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Problems with the application of hydrogeological science to regulation of Australian mining projects: Carmichael Mine and Doongmabulla Springs

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ABSTRACT

Understanding and managing impacts from mining on groundwater-dependent ecosystems (GDEs) and other groundwater users requires development of defensible science supported by adequate field data. This usually leads to the creation of predictive models and analysis of the likely impacts of mining and their accompanying uncertainties. The identification, monitoring and management of impacts on GDEs are often a key component of mine approvals, which need to consider and attempt to minimise the risks that negative impacts may arise. Here we examine a case study where approval for a large mining project in Australia (Carmichael Coal Mine) was challenged in court on the basis that it may result in more extensive impacts on a GDE (Doongmabulla Springs) of high ecological and cultural significance than predicted by the proponent. We show that throughout the environmental assessment and approval process, significant data gaps and scientific uncertainties remained unresolved. Evidence shows that the assumed conceptual hydrogeological model for the springs could be incorrect, and that at least one alternative conceptualisation (that the springs are dependent on a deep fault) is consistent with the available field data. Assumptions made about changes to spring flow as a consequence of mine-induced drawdown also appear problematic, with significant implications for the spring-fed wetlands. Despite the large scale of the project, it appears that critical scientific data required to resolve uncertainties and construct robust models of the springs' relationship to the groundwater system were lacking at the time of approval, contributing to uncertainty and conflict. For this reason, we recommend changes to the approval process that would require a higher standard of scientific information to be collected and reviewed, particularly in relation to key environmental assets during the environmental impact assessment process in future projects.

1. Introduction

Globally, water management is one of the most critical environmental sustainability challenges for the mining industry (ERMITE, 2004; Amezaga et al., 2011; Northey et al., 2016), and there is increasing conflict over impacts to water resources from mining in some regions (e.g. Bebbington and Williams, 2008; Bebbington and Bury, 2009; Kemp et al., 2010; Gleick and Heberger, 2014). Recently in Australia, such conflicts have often focussed on groundwater, upon which many regional communities and ecosystems depend (Harrington and Cook, 2014). Aquifers and the springs and streams they support may be impacted by lowering of the water-table to allow open-pit or underground mining, as well as water withdrawal for mineral processing and other on-site requirements. Water contamination issues are also common.

In this context, mining companies, environmental decision makers and water management agencies must assess the likely impacts of proposed mines on groundwater and any connected surface water and ecosystems. Open-pit mining may lead to impacts that are slow to eventuate and subsequently permanent, and therefore investigations need to predict the post-mine closure hydrogeological conditions. Should a project be approved, monitoring and management strategies must be in place to recognise adverse impacts and, most importantly, remediate them if they occur. These requirements remain for prolonged periods after

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mining has ceased, given that the full impacts may take decades to eventuate (Northey et al., 2016). Scientific input, including collection and assessment of field data, development of conceptual hydrogeological models and predictive (e.g., numerical) modelling, is integral to this process.

The available methods for investigating impacts on hydrogeological systems arising from new stresses, such as mining, lead to significant uncertainties in the resulting predictions of future conditions – such as impacts on a particular groundwater-dependent ecosystem (GDE). An area which can introduce conceptual uncertainty in impact assessment models is the representation of subsurface heterogeneity. In particular, faults and other preferential flow pathways may be neglected or highly simplified. However, these types of heterogeneity may have a strong influence on groundwater flow and the hydraulic connectivity between aquifers and the land surface (Smerdon and Turnadge, 2015). Assessing model uncertainty, which can arise from various conceptual and numerical sources, is critical in guiding monitoring, management and mitigation strategies (Delottier et al., 2017).

Recently, a number of court cases have been heard in Australia where approvals to mining projects have been challenged on the basis that impacts to groundwater have not been adequately considered in the decision and/or design of operating conditions. The concept of 'adaptive management' has been employed in many of these cases, whereby resolution of key scientific uncertainties regarding groundwater has been deferred until after the mine has been approved to commence construction, on the basis that groundwater management can adapt to adverse impacts as they develop. Lee (2014), Lee and Gardner (2014) and Slattery (2016) discuss some of these cases and argue that adaptive management concepts are being misused in some cases in the context of mining approvals.

