GROUNDWATER ASSESSMENT TOOLBOX FOR SSD/SSI

Cumulative Groundwater Impact Assessment Approaches

Information paper

January 2022

Published by NSW Department of Planning and Environment

dpie.nsw.gov.au

Title: Cumulative Groundwater Impact Assessment Approaches

ISBN: 978-1-76058-520-4

First published: January 2022. Version 1

Authors (Stantec):

Rachael Peavler, Hisham Zarour, Kelly Greaser, Abigail Lovett, George Fennemore, Hisham Zarour

Contributors (Department of Planning and Environment)

Fabienne d'Hautefeuille, Richard Green, John Paul Williams, Llyle Sawyer, Rob Brownbill, Greg Russell

Recommended citation:

DPE (2022). Cumulative groundwater impact assessment approaches. Information paper prepared for the Water Division, NSW Department of Planning and Environment as part of the Groundwater Modelling Toolbox Project.

Acknowledgment of Country

The Department of Planning and Environment and Stantec acknowledge the Traditional Owners and Custodians of the land on which we live and work and pays respect to Elders past, present and future.

Executive summary

Human interference with groundwater must carefully balance benefits and risks. Regulations and NSW Government policy regarding water management in New South Wales (NSW) include the Water Management Act 2000 (WMA) and the Aquifer Interference Policy (AIP) which require proposed projects to include an assessment of cumulative impacts of their activity on the wider water source. The primary objectives of this information paper are to enhance the stakeholders' knowledge of cumulative impacts of Major Projects and present practical approaches to assess them. To meet these objectives, the paper presents:

- NSW water management statutory requirements
- theoretical background and framework for water resources cumulative impact analysis
- case studies on cumulative impacts in NSW
- a brief account of the regulatory basis for cumulative impact assessment in other countries
- a summary of best practices applied to model development, reporting, and long-term monitoring and mitigation.

The WMA and AIP define aquifer interference activities which require a water licence (NSW Office of Water, 2012). Groundwater in NSW is managed on a water source scale. Minimum impact requirements are defined for groundwater sources. Project proponents must demonstrate how each of the requirements are met.

A standard definition of cumulative impact includes past, present, and reasonably foreseeable future actions. Consequently, a proposed project requires identification of the spatial and temporal extent of the impacts, plus impacts from other projects that affect the same environment as the proposed project. Due to the complexity and scale of cumulative impacts, the potential for cumulative impacts should be considered during project design. Collaborative planning during project design is critical to incorporate current and potential future developments into a cumulative impact analysis. A qualitative risk assessment conducted during conceptual model development may assist navigating the complexities and scale for cumulative impact analysis.

Major Projects in NSW comprise State Significant Development (SSD) and State Significant Infrastructure (SSI) projects. They include:

- mines
- quarries
- coal seam gas (CSG) extraction
- tunnels, roadways, railways, and other infrastructure
- energy production for residential and commercial purposes
- human services projects.

Impacts generally affect groundwater quantity and quality. NSW case studies with various approaches to cumulative impact assessment are presented for localities that have a high concentration of Major Projects. Case studies in three regions are discussed:

- Southern Coalfields
- Sydney City
- Narrabri region

Common shortcomings in evaluating cumulative hydrogeological impacts are extracted from the analysed case studies.

The basis for assessing cumulative impacts is well established in policies and regulations across the globe. There is consensus that water resources must be managed at a large scale to ensure the limited resources are not depleted and quality is preserved. Due to the complexity and scale of cumulative impact assessments, numerical models are commonly used to assess and predict impacts from proposed projects. Examples of best practices are provided regarding the spatial and temporal scale for numerical models, developing the model approach, model platforms, resolving inconsistencies between models, reporting, and reviews.

Given the predictive nature of cumulative impact assessments and inherent uncertainty, monitoring supplants model analyses and predictions. Operational monitoring programs are discussed. These programs are typically detailed in a monitoring plan and adopted as operating conditions in the water licence or project conditions of approval. For projects in which monitoring results indicate impacts have occurred, typical mitigation measures are discussed.

This information paper provides key recommendations to assist project proponents with planning their approach to predicting and managing the cumulative impact assessments required under the NSW planning approval and water licensing processes.

Contents

Tables

Figures

Acronyms

Acronym	Explanation
©	Copyright
®	Registered trademark
AGMG	Australian Groundwater Modelling Guideline
AIP	Aquifer Interference Policy
ASTM	American Society for Testing and Materials
BLM	U.S. Bureau of Land Management
BLR	Basic Landowner Rights
BTM	Boggabri, Tarrawonga, Maules Creek [Mining Complex]
c.	Circa
CDWR	California Department of Water Resources
CEQ	U.S. Council on Environmental Quality
COA	Conditions of Approval
CSG	Coal Seam Gas
DPE	Department of Planning and Environment
e.g.	For example
EA	Environmental Assessment
ECE	Economic Commission for Europe (United Nations agency)
EIA	Environmental Impact Assessment
EIS	Environmental Impacts Statement
EP&A Act	Environmental Planning and Assessment Act 1979 No 203
et al.	and others
etc.	and other similar things
EU	European Union
GAB	Great Artesian Basin
GABCC	Great Artesian Basin Consultative Council
GDE	Groundwater dependent ecosystem

Acronym	Explanation
GIA	Groundwater Impact Assessments
GMT	Groundwater Modelling Toolbox (Project)
GW-PET	Groundwater Model Assessment Procedures and Evaluation Tool
ha	Hectare (10,000 m^2)
HCM	High complexity groundwater models
HES	Models for high environmental sensitivity projects
i.e.	that is
IAAC	Impact Assessment Agency of Canada
IAEA	International Atomic Energy Agency
IEPMC	Independent Expert Panel for Mining in the Catchment
km	Kilometre
km^2	Kilometre square
L/s	Litre per second
LMCM	Low to medium complexity groundwater models
LMES	Low to medium environmental sensitivity projects
LW	Longwall
m	Metre
m^2	Metre square
mg/L	Milligram per litre
N	North
NDEP	Nevada Division of Environmental Protection
NDEP-BMRR	Nevada Division of Environmental Protection-Bureau of Mining Regulation and Reclamation
NE	Northeast
NEPA	National Environmental Policy Act
NSW	New South Wales
NW	Northwest
pH	Measure of acidity

Acronym	Explanation
RTS	Rapid transit system
RtS	Response to submissions
S	South
S.C	Status of Canada
SCA	Sydney Catchment Authority
SE	Southeast
SEARs	Secretary's Environmental Assessment Requirements
SEEP/W	Finite element modelling software by Geoslope
SGB	Sydney-Gunnedah Basin
SMCRA	Surface Mining Control and Reclamation Act [USA]
SMP	Strategic Management Plan
SSD	State Significant Development
SSI	State Significant Infrastructure
TARP	Triger Action Response Plan
U.S.C.	U.S. Code
UN	United Nations
UN/ECE	United Nations Economic Commission for Europe
USA	United States of America
USACE	U.S. Army Corps of Engineers
US-EPA	United States Environment Protection Agency
USGS	United States Geological Survey
W	West
WAL	Water Access Licence
WAMS	Water Assessment Management System
Water Act	Water Act 1912
WFD	Water Framework Directive [EU]
WMA	Water Management Act 2000
WMP	Water Monitoring Plan

Acronym	Explanation
WMS	Water management strategy
WSP	Water Sharing Plan

1 Introduction

Many natural phenomena and anthropogenic activities impact groundwater quantity and quality. Some activities may impact the structure of the aquifers in which groundwater occurs and flows. Naturally, impacts to groundwater often propagate to interconnected environments. The potential impacts of an activity on groundwater and its life-supporting, social, cultural, ecological, environmental, and economic values are commensurate to the nature and sensitivity of the groundwater resource as well as the characteristics of the project interfering with groundwater including its size, duration, intensity, intentional and incidental water take requirements, and waste generation and management methodology.

The size, intensity, and complexity of many projects in NSW are such that their impacts on groundwater extend much farther than their footprints and persist well beyond their lifetimes. The spatial and temporal overlap of historical, current, and future projects cause cumulative impacts to water resources which are difficult yet critically important to understand. Effective assessment and management of cumulative impacts require public disclosure of activities and data by proponents and resource management agencies and collaborative impact-mitigation planning. Cumulative impact analysis demonstrates due diligence by the decision-maker and informs regional planning beyond individual project plans.

This information paper relied on references from the department, NSW in general, relevant agencies in other countries at state and federal levels as well as multinational and international standard-setting and scientific organisations. Information was also collected from a widely publicised online survey conducted for the benefit of the broader guidelines.

This information paper is focused on the analysis of cumulative impacts related to Major Projects in NSW, which are projects officially declared as State Significant Developments (SSD) or State Significant Infrastructure (SSI). The department intends to draw on the outcomes of this work to generate useful interactions between all stakeholders, including relevant Commonwealth and State government departments, academia, related industries, the professional community, and SSD and SSI proponents.

For the purposes of this document, a ‘project’ may include a Major Project as defined previously while an ‘activity’ includes actions that may impact aquifers or groundwater resources that may need to be considered in a cumulative impact assessment such as irrigation, water use for livestock, private groundwater uses, etc.

1.1 Objectives

The objective of this information paper is to increase the knowledge and application of cumulative impact analysis for improved and sustainable water resources management in NSW, particularly for Major Projects.

1.2 Document organisation

In addition to this introductory chapter, this information paper comprises the following sections:

- **Section 2: NSW Regulatory Framework** – this section describes the regulatory framework and institutional tools for managing water in NSW.
- **Section 3: Considering cumulative impacts on water resources –** this section presents common types of cumulative water resource impacts and the importance of considering cumulative impacts during project design, provides a framework for cumulative impact analysis planning, and discusses the value of completing a qualitative risk assessment in the initial stages of conceptual model development.
- **Section 4: Cumulative Impacts in NSW –** this section presents NSW project examples where carefully planned and executed cumulative impact analysis would provide significant benefit to evaluating and predicting water resource impacts. A description of approaches and common shortcomings is presented.
- **Section 5: International approaches –** this section presents an international perspective on the regulatory basis for cumulative impact analysis and a summary of select best practices as they are applied to model development, reporting, and long-term monitoring and mitigation.
- **Section 6: Guidance for modelling, reporting, and validation** – this section presents guidance for modelling, reporting, and validation of cumulative impact analysis in NSW.
- **Section 7: Recommendations** – this section recommends cumulative impact analysis best practice based on review of NSW project examples, international approaches, and the general guidance described in Section 6.
- **Section 8: References –** list of cited references.

2 NSW Regulatory Framework

The Water Act 1912 (Water Act), the Water Management Act 2000 (WMA), the AIP, and the WSPs form the regulatory framework for groundwater use and mitigation planning in NSW, including management of cumulative impacts. These regulatory tools are summarised below as they relate to cumulative impact analysis.

2.1 Water Management Act and Water Act

The interaction with and use of water in NSW are regulated by the WMA or the Water Act. The WMA governs water approvals and licensing for water sources in areas where WSPs (Section 2.2) have been enacted for those sources. Otherwise, the Water Act applies, i.e. the Water Management Act contains provisions relating to aquifer interference approvals, however those provisions have yet to be commenced by a relevant Proclamation and are not active at this time or does not extend to the specific types of licences or approvals.

The WMA defines aquifer interference activities as activities that involve:

- the penetration of an aquifer
- the interference with water in an aquifer
- the obstruction of the flow of water in an aquifer
- the taking of water from an aquifer while carrying out mining, or any other activity prescribed by the regulations
- the disposal of water taken from an aquifer as referred to in above.

The WMA requires water users to hold and comply with the conditions of:

- Water access licences (WAL) to take water (e.g. open cut or underground void dewatering or consumptive use due to evaporation from legacy mine open cut).
- Water management work approval to construct and use:
  - water supply works (e.g. A pump, bore, or dam); and
  - specified flood works at specified locations, particularly if it alters the natural flow or path of water.
- Water use approvals to use water for particular purposes at particular locations (e.g. Irrigation).
- Controlled activity approvals to carry out any works within 40 metres of a river, lake, or estuary, being waterfront land.

Note that exemptions apply for major projects for most approvals, but not licences.

WSPs (Section 2.2) establish rules for sharing water between the environmental needs of river or aquifers and water users, and between different types of water use such as domestic supply, stock watering, industry, and irrigation. WALs entitle licence holders to:

- specify shares in the available water within a particular water management area or water source (the share component); and
- take water at specified times, rates, or circumstances from specified areas or locations (the extraction component).

To take water for a particular purpose, proponents may need to obtain a WAL nominating water supply work(s).

There are three main categories of approvals that may be granted to proponents:

- **Water supply work approvals** authorise holders to construct and use water supply works at specified locations (e.g. to install and operate a pump, dam, or bore).
- **Water use approvals** authorise holders to use water for a particular purpose, such as irrigation, at a particular location.
- **Flood work approvals** confer rights on their holders to construct and use flood works at specified locations.

Where a Major Project (SSD or SSI) as defined in the Environmental Planning and Assessment Act 1979 would interfere with water sources, the development consent granted for that activity would address the project’s impacts on those water sources and corresponding mitigation measures. The proponents of such projects are not required to obtain water use approvals, water management work approvals or controlled activity approvals under the WMA. However, SSD project proponents are required to hold WAL(s) for the take of water associated with their projects. SSI projects by Roads and Transport Authorities are exempt from holding WALs for construction and maintenance (not operation) with conditions, including keeping records of the water taken. The WMA applies to aquifer interfering activities including mining operations, road construction, and any other large-scale activity that involves excavation.

The WMA principles include that the cumulative impacts of water management licences and approvals and other activities on water sources and their dependent ecosystems should be considered and minimised. The WMA states that aquifer interference activity planning must identify the nature of the aquifer interference causing impacts, including cumulative impacts, on water sources or their dependent ecosystems, and the extent of those impacts.

2.2 Water Sharing Plans

Groundwater in NSW is managed at the ‘water source’ scale under the rules in WSPs, which manage both surface water and groundwater for all uses (e.g. irrigation, environment, industry, towns, and communities). WSPs are a key instrument in the WMA. The WMA articulates:

- sharing of water from a water source must protect the water source and its dependent ecosystems
- sharing of water from a water source must protect basic landholder rights (BLR)
- sharing or extraction of water under any other right must not prejudice the principles set out in paragraphs □ and □.

A groundwater source can include several aquifers and groundwater systems. Groundwater sources in NSW are divided into four broad hydrogeological types:

- alluvial – unconsolidated sediments
- coastal sands – unconsolidated sediments
- porous rock – consolidated sedimentary rocks
- fractured rock – igneous and metamorphic rocks.

Groundwater sources have been defined as either ‘highly productive’ or ‘less productive’. Highly productive groundwater is defined in the AIP (Section 2.3) as a groundwater source that is declared in the regulations and is based on the following criteria:

- has total dissolved solids of less than 1,500 milligrams per litre (mg/L); and,
- contains water supply works that can yield water at a rate greater than 5 litres per second (L/sec).

Different rules apply in the AIP to ‘highly productive’ or ‘less productive’ groundwater sources. On face value the AIP is focused on protecting highly productive aquifers. However, less productive aquifers must be considered in the analysis of impacts of projects, including cumulative impacts. They are becoming more important as technology develops, demand on water grows, competition between various sectors and users intensifies, and incidental takes by industrial developments and civil infrastructure continue and expand. In addition, less productive aquifers could be linked to significant ecological and cultural values. Hence, they are important to be considered in impact assessments of projects and activities.

WSPs form the first line of defence against large-scale depletion of water resources. They set allocation limits for various sources and establish the basis for water licence allocation and trading for various water sources in different areas across the State. Hence, they are the main tool to control cumulative impacts on water sources.

Note on the Great Artesian Basin (GAB) groundwater sources:

The Great Artesian Basin (GAB) groundwater sources were categorised separately because of the GAB's unique hydrogeology and management requirements.

The AIP designates the Great Artesian Basin (GAB) groundwater sources as highly productive. These water sources categorised separately because of the GAB's unique hydrogeology and management requirements (NSW Office of Water, 2012). The GAB underlies an area of about 1,700,000 km^2, straddling the Northern Territory, Queensland, NSW, and South Australia (Figure 1). It is one of the largest groundwater resources in the world and Australia's largest water resource. Hence, its management is complex and requires collaboration between the basin communities and governments.

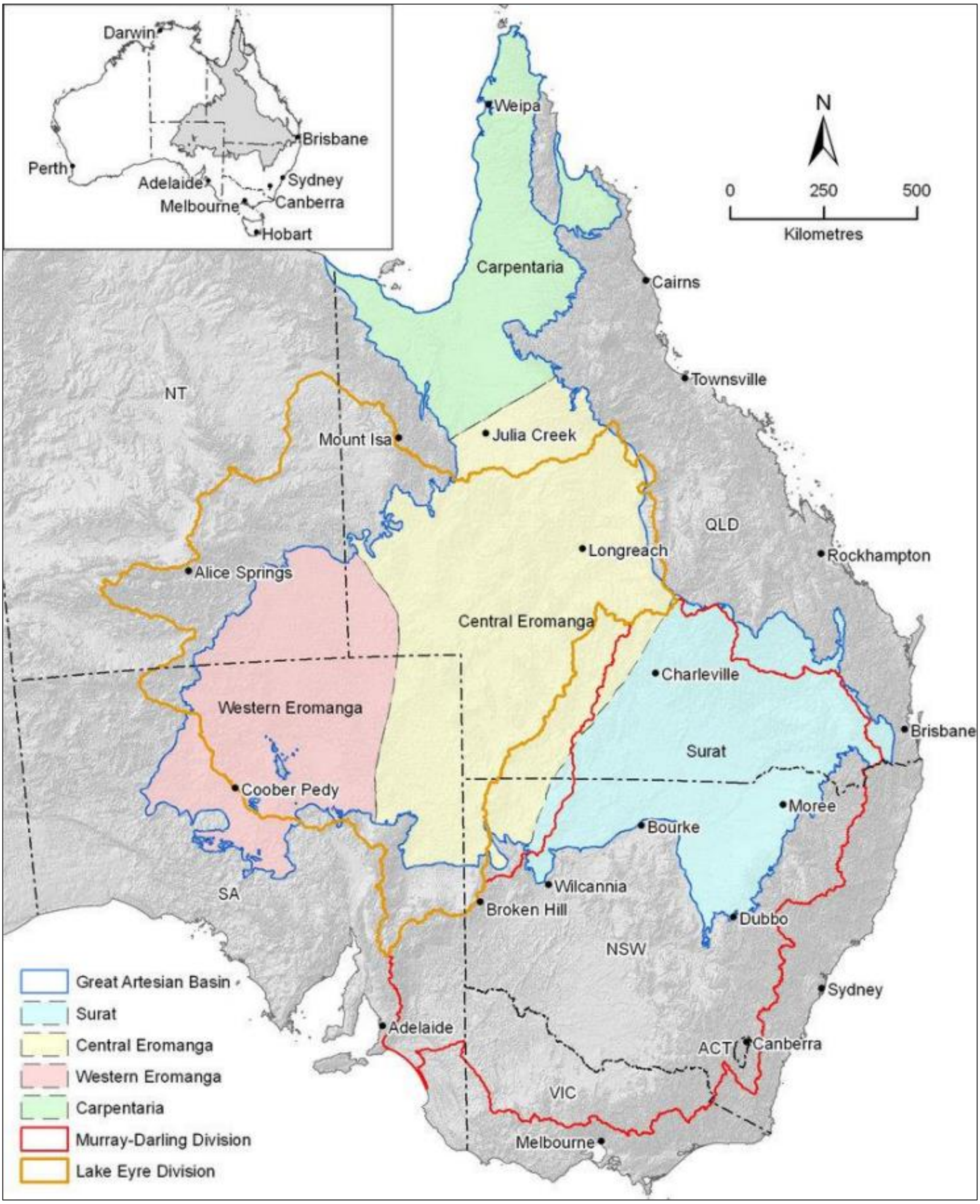

Figure 1: Great Artesian Basin (GAB) extent, basins, and divisions (Department of Agriculture, 2019)

In the period 2000 2015, management of the GAB under various jurisdictions was guided by a Strategic Management Plan (SMP 2000). The SMP was developed collaboratively as a voluntary non-statutory planning document by the Great Artesian Basin Consultative Council (GABCC) and adopted by all governments responsible for the management of the Basin. The SMP 2000 detailed a staged process for implementing the strategies and objectives, as well as reviewing and reporting progress. The plan was reviewed in 2015 by the Australian Government in consultation with the GABCC and the Basin governments. Subsequently, the Great Artesian Basin Strategic Management Plan (SMP 2019) was released to cover the period 2019 – 2034. The successive plan provides guidance for policy, actions, and outcomes in the GAB (Department of Agriculture, 2019). The SMP encourages the utilisation, sharing and development of information (scientific and otherwise) by all stakeholders, including governments. Better understanding of the Basin is intended to support policy, management, activities, usage, and enable balanced and beneficial outcomes to be achieved for the GAB and its communities (Biesaga, 2019). The SMP principals are relevant to assessment and management of cumulative impacts of in the entire Basin and within various jurisdictions.

