack of detail and analysis as evident in rehabilitation legislation, mine rehabilitation guidelines and mine approval consultant rehabilitation reports confirm this.

Whilst this reticence is acknowledged, the authors believe that greater detail than what currently exists would be beneficial upfront, to attain as a minimum adequate maturity and to prepare for resilient rehabilitation planning. The development of a model is advocated to achieve resilience; the model could act as an interface between mine rehabilitation guidelines and mine approval consultant rehabilitation reports and guide subsequent progressive rehabilitation and adaptive management decisions, which could lead to better rehabilitation outcomes.

2.9 Research directions

Further research is required to investigate the integration of the environmental domain evaluative criteria defined in our paper, with other important causal driver criteria such as: mine management actions which may worsen or improve impacts to the environmental domain criteria; controls that could prevent or mitigate impacts; and the type and nature of rehabilitation risk-events that may arise from and be affected by these factors, which could increase rehabilitation risk and ultimately rehabilitation failure. An understanding of these issues could lead towards the development of the advocated model, which should have capabilities for resilient rehabilitation planning; quantitative multi-discipline integration and for rehabilitation risk determination, to determine a site's rehabilitation risk and its ultimate potential for rehabilitation failure. Suitable tools, techniques and methods, based on risk assessment and integrated environmental modelling principles require further investigation to achieve this objective. It is hypothesised that such a model, which would require testing, could be able to identify critical upfront rehabilitation information and planning needs, so that risks and opportunities may be detected early for minimisation or maximisation as required. This would aid current mine approval rehabilitation planning and enhance progressive rehabilitation and adaptive management decisions leading toward improved rehabilitation outcomes.

2.10 Conclusions

Our paper has presented a rehabilitation maturity model which describes the characteristics of mature upfront surface-strip coal mine rehabilitation planning, integration and risk determination. The maturity model addressed seven environmental domain evaluative criteria, deemed critical for the rehabilitation of surface-strip coal mines, from the bottom-up. A systematic review using the maturity model revealed that mine rehabilitation guidelines and mine approval consultant rehabilitation reports in South Africa and Australia, Queensland and New South Wales fall between vulnerable and adequate but are not yet resilient. Legislation is likely driving immaturity, although reforms in some jurisdictions are addressing recognised areas of ambiguity or weakness. Despite the temporal-dynamic nature of mining and the value of progressive rehabilitation, greater detail and analysis than what is currently occurring should be included in upfront rehabilitation planning if companies are to reduce uncertainty and therefore risk in their rehabilitation success. The alternative of companies having larger rehabilitation liabilities toward the end of the mine's life needs to be avoided to achieve sustainable post-rehabilitation outcomes. Our maturity model provides a point of reference for the improvement of mine rehabilitation guidelines and mine approval consultant rehabilitation reports, allowing for the development of evidence-based policy, regulations and plans to be developed.

2.11 Acknowledgements

Contributions are gratefully acknowledged from David Mulligan, Tim O’Connor, Peter Kuyler, James Lake, Phil Tanner and Janice Tooley. The anonymous reviewers are thanked for their valuable contributions to improving the quality of the paper. The University of Pretoria and the Coaltech Research Association are thanked for funding the research.

2.12 References

Anglo Coal Environmental Rehabilitation Improvement Group, 2009. Anglo Coal South Africa rehabilitation way, 9th draft ed. Anglo Coal Environmental, Johannesburg, (ZA).

Argent, R.M., 2004. An overview of model integration for environmental applications—components, frameworks and semantics. Environ Model Softw 19, 219-234 DOI: 10.1016/s1364-8152(03)00150-6

Auditor-General South Africa, 2009. Report of the Auditor-General to Parliament on a performance audit of the rehabilitation of abandoned mines at the Department of Minerals and Energy. Auditor-General South Africa, Pretoria, (ZA), p. 22.

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2011. A guide to leading practice sustainable development in mining: Leading Practice Sustainable Development Program for the mining industry. Leading Practice Sustainable Development Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016a. Mine closure: Leading practice sustainable development program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016b. Mine rehabilitation: Leading practice sustainable development program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Tourism and Resources, 2006. Mine rehabilitation handbook: Leading Practice Sustainable Development Program for the mining industry. Australian Government Department of Industry Tourism and Resources, Canberra, (AU), p. 67.

Brundtland, H., 1987. Report of the World Commission on Environment and Development: Our common future. World Commission on Environment and Development, Oxford, (UK).

Bureau for Food and Agricultural Policy, 2012. Evaluating the impact of coal mining on agriculture in the Delmas, Ogies and Leandra districts: A focus on maize production, BFAP Reports 279783. Bureau for Food and Agricultural Policy, Johannesburg, (ZA), p. 49.

Chamber of Mines of South Africa, 1981. Guidelines for the rehabilitation of land disturbed by surface coal mining in South Africa. Chamber of Mines of South Africa, Johannesburg, (ZA), p. 96.

Chamber of Mines of South Africa, 2007. Guidelines for the rehabilitation of mined land. Chamber of Mines of South Africa, Johannesburg, (ZA), p. 167.

Clewell, A.F., Aronson, J., 2013. Ecological restoration: Principles, values, and structure of an emerging profession, 2nd ed. Society for Ecological Restoration & Island Press, Washington DC, (US).

Council of Standards Australia & New Zealand, 2009. AS/ NZS ISO 31000:2009, joint Australian New Zealand international standard, risk management - Principles and guidelines, 3 ed. Council of Standards Australia & New Zealand, Sydney, (AU) & Wellington, (NZ), p. 35.

Department of Environment and Heritage Protection, 2014. Rehabilitation requirements for mining resource activities. Queensland Government, Brisbane, (AU), p. 30.

Department of Environment and Heritage Protection, 2017. DEHP user guide, mining and petroleum and gas financial assurance calculators. Department of Environment & Heritage Protection, Queensland, (AU).

Department of Environmental Affairs, 2014. National Environmental Management Act, No. 107 of 1998. Environmental Impact Assessment Regulations 2014, Government Gazette. 594 (38282). 4 December. Government notice no. R982, R983, R984 & R985. Government Printing Works, Republic of South Africa, p. 288.

Department of Environmental Affairs, 2015. National Environmental Management Act, No. 107 of 1998. Regulations pertaining to the financial provisions for prospecting, exploration, mining or production operation, Government gazette (39425). 20 November. Government notice no. R1147. Government Printing Works, Republic of South Africa, p. 48.

Department of Environmental Affairs, 2017. National Environmental Management Act, No. 107 of 1998. Amendments to the Environmental Impact Assessment Regulations 2014, Government Gazette. 40772. 7 April. Government notice no. R324, R325, R326 & R327. Government Printing Works, Republic of South Africa.

Department of Mineral Resources, 2009. The national strategy for the management of derelict and ownerless mines in South Africa. Department of Mineral Resources, Pretoria, (ZA).

Department of Minerals and Energy, 1995. Technical guidelines for the environmental management of exploration and mining in Queensland. Department of Minerals and Energy, Brisbane, (AU), p. 12.

Department of Minerals and Energy, 2002. Minerals and Petroleum Resources Development Act, Act No. 28 of 2002, Government gazette. 448 (23922). 10 October. Government notice no. R1273. Government Printing Works, Republic of South Africa, p. 62.

Department of Minerals and Energy, 2004. Minerals and Petroleum Resources Development Act, No. 28 of 2002. Mineral and Petroleum Resources Development Regulations 2004, Government gazette. 466 (26275). 23 April. Government notice no. R527. Government Printing Works, Republic of South Africa, p. 43.

Doley, D., Audet, P., Mulligan, D.R., 2012. Examining the Australian context for post-mined land rehabilitation: Reconciling a paradigm for the development of natural and novel ecosystems among post-disturbance landscapes. Agric Ecosyst Environ 163, 85-93 DOI: http://dx.doi.org/10.1016/j.agee.2012.04.022

Elliott, M., Thomas, I., 2009. Environmental impact assessment in Australia: Theory and practice, 5th ed. ed. The Federation Press, Sydney, (AU).

Erskine, P.D., Fletcher, A.T., 2013. Novel ecosystems created by coal mines in central Queensland's Bowen Basin. Ecol Process 2, 33 DOI: 10.1186/2192-1709-2-33

Gauteng Department of Agriculture Environment and Conservation, 2008. Mining and environmental impact guide. Gauteng Department of Agriculture and Conservation, Johannesburg, (ZA), p. 1119.

Geoscience Australia, ABARE, 2010. Australian energy resource assessment, Report No. 70142. Commonwealth of Australia, Canberra, (AU), p. 358.

Government of Western Australia, Department of Mines and Petroleum, Environmental Protection Authority, 2015. Guidelines for preparing mine closure plans. Department of Mines and Petroleum, Perth, (AU).

Greve, M., Lykke, A.M., Blach-Overgaard, A., Svenning, J.-C., 2011. Environmental and anthropogenic determinants of vegetation distribution across Africa. Global Ecol Biogeogr 20, 661-674 DOI: 10.1111/j.1466-8238.2011.00666.x

Hamilton, S.H., ElSawah, S., Guillaume, J.H.A., Jakeman, A.J., Pierce, S.A., 2015. Integrated assessment and modelling: Overview and synthesis of salient dimensions. Environ Model Softw 64, 215-229 DOI: https://doi.org/10.1016/j.envsoft.2014.12.005

Hancox, P.J., Gotz, A.E., 2014. South Africa's coalfields - a 2014 perspective. International Journal of Coal Geology 132, 170-254 DOI: 10.1016/j.coal.2014.06.019

Hooke, R., Martin-Duque, J., Pedraza, J., 2012. Land transformation by humans: A review. GSA Today 22, 4-10 DOI: 10.1130/GSAT151A.1.

Howell, E.A., Harrington, J.A., Glass, S.B., 2012. Introduction to Restoration Ecology. Island Press, Washington DC, (US).

Hudson, P., 2007. Implementing a safety culture in a major multi-national. Saf Sci 45, 697-722 DOI: 10.1016/j.ssci.2007.04.005

Hudson, P., Parker, D., Van der Graaf, G., 2002. The hearts and minds program: Understanding HSE culture, SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production. Society of Petroleum Engineers Inc., Kuala Lumpur, (MY).

International Council on Mining and Metals, 2003. Mining, minerals and sustainable development project: 10 principles. International Council on Mining and Metals, London, (UK).

International Council on Mining and Metals, 2008. Planning for integrated mine closure: Toolkit. International Council on Mining and Metals, London, (UK), p. 86.

International Institute for Environment and Development and World Business Council for Sustainable Development, 2002. Breaking new ground: The report of the mining, minerals and sustainable development project. Earthscan Publications Ltd., London, (UK) & Sterling, (US).

Ireland, V., 2008. Project management in mining: application of mining phase-gates. South Australia MESA Journal 51, 39-41

Laurence, D., 2006. Optimisation of the mine closure process. Journal of Cleaner Production 14, 285-298 DOI: 10.1016/j.jclepro.2004.04.011

Laurence, D., 2011. Establishing a sustainable mining operation: an overview. Journal of Cleaner Production 19, 278-284 DOI: 10.1016/j.jclepro.2010.08.019

Lechner, A.M., Baumgartl, T., Matthew, P., Glenn, V., 2016a. The impact of underground longwall mining on prime agricultural land: A review and research agenda. Land Degradation & Development 27, 1650-1663 DOI: 10.1002/ldr.2303

Lechner, A.M., Kassulke, O., Unger, C., 2016b. Spatial assessment of open cut coal mining progressive rehabilitation to support the monitoring of rehabilitation liabilities. Resour Policy 50, 234-243 DOI: 10.1016/j.resourpol.2016.10.009

Lechner, A.M., McIntyre, N., Witt, K., Raymond, C.M., Arnold, S., Scott, M., Rifkin, W., 2017. Challenges of integrated modelling in mining regions to address social, environmental and economic impacts. Environ Model Softw 93, 268-281 DOI: 10.1016/j.envsoft.2017.03.020

Limpitlaw, D., Aken, M., Lodewijks, H., Viljoen, J., 2005. Post-mining rehabilitation, land use and pollution at collieries in South Africa, In: Colloquium: Sustainable development in the life of coal mining in South Africa. The South African Institute of Mining and Metallurgy, Boksburg, (ZA), pp. 1-10.

Limpitlaw, D., Mitchell, P., 2013. Mine closure - misplaced planning priorities, in: Tibbett, M., Fourie, A.B., Digby, C. (Eds.), Mine Closure 2013. Australian Centre for Geomechanics, Perth, (AU).

McCullough, C.D., 2016. Key mine closure lessons still to be learned, in: Fourie, A.B., Tibbett, M. (Eds.), In: Processings of Mine Closure Conference Australian Centre for Geomechanics, Perth, (AU), pp. 319-332.

Minerals Council of Australia, 1998. Mine rehabilitation handbook. Minerals Council of Australia, Kingston, (AU), p. 112.

Minerals Council of Australia, 2005. Enduring value: The Australian minerals industry framework for sustainable development: Guidance for implementation. Minerals Council of Australia, ACT, (AU).

Minerals Policy Institute, 2016. Ground truths: Taking responsibility for Australia's mining legacies, in: Roche, C., Judd, S. (Eds.). Minerals Policy Institute, Girrawheen, (AU), p. 38.

Mucina, L., Rutherford, M.C., 2006. The vegetation of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute, Pretoria, (ZA), p. 808.

Newton, G.A., Claassen, V.P., 2003. Rehabilitation of disturbed lands in California: A manual for decision-making. California Department of Conservation & California Geological Survey, California, (US), p. 240.

Principles and Standards Reference Group, Society for Ecological Restoration Australasia, 2016. National standards for the practice of ecological restoration in Australia. Society for Ecological Restoration Australasia, (AU).

Queensland Government, 2012. Queensland Commission of Audit interim report, June 2012. Queensland Government, Queensland, (AU).

Rethman, N.F.G., 2006. A review of causes, symptoms, prevention and alleviation of soil compaction on mined land. Coaltech 2020, Johannesburg, (ZA).

Society for Ecological Restoration International Science & Policy Working Group, 2004. The SER International Primer on ecological restoration, Tucson, (US) ed. Society for Ecological Restoration International, p. 16.

State of Queensland Australia, 1994. Environmental Protection Act 1994, State of Queensland, Australia.

Thackway, R., Wilson, P., Hnatiuk, R., Bordas, V., Dawson, S., 2010. Establishing an interim national baseline 2004 to assess change in native vegetation extent, Report Bureau of Rural Sciences, Canberra, (AU), p. 26.

Thompson, R.J., 2005. Surface strip coal mining handbook, Report No. SACMA 01/03. South African Colliery Managers Association, Johannesburg, (ZA), p. 496.

Tongway, D.J., Ludwig, J.A., 2011. Restoring disturbed landscapes: Putting principles into practice. Island Pr., Washington, (DC).

Unger, C., Lechner, A.M., Glenn, V., Edraki, M., Mulligan, D.R., 2012. Mapping and prioritising rehabilitation of abandoned mines in Australia, Life-of-Mine The Australasian Institute of Mining and Metallurgy, Brisbane, (AU), pp. 259-265.

Unger, C.J., Lechner, A.M., Kenway, J., Glenn, V., Walton, A., 2015. A jurisdictional maturity model for risk management, accountability and continual improvement of abandoned mine remediation programs. Resour Policy 43, 1-10 DOI: 10.1016/j.resourpol.2014.10.008

Wells, J.D., 1986. Long-term planning for the rehabilitation of opencast workings. Journal of the South African Institute of Mining and Metallurgy 86, 89-93

World Energy Council, 2013. World energy resources: 2013 survey, Report World Energy Council, London, (UK), p. 468.

2.13 Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.resourpol.2017.09.013.

Appendix 2.1 Table 1, Summary scoring and Table 2, Mine rehabilitation legislation and document types

Table 1.
Summary scoring of maturity for mine rehabilitation guidelines and mine approval consultant rehabilitation reports, for South Africa and Australia, Queensland and New South Wales, using our maturity model's scoring technique[2]

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Mine approval consultant rehabilitation reports: South Africa								
Arnot Mooifontein Opencast Expansion Project, Golder Associates, Exxaro Arnot Coal. Date accessed 20170712. Rehabilitation Plan, 2011. Minerals and Petroleum Resources Development Act, 2002. http://www.golder.com/modules.php?name=Documents&op=viewlive&sp_id=1030 Strength: The report focuses mostly on vegetation and landuse. Weakness: Mainly goals and objectives are provided. Not detailed.	1.5	1.5	1.5	1.5	2.0	1.5	2.0	1.64

---

[2] A score of (1) is awarded for vulnerable, (2) for adequate and (3) for resilient. Intermediate scores are awarded for when documents do not fall definitively within these three main performance indicators. A score of (1.5) is awarded for falling between vulnerable and adequate and (2.5) for falling between adequate and resilient.

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Comment: The Environmental Impact Assessment and Environmental Management Programme reports could not be found on the web. Specialist studies associated with these reports are likely to contain detail.								
Kleinkopje Colliery, Pit 2A Extension, Shangoni Management Services (Pty) Ltd., Anglo Operations (Pty) Ltd. Date accessed 20170712. Final Decommissioning, Rehabilitation and Closure Plan, Annual Rehabilitation Plan & Geohydrology Specialist Study, 2016. 2015 Financial Provisions Regulations. http://www.shangoni.co.za/wp-content/uploads/ANG-KLE-16-05-03_Dec_Rehab_Closure_Plan_Final.pdf http://www.shangoni.co.za/wp-content/uploads/ANG-KLE-16-05-03_Ann_B_Rehab_Plan_Final.pdf http://www.shangoni.co.za/wp-content/uploads/ANG-KLE-16-05-03_Geohydrology.pdf	2.5	1.5	2.5	2.5	1.5	1.5	1.5	1.93

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Strength: Specialist studies included are detailed, particularly the Geohydrological Risk Assessment and the Landform Study which use modelling software to perform integration. Weakness: Final Decommissioning, Rehabilitation and Closure Plan and Annual Rehabilitation Plan reports generally lack detail and analysis. Comment: The Environmental Impact Assessment and Environmental Management Programme reports could not be found on the web. Specialist studies associated with these reports are likely to contain detail.								
New Vaal Colliery, Shangoni Management Services (Pty) Ltd. & Golder Associates, Anglo Operations (Pty) Ltd. Date accessed 20170712. Environmental Impact Assessment and Environmental Management Programme, Financial	2.5	2.5	2.0	2.5	1.5	1.5	2.5	2.14

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Provisions, Specialist Studies, Risk Assessment and Preliminary Mine Closure Plan, 2017. Minerals Act, 1991 & Minerals and Petroleum Resources Development Act, 2002. http://www.shangoni.co.za/new-vaal-colliery-emp-amendment Strength: The Preliminary Closure Plan by Golder Associates contains useful summaries on how biophysical aspects could affect closure. The landuse analysis section is very detailed. The Groundwater specialist study uses an integrative model. Weakness: The Preliminary Closure Plan could be more analytical. Comment: Not all specialist studies could be found on the web. The Preliminary Closure Plan is very well written.								
Wolvekrans, Jones and Wagener, South 32 Coal South Africa (Pty)	1.5	2.5	1.5	1.5	1.5	1.5	1.5	1.64

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Ltd. Date accessed 20170713. Environmental Impact Assessment, Environmental Management Programme, Specialist Studies & Conceptual Design Report. Predicative Rehabilitation Designs, 2016. Minerals and Petroleum Resources Development Act, 2002. http://www.jaws.co.za/uploads/PPDocs/E812-05_REP-01_r1_th_MvZ_EIR_EMPr_20161025.pdf Strength: Detail is contained in specialist reports. Weakness: Minimal integrated analysis of data has been undertaken. Comment: Not all the specialist studies could be found on the web.								
Vlakfontein Coal Mine Phase 2, SRK Consulting, African Exploration and Mining Finance Corporation SOC Ltd. Date accessed 20150704, no longer available on the web.	2.0	2.0	1.0	2.0	2.0	1.5	1.5	1.71

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Environmental Management Programme Amendment, 2014. Minerals and Petroleum Resources Development Act, 2002. http://www.srk.co.za/en/files/File/South-Africa/publicDocuments1/Vlakfontien/ Strength: Detailed specialist studies are provided, particularly for soils and vegetation. Weakness: Analysis is focused on impacts and not on rehabilitation risk. Rehabilitation discussions are intertwined throughout the report.								
Klipspruit Extension: Weltevreden, Digby Wells Environmental, South 32 Coal South Africa (Pty) Ltd. Date accessed 20170714. Environmental Impact Assessment and Environmental Management Programme, 2015. Minerals and Petroleum Resources Development Act, 2002. http://www.digbywellsdocs.com/Pub	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.57

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
licDocuments/?downloads=bhp3595-south32-sa-coal-holdings-eia-and-emp-klipspruit-extension-weltevreden Weakness: This document on its own lacks detail and analysis. Comment: Specialist studies could not be sourced on the web. These may contain detail but may lack analysis. Generally Environmental Impact Assessment and Environmental Management Programme reports tend to focus on impacts and not on rehabilitation risks.								
Palmietkuilken Mining Project, Digby Wells Environmental, Canyon Resources (Pty) Ltd. Date accessed 20170714. Environmental Impact Assessment and Environmental Management Plan, 2017. Minerals and Petroleum Resources Development Act, 2002. http://www.digbywellsdocs.com/PublicDocuments/?downloads=cnc4065-anglo-operations-limited-draft-eia-	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.57

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
and-emp Weakness: This document lacks detail and analysis. Comment: Specialist studies could not be sourced on the web. These may contain detail but may lack analysis. Generally Environmental Impact Assessment and Environmental Management Programme reports tend to focus on development impacts and not on rehabilitation risks.								
Average score, mine approval consultant rehabilitation reports: South Africa	2.00	1.86	1.64	1.86	1.64	1.50	1,71	1.74
Mine approval consultant rehabilitation reports: Australia, Queensland								
Cavel Ridge, BHP Billiton. Date accessed 20170712. Environmental Impact Statement, Environmental Management Plan, Specialist Studies, 2009. http://www.bhp.com/environment/regulatory-information	2.5	2.5	1.5	2.0	1.5	2.0	1.5	1.93

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Strength: Documents are easily accessible on the web. Transparency is evident. Weakness: The focus is on impacts from mining on the environment, more so than rehabilitation risk as imposed by environmental domain criteria. Comment: A detailed composite Environmental Impact Statement report.								
Isaac Plains East, Hansen Bailey, Date accessed 20170713. Environmental Impact Statement: Rehabilitation and Mine Closure Plan, 2016. http://hansenbailey.com.au/hb-publications-ipe-epbc.html Strength: Documents are easily accessible on the web. Transparency is evident. Weakness: The focus is on impacts	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
from mining on the environment, more so than rehabilitation risk as imposed by environmental domain criteria. Comment: Documentations is broad and management and objective focused.								
Baralaba North Coal Mine, Date accessed 20170713. Rehabilitation Management Plan, 2014. http://baralabacoal.com.au/bar/assets/File/Rehabilitataion%20Management%20Plan.pdf Weakness: Mainly management actions, objectives and criteria-based report. Monitoring measures are also prescribed. Comment: Other documents were not available on the web. The Rehabilitation Management Plan dictates what should be done, but does not analyse rehabilitation risk, nor integrate risks from the	1.0	1.5	1.5	1.5	1.5	1.0	1.0	1.29

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
environmental domain.								
Carmichael Coal Mine, EMM, Adani Mining Pty Ltd. Date accessed 20170713. Closure and Rehabilitation Strategy, 2013. http://eisdocs.dsdip.qld.gov.au/Carmichael%20Coal%20Mine%20and%20Rail/SEIS/Appendices/Appendix%20R/Appendix-R1-Mine-Closure-and-Rehabilitation-Strategy.pdf Weakness: The Closure and Rehabilitation Strategy is management, objective and monitoring based. Comment: Not detailed and specific to rehabilitation planning, integration and risk determination. Documents were difficult to source on the web.	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.43
Average score, mine approval consultant rehabilitation reports: Australia, Queensland	1.63	1.75	1.50	1.63	1.50	1.38	1.38	1.54

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Mine approval consultant rehabilitation reports: Australia, New South Wales								
Mt Arthur Coal - Modification, BHP Billiton. Date accessed 20170712. Environmental Authority with Specialist Studies, 2010 and Rehabilitation Strategies, 2010, 2012 and 2017. http://www.bhp.com/environment/regulatory-information Strength: Documents are easily accessible on the company website and are comprehensive. Transparency is evident. Weakness: The Environmental Authority and Specialist Studies including the Rehabilitation Strategy documents are not detailed in terms of rehabilitation planning and risk. Documents are mainly focused on providing management actions and objectives. Comment: Environmental Authority Specialist Studies provide greater detail. However, rehabilitation	2.0	2.0	1.5	2.0	1.5	1.5	1.5	1.71

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
planning, integration and risk determination is lacking. The focus is on impacts from mining on hydrology, vegetation etc. and not on the rehabilitation risks imposed by the environmental domain.								
Duralie Coal Mine, Duralie Coal, Date accessed 20170713. Environmental Authority with Specialist Studies, including Rehabilitation Strategies, 2010 and 2014. http://www.duraliecoal.com.au/page/environment/duralie-environmental-assessment-documents/ Strength: Documents are easily accessible on the company website and are comprehensive. Transparency evident. Weakness: The Environmental Authority and Specialist Studies including the Rehabilitation Strategy documents are not detailed in terms of rehabilitation planning and risk. Documents are mainly focused on	2.0	2.0	1.5	2.0	1.5	1.5	1.5	1.71

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
providing management actions and objectives. Comment: Initial approval was granted in 1997, extensions were approved in 2010 and 2014 and amendments were approved in 2011, 2012. Environmental Authority Specialist Studies provide greater detail. However, rehabilitation planning, integration and risk determination is lacking. The focus is on impacts from mining on hydrology, vegetation etc. and not on the rehabilitation risks imposed by the environmental domain.								
Drayton South Coal, Anglo Coal, Date accessed 20170713. Environmental Impact Statement, 2015. http://hansenbailey.com.au/documents/drayton/Main_Report.pdf Weakness: Document focuses on impacts from mining on the environment and not the risks of rehabilitation as from the	1.5	1.5	1.5	2.0	1.5	1.5	1.5	1.57

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
environmental domain. Comment: Minimal detail is provided on mine rehabilitation.								
Average score, mine approval consultant rehabilitation reports: Australia, New South Wales	1.83	1.83	1.50	2.00	1.50	1.50	1.50	1.67
Average score, mine approval consultant rehabilitation reports: Australia, Queensland and New South Wales	1.73	1.79	1.50	1.81	1.50	1.44	1.44	1.60
After mine approval consultant rehabilitation reports: Australia, Queensland								
Baralaba North Coal Mine, Date accessed 20170713. Rehabilitation Monitoring Program, 2013. http://bar.rdacms.com.au/index.cfm/baralaba-projects/baralaba-north/baralaba-north-continued-operations-project1/?keywords=rehabilitation Strength: Success criteria include: safe, non-polluting, stable and self-	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.43

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
sustaining. Some useful monitoring methods are described, particularly for soils. Weakness: Target based not integrated risk analysis based. Comment: This report relates to key indicators that should be monitored in the post-mining landscape to evaluate whether the post-mining landscape is meeting success criteria. It is not focused on rehabilitation planning, integration and risk determination.								
After mine approval consultant rehabilitation reports: Australia, New South Wales								
Mt Arthur Coal - Modification, BHP Billiton. Date accessed 20170712 Mine Operation Plan, 2015, Biodiversity and Rehabilitation Management Plan, 2012 & 2015 and various monitoring, auditing and adaptive management reports. http://www.bhp.com/environment/regulatory-information	2.5	2.5	1.5	2.5	2.5	1.5	1.5	2.07

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Strength: Documents are easily accessible on the company website and are comprehensive. Transparency is evident. Weakness: The Mine Operation Plan is management based focusing on goals and objectives. It also has a strong focus on closure more so than rehabilitation. Comment: Adaptive management reports call for greater detail and analysis to prevent or adapt to rehabilitation failure, particularly as related to soils and soils testing. The Mine Operation Plan/ Rehabilitation Management Plan attempts to analyse data, leading towards a resilient status. Rehabilitation planning, integration and risk determination could however still be improved.								
Duralie Coal Mine, Duralie Coal, Date accessed 20170713. Rehabilitation Management Plan,	1.0	1.5	1.0	1.0	1.5	1,0	1.0	1.14

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
2012 and 2015. http://www.duraliecoal.com.au/page/environment/duralie-environmental-assessment-documents/ Strength: Documents are easily accessible on the company website and comprehensive. Transparency is evident. Weakness: Management actions based with goals and objectives. Comment: Very little has been provided for rehabilitation planning, integration and analysis. There is more focus on specifications for rehabilitation with an emphasis on soils and vegetation.								
Drayton, Anglo Coal, Date accessed 20170713. Mine Closure Plan, 2009, Rehabilitation and Offset Management Plan, 2011 and 2013. http://www.angloamerican.com.au/~/media/Files/A/Anglo-American-Australia-	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.43

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
V2/Attachments/environment/Rehabilitation%20and%20Offset%20Management%20Plan.pdf http://www.angloamerican.com.au/~/media/Files/A/Anglo-American-Australia-V2/Attachments/environment/drayton-mine-closure-plan.pdf Weakness: Prepared after mine approval. Forms part of mine Environmental Management System. Comment: Mine closure Plan lacks rehabilitation detail. It is mainly management and objective focused. Rehabilitation and Offset Management Plans are mostly in the format of a specification document. The Mine Operation Plan could not be sourced, this could contain greater detail.								
Sunnyside Coal Mine, Namoi Mining Pty Ltd, Ecological Australia. Date accessed 20170713. Rehabilitation and Landscape Management Plan, including Mine	1.0	1.5	1.5	1.0	1.5	1.0	1.5	1.29

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Closure Plan, 2011. https://www.whitehavencoal.com.au/environment/docs/rehablitation-and-landscape-management-plan.pdf Weakness: Prepared after mine approval. Forms part of mine Environmental Management System. Documents are difficult to acquire on the web. Comment: The Rehabilitation and Landscape Management Plan is mainly management based with objectives, targets and actions prescribed.								
Maules Creek Coal Mine, Aston Coal 2 Pty Ltd., ICRA MC Pty Ltd. and J Power Australia Pty Ltd. Date accessed 20170713. Mine Operations Plan, 2017. https://www.whitehavencoal.com.au/environment/docs/maules-creek-mining-operations-plan.pdf Strength: A strong focus on vegetation establishment.	1.5	1.5	1.5	1.5	2.5	1.0	1.5	1.57

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Weakness: Prepared after mine approval. Forms part of mine Environmental Management System. Documents difficult to acquire on the web. Comment: Mainly management actions and objectives. Minimal focus on rehabilitation planning, integration or risk determination.								
Average score, after mine approval consultant rehabilitation reports: Australia, New South Wales	1.50	1.70	1.40	1.50	1.90	1.10	1.40	1.50
Average score, after mine approval consultant rehabilitation reports: Australia, Queensland and New South Wales	1.50	1.60	1.45	1.50	1.70	1.05	1.45	1.46
Mine rehabilitation guidelines: South Africa								
Leading practice								

Document description	**Geology**	**Soils**	**Topography**	**Hydrology**	**Vegetation**	**Climate**	**Land-use**	**Average score**
(Chamber of Mines of South Africa, 1981) Strength: Water resource contamination prevention, landform and vegetation focus. Detailed appendices Weakness: Techniques may be out-dated, and legislation has changed. Comment: First self-regulatory guideline for the coal industry.	1.50	2.50	2.00	2.50	1.50	1.50	1.50	1.86
(Chamber of Mines of South Africa, 2007) Strength: Landform and vegetation establishment focus. Moderate detailed appendices. Weakness: Techniques may be out-dated, and legislation has changed. Broad and generic. Comment: Minerals industry guideline.	1.00	2.50	2.50	1.00	1.50	1.00	1.50	1.57

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Company								
(Anglo Coal Environmental Rehabilitation Improvement Group, 2009) Strength: Landform and vegetation establishment focus. Weakness: Contains management actions specific to Anglo coal. Comment: Anglo Coal in-house document.	1.00	2.50	2.00	1.00	2.50	1.00	1.50	1.64
Technical								
(Thompson, 2005) Strength: Detailed descriptions of coal mining methods. Weakness: Limited focus on rehabilitation. Comment: Mining engineering focus.	1.50	1.50	1.50	1.50	1.50	1.00	1.00	1.36
(Gauteng Department of Agriculture	2.00	1.50	1.50	1.50	1.00	1.50	1.50	1.50

Document description	**Geology**	**Soils**	**Topography**	**Hydrology**	**Vegetation**	**Climate**	**Land-use**	**Average score**
Environment and Conservation, 2008) Strength: Very detailed document Weakness: Analysis is for impacts not rehabilitation risk. Comment: Minerals industry focus.								
Average score, mine rehabilitation guidelines: South Africa	1.40	2.10	1.90	1.50	1.60	1.20	1.40	1.59
Mine rehabilitation guidelines: Australia								
Leading practice								
(Minerals Council of Australia, 1998) Strength: Landform, soils and vegetation focus. Moderate detailed appendices. Weakness: Information is intertwined throughout. Broad and generic.	2.50	2.50	2.50	1.00	2.00	1.00	1.00	1.79

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Comment: Minerals industry focused.								
(Australian Government and Department of Industry Tourism and Resources, 2006) Strength: Landforms, soils and vegetation focus, described in life-cycle phases. Weakness: Information is intertwined throughout. No appendices. Broad and generic. Comment: Minerals industry focused.	2.50	2.50	1.50	1.50	1.50	2.00	1.00	1.79
(Australian Government et al., 2016b) Strength: Landforms, soils and vegetation focus, described in life-cycle phases. Weakness: Information is intertwined throughout. No appendices. Broad and generic.	1.50	2.50	2.50	1.00	1.50	2.00	1.00	1.71

Document description	**Geology**	**Soils**	**Topography**	**Hydrology**	**Vegetation**	**Climate**	**Land-use**	**Average score**
Comment: Minerals industry focused.								
(Government of Western Australia et al., 2015) Strength: Recent guideline. Risk assessment focus. Weakness: Closure focus, rehabilitation a component of closure. Comment: Minerals industry. Closure.	2.00	1.50	1.50	1.50	1.50	1.50	1.50	1.57
Technical								
(Department of Minerals and Energy, 1995) Strength: Detailed technical sheets provided. Weakness: Limited focus on rehabilitation, more on mining.	2.50	2.00	2.50	1.50	1.50	2.50	2.50	2.14

Document description	Geology	Soils	Topography	Hydrology	Vegetation	Climate	Land-use	Average score
Comment: Minerals industry technical guideline.								
Average score. mine rehabilitation guidelines:	2.20	2.20	2.10	1.30	1.60	1.80	1.40	1.80
Summary score, mine approval consultant rehabilitation reports: South Africa and Australia	1.86	1.82	1.57	1.83	1.57	1.47	1.58	1.67
Summary score, mine rehabilitation guidelines: South Africa and Australia	1.80	2.15	2.00	1.40	1.60	1.50	1.40	1.69
Mine rehabilitation guidelines: Near resilient maturity example from other mining countries								
(Newton and Claassen, 2003)	2.00	2.50	2.50	2.50	2.50	2.50	1.00	2.21

Table 2.
Mine rehabilitation legislation and document types: South Africa and Australia, Queensland and New South Wales

	South Africa		**Australia**	
Mine life-cycle phase	**< 2015 Financial Provisions Regulations**	**> 2015 Financial Provisions Regulations**	**Queensland**	**New South Wales**
Approval	Basic Assessment or Scoping and Environmental Impact Assessment. Environmental Management Programme. Closure Plan & Environmental Risk Assessment. (Rehabilitation specified in body of the above reports) **OR** Mine Rehabilitation Plan. (As a stand-alone appendix attached to the above reports).	Basic Assessment or Scoping and Environmental Impact Assessment. Environmental Management Programme. The following documents form part of the Environmental Management Programme: Annual Rehabilitation Plan; Final Rehabilitation, Decommissioning and Mine Closure Plan; Environmental Risk Assessment; and Financial Provisions.	Environmental Authority. Environmental Impact Statement. Environmental Management Plan no longer required. (Rehabilitation specified in body of Environmental Impact Statement **OR a**s a stand-alone Mine Rehabilitation Plan appended to Environmental Impact Statement). Mine Rehabilitation Plan (At start, later transitions into Progressive Rehabilitation Report/ Final Rehabilitation	Environmental Authority. Environmental Impact Statement (Rehabilitation specified in body of Environmental Impact Statement **OR** as a stand-alone Mine Rehabilitation Plan appended to Environmental Impact Statement) Mine Rehabilitation Plan (At start, later transitions into Mining Operation Plan)

Mine life-cycle phase	**South Africa** **< 2015 Financial Provisions Regulations**	 **> 2015 Financial Provisions Regulations**	**Australia** **Queensland**	 **New South Wales**
			Report)	
Operation	Rehabilitation specification reports. (Often a condition of approval and required prior to start of operation). Mine Rehabilitation Monitoring and Adaptive Rehabilitation Response reports (Update progressively, in-house).	Annual Rehabilitation Plan (Update annually). Final Rehabilitation, Decommissioning and Mine Closure Plan, Environmental Risk Assessment and Financial Provisions (Update progressively).	Progressive Rehabilitation Report (Updated progressively for surrender of a part of a site or for surrender of the Environmental Authority) Plan of Operations (Includes rehabilitation program, financial assurance, needed prior to operation start, after Environmental Authority, updated every 5 years or if changes occur)	Mining Operation Plan ('Hybrid' Mine Rehabilitation Plan and Closure Plan, required prior to operation start-up, after Environmental Authority is granted, valid for 5 years, public document, includes rehabilitation cost estimates, Environmental Risk Assessment, risks of rehabilitation and adaptive management responses. Soon to be renamed Rehabilitation Management Plan.
Closure		Final Rehabilitation, Decommissioning and Mine Closure Plan, Environmental Risk Assessment and Financial	Final Rehabilitation Report (updated for surrender of parts or a whole pf the site, for progressive or final	

Mine life-cycle phase	South Africa < 2015 Financial Provisions Regulations	 > 2015 Financial Provisions Regulations	Australia Queensland	 New South Wales
		Provisions (Finalise at end).	rehabilitation, for surrender of the Environmental Authority) Risk Assessment Residual Risk Calculation	
Legislation	National Environmental Management Act, Act No. 107 of 1998; 2014 EIA Regulations; National Environmental Management: Waste Act, Act No. 59 of 2008; National Water Act, Act No. 36 of 1998; and Minerals and Petroleum Resources Development Act, Act No. 28 of 2002 and its 2004 Regulations. All are National legislation. Assessing Authority was the	National Environmental Management Act, Act No. 107 of 1998; 2014 EIA Regulations, with 2017 amendments; National Environmental Management: Waste Act, Act No. 59 of 2008; 2015 Regulations regarding the planning and management of residue stockpiles and deposits; National Water Act, Act No. 36 of 1998; Minerals and Petroleum Resources Development Act, Act No. 28 of 2002; and 2015 Financial	Minerals Resources Act, 1989; Environmental Protection Act, 1994; Environmental Protection Regulations, 2008; and State Development and Public Works Organisation Act 1971. All are Queensland state legislation. Commonwealth Environmental Protection and Biodiversity Act, 1999 is applied, when the	Environmental Planning and Assessment Act, 1979; Mining Act. 1992; and Protection of the Environment Operations Act, 1997 All are New South Wales state legislation. Commonwealth Environmental Protection and Biodiversity Act, 1999, is applied, when the project has national environmental significance.

	South Africa		**Australia**	
Mine life-cycle phase	**< 2015 Financial Provisions Regulations**	**> 2015 Financial Provisions Regulations**	**Queensland**	**New South Wales**
	National Department of Environmental Affairs and in some cases the Provincial Department	Provisions Regulations. All are National legislation. Assessing Authority is the National Department of Mineral Resources and in some cases the Provincial Department.	project has national environmental significance.	

Synopsis

This paper revealed that mine rehabilitation guidelines and mine approval consultant rehabilitation reports in South Africa and Australia, Queensland and New South Wales fall between vulnerable and adequate but are not yet resilient. The developed maturity model provides a point of reference for the improvement of mine rehabilitation guidelines and mine approval consultant rehabilitation reports.

The paper recommended that further research be undertaken: to investigate the integration of the environmental domain evaluative criteria as defined in the paper, with causal driver criteria such as mine management actions which may worsen or improve impacts to the environmental domain criteria; to assess controls that could prevent or mitigate impacts; and further assessment of the type and nature of rehabilitation risk-events that may arise from and be affected by these factors, which could increase rehabilitation risk and ultimately rehabilitation failure.

The need for the development of model, with capabilities for resilient rehabilitation planning, quantitative multi-discipline integration and for rehabilitation risk determination, to determine a site’s rehabilitation risk and its ultimate potential for rehabilitation failure was noted.

The need for further investigation of suitable tools, techniques and methods, based on risk assessment and integrated environmental modelling principles was noted.

CHAPTER 3:

TECHNIQUES SUITABLE FOR SURFACE-STRIP COAL MINE REHABILITATION RISK ASSESSMENT: A REVIEW

Mine Rehabilitation Risk Assessment Techniques

Vanessa D. Weyer,† and Wayne F. Truter,‡

†[*]Centre for Environmental Studies, University of Pretoria, Private bag X20, Hatfield, Pretoria, 0028, South Africa, e-mail address: vweyer@global.co.za

‡ Department of Plant and Soil Sciences, University of Pretoria, Private bag X20, Hatfield, Pretoria, 0028, South Africa, e-mail address: wayne.truter@up.ac.za

In review: *Integrated Environmental Assessment and Management* (in review)

Preface

This chapter consists of a paper in review and is cited as follows:

Weyer, V.D. & Truter, W.F. (in review). Risk assessment techniques for surface-strip coal mine rehabilitation: A review. Integrated Environmental Assessment and Management.

This paper reviews techniques, based on risk assessment and integrated environmental modelling principles that could be suitable for developing a surface-strip coal mine rehabilitation risk assessment model. The paper further evaluates techniques developed by others for mine rehabilitation risk assessment, to locate the research in the body of prior research, thus confirming a research gap.

The paper was co-authored with Wayne F. Truter. The conceptualisation of the paper, the data analysis and the actual article writing was conducted by me. Wayne F. Truter assisted with reviewing the paper.

3.1 Abstract

Risk events, examples of which among others may include soil compaction and erosion, acid mine drainage (AMD) and low basal vegetation cover can occur during surface-strip coal mine rehabilitation. The extent of these and their sources is largely unknown. The need for the development of a model capable of integrating risk sources, to quantify a site's risk events and ultimate potential for rehabilitation failure is recognised. A review of literature is undertaken to find the best suited technique to use for model development. Model aims are described and criteria to incorporate are listed, and a scoring method is presented based on these. Three quantitative integrative risk assessment techniques are scored and ranked using the scoring method, and the relevance of techniques developed by others are discussed. Bayesian networks (BNs) scored the highest (68%), followed by bow-tie analysis (44%), and lastly fault-tree analysis (41%). The integration and quantification of multidisciplinary risk sources to quantify rehabilitation risk events is best facilitated using BNs. A technique which used BNs to model surface erosion and tunnelling risk for cost-effective management of dispersive mine spoil in Australia, proved relevant to model development, however no technique closely aligns to the model's aims and criteria identified for model inclusion. Research directions to test the use of BNs for a risk assessment model are suggested as well as an alternative investigation using bow-tie analysis.

3.2 Key points

- Criteria for surface-strip coal mine rehabilitation risk assessment inclusion are described.
- A scoring method based on these criteria is presented.
- Three quantitative integrative techniques are scored for suitability for model development.
- Rehabilitation risk assessment techniques developed by others are discussed.
- Bayesian networks are identified as the technique most suited for model development.

3.3 Keywords

Integrated modelling Multidisciplinary mine closure and rehabilitation planning Quantitative risk assessment Bayesian networks bow-tie and fault-tree analysis

3.4 Introduction

There's an adage that, "great wealth comes at a price", and with the recent downturn in the global economy and the end of a profitable mining boom cycle, countries like South Africa and Australia are taking stock of their mine liabilities. There are approximately 6000 abandoned mines (derelict and ownerless or orphaned) of all types in South Africa (Auditor-General South Africa, 2009; Department of Mineral Resources, 2009) and more than 50,000 in Australia (Unger et al., 2012). Campbell et al. (2017) provides further alarming statistics, despite difficulties in attaining data, for Australia, for not just abandoned mines, but also of mines in care and maintenance, mines undergoing final closure and mines closed, rehabilitated and relinquished. They note that there are no examples of major, modern open cut mines completing rehabilitation to the point where the site can be relinquished. Costs of rehabilitation are high, for example approximately $3B AUD is required to rehabilitate the 6,000 abandoned mines in South Africa (Auditor-General South Africa, 2009), whilst in excess of $1B AUD is required to rehabilitate just 15,000 abandoned mines in Queensland (Queensland Government, 2012). Had a mature rehabilitation risk assessment been undertaken during the initial mine planning phases and progressively thereafter, some of these liabilities could have surely been avoided?

Risk assessment and its application to mine closure and rehabilitation have progressively become more important in mine planning (Australian Government et al., 2016b, c, e; Chamber of Mines of South Africa, 2007; Department of Environmental Affairs, 2015; International Council on Mining and Metals, 2008). Risk is defined by the ISO 31000 – Risk management standard process as the effect of uncertainty on objectives. An effect is a deviation from the expected and objectives can have different aspects and categories and can be applied at different levels (Council of Standards Australia & New Zealand, 2009; International Organization for Standardization, 2018; South African Bureau of Standards, 2009). Risk assessment is segregated by ISO 31000 into, "risk identification", "analysis" and "evaluation". Risk identification and analysis are particularly relevant for assessing mine rehabilitation risks.