In Australia, as in many countries, companies applying for approval of a mining project must generally prepare an Environmental Impact Statement (EIS) if the project is considered by the relevant government authority to be significant. The EIS typically considers, among other things, the impact of the proposed mine on groundwater, surface water and ecosystems in the vicinity of the mine. After the EIS is released, it is reviewed by State government bodies, e.g. the Coordinator-General in Queensland (Australia). Large coal mine and coal seam gas (CSG) projects impacting on matters of national environmental significance, including water resources, are referred to the Australian Federal Minister for the Environment. The Minister must ask the Independent Expert Scientific Committee for Large Coal Mining and Coal Seam Gas Development (IESC) for advice before making a decision to approve proposals. The IESC was established due to community concern in Australia over impacts of mining and CSG projects on water resources, and provides independent scientific advice on potential water-related impacts. The EIS for a mining project, and the reviews of the EIS (including advice from the IESC), are typically released for public consultation as part of various approval processes and may be subject to objections, which can be assessed during a court hearing.

Worldwide, there are relatively few studies examining how hydrogeological science informs decisions about mining projects. Younger et al. (2005) examined how scientific and socio-economic considerations were incorporated into risk-based decisions about the treatment of polluted mine waters in the UK, exploring the trade-offs between these. Amezaga et al. (2011) and Northey et al. (2016) provide global overviews of long-term sustainability of mining with a focus on water management, stressing the importance of up-front assessment of likely water impacts through a project's life-cycle, including the post-closure phase. The Comparative Groundwater Law and Policy Program (Casey and Nelson, 2012) examined the science-policy interface in relation to groundwater issues, including the different approaches of scientists and policy makers to groundwater problems, although mining projects were not considered specifically.

In this paper, we discuss a high-profile case study involving a large coal mine proposal (the Carmichael Coal Mine) in central Queensland, examining how hydrogeological science was incorporated into its assessment. The key decision makers in the case included State and Federal government departments and the Land Court of Queensland. Throughout the approval process and design of operating conditions, large uncertainties remained unresolved regarding the conceptual hydrogeological model and numerical model for the mine. This was acknowledged in the Land Court judgement on the case, and the Federal Minister for the Environment's approval conditions for the mine specify that, prior to commencement of excavation, research and monitoring plans must be submitted that address these issues. We discuss in detail how hydrogeological disagreements and misconceptions informed the decision to approve the Carmichael Mine, and were ultimately reflected in the conditions of approval for the mine. We make targeted recommendations which we believe could address such issues in future.

2. Hydrogeological setting of the Carmichael Coal Mine

In 2010, a subsidiary of the Adani Group (Adani), an Indian resource, energy and infrastructure group, submitted a proposal to the Queensland Government to build the Carmichael Coal Mine and Rail Project to supply coal to its Indian power stations (GHD and Adani Mining, 2013a). If constructed, the mine would be the largest open-cut and underground coal mine in Australia's history, covering ~28,000 hectares and extending ~30 km along strike, producing an estimated 2.3 billion tonnes of thermal coal over 60 years. The mine is situated ~300 km inland and there is no local infrastructure; it will be necessary to construct a railway and expand port facilities to export the coal. The proposed mine is located in the catchment of the Burdekin River in an area predominantly used for beef cattle grazing.

The proposed mine is in a semi-arid environment with strongly seasonal rainfall (mean annual rainfall ~500 mm) and there are no permanent watercourses nearby except for part of the Carmichael River, which is spring-fed (see below). Two salt lakes, Buchanan and Galilee, lie in internal drainage basins west of the mine. The topography of the area is subdued, with a maximum relief of 300 m. The drainage divide of the Great Dividing Range, with a maximum elevation of ~500 m above sea level, runs north-south approximately 50 km west of the Carmichael mining lease. The area is mostly covered with open eucalypt woodland.