In NSW, the first WSP for the NSW GAB Groundwater Sources 2008 commenced on 1 July 2008 and was in force until 30 June 2020 (Department of Agriculture, 2019). It set rules for the location of bores to protect access by users to the resources and specifies extraction limits and rules for sharing water between the different types of users, including the environment. On 29 June 2020, the 2008 WSP was replaced by the Water Sharing Plan for the NSW Great Artesian Basin Groundwater Sources 2020 (NSW Government, 2020).

2.3 NSW Aquifer Interference Policy

While the WSPs are the main tool for water management at the source scale, the AIP is the water management tool for impacts on the water users, including the environment.

Ensuring '*no more than minimal harm*' for the granting of water access licences and approvals is a fundamental concept in the WMA. Granting water access licences is conditional to the Minister's satisfaction that adequate arrangements are in force to ensure that no more than minimal harm will be done to any water source due to licensed water takes. The AIP prepared under the WMA sets criteria for acceptable cumulative impacts on water supply works and elements of the environmental, like groundwater dependent ecosystems (GDEs). In particular, the AIP:

- clarifies the requirements for obtaining water licences for aquifer interference activities under NSW water legislation
- establishes and objectively defines considerations in assessing and providing advice on whether more than minimal impacts might occur to a key water dependent asset.

The AIP is applied by proponents of aquifer interference activities in preparing applications and used by the department to assess those applications.

The AIP emphasises its relevance to high-risk activities. It requires proponents to plan their projects based on an '*account for, mitigate, avoid/prevent, and remediate*' approach. For each of the highly productive groundwater sources and the less productive groundwater sources, the AIP specifies a minimum impact requirement for water table level, water pressure, and water quality (Table 1 – Minimal Impact Considerations for Aquifer Interference Activities; AIP). Proponents must demonstrate how each of the requirements are met. Although the AIP applies to all aquifer interference activities, it has been developed to (in particular) address the following activities: mining, other extractive industries, CSG, dewatering, injection works, and contamination activities (water quality and quantity).

Importantly, the AIP defines minimal impact considerations for proposed projects, which include assessment of cumulative impacts. AIP minimal impact considerations are defined as water table or artesian pressure drawdown limits at certain setback distances (e.g. 10% cumulative variation in the water table 40 metres (m) from any high priority GDE or high priority culturally significant site) and at neighbouring water supply works (e.g. 2 m water table decline cumulatively at any water supply work).

3 Considering cumulative impacts on water resources

A standard definition as initially developed by the U.S. Council on Environmental Quality (CEQ 40 CFR Section 1508.7) defines a cumulative impact as:

> *'the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-federal) or person undertakes such actions.'*

The definition of cumulative impacts is evolving and has been revised multiple times since its initial conceptualisation to address challenges associated with the practical implementation of the analysis (see Section 5.3 for more details). The AIP refines this definition by stating:

> *'All cumulative impacts are to be based on the combined impacts of all "post-water sharing plan" activities within the water source.'*

It goes on to set quantitative cumulative impacts criteria as noted in Section 2.3.

Application of this definition to water resources cumulative impact analysis requires identification of three components:

1. the impact(s) of a proposed project
2. the water resource(s) impacted plus spatial and temporal extent of the impact(s)
3. other projects or activities that impact that same environment.

Therefore, cumulative impact analysis starts simply with the identification of a proposed project's impacts. If a proposed project has an impact on an environmental resource such as groundwater, then it has the potential to have a cumulative impact. Conversely, if it does not impact the environmental resource, then it does not have a cumulative impact on that resource.

3.1 Cumulative impact types

Cumulative impacts on an environment affect a specific resource or resources that combine with other resources to form that environment. The development of a cumulative impact analysis initiates with the identification of the impacted resource and the resource area. Resource areas vary in size depending on their nature and location, and can be localised (e.g. noise effects), geographically defined (e.g. watershed effects), regional (e.g. wildlife habitat), or expansive (e.g. air emissions). The temporal characteristics of a cumulative impact may be short-lived (e.g. noise), long-term (e.g. groundwater recovery from pumping), or permanent (e.g. groundwater drawdown due to evaporation from a legacy mine pit lake).

The impacts of SSD or SSI projects often relate to water abstraction for dewatering, consumptive use by operations, and effects of facilities on water chemistry. Specific impact types include:

- drawdown or mounding at an individual Basic Landowner Rights (BLR) or licensed bore
- regional reduction or increase in groundwater levels
- drawdown near a groundwater-fed spring, wetland, or other GDE
- reduction in intermittent, ephemeral, or perennial stream flow
- alteration of drainage patterns resulting in erosion and sedimentation
- ground subsidence associated with groundwater withdrawal or other project-related activities
- water availability (i.e. water rights)

- solute leaching and potential acidification of water by exposed minerals in mined materials.

The water resource area associated with these impacts is typically not defined by project boundaries, but is instead geographical, typically defined by the watershed(s) and/or hydrolithologic basin(s) in the vicinity of the project (Figure 2), with their associated bulk groundwater resources and water availability established through the department.

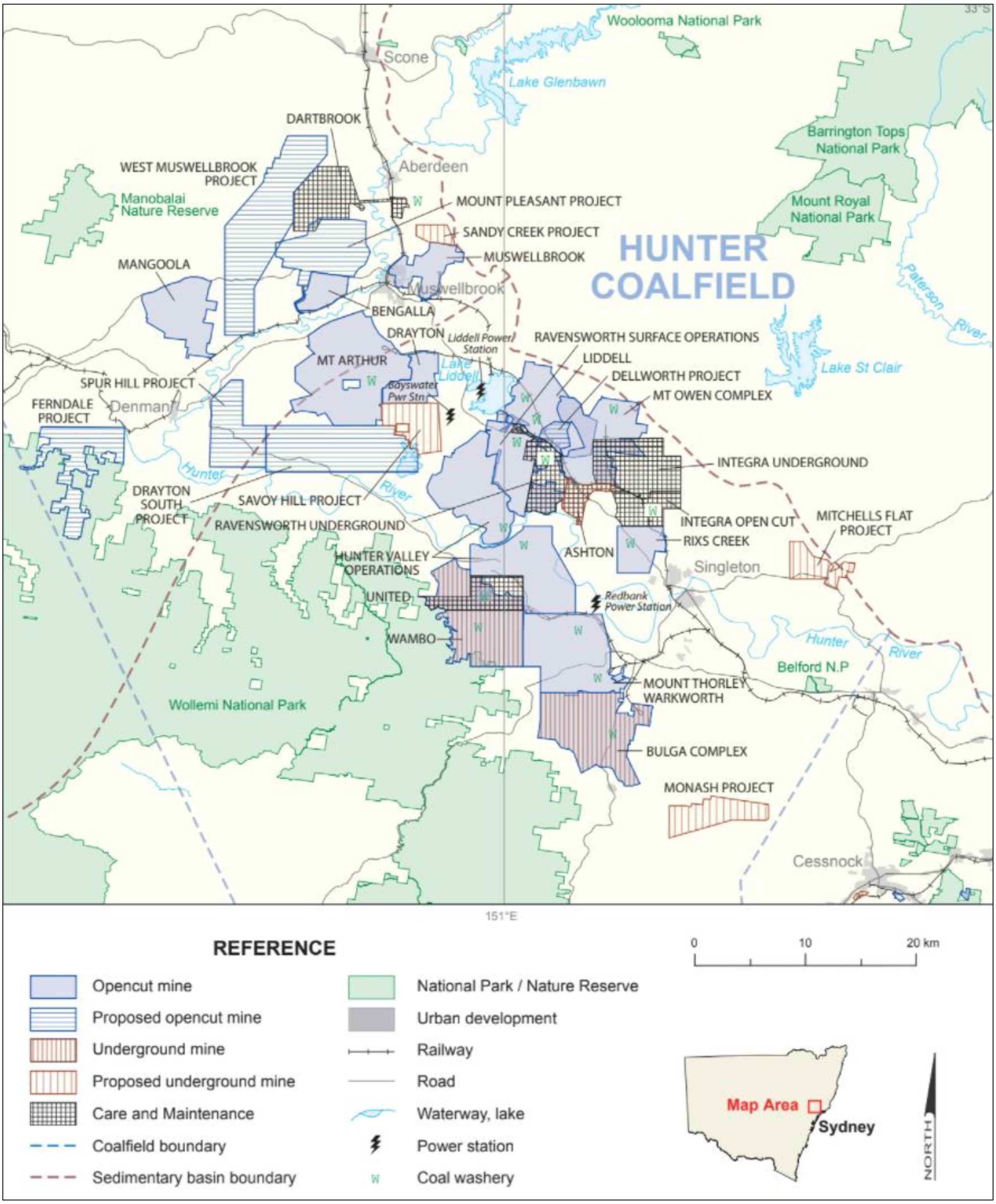

Figure 2: Example of multiple project boundaries in a shared hydrolithologic basin (NSW Government, 2014)

The time-period associated with the impact is determined by the longest lasting water resources impact (Figure 3). The selection of evaluation duration for the cumulative impacts study area is informed by superposition of the anticipated drawdown durations for individual groundwater withdrawals. Superposition involves the additive combination of effects both in terms of the magnitude and the duration of the effects. This duration includes the time periods associated with the drawdown effects of groundwater withdrawal plus the recovery of the groundwater system toward pre-withdrawal conditions. The same concept applies to groundwater mounding due to the addition of water to groundwater resources.

The longest-term impact for a project is often associated with the recovery of a pumped groundwater system that may take decades or longer to recover to near-baseline conditions. Impacts on water chemistry such as pit lakes and seepage from waste rock and tailings storage facilities may also be present for long time periods.

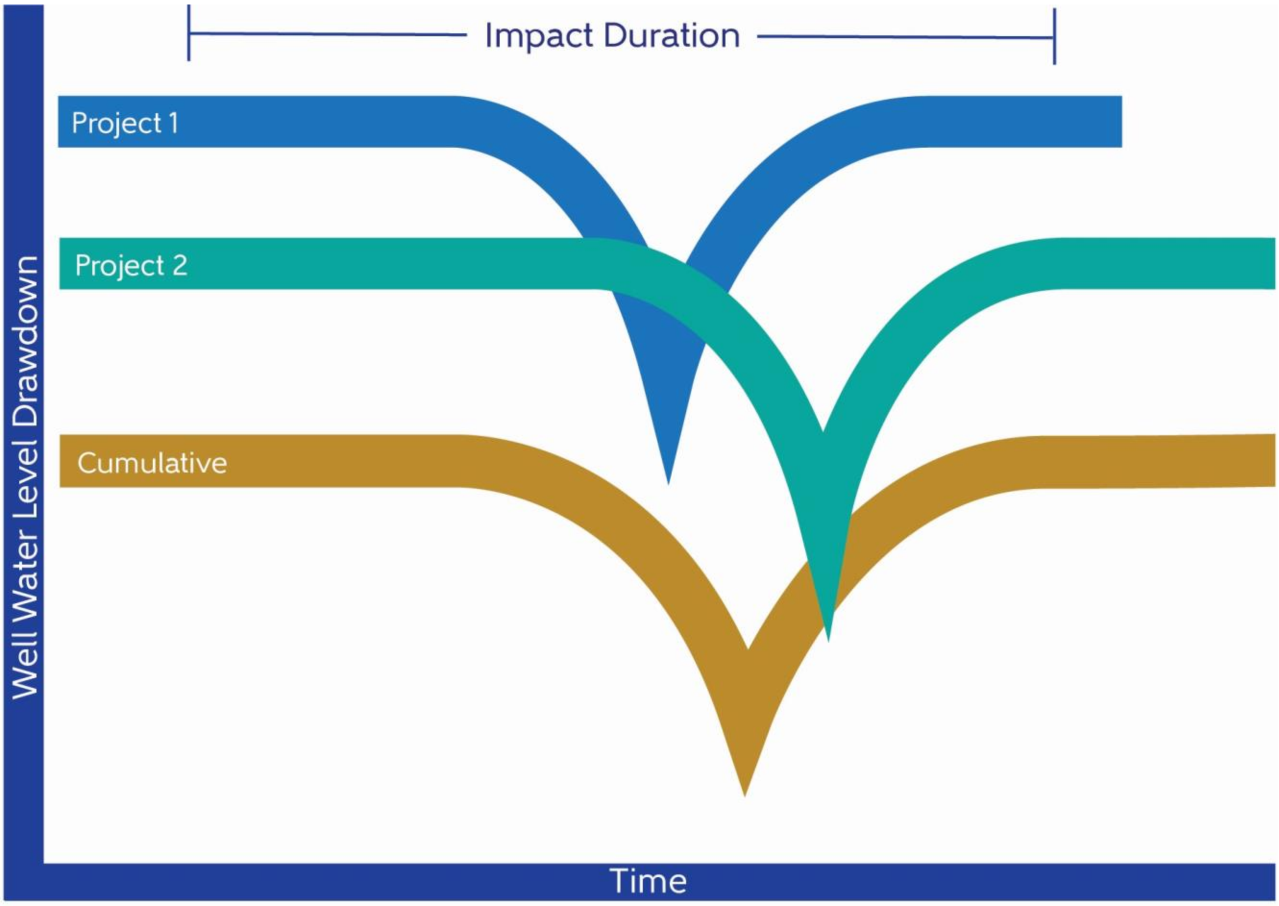

Figure 3: Conceptual duration of cumulative impacts

There are a few methodologies and tools for developing an inventory of past, present, and reasonably foreseeable projects that require consideration in cumulative impact analysis (e.g. USACE, 2016). Most of these involve a mapping exercise associating past, present, and reasonably foreseeable projects to the impacts identified for the analysed proposed project (Figure 4).

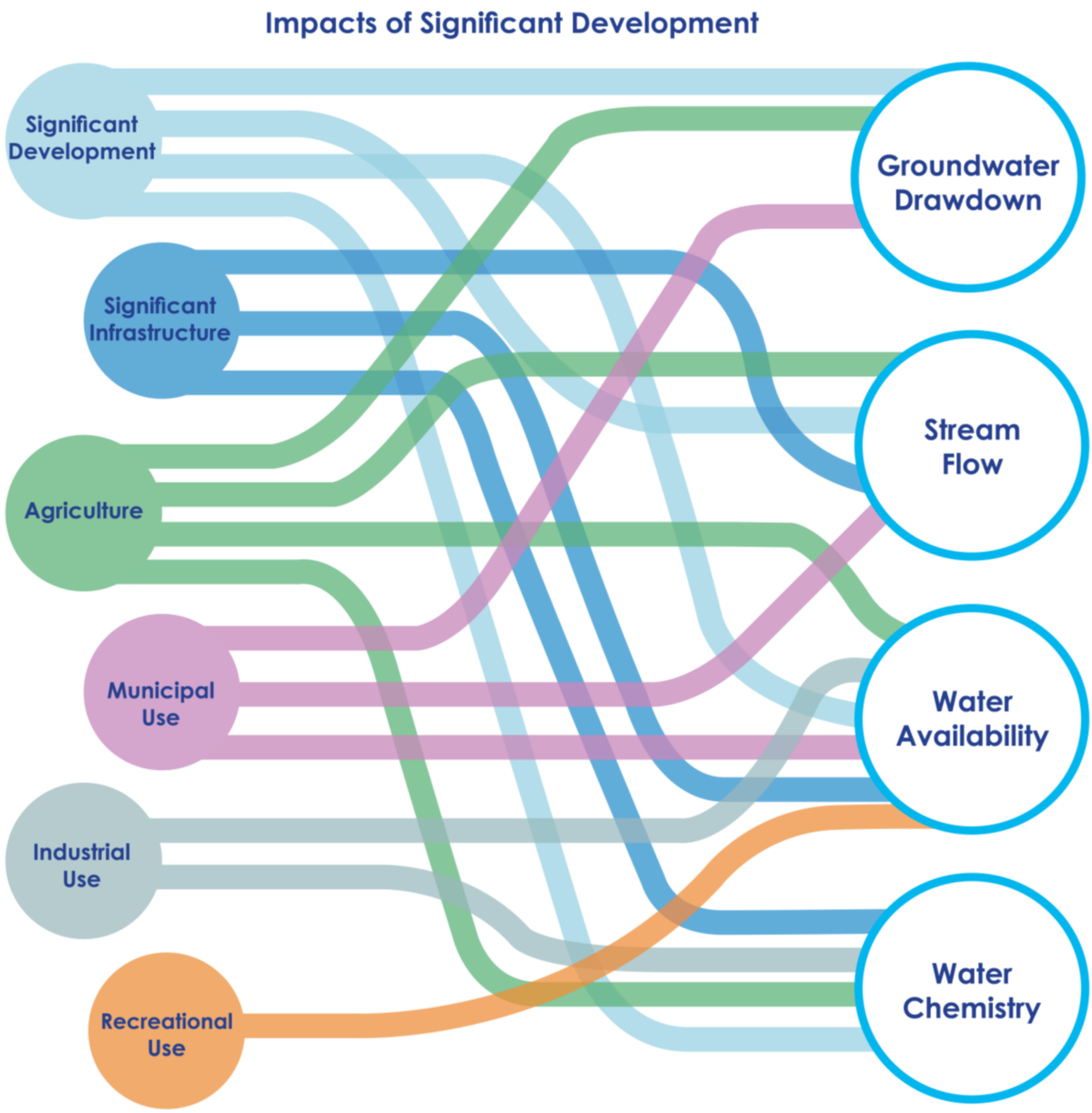

Figure 4: Conceptual map of cumulative impact analysis for significant development and infrastructure projects

The mapping examines the potential individual effects of each project and usage on each category of water resources effects. Some projects/uses will influence all the categories while others may only influence select categories or only one. Projects/uses that do not have an individual effect on a category do not contribute to its cumulative effects. For example, a significant mining development may mine below the local groundwater table giving that development the potential to affect groundwater drawdown, stream flow, water availability, and water chemistry. Another open cut mining development above the groundwater table has the potential to affect stream flow, water availability, and water chemistry, but not necessarily groundwater drawdown. Recreational use in the area does not have the potential to affect groundwater drawdown, streamflow, or water chemistry, but water resource requirements associated with that use may affect the overall availability of water in the area (e.g. minimum stream flow volumes).

The mapping exercise establishes the suite of projects/uses for cumulative impact analysis for each category of water resources effects. This approach manages the inadvertent exclusion of a project/use, the inappropriate inclusion of a project/use, and the potential for double counting impacts from the cumulative impact analysis.

The types of cumulative impacts typically observed in water resources are fully additive effects, partially additive effects, prevailing effects, synergistic effects, and mitigative effects (Figure 5).