Risk identification involves finding, recognising and describing risks, encompassing the identification of "risk sources and events", their causes and their potential consequences. During surface-strip coal mine rehabilitation, numerous risk events can occur, which can ultimately lead to mine site rehabilitation failure at great costs to mining companies and society (Weyer et al., 2017). Examples of risk events may include among others, soil compaction, soil erosion, landform failure or slope-slip, Acid Mine Drainage (AMD), water quality and quantity changes, low vegetation basal cover, weed infestations and stress induced plant senescence. Risk events can be categorised into 3 primary domains and further sub-categorisation into 7 types of risk events. Within these categorisations 25 risk events are identified (Table 3.1). Risk events do not work in isolation but influence one another and may integrate to produce combined mine site rehabilitation risk, that is, a site's potential for rehabilitation failure. A search for real-life mine site risk event examples revealed that these are rare in the literature, particularly for operational mines. A possible reason could be due to mine confidentiality, liability or competitiveness issues, though further investigation would be required to confirm why the mining industry does not readily share this data, which could assist researchers. Risk events are driven by risk sources. Risk sources can be of natural origin, emanating from underlying mine site geology, soils, topography, climate, hydrology, vegetation and land cover. They can also be of anthropogenic origin, that is, related to management actions or choices taken during mine operations.

Risk analysis characterises the nature and level of risk and includes risk estimation. Risk analysis can be undertaken with varying degrees of detail, depending on the risk, the purpose of the analysis, and the information, data and resources available. Analysis can be qualitative, semi-quantitative or quantitative, or a combination of these, depending on the circumstances (Council of Standards Australia & New Zealand, 2009).

Australian Government et al. (2016e) note that mining industry projects and operations continue to suffer unplanned and unwanted incidents and outcomes that substantially affect their profitability, reputation and licence to operate, through poor understanding or poor application of the risk management process. Corder et al. (2010) and McCullough et al. (2018) concur that the extent of rehabilitation risk is largely unknown, during the upfront mine planning and authorisation phases. Weyer et al. (2017) further demonstrate that guidelines and consultants' approval reports for rehabilitation of surface-strip coal mines in South Africa and Australia fall between vulnerable and adequate but are not yet resilient; information is gathered, but seldom analysed, with limited multidisciplinary integration and rehabilitation risk determination. They note a need to investigate the integration of their defined “environmental domain evaluative criteria”, including geology, soils, topography, hydrology, climate, vegetation and landuse and mine management actions, i.e. the integration of risk sources to quantify rehabilitation risk events. The need for the development of a model capable of integrating multidisciplinary risk sources to determine a site’s rehabilitation risk, based on risk events and its ultimate potential for rehabilitation failure is advocated by Weyer et al. (2017). However, before a rehabilitation risk assessment model can be developed, it is necessary to undertake a review to identify the most suited quantitative and integrative technique to use and to be familiar with similar research work by others that could inform the model’s development.

The over-reliance on commonly applied qualitative risk assessment techniques in the mining industry, particularly likelihood and consequence risk matrices and spreadsheets, with limited application of quantitative methods is noted by Australian Government et al. (2016e). During mine rehabilitation risk assessment, it is important to not only apply qualitative techniques but to also assess risk in a more detailed way, that is, by using quantitative multidisciplinary integrative techniques. Integrated risk assessment and modelling techniques can facilitate this (Hamilton et al., 2015).

This paper is a non-systematic or informative review. It aims to analyse literature to aid decision making, i.e. to identify the most suited technique to use for the development of a rehabilitation risk assessment model. The review is of value to mine closure and rehabilitation professionals who may be conducting risk assessment in mine planning. Few such reviews pertaining to risk assessment techniques in mining have been conducted (Australian Government et al., 2016e). Available reviews are broad and do not focus specifically on quantitative, integrative techniques.

This paper reviews literature from several sources including peer-reviewed published journal articles, as well as where necessary grey literature, inclusive of mine closure and rehabilitation guidelines, conference proceedings, reports and internet web searches.

The paper first describes what a rehabilitation risk assessment model should aim to achieve, followed by the criteria that are considered important for inclusion in the model’s development.

We then present a scoring method based on the criteria and use this to score three potential quantitative integrative techniques; fault-tree analysis, bow-tie analysis and BNs. We discuss relevant mine rehabilitation risk assessment techniques developed by others. We conclude by providing research directions to implement the development of the rehabilitation risk assessment model.

3.5 Aims and criteria for rehabilitation risk assessment model development

3.5.1 Model aims

The chosen risk assessment technique should be able to fulfil the rehabilitation risk assessment model's aims as described below.

The rehabilitation risk assessment model should be able to integrate and quantify rehabilitation risk to support surface-strip coal mine rehabilitation planning decisions. The model should be applicable to all life of mine phases and possible postclosure landuses of surface-strip coal mines in South Africa and Australia, with future adaptations possible to other international regions and other mining types.

Life of mine phases include exploration, feasibility, planning and design, construction and commissioning, operations, decommissioning and closure, and postclosure management and monitoring (Australian Government et al., 2016b). Planning for mine closure, inclusive of determining rehabilitation risks, should be done progressively throughout these phases (Australian Government et al., 2016c). Postclosure landuses relevant to surface-strip coal mines may include: native vegetation for grazing (Maczkowiack et al., 2012b) or for conservation (Williams, 2001); novel ecosystems (Doley and Audet, 2013; Erskine and Fletcher, 2013); agricultural pastures and cropping (Australian Government et al., 2016c; Chamber of Mines of South Africa, 2007), including for biodiesel supply (Harris et al., 2015); commercial forestry plantations (Australian Government et al., 2016c); urban development, recreation, tourism or education (Australian Government et al., 2016c).

During mine approval, an Environmental Impact Assessment (EIA) process is conducted in both South Africa and Australia. Although the EIA process differs between the two countries, an investigation of the mine site's biophysical and socioeconomic baseline is a requirement.

Specialist studies are commissioned, and valuable information is gathered. The focus of these studies is however towards assessing environmental impacts and not towards rehabilitation risk identification and assessment. The terms of reference for specialist studies could be streamlined to facilitate linkage with and a focus on rehabilitation planning and for the incorporation of data into a rehabilitation risk assessment model. To aid analysis, risk source data, i.e. geology, soils, topography, hydrology, vegetation and landcover, should be segregated, to gauge individual risk source contributions to a site's composite risk of rehabilitation failure. This approach would allow rehabilitation professionals to focus on critical risk contributors so that appropriate mitigatory decisions may be taken.

3.5.2 Criteria for model inclusion

Criteria considered important for model inclusion are discussed below. These underpin the scoring method used to score the 3 potential quantitative integrative techniques; fault-tree analysis, bow-tie analysis and BNs, in terms of their suitability for model development. This step aligns with the ISO 31000 – Risk management standard process, "risk criteria" listing requirement, which states that risk criteria should be determined and agreed on during the first phase of the risk management process and that these should be used to evaluate the significance of risk and to support decision making purposes (International Organization for Standardization, 2018).

3.5.2.1 Risk assessment ISO 31000 principle incorporation

The model should align with the ISO 31000 – Risk management standard process (Council of Standards Australia & New Zealand, 2009; International Organization for Standardization, 2018; South African Bureau of Standards, 2009). This will assist with the acceptance of the model by mining companies, as ISO 31000 is used extensively in mine planning.

The core of this process, "risk assessment", which is segregated into "risk identification", "analysis" and "evaluation" (Fig. 3.1), is particularly relevant. Risk identification is finding, recognising and describing risks, encompassing the identification of "risk sources" and "events", their causes and their potential consequences. Risk analysis characterises the nature and level of risk and includes risk estimation. Risk evaluation is where the results of the risk analysis process are compared with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable.

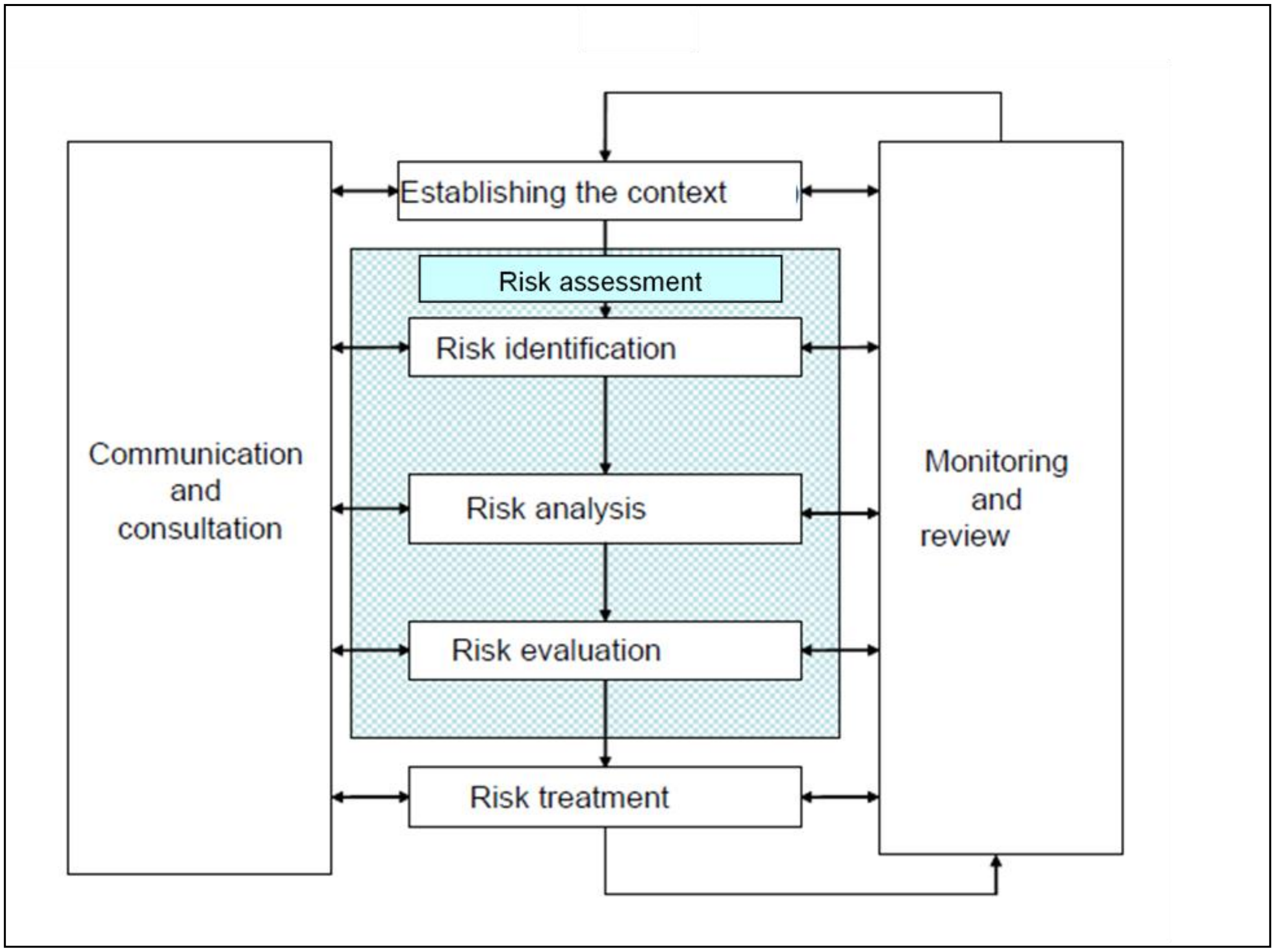


Fig. 3.1 ISO 31000 risk management process. Source: South African Bureau of Standards (2009)

The ISO 31000 definition for a risk event includes: “an occurrence or change of a particular set of circumstances”; “something that is expected which does not happen, or something that is not expected which does happen”; and an “incident or accident” (Council of Standards Australia & New Zealand, 2009; International Organization for Standardization, 2018). Risk events are referred to as, “issues causing problem areas”, by the Chamber of Mines of South Africa (2007), who list lack of topsoil, penetrability to plant roots, water holding capacity, metal toxicity, plant nutrient supply, contamination, acidity and salinity as issues to be dealt with.

To better understand risk events and which events commonly occur in general and surface-strip coal mine rehabilitation, a review of South African and Australian peer-reviewed published journal articles, technical reports and mine rehabilitation guideline documents was undertaken (Table 3.1). Mine site examples are provided where these were found in the literature. Risk events can be categorised into 3 domains: “substrate or soil failure”, “water failure”, and “vegetation failure”. Further sub-categorisation of these domains into 7 risk event types is possible, i.e. within substrate or soil failure, types of “negative soil states”, “slope or surface instability”, and “hazards” can occur. Whilst within water failure, types of “contamination” and “water balance” can be categorised. Within vegetation failure, types of “failure of vegetation to thrive” or “decline in vegetation” are possible. Within these categorisations 25 risk events were identified. The risk events were ranked based on the number of times they were cited out of the total number of documents reviewed (29), expressed as a percentage (Table 3.2). Mine tailing failures, noise, air and socioeconomic related risk events were not included in the evaluation.

Table 3.1 Rehabilitation risk events

Risk event	Description and/or mine site example	Reference
DOMAIN: SUBSTRATE OR SOIL FAILURE **TYPE: NEGATIVE SOIL STATES**		
Soil toxicity	General example.	(Australian Government et al., 2011, 2016c; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 1981, 2007; Department of Minerals and Energy, 1995; Government of Western Australia et al., 2015; Government of Western Australia Environmental Protection Authority, 2006; Laurence, 2011; Limpitlaw et al., 2005; Loch, 2010; Loch and Howard, 2018; Minerals Council of Australia, 1998; Vacher et al., 2004)
Topsoil deterioration and loss	Paterson et al. (2018) investigated stockpile soils at four mines in the vicinity of eMalahleni (Witbank), Ogies and Kriel on the Mpumalanga Highveld, South Africa. Mines are referred to as Mines A, B, C and D for confidentiality.	(Australian Government et al., 2011, 2016c; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 2007; Government of Western Australia et al., 2015; Laurence, 2001; Limpitlaw et al., 2005; Minerals Council of Australia, 1998; Paterson et al., 2018)
Soil compaction	Most South African soils, other than the vertisols, are highly susceptible to compaction (Chamber of Mines of South Africa, 2007).	(Australian Government et al., 2016c; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 1981, 2007; Limpitlaw et al., 2005; Minerals Council of Australia, 1998; Rethman, 2006)
Soil infertility	General example.	(Australian Government et al., 2016c; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 2007; Government of Western Australia Environmental Protection Authority, 2006; Minerals Council of Australia, 1998; Paterson et

Risk event	Description and/or mine site example	Reference
		al., 2018)
Surface crusting or cracking	General example.	(Australian Government et al., 2016c; Chamber of Mines of South Africa, 2007; Minerals Council of Australia, 1998)
Surface ponding or waterlogging	General example.	(Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 2007; Government of Western Australia et al., 2015)

DOMAIN: SUBSTRATE OR SOIL FAILURE
TYPE: SLOPE OR SURFACE INSTABILITY

Soil erosion	Coppabella coal mine (operational), Bowen Basin, Australia, tertiary spoils are recognised as posing problems with both revegetation and erosional stability (Vacher et al., 2004). Sodic soils in Australia are common, and will typically not only produce high rates of runoff and erosion, but will also be extremely difficult to vegetate (Loch, 2010).	(Australian Government et al., 2011, 2016a, b, c; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 1981, 2007; Department of Minerals and Energy, 1995; Howard and Roddy, 2012; Laurence, 2001; Limpitlaw et al., 2005; Loch, 2010; Loch and Howard, 2018; McCullough, 2016; Minerals Council of Australia, 1998; Tasmania Sustainable Land Use Department of Primary Industries and Water, 2009; Vacher et al., 2004)
Landform failure or slope-slip	Williams (2001), provide photographs of unnamed mine site generalised landform instability examples from the Bowen basin, Australia and the Witbank coalfield, South Africa.	(Australian Government et al., 2011, 2016a, b, c; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 2007; Department of Minerals and Energy, 1995; Government of Western Australia et al., 2015; Government of Western Australia Environmental Protection Authority, 2006; Loch, 2010; Loch and Howard,

Risk event	Description and/or mine site example	Reference
		2018; Minerals Council of Australia, 1998; Williams, 2001)
Subsidence	Transvaal and Delagoa Bay colliery (abandoned), Witbank, South Africa (Limpitlaw et al., 2005).	(Australian Government et al., 2016a, b; Australian Government and Department of Industry Tourism and Resources, 2006; Australian Government Department of Environment, 2014; Chamber of Mines of South Africa, 2007; Department of Minerals and Energy, 1995; Government of Western Australia et al., 2015; Limpitlaw et al., 2005; Minerals Council of Australia, 1998)

DOMAIN: SUBSTRATE OR SOIL FAILURE
TYPE: HAZARDS

Spontaneous combustion	Transvaal and Delagoa Bay colliery (abandoned), Witbank, South Africa, abandoned (Limpitlaw et al., 2005).	(Australian Government et al., 2011, 2016a, b, d; Department of Minerals and Energy, 1995; Limpitlaw et al., 2005; Phillips et al., 2011)

DOMAIN: WATER FAILURE (SURFACE AND GROUND WATER)
TYPE: CONTAMINATION

Acid mine drainage and saline drainage	Transvaal and Delagoa Bay colliery (abandoned), Witbank, South Africa (Limpitlaw et al., 2005). The Brugspruit catchment, where some of the earliest mining in the Witbank coal field, South Africa, took place, is particularly affected by AMD (Limpitlaw et al., 2005).	(Anderson and Butler, 2017; Australian Government et al., 2011, 2016a, b, c, d; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 1981; Department of Minerals and Energy, 1995; Government of Western Australia et al., 2015; Laurence, 2001; Limpitlaw et al., 2005; Loch and Howard, 2018; McCullough, 2016; Minerals Council of Australia, 1998; Northern Territory Environmental Protection Authority, 2013)

Risk event	Description and/or mine site example	Reference
	Stockton coal mine, New Zealand (operational), a significant existing environmental liability is associated with historical AMD issues at the site, and the Stockton coalmine expects to be treating this in perpetuity (Australian Government et al., 2016d). Mudd (2010), cite the Rum Jungle (abandoned) uranium mine as an example, where $25 million was spent in the 1980's and yet the adjacent East Finnis River was noted as still being heavily polluted by AMD leaching from rehabilitated waste rock dumps in 2007, some 27 years later. Anderson and Butler (2017) provide an example of the Mary Kathleen (closed) uranium mine in Queensland, where predictions made on the geochemical behaviour of the waste rock dumps and tailings storage facility have proved to be incorrect and not up to standards.	
Water quality decline	Williams (2001) provide photographs of unnamed mine site generalised water quality change examples from the Bowen basin, Australia and the Witbank coalfield, South Africa.	(Australian Government et al., 2011, 2016a, b; Australian Government and Department of Industry Tourism and Resources, 2006; Chamber of Mines of South Africa, 2007; Department of Minerals and Energy, 1995; Government of Western Australia et al., 2015; Government of Western Australia Environmental Protection Authority, 2006; Laurence, 2001; McCullough, 2016; Minerals Council of Australia, 1998; Williams, 2001)

Risk event	Description and/or mine site example	Reference
Chemical spillage	General example.	(Australian Government et al., 2011, 2016a, b; Chamber of Mines of South Africa, 2007; Department of Minerals and Energy, 1995)

DOMAIN: WATER FAILURE (SURFACE AND GROUND WATER
TYPE: WATER BALANCE

Water storage decrease.	Williams (2001) provide photographs of unnamed mine site generalised water quantity change examples from the Bowen basin, Australia and the Witbank coalfield, South Africa.	(Australian Government et al., 2011, 2016a; Chamber of Mines of South Africa, 2007; Department of Minerals and Energy, 1995; Government of Western Australia et al., 2015; Williams, 2001)
Water storage increase	General example.	(Australian Government et al., 2011, 2016a; Chamber of Mines of South Africa, 2007; Department of Minerals and Energy, 1995; Government of Western Australia et al., 2015; McCullough, 2016)

DOMAIN: VEGETATION FAILURE
TYPE: FAILURE TO THRIVE

Weed and invasive grass infestation	General example.	(Australian Government et al., 2011, 2016c; Chamber of Mines of South Africa, 2007; Government of Western Australia et al., 2015; Government of Western Australia Department of Environmental Regulation, 2016; Government of Western Australia Environmental Protection Authority, 2006)
Low basal cover	General example.	(Australian Government et al., 2011, 2016a, b; Chamber of Mines of South Africa, 2007; Government of Western Australia Environmental Protection Authority, 2006)

Risk event	Description and/or mine site example	Reference
Low species richness and/or diversity present	General example.	(Government of Western Australia Department of Environmental Regulation, 2016; Government of Western Australia Environmental Protection Authority, 2006)
Overgrazing	General example.	(Chamber of Mines of South Africa, 2007; Limpitlaw et al., 2005)
Fire damage	General example.	(Government of Western Australia Environmental Protection Authority, 2006)
Low productivity	General example.	(Australian Government et al., 2016a)
Mono-specific grasslands present	General example.	(Limpitlaw et al., 2005)

DOMAIN: VEGETATION FAILURE
TYPE: DECLINE

Senescence (stress induced)	Williams (2001) provide photographs of unnamed mine site generalised failure of vegetation cover examples from the Bowen basin, Australia and the Witbank coalfield, South Africa.	(Australian Government et al., 2016a; Government of Western Australia et al., 2015)
Chlorosis present or diseased	General example.	(Government of Western Australia Department of Environmental Regulation, 2016; Government of Western Australia Environmental Protection Authority, 2006)

Risk event	Description and/or mine site example	Reference
Retrograde succession present	General example.	None.

Table 3.2 Risk event summary scores and ranking

Risk event	**Score**	**Percentage**	**Rank**
Soil erosion	15/29	52%	No. 1
Soil toxicity	14/29	48%	No. 2
Acid mine drainage and saline drainage	13/29	44%	No. 3
Landform failure or slope-slip	11/29	38%	No. 4
Water quality decline	11/29	38%	No. 4
Topsoil deterioration and loss	9/29	31%	No. 5
Soil compaction	7/29	24%	No. 6
Subsidence	8/29	28%	No. 7
Soil infertility	6/29	21%	No. 8
Water storage decrease	6/29	21%	No. 8
Water storage increase	6/29	21%	No. 8
Weed and invasive grass infestation	6/29	21%	No. 8
Spontaneous combustion	5/29	17%	No. 9
Chemical spillage	4/29	14%	No. 10
Low basal cover	4/29	14%	No. 10
Surface crusting or cracking	3/28	10%	No. 11
Surface ponding or waterlogging	3/28	10%	No. 11
Low species richness and/or diversity	2/29	7%	No. 12
present	2/29	7%	No. 12
Overgrazing	2/29	7%	No. 12
Senescence (stress induced)	2/29	7%	No. 12
Chlorosis present or diseased	1/29	3%	No. 13
Fire damage	1/29	3%	No. 13
Low productivity	1/29	3%	No. 13
Mono-specific grasslands present	0/29	0%	No. 14
Retrograde succession present			

In South Africa, soil compaction is considered one of the most common problems, as most South African soils, other than the vertisols, are highly susceptible to compaction (Chamber of Mines of South Africa, 2007). While in Australia soil erosion is more common, due to the common occurrence of sodic soils, which typically produce high rates of runoff and erosion, and which are also extremely difficult to vegetate (Dale et al., 2018; Loch, 2010; Shaw et al., 1994). One of the biggest risks that can occur in mining is undoubtedly AMD, however the documents reviewed were chosen for their focus on mine rehabilitation and not so much for their focus on geohydrological issues, which are extensively documented.

Risk events are influenced by risk sources. The ISO 31000 definition for a risk source includes: "an element which alone or in combination has the potential to give rise to risk" (Council of Standards Australia & New Zealand, 2009; International Organization for Standardization, 2018). Mine rehabilitation risk sources can have natural origins, that is, emanating from inherent site geology, soils, topography, hydrology, climate, vegetation or land cover. These are commonly investigated as part of the specialist studies of the EIA process. Risk sources may also be due to anthropogenic origins, that is, emanating from mine management actions or choices taken during mine operations. For example, by selecting draglines as a choice of machinery as opposed to bowlscrapers, the risk of soil compaction may be influenced differently. Or by handling topsoil when wet, soil compaction may increase. Anthropogenic risk sources act on the inherent baseline natural risk sources and choices made can increase or decrease rehabilitation risk.

3.5.2.2 Multidisciplinary risk source integration

The ability to integrate multidisciplinary based risk sources into the model is important. Parker et al. (2002) note that to gain insight into complex processes, the integration of different disciplines is required. Natural multidisciplinary risk source information such as soils, geology, hydrology etc. and mine management actions are collected by specialists and mine management during the EIA process for mine approval. Integration of this information can be achieved using integrated environmental assessment and modelling techniques (Hamilton et al., 2015). Integrated assessment is a process that combines multiple and diverse components across their social, organisational and conceptual boundaries to provide a comprehensive analysis of the problem. Integrated modelling facilitates this by providing a single platform to explore the linkages and feedbacks between different system components, including the social, economic and ecological implications of different natural or anthropogenic factors (Hamilton et al., 2015). Some researchers refer to integration in terms of cumulative effects or impacts (Franks et al., 2013).

3.5.2.3 Ability to include future temporal and spatial dimensions

The model should be developed to allow future incorporation of temporal and spatial associations. This may not initially be possible as the inclusion of temporal and spatial associations into risk assessment modelling is complex.

Parker et al. (2002) describe integrated assessment and modelling as more than just a model building exercise, but also as a methodology that can be used for gaining insight over an array of environmental problems spanning a wide variety of temporal and spatial scales. Risk sources and events change with time, over the life of the mine. This can extend for decades to even centuries long after mine closure or a worst-case scenario, at mine abandonment.

Risk sources also have spatial associations. For example, each mine and even portions within mine sites will have characteristics unique to their relevant site-specific geology, soils, topography, hydrology, climate, vegetation and landcover risk source states. These can be mapped using Geographic Information Systems (GIS), which in turn can be linked to risk assessment modelling software.

3.5.2.4 Emphasis on quantitative techniques

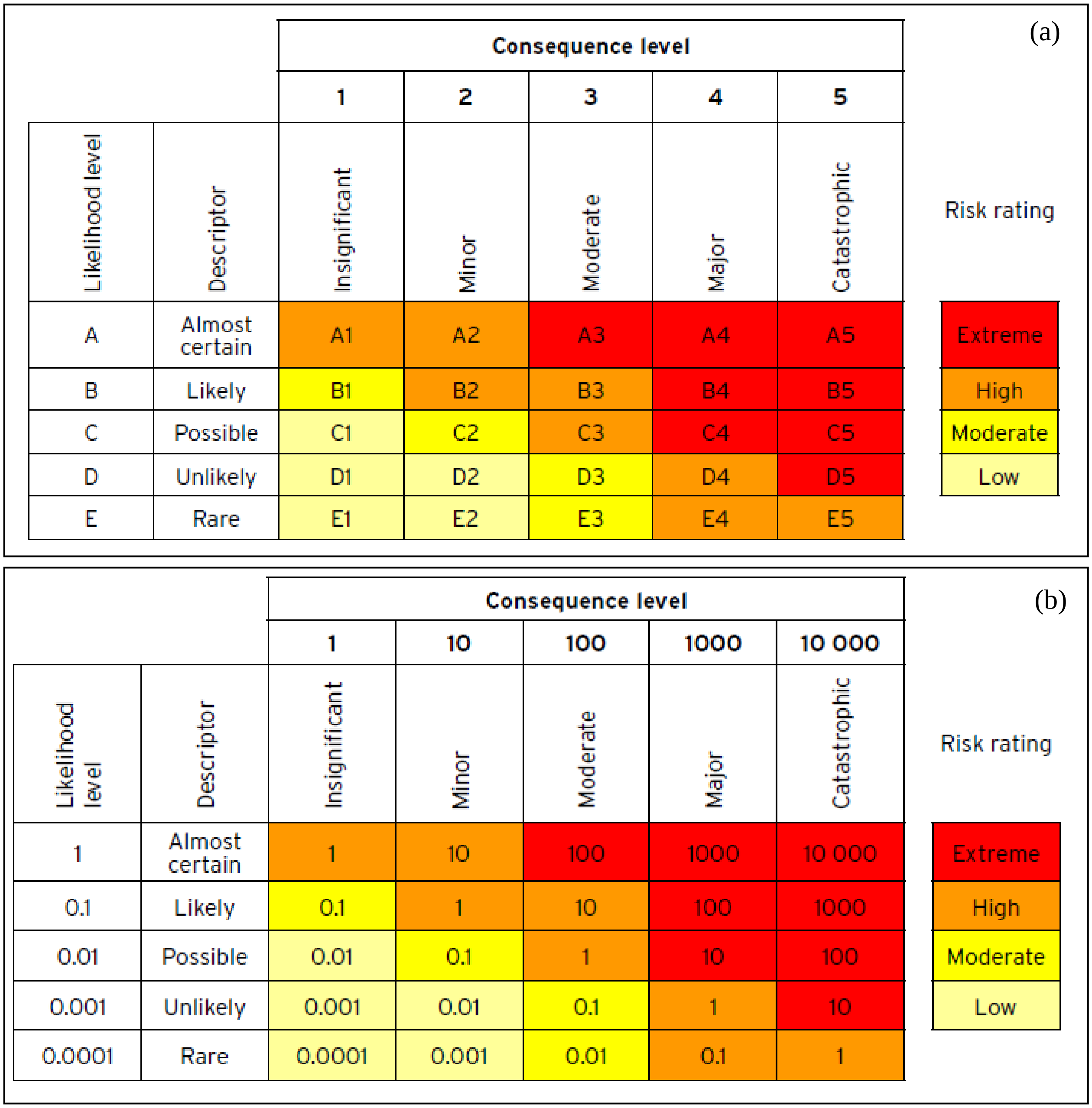
The proposed risk assessment model should aim to incorporate quantitative techniques to provide more accurate defensible risk results, an important requirement for the justification of mine planning and rehabilitation decisions. An important consideration, however as noted by International Electrotechnical Commission (2009), is that even where full quantification has been carried out, it needs to be recognized that the levels of risk calculated are estimates. They advise that care should be taken to ensure that results are not attributed a level of accuracy and precision inconsistent with the accuracy of the data and methods employed. A further consideration is that the design and data input of a system is based on the level of expertise and experience of risk assessors, there is therefore always an element of subjectivity.

Risk assessment has evolved into a highly scientific, statistical and mathematical field, with various techniques developed for specific application into several industries. In mining, risk assessment pertains to health, safety, environmental and geohydrological issues. Techniques can range from simple to highly complex, they can be qualitative, semi-quantitative and fully quantitative. Risk assessment may be undertaken in varying degrees of depth and detail and using one or many complementary techniques (International Electrotechnical Commission, 2009).

To date, qualitative techniques have been favoured most for mine risk assessment, as they are quick and easy to use (Australian Government et al., 2016e). These use descriptive terms to identify and record the consequences and likelihoods of events and resultant risk. They can be imprecise, highly subjective and biased, being influenced by the experience and opinion of the risk assessor. Results are also easy to manipulate to attain a desired outcome. Risk assessment matrices follow a logical, systematic process in order to identify the risk events and to assess the likelihood of their occurrence and the consequences; these are often used, they do not assign values and multipliers, but are descriptive (Fig. 3.2, block (a)). Peace (2017) cautions that poorly designed or inappropriately used risk matrices can result in an increase in uncertainty and potentially adverse effects on people and organizational objectives. It is argued that they should never be used on their own but included as part of an overall risk assessment.

Semi-quantitative methods are a combination of qualitative and quantitative methods, but methods can vary widely with many interpretations. They provide a more detailed prioritisation of risks than qualitative risk assessments, by attributing values and multipliers to the likelihood and consequence groupings (Australian Government et al., 2016e). Consequence-likelihood matrices, consequence-likelihood nomograms and spreadsheet-based semi-quantification may be used (Fig. 3.2, block (b)).

Quantitative methods identify likelihoods as frequencies or probabilities and therefore provide more accurate results, but these require increased time and greater specialist expertise to run the analysis (Australian Government et al., 2016e).


(a)

		Consequence level				
		1	2	3	4	5
Likelihood level	Descriptor	Insignificant	Minor	Moderate	Major	Catastrophic
A	Almost certain	A1	A2	A3	A4	A5
B	Likely	B1	B2	B3	B4	B5
C	Possible	C1	C2	C3	C4	C5
D	Unlikely	D1	D2	D3	D4	D5
E	Rare	E1	E2	E3	E4	E5

Risk rating
Extreme
High
Moderate
Low

(b)

		Consequence level				
		1	10	100	1000	10 000
Likelihood level	Descriptor	Insignificant	Minor	Moderate	Major	Catastrophic
1	Almost certain	1	10	100	1000	10 000
0.1	Likely	0.1	1	10	100	1000
0.01	Possible	0.01	0.1	1	10	100
0.001	Unlikely	0.001	0.01	0.1	1	10
0.0001	Rare	0.0001	0.001	0.01	0.1	1

Risk rating
Extreme
High
Moderate
Low

Fig. 3.2 An example of a simple descriptive qualitative risk matrix (block (a), top) and an example of a slightly more advanced semi-quantitative risk matrix, where values and multipliers have been added as a logarithmic scale (block (b), bottom). Source: Bowden et al. (2001).

3.5.2.5 Ability to include expert's knowledge

The model should be able to incorporate expert knowledge. Expert experience can provide useful information for forecasting, making decisions, and assessing risks (Clemen and Winkler, 1999). Expert opinion has been shown to enter models at different stages of their development, i.e. at the conceptual (formal) modelling stage, at the data provision stage, at the model evaluation stage and at the scenario development stage (Krueger et al., 2012). The ability to include expert knowledge into model development will serve to enhance these and so that the final products are of a high standard and can be used with confidence.

3.5.2.6 Degree of utility

The model should have a high degree of utility, so that it can be easily applied to and used by professionals in the mining industry. Desired characteristics that could facilitate this include: a graphical user and display interface; readily available software that is easy to use, understand and that can easily interpret findings; ability to link the technique to web-based platforms; and where the software is complicated, the ability to link the software to other user-friendly spreadsheet software interfaces. Care should be taken to ensure that the quality of final outcomes is not compromised by ease of utility.

3.6 Scoring method

A qualitative scoring method was developed (Table 3.3) to score the risk assessment techniques considered potentially suitable for the mine rehabilitation risk assessment model's development. The described criteria were weighted from 1-5, based on their level of importance for model inclusion. A score of 5 indicates high importance, whilst a score of 1 indicates low importance. Potential techniques were scored from 1-5 based on how well they could meet the criteria. A score of 5 indicates the criteria could be easily met, whilst a score of 1 indicates that criteria could be poorly met. A score of 0 indicates that no criteria could be met. Scoring of techniques was conducted by multiplying the score values for each technique with the assigned criteria weight, with results displayed in brackets. The total score was calculated by summing all the values for each technique, out of the total value permissible (150), and by expressing the result as a percentage, assuming a maximum of 25-points could be awarded for each.

The method is a double weighted method. A similar triple weighted method was used by Laurence (2001). Other examples include a single weighted method used by Unger et al. (2014) to evaluate techniques suitable for the development of an industry based rehabilitation and closure knowledge management system. Methods were evaluated against objectives or attributes and a score range of three was used. Kelly et al. (2013) used a system to select among 5 modelling approaches for integrated environmental assessment and management. Their listed attributes of each of the modelling approaches were used to develop a guiding framework for selecting an appropriate approach for new applications. A table was created to allow modellers and model users to choose an appropriate model type for their application considering their aims in model development, the types of data available to them, the preferred compromise between breadth and depth of system description, their preferred treatment of uncertainty, and whether they were interested in considering interactions among agents explicitly. No scoring system was used in the table, only checks for meeting common and possible features. The framework was further represented as a decision tree. Römbke et al. (2018) who undertook a review of standard methods for the assessment of structural and functional diversity of soil organisms, relied on existing International Organization for Standardization (ISO) experience rather than ranking methods by scoring or classifying them based on criteria met for each method. For rehabilitation risk assessment, no ISO standards yet exist that can be used.

A further alternative for scoring the techniques could be the use of maturity models. Maturity models originate from the Culture Ladder by Hudson (2007) developed for Health, Safety and Environment in the oil and gas industry. The Hudson Ladder defines a pathway from less to more advanced cultures, with 5 “categories of advancement” including pathological, reactive, calculative, proactive to generative. Adaptations of the Hudson ladder have been used by others (Australian Government et al., 2016e; Unger et al., 2015; Weyer et al., 2017). Maturity models were considered unsuitable as rehabilitation risk assessment techniques cannot be ranked in terms of their maturity or advancement. Every technique has its own unique purpose, relevant to the required model’s aim.

3.7 Risk assessment techniques and fitness for use

Three risk assessment techniques, which were considered by the authors to have the most likelihood of fulfilling the desired model aims and of possessing the listed criteria, are described below, and their comparative strengths and weaknesses are summarised (Table 3.4). These are scored for suitability using the developed scoring method in Table 3.3.

Table 3.3 Scoring of techniques potentially suitable for the development of a rehabilitation risk assessment model

Criteria Weight	**Criteria**	**Fault-tree Analysis**	**Bow-tie Analysis**	**Bayesian networks**
5*	Risk assessment ISO 31000 principle incorporation	4[+] (20)[§]	5 (25)	4 (20)
5	Multidisciplinary risk source integration	0 (0)	0 (0)	5 (25)
2	Ability to include future temporal and spatial dimensions	1 (2)	1 (2)	4 (8)
5	Emphasis on quantitative techniques	3 (15)	3 (15)	5 (25)
3	Ability to include expert's knowledge	4 (12)	4 (12)	5 (15)
3	Degree of utility	4 (12)	4 (12)	3 (9)
Total Score[†]		**61/150 (41%)**	**66/150 (44%)**	**102/150 (68%)**

Note:
* Criteria are weighted from 1-5 based on their level of importance for model inclusion. A score of 5 indicates high importance, whilst a score of 1 indicates low importance.
[+] Potential techniques are scored from 1-5 based on how well they can meet the listed criteria. A score of 5 indicates the criteria are easily met, whilst a score of 1 indicates the criteria are poorly met. A score of 0 indicates that no criteria are met.
[§] Scoring of techniques is done by multiplying the score values for each technique with the assigned criteria weight and the result is shown in parentheses.
[†] The total score is the sum of all values shown in brackets for each technique, out of the total value permissible (150), expressed as a percentage, assuming a maximum of 25 points could be awarded for each.

Table 3.4 Comparison of risk assessment techniques, strengths and weaknesses

Technique	Strength	Weakness
Fault-tree Analysis	Mostly qualitative but can be semi-quantitative or fully quantitative, though this is not frequently applied.	Consequences are not included, only causes.
	If a fault-tree is not able to be applied quantitatively, due to unsuitable input data (assigning probabilities to base events), it is still useful for displaying causal relationships.	Relationships are linear, i.e. they are statistically independent. It is therefore difficult to integrate multi-disciplines.
	Risks events can be applied as top-events and risk sources may be applied to understand their causes.	Controls or mitigation are difficult to include.
	They allow graphical representation.	Cannot link data spatially, for example with the use of a GIS.
	Expert opinion can be included.	Time inter-dependencies cannot be addressed, which could place limitations on including temporal change.
	Software is readily available.	Fault-trees can become enormous when applied to complex systems and their development can be time consuming. A software package is required to properly handle calculations when repeated events are present at several places in the fault-tree (International Electrotechnical Commission, 2009).
	Fault-trees are simple to understand and use.	Probability calculations for top-events require failure rate data of all events in the fault-tree to be known, with uncertainty in data not easily handled (International Electrotechnical

Technique	Strength	Weakness
		Commission, 2009).
		Fault-trees are applied mostly to engineering and industrial problems.
Bow-tie Analysis	Mostly qualitative but can be semi-quantitative or fully quantitative, though this is not frequently applied.	Relationships are linear, i.e. they are statistically independent. It is therefore difficult to integrate multi-disciplines.
	Cause and consequences are included.	Cannot link data spatially, for example using GIS.
	Bow-tie analysis allows barriers to be inserted to prevent causes and to control consequences.	Bow-ties can become enormous and cumbersome, particularly when large amounts of data are entered.
	They are a combined fault and event-trees.	Bow-ties cannot predict where multiple causes occur simultaneously to cause the consequences.
	They allow graphical representation.	Globally accepted standards describing how to construct the diagrams are limited (Muniz et al., 2018).
	Expert opinion can be included.	
	Software is readily available for example, BowTieXP (CGE Risk Management Solutions, 2018) and BowTie Pro™ (Bow Tie Pro Limited, 2018).	
	Bow-tie analysis is simple to understand and use.	

Technique	Strength	Weakness
Bayesian networks	Have strong quantitative capabilities.	Controls or mitigation are difficult to include
	They can be updated when new knowledge becomes available and they can incorporate uncertainty in data by combining observations, model simulation and expert knowledge (Kragt, 2009).	BNs are complex, and they can be difficult to understand and use.
	They are able to analyse data along two lines, by forward or predictive analysis and by a backward or diagnostic analysis (Bobbio et al., 2001).	Difficulties can be experienced with agreeing on Bayesian network (BN) structure and on defining conditional probability tables (CPTs) with experts (Kragt, 2009). Expert bias or subjectivity may also be a difficulty (Pollino and Henderson, 2010). CPTs may grow exponentially, becoming overly complex, which increases the computational power required to update a BN (Pollino and Henderson, 2010).
	Cause and consequences are included. Learning about causal relationships between variables is facilitated.	Difficulties can occur with continuous data representation and problems with software dealing with this (Kragt, 2009).
	Multidiscipline integration is facilitated. They can break down complex causal chains into components that can be addressed separately (Borsuk et al., 2006).	Feedback loops are not possible (Kragt, 2009).
	They can link spatially via GIS. Software can facilitate this. For example using Netica™ and its add-on package GeoNetica™ (Norsys Software, 2018). Johnson et al. (2012) review good practice examples of where BNs and GIS are integrated. They note that this	Kelly et al. (2013) note the assessment of structural uncertainty as often being neglected, but state that this can be addressed by building and comparing outputs from alternative models based on different hypotheses about the system.

Technique	Strength	Weakness
	can take several forms where nodes of BNs may be spatially or geographically described, or the output of the BN can have a spatial interpretation. Alternatively, a BN can be used to describe uncertainty of geographic information, i.e. GIS can inform BNs and BNs can inform GIS. Several research studies further demonstrate this integration (Aalders, 2008; Aitkenhead and Aalders, 2009; Steiniger and Hay, 2009).	
	They allow graphical representation, which can show links between system components (Kragt, 2009).	A major limitation of BNs is their poor representation of temporal dynamics (Pollino and Henderson, 2010). A BN can't run over several iterations, but represents a change in outcome over a stated period, which needs to be pre-defined.
	They allow for the adoption of improved communication and stakeholder participation (Pollino and Henderson, 2010).	Long chains of nodes have reduced sensitivity to model drivers due to propagation (Pollino and Henderson, 2010). Node chains should therefore be kept short and simple.
	Software is readily available for example, Netica™ (Norsys Software, 2018), Hugin®, (HuginExpert, 2018), and Baysialab (Bayesialab, 2018).	

3.7.1 Fault-tree analysis

Fault-tree analysis (Fig. 3.3) is used for identifying and analysing factors that can contribute to a specified undesired top-event, for example a system failure. Causal factors are deductively identified, organized in a logical manner and represented pictorially in a tree diagram to depict their relationship to the top-event (International Electrotechnical Commission, 2009). The methodology is based on the following assumptions: i) events are binary events (working or not-working); ii) events are statistically independent; and iii) relationships between events and causes are represented by means of logical AND and OR gates (Bobbio et al., 2001).

Event-tree analysis is the converse of fault-tree analysis, it is a graphical technique for representing the mutually exclusive sequences of events following an initiating event according to the functioning or non-functioning of the various systems designed to mitigate its consequences (International Electrotechnical Commission, 2009). Event-tree analysis has not been considered for use, as the rehabilitation risk assessment model will have a greater emphasis on the causes of risk events, i.e. their risk sources, rather than their consequences or sequences of events that follow.