The Carmichael mining lease lies within the Galilee Basin, which contains a Permian siliciclastic sequence dominated by fluvial sandstones and shales; in stratigraphic order – the Joe Joe Formation, Colinlea Sandstone and Bandanna Formation (Moya et al., 2014). Overlying the Permian strata are the Triassic Rewan Formation, Dunda Beds and Clematis Sandstone, capped by Tertiary laterite (McKellar and Henderson, 2013; Fig. 2). These Triassic units form part of the Eromanga Basin sequence within the Great Artesian Basin. Coal seams are confined to the Colinlea Sandstone which outcrops or sub-crops at shallow depth along the eastern margin of the basin (Fig. 1), dipping westwards at 2–5° for 10–20 km and then becoming sub-horizontal. The Galilee Basin is yet to be developed for mining; however, a number of coal mines to the south of the Carmichael mining lease have also been proposed and granted approval in the last five years (Lee and Gardner, 2014).

The main aquifer in the mine area is the Colinlea Sandstone/Bandanna Formation; the lower sandstone beds are porous and high yielding with good quality groundwater (electrical

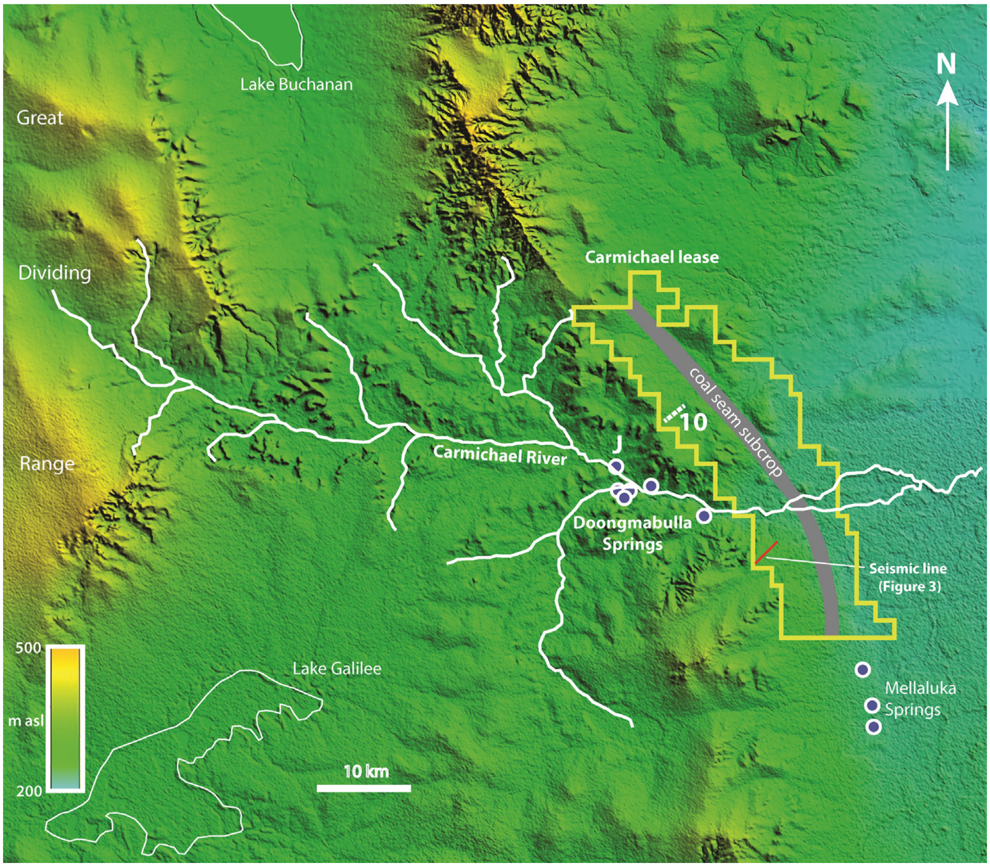

Fig. 1. Location of Carmichael mine and the Doongmabulla Springs (J = Joshua Spring; 10 = seismic line 2011-10).