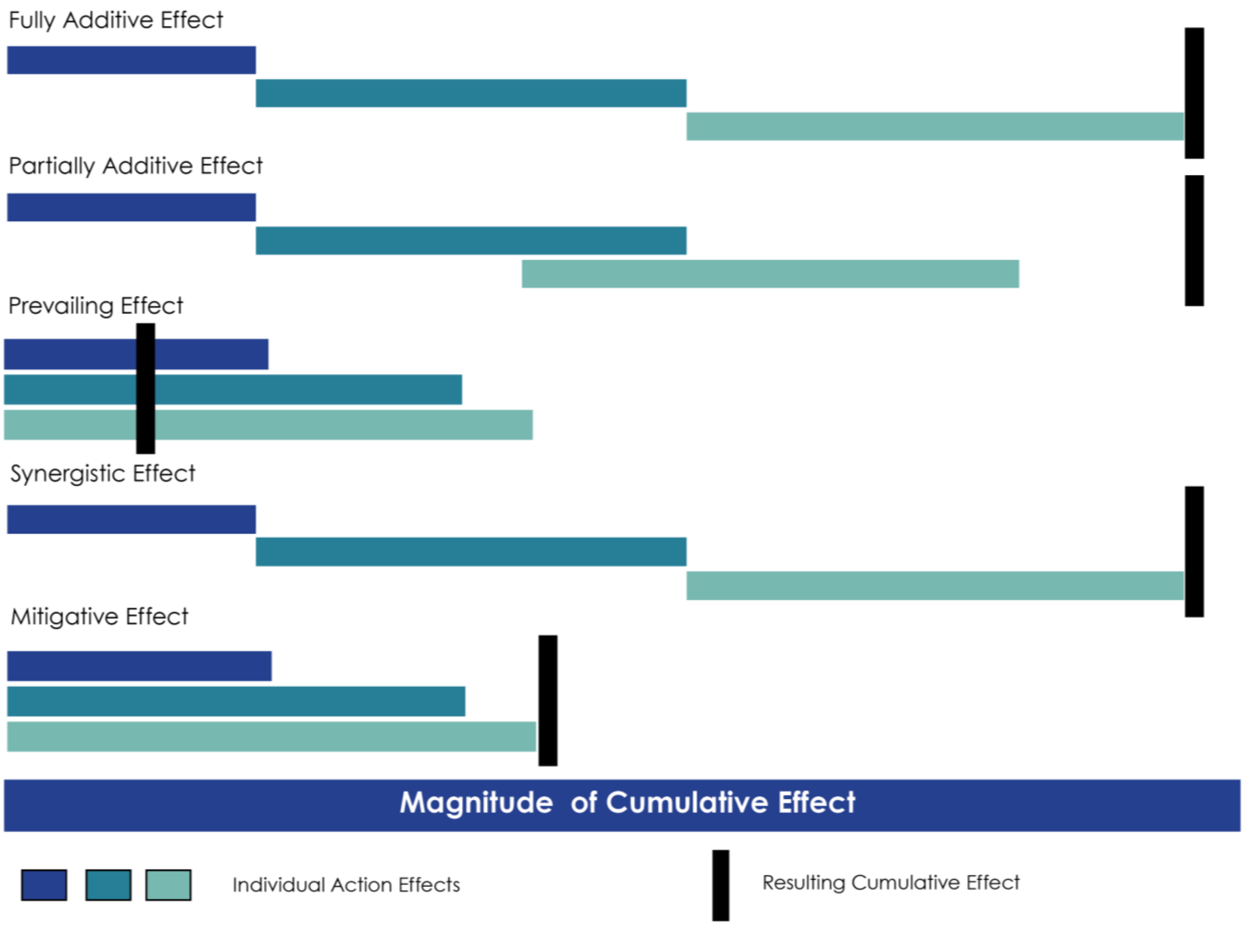

Figure 5: Conceptual diagram of the types of cumulative impacts

Fully additive effects are the simplest cumulative effect where the quantitative measure of each individual effect summed equals the cumulative effect. Partially additive effects feature a cumulative effect that is less than the sum of the individual effects. Prevailing effects have a quantification tied to the maximum individual effect. Synergistic effects involve a cumulative effect that is greater than the sum of individual effects, while mitigative effects have a cumulative effect that is less than the sum of some or all the individual effects. Physical examples of each type of effect are described below.

In water resources, cumulative impacts are commonly fully additive or partially additive such as drawdown of groundwater level at a well location, where the influence of multiple nearby pumping wells is superimposed resulting in a total observed drawdown commensurate with the aggregate of the pumping activities. Additive impacts are likely to increase the duration as well as the magnitude of cumulative effects (see Figure 3). Examples and analyses of well superposition – also known as well interference – are available in groundwater and water engineering references (Todd, 1980).

An example of a prevailing effect could involve stream flow that is fully depleted by the effects of groundwater pumping. Once the stream flow is fully depleted by the first pumping action, additional pumping actions cannot reduce the stream flow further. However, in the absence of the first pumping action, the other pumping actions would have affected stream flow.

Examples of synergistic effects can be found in water chemistry where the combination of flows can result in higher concentrations of constituents of concerns in the aggregate solution than in any individual inflow component. Methylation of metals can occur in instances such as when a solution bearing sulphate and organic material combines with a solution bearing metals such as mercury, increasing the concentration of methylmercury in the aggregate solution.

There are numerous examples of mitigative effects including situations where artificial groundwater recharge offsets the effects of groundwater pumping, surface water discharge maintains flows affected by groundwater withdrawal, or combination of an acidic water with an alkaline water results in pH neutralisation, and metal hydroxide precipitation reduces constituent concentrations in the aggregate solution.

3.2 Project planning

In practice, cumulative impact analysis requires more information and knowledge than understanding the impacts of an individual proposed project alone. Therefore, the potential for cumulative impacts requires consideration during project design, as it is very inefficient to incorporate after-the-fact.

3.2.1 Cumulative impact analysis framework

It is common to use numerical groundwater modelling as the key component in water resource cumulative impact analysis. However, the numerical groundwater model is only one component of a required multi-dimensional framework, as depicted in Figure 6. The framework consists of five progressive categories that include:

1. conceptual modelling
2. water resource characterisation
3. decision criteria
4. evidence-based evaluation
5. ongoing assessment.

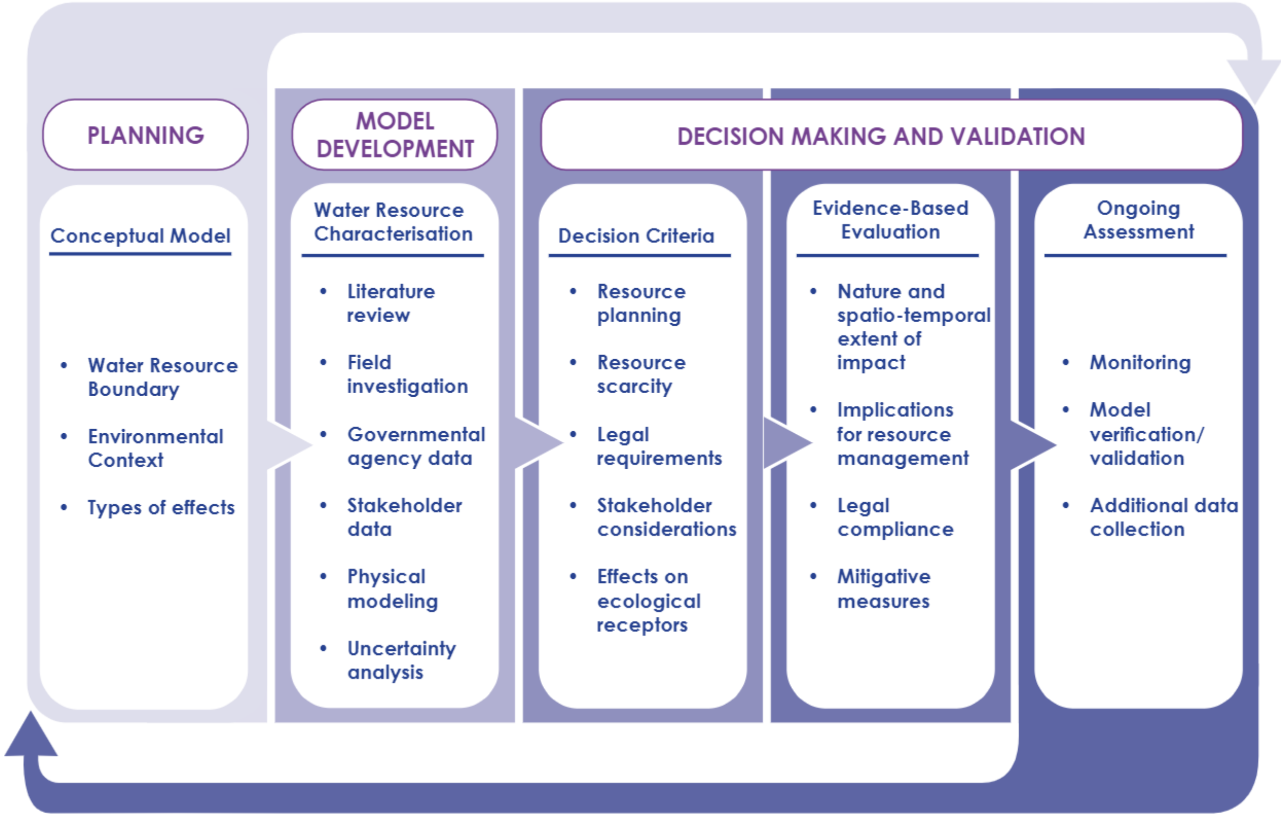

Figure 6: Cumulative impact analysis framework

The evolution of cumulative impact analysis usually involves the design of a conceptual model along with resource characterisation that is based on the water resource boundary and is not restricted to the project boundary. In most cases, the characterisation data are input into a forecasting tool (Dube et al., 2013), such as a numerical model. The forecasting tool has the capability of incorporating changes such as other significant developments that affect the same resource as the proposed project. In addition, consideration of cumulative impacts requires identification of the relevant decision criteria (such as those defined in the NSW AIP discussed in Section 2, for example) in order to conduct an evidence-based evaluation and inform management decisions (Figure 6). An example is provided below which illustrates the value of considering cumulative impacts within the framework presented in Figure 6.

Discussion example: Humboldt River Basin, Northern Nevada, USA

The Great Basin region of the United States is a high elevation desert area between continental mountain ranges. The region has scarce surface water resources due to very low meteoric precipitation conditions but does have substantial groundwater resources attributable to recharge of glacial melt water from the last ice age. While substantial in size, replenishment of groundwater resources is precipitation-limited and constrains sustainable development. Surface water flow is often ephemeral, comprised mostly of precipitation runoff and snowmelt with limited groundwater discharge to support perennial flow.

Original management of regional surface water and groundwater resources used a simplifying assumption that groundwater and surface water resources were effectively independent, and therefore, could be managed individually. However, more than 70 years of monitoring data indicate that the resources are responding

> *interactively to development over the entire drainage area of the river basin. The Nevada State Engineer is, therefore, revising the resource management conceptual model to incorporate surface waters and groundwater within the river basin into a cumulative rather than independent assessment subject to evaluation of the conjunctive use of surface and groundwater by stakeholders. The analysis of the total resource within the basin resource-boundary uses a numerical model developed by the U.S. Geological Survey as informed by the historic and current water resources data collected. The model examines the potential effects of individual water use activities (e.g. pumping) on the entire system to inform regulatory decisions regarding water use decisions and their impact on existing water users (USGS, 2013).*

It is worth noting that the incorporation of multiple activities and stakeholders introduces significant levels of uncertainty into the analysis of cumulative impacts. Therefore, analysis programs often need to develop information that provides evidentiary due diligence and optionality for decision-makers rather than conclusive determinations. Examples of this from the mining industry involve projects that are evaluated and permitted but are never developed due to changes in economic conditions, commodity prices, and/or financing. While the evaluation of potential impacts from mining projects is incumbent on cumulative impact analysis, there is a chance, if not a likelihood, that some of the reasonably foreseeable future actions evaluated never actually occur. Therefore, the results of the cumulative impact analysis represent an examination of future development scenarios subject to future re-evaluation incorporating evolving monitoring information (see Section 6.3 Monitoring and mitigation).

Collaborative planning for cumulative impact analysis with internal and external stakeholders is essential to providing evidence-based evaluations of impacts to decision-makers. Beyond ensuring the quality of those evaluations, planning also establishes objectives and defines scope for the analysis process that allow for completion of this process that could otherwise be open-ended (Milne and Grierson, 2008). A useful cumulative impact analysis for decision-makers defines a water resource, characterises its capacity and sustainable development limitations, and establishes causes for adverse effects, current or potential. Therefore, identification of cause-effect relationships to establish monitoring, preventative measures, and mitigation approaches is more valuable than supposition regarding the precise magnitude and timing of potential future impacts. These preventative measures can then be incorporated proactively into project designs while mitigation measures can be pre-planned and, if appropriate, pre-funded in association with monitoring triggers to pre-empt or minimise the duration of potential impacts on water resources.

3.2.2 Incorporating current and potential future developments

Collaborative planning is critical when incorporating current and potential future developments into the cumulative impact analysis. While past and current cumulative actions are readily identifiable, the information characterising impacts of those actions may not be publicly available or may even be held as confidential. Withholding data, or publication of conflicting or inconsistent data can cast doubt on cumulative impact analysis, resulting in rework and delays.

To avoid these conflicts and benefit collaborative planning and data reporting, supporting characterisation data should be provided in raw format when submitting application documentation that includes groundwater modelling, for example:

- *Tabular numerical reporting of groundwater well location and completion details;*
- *Water level measurements;*
- *Stream flow rates; and,*
- *Water chemistry analyses plus model input/output files.*

Identification of potential future cumulative impacts is more speculative than past and current potential impacts and depends on the definition of ‘reasonably foreseeable future’ projects or activities as applied by decision-makers and regulatory authorities. In practice, these are constrained to projects that have been formally proposed by other resource users, resource planners, and regulatory authorities for authorisation at the time of the cumulative impact analysis.

3.2.3 Groundwater as a limited resource

The most practical rationale for cumulative impact analysis of water resources relates to the fact that water resources are renewable but spatially and/or temporally limited. Water resources and water usage are subject to a growing number of pressures that impact water quantity and quality. There is an increasing number of cases that demonstrate the most significant water resource management challenges do not result from the direct effects of particular projects, but rather from the combination of individual effects – some relatively minor – of multiple projects or activities over time. These challenges include:

- depletion of aquifers due to cumulative pumping withdrawals for consumptive use
- reduced stream baseflows and increased stream temperature due to nearby groundwater pumping
- increased solute concentrations due to anthropogenic water handling and use.

The effects of these challenges can be up to the regional scale, causing problems such as wildlife habitat loss, desertification, and agricultural soil salinisation that demand preventative measures before they adversely affect the human and ecological environment. Competition, and in some instances conflict, for limited water resources has a direct bearing on project viability, costs, and permitting requirements in addition to environmental effects. This competition extends beyond the operational period into the closure and post-closure time periods where impacts may have significant resource management and cost implications over a long-term future. The discussion example below describes where limited water resources and understanding cumulative impacts were critical economic factors in project development.

Discussion example: Diamond Valley, Nevada, USA

Diamond Valley is a hydrographic basin in central Nevada, USA, and the location of a long-standing agricultural community reliant on groundwater pumping for hay and other crop production. There are no irrigation-scale surface water resources in the valley. Hay production in Diamond Valley has been more economically *prosperous than many other areas in the region, resulting in an aggregate pumping rate from dozens of hay producers greater than the sustainable yield of the basin for more than 60 years. Long-term effects of pumping such as ground subsidence and loss of aquifer yield resulted in regulatory action to cease issuance of new water use authorisations and eventually curtail existing authorisations.*

The valley is also prospective from a mineral development standpoint, containing sizable deposits of gold, molybdenum, and lead at locations below the local water table. Therefore, beneficiation of these deposits would necessitate groundwater pumping for mine dewatering and water supply for mining and processing. Relatively low permeability aquifer properties and production designs result in modest pumping requirements compared to other mining projects in the region (BLM, 2019). However, the practical unavailability of water use authorisations and considerable uncertainty regarding the future curtailment of authorisations introduce significant technical constraints, costs, and financial risk into mining projects. In addition, the cumulative impacts evaluation and mitigation planning for impacts have prolonged mine permitting processes (beyond 15 years) and have been the subject of administrative and legal challenges to project authorisations. Although mining groundwater usage would be approximately one percent of the agricultural use, proposed monitoring obligations and establishment of financial trust funding for mitigation of potential cumulative impacts would increase project development costs by multiple millions of dollars.

The water resource closure implications associated with mining and tunnel infrastructure differ from other industries because mining modifies the geology, and hence the hydrogeology: open pit mines form pit lakes attract groundwater and surface waters away from their baseline flow paths; underground mines and tunnels create porosity and preferential flow paths for groundwater to refill and move in. These modifications to hydrogeology within the water resource boundary have the potential to permanently change the condition and use of the resource within the basin. Mitigation of negative change impacts is often long-term or even perpetual, significantly influencing costs associated with mitigation and closure.

Modifications may also have positive change impacts, such as the development of water systems that can enhance future water use, groundwater dependent ecosystems, and economic development. Recognition of these modifications along with their positive and negative implications represent a useful outcome of the cumulative impact analysis. Examples of positive change impacts resulting from cumulative impact planning around water resources include conversion of mine pit lakes into municipal water supply (e.g. McCullough et al., 2009) and fishery aquiculture (e.g. Axler et al., 1998).

3.3 Qualitative risk Assessment

Findings from a qualitative risk assessment conducted during conceptual model development can be used to navigate the challenging process of determining the area of analysis (e.g. model domain). Stantec (Stantec, 2021b) presents a practical qualitative risk assessment framework. A qualitative risk assessment process could be formal or informal and should result in an understanding of the relative scale of spatial and temporal impacts, whether there are receptors that may be affected by the project, and the degree of anticipated uncertainty in the modelled system. While qualitative risk assessment at the conceptual model phase does not provide a quantitative measurement of impact, it should provide stakeholders with an awareness of potential environmental effects and be used as a tool to shape the water resource characterisation plan and subsequent numerical model development. Where the findings from the assessment indicate that the risk is relatively low, it may be justified to use a more restrictive numerical model domain and potentially exclude other developments/infrastructure, thus reducing unnecessary complexity and effort. However, if the findings indicate that the risk is moderate or high, the numerical model domain and inputs should account for the potential cumulative impacts associated with non-project related developments/infrastructure.

3.3.1 The importance of scale

Planning for cumulative impact analysis requires a level of foresight, as the analysis must occur across an area sufficiently large enough to encompass the predicted impacts, though the analysis itself is meant to determine the extent and degree of impacts. This mutually conflicting and dependent condition makes the process of cumulative impact analysis inherently difficult. An overly limited spatial extent can lead to missing or underestimating impacts. An overly large and conservative spatial extent can lead to unnecessary complexity. NSW requirements to assess cumulative impacts associated with existing, approved projects assist in defining this spatial extent for use in the permitting process, reducing the overall complexity compared to a broader prospective resource planning process.

The spatial and temporal scale of a proposed project is likely a key driver in the degree of direct and cumulative impacts to water resources. When planning for cumulative impact analysis, the anticipated magnitude of drawdown and/or groundwater withdrawals should be considered within the context of the affected groundwater resource. This evaluation could include an analytical model using site-specific or literature-based aquifer parameters, review of other nearby similar projects, and/or a review of hydraulic boundary conditions that may influence drawdown or extraction rates (e.g. major structures, watershed boundaries, rivers). The timing of impacts also should be considered. For example, will groundwater withdrawals be short-term and is groundwater recovery expected to occur within months, years, or decades, or will there be a fundamental change to the hydrogeology such that impacts may occur in perpetuity?

3.3.2 Receptors

The type and number of receptors within the expected area of influence, as well as their inferred sensitivity to impacts is a key factor when evaluating the qualitative risk of a project. Receptors may include licensed bores, BLR bores, surface water features such as streams, rivers, lakes, groundwater-fed springs, and GDEs. Receptors should be incorporated into the conceptual model, and it should be understood whether impacts from other projects are predicted to intersect these features.