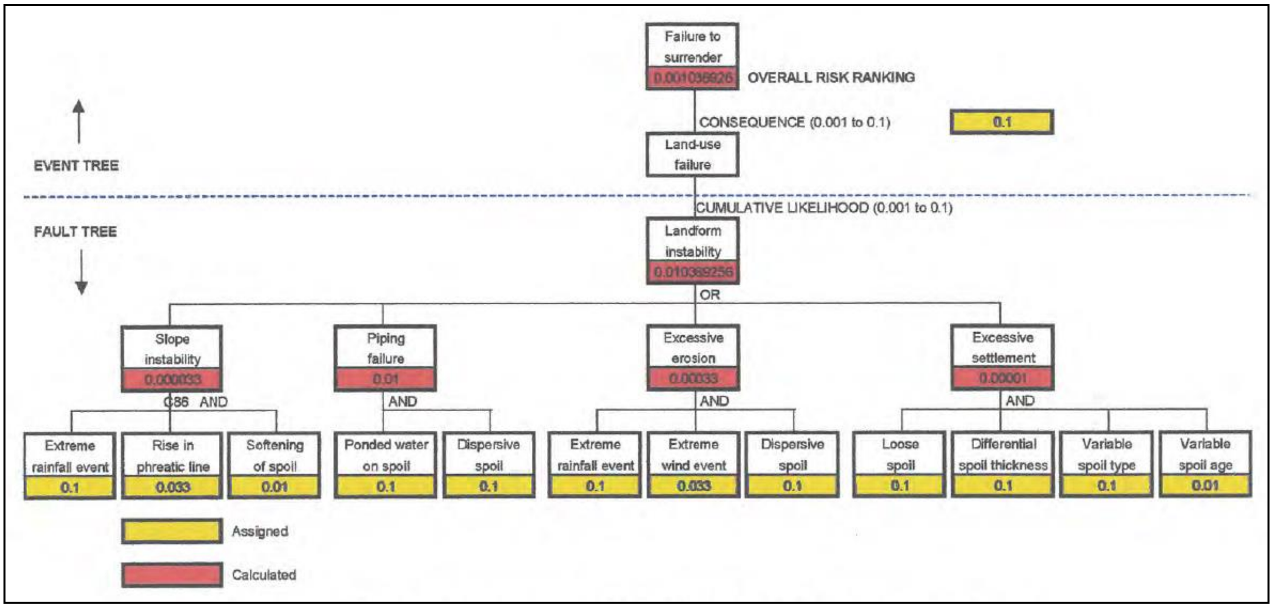
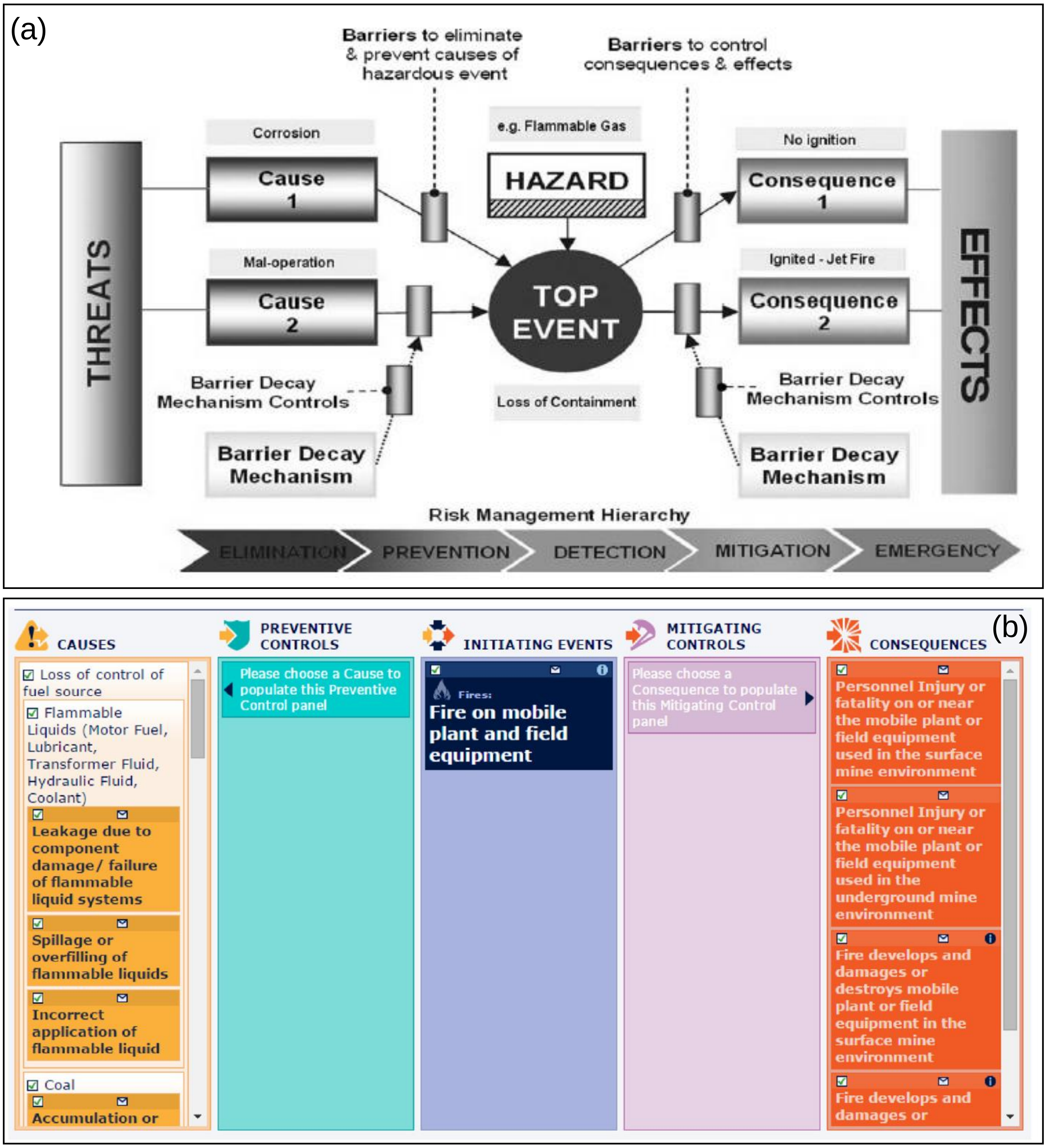


Fig. 3.3 A landform quantitative combined fault and event-tree for risk assessment of spoil rehabilitation in the Bowen basin, Australia. Source: Williams (2001).

3.7.2 Bow-tie analysis

Bow-tie analysis (Fig. 3.4) describes and analyses the pathways of hazards and top events or risks from causes to consequences via a pictorial diagram It is a combination of fault and event-tree analysis but uses bow-ties to focus on the barriers between the causes and the risk and the risk and consequences (International Electrotechnical Commission, 2009). The output is a diagram showing main risk pathways and the barriers in place to prevent or mitigate the undesired consequences or stimulate and promote desired consequences. A hazard is a material, energy source, or activity with a potential for an undesired outcome typically if there is a loss of containment or other form of loss of control, whilst a top event can be thought of as a point in time where there is some change in state that causes a loss of control over the hazard (Pitblado and Weijand, 2014).

Two variants of bow-tie analysis have been used for risk assessment in mining. These include Quantitative Risk Assessment (QRA) and Experience-based Quantification (EBQ) (Australian Government et al., 2016e). The Northparkes and Bronzewing mines in Australia have trialed QRA. The method identifies the incident (or initiating top-event) and then looks at the potential causes, prevention controls, mitigation controls and the range of outcomes. The other variant, EBQ is similar but differs in that it links the bow-tie generator to a spreadsheet that calculates the risk. Software tools are readily available for EBQ.



CAUSES

☑ Loss of control of fuel source

☑ Flammable Liquids (Motor Fuel, Lubricant, Transformer Fluid, Hydraulic Fluid, Coolant)

☑ Leakage due to component damage/ failure of flammable liquid systems

☑ Spillage or overfilling of flammable liquids

☑ Incorrect application of flammable liquid

☑ Coal

☑ Accumulation or

PREVENTIVE CONTROLS

Please choose a Cause to populate this Preventive Control panel

INITIATING EVENTS

☑ Fires:

Fire on mobile plant and field equipment

MITIGATING CONTROLS

Please choose a Consequence to populate this Mitigating Control panel

CONSEQUENCES

☑ Personnel Injury or fatality on or near the mobile plant or field equipment used in the surface mine environment

☑ Personnel Injury or fatality on or near the mobile plant or field equipment used in the underground mine environment

☑ Fire develops and damages or destroys mobile plant or field equipment in the surface mine environment

☑ Fire develops and damages or

Fig. 3.4 Examples using Bow-tie analysis. Bow-tie diagram demonstrating the method (block (a) top). Source: Pitblado and Weijand (2014). Example of RISKGATE system's use of bow-tie analysis (block (b), bottom). RISKGATE has a web-based linked interface. Source: Kirsch et al. (2015).

3.7.3 Bayesian network

A promising technique for use is BNs, which are also referred to as belief or causal probabilistic networks.

A BN consists of a directed acyclic graph (DAG) of “nodes” and connecting “arcs or arrows” that conceptualise a system (Korb and Nicholson, 2011). Parent and child nodes are created (Fig. 3.5), where a parent node represents the causal factors of a child node. Node states and values are set which should be mutually exclusive and exhaustive. States may be: Boolean, i.e. “true” or “false”; ordered values, i.e. “low”, “medium” or “high”; or integral values, i.e. 1 to 120. Nodes are structured to capture the qualitative relationships between the variables. Two nodes may be connected if one affects the other or causes the other, with the arc indicating the direction of the effect. Relationships are quantified between connecting nodes by specifying a conditional probability distribution for each node via an underlying statistical conditional probability table (CPT).

Bayes’ theorem of probability theory is relied on to propagate information between BN nodes (Kragt, 2009). Bayes' theorem is described by Phan et al. (2016) as:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

where P(A) and P(B) are the probabilities of observing A and B without regard to each other; P(AIB) is the conditional probability of A, given B; P(BIA) is the conditional probability of B, given A; and P(BIA)/P(B) is the Bayes factor or likelihood ratio.

Evidence can be entered on any node, regardless of its position in the DAG. This implies that probability updating, or reasoning can happen in the same direction as the arcs (predictive reasoning), or in the opposite direction of the arcs (prescriptive or diagnostic reasoning). Feedback loops are not possible. This concept is illustrated in Fig. 3.5.

Examples of the use of BN are shown in Fig. 3.6.

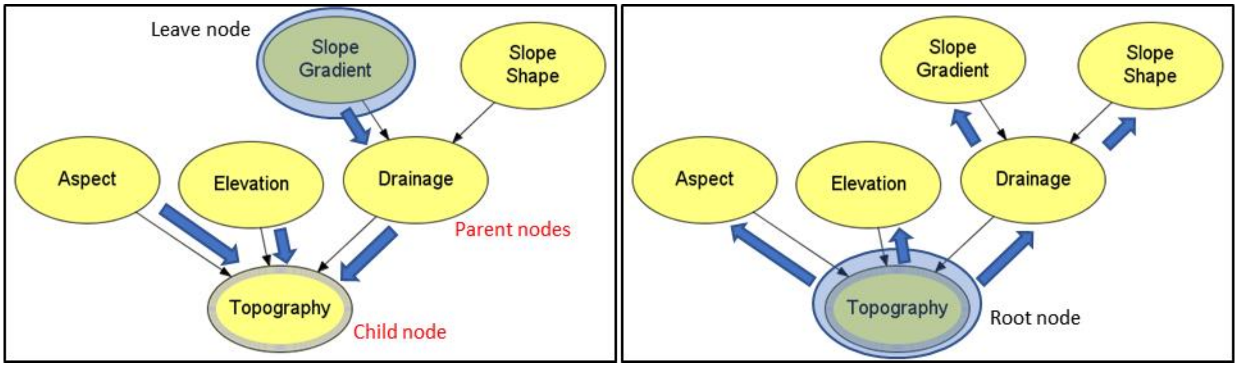


Fig. 3.5 An illustration of the concept of probabilistic inference, the process of updating (also called reasoning or probability propagation). The BN on the left is initiated on a leave node and reasoning occurs in the same direction of the arcs. This is predictive reasoning. In the BN on the right, initiation takes place on a root node and reasoning occurs in the opposite direction of the arcs. This is diagnostic reasoning.

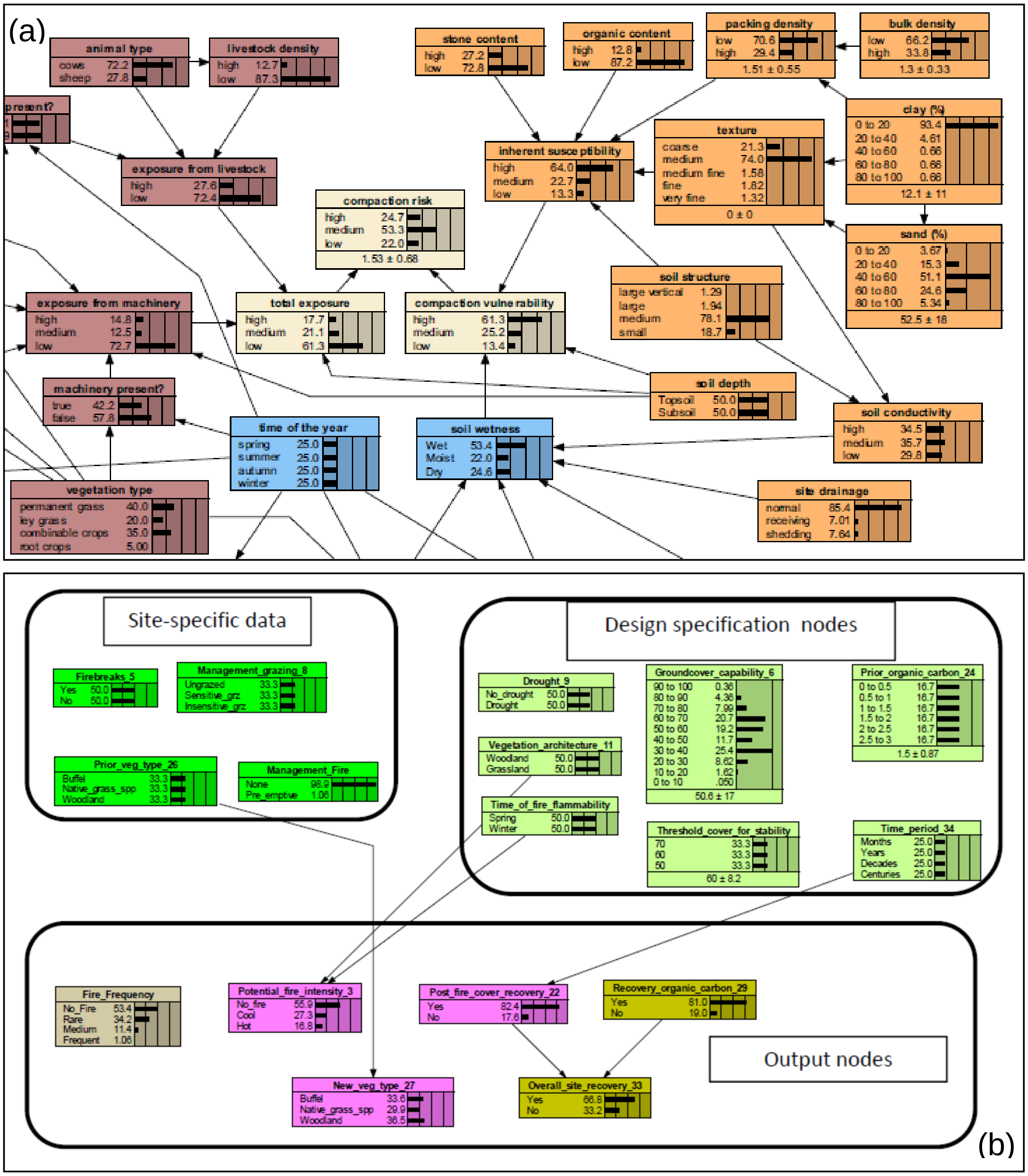


Fig. 3.6 Examples of BNs. Extract of a BN for risk assessment of soil compaction in Scotland (block (a), top). Boxes represent nodes. The numbers in the boxes are the probabilities (%) of the associated state values given average conditions. Blue nodes represent climate variables, orange nodes represent soil variables, red represent land management variables and yellow represents the output query child nodes. Source: Troldborg et al. (2013). Extract of a user's view of a bushfire BN risk model (block (b), bottom). The user enters scenarios by selecting states for the boxes in each of the upper row. Source: Maczkowiack et al. (2013). Netica™ BN software was used in both examples.

3.7.4 Scoring and ranking

The highest score attained was by BNs (68%) (Table 3.3). This was mostly due to the ability of BNs to quantitatively integrate components and to calculate probabilities even under uncertainty when data is unknown. Bow-tie analysis scored the second highest (44%) due to this technique being linear and as relationships between components cannot easily be discerned. Bow-tie analysis allows for the inclusion of barriers of control or prevention, which is not easily achieved using BNs. As bow-tie analysis combines fault and event-trees, it is considered superior to applying fault and event-trees individually. Fault-tree analysis attained the lowest score (41%).

A comparative analysis of the fault-tree and BN approaches by Bobbio et al. (2001) and Khakzad et al. (2011) concur that BNs have more advantages than fault-trees and are therefore likely more suited.

3.8 Mine rehabilitation risk assessment techniques developed by others

Only a few mine rehabilitation risk assessment related techniques, that may be applicable to the proposed model’s development, have been developed by others. These are described, and their applicability evaluated below.

The challenges of integrated modelling in mining regions to address social, environmental and economic impacts was examined by Lechner et al. (2017). The need for inter-disciplinary integration and the assessment of temporal, cumulative and spatial dimensions of social and environmental impacts was identified as lacking in current mine rehabilitation planning. To address this, Lechner et al. (2017) proposed an integrated framework, inclusive of socioeconomic and biophysical issues, using quantitative modelling.

Laurence (2001) developed a classification technique for risk factors associated with mine closure based on the concept of the Closure Risk Factor (CRF). The CRF is a qualitative and quantitative measure that captures significant risk components of mine closure. These components include environmental risks, safety and health risks, community and social risks, final land use risks, legal and financial risks, and technical risks. The CRF is the sum of these. A triple weighting technique is applied where individual components are first assigned a weighting from 1 (minimal risk) to 10 (extreme risk). Secondary and then tertiary issues within these components are further listed and assigned weightings. Weighting are multiplied and summed to provide a closure risk rating. Based on their findings, Laurence (2001) further developed a classification table as a guide to the relationship between the closure risk factor and the risk and complexity of closure.

“RISKGATE”, a health and safety focused technique, used interactive bow-ties, designed to assist with the implementation of safer operations in the Australian coal industry (Kirsch et al., 2012). RISKGATE is web based and provides up-to-date and practical checklists for controlling safety risks across 15 high priority unwanted events. Causal factors and consequences are given for each initiating event and users can generate checklists (Fig. 3.4, block (b)). These are designed to assist with risk assessment, auditing, accident investigation and training on best-practice controls for consideration within their own procedures and practices (Kirsch et al., 2012).

A risk management technique for the comparison and selection of rehabilitation strategies required for the surrender of open cut coal mine spoil areas in the Bowen Basin, Australia was developed by Williams (2001). The semi-quantitative technique incorporated risks and cost-effectiveness as well as stakeholder views in assigning initial likelihood and consequence values. The technique included setting up a combined fault and event-tree as a series of connected boxes in a spreadsheet (Fig. 3.3). Key events (land-use failure and ultimately failure to surrender), causes (landform instability, impact on downstream water and water quality, groundwater impact, failure of the vegetation cover, failure of farmed animals or native fauna, poor perception and negative socioeconomic impact) and sub-causes of these were identified. Probabilities of failure (likelihood) were assigned to the lowest level causes and transferred up the fault-tree. Probabilities were then calculated by a user first rating the combined likelihood and consequence on a 25-point scale and then converting this to logarithmic scales and calculating upper level likelihoods using two sets of equations for AND/OR gates, which link the branches of the fault-tree, to attain overall risk rankings. The overall risk rankings of each main cause were converted back to a 25-point scale and plotted. The technique was developed for application to unmined and mined land and several landuses were included (cropping, doing nothing, forestry, grazing and native habitat). Spoil areas were divided into several domains i.e. external box-cut spoil, internal spoil etc. The risk assessment technique can be applied on a site by site basis, with site specific causal parameters entered. The technique calculates the overall risk ranking for a selected landuse on a selected domain as well as the relative ratings of the seven landuse failure causes. Causes with high relative ratings are targeted for remedial work and the risk assessment can be re-run (Williams, 2001).

Maczkowiack et al. (2013) developed a technique for assessing end-use risks for mined land of the Bowen Basin, Australia and BN risk assessment models for selected end-uses were created (Fig. 3.6, block (b)). A web-based stakeholder survey identified the risks of surface erosion, sub-surface erosion, bushfires, weeds and feral animals and the end-uses of bushland and grazing as being of concern. Conceptual likelihood and consequence risk models were developed. Likelihood was modelled using site characteristics and management factors that influence the occurrence probability of risks like surface erosion, whilst consequence was modelled using a set of site condition indicators and condition thresholds (e.g. changes in root-zone water-holding capacity, soil erodibility, vegetation ground cover and soil organic matter and transition probability to a non-preferred ecosystem type). The factors influencing likelihood and consequence for each risk were integrated using BNs and existing equations, empirical datasets, or expert opinion where data was unavailable was used for parameterisation. The parameterised models assessed grazing and bushland end-uses against erosion, bushfire, weed and feral animal risks for rehabilitated mined land sites, with the purpose of identifying the relative risks associated with each end-use and the landform design specifications and land management practices under which end-use risks could be minimised (Maczkowiack et al., 2012a). Erosion risk was based on the Revised Universal Soil Loss Equation (RUSLE) with expert information supplemented.

Aalders et al. (2011) used BNs to investigate the vulnerability of peat to erosion. Risk source variables included climate, vegetation, topography and soils. A similar study by Troldborg et al. (2013) used BNs to not just focus on one risk, such as erosion, but to ultimately quantify and map areas at risk to multiple soil threats. Soil compaction was used as a case study example (Fig. 3.6, block (a)). Climate, soil (including topography) and land management risk source variables were defined and their contribution to soil compaction risk, vulnerability and exposure was calculated. Other work by Aalders (2008) and Aitkenhead and Aalders (2009) demonstrate how spatial associations using GIS can be incorporated into BNs.

Dale et al. (2018) used BNs to model surface erosion and tunnelling risk for cost-effective management of dispersive mine spoil in Australia. A framework was first developed to capture site characteristics and management interventions based on an expanded form of the Universal Soil Loss Equation (USLE) to include tunnelling influences. The framework was then used to develop a parameterised BN model. The model integrates six key factors which influence the erosion of dispersive mine spoil as identified in the theoretical framework (erosivity, erodibility, landform characteristics, practice control factors, crop management factors, and tunnel initiation factors). Five sub-models were developed to incorporate 104 variables. These included climate (rainfall amount, intensity and timing), spoil characteristics (chemical, physical and spoil amelioration interventions), management practices (landform design, i.e. slope gradient, shape and length; and erosion mitigation, i.e. surface roughness, armouring, run-on controls, contours banks, etc), vegetation management factors, and tunnel initiation factors. The BN model is structured around a risk assessment approach, where risk of surface and tunnel erosion is quantified by combining assessments of “vulnerability or likelihood” comprising the combination of inherent soil erodibility (resistance or susceptibility to erosion), landform design, and soil and vegetation management practices that modify erodibility; and “exposure or consequence” comprising exposure to erosive energy forces (cumulative rainfall, rainfall intensity, frequency, duration). The modelling was informed by an industry survey and field assessments, which were undertaken on seven sites, including: Jeerbropilly (New Hope); Hail Creek (Rio Tinto); Coppabella (Peabody Energy Australia); Oaky Creek (Glencore); Capcoal - German Creek, German Creek East and Lake Lindsay (Anglo American); Foxleigh (previously Anglo American, now Middlemount South owned by Taurus); and Callide (previously Anglo American, now Batchfire). Three field trial sites were also established, across three open cut mines on rehabilitated spoil pits and one underground mine on a spoil stockpile in the Bowen basin. Model sensitivity testing was conducted, and a series of best-case and worst-case model scenarios were run. Independent validation across multiple sites was suggested. Based on the modelling, worst and best-case management practice guidelines are provided.

3.8.1 Evaluation

The techniques by Lechner et al. (2017), Laurence (2001) and Kirsch et al. (2012) are considered the least applicable. The framework by Lechner et al. (2017) is still in its early phase of development. The technique by Laurence (2001) is a triple weighting technique that assesses risks associated with mine closure not rehabilitation. Although Laurence (2001) describes the technique as quantitative, the technique is not based on mathematical formulae. The technique by Kirsch et al. (2012) uses bow-tie analysis, but is focused on health and safety risk and not on mine rehabilitation risk. The technique's accessibility to end users is however of interest, i.e. it is web based and available to Australian Coal Industry's Research Program's members free of charge. The technique is easy to understand and use but is qualitative not quantitative.

The technique by Williams (2001) is considered the fourth most applicable to the model's development. It is focused on surface-strip coal mines in the Bowen Basin, Australia. The technique uses combined fault and event-trees and Microsoft® Excel spreadsheets. The technique incorporates risk sources as a fault-tree and consequences as an event-tree. However, only a few risks are included (landform instability, impact on downstream water and water quality, groundwater impact, failure of the vegetation cover, failure of farmed animals or native fauna, poor perception and negative socioeconomic impact). The technique is difficult to understand and use, particularly as it includes complicated logarithmic scales and equations. The technique is semi-quantitative and is not based on the ISO 31000 Risk assessment process. The technique calculates the overall risk ranking for a selected landuse on a selected domain as well as the relative ratings of the seven landuse failure causes. It is therefore focused on the end land use and not on the risk of rehabilitation based on contributory risk sources.

The technique by Maczkowiack et al. (2013) is considered the third most applicable. It too is focused on surface-strip coal mine rehabilitation in the Bowen Basin, Australia. The technique is fully quantitative, incorporates expert opinion and uses BNs. Maczkowiack et al. (2013) however included only a few risk events: surface and sub-surface erosion; bushfires; weeds; and feral animals and the end objective focused on end land use decisions (bushveld and grazing), with only three contributory risk sources included, i.e. soils, geology and topography. The technique produced not only BN cause models but also consequence models.

The technique by Troldborg et al. (2013) is considered the second most applicable. This technique also used BNs to quantitatively integrate three natural risk sources (soils, topography and climate) and includes an anthropogenic risk source category (land management) to determine one risk event, soil compaction. Individual risk source contributions are however not segregated, with cross-linkages between BN nodes evident. The technique was not applied to mining but is applicable to agriculture in Scotland.

Research by Dale et al. (2018) is considered the most relevant and could complement or inform the development of a rehabilitation risk assessment model. Their work too focuses on surface-strip coal mine rehabilitation in the Bowen Basin, however surface erosion and tunnelling risk are the focus risk event. Only four natural risk sources are included; climate, soils, topography and vegetation. Management risk sources are grouped with natural risk sources. Contributions from individual risk sources are not segregated and analysed individually. Cross-linkage between BN nodes is evident. Dale et al. (2018) followed a similar approach to Troldborg et al. (2013) where the risk was quantified by combining assessments of “vulnerability” and “exposure”. The study was informed by an industry survey and field assessments and trials were undertaken. The outcome of the study was to attain best and worst-case scenarios that could be used to inform a series of best management practice guidelines as related to soil erosion and tunnelling risk. Rehabilitation risk percentages for the soil erosion and tunnelling risk event were not calculated for their individual contributory risk sources, both natural and anthropogenic and validation on mine sites was not conducted. The research by Dale et al. (2018) contains a wealth of soil erosion and tunnelling data.

3.9 Conclusion and recommendations

The ISO 31000 – Risk management standard process, particularly its risk assessment phase is considered essential for inclusion in any rehabilitation risk assessment model’s development. ISO 31000 is well known and used in mine planning.

The most suited technique for the development of a rehabilitation risk assessment model was found to be BNs, which scored 68%. This was as the technique allows multidisciplinary rehabilitation risk sources, both natural and anthropogenic to be integrated, to quantify rehabilitation risk events. The method is graphical and can calculate risk, where data is unknown or missing, based on given probabilities. Expert opinion can enhance data inputs and outputs.

Software is readily available, which can assist with the handling of large amounts of data. The success of using BN has been proven by others (Aalders et al., 2011; Dale et al., 2018; Maczkowiack et al., 2012b; Troldborg et al., 2013). The choice to use BNs best meets the model's aims and the criteria considered important for model inclusion.

Reviewed mine rehabilitation risk assessment techniques developed by others may be applicable to the model's development, however no technique closely aligns to the model's aims and criteria identified for model inclusion, therefore a research gap is confirmed. Some aspects of prior research may however complement or provide linkages, particularly work by Dale et al. (2018).

There is a dire industry need for a rehabilitation risk assessment model. Benefits to mining companies and authorities of quantifying the risks of rehabilitation early could be substantial. Mine sites could be ranked, during mine approval, according to their site rehabilitation risk assessment profiles. Allowing low risk sites to be approved for mining as preferred alternatives and high risk sites to be excluded or mining allowed subject to implementing strict mitigation measures. Model scenario applications during mine operation and progressive rehabilitation could further provide confirmation that chosen management actions would result in low rehabilitation risks, facilitating the progression towards responsible mine closure and relinquishment. Abandoned mines could similarly be ranked from low to high in terms of their rehabilitation risks, aiding prioritisation of which mines to rehabilitate first. Monetary saving could be accrued over the long-term if remedial measures are implemented early or alternative decision choices are made. The incorporation of the concept of restoration or rehabilitation banking, which is the ability of an entity, to gain credits for undertaking proactive restoration or rehabilitation activities, may be a possibility, which could be investigated (Stahl et al., 2008). Once obtained, credits can be applied to an existing liability, held in the event of a future liability, or traded or sold to others that might have need for the credits. Costs and time could further be saved with the streamlining of the terms of references for specialist studies so that critical issues are investigated early and so that specialist studies can be integrated to inform one another, not just focusing on environmental impact assessment, but also the assessment of rehabilitation risks.

3.9.1 Research directions

This paper identified BNs as the most suitable method for model development. It is recommended that a framework be structured first and that a smaller BN proof-of-concept model be developed, based on a single risk event and that this be tested as a case study on mine sites. This would confirm whether BN are indeed the most suitable method to use. Should BNs prove to be unsuitable, bow-tie analysis should be investigated further as an alternative technique to use.

3.10 Acknowledgement

Corinne Unger and Alex Lechner are thanked for offering valuable suggestions regarding the papers structure and content. Alta de Waal is thanked for offering insight into the use of BNs. The University of Pretoria and the Coaltech Research Association are thanked for funding the research. We would like to thank the anonymous reviewers who provided constructive feedback on the manuscript which resulted in significant improvements.

3.11 Disclaimer

The authors declare no conflicts of interest.

3.12 Data accessibility statement

No supplemental data has been included. Should any further information be required this will be made available upon request from the corresponding author, Vanessa D. Weyer, at vweyer@global.co.za.

3.13 References

Aalders, I., 2008. Modeling land-use decision behavior with Bayesian belief networks. Ecol Soc 13, 16 DOI: 10.5751/ES-02362-130116

Aalders, I., Hough, R.L., Towers, W., 2011. Risk of erosion in peat soils – An investigation using Bayesian belief networks. Soil Use Manage 27, 538-549 DOI: 10.1111/j.1475-2743.2011.00359.x

Aitkenhead, M.J., Aalders, I.H., 2009. Predicting land cover using GIS, Bayesian and evolutionary algorithm methods. J Environ Manage 90, 236-250 DOI: https://doi.org/10.1016/j.jenvman.2007.09.010

Anderson, T.R., Butler, A.R., 2017. A standard for design life and durability for engineered mine wastes structures. Journal of Cleaner Production 141, 67-74 DOI: https://doi.org/10.1016/j.jclepro.2016.09.042

Auditor-General South Africa, 2009. Report of the Auditor-General to Parliament on a performance audit of the rehabilitation of abandoned mines at the Department of Minerals and Energy. Auditor-General South Africa, Pretoria, (ZA), p. 22.

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2011. A guide to leading practice sustainable development in mining: Leading Practice Sustainable Development Program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016a. Evaluating performance, monitoring and auditing: Leading Practice Sustainable Development Program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016b. Mine closure: Leading practice sustainable development program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016c. Mine rehabilitation: Leading practice sustainable development program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016d. Preventing acid and metalliferous drainage: Leading Practice Sustainable Development Program for the mining industry. Australian Government Department of Industry Tourism and Resources, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016e. Risk management: Leading practice sustainability program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Tourism and Resources, 2006. Mine rehabilitation handbook: Leading Practice Sustainable Development Program for the mining industry. Australian Government Department of Industry Tourism and Resources, Canberra, (AU), p. 67.

Australian Government Department of Environment, 2014. Subsidence from Coal Mining Activities. Australian Government Department of Environment, Canberra, (AU), p. 82.

Bayesialab, 2018. Bayesialab. [cited 2018 December 3]. http://www.bayesia.com/.

Bobbio, A., Portinale, L., Minichino, M., Ciancamerla, E., 2001. Improving the analysis of dependable systems by mapping fault trees into Bayesian networks. Reliab Eng Syst Saf 71, 249-260 DOI: https://doi.org/10.1016/S0951-8320(00)00077-6

Borsuk, M.E., Reichert, P., Peter, A., Schager, E., Burkhardt-Holm, P., 2006. Assessing the decline of brown trout (Salmo trutta) in Swiss rivers using a Bayesian probability network. Ecol Model 192, 224-244 DOI: https://doi.org/10.1016/j.ecolmodel.2005.07.006

Bow Tie Pro Limited, 2018. BowTie Pro. [cited 2018 November 6]. https://www.bowtiepro.com/software/.

Bowden, A., Lane, M., Martin, J., 2001. Triple Bottom Line Risk Management: Enhancing Profit, Environmental Performance, and Community Benefits. John Wiley & Sons Inc., (US).

Campbell, R., Linqvist, J., Browne, B., Swann, T., Grudnoff, M., 2017. Dark Side of the Boom: What we do and don't know about mines, closure and rehabiliation. The Australian Institute, Canberra, (AU), p. 67.

CGE Risk Management Solutions, 2018. BowTieXP. [cited 2018 October 15]. https://www.cgerisk.com/products/bowtiexp/.

Chamber of Mines of South Africa, 1981. Guidelines for the rehabilitation of land disturbed by surface coal mining in South Africa. Chamber of Mines of South Africa, Johannesburg, (ZA), p. 96.

Chamber of Mines of South Africa, 2007. Guidelines for the rehabilitation of mined land. Chamber of Mines of South Africa, Johannesburg, (ZA), p. 167.

Clemen, R.T., Winkler, R.L., 1999. Combining Probability Distributions From Experts in Risk Analysis. Risk Anal 19, 187-203 DOI: doi:10.1111/j.1539-6924.1999.tb00399.x

Corder, G.D., McLellan, B.C., Green, S., 2010. Incorporating sustainable development principles into minerals processing design and operation: SUSOP®. Miner Eng 23, 175-181 DOI: https://doi.org/10.1016/j.mineng.2009.12.003

Council of Standards Australia & New Zealand, 2009. AS/ NZS ISO 31000:2009, joint Australian New Zealand international standard, risk management - Principles and guidelines, 3 ed. Council of Standards Australia & New Zealand, Sydney, (AU) & Wellington, (NZ), p. 35.

Dale, G., Thomas, E., McCallum, L., Raine, S., Bennett, J., Reardon-Smith, K., 2018. Applying risk-based principles of dispersive mine spoil behaviour to facilitate development of cost-effective best management practices: ACARP C24033. Australian Coal Association Research Program, Brisbane, (AU).

Department of Environmental Affairs, 2015. National Environmental Management Act, No. 107 of 1998. Regulations pertaining to the financial provisions for prospecting, exploration, mining or production operation, Government gazette (39425). 20 November. Government notice no. R1147. Government Printing Works, Republic of South Africa, p. 48.

Department of Mineral Resources, 2009. The national strategy for the management of derelict and ownerless mines in South Africa. Department of Mineral Resources, Pretoria, (ZA).

Department of Minerals and Energy, 1995. Technical guidelines for the environmental management of exploration and mining in Queensland. Department of Minerals and Energy, Brisbane, (AU), p. 12.

Doley, D., Audet, P., 2013. Adopting novel ecosystems as suitable rehabilitation alternatives for former mine sites. Ecol Process 2, 22 DOI: 10.1186/2192-1709-2-22

Erskine, P.D., Fletcher, A.T., 2013. Novel ecosystems created by coal mines in central Queensland’s Bowen Basin. Ecol Process 2, 33 DOI: 10.1186/2192-1709-2-33

Franks, D.M., Brereton, D., Moran, C.J., 2013. The cumulative dimensions of impact in resource regions. Resour Policy 38, 640-647 DOI: https://doi.org/10.1016/j.resourpol.2013.07.002

Government of Western Australia, Department of Mines and Petroleum, Environmental Protection Authority, 2015. Guidelines for preparing mine closure plans. Department of Mines and Petroleum, Perth, (AU).

Government of Western Australia Department of Environmental Regulation, 2016. A guide to preparing revegetation plans for clearing permits, draft v0-3. Government of Western Australia Department of Environmental Regulation, Perth, (AU), p. 43.

Government of Western Australia Environmental Protection Authority, 2006. Guidance for the assessment of anvironmental factors: Rehabilitation of terrestrial ecosystems. Government of Western Australia Environmental Protection Authority, Western Australia, (AU), p. 58.

Hamilton, S.H., ElSawah, S., Guillaume, J.H.A., Jakeman, A.J., Pierce, S.A., 2015. Integrated assessment and modelling: Overview and synthesis of salient dimensions. Environ Model Softw 64, 215-229 DOI: https://doi.org/10.1016/j.envsoft.2014.12.005

Harris, T.M., Zaimes, G.G., Khanna, V., Landis, A.E., 2015. Sunflower Cultivation on Coal Mine Refuse Piles in Appalachia for Diesel Biofuel Production from a Life-cycle Perspective. Procedia Engineering 118, 869-878 DOI: https://doi.org/10.1016/j.proeng.2015.08.525

Howard, E.J., Roddy, B.P., 2012. Evaluation of Water Erosion Prediction Project Model - Validation Data from Sites in Wesyrtn Australia, in: Fourie, A.B., Tibbett, M. (Eds.), Mine Closure 2012. Australian Centre for Geomechanics, Australia, Perth, pp. 81-92.

Hudson, P., 2007. Implementing a safety culture in a major multi-national. Saf Sci 45, 697-722 DOI: 10.1016/j.ssci.2007.04.005

HuginExpert, 2018. Hugin v.8.1. [cited 2018 October 11]. https://www.hugin.com/index.php/2018/03/21/new-release-hugin-v-8-6/.

International Council on Mining and Metals, 2008. Planning for integrated mine closure: Toolkit. International Council on Mining and Metals, London, (UK), p. 86.

International Electrotechnical Commission, 2009. Risk Management - Risk Assessment Techniques, Final Draft, International Standard IEC/FDIS 31010. IEC, Geneva (CH), p. 92.

International Organization for Standardization, 2018. ISO 31000:2018, International Standard, Risk Management - Guidelines 2nd ed. International Organization for Standardization, Geneva, (CH), p. 24.

Johnson, S., Low-Choy, S., Mengersen, K., 2012. Integrating Bayesian networks and geographic information systems: Good practice examples. Integr Environ Assess Manag 8, 473-479 DOI: doi:10.1002/ieam.262

Kelly, R.A., Jakeman, A.J., Barreteau, O., Borsuk, M.E., ElSawah, S., Hamilton, S.H., Henriksen, H.J., Kuikka, S., Maier, H.R., Rizzoli, A.E., van Delden, H., Voinov, A.A., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environ Model Softw 47, 159-181 DOI: https://doi.org/10.1016/j.envsoft.2013.05.005

Khakzad, N., Khan, F., Amyotte, P., 2011. Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. Reliab Eng Syst Saf 96, 925-932 DOI: https://doi.org/10.1016/j.ress.2011.03.012

Kirsch, P., Hine, A., Maybury, T., 2015. A model for the implementation of industry-wide knowledge sharing to improve risk management practice. Saf Sci 80, 66-76 DOI: https://doi.org/10.1016/j.ssci.2015.07.009

Kirsch, P.A., Goater, S., Harris, J., Sprott, D., Joy, J., 2012. RISKGATE: Promoting and Redefining Best Practice for Risk Management in the Australian Coal Industry, In: Proceeding of Coal Operator's Conference 2012. University of Wollongong, Wollongong, (AU), pp. 316-326.

Korb, K.B., Nicholson, A.E., 2011. Bayesian artificial intelligence, 2nd ed. CRC Boca Raton, (FL)

Kragt, M.E., 2009. A Beginners Guide to Bayesian Network Modelling for Integrated Catchment Management, Landscape Logic Technical Report No. 9. Australian Government Department of the Environment, Water, Heritage and the Arts, (AU), p. 22.

Krueger, T., Page, T., Smith, L., Voinov, A., 2012. A guide to expert opinion in environmental modelling and management. Environ Model Softw 36, 1-3 DOI: https://doi.org/10.1016/j.envsoft.2012.01.006

Laurence, D., 2001. Classification of Risk Factors Associated with Mine Closure. Mineral Resources Engineering 10, 315-331 DOI: 10.1142/s0950609801000683

Laurence, D., 2011. Establishing a sustainable mining operation: an overview. Journal of Cleaner Production 19, 278-284 DOI: 10.1016/j.jclepro.2010.08.019

Lechner, A.M., McIntyre, N., Witt, K., Raymond, C.M., Arnold, S., Scott, M., Rifkin, W., 2017. Challenges of integrated modelling in mining regions to address social, environmental and economic impacts. Environ Model Softw 93, 268-281 DOI: 10.1016/j.envsoft.2017.03.020

Limpitlaw, D., Aken, M., Lodewijks, H., Viljoen, J., 2005. Post-mining rehabilitation, land use and pollution at collieries in South Africa, In: Colloquium: Sustainable development in the life of coal mining in South Africa. The South African Institute of Mining and Metallurgy, Boksburg, (ZA), pp. 1-10.

Loch, R.J., 2010. Sustainable landscape design for coal mine rehabilitation: ACARP C18024. Australian Coal Association Research Program, Toowoomba, (AU), p. 101.

Loch, R.J., Howard, E.J., 2018. Material Characterisation - Avoiding Unnecessary Costs and Failures, in: AusIMM (Ed.), From Start to Finish: Life-of-Mine Perspective, Spectrum Series 24. AusIMM, (AU), pp. 3-8.

Maczkowiack, R.I., Smith, C., Erskine, P.D., 2012a. Risk Assessment Models for Post-Mining Land Use, Life-of-Mine 2012 Conference, No 6/2012 ed. The Australian Institute of Mining and Metallurgy, Brisbane, (AU), pp. 33-41.

Maczkowiack, R.I., Smith, C., Erskine, P.D., Mulligan, D., 2013. Risk assessment tools to support end-use decisions for mined land of the Bowen Basin: ACARP C19028. Australian Coal Association Research Program, Brisbane, (AU), p. 158.

Maczkowiack, R.I., Smith, C.S., Slaughter, G.J., Mulligan, D.R., Cameron, D.C., 2012b. Grazing as a post-mining land use: a conceptual model of the risk factors. Agricultural Systems 109, 76-89 DOI: https://doi.org/10.1016/j.agsy.2012.03.002

McCullough, C.D., 2016. Key mine closure lessons still to be learned, in: Fourie, A.B., Tibbett, M. (Eds.), In: Processings of Mine Closure Conference Australian Centre for Geomechanics, Perth, (AU), pp. 319-332.

McCullough, C.D., Harvey, B., Unger, C.J., Winchester, S., McCarthy, B., Coetzee, J., 2018. A perspective on improving sustainable development aspects of life-of-mine practices, in: Australasian Institute of Mining and Metallurgy (AusIMM) (Ed.), From start to finish: Life-of-mine perspective, spectrum series 24. AusIMM, Carlton, (AU), pp. 395 - 400.

Minerals Council of Australia, 1998. Mine rehabilitation handbook. Minerals Council of Australia, Kingston, (AU), p. 112.

Mudd, G.M., 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resour Policy 35, 98-115 DOI: https://doi.org/10.1016/j.resourpol.2009.12.001

Muniz, M.V.P., Lima, G.B.A., Caiado, R.G.G., Quelhas, O.L.G., 2018. Bow tie to improve risk management of natural gas pipelines. Process Safety Progress 37, 169-175 DOI: 10.1002/prs.11901

Norsys Software, 2018. GeoNetica. [cited 2018 October 11]. https://www.norsys.com/WebHelp/NETICA/X_GeoNetica.htm.

Northern Territory Environmental Protection Authority, 2013. Environmental assessment guidelines: Acid and metalliferous drainage, Version 2.0. Northern Territory Environmental Protection Authority, Northern Territory (AU).

Parker, P., Letcher, R., Jakeman, A., Beck, M.B., Harris, G., Argent, R.M., Hare, M., Pahl-Wostl, C., Voinov, A., Janssen, M., Sullivan, P., Scoccimarro, M., Friend, A., Sonnenshein, M., Barker, D., Matejicek, L., Odulaja, D., Deadman, P., Lim, K., Larocque, G., Tarikhi, P., Fletcher, C., Put, A., Maxwell, T., Charles, A., Breeze, H., Nakatani, N., Mudgal, S., Naito, W., Osidele, O., Eriksson, I., Kautsky, U., Kautsky, E., Naeslund, B., Kumblad, L., Park, R., Maltagliati, S., Girardin, P., Rizzoli, A., Mauriello, D., Hoch, R., Pelletier, D., Reilly, J., Olafsdottir, R., Bin, S., 2002. Progress in integrated assessment and modelling1. Environ Model Softw 17, 209-217 DOI: https://doi.org/10.1016/S1364-8152(01)00059-7

Paterson, D.G., Mushia, M.N., Mkula, S.D., 2018. Effects of stockpiling on selected properties of opencast coal mine soils. South African Journal of Plant and Soil, 1-6 DOI: 10.1080/02571862.2018.1493161

Peace, C., 2017. The risk matrix: uncertain results? Policy and Practice in Health and Safety 15, 131-144 DOI: 10.1080/14773996.2017.1348571

Phan, T.D., Smart, J.C.R., Capon, S.J., Hadwen, W.L., Sahin, O., 2016. Applications of Bayesian belief networks in water resource management: A systematic review. Environ Model Softw 85, 98-111 DOI: https://doi.org/10.1016/j.envsoft.2016.08.006

Phillips, H., Uludag, S., Chabedi, K., 2011. Prevention and control of spontaneous comustion: Best practice guidelines for surface coal mines in South Africa. Coaltech Research Association, Johannesburg, (ZA), p. 134.