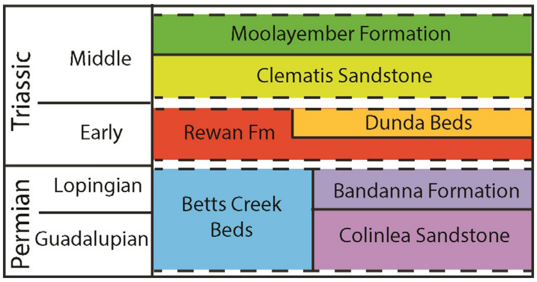

Fig. 2. Galilee Basin stratigraphy (from McKellar and Henderson, 2013; Allen and Fielding, 2007).

conductivities are mostly 2000–3000 μS/cm), which is extensively used for stock watering and domestic purposes in the region. Many properties in the area depend almost entirely on this water source. The Dunda Beds and particularly the Clematis Sandstone also contain porous sandstone beds, and the Clematis Sandstone is a major aquifer in the Great Artesian Basin to the west. The intervening Rewan Formation is predominantly shale and is regarded as a regional aquitard (e.g. GHD and Adani Mining, 2013b). The hydraulic conductivity (K) measurements from this formation are variable according to field surveys conducted by Adani, ranging from 9.5×10^{-5} to 2.9×10^{-1} m/day with a median of 3.1×10^{-4} m/day (GHD and Adani Mining, 2013b).

As faults are a major issue for mine planning, geological surveys have been conducted – predominantly seismic lines and bore-hole logging – to characterise faulting within the proposed mine site (Xenith Consulting, 2009; McClintock, 2012). Faults with significant displacement have been interpreted on the basis of these surveys, including at least one that appears to extend vertically hundreds of meters across multiple strata, from the target coal seams in the Colinlea Sandstone through the Rewan Formation (Fig. 3) (McClintock, 2012). These surveys occurred entirely within the mine lease, and did not extend to the vicinity of the springs discussed below. While some faults act as barriers to horizontal groundwater flow in the Galilee and Eromanga Basins (e.g. Ransley and Smerdon, 2012), there is also evidence of groundwater discharging from deep strata to the surface through faults that cross regional aquitards in these basins. For example, Moya et al. (2014) found evidence of possible upwards discharge of groundwater from hundreds of meters below the surface along regional faults (e.g., Thomson River Fault), some ~400 km southwest of the proposed mine. Similar evidence has been documented elsewhere in the region on the basis of geophysical and modelling techniques (Smerdon and Turnadge, 2015; Inverarity et al., 2016).

The mine will use approximately 12.5 billion litres of water per year (12.5 GL/year) for on-site requirements at peak production (IESC, 2013). This will be derived from both surface water imported through a pipeline and groundwater. The Colinlea Sandstone/Bandanna Formation aquifer in the vicinity of the mine will be dewatered, and the hydrogeological modelling shows that inflow of groundwater from surrounding aquifers to the mine pits is expected to peak at approximately 10 GL/year. This will significantly depressurise the strata over a considerable distance around the mine site, and cause permanent changes to the region's water balance (GHD and Adani Mining, 2013b).

2.1. Doongmabulla Springs Complex (DSC)

Approximately 8 km west of the proposed Carmichael Mine is the Doongmabulla Springs Complex, consisting of a large number