3.3.3 Uncertainty

The degree of uncertainty in the hydrogeological system needs to be considered when establishing the analysis domain and determining whether other projects need to be incorporated into the cumulative impact analysis. The degree of uncertainty should be evaluated based on the quantity and quality of water resource characterisation data, including site-specific and regional geology and hydrostratigraphy, groundwater heads and gradients, aquifer parameters, surface water flows, climate information, and existing and future projects. Uncertainty can also be introduced simply because multiple projects occur within the same water resource boundary. In these cases, an assertion that cumulative impacts do not occur should be evidence based or demonstrated through the cumulative impact analysis (e.g. numerical modelling). Where greater uncertainty is present, analysis should err on incorporating existing and future projects into the analysis.

In summary, development of a cumulative impact analysis involves:

- *Identify the impacts of the proposed project. Projects without impacts to a resource cannot have cumulative impacts. Projects with impacts have the potential for cumulative impacts.*
- *Define the resource boundary, noting that the resource boundary area is frequently different from a project property boundary (Figure 2).*
- *Forecast the duration of impacts from the project (Figure 3).*
- *Utilise the resource boundary and the duration forecast to identify other past, present, and reasonably foreseeable future projects that could impact the resource and map the actions to the specific types of impacts (Figure 4).*
- *Assess the type of cumulative impact (fully additive, partially additive, prevailing, synergistic, mitigative) expected (Figure 5).*
- *Perform data collection, resource modelling, and other forecasting required to inform decision-making and permitting (Figure 6).*

4 Cumulative Impacts in NSW

The definition of cumulative impact and a discussion directed at the general application of cumulative impacts assessment approaches to water resources has been presented in Section 3. In this section, several case studies are used to explore examples of cumulative impacts on water resources in NSW. These examples have been used to explore and demonstrate the complexity of cumulative impacts in NSW and provide examples of instances where carefully planned and executed cumulative impact analysis would produce significant benefit when evaluating and predicting adverse water resource impacts.

Following the presentation of the case studies, a description of approaches and common shortcomings in cumulative impact assessment is presented. Examples of common resource users in NSW that may cause (or affect) cumulative impacts include mines, quarries, CSG projects, infrastructure, energy production, and residential, commercial, and other anthropogenic projects (Table 1). As described in Section 3, each of the activities will have unique impacts on other resource users, including the environment (e.g. GDEs, subterranean fauna, surface water flow). Spatial and temporal variations of these cumulative impacts on water resources will vary considerably and is explored further in this section.

A discussion on the positives, drawbacks, and information gaps for common approaches is provided below. The three case studies discussed include:

- Southern Coalfields
- Sydney City Infrastructure
- Narrabri region.

Table 1: Examples of Major Projects in NSW that require preparation of a groundwater model

Mines and Quarries	Infrastructure and energy production	Residential, commercial, and services
Mining exploration and operation: Underground coal mines (long wall, bord and pillar, drive shafts), hard rock mineral mines (open cut and underground), open cut coal mines, and underground mineral sand mines. **Quarries:** Sand dredge (rivers or coastal dunes), hard rock, gravel (river dredge), and limestone. **Gas:** Coal seam, and conventional	**Power stations:** Solar farm, hydroelectric, transmission lines, substations, wind farm, and battery farms. **Roading infrastructure:** Motorways, tunnels, road cuttings, and bridges. **Railway infrastructure:** Overground railway lines, underground railway lines, underground stations, tunnels, and bridges. **Utilities:** Water supply (pipelines groundwater supply bore fields), and waste management facilities (landfill).	**Residential:** Subdivisions, basement car parks, and tower blocks **Commercial:** Transport depots, intensive farming (piggeries, chickens, fish), abattoirs and industrial estates. **Services:** Hospital, and correctional facility.

4.1 Southern coalfields case study

The Sydney-Gunnedah Basin (SGB) is approximately 500 – 600 km kilometre (km) long by 150 – 200 km wide. The SGB extends from south of Wollongong to north of Newcastle and north-westerly through Narrabri into Queensland (Figure 7). The system evolved as a large, elongate geological complex approximately 310 – 230 million years ago (Australian Government, 2020). Development of the SGB included a prolonged, subsiding basin environment that was suitable for coal accumulation. As a result, the SGB contains and the major coal resources in NSW. There are five major coalfields within the basin including: Hunter, Newcastle, Southern, Western, and Gunnedah. Minor coal resources are also located in the adjacent Gloucester and further distant Oaklands Basins.

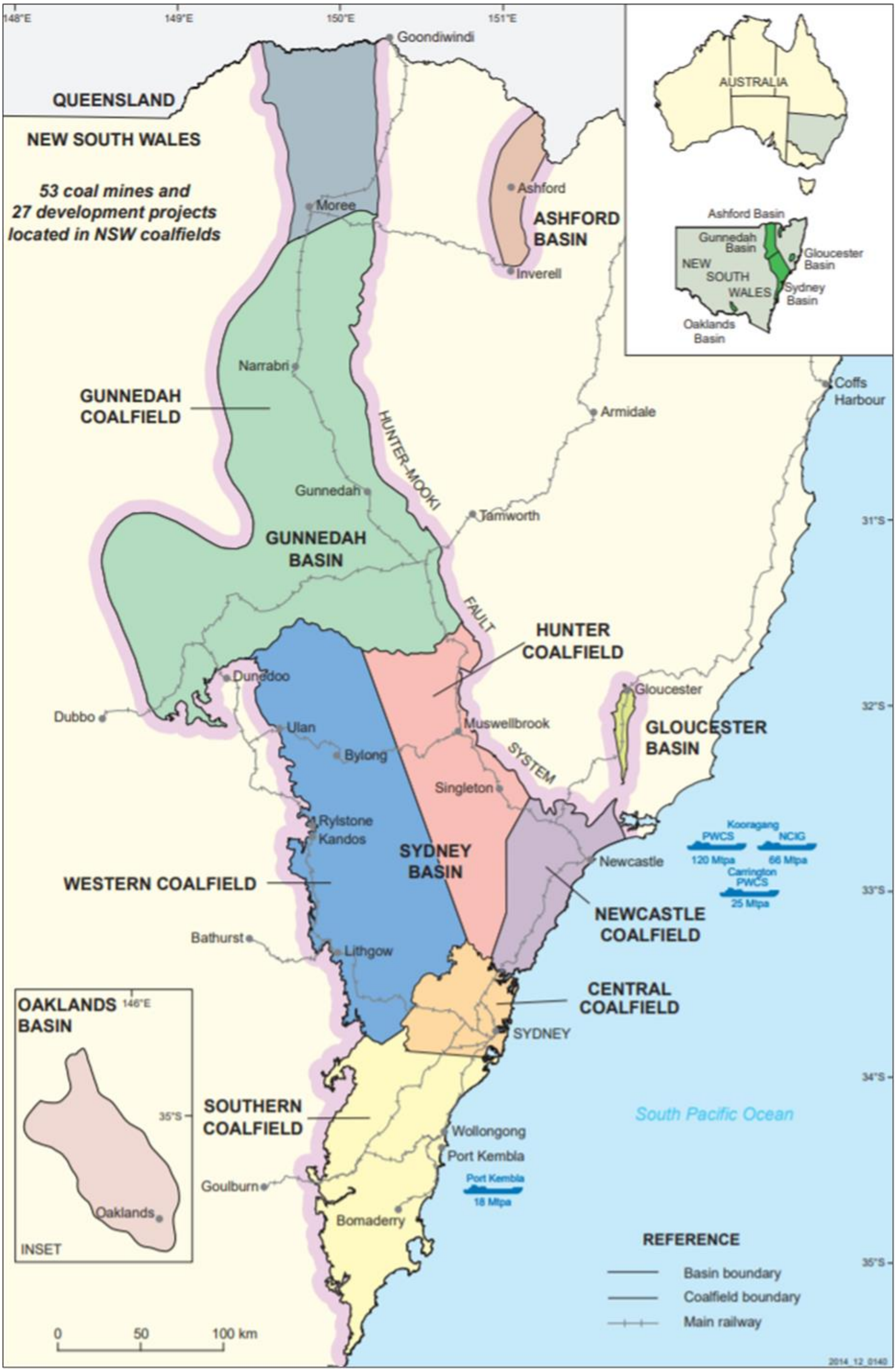

Figure 7: Location of NSW coalfields (NSW Government, 2014)

4.1.1 Area description

The Southern Coalfield is located approximately 30 to 100 km southwest of Sydney (Figure 8). Several current SSD mining projects are located within the basin as described in Table 2. It is recognised that continued development of these resources needs to account for competing land uses and a range of environmental issues. Large areas of natural bushland are located within the Southern Coalfield region. Significant natural features include rivers and higher order streams, sandstone river gorges, major cliff lines and upland swamps. These environments contain important flora, fauna, and aquatic ecosystems, and include many listed threatened species, populations, and endangered ecological communities. The area includes a significant number of Aboriginal heritage sites. The area is within a major water supply catchment for the Sydney and Illawarra regions and includes major water storage infrastructure.

4.1.2 Projects and activities

Initial mining resumed in the 1800s in the Southern Coalfields. Many historic mines were not properly decommissioned, particularly those that used bord and pillar methods. There is the potential that historic workings may not be fully collapsed and/or the working may contain water. More recent mining within the Southern Coalfield predominantly includes underground coal mining that target the Bulli Seam (c. 320 – 420 m depth) or the slightly deeper Wongawilli Seam. A description of mining operations and activities for each mine is provided in Table 2. Overall, methods of underground coal mining have progressed from bord and pillar (e.g. 1970s to 1980s) to longwall mining, which is currently the most common method. Recently there have been increases in the widths of longwall panels. Most mines are currently in the operational phase. There are several amalgamated mines which form part of the closure/maintenance phase of the Wongawilli Colliery which was initially mined in the late 1800s. Many of the current and/or proposed mine sites have overlapping catchment and/or project boundaries. In addition, mining activities vary considerably over a timescale from exploration to closure, and include historic, current, and proposed mining activities.

Table 2: Summary of the main coal mining operations in the Southern Coalfields

Mine	Description
Tahmoor North Coalfield	Operational – underground coal mine targeting the Bulli Coal Seam (~320 to 420 m depth). Mining methods include bord and pillar (1979 to 1987) and longwall (1987 to present) with recent increase in longwall widths (e.g., 283 m since panel 22). Key impacts from mining on surface water features include subsidence and loss of surface water flow (e.g., Redbank, Myrtle Creeks).
Tahmoor South Coal Project	Proposed – underground coal mine extension to the existing Tahmoor North Coal Mine. Targets the Bulli Seam coal resource including 14 longwall panels with a maximum cutting height of 2.6 m and widths of 285 metres. The project has an expected mine life of about 13 years (2022 to 2035) and is planned to follow cessation of mining at Tahmoor North.

Mine	Description
Appin, West Cliff (Appin North), Tower	Operational – Appin underground coal mine commences in 1962 with longwall mining starting in 1969. West Cliff was merged to Appin North and operated as an underground longwall coal mine. Associated projects include the Appin and Tower Power Stations that operate on waste coal mine gas (1996 to present).
Dendrobium	Operational – underground coal mine resuming operations in 2002. Underground mining methods target the Wongawilli Seam (10 m thick, beneath the Bulli Seam); recent 'Dendrobium extension' has been declined as design risks long-term and irreversible damage to Greater Sydney and the Illawarra's drinking water catchment (SSD8194).
Wongawilli (mine colliery)	Closure/maintenance – exploration in the 1800s led to coal mining resuming in 1906 under various ownerships and methods prior to care and maintenance (2014 to 2019).
Bargo	Historic/future: exploration resumed in 1970, construction from 1978 and production from 1985 – targeting the Bulli and Wongawilli Seams.
Russel Vale	Operational – underground coal mining operation west of Russel Vale township. Multiple seam mining. Expansion approved in 2020 permits use of bord and pillar methods (25 m of longwall) for up to a further 5 years (once exercised). Move from longwall mining to first working bord and pillar methods to manage subsidence and groundwater impacts.
Metropolitan Coal	Operational – Metropolitan Coal started in 1888 and is the oldest operating coal mine in Australia. Extraction was initially by hand working and became mechanised bord and pillar extraction in 1951, then longwall mining from 1995. Coal extraction targets the Bulli Seam.
Cordeaux Colliery	Care and maintenance – production stopped in 2001.

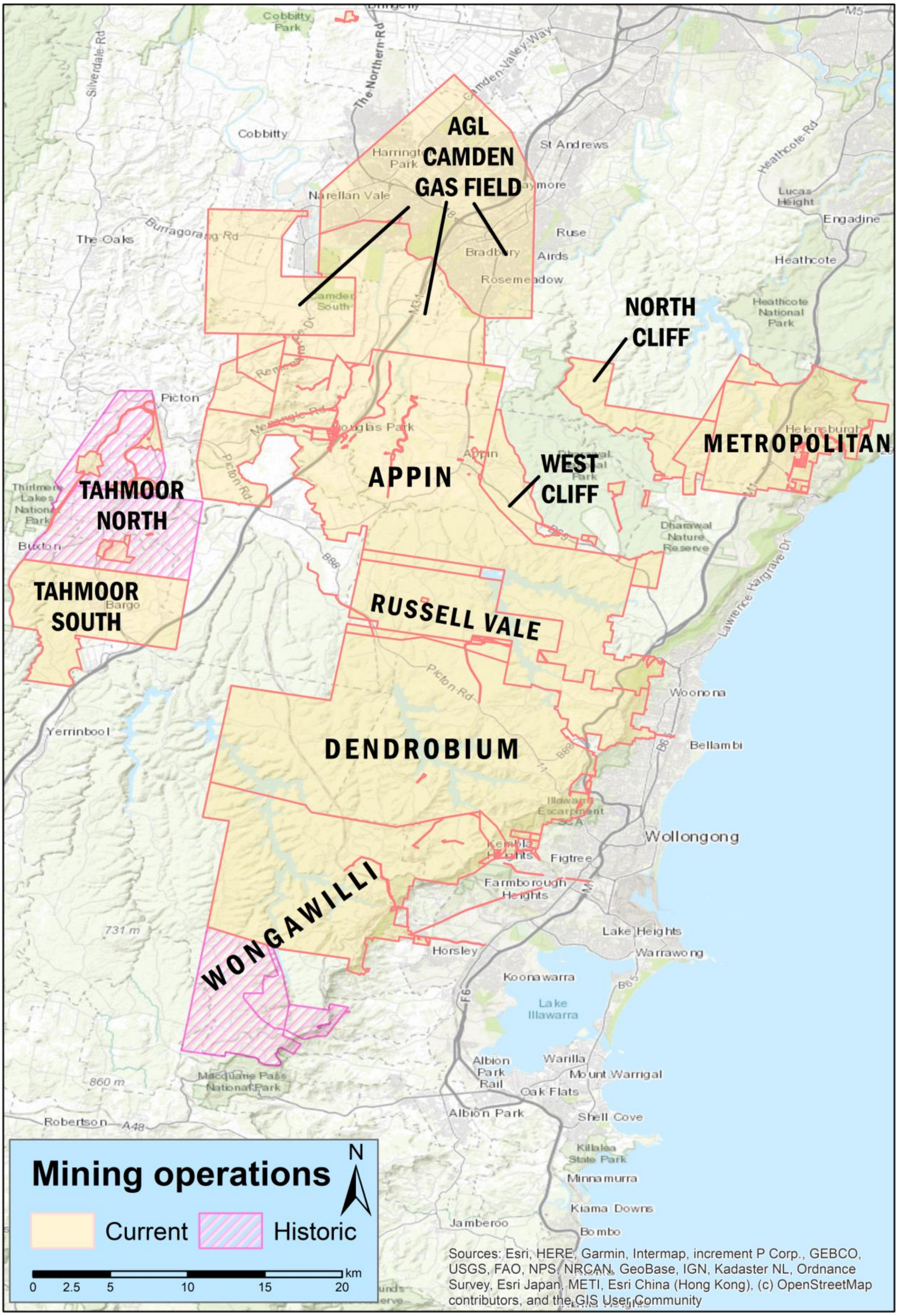

Figure 8: Southern Coalfields and Oaklands Basin projects

In addition to coal mining, other activities rely on water resources within the wider Southern Coalfields, including municipal water supply dams, GDEs, and private groundwater users (Table 3, Figure 9, Figure 10). The Upper Nepean water supply dams (Cataract, Cordeaux, Avon, and Nepean) were constructed from 1907 to 1935. They are used to collect water in the respective rivers, which are all tributaries of the Upper Hawkesbury-Nepean River. These systems supply municipal and drinking water to the Macarthur and Illawarra regions, the Wollondilly Shire, and metropolitan Sydney. All these dams are located within or adjacent to Colliery Holdings (Figure 9).

Thirlmere Lakes National Park is part of the Greater Blue Mountains World Heritage Area. The associated Thirlmere Lakes are a GDE located within the National Park and comprise a series of shallow freshwater bodies located along a horseshoe bend in Blue Gum Creek. The easternmost Thirlmere Lake (Couridjah) is about 650 – 750 m from the nearest Tahmoor North longwalls (mined late 1990s to early 2000s) and more than 3.5 km from the proposed Tahmoor South longwalls.

Surface waterways overlie the areas of underground mining, including Myrtle, Redbank, Allens, and Harris creeks and the Nepean River. In addition, many private bore users draw groundwater for consumptive use, including irrigation, stock, and drinking. In the locality of Appin, private bore users target groundwater from 70 to 240 m deep within the low producing Hawkesbury Sandstone, or minor perched horizons within the Wianamatta Group shale. Most of the bores located within the Southern Coalfield are accessed through BLR rather than licensing. The location of the bores is known, but there is often limited or no information available on their yield and extraction rates (i.e. basic hydraulic properties), in particular within operational and proposed mining areas.

Table 3: Summary of Major Projects, activities, and potential impacts on groundwater resources within the Southern Coalfields

Projects	Activities	Impacts
Mining: Tahmoor North (SSD), Tahmoor South (SSD), Appin Complex (SSD), Dendrobium (SSD), Cordeaux (SSD); Wongawilli (SSD), Metropolitan Coal (SSD), Russel Vale (SSD). **Infrastructure:** Cordeaux, Avon, Cataract, and Nepean Dams (SSI); Appin and Tower Power Stations.	**Underground mining:** longwall method, dewatering, coal extraction, methane release. Surface water catchment dams (Avon, Cataract, Nepean, Cordeaux) **Landuse**: a number of national parks including the Thirlmere Lakes National Park (GDE) **Methane gas:** releases, power plant operation, flaring Private groundwater users (BLR or licensed); farm dams	**Water Quantity:** Drawdown from dewatering, loss of surface water **Water Quality:** Containment loads to surface water from shallow and deep groundwater within the mining operation; methane releases; ferruginous springs, geochemical reaction and release to surface water **Land:** Ground subsidence, deformation, fracturing of overlaying strata, depressurisation of geological strata (reduced bore yield).