Pitblado, R., Weijand, P., 2014. Barrier diagram (Bow Tie) quality issues for operating managers. Process Saf Prog 33, 355-361 DOI: 10.1002/prs.11666

Pollino, C.A., Henderson, C., 2010. Bayesian networks: A guide for their application in natural resource management and policy, Landscape Logic Technical Report No. 14. Australian Government Department of the Environment, Water, Heritage and the Arts, (AU), p. 48.

Queensland Government, 2012. Queensland Commission of Audit interim report, June 2012. Queensland Government, Queensland, (AU).

Rethman, N.F.G., 2006. A review of causes, symptoms, prevention and alleviation of soil compaction on mined land. Coaltech 2020, Johannesburg, (ZA).

Römbke, J., Bernard, J., Martin-Laurent, F., 2018. Standard methods for the assessment of structural and functional diversity of soil organisms: A review. Integr Environ Assess Manage 14, 463-479 DOI: doi:10.1002/ieam.4046

Shaw, R., Brebber, L., Ahern, C., Weinand, M., 1994. A review of sodicity and sodic soil behavior in Queensland. Soil Res 32, 143-172 DOI: https://doi.org/10.1071/SR9940143

South African Bureau of Standards, 2009. SANS 31000:2009, South African national standard, risk management - Principles and guidelines, 1st ed. SABS Standards Division, Pretoria, (ZA).

Stahl, R.G., Gouguet, R., DeSantis, A., Liu, J., Ammann, M., 2008. Prospective environmental restoration/restoration up front: A concept for an incentive-based program to increase restoration planning and implementation in the United States. Integr Environ Assess Manage 4, 6-14 DOI: doi:10.1897/IEAM_2007-041.1

Steiniger, S., Hay, G.J., 2009. Free and open source geographic information tools for landscape ecology. Ecological Informatics 4, 183-195 DOI: https://doi.org/10.1016/j.ecoinf.2009.07.004

Tasmania Sustainable Land Use Department of Primary Industries and Water, 2009. Dispersive soils and their management: Technical reference manual. Tasmania Sustainable Land Use Department of Primary Industries and Water, Hobart (AU), p. 40.

Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., Lilly, A., Ball, B.C., Hough, R.L., 2013. Application of Bayesian belief networks to quantify and map areas at risk to soil threats: Using soil compaction as an example. Soil Tillage Res 132, 56-68 DOI: https://doi.org/10.1016/j.still.2013.05.005

Unger, C., Lechner, A.M., Glenn, V., Edraki, M., Mulligan, D.R., 2012. Mapping and prioritising rehabilitation of abandoned mines in Australia, Life-of-Mine The Australasian Institute of Mining and Metallurgy, Brisbane, (AU), pp. 259-265.

Unger, C., Woodley, A., Gillespie, M., Baumgartl, T., Smith, C., Erskine, P., Fletcher, A., 2014. Industry-based Rehabilitation and Closure Knowledge Management System: Scoping Study ACARP C23023. ACARP, Brisbane, (AU), p. 61.

Unger, C.J., Lechner, A.M., Kenway, J., Glenn, V., Walton, A., 2015. A jurisdictional maturity model for risk management, accountability and continual improvement of abandoned mine remediation programs. Resour Policy 43, 1-10 DOI: 10.1016/j.resourpol.2014.10.008

Vacher, C.A., Loch, R.J., Raine, S.R., 2004. Identification and Management of Dispersive Mine Spoils. Australian Centre for Mining Environmental Research, Brisbane, (AU).

Weyer, V.D., Truter, W.F., Lechner, A.M., Unger, C.J., 2017. Surface-strip coal mine land rehabilitation planning in South Africa and Australia: Maturity and opportunities for improvement. Resour Policy 54, 117-129 DOI: https://doi.org/10.1016/j.resourpol.2017.09.013

Williams, D., 2001. Risk Assessment of Bowen Basin Spoil Rehabilitation: ACARP C8039. ACARP, Brisbane, (AU), p. 133.

3.14 Supplemental data

No supplemental data has been included.

3.15 ORCID

Vanessa D Weyer ID https://orcid.org/0000-0003-3960-578X

Synopsis

This paper identified BNs as the most suited technique to use for the development of a rehabilitation risk assessment model. The inclusion of the ISO 31000 – Risk management standard process is considered essential.

No mine rehabilitation risk assessment technique developed by others closely aligns with the model’s aims and identified criteria for model inclusion. Some aspects of prior research may however provide linkages, particularly work by Dale et al. (2018).

The paper recommended that a framework be structured first and that a smaller BN proof-of-concept model then be developed, based on a single risk event and that this be tested as a case study on mine sites to confirm that BN are indeed the best technique for use.

CHAPTER 4:

QUANTIFYING REHABILITATION RISKS FOR SURFACE-STRIP COAL MINES USING A SOIL COMPACTION BAYESIAN NETWORK IN SOUTH AFRICA AND AUSTRALIA: TO DEMONSTRATE THE R^{2}AIN FRAMEWORK

R^{2}AIN Framework and Soil Compaction Bayesian Network

Vanessa D. Weyer,[†] Alta de Waal,[‡§] Alex M. Lechner,[‖#] Corinne J. Unger,[††‡‡] Tim G. O'Connor,[§§] Thomas Baumgartl,[‡‡] Roland Schulze,[‖‖] and Wayne F. Truter,[##]

[†] Centre for Environmental Studies, University of Pretoria, Private Bag X20, Hatfield, Pretoria, 0028, South Africa, e-mail address: vweyer@global.co.za

[‡] Department of Statistics, University of Pretoria, Private Bag X20, Hatfield, Pretoria, 0028, South Africa, e-mail address: Alta.DeWaal@up.ac.za

[§] Centre for Artificial Intelligence Research (CAIR), Pretoria, 0028, South Africa

[‖] School of Environmental and Geographical Sciences, University of Nottingham Malaysia Campus, Semenyih, Selangor, Malaysia, e-mail address: alex.lechner@nottingham.edu.my

[#] Centre for Water in the Minerals Industry, Sustainable Minerals Institute, University of Queensland, St Lucia, Brisbane, Queensland, 4072, Australia, e-mail address: a.lechner@uq.edu.au

[††] University of Queensland Business School, University of Queensland, St Lucia, Brisbane, Queensland, 4072, Australia, e-mail address: c.unger@business.uq.edu.au

[‡‡] Centre for Mined Land Rehabilitation, Sustainable Minerals Institute, University of Queensland, St Lucia, Brisbane, Queensland, 4072, Australia, e-mail addresses: t.baumgartl@uq.edu.au

[§§] South African Environmental Observation Network, P.O. Box 2600, Pretoria, 0001, South Africa, e-mail address: tim@saeon.ac.za

[‖‖] Centre for Water Resources Research, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, 3209, South Africa, e-mail address: schulzer@ukzn.ac.za

[##] Department of Plant and Soil Sciences, University of Pretoria, Private bag X20, Hatfield, Pretoria, 0028, South Africa, e-mail address: wayne.truter@up.ac.za

Published in: *Integrated Environmental Assessment and Management* (2019) 15 (2):190-208

Preface

This chapter consists of a published paper and is cited as follows:

Weyer, V.D., de Waal, A., Lechner, A.M., Unger, C.J., O'Connor, T.G., Baumgartl, T., Schulze, R. and Truter, W.F. 2019. Quantifying rehabilitation risks for surface-strip coal mines using a soil compaction Bayesian network in South Africa and Australia: To demonstrate the R^{2}AIN framework. Integrated Environmental Assessment and Management 15 (2), 190-208. http://dx.doi.org/10.1002/ieam.4128

This paper describes a framework, as a process towards developing several BN risk event models that can amalgamate to form a composite rehabilitation risk assessment model.

A case study soil compaction BN model is used to demonstrate the framework in South Africa on the Kleinkopje mine in the Witbank coalfield and in Australia on the Caval Ridge mine in the Bowen Basin. The framework and soil compaction BN model are aligned with the ISO 31000 risk assessment process.

This paper has several co-authors. The reason for this is that it is a multi-disciplinary paper and that it applies to two countries. Further to enable the development of the framework and the BN soil compaction case study model, the integration of specialist co-author knowledge was necessary. This could not have been achieved without an integrative multi-disciplinary approach.

The following contributions were provided by co-authors:

T. Baumgartl:	Provided soil data for setting the values for the BN nodes and their states and for the universal / site/ regional input data, particularly for Australia;
R. Schulze:	Provided agro-hydrological data for setting the values for the nodes and their states and the universal/ site/ regional input data as related to the South African Quinary catchment database;

A.M. Lechner, C.J. Unger, T.G. O' Connor and W.F. Truter:
Assisted with developing the paper's structure and with reviewing the paper; and

A. de Waal: Assisted with setting up the statistical aspects of the BN models, the CPTs and with commenting on Bayesian network evaluation.

The conceptualisation of the paper, the data analysis and the actual article writing was conducted by me. The BN model's main structure, its nodes and input state values were developed mostly by me, except where specialist assistance was required from T. Baumgartl, R. Schulze and A. de Waal, the contributions of which are stated above.

4.1 Abstract

Environmental information is acquired and assessed during the environmental impact assessment process for surface-strip coal mine approval. However, integrating these data and quantifying rehabilitation risk using a holistic multidisciplinary approach is seldom undertaken. We present a rehabilitation risk assessment integrated network (R^2AIN™) framework that can be applied using Bayesian networks (BNs) to integrate and quantify such rehabilitation risks. Our framework has 7 steps, including key integration of rehabilitation risk sources and the quantification of undesired rehabilitation risk events to the final application of mitigation. We demonstrate the framework using a soil compaction BN case study in the Witbank Coalfield, South Africa and the Bowen Basin, Australia. Our approach allows for a probabilistic assessment of rehabilitation risk associated with multidisciplines to be integrated and quantified. Using this method, a site's rehabilitation risk profile can be determined before mining activities commence and the effects of manipulating management actions during later mine phases to reduce risk can be gauged, to aid decision making.

4.2 Key points

- An integrated mine rehabilitation risk assessment (R^2AIN) framework is described.
- The framework was designed for surface-strip coal mine rehabilitation planning.
- A soil compaction Bayesian network is demonstrated in South Africa and Australia.
- Probabilistic predictions for rehabilitation risk are achievable using this process.
- Research directions to develop a fully synthesised R^2AIN model are discussed.

4.3 Keywords

Integrated models and frameworks Multidisciplinary mine rehabilitation planning Cumulative effects Risk assessment Mine closure

4.4 Introduction

Surface-strip coal mining is a highly destructive land use, more so than underground coal mining (Tongway and Ludwig, 2011). During the process of removing coal, wastes are placed above ground, exposing them to weathering with toxicity problems likely. Extensive changes to landcover and drainage also occur. Rehabilitation aims to ameliorate these, at times, dramatic changes and helps anthropomorphic landscapes to blend back into their regional context.

The need to evaluate risks associated with mine rehabilitation, as part of closure and postclosure risk, is stipulated by leading practice guidelines and legislation (Australian Government et al., 2016a, b, c; Chamber of Mines of South Africa, 2007; Department of Environmental Affairs, 2015; International Council on Mining and Metals, 2008). Despite being advocated, rehabilitation risk assessment is however conducted with minimum requirements being met. Weyer et al. (2017) found that guidelines and consultants' approval reports for rehabilitation of surface-strip coal mines in South Africa and Australia fall between vulnerable and adequate but are not yet resilient. Information is gathered, but seldom analysed, with limited integration and rehabilitation risk determination. Others further concur that rehabilitation risk is rarely addressed early in mining operations (Corder et al., 2010; McCullough et al., 2018).

Risk is defined by the International Organization for Standardization (2018) as the effect of uncertainty on objectives. An effect is a deviation from the expected, which can be positive or negative or both. Objectives can have different aspects and categories, and these can be applied at different levels. Risk is expressed in terms of risk sources, potential events, their consequences, and their likelihood. The Council of Standards Australia & New Zealand (2009) define an "event", (also an "incident" or "accident") as an occurrence or change in circumstances that may have several sources and causes. Risk is characterised by reference to these potential events.

In the context of mine rehabilitation, a potential unwanted risk event could include soil compaction, soil erosion, or landform failure, among others. Sources of these events could emanate from inherent preexisting site conditions, derived from the site's geology, soils, topography, climate, vegetation, and landcover or from site mining management actions. For any site, if rehabilitation risk is not addressed and rehabilitation consequently fails, that site is unlikely to support a sustainable postmining land use identical or similar to that which existed premining (e.g., agriculture or natural vegetation); rather a novel system is likely to emerge (Doley and Audet, 2013). Risk profiles, describing a set of risks, are also stipulated by International Organization for Standardization (2018). Risk events determine the overall level of site rehabilitation risk, that is, a site's risk profile, that should be constrained by addressing individual and collective or interacting risk events.

Soil compaction is regarded as a common and severe risk event of mine rehabilitation, which can contribute to rehabilitation failure (Anglo Coal Environmental Rehabilitation Improvement Group, 2009; Chamber of Mines of South Africa, 2007; Minerals Council of Australia, 1998; Rethman, 2006; Saperstein et al., 1991). Soil is a nonrenewable resource and the prevention of soil compaction is important, inter alia for future global food security (Hamza and Anderson, 2005; Lal, 2009; Mueller et al., 2010; Nawaz et al., 2013) but also for protecting the soil resource and preventing negative consequences to the environment (Alaoui et al., 2018). Soil compaction adversely affects soil storage and supply of water and nutrients through increasing soil bulk density and soil strength and decreasing porosity, soil water infiltration, and water holding capacity. As a result, plant water and nutrient use efficiency, and plant growth and production are reduced, while the risk of water-logging, runoff and soil erosion are increased (Hamza and Anderson, 2005). Soil compaction may result from natural and/ or anthropogenic risk sources, with anthropogenic risk sources having more severe consequences (Batey, 2009; DeJong-Hughes et al., 2001; Limpitlaw et al., 2005; Nawaz et al., 2013). Natural risk sources are mainly related to soil properties and climate variables, while anthropogenic risk sources are linked to management practices and machinery use (Batey, 2009; DeJong-Hughes et al., 2001). Natural and anthropogenic risk sources interact and may combine to influence soil compaction (Troldborg et al., 2013).

Integrated environmental assessment and modelling can assist with joint consideration of natural and anthropogenic risk sources, during all mine phases, to indicate soil compaction risk. Integrated assessment is a process that combines multiple and diverse components across their social, organisational, and conceptual boundaries to provide a comprehensive analysis of the problem (Hamilton et al., 2015). Integrated modelling facilitates this, by providing a single platform to explore the linkages and feedbacks amongst different system components, including social, economic, and ecological aspects of natural or anthropogenic factors (Hamilton et al., 2015). Some researchers refer to integration as cumulative effects or impacts (Franks et al., 2013).

Several integrated frameworks and models have been developed for natural resource management (Ban et al., 2013; Barton et al., 2012; Borsuk et al., 2012; Farmani et al., 2012; Henriksen et al., 2012; Johnson and Mengersen, 2012; Koen et al., 2017; Uusitalo et al., 2012; van Delden et al., 2007; Varis et al., 2012). Few have, however been developed for mining applications (Kirsch et al., 2014; Lechner et al., 2017; Maczkowiack et al., 2013; Williams, 2001), and even fewer that are specific to soils. Bayesian networks (BNs) were used to investigate the vulnerability of peat to erosion (Aalders et al., 2011) and for assessing the risk of soil degradation, particularly soil compaction (Troldborg et al., 2013). The present research was in response to a need to identify “risk areas” as part of the European Union Soil Framework Directive (European Commission, 2006) and focused on agriculture in Scotland, but the approach is applicable to other land uses and threats, including mining and rehabilitation failure. BNs are the most popular risk assessment technique used in these integrated frameworks and models mentioned, although other potential tools are available that could have been used, such as bow-ties analysis, fault and event trees, and failure mode effect analysis.

Bayesian networks are graphical models for reasoning under uncertainty, in which nodes represent a set of random variables, whilst connecting arrows or arcs represent direct causal connections between them, in directed acyclic graphs. The quantitative strength of the connections between variables is modelled, using probability calculus, allowing probabilistic beliefs about them to be updated automatically, as new information becomes available (Korb and Nicholson, 2011; Xu et al., 2016). Due to their ability to deal with uncertainty in a natural way, BNs are advantageous (Barton et al., 2008). Further they can combine data with expert knowledge (Pollino et al., 2007); they provide a high level of prediction accuracy, despite small sample sizes and/or incomplete data sets (Renken and Mumby, 2009); variables can be specified as probability distributions, conditional on the configuration of parent variables (Barton et al., 2008); and they facilitate integrated modelling (Borsuk et al., 2004; Kragt et al., 2011). We present a similar framework approach to that of Troldborg et al. (2013), together with a case study using a BN model. Our approach differs in that our framework and model's design is aligned with leading practice, mine approval, environmental impact assessment and mine rehabilitation processes. It further incorporates multidiscipline integration with familiar risk assessment concepts.

In the present paper we therefore describe a framework that can be applied using BNs to integrate and quantify rehabilitation risk to support surface-strip coal mine rehabilitation planning decisions. We demonstrate its application using a BN case study, by assessing a single component of that framework, namely, a soil compaction risk event. We develop the soil compaction BN structure, quantify it using expert knowledge, and gauge its utility by field testing it on 2 mines, with differing site characteristics, 1 mine situated in South Africa and the other in Australia. We validate the BN by conducting sensitivity analysis and accuracy testing concurrently with field testing. Soil compaction premining phase "vulnerability probabilistic" risk predictions, as well as mining to postmining phase "diagnostic or prescription probabilistic" risk predictions, are demonstrated. Rehabilitation risk profile calculations for each mine are provided. We conclude by discussing research directions leading towards the development of a fully synthesised model emanating from the framework presented.

4.5 Framework development

Framework development is the first step in quantitative modelling (Argent et al., 2016; Gupta et al., 2012; Liu et al., 2008; McCann et al., 2006). The Rehabilitation Risk Assessment Integrated Network (R^2AIN) framework (Fig. 4.1) was developed to support the assessment of mine site rehabilitation risk, both at the premining phase and for different management scenarios during the mining to postmining phases.

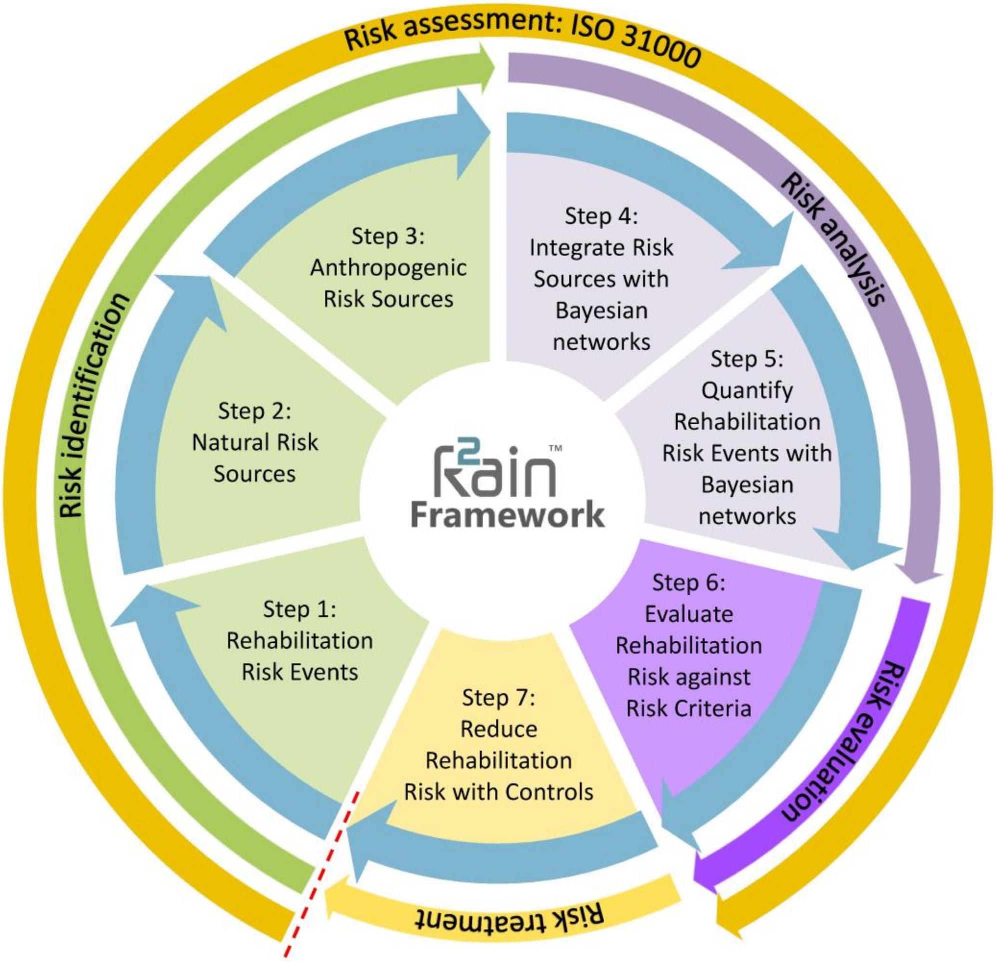


Fig. 4.1 Visual representation of the 7-step R^{2}AIN framework (inner ring). Alignment is illustrated with the ISO 31000 - Risk management standard process (outer two rings).

The framework is applied using a 7-step process: 1) identify rehabilitation risk events of potential concern; identify natural 2) and anthropogenic 3) risk sources relevant to each identified risk event; 4) integrate risk sources using BNs; 5) quantify each rehabilitation risk event using BNs and sum their cumulative values; 6) evaluate rehabilitation risk against known risk criteria; and 7) reduce rehabilitation risk, with controls, which could include adapting management actions from identified anthropogenic sources. These steps are triggered by the detection of undesired rehabilitation risk events, allowing for the assessment of their sources, to quantifying their end effect, until lastly, mitigation is applied to reduce possible risk.

The framework is consistent with the ISO 31000 - Risk management standard process (Council of Standards Australia & New Zealand, 2009; International Organization for Standardization, 2018; South African Bureau of Standards, 2009), where risk assessment includes risk identification, analysis, and evaluation (Fig. 4.1, outer two rings). Framework steps 1, 2 and 3 are part of the risk identification process, defined by ISO 31000 as finding, recognising and describing risks, encompassing the identification of risk sources, events, their causes and their potential consequences. A risk source is defined as an element that, alone or in combination with other sources, has the potential to give rise to risk; for example, geology, soil and climate. Wet soil is a risk source for soil compaction, as an example. An unwanted event is defined as an occurrence or change of circumstances that may have several causes and consequences. Framework steps 4 and 5 perform a risk analysis, which characterises the nature and level of risk and includes risk estimation. Framework step 6 is part of risk evaluation, where the results of the risk analysis process are compared with risk criteria to determine whether the risk and/ or its magnitude is acceptable or tolerable. This step enables decisions to be made about the significance of the risk and the requirement, or otherwise, for risk treatment. Framework step 7, to reduce rehabilitation risk with controls, falls within the ISO 31000 risk treatment process, the purpose of which is to select and implement options for addressing risk. The International Organization for Standardization (2018), also describes an ongoing process of monitoring and review, which connects with all risk processes. To facilitate an improved understanding of concepts, we will describe the R^{2}AIN framework in greater detail in the following sections. Specific examples will be provided of how the framework could be applied using BN modelling.

4.5.1 Step 1: Identify rehabilitation risk events

Rehabilitation risk events are categorised into 3 risk event domains: 1) substrate or soil failure, 2) water failure, and 3) vegetation failure (Fig. 4.2). This categorisation is based on the view that rehabilitation starts from the bottom up, and that if you can get the substrate or soil correct and reduce risks here, you will likely achieve a successful outcome with vegetation establishment.

Water is the interface between the two and it is therefore important that risks are minimised in this domain too. Relationships exist between the domains, with feedback mechanisms affecting restoration success (Perring et al., 2015). The 3 risk event domains are categorised further into 7 risk event types (Fig. 4.2). Risk events are then ordered within these types in levels from L1 (low risk) to L6 (high risk), based on their importance as a contributor to rehabilitation failure. As noted previously, soil compaction is regarded as a severe risk event that can contribute to rehabilitation failure. Soil compaction has therefore been classed as high risk (highlighted red in Fig. 4.2). All identified rehabilitation risk events require the development of separate BN component models, and each should be capable of computing an end risk percentage. Risk events falling in the L6 level should be prioritised. To quantify a site's cumulative rehabilitation risk, and hence to create a fully synthesised model, requires the coupling of all contributing rehabilitation risk event BN component models. Listed risk events are dynamic; as the full model evolves, additional risk events may be identified, and some may become redundant. Continuous updating of these will be required.

4.5.2 Step 2 and 3: Identify natural and anthropogenic risk sources

Rehabilitation risk was assessed for the premining to postmining phases through identifying first the natural and then the anthropogenic risk sources (Fig. 4.2). The natural risk source identification process is applicable mostly to the premining environmental baseline. Natural risk sources fall within 7 types: geology, soils, topography, vegetation, hydrology, climate and land cover. These conform with the "environmental domain evaluative criteria" defined by Weyer et al. (2017), who emphasized their importance as foundation rehabilitation factors. They influence the potential for rehabilitation failures as well as opportunities because they determine the long-term viability of land for sufficient ecosystem restoration and are important for building a landscape from the bottom up. The 7 types enable a linkage with the multidisciplinary specialist studies that are undertaken as part of the mine approval phase.

Anthropogenic risk sources fall within 5 types: machinery management, soil management, slope management, site disturbance, and site contamination. These are based on mine planning and design, as well as actions that carry risk from human error, which may affect risk events.

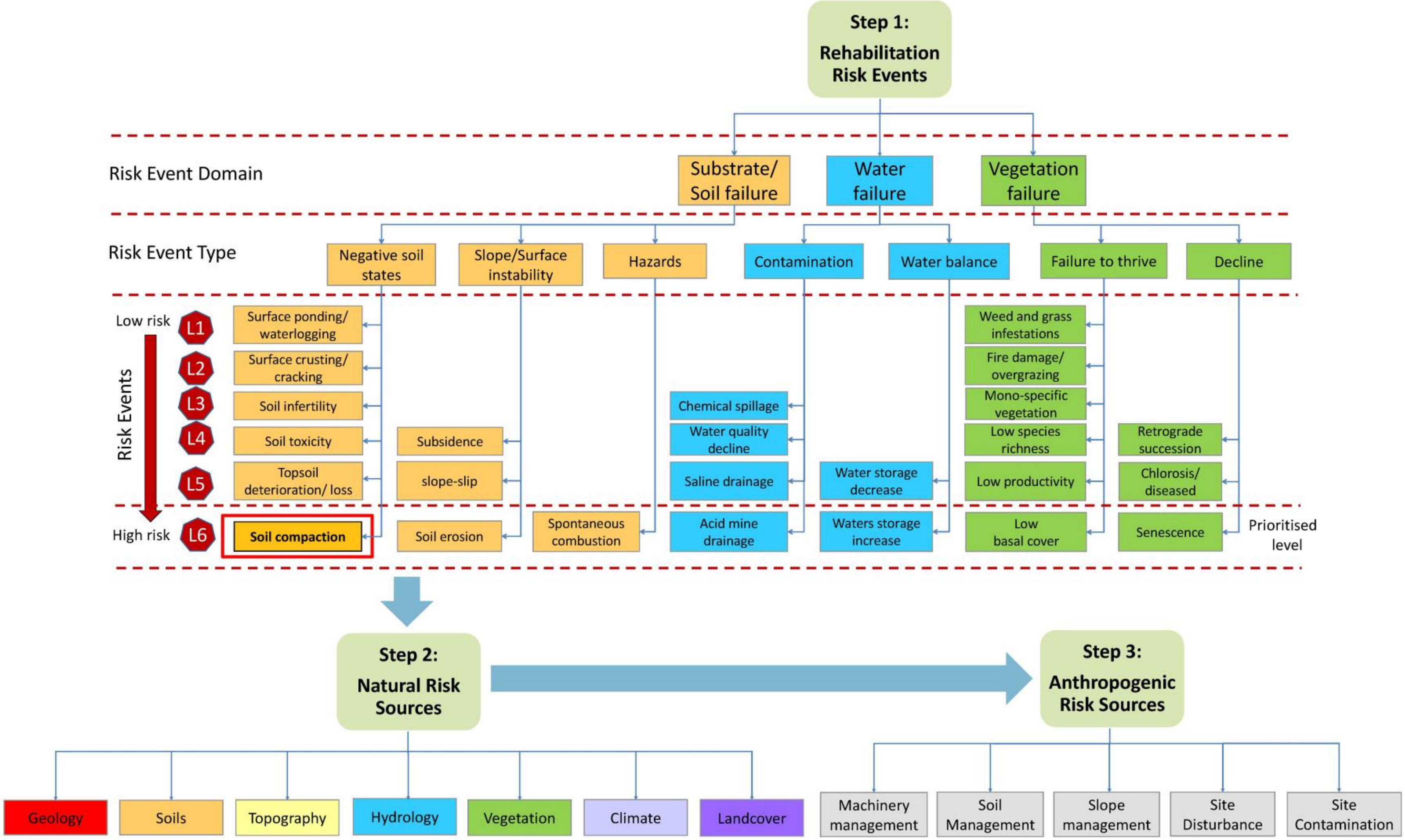


Fig. 4.2 Rehabilitation risk event categories (step 1), and as ordered in levels from L1 (low risk) to L6 (high risk). Soil compaction, the subject of this paper, highlighted red, falls within the high risk L6 level. Natural and anthropogenic risk source categories are shown under step 2 and 3 respectively.

The natural and anthropogenic risk source identification processes may be undertaken individually or collectively for each mine phase assessment outcome. Not all identified categories may be applicable to each rehabilitation risk event being evaluated.

4.5.3 Steps 4 and 5: Integrate risk sources and quantify risk events with BNs

Risk source integration (step 4) and quantification of risk events (step 5) are undertaken using BNs. This involves the conceptual qualitative component and the quantitative component of the BN model development process, respectively. These processes are demonstrated and described in the soil compaction risk event case study.

4.5.4 Step 6: Evaluate rehabilitation risk against risk criteria

During step 6, the results from the integration of the identified risk sources (step 4) and the quantification of the risk events (step 5) are compared against defined “rehabilitation risk criteria” (RRC), that is, acceptable quantitative levels of risk outcome, to determine whether the risk or its magnitude is acceptable or tolerable. At present, RRC have not been defined as they lie outside the scope of the present research. During the next phase of research, RRC need to be developed. This evaluation will aid decisions about risk treatment and the application of controls that take place in step 7. A body of research exists for rehabilitation completion criteria and performance indicators, rehabilitation and restoration monitoring, Australian ecological restoration standards, soil condition, and geomorphic stability (Blommerde et al., 2015; Hancock et al., 2003; McDonald et al., 2016; Tongway and Hindley, 2004). However, these are not specific to “rehabilitation risks”. As individual risk event BN models are developed and tested by industry, within the R^2AIN framework, the outcomes could be used to develop acceptable RRC. These could then be used to specify performance-based rehabilitation completion criteria.

4.5.5 Step 7: Reduce rehabilitation risk with controls

To prevent or reduce rehabilitation risk, controls must be applied. Controls may include taking a “no-go” decision not to develop a high-risk site, developing a lower risk portion of a site, or preventing or reducing rehabilitation risk with mitigation or by manipulating management actions within the identified anthropogenic risk sources. The effects of manipulating management actions are demonstrated and described in the section on management scenarios in the case study results and discussion.

4.6 Case study: Soil compaction risk event

In the previous section, soil compaction was identified as an L6 high risk, that is, a risk event of concern, and prioritised for BN component model development. In this section, we illustrate step 4 integration and step 5 quantification of the R^2AIN framework by developing soil compaction BN models for 2 mine sites (Fig. 4.3). The first site is Anglo American’s Kleinkopje (now Khwezela Bokgoni) Colliery, which is situated in the Witbank Coalfield, Mpumalanga Province, South Africa (26°0'38.33"S 29°13'25.50"E). The second site is the Caval Ridge coal mine of BHP Billiton Mitsubishi Alliance Coal Operations (BMA), which is situated in the Bowen Basin, Queensland, Australia (22°8'40.33"S 148°3'52.08"E). South Africa and Australia were chosen for comparison, to establish the extent of regional applications of the R^2AIN framework and its BN component models. The chosen sites have very different site characteristics, allowing final model outcomes to be confirmed. A rehabilitation risk of concern, associated with Kleinkpopje, is likely to be soil compaction because it is well known that South African soils other than the Vertisols, are highly susceptible to compaction (Chamber of Mines of South Africa, 2007). Caval Ridge is likely to be affected more by soil erosion, due to the common occurrence of sodic soils in Australia, which typically produce high rates of runoff and erosion (Dale et al., 2018; Loch, 2010; Shaw et al., 1994).

4.6.1 Integrate natural and anthropogenic risk sources with BNs

Step 4 of the R^2AIN framework is the integration of risk sources using BNs. The Knowledge Engineering for Bayesian Networks (KEBN) process by Korb and Nicholson (2011) was used to develop the BN models. This process describes the development of a BN as starting with defining the nodes and their states. For the soil compaction models, nodes represent risk sources and variables that influence them. The states of a node are defined as the possible mutually exclusive states in which that node can exist. The second step is to connect the nodes with directed arcs. Two nodes may be connected if one affects the other or causes the other, with the arc indicating the direction of the effect. In other words, the arcs in the BN structure indicate causal connections between the nodes. The result of this step is a BN structure that captures the qualitative information of the model.

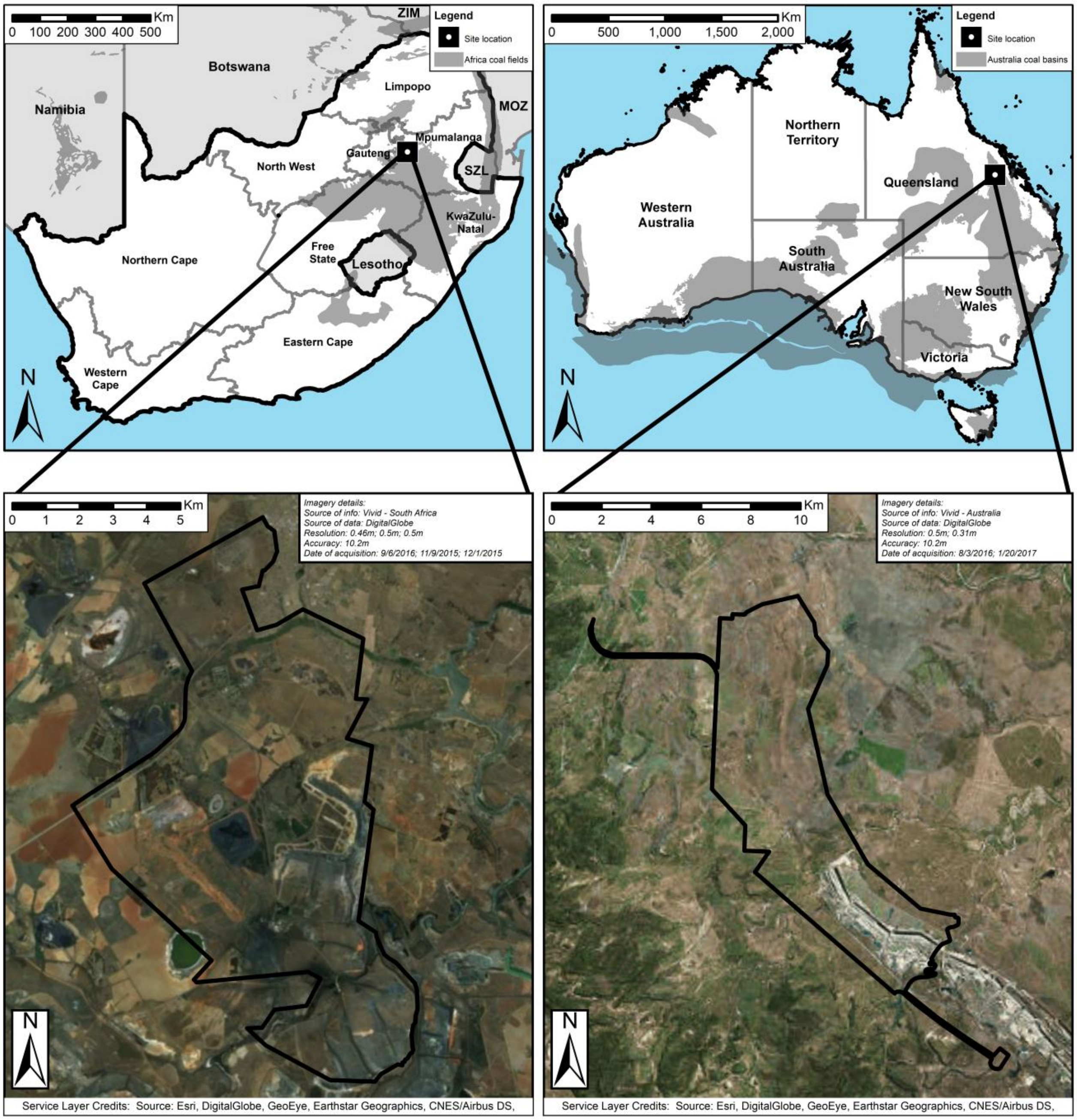


Fig. 4.3 Location and context of the Kleinkopje mine in South Africa (left) and the Caval Ridge mine in Australia (right). Source spatial datasets: Coal-bearing areas in Africa (Merrill and Tewalt, 2008), Australian coal basins (Geoscience Australia, 2013), and aerial photograph sources as noted on images.

We developed 2 soil compaction BN models using Hugin v.8.1. educational software (HuginExpert, 2018): one for the premining phase and another for the mining to postmining phase (Fig. 4.4). For the premining phase BN model, relevant natural risk sources were included: topography (block 1), vegetation (block 2), hydrology (block 3), soils (block 4) and climate (block 5). The premining phase model may also be described as representative of inherent rehabilitation risk. The natural risk sources were integrated as component models to the target node “premining soil compaction risk” (block a). For the mining to postmining phases BN model, the premining phase BN model was combined with an anthropogenic risk sources BN component model, which included machinery (block 6) and soil management (block 7) risk sources. The target node is “mining to postmining soil compaction risk”.

Variables for all risk source component model nodes, their states and values, can be found in Table 4.1 and 4.2. The full versions of these tables, including their supporting references can be found in Supplemental Data Appendix 4.2. States were defined as L-low, M-medium and H-high (in some cases only low and high), to align with mine approval environmental impact assessment and rehabilitation process terminology. Values were defined based on universal parameters (i.e., can be applied to any region and include well-known specialist terminology) or regional South African and Australian parameters. All the end nodes of the component models were set as percentage risk, ranging from 0 to 100 in discretised states, to quantify risk individually for each component model.

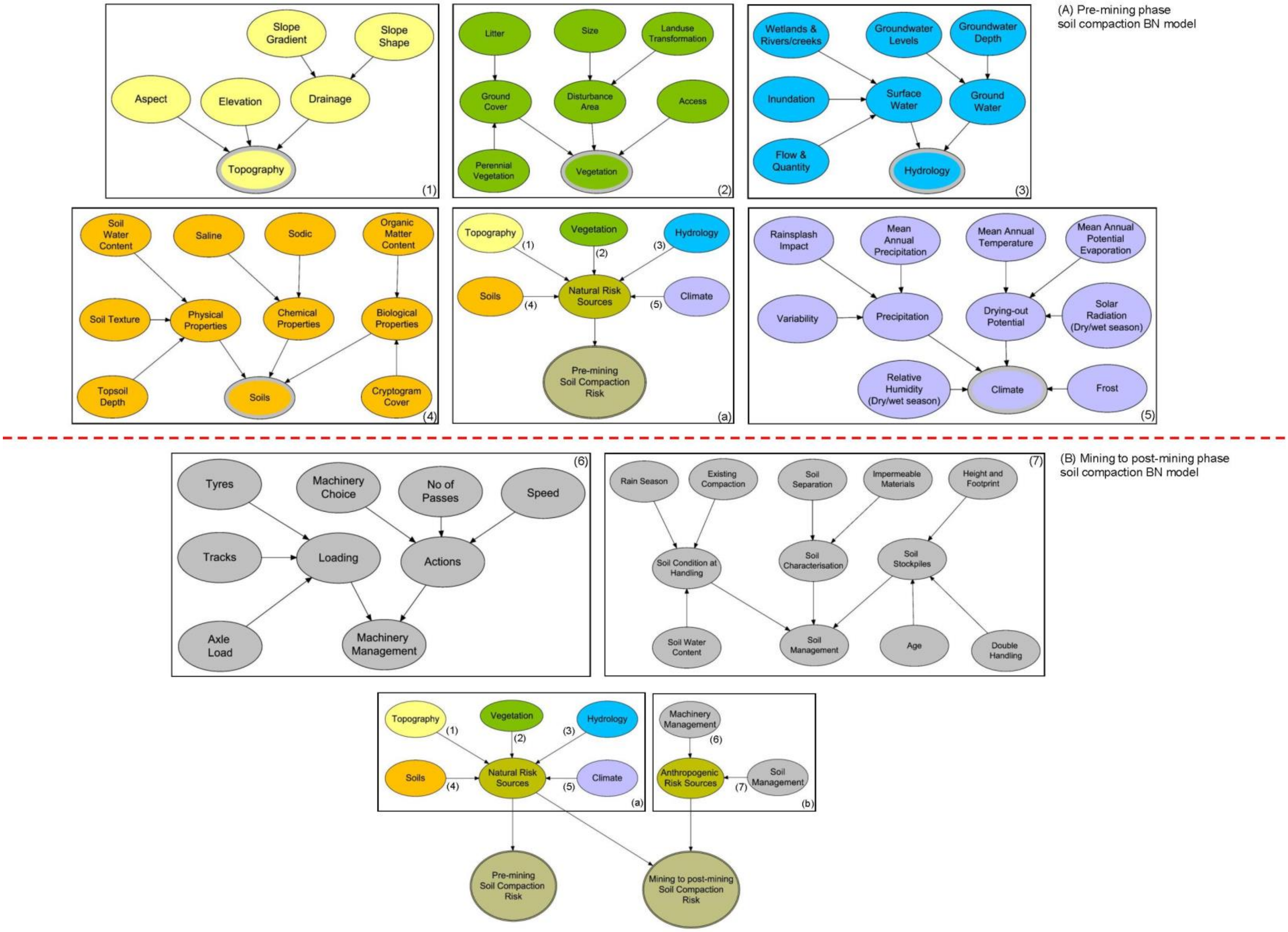


Fig. 4.4 Premining phase soil compaction BN model (A, top section). Natural risk sources are integrated as component models: topography (block 1), vegetation (block 2), hydrology (block 3) soils (block 4), and climate (block 5) to the target node “pre-mining soil compaction risk” (block a). Mining to postmining phase soil compaction BN model (B, bottom section). The premining phase BN model (block a) was combined with an anthropogenic risk sources BN component model (block b), which included machinery management (block 6) and soil management (block 7) risk sources. The target node is “mining to post-mining soil compaction risk”. BN = Bayesian network.

Table 4.1 Natural risk source component model nodes, states and their values

Nodes	**States and #values[a]**	**Nodes**	**States and #values[a]**
SOILS	% risk	**SOILS**	% risk
Physical properties	L risk H risk	**Chemical properties**	L risk H risk
PAW (Note: PAW could replace the: Soil water content, Soil texture and Topsoil depth nodes.) PAW has not been used in the soil compaction BN model.	L (<20-40 mm.m^{-1}, SA) M (40-60 mm.m^{-1}, SA) H (60 to >100 mm.m^{-1}, SA) Regional values. L (<100 mm.m^{-1}, AU) M (100-200 mm.m^{-1}, AU) H (>200 mm.m^{-1}, AU) Regional values.	Saline	L (chloride levels >0.5% or EC >8-16 dS/cm, SA, AU) M (chloride levels >0.2% or EC >4-8 dS/cm, SA, AU) H (not saline <4 dS/cm, SA, AU) Universal values.
Soil water content	L (wilting point, –1500 kPa, SA, AU) M (field capacity, -5 to -55 kPa, SA, AU) H (saturated, SA, AU) Universal values.	Sodic	L (not sodic, SA, AU) M (sodic ESP >6, SA, AU) H (strongly sodic ESP >15, SA, AU) Universal values.
Soil texture	L (light: sands and loamy sands, SA, AU) M (medium: loamy sands, clayey sands, and sandy loams, SA, AU) H (heavy: loams, clay loams and clay soils, SA, AU) Universal values.	**Biological properties**	L risk H risk

Nodes	**States and #values**[a]	**Nodes**	**States and #values**[a]
Topsoil depth	L (0.25–0.6 m, arable land, SA, AU) H (0.15-0.25 m, wilderness and grazing land, SA, AU) Regional values. or L (Class I-IV, suitable for cultivation, AU) H (Class V-VIII, not suitable for cultivation and grazing AU) Regional values.	Organic matter content	L (1.6 to >7%, SA, AU) H (< 1-1.6%, SA, AU) Universal values.
		Cryptogram cover	L (10 to >50% contribution, SA, AU) H (1 to 10% contribution, SA, AU) Universal values.
TOPOGRAPHY	% risk	**TOPOGRAPHY**	% risk
Aspect	L (north hot and dry, SA, AU) M (east, west or flat, SA, AU) H (south cold and wet, SA, AU) Universal values.	**Drainage**	L risk H risk
Elevation or altitude	L (0-600 m, SA) M (600-1250 m, SA) H (1250-2500 m, SA) Regional values. L (0-300 m, AU) M (300-600 m, AU) H (>600 m, AU) Regional values.	Slope gradient	L (<33% or <1:3, SA, AU) M (20% or 1:5, SA, AU) H (>1% or 1:100, SA AU) Universal values.