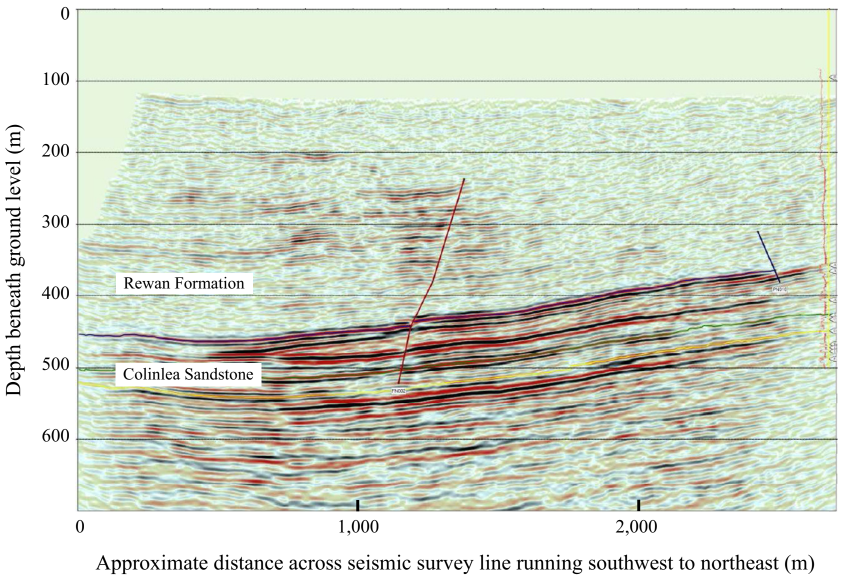

Fig. 3. Interpreted east-west 2D seismic survey line 2011-10 showing probable fault (red line) offsetting top coal seams (thick black lines) in Colinlea Sandstone by 6–10 m. Note westwards dip of strata. See Fig. 1 for location. From McClintock (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of permanent freshwater springs feeding ~160 wetlands up to 8.7 ha in size (Fensham et al., 2016). Doongmabulla Springs represent a rare source of reliable water in this region and are of high cultural and ecological significance (Wangan and Jagalingou Family Council, 2015). They are protected under a Nature Refuge Conservation Agreement between the landholders and the State of Queensland, and also the Federal *Environment Protection and Biodiversity Conservation Act 1999*, Australia's primary federal environmental legislation. This protection recognises the diversity of vegetation types and the high level of ecological endemism associated with these springs and others within the Great Artesian Basin (Fensham et al., 2010, 2016).

The largest spring, Joshua Spring, has a flow rate of approximately 5 L/s into a small earth dam (locally known as a "turkey-nest dam"), within which the water level is 2–3 m above the surrounding land surface. The outflow from Joshua Spring and other nearby springs (including Moses and Little Moses Springs) provides base flow to the Carmichael River, which subsequently flows for approximately 20 km downstream of the springs, discharging into the Belyando River. The river is otherwise dry in sections upstream of the springs. The discharge from Doongmabulla Springs occurs both as prominent vents and as diffuse discharge through a large number of surface seeps within and adjacent to the extensive system of wetlands.

A second spring complex, the Mellaluka Springs, is found near the proposed mine site. This group of three artesian, freshwater springs (Mellaluka, Lignum and Stories Springs) lies approximately 35 km southeast of Doongmabulla Springs and 5–10 km south of the proposed mine. Flow rates are low relative to the main vents at Doongmabulla Springs (e.g. Joshua Spring). The Mellaluka Springs lie to the east of the sub-crop of the coal seams and are thought to receive water from the basal sandstone in the Colinlea Sandstone and/or a permeable unit at the top of the underlying Joe Joe Formation (GHD and Adani Mining, 2014). The three springs lie in an approximately north-south orientation, likely representing the influence of a fault or other preferential flow pathway (e.g. fracture), although this requires further investigation. Because these springs are small, heavily disturbed and are not known to provide habitat for any threatened or endemic species, they are considered to have lesser ecological significance than the Doongmabulla Springs (GHD and Adani Mining, 2014).

3. Environmental approval and objection to the Carmichael Mine

After Adani applied for the Carmichael mining lease in 2010, the Queensland Government Coordinator-General declared it a significant project for which an EIS was required. The EIS and Supplementary EIS were published and public submissions were invited in 2012 and 2013. The Coordinator-General's report on the project, delivered in May 2014, recommended that the mine be approved subject to conditions. The mine was also granted approval (with conditions) by the Federal Minister for the Environment in October 2015. Objections to the Carmichael mine by several parties, including Land Services of Coast and Country Inc. (LSCC), were referred to the Queensland Land Court in September 2014 and heard in 2015. Regarding impacts of the mine on groundwater, LSCC argued (among other things) that: *"If the mine proceeds, it will impact groundwater dependent springs and systems that are important for human use, agriculture and biodiversity, including but not limited to: (a) the Doongmabulla Springs Complex – including Moses, Little Moses and Joshua; (b) the Mellaluka Springs Complex – including Mellaluka Spring, Lignum Spring and Stories Spring."* (Land Court of Queensland, 2015a).