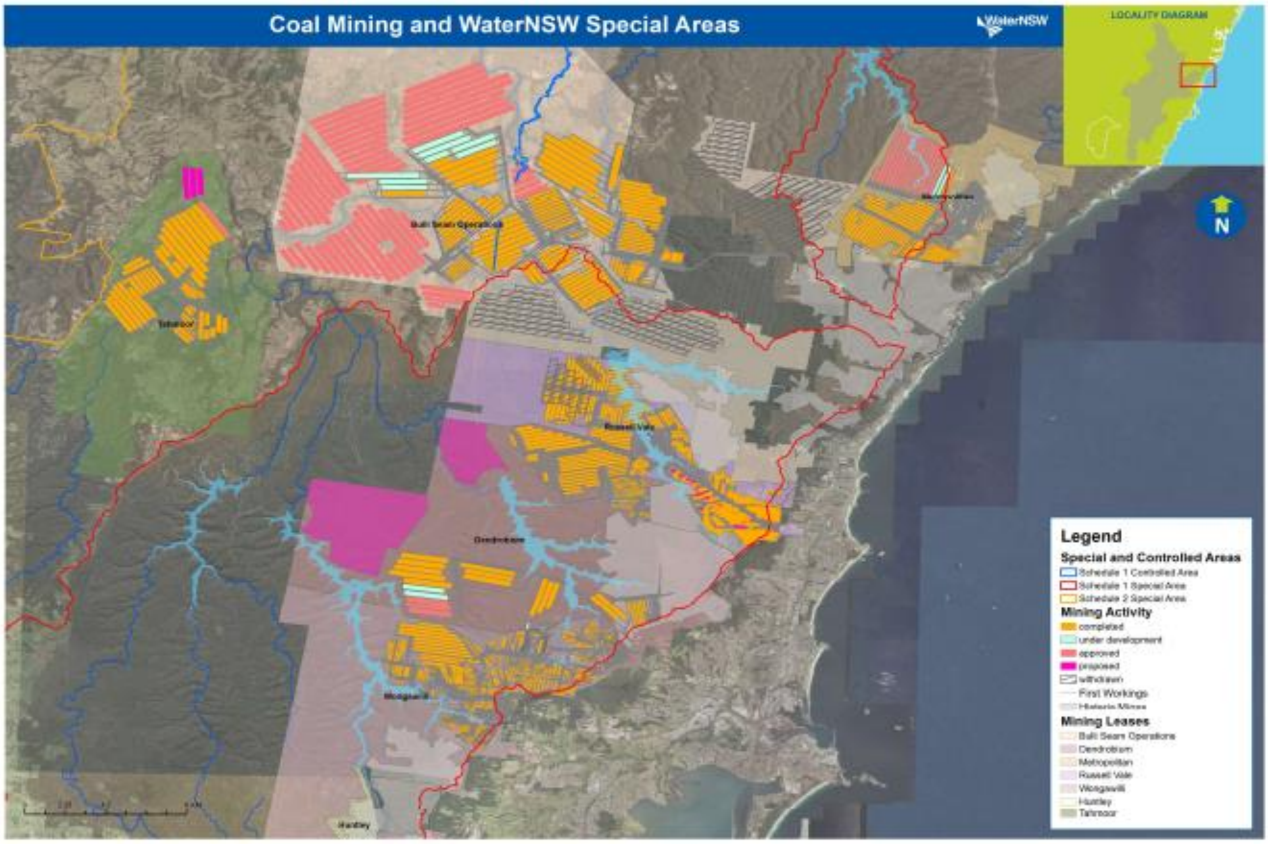

Figure 9: Map showing the location of the Southern Coalfield colliery holdings and WaterNSW water supply assets (WaterNSW, 2018)

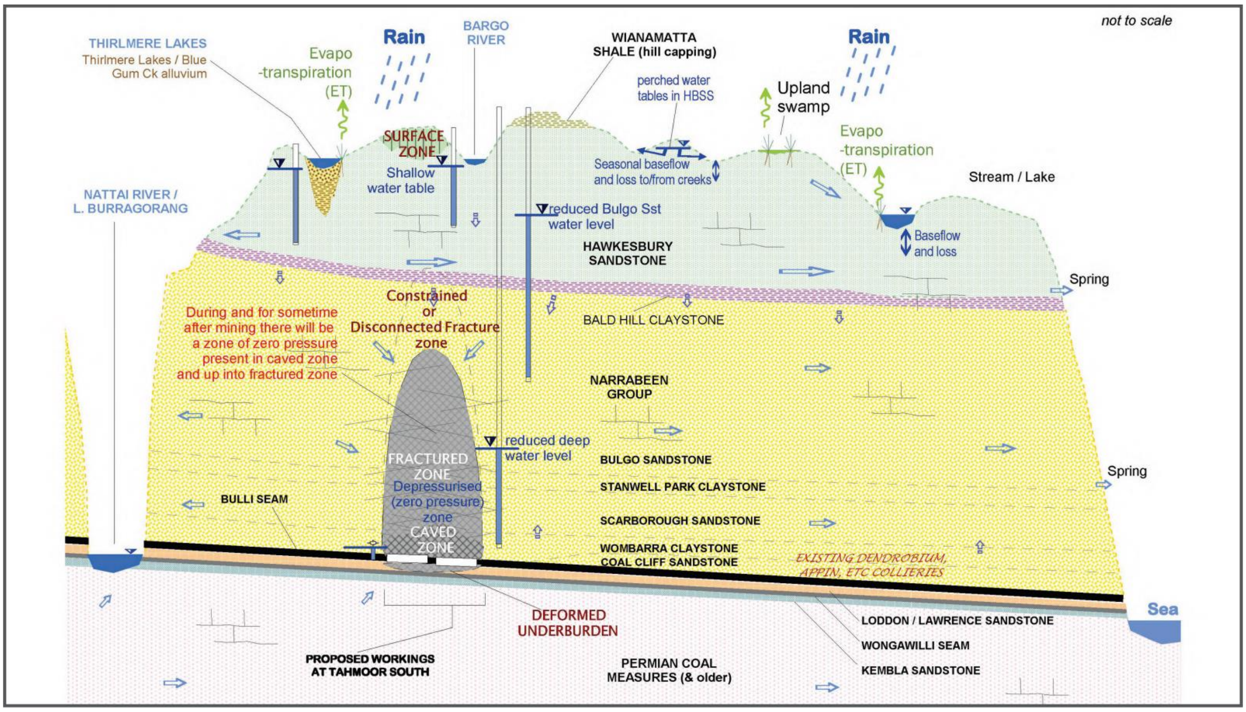

Figure 10: Schematic cross-section showing the geology of the Southern Coalfields and potential impacts of mining on the geology and hydrogeology (AECOM, 2018)

4.1.3 Assessment of cumulative impacts on groundwater

Two independent investigations associated with the impacts of coal mining in the Southern Coalfields have been undertaken. The first was an independent inquiry focussed on past and potential future impacts of mine subsidence on significant natural features in the Southern Coalfield (NSW Government, 2008). The inquiry was driven by public and government concern and was initiated following observations of cracking in the bed of the Cataract River in 1994 and associated subsidence impacts. The inquiry included a strategic review of the impacts of underground mining in the Southern Coalfield on significant natural features (rivers and significant streams, swamps, and cliff lines), with particular emphasis on risks to water flows, water quality and aquatic ecosystems. Advice on best practice for assessment, avoiding, and mitigation subsidence impacts were presented.

Subsequently, in 2017 an Independent Expert Panel for Mining in the Catchment (IEPMC) was established to provide informed expert advice to Planning and Environment (DPE) on the impact of mining activities in the Greater Sydney Water Catchment Special Areas, with a particular focus on risks to the quantity of water in the Catchment. Advice focus is on risks to the total water quantity and holding capacity of surface and groundwater systems, including swamps and reservoirs, and the types and reliabilities of methodologies used to predict, monitor, assess and report on mining effects, impacts and consequences. The IEPMC provided a source of expert advice on mining applications, including monitoring and management plans, and produced two reports to DPE (IEPMC, 2019a, 2019b).

More generally, since unpredicted impacts of subsidence on rivers and significant streams in the Southern Coalfield first came to public attention, the coal mining industry has made significant advances in its understanding of and ability to predict non-conventional subsidence effects. Environmental impacts in the Southern Coal fields are considerable and are often associated with subsidence (e.g. valley closure, upsidence, stream bed cracking) and associated impacts on water quality and quantity (e.g. loss of surface water to groundwater). A summary of recent approaches to assessment of cumulative impacts on groundwater resources from coal mining in the Southern Coalfields using groundwater modelling is presented below.

Tahmoor North

Tahmoor Coal has previously mined 32 longwalls to the north and west of the current pit top location at Tahmoor North. Underground coal mining has recently extended to the northwest of the Main Southern Railway, the area termed the ‘Western Domain’, e.g. Longwalls West 1 (LW W1) to Longwall West 4 (LW W4). The first two longwalls to be mined are LW W1 and LW W2, for which a Water Management Plan was prepared (SIMEC, 2020). The cumulative impact assessment for the Tahmoor North Coalfield was performed to assess impacts from mining under creeks (e.g. Matthews, Ceder, Stonequarry), setback distances, best practice extraction plan, and adaptive management. The assessment demonstrated there was no subsidence impact or environmental consequence greater than minor[1] and no connective cracking between the surface, or the base of the alluvium, and the underground workings.

Tahmoor South

The proponent for the Tahmoor South Coal Project used a groundwater model to assess impacts from adjacent mines on groundwater, including status of operations (operational, closure). The cumulative impacts were benchmarked to impacts from existing Tahmoor North mine and nearby mines. The proponent concluded that cumulative impacts of mining activities (including historical operations at Tahmoor North mine) had been modelled, quantified, and assessed as being minor. The reviewer was satisfied with the inclusion of all mines within 15 – 20 km of the current operation. However, the reviewer indicated that a Trigger Action Response Plan (TARP) was

[1] The definition of minor is ‘*not very large, important, or serious.*’

required to address all criteria exceedances and to provide confidence that adverse impacts can be successfully identified should they occur.

The assessment did not consider potential impacts from mines located further to the east and south including the Russell Vale, Wongawilli/Eloura, Avondale, and Huntley operations. The model also did not incorporate the cumulative impacts of non-mining groundwater pumping, for which there was substantial uncertainty on the extraction volumes and pumping schedules. Consequently, the model isolated the effect of mining on groundwater levels. However, a predictive sensitivity scenario was used to represent pumping from registered bores, the results of which indicated greater drawdown at Thirlmere Lakes than was predicted from the Tahmoor South or the cumulative mining scenarios. It was noted that due to the lack of data, the prediction of non-mining drawdown impacts could not be validated. The predicted effects of drawdown due to mining were documented for registered and unregistered bores. As a best practice, a monitoring program was designed based on the predictive results to provide data for further model improvements and assessment of uncertainties (e.g. by applying pilot points and/or regularisation methods, and/or detailed uncertainty analyses with a refined model).

Wongawilli

A numerical model was developed for the Wongawilli mine, with fundamental shortcomings, resulting in low confidence in the quality of the predictions. Further, the model lacked consideration of cumulative impacts (e.g. Avon Dam and adjacent coal mining operations). As a result, the cumulative impact assessment completed was not considered suitable.

Dendrobium

A numerical model was used to investigate cumulative impacts of the Dendrobium extension using a model domain of 40 km by 40 km. A sensitivity analysis was undertaken and predicted the median drawdown estimate would be zero. For the worst-case uncertainty scenario, up to five water supply works would be affected by greater than 2 m drawdown. The proponent used a groundwater model to determine a ‘very low risk’ of the project causing drawdown more than the minimal impact criterion (maximum 2 m drawdown) at private bores, as defined in the AIP. Bores were predicted to experience greater than 2 m drawdown due to historic and/or cumulative mining that is not associated with Dendrobium. The current lack of evidence of water quality consequences was assumed to continue long-term. The reviewer indicated the regional scale and resolution of the model (space and time) were unsuitable for predicting impacts on natural and manmade surface water features (wetlands, dam lakes, streams). In addition, potentially impacted surface water features had not been adequately characterised, subsidence and cracking were expected to be from the goaf to surface (e.g. providing a full pathway for water movement); no sensitivity or uncertainty analysis had been undertaken on relevant parameters (e.g. bed conductance); and there was unsatisfactory simulation of the groundwater system behaviour and responses to historical mining stresses. It was also concluded by the reviewer that, *‘the assessment of potential for adverse consequences on stream and reservoir water quality lacked consideration of long-term cumulative contaminant loads, including emergence of contaminated shallow and deep groundwater post-closure. It is not sufficient to assume, as the Environmental Impact Statement (EIS) does, that the current lack of evidence of water quality consequences will continue long term.’*

4.2 Sydney city infrastructure case study

4.2.1 Site description

Sydney has a population of over five million people resulting in a heavy concentration of road and railway infrastructure that has evolved over time. Initial transport was provided by road with Sydney's railway initially constructed in 1854. Progressive extension to the railway network has resulted in the current suburban rail servicing 175 stations. More recent developments include the

Sydney Metro, which is a driverless rapid transit system (RTS) separate from the suburban commuter network. It commenced operation in May 2019. There are currently 13 Sydney Metro stations, with plans in place to extend the network into the city and southwest in 2024, greater west and new airport in 2026, and through the inner west to Parramatta in 2030. Many of the developments are underground and require assessment of impacts to groundwater.

Groundwater resources beneath Sydney are typically hosted within the Hawkesbury Sandstone. The aquifer is characterised by very low productivity, poor water quality including increased acidity (e.g. pH < 5) and in places increased salinity. As a result, there are very few active bores within the Sydney area. Small springs naturally discharge from the sandstone in areas adjacent to the Harbour (e.g. Iron Cove, Cave Bay). The case study focusses on the recent roading and railway infrastructure developments that have been undertaken in Rozelle, located in the inner west of Sydney.

4.2.2 Projects and activities

Many of the projects for road and railway infrastructure will require dewatering and therefore need to assess the impact on groundwater, including the cumulative impact with other projects and activities (Table 4). Infrastructure includes the Rozelle roading interchange, the WestConnex M4/M5 roading link, The Bays metro station, and the Western Harbour Railway Tunnel, which are more or less being constructed simultaneously. The local area is adjacent to Sydney Harbour and several previous industrial sites with potentially contaminated land and/or groundwater.

- WestConnex M4/M5 includes the construction of the M5 Link Main Tunnel motorway. Once completed, the roading project will link the WestConnex M4 East and the WestConnex New M5 motorways. The project involves construction of northbound and southbound carriageways and new exit/entry ramps and includes provision for a future connection to the future Rozelle Interchange. The mainline carriageways will be constructed entirely underground as drained excavations below the existing groundwater table, with tunnel invert levels ranging from approximately 15 to 45 m below the existing land surface. The new ramps will also be constructed predominantly underground and below the existing groundwater table, except for short sections where the ramps emerge at the ground surface and connect with the existing traffic network.
- Rozelle Interchange and Iron Cove Link is a new underground motorway interchange which will provide connectivity to City West Link and the new M4 and new M5 (known as the M8) tunnels, bypassing Victoria Road between the Iron Cove Bridge and the Anzac Bridge. The tunnel from Iron Cove Bridge to Anzac Bridge is scheduled for December 2023. The interchange in Rozelle will be mostly underground and located at the site of the old Rozelle Rail Yards. A construction zone of up to 10 m will exist around the main line tunnels to allow for services, rock anchors, and other tunnel support facilities.
- The WestConnex Project is being constructed over sites that have had previous minor filling for housing and light commercial buildings and significant controlled filling for the construction of large commercial/industrial units, infrastructure projects and reclaimed land (bay areas). Landfills developed within former shale quarries (brick pits), include Alexandria Landfill, Sydney Park, Camdenville Park, O'dea Reserve and Algie Park. The landfills have been backfilled with varying waste materials, including putrescible and industrial wastes, and were not lined at the time of landfilling.

Table 4: Summary of Major Projects, activities, and potential impacts on groundwater resources related to Sydney infrastructure development

Projects	Activities	Impacts
Roading infrastructure: Rozelle interchange roading (Lilyfield); WestConnex M4-M5 link (major underground tunnel, 8 lanes) **Railway infrastructure:** Western Harbour Tunnel: The Bays station (new metro line) underground tunnel	Underground railway tunnelling Underground roading Historic industrial sites Sydney Harbour, groundwater, springs	**Land:** subsidence on reclaimed land (urban and non-urban), asset damage **Water Quantity:** Loss of spring flow, subsidence **Water Quality:** Seawater intrusion contaminated site (tanneries, chrome, metals, ship building, anti-fouling, coal power station); surface water impacts

4.2.3 Assessment of cumulative impacts on groundwater

Key issues associated with successive development of road and railway infrastructure in Sydney include the following:

- Often impacts on groundwater are considered at the time of each development, without the ability to understand the successive developments that will potentially be completed. For example, a numerical groundwater model was first developed for the Rozelle Interchange-M4/M5 Link at a stage in which there was no proposal for metro stations or tunnels within the local area (Figure 11). Later, Sydney West Metro tunnels and stations were proposed. This has resulted in the following:
  - tunnels not assessed for drawdown
  - stations assessed in isolation
  - cumulative impacts of nearby urban developments (e.g. Tower buildings) not considered
  - cumulative impacts with Rozelle Interchange-M4/M5 link project not modelled.
- There are a range of impacts from infrastructure development in Sydney such as potential subsidence, dewatering, diversion of groundwater flow direction, depressurisation, saline intrusion, and groundwater quality impacts. It is often difficult for a proponent to suitably address all the potential impacts of the proposed activity. Some assessments (e.g. on tower developments, basement carparking) may be relatively straightforward and are undertaken suitably. On the other hand, predicting the impacts from saline intrusion, mobilisation of contaminated sites, and long-term diversions are often more difficult and at times overlooked.

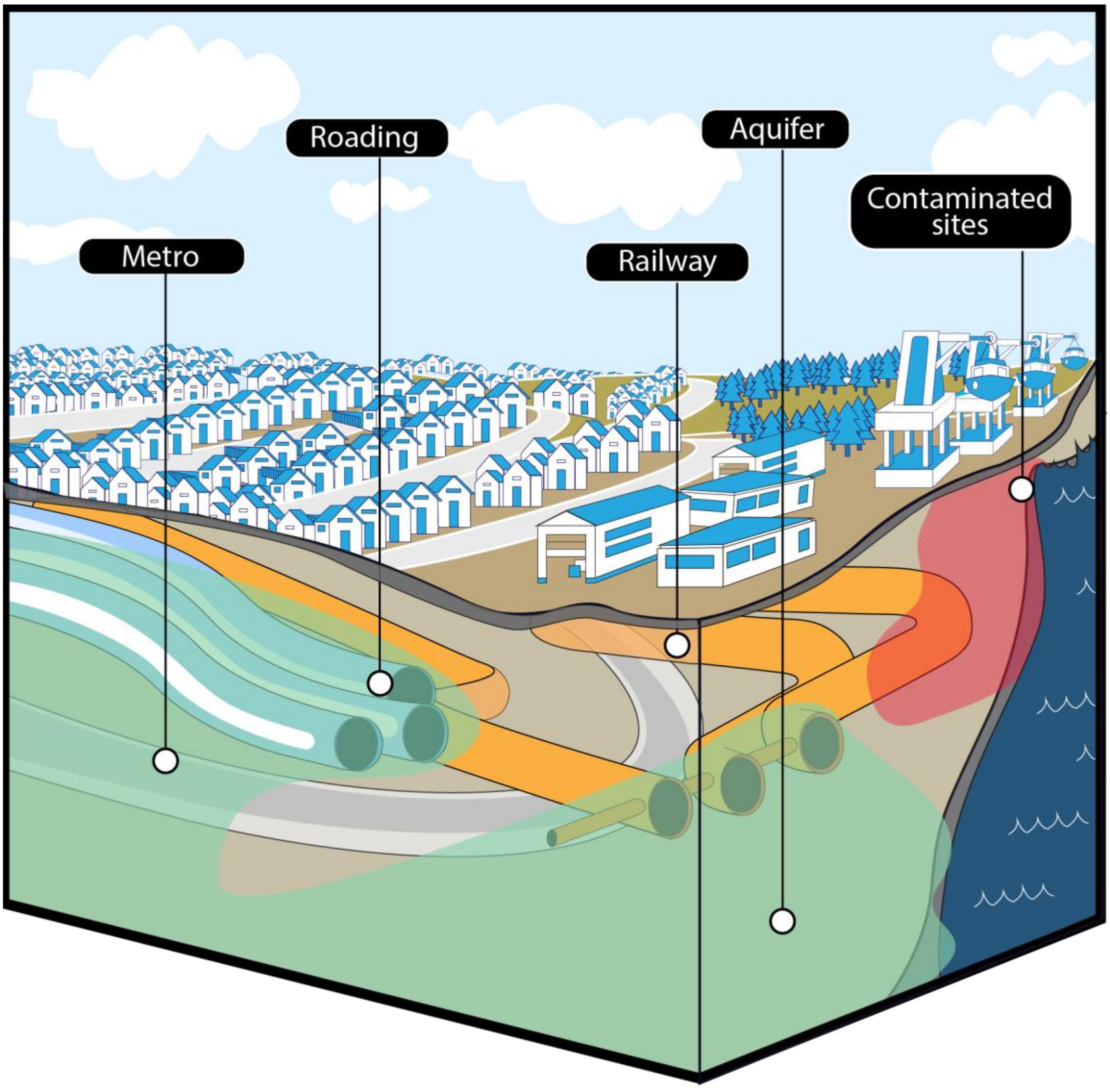

Figure 11: Schematic of the Sydney City roading and rail infrastructure (Rozelle Interchange-M4/M5 Link)

- Models used for one project are not necessarily available for the next project. This can be due to:
  - Changes in the proponent and/or consultant staff
  - Changes in the proponent consultancy company
  - Selection of different groundwater modelling software to achieve the specific model objectives
  - Upgrade of modelling software between projects.