Nodes	**States and #values[a]**	**Nodes**	**States and #values[a]**
		Slope shape	L (convex, SA, AU) M (rectilinear, SA, AU) H (concave, SA, AU) Universal values.
VEGETATION	% risk	**VEGETATION**	% risk
Ground cover	L risk H risk	**Disturbance**	L risk H risk
Perennial vegetation	L (>20%, high belowground contribution, SA, AU) M (1-20% low to moderate belowground contribution, SA, AU) H (1% or less, no belowground contribution, SA, AU) Universal values.	Size	L (small site, SA, AU) M (intermediate site, SA, AU) H (large site, SA AU) Universal values.
Litter	L (50-100% cover of plant litter, SA, AU) H (<10-50% cover of plant litter, SA AU) Universal values.	Land use transformation	L (wilderness vegetation, SA, AU) M (agricultural pastures, SA, AU) H (agricultural cropping, SA, AU) Universal values.
Access	L (people, SA, AU) M (animals, SA, AU) H (vehicles, SA AU) Universal values.		
HYDROLOGY	% risk	**HYDROLOGY**	% risk
Surface water	L risk H risk	**Groundwater**	L risk H risk
Wetlands and rivers/creeks	L (not present, SA, AU) H (present, SA, AU) Universal values.	Groundwater levels	L (deep, >15 mbs, SA, AU) H (shallow, 1-15 mbs,

Nodes	**States and $^{\#}$values^{a}**	**Nodes**	**States and $^{\#}$values^{a}**
			SA, AU) Universal values.
Inundation	L (infrequent, shallow or short duration, SA, AU) H (frequent, deep or long duration, SA, AU) Universal values.	Groundwater depth	L (thin layer, SA, AU) H (thick layer, SA, AU) Universal values
Flow and quantity	L (high velocity or low volume, SA, AU) H (low velocity or high volume, SA, AU) Universal values.		
CLIMATE	% risk	**CLIMATE**	% risk
Precipitation	L risk H risk	**Drying-out potential**	L risk H risk
Mean annual precipitation	L (<100-600 mm, SA) M (600-800 mm, SA) H (800 to >1200 mm, SA) Regional values. L (50-200 mm, AU) M (200-400 mm, AU) H (400-3000 mm, AU) Regional values.	Mean annual temperature	L (18 to >22 ^{0}C, SA) M (14-18 ^{0}C, SA) H (<8-14 ^{0}C, SA) Regional values. L (39-24 ^{0}C, AU) M (24-18 ^{0}C, AU) H (18 to -3 ^{0}C, AU) Regional values
Variability	L (35 to >40%, CV, SA) M (30-35%, CV, SA) H (<20-30%, CV, SA) Regional values. L (L to M, 0-0.75 percentile, AU) M (M to H, 0.75-1.25 percentile, AU) H (H to extreme, 1.25 to >2 percentile, AU) Regional values.	Mean annual potential evaporation	L (2400 >3000 mm, SA) M (2000-2400 mm, SA) H (< 1400-2000 mm, SA) Regional values. L (4000-2800 mm, AU) M (2800-2000 mm, AU) H (2000-1000 mm, AU) Regional values.

Nodes	**States and $^{\#}$values^{a}**	**Nodes**	**States and $^{\#}$values^{a}**
Rainsplash impact	L (High to very high rainsplash protection, 30 to >50% projected cover, SA, AU) M (Moderate rainsplash protection, 15-30% projected cover, SA, AU) H (No to low rainsplash protection, <1% to 15% projected cover, SA, AU) Universal values.	Solar radiation (dry/wet season)	L (18 to >19 MJ.m^{-2}.d^{-1}, July, SA) M (16-18 MJ.m^{-2}.d^{-1}, July, SA) H (<12-16 MJ.m^{-2}.d^{-1}, July, SA) Regional values. L (32 to 22 MJ.m^{-2}.d^{-1}, July, AU) M (22-18 MJ.m^{-2}.d^{-1}, July, AU) H (18-6 MJ.m^{-2}.d^{-1}, July, AU) Regional values.
Frost	L (frost-free area, SA) M (1-30 d <0 ^{0}C, SA) H (31 to >120 d < 0 ^{0}C, SA) Regional values. L (frost-free areas, AU) M (0-20 d, AU) H (20-150 d, AU) Regional values.	**Relative humidity, daily mean (Winter, July)**	L (<52-58%, July, SA) M (58-64%, July, SA) H (64 to >68%, July, SA) Regional values. L (0-50%, July, AU) M (50-70%, July, AU) H (70-100%, July, AU) Regional values.

Note:
AU = Australia; AWC = available water capacity; CV =coefficient of variation; EC = electrical conductivity; ESP = exchangeable sodium percentage; H = high; L = low; M = medium; PAW = plant available water; SA = South Africa.

[a] Numeric values were defined based on universal values (i.e., can be applied to any region and include well known specialist terminology) or regional South African and Australian values.

Table 4.2 Anthropogenic risk source component model nodes, states and their values

Nodes	**States and $^{\#}$values[a]**	**Nodes**	**States and $^{\#}$values[a]**
SOIL MANAGEMENT	% risk	**SOIL MANAGEMENT**	% risk
Soil condition at handling	L risk H risk	**Soil characterisation**	L risk H risk
Soil water content	L (wilting point, –1500 kPa, SA, AU) M (field capacity, -5 to -55 kPa, SA, AU) H (saturated, SA, AU) Universal values.	Soil separation	L (yes) H (no) Universal values.
Rain season	L (dry season) H (rain season) Universal values.	Impermeable material	L (below) H (above) Universal values.
Existing compaction	L (Soil strength 0.5-3 MPa or Bulk density 1.0-1.50 g/cm^3). H (Soil strength 3-5.5 MPa or Bulk density 1.5-2.0 g/cm^3). Universal values.		
Soil stockpiles	L risk H risk		
Height and footprint	L (no stockpiles) M (1.5-3 m, medium surface area) H (>3 m, small surface area) Universal values.		
Double handling	L (No) H (Yes) Universal values.		

Nodes	**States and #values**[a]	**Nodes**	**States and #values**[a]
Age	L (<9 mo old) M (9-24 mo old) H (>24 mo old) Universal values		
MACHINERY MANAGEMENT	% risk value	**MACHINERY MANAGEMENT**	% risk value
Loading	L risk H risk	**Actions**	L risk H risk
Tyres	L (low pressure and/or wide) H (high pressure and/or narrow) Universal values.	Machinery choice	L (draglines) L to M (truck and shovel) M (dozers with tracks) M to H (graders with wheels) H (scrapers/ bowlscrapers) Universal values.
Tracks	L (wide) H (narrow) Universal values.	Nr of passes	L (<3) M (3-8) H (>8) Universal values.
Axle load	L (range) M (range) H (>5 tons per axle) Universal values.	Speed	L (fast) H (slow) Universal values.

Note:
AU = Australia; L = low; H = high; M = medium; SA = South Africa.
[a] Numeric values were defined based on universal values (i.e., can be applied to any region and include well-known specialist terminology)

4.6.2 Quantify rehabilitation soil compaction risk event with BNs

Step 5 of the R^2AIN framework is the quantification of rehabilitation risk events. This step assumes a BN structure, which is the output of step 4. Relationships between nodes in a BN are quantified among connecting nodes by specifying conditional probability distributions for each node. The probabilities are based on expert knowledge or they can be machine learned, where data are available.

Child nodes (i.e., nodes with arcs feeding into them from parent nodes) have conditional probability tables (CPTs) that represent combinations of all states of their parent nodes. These increase exponentially in size as more nodes are added to the parent set. While this is not a problem with machine-learned probabilities, it becomes problematic when experts need to provide the numbers. Several knowledge engineering techniques exist to facilitate knowledge elicitation and also to check for inconsistency and bias (Johnson et al., 2010; Korb and Nicholson, 2011). De Waal et al. (2016) introduced a 3D elicitation technique that relies on experts' colour pattern recognition capabilities rather than their ability to encode probabilities. To visualise the assessment, the 1-dimensional CPT can be collapsed into a colour-formatted matrix, using spreadsheet software. A pattern is created that can alleviate the tediousness of working through a long CPT in which not all the probabilities are visible at once.

Consider a child node "soil stockpiles" which has 3 parent nodes feeding into it (with states in brackets): age (low, medium, high), double handling (low, high) and height and footprint (low, medium, high). "Soil stockpiles" has 2 states: low and high risk. In this case we chose to assess low risk. The CPT has 18 parent node configurations to be parameterised. Table 4.3 illustrates the CPT: The states of age and double handling are indicated as rows, and the states of height and footprint are indicated as columns. The application of conditional colour formatting on the probabilities can create a probability heat-map of the CPT. An example of an assessment is the following: Given a low risk (<9 mo old) for age, a low risk (no) for double handling, and a medium risk (1.5-3 m, medium surface area) for height and footprint, the probability of low risk for soil stockpiles is 0.7. Conversely, the probability of high risk for soil stockpiles would be 0.3 (not indicated in Table 4.3).

Table 4.3 Conditional probability table for the “Soil Stockpiles” child node in a spreadsheet format, for low risk for soil compaction

Age	Double Handling	Height and footprint		
		Low (no stockpiles)	Medium (1.5-3 m high, medium surface area)	High (> 3 m high, small surface area)
Low (<9 months old)	Low (No)	1	0,7	0,6
	High (Yes)	0,6	0,5	0,5
Medium (9-24 months old)	Low (No)	0,4	0,3	0,2
	High (Yes)	0,3	0,2	0,1
High (>24 months old)	Low (No)	0,4	0,3	0,2
	High (Yes)	0,3	0,1	0

Note: Spreadsheet software can be used to apply the 3D visual elicitation technique developed by De Waal et al. (2016) to the conditional probability table. Colour patterns are applied by using colour scales in the conditional formatting function to create a heat map. This aids experts’ colour pattern recognition capabilities rather than relying on their ability to encode probabilities. Low risk for soil compaction is numbered 1 and high risk is numbered 0. The heat map could be created by applying red to high risk values and blue to low risk to create the visual colour range.

4.7 Case study results and discussion

Once a BN is constructed, it allows for inference based on observations (Troldborg et al., 2013). In practice, this means that observations are entered as evidence into the BN and all other probabilities in the BN are updated according to this new information. The process of updating is called “probabilistic inference” (also called “reasoning” or “probability propagation”). The updated probabilities are called “posterior probabilities”. Evidence can be entered on any node, regardless of its position in the directed acyclic graphs. This allows the modeller to answer interventional and counterfactual questions such as, “Was it ’ that caused Y?” or “What if I do X?”.

We consider data for the 2 sites described earlier to perform field testing of the BN models. Field testing puts the BN into actual use, allowing utility to be evaluated (Korb and Nicholson, 2011).

Field testing is a sound validation method for modelling scenarios in which expert knowledge is used for BN construction and parameterisation.

4.7.1 Premining phase site predictions

Soil compaction risk was assessed for each mine site's premining phase by using the quantified premining phase BN model and deciding, for all nodes, which node state and its value best described each site and selecting these. For example, Kleinkopje has a mean annual precipitation of 648 mm, therefore the "mean annual precipitation" node's state was selected as M-medium (600-800 mm) (Supplemental Data Appendix 4.2).

Site specific data were obtained from environmental mine approval reports in the public domain and from regional databases. The Quinary Catchment database by Schulze et al. (2011), was used to obtain South African data. Expert opinion was further sought from the paper's authors. In cases where data were unobtainable, "hypothetical" value scenarios were entered. This is not considered a weakness of the present study because its main purpose is to demonstrates a process, not a fully evaluated data set. The nodes, states, and values are dynamic, and these were designed for continuous improvement with repeated model application. Data were entered into the BN models as observations (indicated with red bars) and the new information was then propagated through the rest of the BN to update the probability distributions of other nodes (indicated with green bars) (Supplemental Data Appendix 4.2).

The climate natural source component model is illustrated as a comparative example for Kleinkopje and Caval Ridge (Fig. 4.5). All component models, including those also for soils, topography, hydrology and vegetation may be found in Supplemental Data Appendix 4.2. The percentage results for the component models and their averages are listed in Table 4.4. Manual combining and averaging of the component models, as opposed to using BN software (in our case, Hugin) for coupling was preferred, because this prevented information from becoming diluted and allowed for the better interpretation of the multidisciplinary information. Iwanaga et al. (2018), similarly note difficulties with component model coupling and note that this process may be error prone.

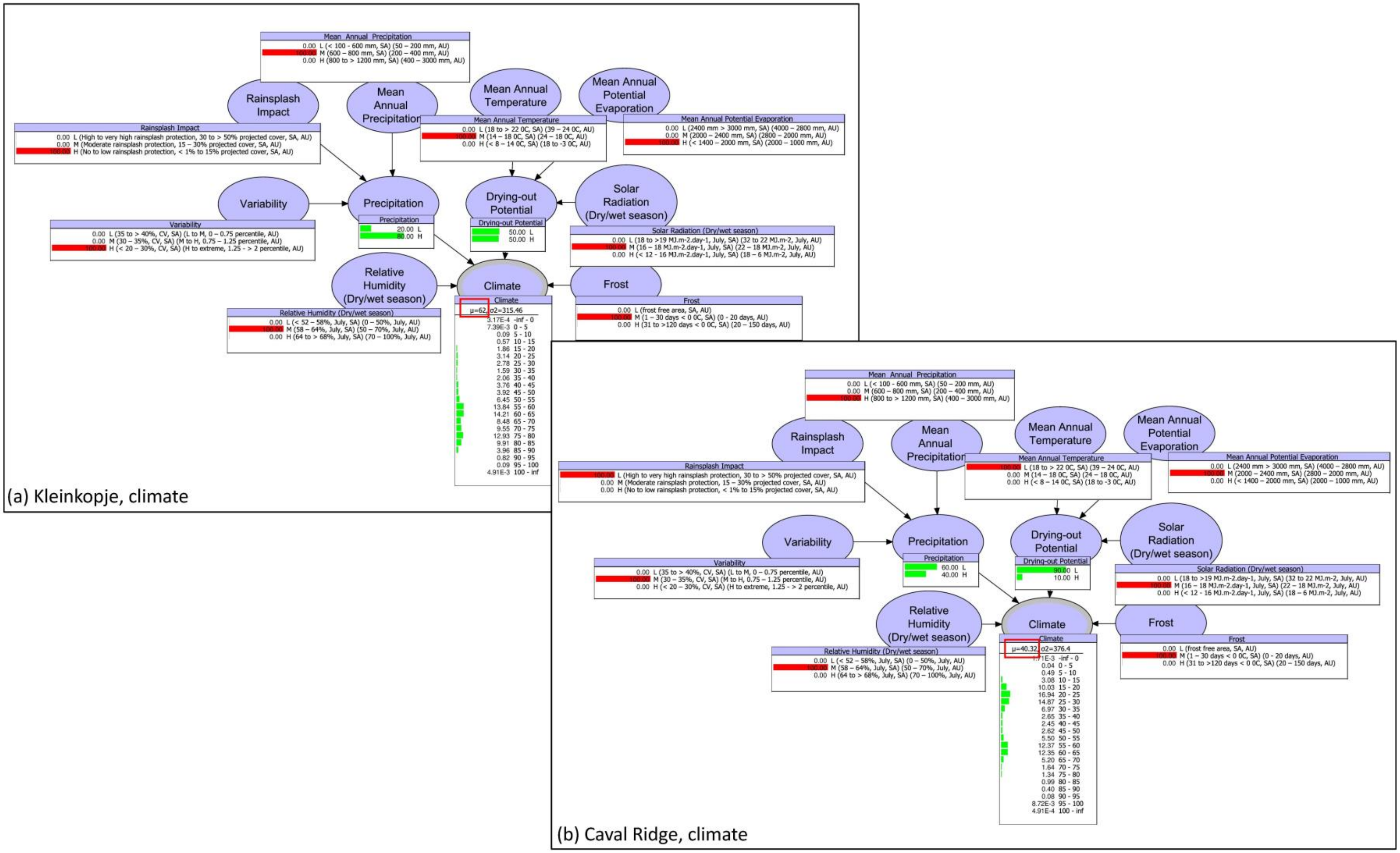


Fig. 4.5 Comparative results, for the Climate component BN model for Kleinkopje (a) and Caval Ridge (b). Data are entered into the BN models as observations and are indicated with red bars. This new information is then propagated through the rest of the BN to update the probability distributions of other nodes, indicated with green bars. AU = Australia; BN = Bayesian network; H = high; L = low; M = medium; SA = South Africa.

Table 4.4 Premining soil compaction rehabilitation risk for Kleinkopje Colliery (Witbank Coalfield, Mpumalanga Province, South Africa) and Caval Ridge coal mine (Bowen Basin, Queensland, Australia)

	Premining soil compaction rehabilitation risk	
Natural risk source	**Kleinkopje**	**Caval Ridge**
Topography	60%	47%
Hydrology	82%	56%
Vegetation	70%	40%
Climate	62%	40%
Soils	76%	55%
Average	70%	48%

Note:
Percentages given for each natural risk source, for instance for topography, are the cumulative values of all nodes in that risk source component model.

Overall Kleinkopje was found to have a higher risk (70%) under premining conditions and therefore was considered more vulnerable to soil compaction than Caval Ridge (48%). The model component with the highest influence on risk for both Kleinkopje and Caval Ridge was hydrology, followed by soils. Kleinkopje had a higher hydrological risk (82%) than Caval Ridge (56%), owing to Kleinkopje having several wetlands present, with standing water and with groundwater set as being closer to the surface in contrast to the ephemeral creek systems of Caval Ridge. The soils risk for Kleinkopje was higher (76%), when compared to that of Caval Ridge (55%). A higher soil water content risk was assigned to Kleinkopje, owing to the site's mean annual temperature higher risk rating, that is, temperature ranges are lower for Kleinkopje, suggesting that soils will be slower to dry out and therefore likely more prone to soil compaction. Hypothetical value scenarios were entered for several Kleinkopje soil nodes beacuse data from baseline soil studies were inaccessible. Kleinkopje had a higher topography risk (60%), compared with Caval Ridge (47%), because the state for the node "elevation" (also referred to as "altitude") differed between the 2 sites, with Kleinkopje having the higher risk elevation node. The input data for all other nodes were the same. The vegetation risk for Kleinkopje was higher (70%), compared with Caval Ridge (40%), as Kleinkopje was previously cultivated whereas

Caval Ridge originally supported wilderness or grazing. Kleinkopje’s climate risk was higher (62%), compared with Caval Ridge (40%) because Kleinkopje had higher mean annual temperature and mean annual potential evaporation risk ratings.

Arnold et al. (2013) describe the Brigalow Belt, in which Caval Ridge falls, as having average rainfall ranges of between 500 and 800 mm, yet notes that the area, owing to its location, is not dominated by seasonal rain-bearing systems. The region experiences erratic rainfall patterns, with short intensive storm events during summer. The observation of online aerial photographs for Caval Ridge (Fig. 4.3) shows erosion gullies present in unmined areas and as noted by others the common occurrence of sodic soils in Australia, is likely to predispose soils at Caval Ridge to soil erosion (Dale et al., 2018; Loch, 2010; Shaw et al., 1994). The site appears to be a dry site, and soil compaction would likely not be an issue. Our rehabilitation risk modelling results for Caval Ridge support this hypothesis.

4.7.2 Management scenarios

Poor and improved management scenarios were run for the machinery and soil management anthropogenic source component models. The Soil management component model is illustrated as a comparative example for poor and improved management (Fig. 4.6). The Machinery management component model may be found in Supplemental Data Appendix 4.2. For machinery management the query was to see what the change in risk would be with a poor decision choice, namely, to use high rehabilitation risk scrapers or bowlscapers versus an improved management choice, namely, the use of draglines where the focus is on the machine’s contact with the ground surface. For soil management, for both the poor and improved management scenarios, the soil was set as handled when wet. However, for the poor management scenario, the stockpiles and soil characterisation were additionally set as being poorly managed, therefore increasing the rehabilitation risk. Percentage results and averages are listed in Table 4.5. Overall, the poor management scenario (82%) may have risk reduced by 35 percentage points with improved management decision choices.

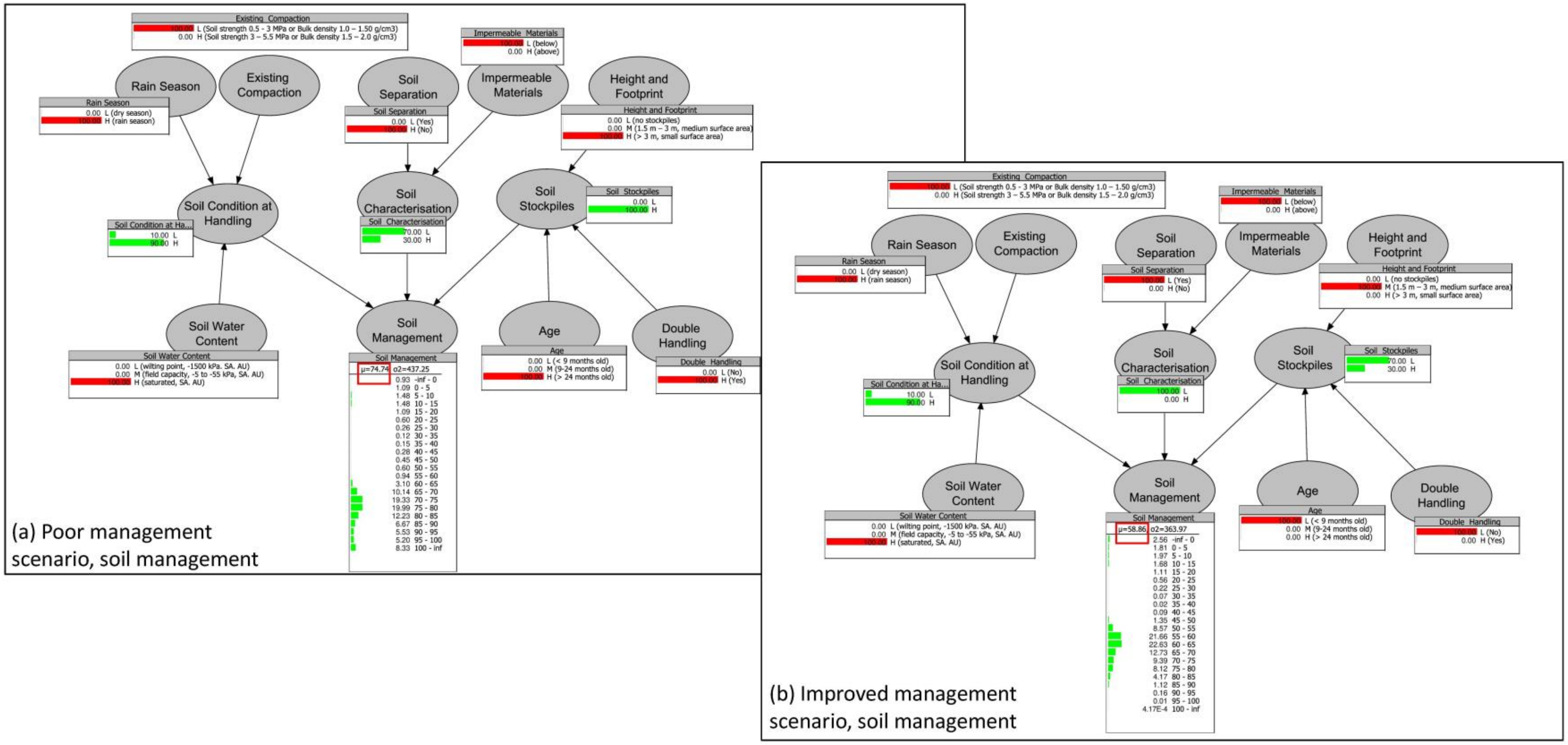


Fig. 4.6 Comparative results, for the Soil Management component BN model with a poor (a) and an improved (b) management scenario. Data are entered into the BN models as observations and are indicated with red bars. This new information is then propagated through the rest of the BN to update the probability distributions of other nodes, indicated with green bars. AU = Australia; BN = Bayesian network; H = high; L = low; M = medium; SA = South Africa.

Table 4.5 Soil compaction rehabilitation risk, for poor and improved management scenarios

Scenario	Poor management	Improved management
Soil management	75%	59%
Machinery management	88%	34%
Average	82%	47%

4.7.3 Mining to postmining phase site predictions

We assessed soil compaction risk for each mine site’s mining to postmining phase. This was achieved by combining the results from the quantified soil compaction premining phase BN model with the results from the soil and machinery management anthropogenic risk source component models with their poor and improved management scenarios (Table 4.6).

Table 4.6 Soil compaction rehabilitation risk, for the mining to postmining phases for Kleinkopje Colliery (Witbank Coalfield, Mpumalanga Province, South Africa) and Caval Ridge coal mine (Bowen Basin, Queensland, Australia), with poor and improved management scenarios.

	Soil compaction rehabilitation risk	
Scenario	Kleinkopje	Caval Ridge
Premining phase	70%	48%
Poor management scenario, soil and machinery management	82%	82%
Improved management scenario, soil and machinery management	47%	47%
Mining to postmining phase, with poor management scenario	76%	65%
Mining to postmining phase, with improved management scenario	59%	48%

The premining phase soil compaction risk for Kleinkopje increased from 70 to 76%, with poor management, applied during the mining to postmining phases, whereas with improved management, the risk was reduced from 70 to 59%. This is a rehabilitation risk value lower than that of the premining rehabilitation risk. For Caval Ridge, the premining phase soil compaction risk of 48% increased to 65% with poor management, whereas with improved management it returned to 48%.

By implementing improved management choices, soil compaction risk calculations can be reduced, sometimes to values lower than a premining baseline. This is not impossible, particularly if a site was originally severely degraded, the rehabilitation risk factors were mostly in the high-risk range, and an emphasis was placed on applying multiple improved management actions. Not all mines start from a pristine and healthy well-managed condition. Examples include historical land degradation from overgrazing, droughts and intense rainfall, prior to metalliferous mining in the Hunter Valley, New South Wales, Australia (Green, 1989) and the clearing of the Brigalow Belt Bioregion, Australia (Arnold et al., 2013).

To justify the mining of high-risk sites, during mine approval, a mining company could commit to improved rehabilitation management actions as mitigation, the magnitude of which would depend on the amount of risk to be reduced. A risk value lower than the premining baseline, is an indicator that the site “in principle” could be improved to a more optimum state, provided most of the improved management mitigation actions are applied. In reality it is difficult to match pre-mining land-use standards, for productive agriculture or biodiversity, let alone achieving higher standards (Butler and Anderson, 2018; Doley et al., 2012; Erskine and Fletcher, 2013).

4.8 Conclusions

By applying a framework approach, we were able to summarize our abstract state of knowledge about the structure and working of our rehabilitation risk assessment system. The R^{2}AIN framework enabled us to integrate multidisciplines that inform soil compaction risk from premining onwards. Using this baseline, we were able to gauge responses to soil and machinery management scenarios that would occur during the mining to postmining phases, to reduce rehabilitation risk. The use of BNs allowed us to quantify soil compaction risk and to segregate risk into contributing multidisciplines for analysis. Cross-links between multidisciplines were not made, although these relationships occur. The multidisciplinary approach was adopted to allow alignment with environmental impact and risk assessment processes. Due to their graphic nature and their ability to integrate and quantify multidisciplinary risk, BNs demonstrate benefits over other popular alternative risk assessment techniques, such as fault and event tree analysis, as well as bow-tie analysis.

The R^{2}AIN framework should have the potential to be globally applied to any mining type and to any development activity. The case study soil compaction BN model, however, is region specific but highly applicable for environments with extended periods of time with high soil moisture leading to higher susceptibility to compaction. It was developed for use in the Witbank Coalfield, South Africa and the Bowen Basin, Australia. The states (i.e., low, medium or high) are fixed; however, their values (i.e., ranges of 600-800 mm rainfall etc.), were set for each of these regions and where possible universal values were used. The soil compaction BN model could be adapted for use in other southern or northern hemisphere mining countries by resetting the regional values, specific to each query country. Use should be made of region-relevant systems, such as Schulze (1997) and Tongway and Hindley (2004). When applying the model to a mine site, the state of either low, medium, or high would be selected, based on the “state” range values set for that region and whether the site falls within the low, medium, or high categories. The CPT weightings will be different, based on experts’ contributions relevant to each region and the risk event being investigated. The framework and the soil compaction BN model are designed for strategic use, to guide site-specific specialist investigations. The need for detailed site investigation is supported by others (Rethman, 2006; Troldborg et al., 2013).

Soil compaction risk was assessed for each mine site’s premining phase by using the quantified soil compaction premining phase BN model. For the mining to post mining phases, the premining phase BN model was combined with the soil and machinery management BN models, running poor and improved management scenarios. Should a user wish to attain greater sensitivity in results, the premining phase BN model could be adapted and applied as an intermediate additional step, particularly for progressive rehabilitation risk queries. Some nodes would then remain static. For example, some climate variables do not change over the short term (if climate change is not factored in), whilst others will alter, particularly the soils and topography nodes, which may be influenced by mining activities.

4.8.1 Future research

The present paper has shown that the R^{2}AIN framework defines a process for the development of a future synthesis R^{2}AIN model, inclusive of prioritised rehabilitation risk event BNs. The soil compaction case study demonstrates the methodology and its workability. Probabilistic rehabilitation risk is quantifiable with calculations permissible for separate multidisciplines for each site. Site rehabilitation risk profiling before mining activities commence is possible and the effects of manipulating management actions during the latter mine phases to reduce risk, can be gauged, to aid decision making. Resilient rehabilitation planning; qualitative and quantitative multidiscipline integration and upfront rehabilitation risk determination is facilitated.

This research could be used to inform mine rehabilitation policy, firstly by stipulating the need for the use of the R^{2}AIN framework for rehabilitation risk assessment for upfront mine approval and closure planning, and secondly, by proposing the use of BNs for quantification calculations during upfront planning and in addition with progressive rehabilitation and financial relinquishment. It could be incorporated into financial provision requirements, with possible financial incentives given for meeting targets set. The framework is intended to assist professionals to better evaluate rehabilitation risk and to aid authority decision making. This methodology is generalised enough to allow its application to other research fields, where there is a need to quantify and integrate multi-discipline risks from several contributing and interacting systems.

Alpha and beta testing should be conducted (Korb and Nicholson, 2011) by developing each rehabilitation risk event BN, with the full R^{2}AIN model, for each site application. “Alpha testing” refers to the intermediate test of the system by in-house staff, not directly involved in developing it but having expert BN experience, such as other BN modellers. “Beta testing” involves the application of the system by an end user to identify flaws and opportunities for improvement, such as testing by mining industry rehabilitation professionals. Lastly, “acceptance testing” is required, whereby end users will need to be sufficiently familiar with the framework, BN process and software to use these with confidence for their specific needs. After this it will be possible to make the risk event BNs and the R^{2}AIN model available to industry for implementation. Rehabilitation risk criteria emanating from a future synthesis R^{2}AIN model should then be investigated for inclusion in the development of performance-based rehabilitation completion criteria.

A rigorous evaluation process should be implemented. Evaluation of a BN includes more informal methods such as case-based evaluation where cases are generated to test a wide variety of scenarios to which the BN model could be exposed to (Korb and Nicholson, 2011). More formal methods include explanation methods, such as “most probable explanation” (MPE) (Kwisthout, 2011) which can be thought of as the most plausible explanation for the observed findings. Explanation methods are useful in evaluating a BN as the independence-dependence relations in a BN structure are not always obvious to users of the model. The explanation of conclusions drawn about the domain using the BN contribute to the acceptance of the BN model by domain experts and users (Korb and Nicholson, 2011).

For industry to accept and use the R^{2}AIN framework, the risk event BNs and a R^{2}AIN model benefits must be evident. Potential benefits include simplicity of use, data improvement, and improved products leading to early detection of rehabilitation risks. Long-term cost savings are possible, when rehabilitation risks are detected early, allowing mitigation measures to be implemented in a timely manner or alternative decisions to be made thereby reducing rehabilitation liability later in the mine’s life. The tools presented provide an improved scientific system for mine rehabilitation planning than that currently available.

The R^{2}AIN framework and a future synthesis R^{2}AIN model inclusive of rehabilitation risk event BNs are intended to be evidence based, yet practical. These tools facilitate the placing of data into a validated system for practical use and analysis, in contrast to collecting data and leaving it in mine approval documentation with limited application. The present research bridges industry practicalities with scientific foundations.

4.9 Acknowledgement

Contributions from David Doley, Andrew Butler, Rudolph Botha, and Martin Platt are acknowledged. Anglo American are thanked for providing data for Kleinkopje. Nigel Berjak is thanked for preparing the mine site locality figures. The University of Pretoria and the Coaltech Research Association are thanked for funding the research. We would like to thank the anonymous reviewers who provided constructive feedback on the manuscript which resulted in significant improvements.

4.10 Disclaimer

The authors declare no conflicts of interest.

4.11 Data accessibility

Data are contained in the Supplemental Data and any further required data are available upon request from the corresponding author, Vanessa D. Weyer, at vweyer@global.co.za.

4.12 References

Aalders, I., Hough, R.L., Towers, W., 2011. Risk of erosion in peat soils – An investigation using Bayesian belief networks. Soil Use Manage 27, 538-549 DOI: 10.1111/j.1475-2743.2011.00359.x

Alaoui, A., Rogger, M., Peth, S., Blöschl, G., 2018. Does soil compaction increase floods? A review. J Hydrol 557, 631–642 DOI: 10.1016/j.jhydrol.2017.12.052

Anglo Coal Environmental Rehabilitation Improvement Group, 2009. Anglo Coal South Africa rehabilitation way, 9th draft ed. Anglo Coal Environmental, Johannesburg, (ZA).

Anglo Operations (Pty) Ltd, 2018. Environmental Authorisation Application and Water Use Licence Application for the Proposed Pit 2A Extension. [cited 2018 June 15]. http://www.shangoni.co.za/kleinkopje-colliery/.

ARC-Institute for Soil Climate and Water, 2016. Stockpiling of Coal Mine Soils. Coaltech, Pretoria, (ZA).

Argent, R.M., Sojda, R.S., Giupponi, C., McIntosh, B., Voinov, A.A., Maier, H.R., 2016. Best practices for conceptual modelling in environmental planning and management. Environ Model Softw 80, 113-121 DOI: https://doi.org/10.1016/j.envsoft.2016.02.023

Arnold, S., Audet, P., Doley, D., Baumgartl, T., 2013. Hydropedology and ecohydrology of the Brigalow Belt, Australia: Opportunities for ecosystem rehabilitation in semiarid environments. Vadose Zone J 12 DOI: 10.2136/vzj2013.03.0052

Australian Collaborative Land Evaluation Program, 2018. Soil and Landscape Grid of Australia. [cited 2018 June 14). http://www.clw.csiro.au/aclep/soilandlandscapegrid/.

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016a. Mine closure: Leading practice sustainable development program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016b. Mine rehabilitation: Leading practice sustainable development program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Innovation & Science, Department of Foreign Affairs & Trade, 2016c. Risk management: Leading practice sustainability program for the mining industry. Leading Practice Sustainability Program for the Mining Industry, Canberra, (AU).

Australian Government, Department of Industry Tourism and Resources, 2006. Mine rehabilitation handbook: Leading Practice Sustainable Development Program for the mining industry. Australian Government Department of Industry Tourism and Resources, Canberra, (AU), p. 67.

Australian Government Geoscience Australia, 2018. Elevations. [cited 2018 June 15]. http://www.ga.gov.au/scientific-topics/national-location-information/landforms/elevations.

Ban, N.C., Mills, M., Tam, J., Hicks, C.C., Klain, S., Stoeckl, N., Bottrill, M.C., Levine, J., Pressey, R.L., Satterfield, T., Chan, K.M.A., 2013. A social-ecological approach to conservation planning: Embedding social considerations. Front Ecol Environ 11, 194-202 DOI: http://www.jstor.org/stable/23470948

Barton, D.N., Kuikka, S., Varis, O., Uusitalo, L., Henriksen, H.J., Borsuk, M., de la Hera, A., Farmani, R., Johnson, S., Linnell, J.D.C., 2012. Bayesian networks in environmental and resource management. Integr Environ Assess Manag 8, 418-429 DOI: 10.1002/ieam.1327

Barton, D.N., Saloranta, T., Moe, S.J., Eggestad, H.O., Kuikka, S., 2008. Bayesian belief networks as a meta-modelling tool in integrated river basin management — Pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. Ecol Econ 66, 91-104 DOI: https://doi.org/10.1016/j.ecolecon.2008.02.012

Batey, T., 2009. Soil compaction and soil management – A review. Soil Use Manage 25, 335-345 DOI: 10.1111/j.1475-2743.2009.00236.x

BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018. Caval Ridge Mine Project Draft Environmental Impact Statement. [cited 2018 June 14]. https://www.bhp.com/environment/regulatory-information.

Blommerde, M., Taplin, R., Raval, S., 2015. Assessment of rehabilitation completion criteria for mine closure evaluation, In: Proceedings of the 7th International Conference on Sustainable Development in the Minerals Industry Sustainable Development in the Minerals Industry Vancouver, (CA), pp. 1-17.

Borsuk, M.E., Schweizer, S., Reichert, P., 2012. A Bayesian network model for integrative river rehabilitation planning and management. Integr Environ Assess Manag 8, 462-472 DOI: 10.1002/ieam.233

Borsuk, M.E., Stow, C.A., Reckhow, K.H., 2004. A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. Ecol Model 173, 219-239 DOI: https://doi.org/10.1016/j.ecolmodel.2003.08.020

Bureau of Meteorology, 2018a. Global Solar Exposure 1 April 2017 to 31 March 2018. [cited 2018 April 3]. http://www.bom.gov.au/jsp/awap/solar/index.jsp?colour=colour&time=latest&map=solarave&period=12month&step=0&area=qd.

Bureau of Meteorology, 2018b. Maps of Average Conditions. [cited 2018 March 16]. http://www.bom.gov.au/climate/averages/maps.shtml.

Bureau of Meteorology, 2018c. Summary Statistics for Moranbah Water Treatment Plant. [cited 2018 March 16]. http://www.bom.gov.au/climate/averages/tables/cw_034038.shtml.

Butler, A., Anderson, T., 2018. Reassessing rehabilitation objectives and targets for mature mining operations in Queensland, in: of, A.I., (AusIMM), M.a.M. (Eds.), From start to finish: Life-of-mine perspective, spectrum series 24. AusIMM, Carlton, (AU), pp. 233 - 242.

Chamber of Mines of South Africa, 1981. Guidelines for the rehabilitation of land disturbed by surface coal mining in South Africa. Chamber of Mines of South Africa, Johannesburg, (ZA), p. 96.

Chamber of Mines of South Africa, 2007. Guidelines for the rehabilitation of mined land. Chamber of Mines of South Africa, Johannesburg, (ZA), p. 167.

Corder, G.D., McLellan, B.C., Green, S., 2010. Incorporating sustainable development principles into minerals processing design and operation: SUSOP®. Miner Eng 23, 175-181 DOI: https://doi.org/10.1016/j.mineng.2009.12.003

Council of Standards Australia & New Zealand, 2009. AS/ NZS ISO 31000:2009, joint Australian New Zealand international standard, risk management - Principles and guidelines, 3 ed. Council of Standards Australia & New Zealand, Sydney, (AU) & Wellington, (NZ), p. 35.

Dale, G., Thomas, E., McCallum, L., Raine, S., Bennett, J., Reardon-Smith, K., 2018. Applying risk-based principles of dispersive mine spoil behaviour to facilitate development of cost-effective best management practices: ACARP C24033. Australian Coal Association Research Program, Brisbane, (AU).

Davies, S., Lacey, A., 2011. Subsurface Compaction a Guide for Western Australia Farmers and Consultants: Bulletin 4818. Department of Agriculture and Food, Perth, (AU), p. 44.

De Waal, A., Koen, H., de Villiers, P., Roodt, H., Moorosi, N., Pavlin, G., 2016. Construction and evaluation of Bayesian networks with expert-defined latent variables, In: Proceedings of the 19th Conference of Information Fusion. International Society of Information Fusion, Heidelberg, (DE), pp. 1-8.

DeJong-Hughes, J., Montcrief, J.F., Voorhees, W.B., Swan, J.B., 2001. Soil compaction, causes, effects and control. College of Agriculture, Food, and Environmental Sciences, Univ of Minnesota, Minneapolis, (MN), p. 16.

Department of Environmental Affairs, 2015. National Environmental Management Act, No. 107 of 1998. Regulations pertaining to the financial provisions for prospecting, exploration, mining or production operation, Government gazette (39425). 20 November. Government notice no. R1147. Government Printing Works, Republic of South Africa, p. 48.

Department of Minerals and Energy, 1995. Technical guidelines for the environmental management of exploration and mining in Queensland. Department of Minerals and Energy, Brisbane, (AU), p. 12.

Doley, D., Audet, P., 2013. Adopting novel ecosystems as suitable rehabilitation alternatives for former mine sites. Ecol Process 2, 22 DOI: 10.1186/2192-1709-2-22

Doley, D., Audet, P., Mulligan, D.R., 2012. Examining the Australian context for post-mined land rehabilitation: Reconciling a paradigm for the development of natural and novel ecosystems among post-disturbance landscapes. Agric Ecosyst Environ 163, 85-93 DOI: http://dx.doi.org/10.1016/j.agee.2012.04.022

Erskine, P.D., Fletcher, A.T., 2013. Novel ecosystems created by coal mines in central Queensland's Bowen Basin. Ecol Process 2, 33 DOI: 10.1186/2192-1709-2-33

European Commission, 2006. Proposal for a directive of the European parliament and of the council establishing a framework for the protection of soil and amending Directive 2004/35/EC., Brussels, (BE).

Farmani, R., Henriksen, H.J., Savic, D., Butler, D., 2012. An evolutionary Bayesian belief network methodology for participatory decision making under uncertainty: An application to groundwater management. Integr Environ Assess Manag 8, 456-461 DOI: 10.1002/ieam.192

Franks, D.M., Brereton, D., Moran, C.J., 2013. The cumulative dimensions of impact in resource regions. Resour Policy 38, 640-647 DOI: https://doi.org/10.1016/j.resourpol.2013.07.002

Geoscience Australia, 2013. Australian Coal Basins. Bioregional Assessment Source Dataset. [cited 2018 July 18]. http://data.bioregionalassessments.gov.au/dataset/9d5a8d74-a201-42bd-9d49-3c392244be16. Geoscience Australia, (AU).

Green, D.R., 1989. Rangeland restoration projects in western New South Wales. Aust Rangel J 11 (2), 110-116

Gupta, H.V., Clark, M.P., Vrugt, J.A., Abramowitz, G., Ye, M., 2012. Towards a comprehensive assessment of model structural adequacy. Water Resour Res 48 DOI: 10.1029/2011WR011044

Hamilton, S.H., ElSawah, S., Guillaume, J.H.A., Jakeman, A.J., Pierce, S.A., 2015. Integrated assessment and modelling: Overview and synthesis of salient dimensions. Environ Model Softw 64, 215-229 DOI: https://doi.org/10.1016/j.envsoft.2014.12.005

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Tillage Res 82, 121-145 DOI: https://doi.org/10.1016/j.still.2004.08.009

Hancock, G.R., Loch, R.J., Willgoose, G.R., 2003. The design of post-mining landscapes using geomorphic principles. Earth Surf Processes Land 28, 1097-1110 DOI: 10.1002/esp.518

Hazelton, P., Murphy, B., 2007. Interpreting Soil Test Results: What do all the Numbers Mean?, 2 ed. CSIRO, Victoria, (AU).

Henriksen, H.J., Zorrilla-Miras, P., de la Hera, A., Brugnach, M., 2012. Use of Bayesian belief networks for dealing with ambiguity in integrated groundwater management. Integr Environ Assess Manag 8, 430-444 DOI: 10.1002/ieam.195

HuginExpert, 2018. Hugin v.8.1. [cited 2018 October 11]. https://www.hugin.com/index.php/2018/03/21/new-release-hugin-v-8-6/.

International Council on Mining and Metals, 2008. Planning for integrated mine closure: Toolkit. International Council on Mining and Metals, London, (UK), p. 86.

International Organization for Standardization, 2018. ISO 31000:2018, International Standard, Risk Management - Guidelines 2nd ed. International Organization for Standardization, Geneva, (CH), p. 24.

Iwanaga, T., Rahman, J., Partington, D., Croke, B., Jakeman, A., 2018. Software development practices in integrated environmental model development, in: Arabi, M., David, O., Carlson, J., Ames, D. (Eds.), International Congress on Environmental Modelling and Software. International Environmental Modelling and Software Society, Fort Collins, (CO).