The above considerations highlight the difficulties in groundwater modelling for successive infrastructure development. Other aspects that have not been addressed appropriately can be controlled by the proponents and/or consultant. Examples include selection of an inappropriate groundwater modelling package (e.g. SEEP/W) which does not have the ability to consider cumulative impact potential on groundwater from a wider (e.g. regional) area.

4.3 Narrabri region case study

4.3.1 Site description

The Gunnedah Basin is a structural trough located in northeast NSW that extends 1,700 km from central Queensland to the eastern coast. The basin geology is characterised by up to 1,200 m thick sequence of marine and non-marine Permian and Triassic sediments (Figure 7), underlain by basement (Australian Government, 2020). The basin is bounded by the Lachlan Fold Belt to the west, New England Fault Belt to the east, and is continuous with the Bowen basin to the north.

The Namoi subregion comprises two major aquifer systems – the Namoi Alluvial aquifer (Upper and Lower Namoi) and the Pilliga Sandstone aquifer. The most widely used aquifer in the Namoi subregion is the Namoi alluvium which contains significant resources of high-quality groundwater. Groundwater is heavily utilised for irrigation, town water supply, stock, and domestic use. The Pilliga Sandstone is part of the Surat Basin and is a major regional aquifer. Minor groundwater resources occur in the Gunnedah Basin. However, they are rarely utilised for stock and domestic purposes, only where the alluvium is absent. There are considerable coal resources within the Gunnedah Basin, in particular within the locality of Narrabri.

4.3.2 Projects and activities

There are several activities that rely on consumptive use of groundwater and/or may have a cumulative impact on water resources within the Gunnedah Basin. Both underground and open cut coal mines in the region are at different stages of development, including exploration, construction, extraction, and closure (Table 5, Figure 12). Each of these coal mines will have impacts on the quality and quantity of water resources, including both direct impacts and cumulative impacts. The main operational open cut coal mines include Boggabri, Tarrawonga, and Maules Creek with Narrabri (North and South) being the predominant underground coal mines. These mines generally access the Maules Creek, Mullaley, Black Jack, and Bohena coal seams. The project boundaries of Boggabri Mine and expansion, Maules Creek Mine, and Tarrawonga Mine and expansion are located within 10 – 15 km of each other, and within the Maules creek sub-basin.

Other land use in the Narrabri region includes agriculture, infrastructure, state forest (e.g. Pillaga) and towns (Table 6, Figure 13). These activities rely on local surface water and groundwater resources. Further, the Narrabri CSG Project proposes to target coal seams that are generally located at depths of 800 – 1,200 m and was approved by the Independent Planning Commission in 2020. The project proposed progressive development of a CSG field over 20 years, with up to 850 gas wells and ancillary infrastructure (e.g. gas processing and water treatment facilities). The proposed project covers an area of 95,000 ha and extends 10 – 50 km south and southwest of Narrabri, incorporating areas of the Pilliga Forest. Overlying aquifer systems include the Surat Basin and Namoi Alluvium. The Narrabri gas field is on the edge of the eastern recharge zone to the Great Artesian Basin and includes the project boundary of the Narrabri Coal mine (Table 6).

Table 5: Summary of coal mining activities in Narrabri region in the Gunnedah Basin

Mine	Description
Boggabri	Operational since 2006, open-cut coal mine located c. 17 km NE of Boggabri.
Tarrawonga	Operational since 2006, open-cut coal mine located c. 16 km NE of Boggabri.
Maules Creek	Operational since 2015. An open-cut coal mine, located c. 45 km SE of Narrabri (c. 12 km NE of Boggabri).
Vickery and Vickery Extension	Operational (and proposed) open-cut coal mine, located c. 25 km N of Gunnedah.
Gunnedah Colliery	Underground and open-cut mine, commenced operations in 1895 and put under Care and Maintenance (2000).
Sunnyside	Open-cut coal mine located 15 km W of Gunnedah. Operational from 2008 – 2012, then placed in Care and Maintenance until mining of the remaining coal resumed in 2017. The mine will be rehabilitated following completion of mining.
Rocglen	In closure/rehabilitation, former open-cut coal mine operational from 2008 – 2019. Located 28 km N of Gunnedah.
Werris Creek	Operational since 2005, open-cut coal mine located 4 km S of Werris Creek. The mine overlays and interests the former Werris Creek Colliery which was an underground bord-and-pillar coal mine from 1925 – 1963.
Narrabri (North and South)	Operational since 2012, underground coal mine located 20 – 30 km SE of Narrabri (70 km NW of Gunnedah). Has previously included bord-and-pillar methods with recent focus on longwall mining.
Brickworks Paddock	Closed. Former open cut coal mine, commenced operations in 1996 and accepted coal washery rejects disposal (2001 –).
Curlewis Colliery	Closed. Former underground mine, commenced in 1890 and placed into care and maintenance in 1998.
Narrabri Gas Project	Proposed Coal Seam Gas project, located within Mullaley (Bohena Trough) basin, targeting Black Jack Group and Maules Creek Group coal seams.

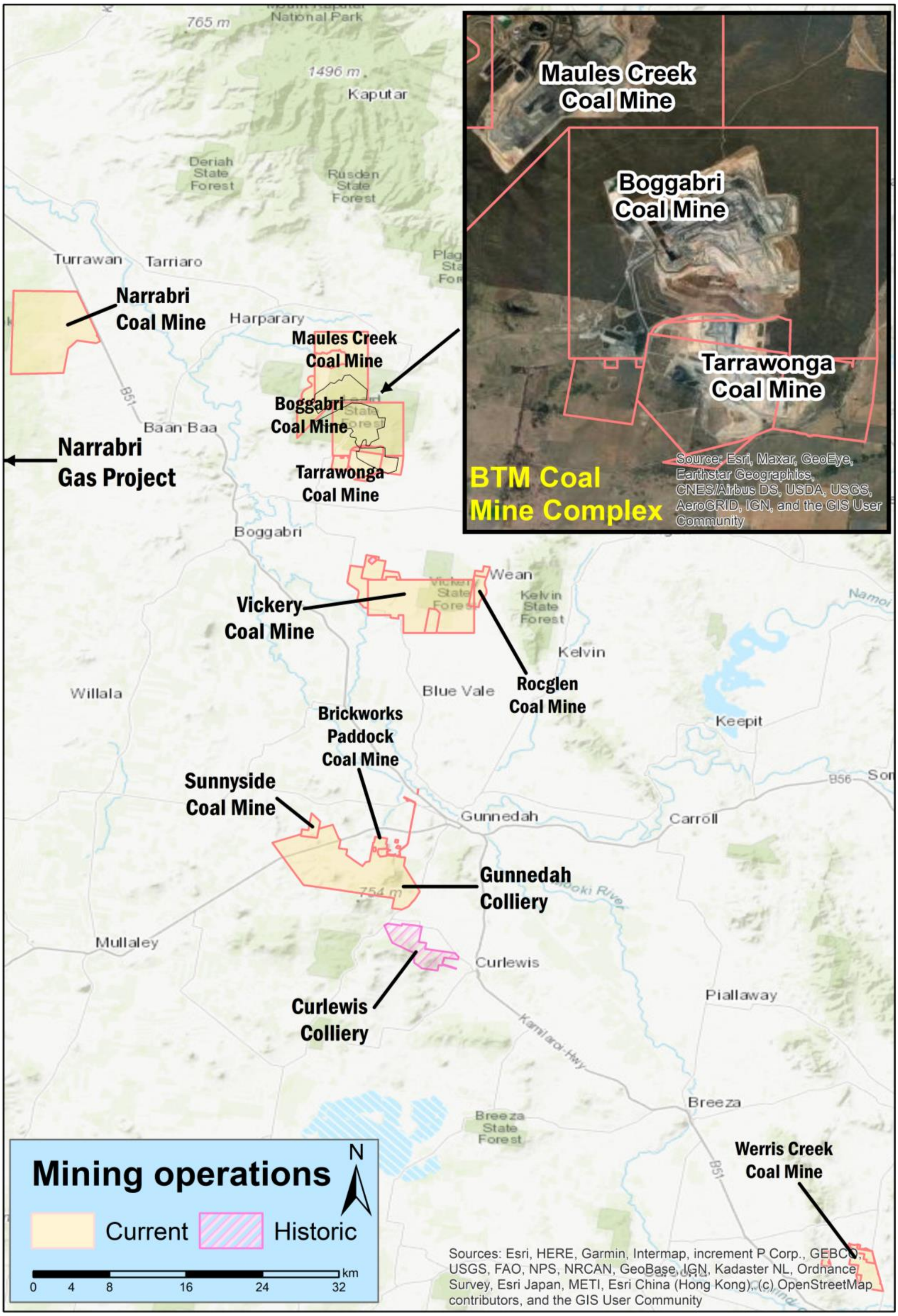

Figure 12: Location of coal projects in the Narrabri region in the in the Gunnedah Basin

Table 6: Summary of projects, activities, and impacts in the Gunnedah Basin

Projects	Activities	Impacts
Coal Seam Gas: Narrabri (1 km BGL) **Coal mining:** underground, opencut, operational and closing **Infrastructure:** Inland Rail – Narromine to Narrabri (SSI), Leewood existing infrastructure, Bibblewindi existing infrastructure	**Agriculture:** farm dams, groundwater for irrigation, private groundwater users Pilliga forest Drinking water supply GDEs	Namoi alluvium (GDE) Groundwater depressurisation (Great Artesian Basin), groundwater drawdown, potential subsidence impacts on the environment, including ground and surface water management Salt waste disposal, potential contamination of groundwater and surface water

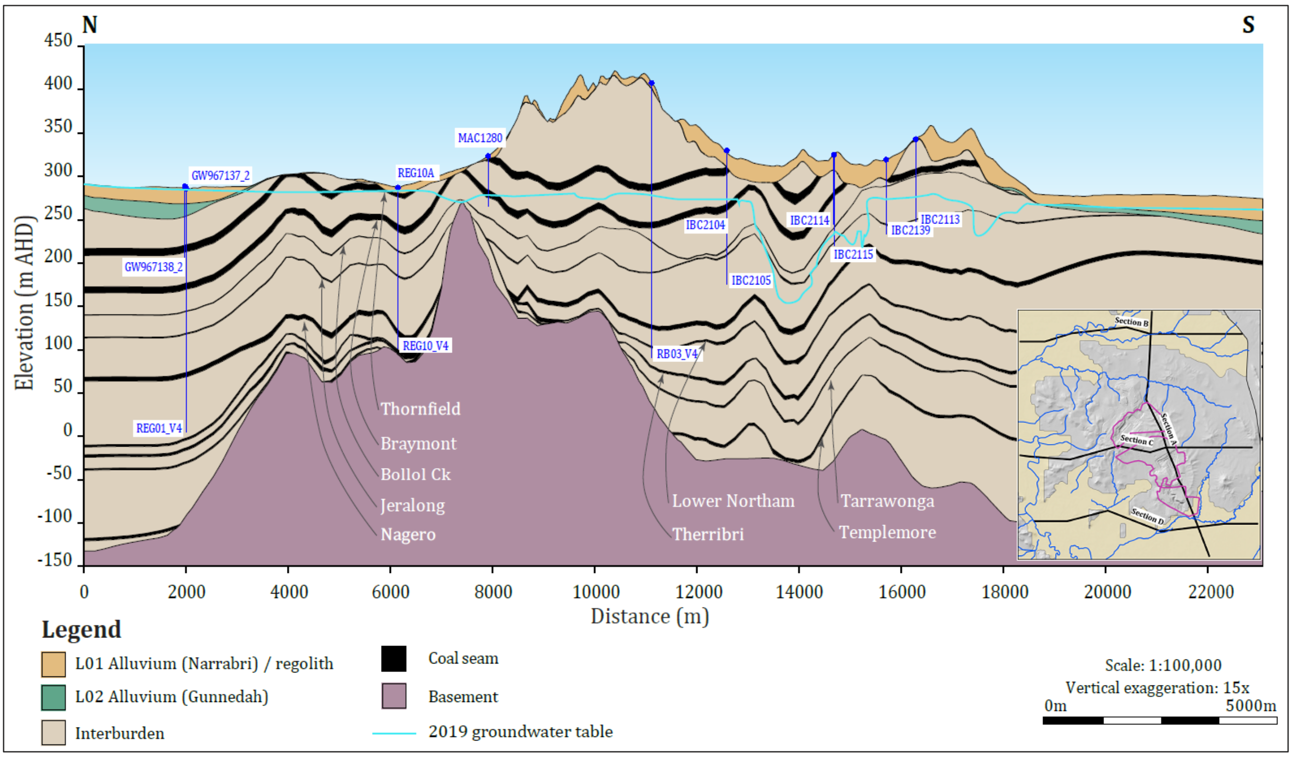

Figure 13: North-south cross-sectional through the Boggabri Tarrawonga Maules Creek (BTM) mining complex in the Narrabri region (sourced from AGE, 2020)

4.3.3 Assessment of cumulative impacts on groundwater

The Boggabri, Tarrawonga, Maules Creek (BTM) mining complex (BTM Complex) comprises three adjacent open cut coal mines located in the Gunnedah Basin located approximately 15 km northeast of Boggabri in north-western NSW (Figure 12). Mines within the BTM Complex are operated independently, with several companies involved in the overall ownership of each mine. The BTM Complex is located within and around the Leard State Forest. Coal from these mines is extracted from the seams of the Maules Creek Formation. The major groundwater aquifers within the Maules Creek Formation are the coal seams such as the Merriown Seam. The Maules Creek Formation aquifers are confined to semi-confined, bounded below by fresh volcanic bedrock and above by low permeability sandstones and conglomerates. Groundwater flow within the Maules

Creek coal seams is controlled primarily by lateral flow within the seams. The slopes and upland areas of the BTM Complex are drained by a series of ephemeral streams rising in the Willowtree Range, including Maules Creek, Back Creek, Nagero Creek, Goonbri Creek, and Bollol Creek (Whitehaven Coal and Idemitsu Boggabri Coal, 2019).

Groundwater impacts from the BTM Complex mines do not interfere with those from the Vickery mine to the south and the Narrabri Coal Mine to the west due to large separating distances between these operations and the BTM Complex, more than 12 km and more than 20 km, respectively. In addition, analytical and numerical groundwater modelling assessments do not suggest overlapping of impacts between the BTM Complex and the operations to the south and west. Hence, there is no need to include impacts from the Vickery and Narrabri mines in BTM Complex assessments, and vice versa.

Due to the close proximity of the mines and associated cumulative impacts on water resources, a BTM Complex Water Management Strategy (BTM-WMS) has been developed. The BTM-WMS has been developed to satisfy each mine's project approval conditions, which require the preparation of a suite of environmental strategies developed in partnership by all three mines of the BTM Complex. Overall, the BTM-WMS allows for collective monitoring and management of cumulative impacts from mining operations on surface water and groundwater. The BTM-WMS provides details of the water resources, potential cumulative impacts on the water resources, and cumulative water management protocols within the BTM Complex. In addition, the BTM Complex mines contribute to the Leard Forest Mining Precinct Water Management Strategy.

Conditions of approval mining operations in the BTM Complex require that the impacts to groundwater predicted by numerical models are verified against observed datasets every three years. These models are also required to be reviewed independently. The current numerical model domain includes alluvial management zones to the north, west and south of the complex, with the eastern boundary is defined by the Mooki Thrust System. Continued validation and re-running of the numerical model is required to allow for actual environmental impacts to be compared to those predicted during the initial modelling and approval phase. Model predictions will change over time as additional data is collected and the model is improved, which will likely result in some change in model predictions. Ultimately, the key outcome of the modelling is to determine the environmental impacts and to address any impacts through mining management.

The most recent model for the area has been developed combinedly for the three mining operations. It is being used to meet the COA for each of the individual mines, including provision relating to data exchange and coordination of models as required in the Leard Forest Mining Precinct Water Management Strategy. This is a good example of beneficial collaboration between Major Projects proponents. It resolves previous difficulties relating to inconsistencies between models, assessment and apportionment of effects, compliance dates.

4.4 Common shortcomings in evaluating cumulative hydrogeological Impacts

Based on the above discussion, a summary of common deficiencies and shortcomings in hydrogeological cumulative impact assessments has been collated. These shortcomings can be grouped into three main areas, broadly related to: (1) quality and diligence of the cumulative impact assessment, (2) data availability and limitations, and (3) temporal variability of impacts. Further, a number of factors contribute to the varying quality of cumulative impact assessment presented by the proponents. This includes the diligence level of the proponents' consultants, their experience, and expectations of the assessment.

- **Quality and diligence of cumulative impact assessment;**
    - The spatial extent for cumulative impacts analysis is not always easy to define. Selection of appropriate spatial scale for cumulative impact assessment (vertical and horizontal) can often be difficult to select and may vary considerably between adjacent and/or overlapping Major Projects. Often the impacts of an activity go beyond a project boundary, but it is difficult for the proponent to identify the appropriate extent for the assessment.
    - The proponent may make unsubstantiated assumptions about the lack of cumulative impacts and the necessary analysis is excluded from consideration.
    - The proponent may select inappropriate modelling software or make errors in the model development (e.g. extent, cell size, layers, boundary conditions). Other examples include making assumptions that past projects within a model domain (e.g. historical mine workings, contaminated sites) have a negligible impact on groundwater. This also relates to spatial and temporal variability.
    - The interpretation of modelling results may not be undertaken satisfactorily (e.g. inappropriate or insufficient uncertainty analyses).
    - There is currently no standardised method or procedure that a proponent can use that defines how cumulative impacts should be characterised. Therefore, the cumulative impact analysis is often highly variability between Major Projects, including diligence level, spatial extent, temporal extent, and data inputs.
- **Often data availability and data quality limitations negatively impact on cumulative impact assessments; and,**
    - Restricted data availability may lead to an inability to assess an aspect of the impacts and/or an adjacent project. Examples include:
        - The location of private bores is generally known, but often there is little or no data on hydraulic properties and aquifer conditions (e.g. pumping duration, pumping volume, static water level, bore capacity). In particular, there is a lack of information when BLR are exercised as their volumes of take are often unknown.
        - Adjacent mines may be owned by same or different companies, with some information publicly available and other information proprietary.
        - Groundwater models for adjacent infrastructure may be developed by the same consulting company, but restrictions on data sharing may prevent the groundwater model from including information from adjacent projects. In addition, it is not uncommon for models for adjacent mines to be developed by different teams within the same consulting company with limited or no exchange of information between the modelling teams.
    - The impact of seasonal and annual changes in weather patterns and/or consideration of longer-term climate change can be difficult to implement into modelling of cumulative impacts. Use of modelled climate change predictions may allow for longer term trends to be incorporated into cumulative impacts assessment. Incorporation of extreme weather events (e.g. drought, flood) is more difficult to predict in cumulative impacts modelling.
- **Incorporation of temporal variability into cumulative impact assessment can be difficult;**
    - The impact of a particular activity on water resources changes over the lifespan of the project. The actual impact is difficult to predict and may require monitoring. For example:
        - In open cut mining projects, the cumulative impact of dewatering during operation will be different compared to the cumulative impact of mine closure

and rehabilitation. Monitoring data may need to be collected in the future (e.g. for prediction of cumulative impact assessment purposes). It is difficult to predict the impact of depressurisation on water quality. Potential for significant localised ecological and visual impacts at points of groundwater emergence following re-pressurisation, should the mine be sealed.