Johnson, S., Mengersen, K., 2012. Integrated Bayesian network framework for modeling complex ecological issues. Integr Environ Assess Manag 8, 480-490 DOI: 10.1002/ieam.274

Johnson, S., Mengersen, K., de Waal, A., Marnewick, K., Cilliers, D., Houser, A.M., Boast, L., 2010. Modelling cheetah relocation success in southern Africa using an iterative Bayesian network development cycle. Ecol Model 221, 641-651 DOI: https://doi.org/10.1016/j.ecolmodel.2009.11.012

Kirsch, P.A., Harris, J., Sprott, D., Cliff, D., 2014. Industry-scale knowledge management - RISKGATE and Australian coal operations. CIM J 5, 79-86

Koen, H., de Villiers, J.P., Roodt, H., de Waal, A., 2017. An expert-driven causal model of the rhino poaching problem. Ecol Model 347, 29-39 DOI: https://doi.org/10.1016/j.ecolmodel.2016.12.007

Korb, K.B., Nicholson, A.E., 2011. Bayesian artificial intelligence, 2nd ed. CRC Boca Raton, (FL)

Kragt, M.E., Newham, L.T.H., Bennett, J., Jakeman, A.J., 2011. An integrated approach to linking economic valuation and catchment modelling. Environ Model Softw 26, 92-102 DOI: https://doi.org/10.1016/j.envsoft.2010.04.002

Kwisthout, J., 2011. Most probable explanations in Bayesian networks: Complexity and tractability. Int J Approx Reason 52, 1452-1469 DOI: https://doi.org/10.1016/j.ijar.2011.08.003

Lal, R., 2009. Soils and food sufficiency. A review. Agron Sustainable Dev 29, 113-133

Lechner, A.M., McIntyre, N., Witt, K., Raymond, C.M., Arnold, S., Scott, M., Rifkin, W., 2017. Challenges of integrated modelling in mining regions to address social, environmental and economic impacts. Environ Model Softw 93, 268-281 DOI: 10.1016/j.envsoft.2017.03.020

Limpitlaw, D., Aken, M., Kilani, J., Mentis, M., Nell, J.P., Tanner, P.D., 1997. Rehabilitation and Soil Characterization, In: Proceedings of the 11th International Conference on Coal Research, Calgary, (CA), pp. 297-309.

Limpitlaw, D., Aken, M., Lodewijks, H., Viljoen, J., 2005. Post-mining rehabilitation, land use and pollution at collieries in South Africa, In: Colloquium: Sustainable development in the life of coal mining in South Africa. The South African Institute of Mining and Metallurgy, Boksburg, (ZA), pp. 1-10.

Liu, Y., Gupta, H., Springer, E., Wagener, T., 2008. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. Environ Model Softw 23, 846-858 DOI: https://doi.org/10.1016/j.envsoft.2007.10.007

Loch, R.J., 2010. Sustainable landscape design for coal mine rehabilitation: ACARP C18024. Australian Coal Association Research Program, Toowoomba, (AU), p. 101.

Maczkowiack, R.I., Smith, C., Erskine, P.D., Mulligan, D., 2013. Risk assessment tools to support end-use decisions for mined land of the Bowen Basin: ACARP C19028. Australian Coal Association Research Program, Brisbane, (AU), p. 158.

McCann, R.K., Marcot, B.G., Ellis, R., 2006. Bayesian belief networks: Applications in ecology and natural resource management. Can J For Res 36, 3053-3062 DOI: 10.1139/X06-238

McCullough, C.D., Harvey, B., Unger, C.J., Winchester, S., McCarthy, B., Coetzee, J., 2018. A perspective on improving sustainable development aspects of life-of-mine practices, in: Australasian Institute of Mining and Metallurgy (AusIMM) (Ed.), From start to finish: Life-of-mine perspective, spectrum series 24. AusIMM, Carlton, (AU), pp. 395 - 400.

McDonald, T., Jonson, J., Dixon, K.W., 2016. National standards for the practice of ecological restoration in Australia. Restor Ecol 24, S4 - S32

Merrill, M.D., Tewalt, S.J., 2008. GIS Representation of Coal-Bearing Areas in Africa: U.S. Geological Survey Open-File Report 2008-1258. [cited 2018 July 25]. https://pubs.usgs.gov/of/2008/1258/.

Minerals Council of Australia, 1998. Mine rehabilitation handbook. Minerals Council of Australia, Kingston, (AU), p. 112.

Mueller, L., Schindler, U., Mirschel, W., Shepherd, T.G., Ball, B.C., Helming, K., Rogasik, J., Eulenstein, F., Wiggering, H., 2010. Assessing the productivity function of soils. A review. Agron for Sustainable Dev 30, 601-614 DOI: 10.1051/agro/2009057

Nawaz, M., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron Sustainable Dev 33, 291-309 DOI: 10.1007/s13593-011-0071-8

Newton, G.A., Claassen, V.P., 2003. Rehabilitation of disturbed lands in California: A manual for decision-making. California Department of Conservation & California Geological Survey, California, (US), p. 240.

Perring, M.P., Standish, R.J., Price, J.N., Craig, M.D., Erickson, T.E., Ruthrof, K.X., Whiteley, A.S., Valentine, L.E., Hobbs, R.J., 2015. Advances in restoration ecology: Rising to the challenges of the coming decades. Ecosphere 6, art131 DOI: doi:10.1890/ES15-00121.1

Pollino, C.A., Woodberry, O., Nicholson, A., Korb, K., Hart, B.T., 2007. Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment. Environ Model Softw 22, 1140-1152 DOI: https://doi.org/10.1016/j.envsoft.2006.03.006

Renken, H., Mumby, P.J., 2009. Modelling the dynamics of coral reef macroalgae using a Bayesian belief network approach. Ecol Model 220, 1305-1314 DOI: https://doi.org/10.1016/j.ecolmodel.2009.02.022

Rethman, N.F.G., 2006. A review of causes, symptoms, prevention and alleviation of soil compaction on mined land. Coaltech 2020, Johannesburg, (ZA).

Rosser, J., Swartz, G.L., Dawson, N.M., Briggs, H.S., 1974. A Land Capability Classification for Agricultural Purposes. Div. Land Utilization, Tech. Rep.14.

Saperstein, L.W., Sweigard, R.J., Wells, L.G., Barnhisel, R.I., Simpson, D.L., University of Kentucky, 1991. Techniques to reduce soil compaction in reclaimed soils. Office of Surface Mining Reclamation and Enforcement , US Department of the Interior, Washington, (DC), p. 129.

Schulze, R.E., 1997. South African atlas of agrohydrology and climatology. Water Research Commission, Pretoria, (ZA), p. 276.

Schulze, R.E., Hutson, J.L., Cass, A., 1985. Hydrological characteristics and properties of soils in Southern Africa 2: Soil water retention models. Water SA 11, 129-136

Schulze, R.E., Knoesen, D.M., Kunz, R.P., Lumsden, T.G., 2011. General circulation models and downscaling for South African climate change impacts studies: A 2011 perspective, in: Schulze, R.E. (Ed.), A 2011 perspective on climate change and the South African water sector. Water Research Commission, Pretoria, (ZA), pp. 21 - 30.

Shaw, R., Brebber, L., Ahern, C., Weinand, M., 1994. A review of sodicity and sodic soil behavior in Queensland. Soil Res 32, 143-172 DOI: https://doi.org/10.1071/SR9940143

Soane, B.D., 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil and Tillage Research 16, 179-201 DOI: https://doi.org/10.1016/0167-1987(90)90029-D

South African Bureau of Standards, 2009. SANS 31000:2009, South African national standard, risk management - Principles and guidelines, 1st ed. SABS Standards Division, Pretoria, (ZA).

Tongway, D.J., Hindley, N.L., 2004. Landscape function analysis: Procedures for monitoring and assessing landscapes - With special reference to minesites and rangelands. CSIRO, Canberra, (AU), p. 80.

Tongway, D.J., Ludwig, J.A., 2011. Restoring disturbed landscapes: Putting principles into practice. Island Pr., Washington, (DC).

Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., Lilly, A., Ball, B.C., Hough, R.L., 2013. Application of Bayesian belief networks to quantify and map areas at risk to soil threats: Using soil compaction as an example. Soil Tillage Res 132, 56-68 DOI: https://doi.org/10.1016/j.still.2013.05.005

Uusitalo, L., Kuikka, S., Kauppila, P., Söderkultalahti, P., Bäck, S., 2012. Assessing the roles of environmental factors in coastal fish production in the northern Baltic Sea: A Bayesian network application. Integr Environ Assess Manag 8, 445-455 DOI: 10.1002/ieam.180

van Delden, H., Luja, P., Engelen, G., 2007. Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management. Environ Model Softw 22, 223-238 DOI: https://doi.org/10.1016/j.envsoft.2005.07.019

Varis, O., Rahaman, M.M., Kajander, T., 2012. Fully connected Bayesian belief networks: A modeling procedure with a case study of the Ganges river basin. Integr Environ Assess Manag 8, 491-502 DOI: 10.1002/ieam.222

Voorhees, W.B., Nelson, W.W., Randall, G.W., 1986. Extent and persistence of subsoil compaction caused by heavy axle loads. Soil Sci. Soc. Am.J. 50, 428-433

Weyer, V.D., Truter, W.F., Lechner, A.M., Unger, C.J., 2017. Surface-strip coal mine land rehabilitation planning in South Africa and Australia: Maturity and opportunities for improvement. Resour Policy 54, 117-129 DOI: https://doi.org/10.1016/j.resourpol.2017.09.013

Williams, D., 2001. Risk management strategies for the surrender of open cut dragline spoil pile areas: ACARP C8039. Australian Coal Association Research Program, Brisbane, (AU).

Xu, X.-f., Sun, J., Nie, H.-t., Yuan, D.-k., Tao, J.-h., 2016. Linking structural equation modeling with Bayesian network and its application to coastal phytoplankton dynamics in the Bohai Bay. China Ocean Eng 30, 733-748 DOI: 10.1007/s13344-016-0047-1

4.13 Supplemental data included in paper for publication

Supplemental Information, Appendix 4.1. Risk source component BN model tables. Two tables are included: a table with natural risk source component model nodes, states and their values with input site specific data for Kleinkopje and Caval Ridge shown; and a table with anthropogenic risk source component model nodes, states and their values with input data for poor and improved management scenarios shown.

Supplemental Information, Appendix 4.2. Risk source component BN model figures. Five figures are included showing comparative BN modelling results for Kleinkopje and Caval Ridge for: soils, climate, topography, hydrology, vegetation. A further two figures are included showing comparative BN modelling results for poor and improved management scenarios for machinery management and soil management.

Appendix 4.1 Risk source component BN model tables

Table 1.
Natural risk source component model nodes, states and their values with input site specific data for Kleinkopje and Caval Ridge shown

Nodes	States and [#]values[a]	Input data, Kleinkopje	Input data, Caval Ridge	Description and supporting references
SOILS	% risk			Child node
Physical Properties	L risk H risk			Parent node.
PAW Note: PAW could replace the: Soil Water Content, Soil Texture and Topsoil Depth nodes. PAW has not been used in the soil compaction BN model.	L (< 20-40 mm.m^{-1}, SA) M (40-60 mm.m^{-1}, SA) H (60 to >100 mm.m^{-1}, SA) Regional values. L (<100 mm.m^{-1}, AU) M (100-200 mm.m^{-1}, AU) H (>200 mm.m^{-1}, AU) Regional values.	PAW: 44.6 mm.m^{-1} (Quinary 449, data). = M	PAW: [+]Hypothetical = L AWC: 5-15% in top 0-5 cm (Australian Collaborative Land Evaluation Program, 2018).	Plant Available Water (PAW) of a soil profile or soil horizon is that store of soil water readily available to a plant for purposes of transpiration and consequently growth (Schulze, 1997). This may also be an indicator for soil compaction, as soil compaction is closely dependent on soil moisture. PAW is calculated by taking into consideration soil depth, soil water content and texture. The depth and extent of compaction increases when soil is disturbed when wet (Voorhees et al., 1986). The Australian Collaborative Land Evaluation Program (2018) describe Available Water Content (AWC) as computed for each of the specified depth increments, measured as a %. State values for South Africa adapted from Schulze (1997). State values for Australia adapted from Hazelton

Nodes	**States and #values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
				and Murphy (2007).
Soil Water Content	L (wilting point, –1500 kPa, SA, AU) M (field capacity, -5 to -55 kPa, SA, AU) H (saturated, SA, AU) Universal values.	Wilting point: topsoil: 0.156 m/m and subsoil 0.189 m/m (Quinary 449) Field capacity: topsoil: 0.233 m/m and subsoil 0.263 m/m (Quinary 449). Saturated: topsoil 0.435 and subsoil 0.413 m/m (Quinary 449) Hypothetical = M	+Hypothetical = L	The onset of stress is expressed as the critical soil water content at which the plant's total evaporation is reduced to below its maximum evaporation (Schulze, 1997). Ideally, soils should be stripped and replaced at a moisture content of between 10% and 15% to avoid the adverse effects of compaction and structural breakdown (Australian Government et al., 2016b). Stripping of soils should be done when moisture content is < 10% to minimize soil compaction risk (Anglo Coal Environmental Rehabilitation Improvement Group, 2009). Wilting point is taken as the dry limit for water available to plants. At wilting point water cannot move over even short distances to the roots fast enough to satisfy the transpirational demand (Schulze et al., 1985). Field capacity is the soil water condition reached when water has been allowed to drain naturally from the soil until drainage ceases and the water remaining is held by capillary forces that are great enough to resist gravity, i.e. the wet limit of the moisture available to plants (Schulze et al., 1985).

Nodes	**States and $^{\#}$values^{a}**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
				State values for South Africa and Australia provided by experts.
Soil Texture	L (light: sands and loamy sands, SA, AU) M (medium: loamy sands, clayey sands and sandy loams, SA, AU) H (heavy: loams, clay loams and clay soils, SA, AU) Universal values.	Bainsvlei, Avalon, Mispah and Clovelly/Hutton, most abundant soil forms (Anglo Operations (Pty) Ltd, 2018). Range between fine, sandy loam, sandy loam and loamy sand (Anglo Operations (Pty) Ltd, 2018) = M	Yellow Duplex soils, Red Brown Duplex Soils, Deep Sandy Loams, Uniform Clays, Brigalow Clays, Shallow Heavy Clays, Skeletal Clays, Shallow Sandy Soils and Dark Heavy Clays. Textures include clay loam to light clay, with a weak to moderate platy to sub-angular blocky structure. Clay content varies between 17% and 39%. (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018).	The relative proportion of sand to silt to clay-sized particles determines the soil property known as texture. Sandy textured soils have percent sand content > 45 to 50% and rapid infiltration of rain occurs as well as rapid draining. Clay soils have > 40% clay and are susceptible to compaction. Loamy soils have approximately equal proportions of sand and silt, with smaller amounts of clay (Newton and Claassen, 2003). Fine materials (0.2 to 0.02 mm diameter) are most susceptible to compaction and the formation of high bulk densities (Chamber of Mines of South Africa, 1981, 2007). Problem soils in South Africa include: Sandy kaolinthic soils, gleyed, melanic and vertic (Chamber of Mines of South Africa, 2007). Red and yellow apedal soils (which predominate on many surface mines) are very susceptible to compaction (Rethman, 2006). State values for South Africa and Australia adapted from Davies and Lacey (2011).

Nodes	States and $^{\#}$values^{a}	Input data, Kleinkopje	Input data, Caval Ridge	Description and supporting references
			= M	
Topsoil Depth	L (0.25-0.6 m, arable land, SA, AU) H (0.15-0.25 m, wilderness and grazing land, SA, AU) Regional values. or L (Class I-IV, suitable for cultivation, AU) H (Class V-VIII, not suitable for cultivation and grazing AU) Regional values.	Thickness of topsoil: 0.24 m (Quinary 449). 0-1.0 m predominantly (Anglo Operations (Pty) Ltd, 2018) = H	< 0.25-1.25 m (Australian Collaborative Land Evaluation Program, 2018). Class V-VIII – not suitable for cultivation or grazing (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018) 0.15 m (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018) = H	This is given as a depth (mm) for the entire soil profile for both the dominant and subdominant soil groups per zone (Schulze, 1997). Australian Collaborative Land Evaluation Program (2018) describe Depth of Soil as Depth of soil profile (A & B horizons), measured in m. State values for South Africa adapted from land capability classes (Chamber of Mines of South Africa, 1981, 2007). State values for Australia adapted from (Rosser et al., 1974).
Chemical Properties	L risk H risk			Parent node.
Saline	L (chloride levels > 0.5% or EC > 8-16 dS/cm, SA, AU) M (chloride levels >	EC < 200 mS/m (Anglo Operations (Pty) Ltd, 2018) = M	The topsoil is non-saline (EC 0.04 to 0.32 dS/m) (BHP Billiton	Excessive salt in soil water decreases the effective moisture content (Newton and Claassen, 2003). This can occur via capillary rise into the topsoil and

Nodes	States and #values[a]	Input data, Kleinkopje	Input data, Caval Ridge	Description and supporting references
	0.2% or EC >4-8 dS/cm, SA, AU) H (not saline <4 dS/cm, SA, AU) Universal values.		Mitsubishi Alliance Coal Operations Pty Ltd, 2018). = H	via saline seepage where saline materials are placed in and above ground landforms (Australian Government and Department of Industry Tourism and Resources, 2006). Surface horizons of most soil types in coal mining areas in Australia are generally low in salt, but subsoils may contain levels high enough to adversely affect plant growth (Department of Minerals and Energy, 1995). Overburden in the Bowen Basin is frequently high in soluble salts (Department of Minerals and Energy, 1995). State values for South Africa and Australia adapted from Department of Minerals and Energy (1995) and provided by experts. EC method to include saturated paste extract method.
Sodic	L (not sodic, SA, AU) M (sodic ESP >6, SA, AU) H (strongly sodic ESP >15, SA, AU) Universal values.	+Hypothetical = M	An ESP value of between 6% and 14% indicates that these materials are regarded as marginally sodic to sodic (BHP Billiton Mitsubishi Alliance	Sodium causes soil aggregates to disintegrate, making soils susceptible to compaction and water infiltration difficult (Newton and Claassen, 2003). Soils affected by salinity and sodicity commonly occur in arid and semi-arid areas (Minerals Council of Australia, 1998).

Nodes	**States and #values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
			Coal Operations Pty Ltd, 2018). =M	Sodicity is a measure of ESP (Department of Minerals and Energy, 1995). State values for South Africa and Australia adapted from Department of Minerals and Energy (1995) and provided by experts.
Biological Properties	L risk H risk			Parent node.
Organic Matter Content	L (1.6 to >7%, SA, AU) H (<1-1.6%, SA, AU) Universal values.	1.11% (Anglo Operations (Pty) Ltd, 2018) = H	0.2-2.0% in 0-5 cm) (Australian Collaborative Land Evaluation Program, 2018) = H	Organic matter reduces the potential for compaction to occur and can also mitigate compaction once it has occurred. Soils with high organic matter hold the soil particles apart so that they don't pack and adhere tightly together (Newton and Claassen, 2003). Soane (1990) describes organic matter as comprising of either: living or directly related to living organisms or as roots, fungal hyphae or faecal pellets. For arable and pasture land carbon % >2% is recommended (Anglo Coal Environmental Rehabilitation Improvement Group, 2009). Australian Collaborative Land Evaluation Program (2018), describes Organic Carbon as the mass fraction of carbon by weight in the <2 mm soil material as determined by dry combustion at 90 degrees Celsius, measured as a %.

Nodes	**States and #values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
				State values for South Africa and Australia provided by experts and adapted from Hazelton and Murphy (2007).
Cryptogram Cover	L (10 to >50% contribution, SA, AU) H (1 to 10% contribution, SA, AU) Universal values.	+Hypothetical = H	+Hypothetical = L	‘Cryptogam’ is a generic term that includes algae, fungi, lichens, mosses, liverworts and fruiting bodies of mycorrhizas (Tongway and Hindley, 2004).Their presence would reduce soil compaction. South African and Australian state values adapted from Tongway and Hindley (2004).
TOPOGRAPHY	% risk			Child node
Aspect	L (north hot and dry, SA, AU) M (east, west or flat, SA, AU) H (south cold and wet, SA, AU) Universal values.	Flat = M	Flat to undulating (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018) = M	In the southern hemisphere north facing slopes are hot and dry, whilst south facing slopes are cold and wet and therefore retain more moisture and may be more susceptible to soil compaction. Australian Collaborative Land Evaluation Program (2018), describe Aspect as measuring the direction in which a land surface slope’s face. The direction is expressed in degrees from north. State values for South Africa and Australia provided by experts.

Nodes	**States and #values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
Elevation/ Altitude	L (0-600 m, SA) M (600-1250 m, SA) H (1250-2500 m, SA) Regional values. L (0-300 m, AU) M (300-600 m, AU) H (>600 m, AU) Regional values.	1500-1750 m (Schulze, 1997). 1498-1590 m (Anglo Operations (Pty) Ltd, 2018) = H	260 m (Moranbah Water Treatment Works) (Bureau of Meteorology, 2018c). 220 m to 274 m across the site (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018) = L	Altitude influences climate and hence hydrological responses. Altitude can act as a barrier to rain-bearing masses or can force moist air to rise by orographic lifting, with windward facing slopes experiencing more total rainfall and more raindays. Increased thunderstorm activity and higher stormflow producing events may result (Schulze et al., 2011). Higher altitudes have reduced temperatures and reduced evaporative losses, therefore are more at risk to soil compaction. State values for South Africa adapted from Schulze (1997). State values for Australia adapted from Australian Government Geoscience Australia (2018).
Drainage	L risk H risk			Parent node.
Slope Gradient	L (<33% or <1:3, SA, AU) M (20% or 1:5, SA, AU) H (>1% or 1:100, SA AU) Universal values.	Gently undulating terrain = H	Low (Australian Collaborative Land Evaluation Program, 2018). <1% (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018)	The flatter the slope, the more likely it is to retain water and the more susceptible it is to soil compaction. Australian Collaborative Land Evaluation Program (2018), describe Slope as measuring the inclination of the land surface from the horizontal and is measured as a %.

Nodes	**States and [#]values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
			= H	State values for South Africa and Australia provided by experts.
Slope Shape	L (convex, SA, AU) M (rectilinear, SA, AU) H (concave, SA, AU) Universal values.	Rectilinear = M	Rectilinear = M	Concave slopes hold water, whilst convex slopes do not. State values for South Africa and Australia provided by experts.
VEGETATION	% risk			Child node
Ground Cover	L risk H risk			Parent node
Perennial Vegetation	L (>20%, high belowground contribution, SA, AU) M (1-20% low to moderate belowground contribution, SA, AU) H (1% or less, no belowground contribution, SA, AU) Universal values.	[+]Hypothetical = M	[+]Hypothetical = L	South African and Australian state values adapted from Tongway and Hindley (2004).
Litter	L (50-100% cover of plant litter, SA, AU) H (<100-50% cover of plant litter, SA AU) Universal values.	[+]Hypothetical = H	[+]Hypothetical = L	Undecomposed organic matter can accumulate on the soil surface. Frequently this is fibrous or, in the case of forests, woody material which may form a continuous layer several centimetres thick. Such a layer might be expected to have the effect of

Nodes	**States and [#]values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
				increasing the effective contact area of wheels or tracks, thus reducing contact stress and reducing compaction within the surface layers of the soil (Soane, 1990). South African and Australian state values adapted from Tongway and Hindley (2004).
Disturbance	L risk H risk			Parent node
Size	L (small site, SA, AU) M (intermediate site, SA, AU) H (large site, SA AU) Universal values.	The mine boundary area of the Kleinkopje Colliery is approximately 4000 ha in size (Anglo Operations (Pty) Ltd, 2018). = H	[+]Hypothetical = M	State values for South Africa and Australia provided by experts.
Landuse Transformation	L (wilderness vegetation, SA, AU) M (agricultural pastures, SA, AU) H (agricultural cropping, SA, AU) Universal values.	Before transformation was grassland. Agricultural cropping – predominant, some grazing (Anglo Operations (Pty) Ltd, 2018) = H	Brigalow. (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018). = L	States for South Africa and Australia provided by experts

Nodes	States and [#]values[a]	Input data, Kleinkopje	Input data, Caval Ridge	Description and supporting references
Access				Parent node
Access	L (people, SA, AU) M (animals, SA, AU) H (vehicles, SA AU) Universal values.	Vehicles from past cultivation = H	The project site and adjoining areas have historically been and are currently used for cattle grazing (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018). = M	State values for South Africa and Australia provided by experts.
HYDROLOGY	% risk			Child node
Surface water	L risk H risk			Parent node
Wetlands and Rivers/Creeks	L (not present, SA, AU) H (present, SA, AU) Universal values.	Present (River and wetlands) = H	Present (Creeks). Alluvial plains (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018) = H	Wetland soils, which are wet and high in clay, will remain compacted for decades after compaction and cannot be loosened because they never adequately dry out (Newton and Claassen, 2003). State values for South Africa and Australia provided by experts.
Inundation	L (infrequent, shallow or short duration, SA,	Frequent, deep or long duration	Infrequent, shallow or short duration.	State values for South Africa and Australia provided by experts.

Nodes	States and $^{\#}$values^{a}	Input data, Kleinkopje	Input data, Caval Ridge	Description and supporting references
	AU) H (frequent, deep or long duration, SA, AU) Universal values.	= H	All watercourses and tributaries within the project site are ephemeral watercourses. Periods of flow are generally short and limited to periods during and immediately after rainfall (BHP Billiton Mitsubishi Alliance Coal Operations Pty Ltd, 2018). = L	
Flow and Quantity	L (high velocity or low volume, SA, AU) H (low velocity or high volume, SA, AU) Universal values.	Low velocity or high volume = H	High velocity or low volume = L	State values for South Africa and Australia provided by experts.
Groundwater	L risk H risk			Parent node
Groundwater Levels	L (deep, >15 mbs, SA, AU) H (shallow, 1-15 mbs, SA, AU)	1-15 mbs (Anglo Operations (Pty) Ltd, 2018) = H	$^{+}$Hypothetical = L	In Australia's arid and semi-arid regions, the groundwater is deep, with a low permeability, unsaturated zone above (Australian Government and Department of Industry Tourism and

Nodes	States and $^{\#}$values^{a}	Input data, Kleinkopje	Input data, Caval Ridge	Description and supporting references
	Universal values.			Resources, 2006). State values for South Africa and Australia provided by experts.
Groundwater Depth	L (thin layer, SA, AU) H (thick layer, SA, AU) Universal values.	$^{+}$Hypothetical = L	$^{+}$Hypothetical = L	State values for South Africa and Australia provided by experts.
CLIMATE	% risk			Child node
Precipitation	L risk H risk			Parent node
Mean Annual Precipitation	L (<100-600 mm, SA) M (600-800 mm, SA) H (800 to >1200 mm, SA) Regional values. L (50-200 mm, AU) M (200-400 mm, AU) H (400-3000 mm, AU) Regional values.	648 mm (Quinary 449). 696 mm (Anglo Operations (Pty) Ltd, 2018) = M	614 mm (Moranbah Water Treatment Works) (Bureau of Meteorology, 2018c). = H	The long-term quantity of water available to a region for hydrological purposes (Schulze et al., 2011). South African state values adapted from Schulze (1997). Australian state value adapted from Bureau of Meteorology (2018b). Note: The Wentworth, Queensland weather station states MAP as 495 mm. Rainfall statistics are calculated for this station since 1963. No climate statistics are however available; hence the

Nodes	**States and #values**[a]	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
				Moranbah weather station was used for data input for Caval Ridge.
Variability	L (35 to >40%, CV, SA) M (30-35%, CV, SA) H (<20-30%, CV, SA) Regional values. L (L to M, 0-0.75 percentile, AU) M (M to H, 0.75-1.25 percentile, AU) H (H to extreme, 1.25 to >2 percentile, AU) Regional values.	CV of Annual Rainfall: 20.4% (Quinary 449). = H	0.75-1.0 (Bureau of Meteorology, 2018b) = M	CV is the natural year to year variability of rainfall that occurs, it is expressed as a percentage (Schulze, 1997). The higher the CV the more variable the year-to-year rainfall of a locality is. It indicates climate risk. The Mpumalanga Highveld in South Africa is characterized by rainfall distribution (over the year) and variability (from year to year) which can result in either drought stress and/or waterlogging both within and between seasons (Rethman, 2006). South African state values adapted from Schulze (1997). Australian state values adapted from Bureau of Meteorology (2018b).
Rainsplash impact	L (High to very high rainsplash protection, 30 to >50% projected cover, SA, AU) M (Moderate rainsplash protection, 15-30% projected cover, SA, AU) H (No to low	+Hypothetical = H	+Hypothetical = L	Raindrop impact is noted by Limpitlaw et al. (1997) as of importance and its link with slope steepness, slope length and plant cover. South African and Australian state values adapted from Tongway and Hindley (2004).

Nodes	**States and [#]values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
	rainsplash protection, <1 to 15% projected cover, SA, AU) Universal values.			
Drying-out Potential	L risk H risk			Parent node
Mean Annual Temperature	L (18 to >22 ^{0}C, SA) M (14-18 ^{0}C, SA) H (<8-14 ^{0}C, SA) Regional values. L (39-24 ^{0}C, AU) M (24-18 ^{0}C, AU) H (18 to -3 ^{0}C, AU) Regional values	15.3 ^{0}C (Quinary 449). = M	27-30 ^{0}C (Bowen Basin) (Bureau of Meteorology, 2018b). = L	The colder temperature regions are more susceptible to soil compaction as the cool temperatures prevent the soils from drying out. South African state values adapted from Schulze (1997). Australian state values adapted from Bureau of Meteorology (2018b)
Mean Annual Potential Evaporation	L (2400 > 3000 mm, SA) M (2000-2400 mm, SA) H (<1400-2000 mm, SA) Regional values. L (4000-2800 mm, AU) M (2800-2000 mm, AU) H (2000-1000 mm,	Mean Annual Potential Evap (Penman-Monteith method): 1644 mm (For A-pan equivalent 1644x1.23) (Quinary 449). = H	2000-2400 mm (Bowen Basin) (Bureau of Meteorology, 2018b). = M	Regions with low mean annual potential evaporation tend to hold soil moisture more and therefore are more susceptible to soil compaction. South African state values adapted from Schulze (1997). Australian state values adapted from Bureau of Meteorology (2018b).

Nodes	States and $^{\#}$values^{a}	Input data, Kleinkopje	Input data, Caval Ridge	Description and supporting references
	AU) Regional values.			
Solar Radiation (Dry/wet season)	L (18 to >19 MJ.m^{-2}.d^{-1}, July, SA) M (16-18 MJ.m^{-2}.d^{-1}, July, SA) H (< 12-16 MJ.m^{-2}.d^{-1}, July, SA) Regional values. L (32-22 MJ.m^{-2}.d^{-}, July, AU) M (22-18 MJ.m^{-2}.d^{-}, July, AU) H (18-6 MJ.m^{-2}.d^{-}, July, AU) Regional values.	17 - 19 MJ.m^{-2}.d^{-1} (Schulze, 1997). = M/L	20 – 22 MJ.m^{-2}.d^{-} (Bowen Basin) (Bureau of Meteorology, 2018a) = M	High altitudes have reduced atmospheric pressure, which enhances the transmissivity of solar radiation and increases the rate at which water can vaporise under clear sky conditions (Schulze, 1997). Based on Clemence's equation. South African state values adapted from Schulze (1997). Australian state values adapted from Bureau of Meteorology (2018a).
Other				
Frost	L (frost free area, SA) M (1-30 days <0 ^{0}C, SA) H (31 to >120 days <0 ^{0}C, SA) Regional values. L (frost free areas, AU) M (0-20 days, AU)	1-30 days (Schulze, 1997). = M	0-10 days (Bowen Basin) (Bureau of Meteorology, 2018b). = M/L	Frost and snow prevent the soil from drying out and therefore increase susceptibility to soil compaction. Refers to number of days with frost. Although Caval Ridge is noted as having 0 -10 days of frost (M), frost generally disappears with sunrise, therefore L is also applicable. For interest we have chosen to apply M for Caval Ridge.

Nodes	**States and #values[a]**	**Input data, Kleinkopje**	**Input data, Caval Ridge**	**Description and supporting references**
	H (20-150 days, AU) Regional values.			South African state values adapted from Schulze (1997). Australian state values adapted from Bureau of Meteorology (2018b).
Relative Humidity, Daily Mean (Winter, July)	L (<52-58%, July, SA) M (58-64%, July, SA) H (64 to >68%, July, SA) Regional values. L (0-50%, July, AU) M (50-70%, July, AU) H (70-100%, July, AU) Regional values.	56-60% (Schulze, 1997). = M	67%, 9 am (Moranbah Water Treatment Works) (Bureau of Meteorology, 2018c). = M	Winter states have been used as mean annual temperatures are coldest and soil will therefore be moister at this extreme time of year. Humid area will have moister soil and it is expected that the soil will not dry out easily. South African state values adapted from Schulze (1997). Australian state values adapted from Bureau of Meteorology (2018b).

Note:

AU = Australia; AWC = available water capacity; CV =coefficient of variation; EC = electrical conductivity; ESP = exchangeable sodium percentage; H = high; L = low; M = medium; PAW = plant available water; SA = South Africa.

[a] Numeric values were defined based on universal values (i.e., can be applied to any region and include well known specialist terminology) or regional South African and Australian values.

[+] "Hypothetical" data scenarios were entered when site data was unobtainable.

Table 2.
Anthropogenic risk source component model nodes, states and their values with input data for poor and improved management scenarios shown

Nodes	States and [#]values[a]	Input data, Poor and improved management	Description and supporting references
SOIL MANAGEMENT	% risk		Child node
Soil Condition at Handling	L risk H risk		Parent node.
Soil Water Content	L (wilting point, –1500 kPa, SA, AU) M (field capacity, -5 to -55 kPa, SA, AU) H (saturated, SA, AU) Universal values.	[+]Hypothetical = L and H	Handling soils when wet increases soil compaction risk. Compaction is usually greatest when soils are moist, soils should therefore be stripped when moisture content is as low as possible. Stripping and replacement of soil should be done during the dry winter months (summer months in Mediterranean climate areas) when rainfall is at its lowest and soils are driest (Anglo Coal Environmental Rehabilitation Improvement Group, 2009). State values provided by experts.
Rain Season	L (dry season) H (rain season) Universal values.	[+]Hypothetical = L and H	Rehabilitation should preferably be undertaken in the dry season. State values provided by experts
Existing Compaction	L (Soil strength 0.5-3 MPa or Bulk density 1.0-1.50 g/cm^3). H (Soil strength 3-5.5	[+]Hypothetical = L and H For Kleinkopje, 1.56	Soils that are already compacted should be handled with care or ameliorated. Bulk density is expressed as the dry weight of soil per unit area e.g.

Nodes	States and [#]values[a]	Input data, Poor and improved management	Description and supporting references
	MPa or Bulk density 1.5-2.0 g/cm^3). Universal values.	g/cm^3 (Anglo Operations (Pty) Ltd, 2018) = L For Caval Ridge 1.0-1.6 g/cm^3 (Australian Collaborative Land Evaluation Program, 2018) = L	g/cm^3 (Newton and Claassen, 2003). Low/ hard bulking factors can expand by 25% and high/ soft bulking factors can compact by 15% (Chamber of Mines of South Africa, 2007). Soil strength values: low (<2 MPa), medium (2.5-3 MPa) or high (>3 MPa) (Rethman, 2006). Australian Collaborative Land Evaluation Program (2018), describes Bulk Density of the whole soil (including coarse fragments) in mass per unit volume by a method equivalent to the core method, measured as in g/cm^3. State values provided by experts and as adapted from Rethman (2006) and the Australian Collaborative Land Evaluation Program (2018).
Soil Characterisation	L risk H risk		Parent node.
Soil Separation	L (yes) H (no) Universal values.	[+]Hypothetical = L and H	When care has not been taken to separate soil types, there is an increased risk of compaction occurring, i.e. clay soils which are more susceptible to compaction may become mixed with other soils. State values provided by experts.
Impermeable Material	L (below) H (above) Universal values.	[+]Hypothetical = L and H	If impermeable materials are placed as a top layer, the risks of compaction increase, as drainage is impeded. State values provided by experts.

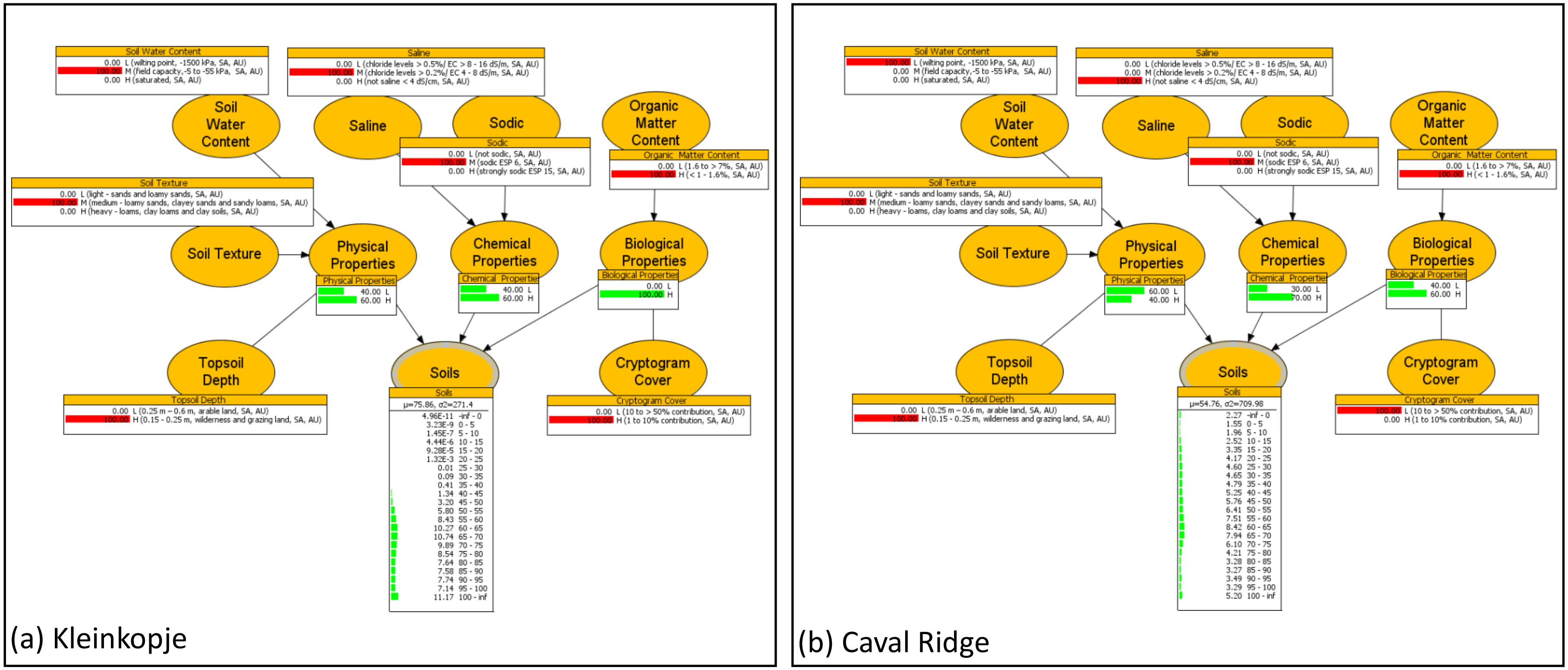
Nodes	**States and [#]values[a]**	**Input data, Poor and improved management**	**Description and supporting references**
Soil Stockpiles	L risk H risk		Parent node.
Height and Footprint	L (no stockpiles) M (1.5 m-3 m, medium surface area) H (>3 m, small surface area) Universal values.	[+]Hypothetical = L and H	Stockpiling may have certain negative impacts on soils. These may include among other the increase in bulk density (Rethman, 2006). The higher the stockpile and the smaller its surface area the greater the risks of compaction (Anglo Coal Environmental Rehabilitation Improvement Group, 2009; Rethman, 2006). Fairly large areas (footprints) and low heights are recommended. While heights of 2 – 3 m would be acceptable, a maximum height of 1.5 m would be preferred (Rethman, 2006). The maximum height of topsoil stockpiles must be 3 m to minimize soil compaction (Anglo Coal Environmental Rehabilitation Improvement Group, 2009). State values provided by experts and as recommended by ARC-Institute for Soil Climate and Water (2016).
Double Handling	L (No) H (Yes) Universal values.	[+]Hypothetical = L and H	Double handling increases the risks of compaction. Wherever possible, stripping and replacing of soils should be done in a single action (live placement) (Anglo Coal Environmental Rehabilitation Improvement Group, 2009) State values provided by experts.

Nodes	States and [#]values[a]	Input data, Poor and improved management	Description and supporting references
Age	L (< 9 mo old) M (9-24 mo old) H (> 24 mo old) Universal values.	[+]Hypothetical = L and H	Soils that have been stockpiled for long periods of time become compacted. State values provided by experts.
MACHINERY MANAGEMENT	% risk value		Child node
Loading	L risk H risk		Parent node.
Tyres	L (low pressure and/or wide) H (high pressure and/or narrow) Universal values.	[+]Hypothetical = L and H	State values provided by experts.
Tracks	L (wide) H (narrow) Universal values.	[+]Hypothetical = L and H	State values provided by experts.
Axle load	L (range) M (range) H (>5 tons per axle) Universal values.	[+]Hypothetical = L and H	State values provided by experts.
Actions	L risk H risk		Parent node.

Nodes	**States and #values[a]**	**Input data, Poor and improved management**	**Description and supporting references**
Machinery choice	L (draglines) L to M (truck and shovel) M (dozers with tracks) M to H (graders with wheels) H (scrapers/ bowlscrapers) Universal values.	+Hypothetical = L and H	Draglines (Removal of topsoil (partial), overburden (major) and replacement of topsoil (partial). Scrapers/ bowlscrapers (topsoil replacement). Shovel (backhoe) and truck (topsoil replacement). Graders (smoothing of replaced soil). Dozer (smoothing of replaced soils). State values provided by experts.
No of passes	L (<3) M (3-8) H (>8) Universal values.	+Hypothetical = L and H	Soil compaction increases with number of passes. State values adapted from Troldborg et al. (2013).
Speed	L (fast) H (slow) Universal values.	+Hypothetical = L and H	State values provided by experts.

Note:
AU = Australia; L = low; H = high; M = medium; SA = South Africa.
[a] Numeric values were defined based on universal values (i.e., can be applied to any region and include well-known specialist terminology).
[+] “Hypothetical” data scenarios were entered as examples.

Appendix 4.2 Risk source component BN model figures



(a) Kleinkopje

(b) Caval Ridge

Fig. 1. Comparative results, for the Soils component BN model for Kleinkopje (a) and Caval Ridge (b). Data are entered into the BN models as observations and are indicated with red bars. This new information is then propagated through the rest of the BN to update the probability distributions of other nodes, indicated with green bars.

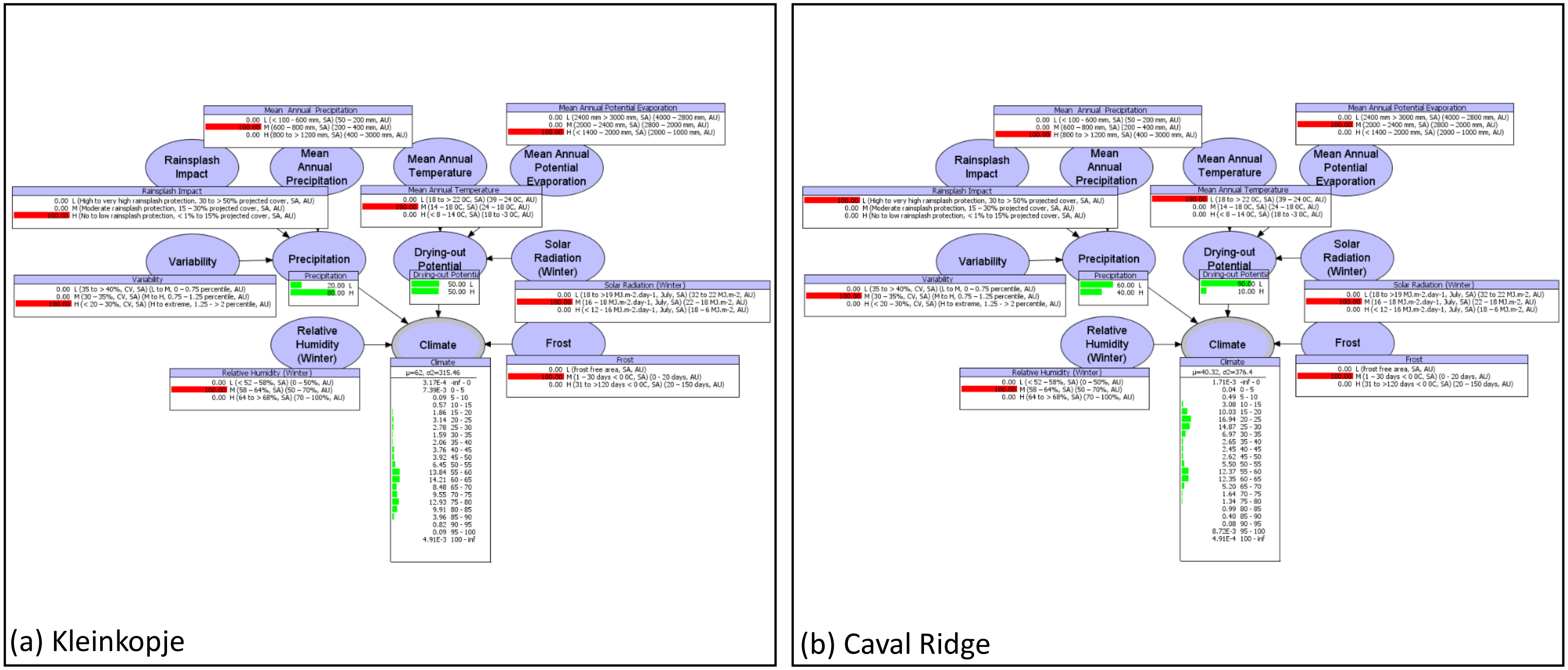
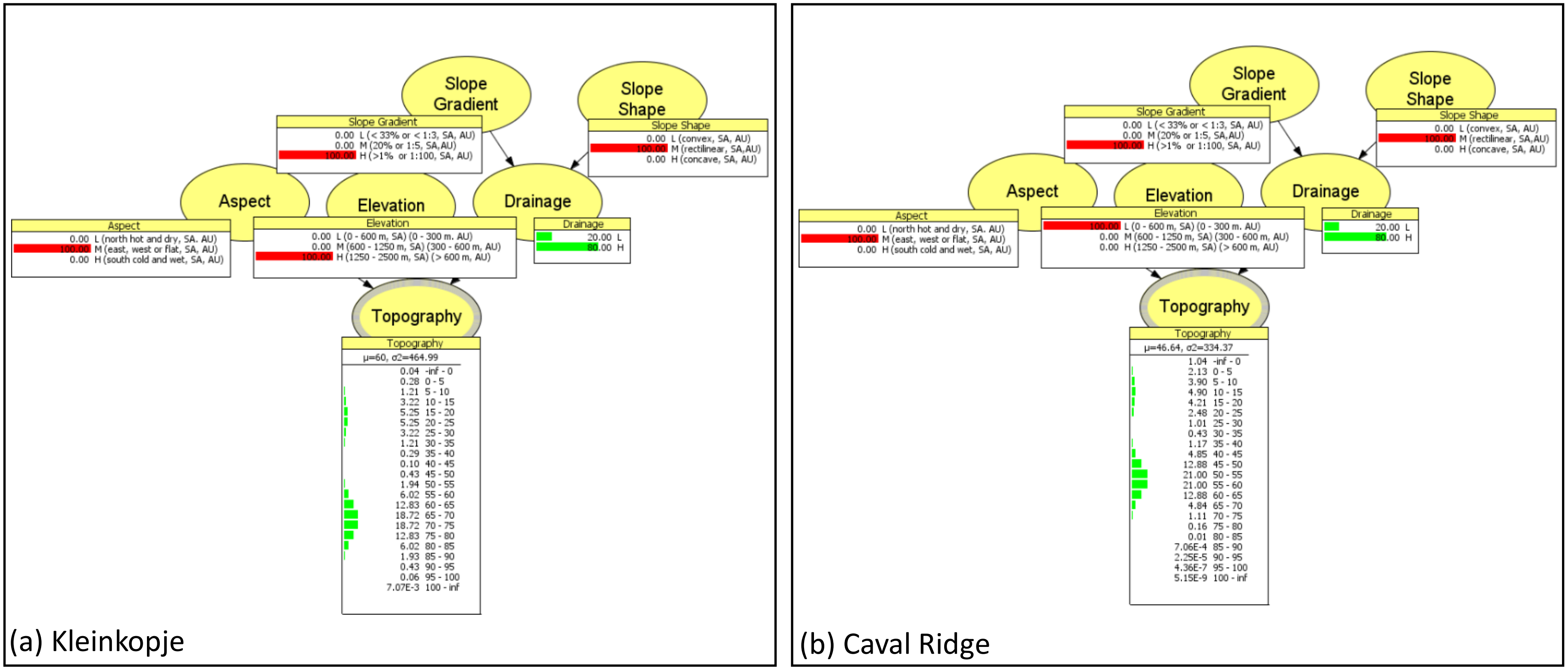


Fig. 2. Comparative results, for the Climate component BN model for Kleinkopje (a) and Caval Ridge (b).



(a) Kleinkopje

(b) Caval Ridge

Fig. 3. Comparative results, for the Topography component BN model, for Kleinkopje (a) and Caval Ridge (b).

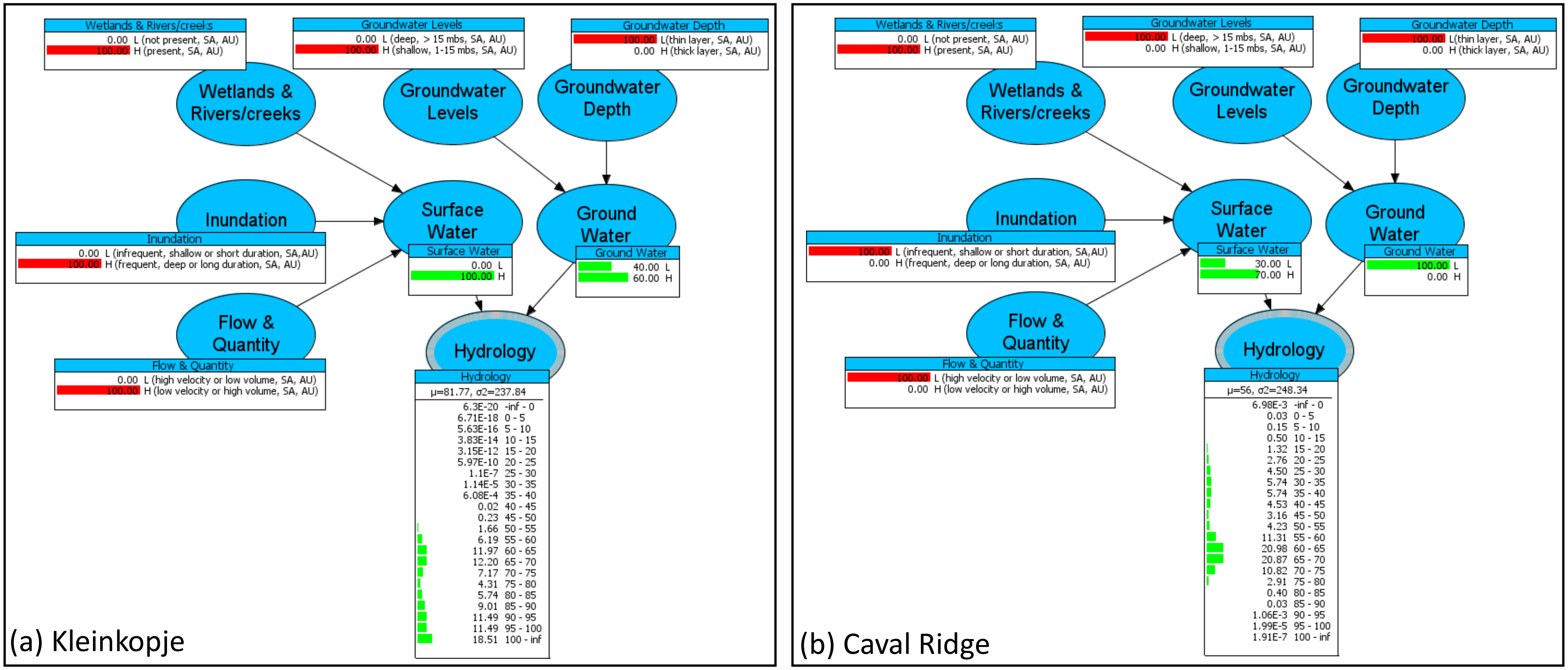


Fig. 4. Comparative results, for the Hydrology component BN model, for Kleinkopje (a) and Caval Ridge (b).

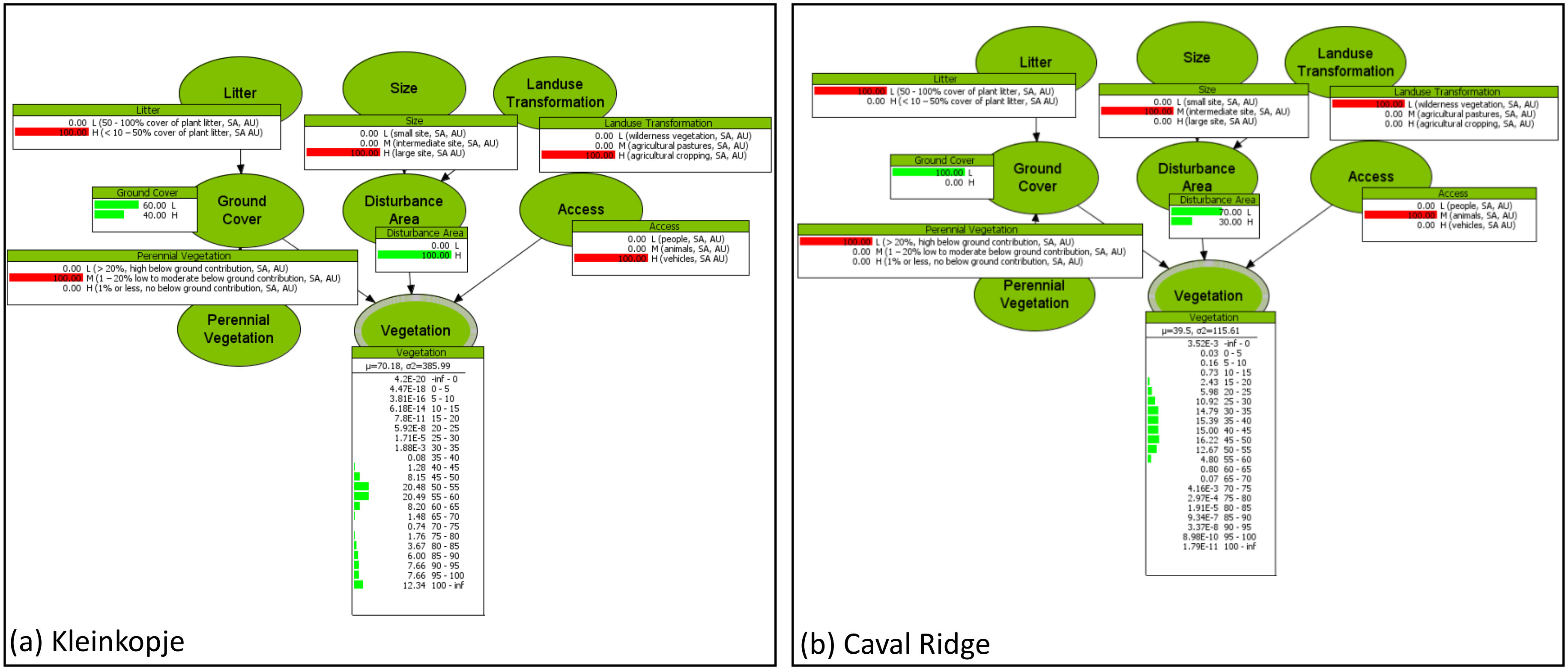
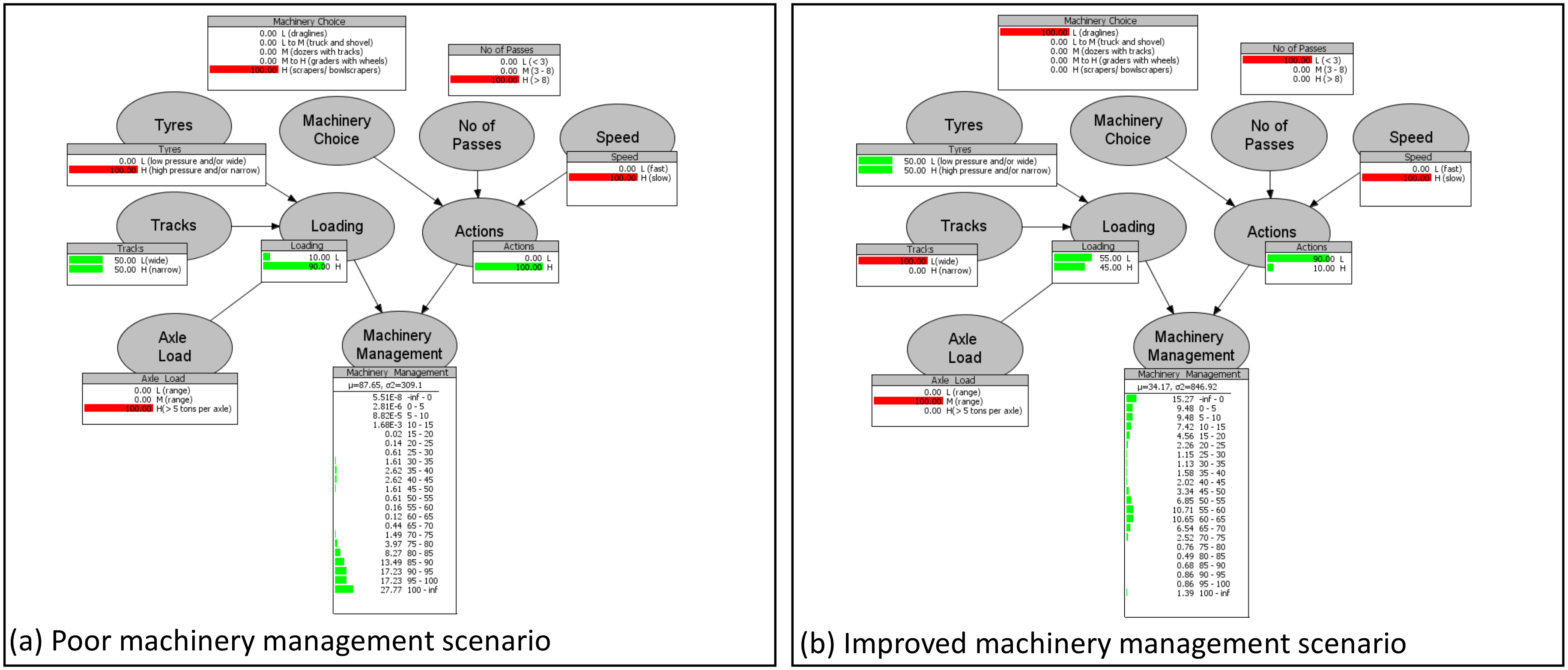


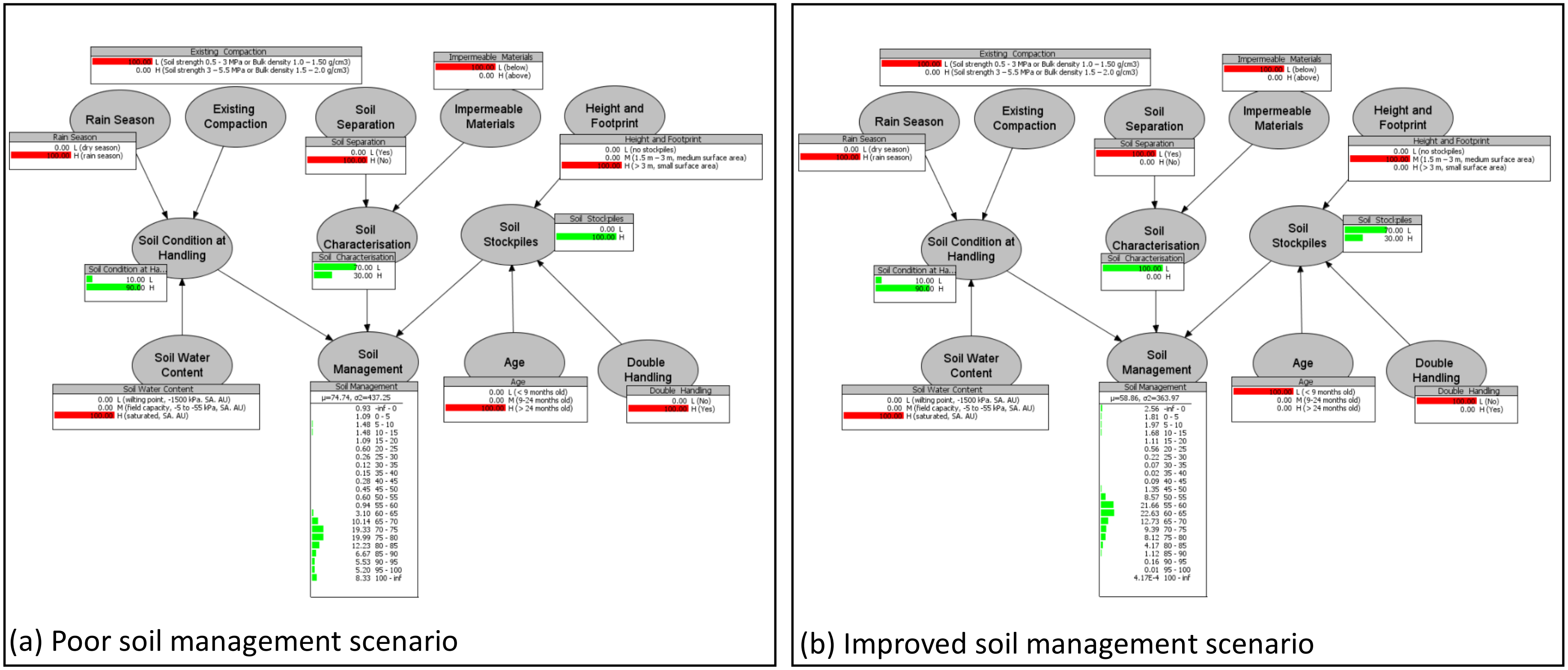
Fig 5. Comparative results, for the Vegetation component BN model for Kleinkopje (a) and Caval Ridge (b).



(a) Poor machinery management scenario

(b) Improved machinery management scenario

Fig 6. Comparative results for the Machinery Management component BN model with a poor (a) and an improved management scenario (b).



(a) Poor soil management scenario

(b) Improved soil management scenario

Fig 7. Comparative results for the Soil Management component BN model with a poor (a) and an improved (b) management scenario.

4.14 Supplemental data included as background information for examiners only

Appendix 4.3 Soil compaction Bayesian network model conditional probability tables

Soil BN Model CPTs

Node: Soil

Biological	L				H			
Physical	L		H		L		H	
Chemical	L	H	L	H	L	H	L	H
Mean risk for Soil:	5	25	35	45	55	65	75	95
Standard dev.	10	9	7	7	8	8	9	10

Risk contribution ranking:
No 1: Physical
No 2: Biological
No 3: Chemical

Node: Physical Properties

State to quantify: Low risk

Soil Water Content	**Topsoil Depth**	**Soil Texture**		
		L (light)	M (medium)	H (heavy)
L (wilting point)	L (0.25 m – 0.6 m, arable land)	1	0,7	0,6
	H (0.15 - 0.25 m, wilderness and grazing land)	0,7	0,6	0,5
M (field capacity)	L (0.25 m – 0.6 m, arable land)	0,6	0,5	0,4
	H (0.15 - 0.25 m, wilderness and grazing land)	0,5	0,4	0,3
H (saturated)	L (0.25 m – 0.6 m, arable land)	0,4	0,3	0,2
	H (0.15 - 0.25 m, wilderness and grazing land)	0,3	0,1	0

Risk contribution ranking:
No 1: Soil Water Content
No 2: Soil Texture
No 3: Topsoil Depth

Node: Chemical Properties
State to quantify: Low risk

Saline	**Sodic**		
	L (not sodic)	M (sodic ESP 6)	H (strongly sodic ESP 15)
L (chloride levels > 0.5%)	1	0,6	0,4
M (chloride levels > 0.2%)	0,6	0,4	0,3
H (not saline)	0,4	0,3	0

Risk contribution ranking:
Equal for Saline and Sodic

Node: Biological Properties
State to quantify: Low risk

Organic Matter Content	**Crytogram Cover**	
	L (present)	H (not present)
L (1.6 to > 7%)	1	0,6
H (< 1 - 1.6%)	0,4	0

Risk contribution ranking:
No 1: Organic Matter
No 2: Crytogram Cover

Topography BN Model CPTs

Node: Topography																		
Drainage	L									H								
Aspect	L			M			H			L			M			H		
Elevation	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Mean risk for Topography:	5	10	11	13	15	20	25	30	35	40	45	50	55	60	70	75	80	95
Standard dev.	10	9	8	8	8	7	6	6	6	6	6	6	7	8	8	8	9	10
Risk contribution ranking:																		
No 1: Drainage																		
No 2: Aspect																		
No 3: Elevation																		

Node: Drainage			
State to quantify: Low risk			
Slope Gradient	**Slope Shape**		
	L (convex)	M (rectilinear)	H (concave)
L (< 33% or < 1:3)	1	0,7	0,6
M (20% or 1:5)	0,7	0,6	0,2
H (>1% or 1:100)	0,6	0,2	0
Risk contribution ranking:			
Equal for Slope Gradient and Slope Shape			

Vegetation BN Model CPTs

Node: Vegetation												
Ground Cover	L						H					
Disturbance Area	L			H			L			H		
Access	L	M	H	L	M	H	L	M	H	L	M	H
Average risk for Vegetation	5	35	40	45	50	55	60	75	70	80	85	95
Standard dev.	10	9	7	6	5	5	5	5	6	7	9	10

Node: Disturbance Area

State to quantify: Low risk

Size	**Landuse Transformation**		
	L (wilderness vegetation)	M (agricultural pastures)	H (agricultural cropping)
L (small site)	1	0,8	0,6
M (intermediate site)	0,7	0,5	0,3
H (large site)	0,5	0,4	0

Risk contribution ranking:
No 1: Land Transformation
No 2: Size

Node: Ground Cover

State to quantify: Low risk

Perennial Vegetation	**Litter**	
	L (50-100% cover)	H (< 10-50% cover)
L (> 20%)	1	0,8
M (1-20%)	0,8	0,6
H (1% or less)	0,3	0

Risk contribution ranking:
No 1: Perennial Vegetation
No 2: Litter

Hydrology BN Model CPTs

Node: Hydrology				
Surface Water	Low		High	
Ground Water	Low	High	Low	High
Mean risk for Hydrology:	35	75	65	95
Standard dev.	10	7	6	10

Node: Surface Water			
State to quantify: Low risk			
Wetlands & Rivers/creeks	**Inundation**	**Flow & Quantity**	
		L (high velocity or low volume)	H (low velocity or high volume)
L (not present)	L (infrequent)	1	0,7
	H (frequent)	0,6	0,5
H (present)	L (infrequent)	0,3	0,2
	H (frequent)	0,1	0

Risk contribution ranking:
No 1: Wetands & Rivers/creeks
No 2: Inundation
No 3: Flow & Quantity

Node: Ground Water		
State to quantify: Low risk		
Groundwater Levels	**Groundwater Depth**	
	L (thin layer)	H (thick layer)
L (deep)	1	0,6
H (shallow)	0,4	0

Risk contribution ranking:
No 1: Groundwater Levels
No 2: Groundwater Depth

Climate BN Model CPTs

Node: Climate

Relative Humidity (Winter)	L												M												H											
Frost	L				M				H				L				M				H				L				M				H			
Drying-out Potential	L		H		L		H		L		H		L		H		L		H		L		H		L		H		L		H		L		H	
Precipitation	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
Mean risk for Climate:	5	10	15	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	85	90	95
Standard dev.	10	9	8	7	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	7	8	9	10

Precipitation	L																		H																	
Drying-out Potential	L									H									L									H								
Relative Humidity (Winter)	L			M			H			L			M			H			L			M			H			L			M			H		
Frost	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Mean risk for Climate:	Normal	Normal																																		
	(5, 100)	(10, 81)																																		

Risk contribution ranking:
No 1: Precipitation
No 2: Drying-out Potential
No 3: Relative Humidity
No 4: Frost

Node: Drying-out Potential

State to quantify: Low risk

Mean Annual Temperature	Mean Annual Potential Evaporation	Solar Radiation (Winter)		
		L (18 to >19 MJ.m-2.day-1, SA)	M (16 – 18 MJ.m-2.day-1, SA)	H (< 12 - 16 MJ.m-2.day-1, SA)
L (18 to >22 0C, SA)	Low (2400 mm > 3000 mm, SA)	1	0,9	0,9
	Medium (2000 – 2400 mm, SA)	0,9	0,9	0,8
	High (< 1400 – 2000 mm, SA)	0,9	0,8	0,7
M (14 – 18 0C, SA)	Low (2400 mm > 3000 mm, SA)	0,8	0,7	0,6
	Medium (2000 – 2400 mm, SA)	0,7	0,6	0,5
	High (< 1400 – 2000 mm, SA)	0,6	0,5	0,4
H (< 8 – 14 0C, SA)	Low (2400 mm > 3000 mm, SA)	0,5	0,4	0,3
	Medium (2000 – 2400 mm, SA)	0,4	0,3	0,2
	High (< 1400 – 2000 mm, SA)	0,2	0,1	0

Risk contribution ranking:
No 1: Mean Annual Temperature
No 2: Mean Annual Potential Evaporation
No 3: Solar Radiation

Node: Precipitation

State to quantify: Low risk

Variability	**Mean Annual Precipitation**	**Rainsplash Impact**		
		L	M	H
L	L (< 100 - 600 mm, South Africa (SA))	1	0,9	0,9
	M (600 – 800 mm, SA)	0,9	0,9	0,8
	H (800 to > 1200 mm, SA)	0,9	0,8	0,7
M	L (< 100 - 600 mm, South Africa (SA))	0,8	0,7	0,6
	M (600 – 800 mm, SA)	0,7	0,6	0,5
	H (800 to > 1200 mm, SA)	0,6	0,5	0,4
H	L (< 100 - 600 mm, South Africa (SA))	0,5	0,4	0,3
	M (600 – 800 mm, SA)	0,4	0,3	0,2
	H (800 to > 1200 mm, SA)	0,2	0,1	0

Risk contribution ranking:
No 1: Mean Annual Precipitation
No 2: Variability
No 3: Rainsplash Impact

Soil Management BN Model CPTs

Node: Soil Management

Soil conditioning at handling	Low				High			
Soil characterisation	Low		High		Low		High	
Soil stockpiles	Low	High	Low	High	Low	High	Low	High
Mean risk for soil management:	5	10	40	55	60	75	80	95
Standard dev.	10	9	7	5	5	6	9	10

Node: Soil condition at handling

State to quantify: Low risk

Rain season	Existing Compaction	Soil Water Content		
		L (wilting point)	M (field capacity)	H (saturated)
L (dry season)	L (No)	1	0,5	0,4
	H (Yes)	0,8	0,3	0,2
H (rain season)	L (No)	0.6	0,2	0,1
	H (Yes)	0.4	0,1	0

Node: Soil Stockpiles

State to quantify: Low risk

Age	Double Handling	Height and footprint		
		L (no stockpiles)	M (1.5 - 3 m, medium surface area)	H (> 3 m high, small surface area)
L (< 9 months old)	L (No)	1	0,7	0,6
	H (Yes)	0,6	0,5	0,5
M (9-24 months old)	L (No)	0,4	0,3	0,2
	H (Yes)	0,3	0,2	0,1
H (> 24 months old)	L (No)	0,4	0,3	0,2
	H (Yes)	0,3	0,1	0

Node: Soil Characterisation

State to quantify: Low risk

Soil separation	**Impermeable materials**	
	Low (below)	High (above)
Low (Yes)	1	0,8
High (No)	0,7	0

Machinery Management BN Model CPTs

Node: Machinery Management

Loading	Low		High	
Actions	Low	High	Low	High
Mean risk for Machinery Management:	5	40	60	95
Standard dev.	10	7	7	10

Node: Loading

State to quantify: Low risk

Axle Load	Tracks	Tyres	
		L (low pressure and/or wide)	H (high pressure and/or narrow)
L (range)	L(wide)	1	0,7
	H (narrow)	0,7	0,6
M (range)	L (wide)	0,6	0,5
	H (narrow)	0,5	0,4
H (>5 tons per axle)	L(wide)	0,4	0,2
	H (narrow)	0,3	0

Risk contribution ranking:
No 1: Axle load
No 2: Tyres
No 3: Tracks

Node: Actions

State to quantify: Low risk

Number of Passes	**Speed**	**Machinery Choice**				
		low (draglines)	low-medium (truck and shovel)	medium (dozers with tracks)	medium-high (graders with wheels	high (scrapers/ bowlscrapers)
Low (< 3)	Low (fast)	1	0,9	0,8	0,6	0,5
	High (slow)	0,9	0,8	0,7	0,5	0,4
Medium (3-8)	Low (fast)	0,8	0,7	0,6	0,4	0,3
	High (slow)	0,7	0,6	0,5	0,3	0,2
High (>8)	Low (fast)	0,6	0,5	0,4	0,2	0,1
	High (slow)	0,5	0,4	0,3	0,1	0

Risk contribution ranking:
No 1: Machinery Choice
No 2: Number of Passes
No 3: Speed

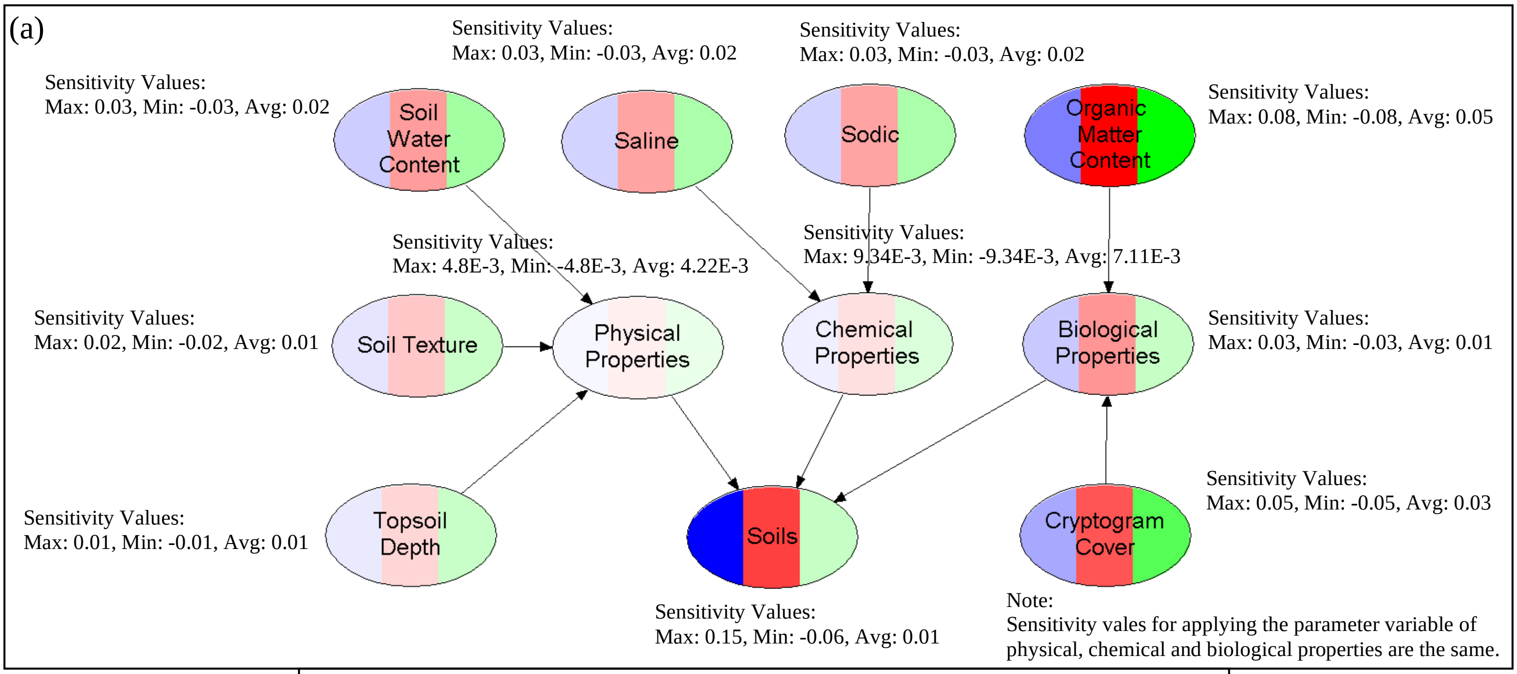
Appendix 4.4 Soil Bayesian network model parameter sensitivity analysis as an example

A parameter sensitivity analysis of the soil compaction BN model, for only the soils BN, was conducted as an example. The 'parameter sensitivity wizard' contained in Hugin® v.8.1. educational software (HuginExpert, 2018) was used. The wizard produces a sensitivity function graph (block (b) of Fig. 1-7) and a linked network diagram (block (a) of Fig. 5.1, 5.2, 5.5 and 5.6) that visually captures the results.

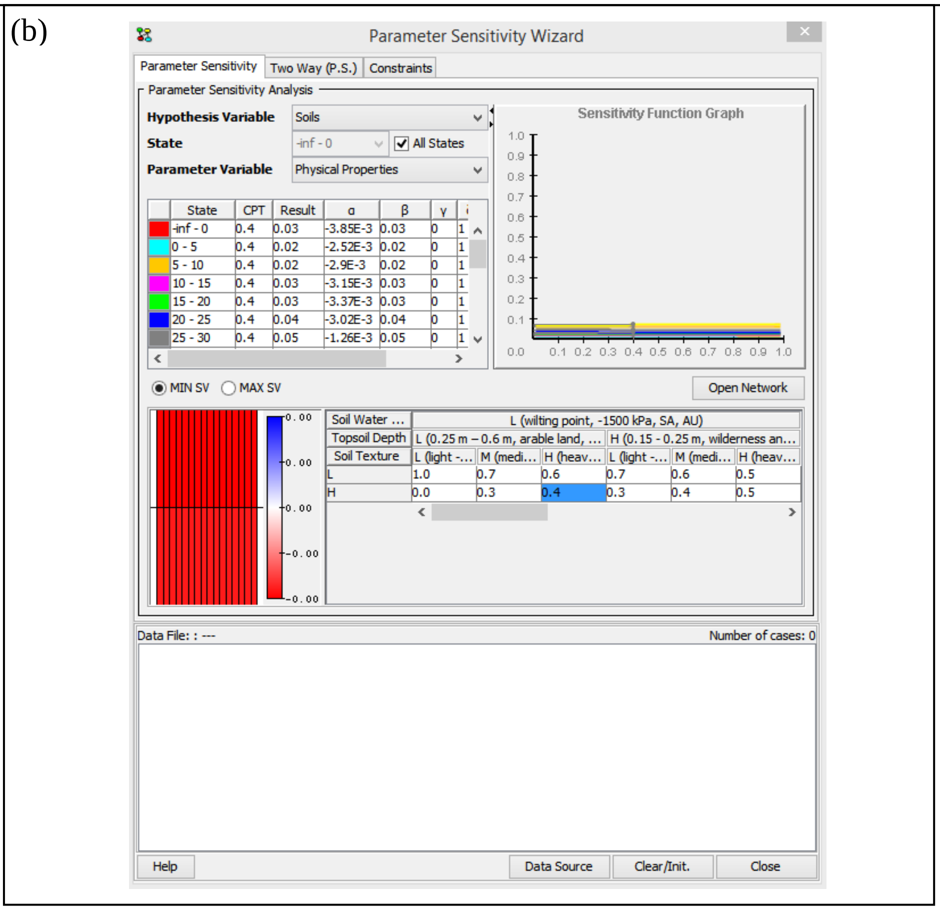
Graphs show lines that represent how sensitive the states of the hypothesis variable are, to changes of the parameter values, i.e., the entry of the CPT selected (highlighted blue all bock (b's), middle section).

In the network diagram, nodes are coloured blue, red and green, based on how sensitive they are, based on the selected hypothesis variable and its changes in the parameters selected for each node. Blue represents the maximum sensitivity value, red the minimum sensitivity value, whilst green represents the average sensitivity value. The tone of each colour indicates how high the value they represent is. Darker tones show higher values.

The network diagram allows for easy discernments of which nodes of the hypothesis variable have the highest values and are therefore the most sensitive to changes in parameter values. By understanding which nodes are the most sensitive to changes, amendment to the design of BN models can be made where required.



Note:
Sensitivity vales for applying the parameter variable of physical, chemical and biological properties are the same.



Hypothesis Variable Soils
State -inf - 0 ☑ All States
Parameter Variable Physical Properties

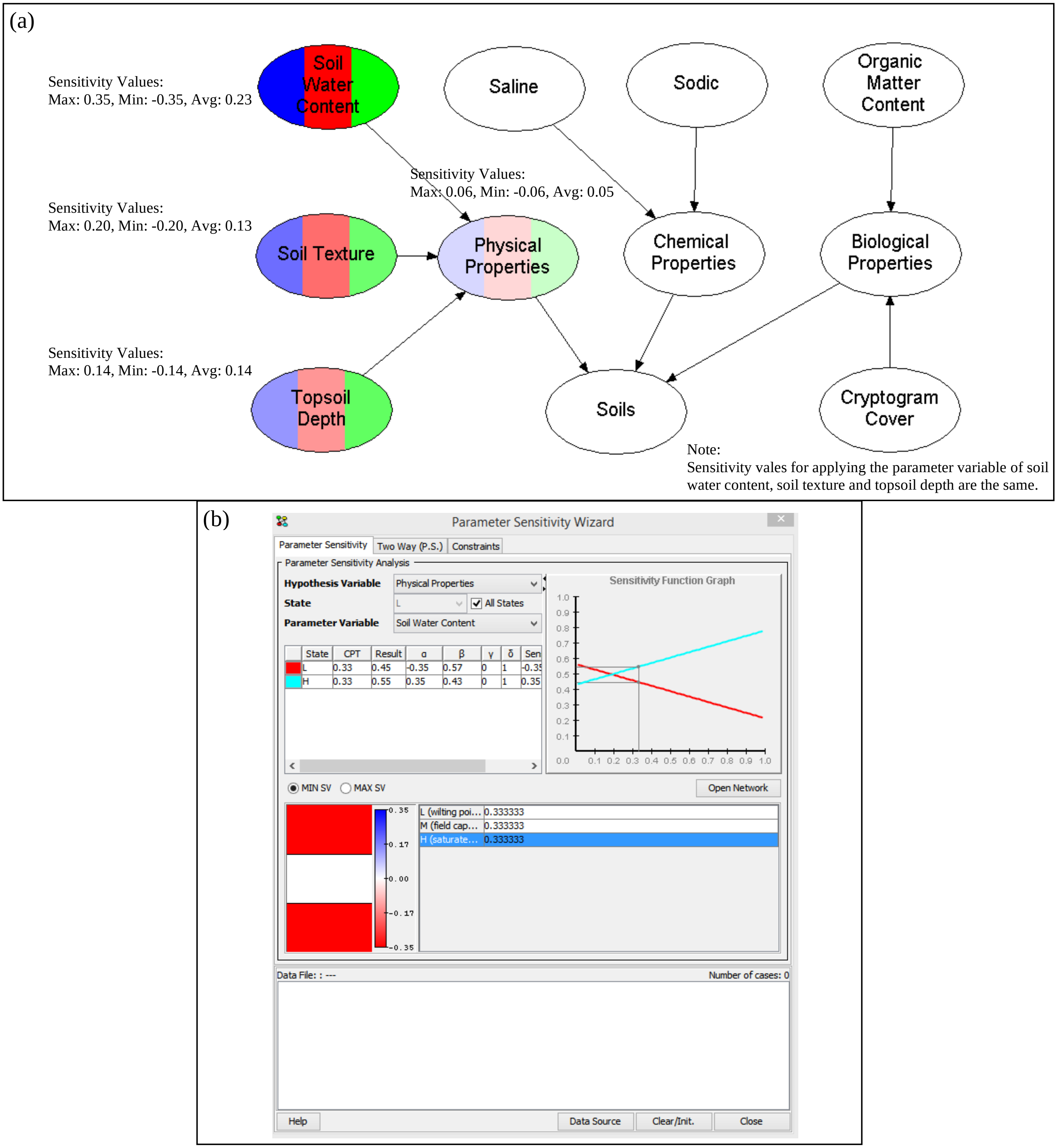
	State	CPT	Result	α	β	γ	
🟥	-inf - 0	0.4	0.03	-3.85E-3	0.03	0	1
🟦	0 - 5	0.4	0.02	-2.52E-3	0.02	0	1
🟨	5 - 10	0.4	0.02	-2.9E-3	0.02	0	1
🟪	10 - 15	0.4	0.03	-3.15E-3	0.03	0	1
🟩	15 - 20	0.4	0.03	-3.37E-3	0.03	0	1
🟦	20 - 25	0.4	0.04	-3.02E-3	0.04	0	1
⬛	25 - 30	0.4	0.05	-1.26E-3	0.05	0	1

● MIN SV ○ MAX SV

Soil Water …	L (wilting point, -1500 kPa, SA, AU)					
Topsoil Depth	L (0.25 m – 0.6 m, arable land, …			H (0.15 - 0.25 m, wilderness an…		
Soil Texture	L (light -…	M (medi…	H (heav…	L (light -…	M (medi…	H (heav…
L	1.0	0.7	0.6	0.7	0.6	0.5
H	0.0	0.3	0.4	0.3	0.4	0.5

Data File: : --- Number of cases: 0

Fig. 1. Parameter sensitivity analysis function graph, for the hypothesis variable soils node, using the parameter variable physical properties (block b). As the hypothesis node has many states the graph shows many overlapping function lines. Sensitivity values are shown in the network diagram (block a).



Sensitivity Values:
Max: 0.35, Min: -0.35, Avg: 0.23

Sensitivity Values:
Max: 0.06, Min: -0.06, Avg: 0.05

Sensitivity Values:
Max: 0.20, Min: -0.20, Avg: 0.13

Sensitivity Values:
Max: 0.14, Min: -0.14, Avg: 0.14

Note:
Sensitivity vales for applying the parameter variable of soil water content, soil texture and topsoil depth are the same.

Hypothesis Variable Physical Properties
State L ☑ All States
Parameter Variable Soil Water Content

	State	CPT	Result	α	β	γ	δ	Sen
🟥	L	0.33	0.45	-0.35	0.57	0	1	-0.3
🟦	H	0.33	0.55	0.35	0.43	0	1	0.35

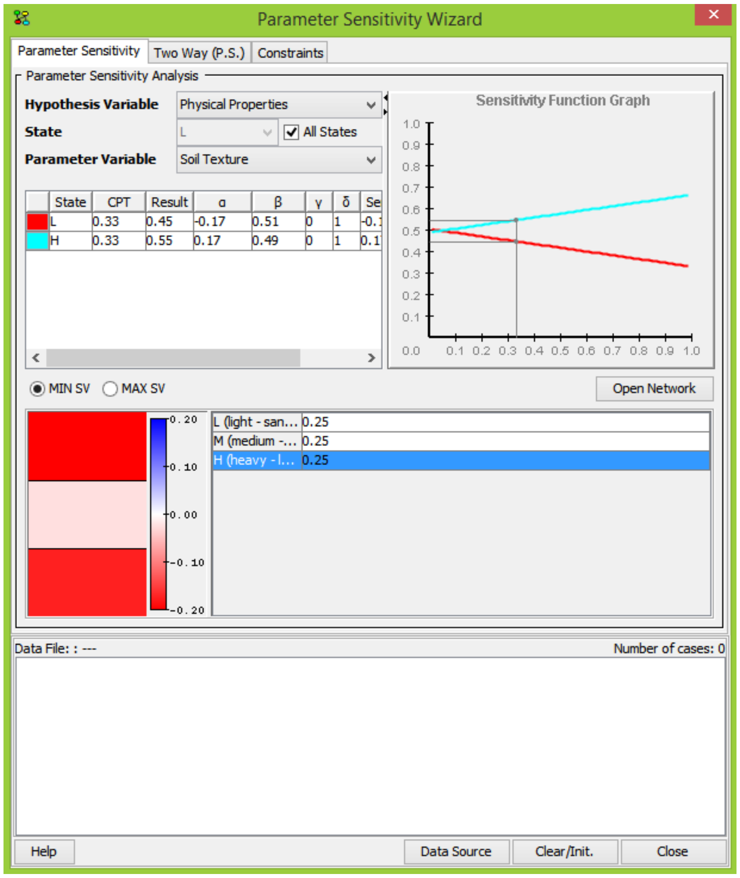
● MIN SV ○ MAX SV

L (wilting poi…	0.333333
M (field cap…	0.333333
H (saturate…	0.333333

Data File: : ---
Number of cases: 0

Fig. 2. Parameter sensitivity analysis function graph, for the hypothesis variable physical properties node, using the parameter variable soil water content (block b). Sensitivity values are shown in the network diagram (block a).

(b)



Hypothesis Variable Physical Properties
State L ☑ All States
Parameter Variable Soil Texture

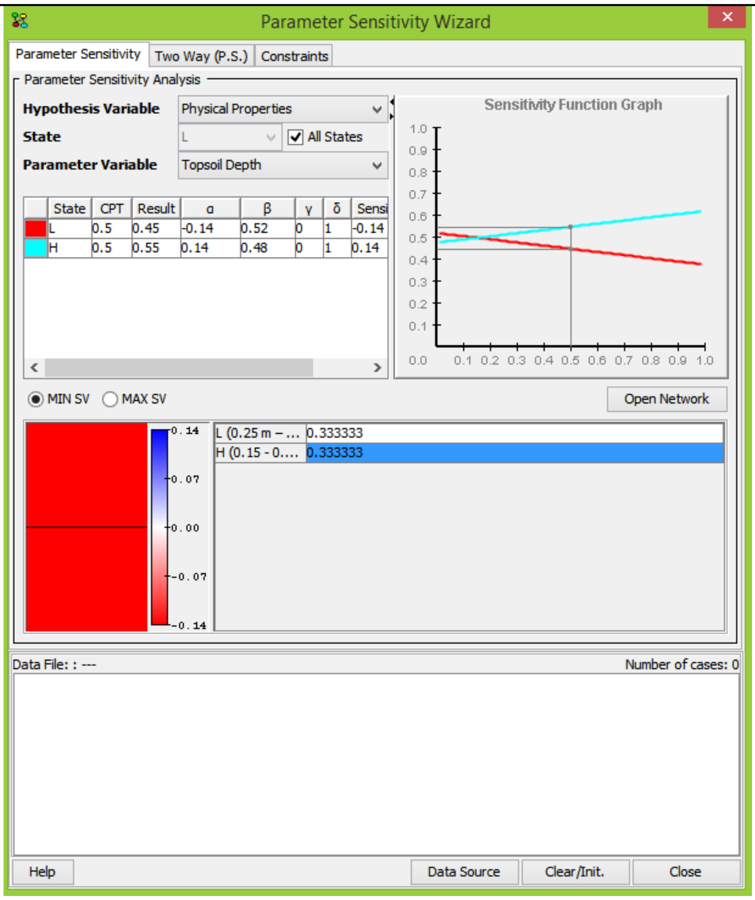
	State	CPT	Result	α	β	γ	δ	Se
🟥	L	0.33	0.45	-0.17	0.51	0	1	-0.1
🟦	H	0.33	0.55	0.17	0.49	0	1	0.1

● MIN SV ○ MAX SV

L (light - san…	0.25
M (medium -…	0.25
H (heavy - l…	0.25

Fig. 3. Parameter sensitivity analysis function graph, for the hypothesis variable physical properties node, using the parameter variable soil texture (block b).