    - Cumulative impacts on groundwater and surface water quality may take some time to be detected (e.g. years), by which time it is difficult to attribute the change to a specific activity if there are multiple, catchment-wide projects.
    - Unknown impacts can be managed through adaptive management, make good measures, and putting burden of proof on the proponent rather than the affected parties. For example, the proponent could be required to compensate bore owners (e.g. if groundwater level decreases in a bore beyond the allowable maximum) until the proponent can demonstrate that the impact was not caused by their activity.

  - Timing of the proponent's project in relation to existing and future projects that will each contribute to cumulative impacts, particularly when developed simultaneously. For example, Sydney City infrastructure development (underground roads, railways, and metro) was constructed simultaneously with little or no consideration of other proposed underground projects.
  - Lack of attribution of responsibility for a particular impact often occurs, particularly in areas where there are multiple activities (e.g. Sections 4.1 – 4.3). In these situations, it is difficult to attribute which activity has caused the impact or what proportion of impact is from which activity. Therefore, there is lack of clarity in who is responsible for remediation and/or make good measures. Further, management plans are often non-committal so those parties that likely caused the impact may not actually contribute to the make good or remediation.

Overall, these difficulties are largely alleviated when resource management agencies and proponents work together early in project development to apply and require guidelines for the water resource study and cumulative impact analysis such as the situation with the BTM Complex (Section 4.3). The model assessment checklists presented in the department’s Water division’s minimum groundwater modelling requirements (Stantec, 2021a) outline Major Projects cumulative impact assessment requirements in NSW.

5 International approaches

The basis for assessing cumulative impacts is well established in regulatory requirements internationally within individual countries, governing bodies representing multiple countries (e.g. the European Union), or advisory bodies providing international guidelines (e.g. the International Atomic Energy Agency and the United Nations). Although each regulation refers to cumulative impacts in different ways, the intent is similar: to assess impacts, effects, or risks on a sufficiently large scale to protect the water resource, rather than simply a local scale for an individual project.

5.1 Canada

In Canada, Impact Assessments are required under the Impact Assessment Act (Status of Canada (S.C). 2019, chapter 28, section 1) in areas of federal jurisdiction. Guidelines for the Act state decisions are based on whether the potential adverse effects in areas of federal jurisdiction are in the public interest (IAAC, 2019). Factors to consider in the Impact Assessment include:

> *'any cumulative effects that are likely to result from the designated project in combination with other physical activities that have been or will be carried out; and the result of any interaction between those effects.' A Cumulative Effects Assessment 'must identify and assess the designated project's cumulative effects using the approach described in the Agency's guidance documents related to cumulative environmental, health, social and economic effects… Cumulative effects are defined as changes to the environment, health, social and economic conditions as a result of the project's residual environmental, health, social and economic effects combined with the existence of other past, present and reasonably foreseeable physical activities, as well as within activities of the project itself from multiple emissions and discharges (e.g. simultaneous operations) to understand synergistic or additive effects.'*

For actions outside of federal jurisdiction in Canada, cumulative impacts are also required in several states. For example, guidelines for hydrogeological assessments related to permit applications in Ontario (Cuddy et al., 2013) require the assessment to consider impact to existing groundwater uses and potential interference from other groundwater users which may result in unacceptable interference (Ontario, 2021).

5.2 South Africa

Guidelines for the Environmental Impact Assessment process in South Africa (Saayman, 2005) state:

> *'Groundwater is particularly susceptible to the cumulative effect of numerous small impacts. Due regard must be given to this during the assessment, and should be thoroughly considered in a designated section of the specialist report… Specialists need to trace likely cause-effect pathways to determine all potentially significant direct, indirect and cumulative impacts… The determination of impact significance needs to consider the predicted impact of the proposed development in light of the vision for the area, including its water resources, rather than in terms of the impact on the current baseline conditions.'*

Further, the National Water Act of 1998 recognises the need for integrated management of all aspects of water resources to a regional or catchment level and the catchment management strategies must be in harmony with the national water resource strategy to enable everyone equal access to water.

5.3 United States

Multiple regulations require inclusion of cumulative impacts in the United States including the Surface Mining Control and Reclamation Act (SMCRA, 2012; 30 U.S.C. §§1201-1211, 1231-1251, 1252-1328) and the National Environmental Policy Act (US-EPA, 1970; 40 CFR § 1500 to 1518 (2020)). The SMCRA requires coal mining and reclamation activities be conducted in a manner that minimises disturbance to the existing hydrological balance and prevents long-term adverse impacts to areas both on and off the permitted site (30 CFR § 780.21(h)). Regulations also require the mining operation be designed in a way that will prevent material damage to the hydrological balance outside the permit area (30 CFR § 780.21(h)). A cumulative hydrological impact assessment is a consideration of how effects on surface and groundwater by a proposed mining operation might combine with similar effects from any existing operation within a specified cumulative impact area. A cumulative hydrological impact assessment examines how the hydrological effects of the proposed operation might add to those effects from other operations. The cumulative hydrological impact assessment is necessary to assure that such aggregate impacts will not be overlooked in the routine processing of individual permit applications (Basuki, 2007).

Requirements in SMCRA are general performance-type standards in that they identify hydrological objectives but do not prescribe exact methodologies for their accomplishment. As such, regional authorities have ample flexibility to set forth the combination of specifications, verifications, and controls needed to produce a technically-sound hydrological impact analysis and, ultimately, supportable permitting decisions. In some cases, a coal mining operation may be proposed in an area where the effects of mining will overlap those of non-SMCRA regulated activities (Office of Surface Mining, 2002). For example, logging, coal-bed methane extraction, in-situ mining, municipal or other large water users, impoundments, impacts from urban lands, surface water diversions, and agricultural activities may have significant hydrological impacts on surface and groundwater projecting the effects and relative contribution of these activities (Lumb, 1982; Office of Surface Mining, 2002). Therefore, when evaluating the hydrological impacts of the proposed operation it may be necessary to collect information to evaluate the effect of these non-SMCRA activities while characterising the ambient hydrological condition and projecting the effects and relative contribution of these activities (Office of Surface Mining, 2002).

The current rule for NEPA states:

> *'The environmental impact statement shall succinctly describe the environment of the area(s) to be affected… including the reasonably foreseeable environmental trends and planned actions in the area(s). Data and analyses… shall be commensurate with the importance of the impact (40 CFR § 1502.15 (2020))'.*

The rule defines effects or impacts as:

> *'changes to the human environment from the proposed action or alternatives that are reasonably foreseeable and have a reasonably close causal relationship to the proposed action or alternatives, including those effects that occur at the same time and place as the proposed action or alternatives and may include effects that are later in time or farther removed in distance from the proposed action or alternatives (40 CFR § 1508.1 (2020)).'*

The current rule includes a definition of cumulative impacts that encompass all effects that are reasonably foreseeable and have a reasonably close causal relationship to the proposed action or alternatives. This may include non-Federal activities that are reasonably foreseeable. Further, the rule emphasises agencies should focus their efforts on analysing effects that are most likely to be potentially significant. The recent revisions to the rule were partially based on the challenges associated with establishing the spatial and temporal boundaries to define cumulative effects. If boundaries were too broad, the analysis became speculative and unwieldy; if boundaries were too narrow, important issues may have been overlooked (Keifer and Effenberger, 1997).

5.4 European Union and member countries

The European Union (EU) developed the Water Framework Directive (WFD; 2000/60/EC) to establish a common strategy in the field of water policy. Among other actions, guidance documents provide recommendations and technical guidance regarding the policy. The EU guidance document on risk assessments and the use of conceptual models for groundwater (European Communities, 2010) states:

> *'The main focus of this document is to describe a coherent approach on how to assess risks caused by different pressures (such as diffuse and point source pollution with respect to groundwater quality and abstraction with respect to groundwater quantity) at different scales ranging from site scale (local) up [to] the scale of a groundwater body'*

where local scale may include impacts on individual dependent surface waters or terrestrial ecosystems to groundwater body scale which could include the available resource balanced against the recharge and abstraction. Like regulations regarding cumulative impact assessments in other countries, the guidance states:

> *'A key part of the risk assessment will be consideration of not only the impact of past and current land use activities but what are also the likely future land uses that may have an impact on the predicted trends. Planned measures will need to be factored into the assessment.'*

A similar guideline based on the WFD was based on the need to evaluate and develop solutions to mine water management problems specifically at the catchment scale and towards more integrated, targeted, and prioritised approaches to management of water quantity and quality at the catchment scale (Younger and Sapsford, 2004).

Within member states of the EU, various regulations and guidance further refine the WFD. In Finland, guidelines regarding mine water management state:

> *'regional impacts and interactions regarding surface and groundwater systems between adjacent mines and other local activities should be studied' (Punkkinen et al., 2016).*

The Finnish Act on Environmental Impact Assessment Procedure (Finnish and Swedish Ministry of the Environment, 1994) requires the environmental impact assessment include

> *'cumulative impacts of different projects.'*

Similarly, a guide on the Environmental Impact Assessment Procedure states:

> *'The assessment should also define the cumulative impacts of the project together with those of other relevant existing or planned projects… The European Union Court of Justice has also ruled that assessments of cumulative impacts are also required under the EIA[2] directive… Cumulative impacts [are] impacts that arise when the planned project and other past, present or reasonably foreseeable projects together result in incremental changes that combine to generate various kinds of cumulative impacts' (Jantunen et al., 2015).*

Cumulative impacts must also be considered for Environmental Impact Statements in Ireland where cumulative is defined as

[2] EIA: Environmental Impact Assessment.

> *'The addition of many small impacts to create one larger, more significant impact' (Institute of Geologists of Ireland, 2013).*

Although the United Kingdom withdrew from the EU, current regulations remain based on the WFD. In England, guidance on how to assess the hydrogeological impact of groundwater abstractions in connection with dewatering operations at quarries, mines, and engineering works includes a 14-step methodology for hydrogeological impact appraisals. The guidance states:

> *'It is the Environment Agency's role to assess the cumulative impacts of all abstractions in a certain groundwater management unit or groundwater body' (Boak et al., 2007). The methodology states 'It is important not to consider the abstraction in isolation, but to consider possible cumulative effects of all the abstractions that are in hydraulic continuity with the site'*

to assess the significance of the effect from a particular abstraction.

5.5 Advisory groups

A United Nations (UN) Convention on the Protection and Use of Transboundary Watercourses and International Lakes addressed measures to prevent, control, and reduce impact to transboundary waters. Given surface and groundwater are not bound by political boundaries between various countries, impacts to transboundary waters inherently must consider impacts beyond individual projects. A guidance document developed following the convention provides the following definition for transboundary impact:

> *'Any significant adverse effect on the environment resulting from a change in the conditions of transboundary groundwaters caused by a human activity, the physical origin of which is situated wholly or in part within an area under the jurisdiction of a Party, within an area under the jurisdiction of another Party' (UN/ECE, 2000).*

This demonstrates the need to understand impacts across political boundaries because the impact from one country may influence the water within another country. The guidance document provides recommendations regarding strategies for monitoring and assessment. The guidelines note monitoring should be completed

> *'to detect and quantify the superimposed impacts of human activities.'*

The guidelines also discuss the need to establish baseline information beyond the local scale regarding anthropogenic and natural impacts.

The International Atomic Energy Agency (IAEA) developed a guidebook regarding environmental impact assessments for in situ leach mining projects (IAEA, 2005). The guidebook states:

> *'cumulative impacts from past, current and potential future industrial and agricultural activities also need to be considered along with their potential linkages and interactions among all the predicted impacts' to identify potential environmental impacts. In addition, 'documentation of groundwater use within the area that may be affected by mining, is essential in order to identify competing interests for groundwater allocation'.*

5.6 Summary

While the previous discussion is not exhaustive, the examples presented clearly demonstrate that considering cumulative impacts is well established in regulations and guidance across the world. It is clear a holistic approach to water management must include a cumulative impact assessment.

6 Guidance for modelling, reporting, and validation

This section presents guidance for modelling, reporting, and validation of cumulative impact analysis in NSW.

6.1 Using Models to evaluate cumulative impacts

Numerical models are commonly used to assess cumulative impacts due to factors such as the large area to be simulated; long temporal scale to assess impacts; the presence of multiple aquifers, multiple groundwater users, and GDEs; surface and groundwater interactions; and coalescing data, impacts, and models from multiple projects.

6.1.1 Conceptual model development and review

A conceptual model forms the foundation of any numerical model. This section expands the discussion in Section 3 to the factors to consider when developing conceptual and numerical models that may be used to assess cumulative impacts. Further information and recommendations regarding numerical models are provided in the technical note on minimum groundwater modelling requirements (Stantec, 2021a).

Area of analysis

To cover the different needs for management of groundwater bodies, spatial investigation scales vary from small (10s – 100s m^2) to large (100s – 1,000s km^2). The investigation scale depends on the specific tasks and factors affected by the project (e.g. groundwater quantity, chemical composition, point source pollution, diffuse pollution, interaction with surface waters, land use, etc.). Furthermore, to prepare for cumulative impact analyses, the investigation scale must also be subsequently determined by the areas with which the project impacts are anticipated to intersect with other project impacts. The scale of investigation should be defined during the development of the conceptual model, regardless of whether a numerical model will be developed or not. Baseline data must be collected for the project area and adjacent areas that may be impacted by other projects to adequately assess cumulative impacts. As such, the area over which baseline data are collected is likely to be larger than the area for any one project. Due to the interdependency of surface and groundwater, as well as potentially merging impacts from multiple projects, considerable care should be exercised in defining the area to collect baseline data.

Conceptual models should include land use and potential stress factors, risks, and emissions from agriculture, industry, infrastructure, abstraction and infiltration, heat storage or extraction, mining, waste management activities or other projects that may impact the environment. Where boundaries may be uncertain, it is better to choose the boundaries well beyond the area of interest so that cumulative impacts can be evaluated. These can subsequently be reduced as hydrogeological/physical information allows the zone of potential influence to be delineated more precisely (e.g. as groundwater flow direction or the geological boundaries of an aquifer system are established).

To define the area to collect surface and groundwater baseline data, a primary consideration is the type of project and associated types and degree of impacts to be expected. In this context, the extent of water level drawdown expected by the operation would be a major factor. Impacts from other projects and potential future projects must also be considered. Baseline data should be collected for the areas where this drawdown is expected over the life of the operation or into closure and the overlapping area likely impacted by other projects. This area may be estimated using analytical drawdown calculations. The distance to known or expected recharge or discharge areas is also important as is the identification/location of any boundaries such as outcrops, streams or faults that may affect recharge or discharge. A surface and groundwater use inventory should be conducted within the area of expected drawdown and areas of other impacts.

Another major consideration is the proposed effects of the project on groundwater and surface water chemistry. Estimates should be made of the type and concentration of pollutants expected from the proposed operation and the direction and magnitude of surface and groundwater movement during and after the project. Surface and groundwater chemistry impacts from other projects should also be considered, especially if pollutants from the project may mix with pollutants from other projects. Generally, the area for baseline data collection is likely to be a groundwater basin, surface watershed, or multiple basins and watersheds depending on the location of the project in relation to basin and watershed boundaries and whether impacts from other projects may cross these natural boundaries. To be on the safe side, it is recommended to extend the data search into a suitable buffer around the target area. The size of the buffer zone must be determined considering the potential risks and environmental settings of the project and surrounding projects.

Temporal scale

The temporal scale for a numerical model should consider similar factors as those discussed above for the spatial scale. For many impacts, there may be a delay between initiating an operation and measurable impacts in surface or groundwater. Similarly, following termination of an operation, the recovery of surface and groundwater may also be delayed. The effect of any measures taken to mitigate impacts may also be delayed following implementation. The timing of impacts from nearby projects and future land uses must also be considered when developing a model. In addition to the common lag between activities and effects, measurement precision and the possibility of monitoring at sites positioned at longer flow paths must be considered. For example, there may be unknown preferential flow paths that will result in quicker or slower responses in the hydrological system than initially anticipated.

There is a relationship between temporal and spatial spaces. Generally speaking, larger areas of expected impact and/or larger volumes of surface and groundwater expected to be impacted require longer temporal scales for numerical models, on the order of tens to hundreds of years.

Assessing model approach

The approach for the conceptual model and the numerical model should be developed prior to commencing baseline data collection. The department encourages proponents to submit their approaches for review and to collaborate with the department’s Water division and other agencies to confirm the scope of the required technical study and numerical model. This is consistent with guidance in other countries (Cuddy et al., 2013; European Communities, 2010; Office of Surface Mining, 2002; Saayman, 2005).

The numerical model approach to assess cumulative impacts should include definition of the model area and discretisation as well as the methods to assign model inputs such as boundary conditions and hydraulic properties. Preferably, models in the same region should adopt compatible model designs, boundary conditions, hydraulic properties and impacts from other projects. This requires careful review of existing models in the project’s general region. Where an approach from an existing model is not employed for a subsequent model, the proponent must justify the deviation. The modelling approach includes the model code to be used for the project and model conditions such as whether simulations will be steady-state or transient, and the temporal scale if transient simulations are completed. Methods for calibration should also be described, as well as the uncertainty and sensitivity analysis. Finally, any predictive modelling to be completed should also be described, including predictive uncertainty analysis.

Following initial review of the technical report on the conceptual and numerical model approaches for the project, the proponent is encouraged to meet with the department and other agencies to discuss and agree an appropriate cumulative impact assessment approach. Given the complexity of assessing cumulative impacts from potentially multiple projects in a large area, the meeting will enable collaboration between the proponent and relevant agencies to confirm the area of study, the temporal scale for the modelling, existing models to incorporate, data and methods to assign boundary conditions and hydraulic properties, the planned model code, and further details regarding the numerical modelling. The meeting will enable identification of any weaknesses and opportunities for refinement and improvement early in the project. Further, the relevant agencies could confirm whether proponents are aware of existing, publicly available data that could be used for the project and model development. Following data collection and model completion, data and predicted impacts should be submitted to the department to enable public release of non-proprietary data and predicted impacts to support additional cumulative impact assessments.

Requirements for publication of water resources data and impact predictions will be incorporated into permit conditions for consent. However, availability of peripheral datasets should not diminish the proponents' responsibility to fulfil sufficient spatial and temporal scale data collation both on and off-site (e.g. water census surveys). Any commercial in-confidence data (e.g. thickness of coal seam) should be declared and not be used as an argument to limit making digitally available all other relevant data for water modelling. Comprehensive online data/information around the baseline and ongoing monitoring should be made available on demand to the regulatory agencies as a minimum (if not to the public).

Several studies have demonstrated the significant benefits of assessing cumulative impacts on regional scales, collaboration and data sharing between stakeholders, and integrated decision-support tools and processes such as modelling, monitoring, and adaptive management (Kuells and Wilhelm Bittner, 2013; Scott et al., 2013; Zingelmann et al., 2016).

6.1.2 Open source models

Numerous groundwater modelling codes exist including open-source, publicly available codes and proprietary, which are owned by a company and not open for public use or review. Proprietary codes are not appropriate for use in numerical models used to assess impacts that may affect the public or the environment. While proprietary codes may sufficiently solve groundwater flow problems, the lack of transparency regarding the codes is not acceptable.

If a proponent chooses to use a proprietary code, or an open-source code with undocumented performance, an assessment must be made as to the reliability of the code. Several documents discuss the testing and reliability of modelling codes (e.g. ASTM International, 2008; Kolm and Van Der Heijde, 1996; van der Heijde and Kanzer, 1997). Reporting of code testing should be consistent with these documents and submitted to the department for approval. Preference to use open-source codes or complete code testing is consistent with many international regulations (e.g. Boak et al., 2007; CDWR, 2016; NDEP, 2018; Punkkinen et al., 2016). In addition, final model files should be submitted to the department for detailed review and will be made publicly available to support subsequent cumulative impact assessments. This is also consistent with several international regulations (NDEP, 2018; Ontario, 2021).