(b)



Hypothesis Variable Physical Properties

State L ☑ All States

Parameter Variable Topsoil Depth

	State	CPT	Result	α	β	γ	δ	Sensi
🟥	L	0.5	0.45	-0.14	0.52	0	1	-0.14
🟦	H	0.5	0.55	0.14	0.48	0	1	0.14

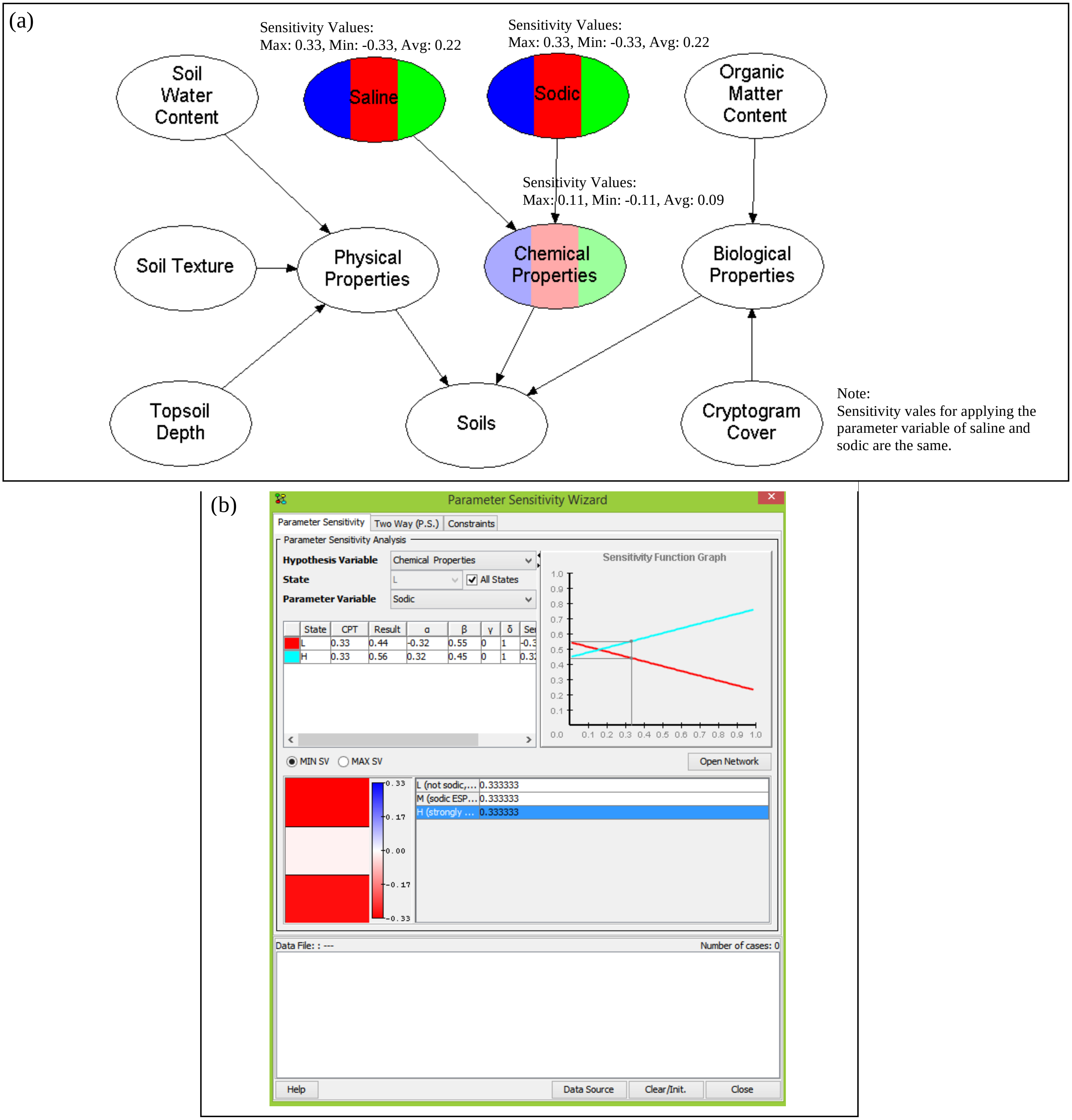
● MIN SV ○ MAX SV

L (0.25 m – …	0.333333
H (0.15 - 0.…	0.333333

Data File: : ---

Number of cases: 0

Fig. 4. Parameter sensitivity analysis function graph, for the hypothesis variable physical properties node, using the parameter variable topsoil depth (block b).



Sensitivity Values:
Max: 0.33, Min: -0.33, Avg: 0.22

Sensitivity Values:
Max: 0.33, Min: -0.33, Avg: 0.22

Sensitivity Values:
Max: 0.11, Min: -0.11, Avg: 0.09

Note:
Sensitivity vales for applying the parameter variable of saline and sodic are the same.

Hypothesis Variable Chemical Properties
State L ☑ All States
Parameter Variable Sodic

	State	CPT	Result	α	β	γ	δ	Se
🟥	L	0.33	0.44	-0.32	0.55	0	1	-0.3
🟦	H	0.33	0.56	0.32	0.45	0	1	0.3

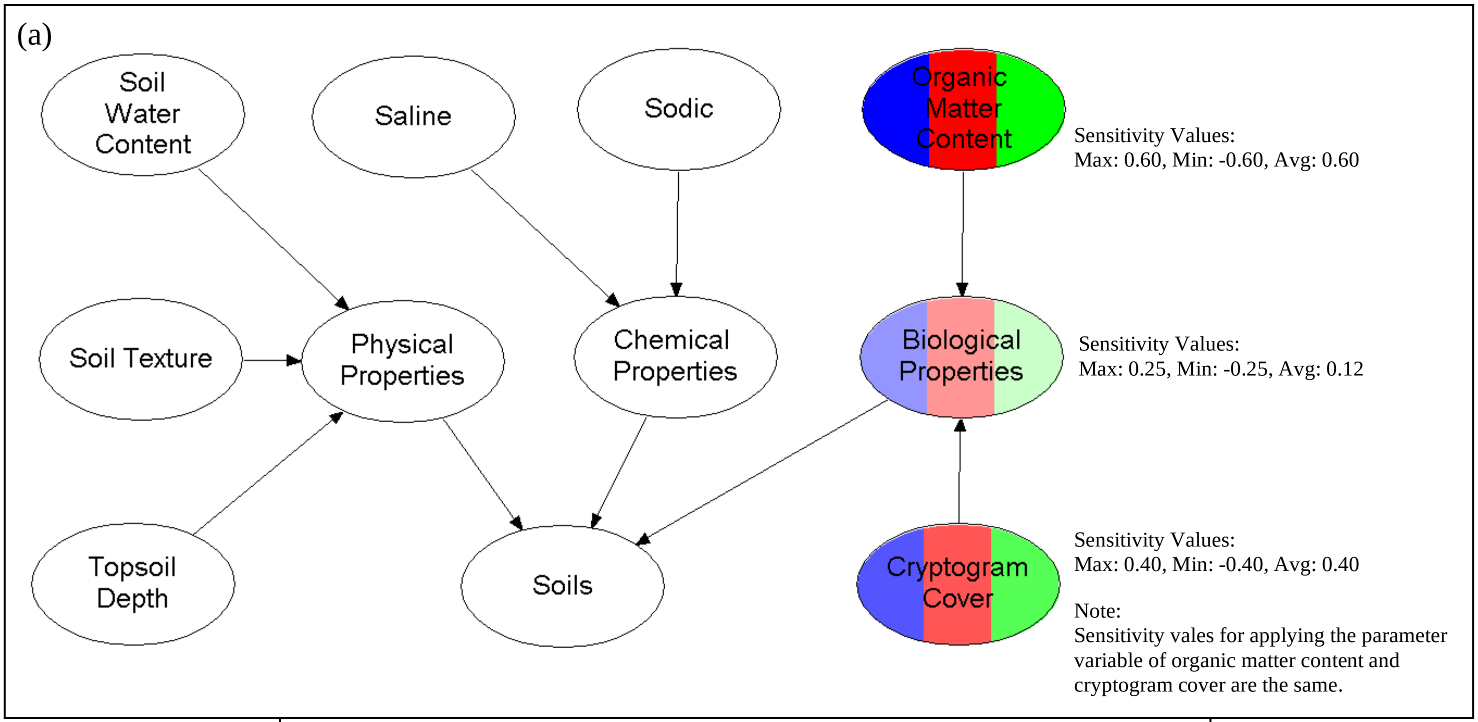
● MIN SV ○ MAX SV

L (not sodic,…	0.333333
M (sodic ESP…	0.333333
H (strongly …	0.333333

Data File: : ---
Number of cases: 0

Fig. 5. Parameter sensitivity analysis function graph, for the hypothesis variable chemical properties node, using the parameter variable sodic and saline (block b). Sensitivity values are shown in the network diagram (block a).

(a)



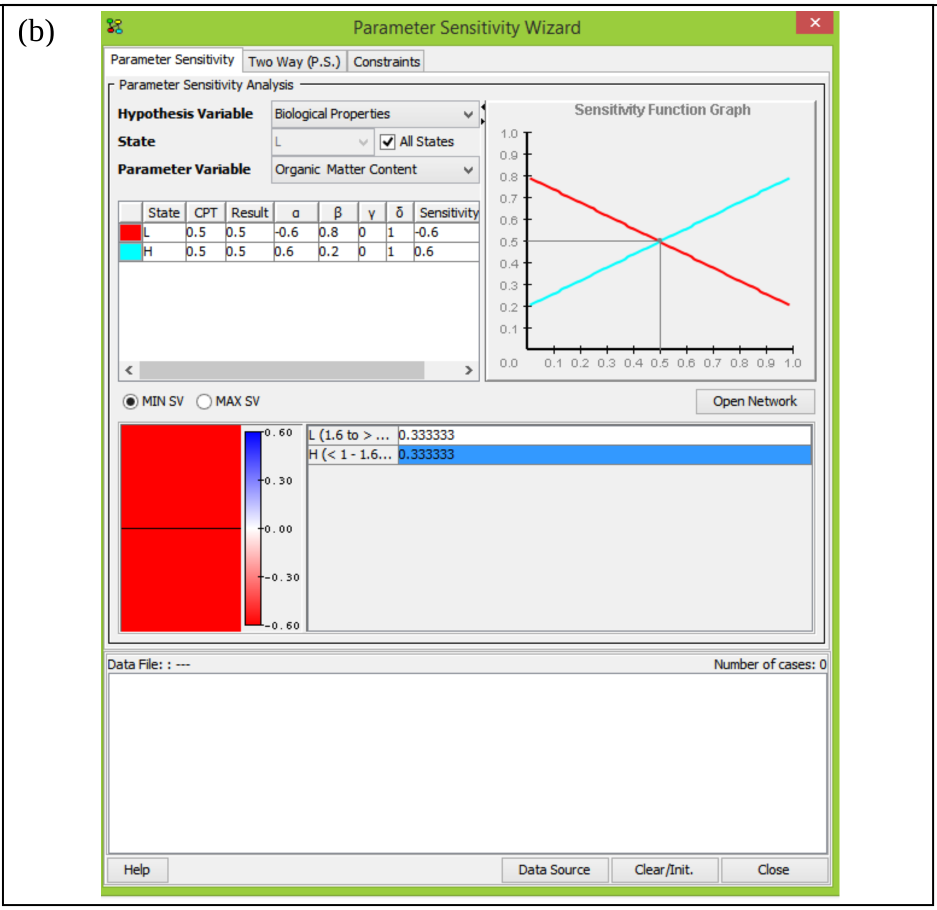
Sensitivity Values:
Max: 0.60, Min: -0.60, Avg: 0.60

Sensitivity Values:
Max: 0.25, Min: -0.25, Avg: 0.12

Sensitivity Values:
Max: 0.40, Min: -0.40, Avg: 0.40

Note:
Sensitivity vales for applying the parameter variable of organic matter content and cryptogram cover are the same.

(b)



Hypothesis Variable Biological Properties
State L ☑ All States
Parameter Variable Organic Matter Content

	State	CPT	Result	α	β	γ	δ	Sensitivity
🟥	L	0.5	0.5	-0.6	0.8	0	1	-0.6
🟦	H	0.5	0.5	0.6	0.2	0	1	0.6

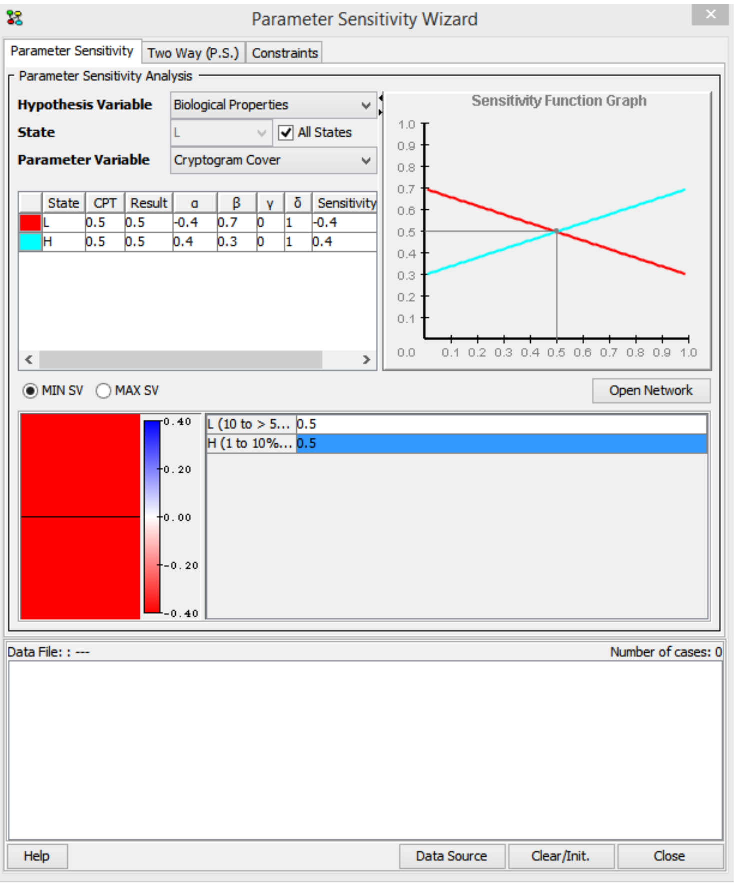
● MIN SV ○ MAX SV

L (1.6 to > ... 0.333333
H (< 1 - 1.6... 0.333333

Data File: : ---
Number of cases: 0

Fig. 6. Parameter sensitivity analysis function graph, for the hypothesis variable biological properties node, using the parameter variable organic matter content (block b). Sensitivity values are shown in the network diagram (block a).

(b)



Hypothesis Variable Biological Properties
State L ☑ All States
Parameter Variable Cryptogram Cover

	State	CPT	Result	α	β	γ	δ	Sensitivity
🟥	L	0.5	0.5	-0.4	0.7	0	1	-0.4
🟦	H	0.5	0.5	0.4	0.3	0	1	0.4

● MIN SV ○ MAX SV

L (10 to > 5...	0.5
H (1 to 10%...	0.5

Data File: : ---
Number of cases: 0

Fig. 7. Parameter sensitivity analysis function graph, for the hypothesis variable biological properties node, using the parameter variable cryptogram cover (block b).

4.15 ORCID

Vanessa D Weyer ID https://orcid.org/0000-0003-3960-578X

Synopsis

This paper has shown that the R^2AIN framework defines a process for the development of a future synthesis rehabilitation risk assessment model, inclusive of prioritised rehabilitation risk event BNs. The soil compaction case study demonstrates the methodology and its workability.

Probabilistic rehabilitation risk is quantifiable with calculations permissible for separate multi-disciplines for individual sites. Site rehabilitation risk profiling before mining activities commence is possible and the effects of manipulating management actions during the latter mine phases to reduce risk, can be gauged, to aid decision making. Resilient rehabilitation planning; qualitative and quantitative multi-discipline integration and upfront rehabilitation risk determination is facilitated. Alignment with the environmental impact and risk assessment processes is possible.

The paper recommends that further research be undertaken including:

1. Alpha testing, i.e. the intermediate test of the system by in-house staff, not directly involved in developing it, but who have expert BN experience, such as other BN modellers;
2. Beta testing i.e. the application of the system by an end-user, to identify flaws and opportunities for improvement, such as testing by mining industry rehabilitation professionals;
3. Acceptance testing, i.e. whereby end-users will need to be sufficiently familiar with the framework, BN process and software to use these with confidence for their specific needs; and
4. A rigorous evaluation process, including informal and formal methods.

The R^2AIN framework and a future synthesis model can facilitate the placing of data into a validated system for practical use and analysis, in contrast to collecting data and leaving it in mine approval documentation with limited application. This research bridges industry practicalities with scientific foundations.

CHAPTER 5:
CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter synthesizes the main findings of the research and discusses its integration within the thesis chapters. The research question is answered in relation to the problem statement, the research aim and objectives, the research hypothesis, prior research and the research gap. Limitations of the study are discussed and then recommendations for further research are provided. Finally, a concluding summary is given, including a statement on the study's overall contribution to research.

5.2 Main findings of the research and integration with thesis chapters

This thesis revealed that upfront surface-strip coal mine rehabilitation planning is being conducted with minimum requirements being met by rehabilitation professionals. Valuable multi-disciplinary specialist information that is gathered at the mine approval phase is seldom analysed and integrated, with a focus on rehabilitation risk.

The development of a surface-strip coal mine rehabilitation maturity model, in Chapter 2, and the application of this to mine rehabilitation guidelines and approval reports in South Africa and Queensland and New South Wales, Australia, provided substantiation of this. Reports were found to be vulnerable to adequate, but not yet resilient.

To address this issue, the need for the development of an integrative, quantitative, multi-disciplinary rehabilitation risk assessment model was identified. However, before such a model could be developed it was necessary to first identify the technique most suited for the model's development and to know what other mine rehabilitation risk assessment techniques have been developed by others that could be relevant. Then to define a process towards developing the model.

In Chapter 3, fault-tree analysis, bow-tie analysis and BNs were reviewed as potential techniques for use. The most suited technique proved to be BNs. No technique developed by others was found to be closely aligned. However, some aspects of prior research could facilitate future linkages, particularly work by Dale et al. (2018).

In Chapter 4, a R^{2}AIN framework was developed based on the ISO 31000 - Risk management standard process (Council of Standards Australia & New Zealand, 2009, South African Bureau of Standards, 2009, International Organization for Standardization, 2018). The framework enables the integration of risk sources, both of natural and anthropogenic origin and risk events to assess rehabilitation risk and ultimately a mine site's potential for rehabilitation failure.

A soil compaction risk event BN model was developed as a case study and used to demonstrate the workings of the framework. This was applied to two mines, one in the Witbank Coalfield, South Africa and another in the Bowen Basin, Australia. The case study showed that it is possible to not only integrate, but also to quantify rehabilitation risk and most importantly to segregate the risk into their individual multi-disciplines of soils, topography, vegetation etc. for analysis. This approach aligns with environmental impact and risk assessment processes. Additional rehabilitation risk events, other than soil compaction, were prioritised for future BN model development. These when amalgamated could form a synthesis rehabilitation risk assessment model. A research process is provided to achieve this goal in the future.

5.3 Research questions answered

5.3.1 In relation to the problem statement

The study highlighted immaturity in upfront surface-strip coal mine rehabilitation planning in South Africa and Australia. It further shows that gathered specialist multi-disciplinary information is seldom analysed and integrated quantitatively, with a focus on rehabilitation risk.

In response, tools and a technique to improve this situation were developed. Firstly, with the development of the R^{2}AIN framework and then by demonstrating it with a case study of soil compaction using a BN model (Chapter 4). A method to develop a synthesis rehabilitation risk assessment model was further described. The tools and technique can integrate multi-disciplinary data from several contributory rehabilitation risk sources, both natural and anthropogenic, to inform rehabilitation risk events, enabling the assessment of rehabilitation risk, which could be applied per site, per mine phase, for site risk profiling.

5.3.2 In relation to the research aim and objectives

Refer to Chapter 1, Table 1.1 for the overview of the thesis chapters and how they relate to the objectives of the study.

Aim: ***The aim was to investigate how a rehabilitation risk assessment model could best be developed. The model should have the ability to integrate and quantify multi-disciplinary surface-strip coal mine rehabilitation risks, in order to calculate a mine site's risk profile for susceptibility to rehabilitation failure. The ability to include risk prevention and mitigation is an added benefit. The model should be designed to operate at a strategic level to aid upfront as well as progressive life of mine rehabilitation planning. It should be based on an understanding of risk, including natural and anthropogenic risk sources, which influence risk events***.

Achieved: *A methodology to enable the development a future synthesis rehabilitation risk assessment model has been provided.*

The R^{2}AIN framework as presented in Chapter 4 provides a seven-step process to identify, analyse, evaluate and treat rehabilitation risks. The soil compaction BN model demonstrates analysis of risks in detail, including their integration and quantification. Risk evaluation and treatment have not been investigated in this study. Risk evaluation involves comparing risk against defined 'rehabilitation risk criteria'. Criteria are currently undefined in literature; therefore, comparison was not possible. The incorporation of controls of risk prevention and mitigation were not included in the BN modelling due to their complexity. Once BN modelling has been developed and tested further, controls can be incorporated. The segregation of rehabilitation risk percentage results into discrete contributing multi-disciplines of geology, soils, topography etc. enables the *calculation of a mine site's risk profile for susceptibility to rehabilitation failure. The tools and techniques presented can be applied at a strategic level to all life of mine phases.*

Objective 1: **To set research foundations and confirm the need for the research.**

Achieved: *Research foundations were set in Chapter 2. This was achieved via the development and application of a maturity model to evaluate mine approval consultant rehabilitation reports and the mine rehabilitation guidelines likely used by consultants to prepare these, in South Africa and Australia, Queensland and New South Wales. In Chapter 3, techniques developed by others were reviewed and the need for the research was further confirmed.*

Objective 2: **To assess rehabilitation risk events of concern, associated with surface-strip coal mining.**

Achieved: *In Chapter 3, Table 3.1 & 3.2, risk events were identified, described, scored and ranked based on a review of literature. In Chapter 4, the R²AIN framework allows for risk events to be identified in step 1 and then analysed in step 5, using BNs (Fig. 4.1). Risk events are also listed and categorised in Fig. 4.2.*

Objective 3: **To assess natural (geology, soils, topography, climate, hydrology, landcover and vegetation) and anthropogenic (as related to management actions) risk sources, which influence risk events.**

Achieved: *Risk sources are described in Chapter 3 & 4. The need for their identification is included in Chapter 4 in the R²AIN framework, step 2 & 3 and their integration using BNs as step 4. Seven natural risk sources and five anthropogenic risk sources are listed in Fig. 4.2.*

Objective 4: **To review techniques considered most suited for the development of a rehabilitation risk assessment model, in order to identify the best technique to use. To review applicable techniques developed by others.**

Achieved: *In Chapter 3, techniques suitable for model development and techniques developed by others were reviewed.*

Objective 5: ***To develop a framework and a methodology to integrate and quantify the relationships between rehabilitation risk sources and events.***

Achieved: *The R²AIN framework is presented in Chapter 4, which meets these objectives.*

Objective 6: ***To test the concept using a proof-of-concept case study based on a Bayesian network analysis of soil compaction risk.***

Achieved: *The R²AIN framework is tested in a soil compaction BN in Chapter 4.*

Objective 7: ***To provide a research process for the future development of other risk event BN models, which can combine to form a composite rehabilitation risk assessment model.***

Achieved: *The outcomes from Chapter 4 provide a method for the development of a future synthesis rehabilitation risk assessment model.*

5.3.3 In relation to the research hypothesis

Hypothesis: ***This study is guided by the hypothesis that a rehabilitation risk assessment model can calculate and profile a mine site's susceptibility to rehabilitation failure, for all life-of-mine phases, based on the site's inherent baseline characteristics and subsequent operational management actions taken and how these influence potential risk events.***

This formulation could be supported by first developing a small proof-of-concept case study model and by testing this on mine sites.

Achieved: *A soil compaction BN risk event proof-of-concept case study model was developed, and this was tested on two mine sites; one situated in the Witbank coalfield, South Africa and the other in the Bowen basin, Australia. The proof-of-concept study showed that a mine site's susceptibility to rehabilitation failure can* *be calculated and profiled, per mine phase, per inherent multi-discipline baseline site characteristic and in response to management choices.*

5.3.4 In relation to prior research and the research gap

The review of techniques suitable for surface-strip coal mine rehabilitation risk assessment (Chapter 3), which also included a review of similar risk assessment techniques developed by others (Williams, 2001, Maczkowiack et al., 2012, Troldborg et al., 2013, Dale et al., 2018, Lechner et al., 2017, Laurence, 2001, Kirsch et al., 2012, Aalders et al., 2011), revealed that the research outcomes presented in this thesis do not duplicate prior research. Rather, the aim and objectives fulfilled by this research are unique and specific.

Opportunities exist for collaboration with research by Dale et al. (2018), who used BNs to model surface erosion and tunnelling risk for cost-effective management of dispersive mine spoil in Australia. The outcome of their study was to provide best and worst-case scenarios that could be used to inform a series of best management practice guidelines as related to soil erosion and tunnelling risk. Their study differs in that its focus was on soil erosion and tunnelling risk, a single rehabilitation risk event. This thesis first provides the R^{2}AIN framework, which describes how several other risk event BN models could be developed based on ISO 31000 risk assessment principles that can be amalgamated into a synthesis rehabilitation risk assessment model in the future. A case study soil compaction BN model was then developed to demonstrate the framework. The outcome of this research was to provide a methodology for future risk event model development and the synthesis of these into a composite rehabilitation risk assessment model. The end-product would be to enable the profiling of a site in terms of its inherent rehabilitation risk, per multi-discipline and to be able to gauge what happens to this risk profile when management actions are manipulated. Risk percentages, per multi-discipline, per site, per mine phase can be provided. The research would be of value mostly for authority decision making, i.e. do not develop a high rehabilitation risk mine site, or if it must be developed, certain conditions should be adhered to, to minimize rehabilitation risk. Or at mine closure or relinquishment, to reduce rehabilitation risk and costs, do ‘X’ or ‘Y’. The research would benefit mine approval and progressive rehabilitation sign-off, linking with the EIA/ EIS and risk assessment processes. The method presented by Dale et al. (2018), would likely be of assistance more for hands-on on site management, assisting soil scientists and mine personnel. The two methods could however complement and add value to one another. They could also be used to validate one another. Opportunities exist for co-authoring of further papers.

The research gap includes the need for the development of an integrative, quantitative, rehabilitation risk assessment methodology and tools for use to improve surface-strip coal mine rehabilitation planning decisions; this research gap has not been adequately addressed by others. The need for applied industry research and for linkage with authority mine approval, EIA and risk assessment processes are considered critical.

The R^{2}AIN framework, the soil compaction BN model and the proposed risk event BN models which will link into a synthesis model address this research gap.

5.4 Limitations of study

During the research process, several study limitations became evident, which resulted in the identification of new research challenges, which should be addressed in the future.

Difficulties were experienced with accessing mine site data, particularly data pertaining to rehabilitation failures. This data is generally not in the public domain and is withheld by mine companies due to confidentiality, liability and competition issues. Very little of this ‘grey’ data has been used in research and has been published, making it difficult for researchers to learn from historical mistakes. It is not uncommon for mine rehabilitation failures to be frequently repeated, or for researchers to repeat work by others.

To address the lack of data availability, a web-search was conducted to source mine approval documents in the public domain. These documents have been cited in the paper presented in Chapter 2, which emphasizes immaturity in mine rehabilitation guideline and approval documents. Few adaptive rehabilitation management documents could however be sourced for assessment.

In Chapter 4, a paper is presented which describes the R^{2}AIN framework and a soil compaction BN model, towards the development of a synthesis rehabilitation risk assessment model. Similarly, difficulties were experienced with attaining site data to enter into the soil compaction

BN model to test it on two case study mine sites; one situated in the Witbank coalfield South Africa and the other in the Bowen basin, Australia. In many instances, hypothetical data were entered in the model.

Model nodes, their states and values were defined based on regional and universal parameters. Further refinements of these are required with the assistance of experts. This is not an oversight, as the model was not intended to be a perfect representation of reality. Its purpose was rather to demonstrate a process, applied within the R^2AIN framework, towards developing a future synthesis rehabilitation risk assessment model. Pollino et al. (2007), similarly note that often uncertainties in our understanding of a complex system may be large at first, but with further data collection and analysis, these uncertainties can be reduced.

At the commencement of the research the author aspired to develop several risk event BN models, not only pertaining to soil compaction and to use these to develop a synthesis rehabilitation risk assessment model. However, as the study progressed it became evident that in order to develop further models, the assistance of numerous experts would be required, due the multi-disciplinary nature of the research and the modelling process. The development of the soil compaction BN model revealed that extensive data is required for each model and that model development is highly time consuming. The author chose to narrow the scope of the research and to develop one model as an example, using it to perfect the model development process, to facilitate the development of future BN models and a synthesis model.

5.5 Recommendation for further research

It is recommended that other risk event BN models be prioritised for development and that a rehabilitation risk assessment model be developed to synthesise these into one model. This will require continuous improvements in the method, to build confidence, including extensive risk event and synthesis BN model site evaluation and testing; improved BN input data for nodes, states and values, based on expert knowledge; and simplification of the conditional probability table construction methods. Adaptation to other mining types, development activities and other regions should be investigated, as well as spatial linkages to geographic information systems.

5.5.1 Develop prioritised risk event Bayesian network models

Rehabilitation risk event categories were defined in Chapter 4, Fig. 4.2. It is recommended that risk events in the substrate/ soil failure risk event domain be developed next as component BN models. This could be followed by risk events in the vegetation failure risk event domain. The water failure risk event domain is highly complex; hence it is recommended that BNs in this domain be developed last and only once the process is fully established.

The substrate/ soil failure risk event domain BN models would require expertise from soil scientists, whilst the vegetation failure risk event domain models would require contributions from ecologists and/or agricultural scientists.

Risk events are dynamic and will likely change as the research process progresses. Some risk events may become redundant and others could be added.

5.5.2 Develop a synthesis rehabilitation risk assessment model

The synthesis model's purpose would be to amalgamate all component BN risk event models, once developed, to calculate a site's total rehabilitation risk and potential for rehabilitation failure, i.e. to profile the site's rehabilitation risk. As discussed in Chapter 4, manual combining and averaging of component models, as opposed to using BN software for coupling is preferred. This prevents dilution of information and allows for experts to better interpret the multi-disciplinary data. This is applicable to all component BN models that may feed into the synthesis model.

There is a further need for the development of a system to convert BN output data from the synthesis model with its component risk event BN models, to a format that is easy to understand and use by rehabilitation professionals. This could be facilitated by using spreadsheet software, by developing an interactive web-site or by the development of a computer application for use on mobile devices, such as tablets and smartphones.

5.5.3 Continuous improvement of the methodology

5.5.3.1 *Risk event and synthesis Bayesian network model evaluation*

Evaluation is the assessment of the non-quantitative (model structure, nodes and states) and the quantitative (statistical) performance of a model (Pollino and Henderson, 2010, Pollino et al., 2007). Evaluation is also sometimes referred to as 'validation' and 'verification' (Schietekat et al., 2016, Pitchforth and Mengersen, 2013).

Evaluation of a BN may include informal methods such as case-based evaluation where cases are generated to test a wide variety of scenarios to which the BN model could be exposed (Korb and Nicholson, 2011). Case-based informal evaluation has been conducted by applying the soil compaction risk event BN model, with its natural risk BN models (soils, climate, topography, vegetation and hydrology) on two sites, in two different southern hemisphere countries. Refer to Chapter 4. One site is situated in the Witbank Coalfiield, South Africa and the other is in the Bowen Basin Australia. Poor and improved management scenarios were also tested for the soil and machinery management anthropogenic risk BN models.

More formal evaluation methods may include explanation methods, such as 'most probable explanation' (MPE) (Kwisthout, 2011), which can be thought of as the most plausible explanation for the observed findings. Explanation methods are useful in evaluating a BN as the independence-dependence relations in a BN structure are not always obvious to users of the model. The explanation of conclusions drawn about the domain using the BN contribute to the acceptance of the BN model by domain experts and users (Korb and Nicholson, 2011).

Sensitivity testing is another kind of evaluation, which involves analysing how sensitive the BN is by determining how responsive the probabilities of query nodes are to changes in parameter inputs (Pollino et al., 2007). Through sensitivity analysis one can identify which variable in a BN have the greatest influence on the endpoints and the importance, strength and relevance of the inputs in determining the variation of the output can be ordered (Pollino and Henderson, 2010). Sensitivity analysis can involve computing 'sensitivity to findings', as well as 'sensitivity to parameters', though Pollino and Henderson (2010) note that to date researchers appear to have utilised only one or the other of these methods in any one study. Korb and Nicholson (2011) state that sensitivity to findings can use the probabilities of d-separation, i.e. when nodes in a causal graph are conditionally independent, to determine whether evidence about one variable may influence belief in a query variable. Sensitivity to parameters is when the analysis is performed using an empirical approach in which each of the parameters of the query nodes are altered and the related changes in the posterior probabilities of the query node are observed (Pollino and Henderson, 2010).

Parameter sensitivity analysis of the soil compaction BN model, for only the soils BN, was conducted as an example. Refer to Chapter 4, Appendix 4.4. No sensitivity to findings analysis has been performed.

Korb and Nicholson (2011) advocate alpha, beta and acceptance testing. Alpha testing refers to the intermediate test of the system by in-house staff, not directly involved in developing it, but who have expert BN experience, such as other modellers. Beta testing involves the application of the system by an end-user, i.e. the specialist experts and rehabilitation professionals, to identify flaws and opportunities for improvement. Acceptance testing refers to end-users being sufficiently familiar with the framework, BN process and software to use these with confidence for their specific needs. Implementation is the final step where the BN products are made available to industry.

It is recommended that informal and formal model evaluation, including sensitivity testing, as well as alpha, beta and acceptance testing be conducted continuously as new risk event BN models and the synthesis model are developed. This will help to improve confidence in the developed models.

A paper is planned, which will use the soil compaction BN model as a case-study example for model evaluation. There are several methods that could be followed that require further investigation (Pitchforth and Mengersen, 2013, Schietekat et al., 2016, Pollino et al., 2007, Korb and Nicholson, 2011). Several Bayesian network computer software could further be evaluated during the process.

5.5.3.2 *Improved Bayesian network input data for nodes, states and values*

In Chapter 4 it is stated that BN nodes, states and values are dynamic and that these were designed for continuous improvement with repeated model application. This will be true for all future risk event BN models that are developed. The role of experts and rehabilitation professionals in continuously updating these nodes, states and values is critical and could be facilitated should future developed BN models be made available as, ‘open data’.

Several data systems exist that could inform the values of the nodes and states. Data generated from the BN models could likewise feed back into these systems. Examples include: soil classification and land-capability studies (Chamber of Mines of South Africa, 1981, Manson et al., 1995); the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) (USDA-Agricultural Research Services, 2008); Landscape Function Analysis (Tongway and Ludwig, 2011); and restoration framework processes (Howell et al., 2012, Clewell and Aronson, 2013).

5.5.3.3 *Simplification of the conditional probability table construction methods*

As noted in Chapter 4, child nodes (i.e. nodes with arcs feeding into them from parent nodes) have CPTs that represent combinations of all states of their parent nodes. Conditional probability distributions for each node are specified based on expert knowledge or they can be machine learned, where data are available. Therefore, there is an element of initial subjectivity when experts propagate data into the CPTs. Experts need to agree on the relative weightings specified. Further, when using BN software, propagation of the CPTs can be highly complex. This step was found to be the most difficult and confusing in developing and quantifying the soil compaction BN model. The 3D elicitation technique by De Waal et al. (2016), that relies on experts’ colour pattern recognition capabilities rather than their ability to encode probabilities helped immensely to overcome this difficulty and it is recommended that this technique be used for future CPT propagation. Refer to Appendix 5.2 for the CPTs showing their associated 3D colour pattern recognition spreadsheets.

5.5.4 Adaptation to other mining types, development activities and other regions

As discussed in Chapter 4, the R^{2}AIN framework may potentially be applied globally to any mining type and to any development activity. Component risk event BN models are however region specific. Their states (i.e. low/ medium or high) are fixed, and their values (i.e. ranges of 600 - 800 mm rainfall etc.), are set for each region in question. To adapt these to other regions, regional values will need to be altered to suit the region in question, i.e. to suit southern or northern hemisphere mining countries or unique regions. Use should be made of region relevant systems, such as Schulze (1997) and Tongway and Hindley (2004). When applying the model to a mine site, the state of either low, medium or high would be selected, based on the state range values set for that region and whether the site falls within the low, medium or high categories. The CPT weightings will be different, based on experts' contributions relevant to each region and the risk event being investigated.

5.5.5 Spatial linkages to geographic information systems

The future synthesis rehabilitation risk assessment model with its component BN risk event models should be adapted to incorporate spatial linkages to geographic information. Johnson et al. (2012) note that this can take several forms. Nodes of a BN may be spatially or geographically described, or the output of the BN itself can have a spatial interpretation. Alternatively, a BN can be used to describe uncertainty of geographic information. These linkage interactions and compatible GIS and BN software require further investigation.

5.6 Summary

This thesis provides a method for addressing immaturity in upfront surface-strip coal mine rehabilitation planning, where rehabilitation risk assessment, despite being advocated, is conducted at a basic level, with minimum requirements being met.

The need for the research has been confirmed and research foundations set. An improved understanding of natural and anthropogenic risk sources associated with surface-strip coal mining and the identification of rehabilitation risk events of concern has been achieved. This knowledge is translated into the R^{2}AIN framework and a methodology is demonstrated, via a case study soil compaction BN component model, to integrate risk sources and events to assess and calculate rehabilitation risk, expressed as a percentage, per multi-disciplinary risk source, per mine phase, per mine sites. Research directions to develop other risk event BN component models and a synthesis rehabilitation risk assessment model are provided.

The tools and techniques developed are aligned with existing risk and environmental impact assessment processes. Adaptation to other mining types, development activities and other global regions is possible.

This research contribution improves upfront mine rehabilitation planning and decision making, providing improved tools and techniques than what are currently available.

No other rehabilitation risk assessment techniques developed by others are closely aligned and adequately address this. There is however potential for linkage with research work by Dale et al. (2018).

The research aims to attain a balance between academic needs and mining practicalities.

5.7 References

AALDERS, I., HOUGH, R. L. & TOWERS, W. 2011. Risk of erosion in peat soils – An investigation using Bayesian belief networks. *Soil Use Manage,* 27**,** 538-549.

CHAMBER OF MINES OF SOUTH AFRICA 1981. Guidelines for the rehabilitation of land disturbed by surface coal mining in South Africa. Johannesburg, (ZA): Chamber of Mines of South Africa.

CLEWELL, A. F. & ARONSON, J. 2013. *Ecological restoration: Principles, values, and structure of an emerging profession,* Washington DC, (US), Society for Ecological Restoration & Island Press.

COUNCIL OF STANDARDS AUSTRALIA & NEW ZEALAND 2009. AS/ NZS ISO 31000:2009, joint Australian New Zealand international standard, risk management - Principles and guidelines. 3 ed. Sydney, (AU) & Wellington, (NZ): Council of Standards Australia & New Zealand.

DALE, G., THOMAS, E., MCCALLUM, L., RAINE, S., BENNETT, J. & REARDON-SMITH, K. 2018. Applying risk-based principles of dispersive mine spoil behaviour to facilitate development of cost-effective best management practices: ACARP C24033. Brisbane, (AU): Australian Coal Association Research Program.

DE WAAL, A., KOEN, H., DE VILLIERS, P., ROODT, H., MOOROSI, N. & PAVLIN, G. 2016. Construction and evaluation of Bayesian networks with expert-defined latent variables. *In: Proceedings of the 19th Conference of Information Fusion.* Heidelberg, (DE): International Society of Information Fusion.

HOWELL, E. A., HARRINGTON, J. A. & GLASS, S. B. 2012. *Introduction to Restoration Ecology,* Washington DC, (US), Island Press.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 2018. ISO 31000:2018, International Standard, Risk Management - Guidelines 2nd ed. Geneva, (CH): International Organization for Standardization.

JOHNSON, S., LOW-CHOY, S. & MENGERSEN, K. 2012. Integrating Bayesian networks and geographic information systems: good practice examples. *Integr Environ Assess Manag,* 8**,** 473-479.

KIRSCH, P. A., GOATER, S., HARRIS, J., SPROTT, D. & JOY, J. 2012. RISKGATE: Promoting and Redefining Best Practice for Risk Management in the Australian Coal Industry. *In: Proceeding of Coal Operator's Conference 2012.* Wollongong, (AU): University of Wollongong.

KORB, K. B. & NICHOLSON, A. E. 2011. *Bayesian artificial intelligence,* Boca Raton, (FL) CRC

KWISTHOUT, J. 2011. Most probable explanations in Bayesian networks: Complexity and tractability. *Int J Approx Reason,* 52**,** 1452-1469.

LAURENCE, D. 2001. Classification of Risk Factors Associated with Mine Closure. *Mineral Resources Engineering,* 10**,** 315-331.

LECHNER, A. M., MCINTYRE, N., WITT, K., RAYMOND, C. M., ARNOLD, S., SCOTT, M. & RIFKIN, W. 2017. Challenges of integrated modelling in mining regions to address social, environmental and economic impacts. *Environ Model Softw,* 93**,** 268-281.

MACZKOWIACK, R. I., SMITH, C. S., SLAUGHTER, G. J., MULLIGAN, D. R. & CAMERON, D. C. 2012. Grazing as a post-mining land use: a conceptual model of the risk factors. *Agricultural Systems,* 109**,** 76-89.

MANSON, A. D., CAMP, K. G. T. & SMITH, J. M. B. 1995. Soil Potential and Land Capability Course Notes. Cedara South Africa: KwaZulu-Natal Department of Agriculture.

PITCHFORTH, J. & MENGERSEN, K. 2013. A proposed validation framework for expert elicited Bayesian Networks. *Expert Systems with Applications,* 40**,** 162-167.

POLLINO, C. A. & HENDERSON, C. 2010. Bayesian networks: A guide for their application in natural resource management and policy. *Landscape Logic Technical Report No. 14.* (AU): Australian Government Department of the Environment, Water, Heritage and the Arts.

POLLINO, C. A., WOODBERRY, O., NICHOLSON, A., KORB, K. & HART, B. T. 2007. Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment. *Environ Model Softw,* 22**,** 1140-1152.

SCHIETEKAT, S., DE WAAL, A. & GOPAUL, K. G. 2016. Validation & verification of a Bayesian network model for aircraft vulnerability. *12th INCOSE SA Systems Engineering Conference.* Pretoria, (ZA): INCOSA.

SCHULZE, R. E. 1997. South African atlas of agrohydrology and climatology. Pretoria, (ZA): Water Research Commission.

SOUTH AFRICAN BUREAU OF STANDARDS 2009. SANS 31000:2009, South African national standard, risk management - Principles and guidelines. 1st ed. Pretoria, (ZA): SABS Standards Division.

TONGWAY, D. J. & HINDLEY, N. L. 2004. Landscape function analysis: Procedures for monitoring and assessing landscapes - With special reference to minesites and rangelands. Canberra, (AU): CSIRO.

TONGWAY, D. J. & LUDWIG, J. A. 2011. *Restoring disturbed landscapes: Putting principles into practice*, Washington, (DC), Island Pr.

TROLDBORG, M., AALDERS, I., TOWERS, W., HALLETT, P. D., MCKENZIE, B. M., BENGOUGH, A. G., LILLY, A., BALL, B. C. & HOUGH, R. L. 2013. Application of Bayesian belief networks to quantify and map areas at risk to soil threats: Using soil compaction as an example. *Soil Tillage Res,* 132**,** 56-68.

USDA-AGRICULTURAL RESEARCH SERVICES 2008. User's reference guide: Revised Universal Soil Loss Equation Version 2 (RUSLE). Washington DC, (US): USDA-Agricultural Research Services.

WILLIAMS, D. 2001. Risk Assessment of Bowen Basin Spoil Rehabilitation: ACARP C8039. Brisbane, (AU): ACARP.