6.1.3 Assessing differences between models

Proponents should be aware that, in the event two or more models involve fundamental differences in model development (e.g. definition of boundary conditions) or the predicted impacts for an area, resolution of differences most commonly invokes the 'Precautionary Principle.' In these cases, the worst-case impact would be considered the most likely and all parties would need to accommodate the associated impact mitigation. Ways to avoid the application of this worst-case scenario include:

- Collaboration with the department from the initial scoping process through to final submittals. Given the progression of conceptual models and numerical models is an iterative process, the department can provide input throughout the project and ultimately if models are different, the department can provide recommendations on how to resolve the differences or provide a technical opinion as to which model is more representative. In addition, as stated previously, collaboration with the department will help avoid or resolve fundamental inconsistencies between model processes.

- Submission of data collected for the project to the department to allow its use to be public. Use of shared data and associated conclusions would reduce inconsistencies between nearby cumulative effect analyses by providing a common baseline characterisation from which project impacts would be forecast.
- Collaborative model development. Single large-scale models can be developed for neighbouring projects to maximise data availability and avoid inconsistent assessment of direct and cumulative effects. This arrangement can be reached voluntarily between proponents or be facilitated or required by regulatory agencies. For example, the Leard Forest Mining Precinct Water Management Strategy provides a framework for collaboration between mining operations in terms of data exchange and assessment of effects through modelling (see Section 4.3).

In addition to differences in model development and forecasting of physical conditions, assessments may vary in their interpretation of impacts. For example, impact assessment may be based on criteria utilising mean, median, or 95th percentile characteristics of forecasted conditions. Therefore, impact analyses should examine the approved criteria applied to existing projects during their assessments to evaluate impacts in a comparable context with comparable metrics.

6.2 Reporting and reviews

Careful consideration of licensing requirements, attention to transparent reporting, and cooperative efforts that include the department, stakeholders, and third-party reviewers will benefit the cumulative impact assessment and reduce the likelihood that important factors are overlooked. Key factors and types of disclosures are discussed below.

6.2.1 Licensing requirements

As water is a limited resource shared amongst multiple users, water resource management planning needs to be informed by comprehensive data and evaluation for decision-making. Case-by-case evaluations introduce localised and near-term bias into decision-making that could impede effective planning. Humans and ecological receptors rely on that decision-making to establish sustainable limits for groundwater withdrawals and consumptive use within the resource boundary. These decisions also determine the number and location of rights and licenses required by a project, which in turn influences their availability and cost to acquire.

Further, depending on the results of the impact analyses, holding water take licenses may be required beyond the operating life of a project and into the post-closure period. These post-closure rights may be required for mitigation measures such as surface flow substitution, water treatment, or evaporative losses.

6.2.2 Transparency

Transparent presentation of cumulative impact assessments depends on disclosure and documentation of the conceptualisation, methods, results, and uncertainty analyses. These disclosures take the form of:

- a listing of the impacts of a project along with a quantitative description of the magnitude and duration of those impacts
- a map of the resource boundary showing the project location within the boundary
- a tabulation of past, current, and reasonably foreseeable future actions with those actions tied to a specific location represented on the resource boundary map
- a presentation of the conceptual model for cumulative impacts evaluation along with a description of the environmental context

- a presentation of the information utilised to inform the impacts evaluation
- a listing of the cumulative impacts forecasted along with presentation of the spatio-temporal extents (e.g. mapping of predicted potentiometric surface changes during operations and post-closure, extents of drawdown at one or more discrete time steps and maximum extent of drawdown, recovery curves for groundwater levels or fluxes at critical locations)
- an account of the cumulative impact implications for resource management and legal compliance
- a clear presentation of the level of confidence and uncertainties associated with the analysis, as well as suggestions to reduce uncertainty in future models (e.g. data gathering, additional testing, model validation, etc.)
- a presentation of mitigative measures and controls along with an assessment of their effectiveness in offsetting impacts along with the ownership of the mitigation and the accountability protocol for its implementation
- a presentation of a monitoring plan to verify and update the cumulative impact analysis as needed, including modelling.

6.2.3 Government agency and third-party reviews

Resource management decisions are seldom the purview of a single decision-maker and typically have implications for other resources and their decision-making authorities. Therefore, focal areas for review of cumulative impact analysis include:

- data completeness
- methodological correctness of evaluation tools and models
- validation and benchmarking of forecasts
- multidisciplinary assessment of evaluation conclusions and their implications.

Assessment of methodologies and validation of forecast results should be accomplished via third-party reviews that compare the evaluation to industry standards plus past observations and forecast results for similar resource management scenarios.

Review by State and Commonwealth government agencies – some not necessarily responsible for regulating water resources – along with public review and comment assists in establishing the completeness of the dataset utilised and improves confidence that the implications of the cumulative impacts have been recognised. Academic and professional organisations could also contribute to impact assessment reviews.

6.3 Monitoring and mitigation

Assessment of cumulative impacts begins, in part, with pre-activity baseline characterisation and modelling forecasts, but over time, monitoring supplants forecasting as the preferred tool for assessing impacts. Through that evolution, regular model updates are useful to validate the predictive model results, incorporating new information as it becomes available to provide updated forecasts for decision-makers while reducing the level of model uncertainty and the reliance on precautionary assumptions. Conventional objectives of water resources cumulative impacts monitoring are to:

- support quantification of the overall water balance
- characterise the quantity and quality of groundwater
- characterise stream flows (rates and chemistry)
- provide consistency and continuity in water resources data
- document water resource trends both naturally occurring, and project related.

These objectives and their associated monitoring activities are typically detailed in a Water Monitoring Plan (WMP) which is adopted as a condition of approval. Monitoring results are customarily reported to the regulatory agencies who review the reporting and make the data available to the public (BLM, 1996). The most common types of monitoring data collected for a water resource boundary are:

- meteorological data including precipitation and pan evaporation rates
- volume and rate of groundwater extraction by pumping wells and from void spaces
- groundwater elevations from wells and piezometers
- water chemistry from monitoring and/or pumping wells
- volume and rate of any artificial recharge to groundwater
- volume and rate of surface water diversion for consumptive use
- flow rates for streams, springs, and seeps
- water chemistry for flowing surface water
- size and characteristics of riparian areas around surface water resources.

Monitoring results that exhibit trends toward impacts and/or observe actual impact typically trigger mitigation requirements along with additional, focused monitoring. This is commonly presented in the form of Triger Action Response Plan (TARP). The actual mitigation depends on the use of the affected water resource plus the owners and stakeholders, both human and ecological, of that resource. Conventional forms of mitigation include:

- lease, sale, or trade of ownership rights of affected water resources
- supplementation of water resources at the impacted location
- redevelopment of infrastructure at the impacted location (e.g. deeper pumping wells, spring boxes)
- development of a new water resource (e.g. replacement pumping well, wildlife guzzler, piping from another location)
- water treatment to modify solute concentrations in water chemistry.

The responsibility for monitoring and mitigation of cumulative impacts may be shared between multiple parties or, in instances where cumulative impacts are between a project’s activity and natural conditions, the responsibility may reside with a single operator. Regulatory agencies may compel fulfillment of obligations amongst multiple parties through adoption of constructs such as management, monitoring, and mitigation plans and/or Water Boards for the resource area (e.g. Nevada State Engineer, 2020, 2009). Alternatively, stakeholders can voluntarily assume monitoring and mitigation responsibilities via agreements between parties such as water use arrangements, data sharing agreements, or the formation of water user cooperatives and/or incorporated water districts. Whether on a voluntary or compulsory basis, the responsible entity would rely on the cumulative impact assessment enhanced by regular monitoring-based updates to guide the mitigation activities.

6.4 Apportionment of responsibilities

Project proponents are accountable for management of cumulative impacts including maintaining monitoring programs, performing data-based updates of impact forecasts, and conducting mitigation activities. Consequently, management of the cumulative effects may be incorporated into the terms of operating licences and financial sureties associated with reclamation and restoration of environmental conditions.

Where applicable, voluntary constructs amongst multiple proponents have proven effective to achieve management and economic efficiencies in the conduct and funding of these activities. Water management cooperatives are commonplace in agricultural practice and have established track records in the sustainable management of water resources over extended periods of time. In cases where voluntary accountability is not achieved, regulatory agencies may convene management constructs such as Water Boards that have the duty to maintain monitoring programs, update forecasts, and enact mitigation measures utilising compulsory funding from project proponents. Compulsory management would report to the regulating authority who would assign operational, monitoring, and financial accountabilities to its permittees.

Multiple scenarios may exist with various projects impacting groundwater resources at different times and to different degrees. While it would not be possible to account for all such scenarios within the scope of this information paper, it is critical to the permitting process that apportionment of responsibilities be considered thoughtfully and based on the best available science, data, and predictive modelling as justified by the project's foreseeable impacts. To do so, predictions of cumulative impacts must consider previous impacts on groundwater, whether those impacts are diminishing with time or if the impacts persist at steady state indefinitely. Furthermore, it is expected that proponents of new projects take responsibility for additional predicted impacts beyond a predetermined threshold, as determined by the department during the initial project scoping/planning phase.

7 Recommendations

The department requires that best practices are used during the application of cumulative impact analysis. Based on this standard and the previous sections summarising background information, case studies, and literature review of cumulative impact analysis, key recommendations are provided below. These recommendations should be considered by Major Project proponents during early stages of project planning to improve the prediction capability of the models and reduce the likelihood of permit delays due to incomplete cumulative impact assessments.

- Include cumulative impact analysis as part of the design of a study. It is very difficult to account for retroactively.
- Develop the approach for a conceptual model and a numerical model prior to commencing baseline data collection. Submit approaches for review and collaborate with the department and other agencies to confirm the scope of the required technical study and numerical model. Coordinate a meeting with the department and other agencies to discuss the approach.
- Collaborate with the department from initial scoping through final submittals for the proposed project.
- Define the spatial scope of cumulative impact studies on the extent of potential resource impacts, rather than the boundaries of the project.
- Consider the timing of impacts, as impacts to water resources, especially groundwater, may be delayed compared to operational periods for projects.
- Consider the degree of uncertainty in the hydrogeological system when establishing the area for analysis and determining whether other projects need to be incorporated into the analysis.
- Collaborate on planning with internal and external stakeholders while performing cumulative impact analyses.
- Conduct a qualitative risk assessment during conceptual model development since it can be used to navigate the challenging process of determining the area of analysis.
- Incorporate receptors (e.g. GDEs, BLR bores) into the conceptual model and understand whether impacts from other projects are predicted to intersect these features.
- Communicate and apply regulatory agency standards to resource studies and use open-source models, standard methods, common analyte lists, etc.
- Collaborate by sharing data collection and modelling as this provides decision-makers with alternatives to planning rather than relying on precautionary worst-case scenarios.
- Formulate predictions based on data collection and evidence (e.g. measurements, raw data, collected information, etc.).
- Disclose and document the conceptualisation, methods, results, and sensitivity analyses to ensure a transparent presentation of cumulative impact analyses.
- Create a monitoring plan to update the analysis and predictions as required. Include mitigation in the event impacts are measured.
- Apportion mitigation measure responsibility between multiple operators based on the degree of their respective individual impacts when the cumulative impacts are additive.
- Apportion mitigation measure responsibility between multiple operators equally when the cumulative impacts are non-additive.

8 References

AECOM, 2018. Tahmoor South Project Environmental Impact Statement.

AGE, 2020. Report on Boggabri, Tarrawonga, Maules Creek Complex groundwater model update. Prepared for Boggabri, Tarrawonga, Maules Creek (BTM).

ASTM International, 2008. Standard guide for developing and evaluating groundwater modeling codes (Withdrawn 2017).

Australian Government, 2020. Bioregional Assessment Program [WWW Document]. URL https://www.bioregionalassessments.gov.au/bioregional-assessment-program

Axler, R., Yokom, S., Tikkanen, C., McDonald, M., Runke, H., Wilcox, D., Cady, B., 1998. Restoration of a mine pit lake from aquacultural nutrient enrichment. Restor. Ecol. 6, 1–19.

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A., Boronkay, A., 2012. Australian groundwater modelling guidelines, Waterlines Report Series. Canberra.

Basuki, K., 2007. Hydrologic considerations for permitting and liability release.

Biesaga, C.A., 2019. Setting the strategic direction for the Great Artesian Basin. Oral presentation. NCGRT/IAH Australasian Groundwater Conference 2019.

BLM, 2019. Final Environmental Impact Statement for the Mount Hope Project. U.S. Bureau of Land Management (BLM).

BLM, 1996. Record of Decision and Plan of Operations Approval, Cortez Pipeline Deposit. U.S. Bureau of Land Management (BLM).

Boak, R., Bellis, L., Low, R., Mitchell, R., Hayes, P., McKelvey, P., Neale, S., 2007. Hydrogeological impact appraisal for groundwater abstractions. Science report-SCo40020/SR1.

CDWR, 2016. Best management practices and guidance documents [WWW Document]. URL https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents

CEQ, 1997. Considering cumulative effects under the National Environmental Policy Act. Council on Environmental Quality (CEQ).

Cuddy, S., Chan, G.S., Pos, R., 2013. Hydrogeological assessment submissions, conservation. Authority guidelines for development applications.

Department of Agriculture, 2019. Great Artesian Basin Strategic Management Plan.

Dube, M., Duinker, P., Greig, L., Carver, M., 2013. A framework for assessing cumulative effects in watersheds: an introduction to Canadian case studies.

European Communities, 2010. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance Document No. 26. Guidance on Risk Assessment and the Use of Conceptual Models for Groundwater. Luxembourg.

IAAC, 2019. Tailored impact statement guidelines template for designated projects subject to the Impact Assessment Act and the Nuclear Safety and Control Act. Practitioner’s guide to the Impact Assessment Act.

IAEA, 2005. Guidebook on environmental impact assessment for in situ leach mining projects. International Atomic Energy Agency, Vienna Austria.

IEPMC, 2019a. Independent Expert Panel for Mining in the Catchment Report: Part 1. Review of specific mining activities at the Metropolitan and Dendrobium coal mines. Prepared for the NSW Department of Planning, Industry and Environment.

IEPMC, 2019b. Report of the Independent Expert Panel for Mining in the Catchment: Part 2. Coal mining impacts in the Special Areas of the Greater Sydney Water Catchment.

Institute of Geologists of Ireland, 2013. Guidelines for the preparation of soils, geology and hydrogeology chapters of environmental impact statements.

Jantunen, J., Kauppila, T., Räisänen, M.L., Komulainen, H., Kauppila, P., Kauppinen, T., Törmä, H., Leppänen, M., Tornivaara, A., Pasanen, A., Kemppainen, E., Raunio, A., Marttunen, M., Mustajoki, J., Kauppi, S., Ekholm, P., Huttula, T., Makkonen, H., Loukola-Ruskeeniemi, K., Ministry of Employment and the Economy, F., 2015. Environmental Impact Assessment Procedure for mining projects in Finland, MEE guidelines and other publications.

Keifer, G., Effenberger, F., 1997. Considering cumulative effects under the National Environmental Policy Act, Angewandte Chemie International Edition.

Kolm, K.E., Van Der Heijde, P.K.M., 1996. Conceptualization and characterization of envirochemical systems. IAHS-AISH Publ. 237, 267–275.

Kuells, C.J., Wilhelm Bittner, A.F., 2013. Strategic assessment of water resources for the Erongo Uranium Province.

Lumb, A.M., 1982. Procedures for assessment of cumulative impacts of surface mining on the hydrologic balance. Open File Report 82-334.

McCullough, C., Hunt, D., Evans, L., 2009. Sustainable development of open pit mines: creating beneficial end uses for pit lakes, in: Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustanability. Kentucky.

Milne, P., Grierson, S., 2008. When is enough, enough? Dealing with cumulative effects under the Resource Management Act. Report to Minstry for the Environment (New Zealand).

NDEP, 2018. Listing of accepted codes for groundwater and geochemical modeling at mine sites. Nevada Division of Environmental Protection. Bureau of Mining Regulation and Reclamation.

Nevada State Engineer, 2020. Order of determination of the relative rights in and to all waters of the Diamond Valley hydrographic basin.

Nevada State Engineer, 2009. Diamond Valley water resource management.

NSW Government, 2021. Environmental Planning and Assessment Act 1979 No 203. NSW Government.

NSW Government, 2020. Water Sharing Plan for the NSW Great Artesian Basin Groundwater Sources 2020 under the Water Management Act 2000.

NSW Government, 2014. New South Wales coal industry profile. Volume 1.

NSW Government, 2008. Impacts of underground coal mining on natural features in Southern Coalfield.

NSW Office of Water, 2012. NSW Aquifer Interference Policy.

Office of Surface Mining, 2002. Permitting hydrology. A technical reference document for the determination of probably hydrologic consequences (PHC) and cumulative hydrologic impact assessments (CHIA).

Ontario, 2021. Technical guidance document for hydrogeological studies in support of Category 3 applications [WWW Document]. URL https://www.ontario.ca/page/technical-guidance-document-hydrogeological-studies-support-category-3-applications

Punkkinen, H., Räsänen, L., Mroueh, U.-M., Korkealaakso, J., Luoma, S., Kaipainen, T., Backnäs, S., Turunen, K., Hentinen, K., Pasanen, A., Kauppi, S., Vehviläinen, B., Krogerus, K., 2016. Guidelines for mine water management, VTT Technology.

Saayman, I., 2005. Guideline for involving biodiversity specialists in EIA processes, Republic of

South Africa, Provincial Government of the Western Cape, Department of Environmental Affairs & Development Planning, Cape Town.

Scott, M., Beckers, J., Klebek, M., Environment, A., Development, S.R., 2013. Managing regional cumulative effects on groundwater resources – Case studies. https://doi.org/10.13140/2.1.1009.9846

SIMEC, 2020. Tahmoor Coal Pty Ltd Water Management Plan: Tahmoor North Western Domain Longwalls West 1 and West 2.

SMCRA, 2012. Surface Mining Control and Reclamation Act of 1977 (SMCRA). US.

Stantec, 2021. Minimum groundwater modelling requirements for Major Projects in NSW. Technical note prepared for the Water Division, NSW Department of Planning, Industry and Environment as part of the Groundwater Modelling Toolbox Project.

Stantec, 2021. Groundwater model assessment procedures and evaluation tool (GW-PET). Technical note prepared for the Water Division, NSW Department of Planning, Industry and Environment as part of the Groundwater Modelling Toolbox Project.Unpublished.

Todd, by D.K., 1980. Groundwater hydrology (2nd edn). Wiley, New York.

UN/ECE, 2000. Guidelines on monitoring and assessment of transboundary grounwaters. UN/ECE Task Force on Monitoring and Assessment.

US-EPA, 1970. US-EPA.

USACE, 2016. Cumulative effects evaluation process for nationwide permits. Happy Groundhog Day.

USGS, 2013. Water resources of the Upper Humboldt River Basin. USGS Sci. Investig. Rep.

van der Heijde, P.K.M., Kanzer, D.A., 1997. Ground-water model testing: systematic evaluation and testing of code functionality and performance. Environ. Prot.

Whitehaven Coal, Idemitsu Boggabri Coal, 2019. Boggabri - Tarrawonga - Maules Creek Complex Water Management Strategy.

Younger, P.L., Sapsford, D.J., 2004. Evaluating the potential impact of opencast coal mining on water quality (Groundwater Regulations 1998): An assessment framework for Scotland.

Zingelmann, M., Bittner, A., Winker, F., Muresan, M., Ellerton, J., 2016. Cumulative groundwater impact of mining in the Kalahari Manganese Field and the need for a strategic environmental assessment approach. Min. Meets Water - Conflicts Solut. 43–44.