Before the court hearing, independent expert hydrogeologists engaged by both the objector (LSSC) and the applicant (Adani Mining) prepared reports on the hydrogeological evidence presented in the EIS and Supplementary EIS, and then met in order to determine issues of disagreement. The relevant reports are: Bradley (2015), Merrick (2015a), Webb et al. (2015), Webb (2015), and Werner (2015). The expert witness meeting is required by state legislation, and can considerably shorten court proceedings by identifying areas of agreement and disagreement between the experts and limiting the issues disputed in the hearing. Doongmabulla Springs were agreed by all parties to possess "exceptional ecological value" and hence their protection was a key environmental management priority (Land Court of Queensland, 2015a). It was also agreed that the drawdown associated with dewatering for the Carmichael

Mine will decrease the groundwater pressure at Mellaluka Springs such that there will no longer be artesian pressures and these springs will consequentially dry up. However, there was no agreement as to the conceptual hydrogeological model of Doongmabulla Springs and the likely level of impact (e.g., reduction in flow) due to proposed mining activities. During the court hearing, these areas of scientific dispute were subjected to extended scrutiny.

4. Key areas of scientific dispute

Several scientific issues were addressed throughout the court proceedings, in particular the conceptual and numerical hydrogeological models of the area and Doongmabulla Springs specifically, and the impact of mining on spring flow. These proved to be pivotal issues in the final judgment on the case, and are discussed in detail in the sections that follow.

4.1. Conceptual hydrogeological model of Doongmabulla Springs

Two different conceptual models were presented for the hydrogeology of the Doongmabulla Springs. Bradley (2015) proposed that the springs issue from Triassic sandstones, and that recharge was occurring through outcrops of these strata in the range to their north, with "discharge occurring in topographically low areas where preferential pathways for upward groundwater flow are developed" and where "groundwater pressure is able to exploit weaknesses in the rock strata". In contrast, Webb (2015) proposed that the flow from the springs was "derived at least partially from the underlying Permian aquifers", which are over 500 m below the surface at this point (due to the regional dip of the strata), with upwards flow along a fault through the confining beds of the overlying Rewan Formation. This conceptualisation was based on several lines of evidence. Firstly, groundwater flow in the Colinlea Sandstone (from the north, south and west) appears to converge on the springs, thereby indicating that the springs act as discharge from that unit. Aside from discharge to the Doongmabulla Springs and the nearby Carmichael River, there are limited alternative explanations for this flow pattern (such as drawdown induced by groundwater extraction, which is minimal in the region) (GHD and Adani, 2013b). Secondly, the potentiometric surface of the Permian units is sufficiently elevated to drive groundwater flow to the land surface at the location of the springs. The nearby Mellaluka Springs are thought to rely on flow from the Permian strata (GHD and Adani Mining, 2014). Thirdly, there is seismic and borehole evidence of faulting in the Colinlea Sandstone elsewhere in the region (within the mine lease), including a fault which appears to cross the Rewan Formation (Fig. 3). Fourthly, Webb (2015) found that there is little evidence of major confining layers within the Triassic sandstones sufficient to cause the artesian pressures necessary for spring flow. The model preferred by Bradley (2015) was adopted primarily for its greater simplicity – in the absence of any field evidence to confirm or negate the existence of faulting, the Rewan Formation was assumed to be a competent aquitard, preventing connection with the deeper Permian strata. The limited data available on the groundwater chemistry of Doongmabulla Springs (major ion chemistry and strontium isotopes) were inconclusive as to the source aquifer (Webb, 2015).

The source aquifer of the springs is critical to considering any potential impact of the proposed mine. For example, if the springs are fed entirely from the Triassic strata (see Fig. 2), and the Rewan Formation acts as a regional aquitard, then the de-watering of the Colinlea Sandstone may cause only minor drawdown in the overlying Triassic aquifers. This is the 'best-case scenario' for the Doongmabulla Springs, and was adopted by GHD and Adani Mining (2013b) for the modelling and predictions of impacts on the springs from mining. Under this case, groundwater modelling suggests that the springs will lose some 19 cm of driving head during peak mine operation (GHD and Adani Mining, 2013b). The alternative possibility, whereby the springs are fed from the Colinlea Sandstone via a preferential pathway through the Rewan Formation, would mean that de-pressurisation due to mining would have a far more significant effect on the springs. The four experts agreed that in all likelihood they would cease to flow if this was the case (Land Court of Queensland, 2015a). This outcome would likely be catastrophic for GDEs of the region, leading to complete loss of spring wetlands and eradication of all spring-dependent ecosystems, including rare endemic plant species (Fensham, 2015). Some combination of the two scenarios (a mixture of water sourced from the two aquifers providing spring flow) is also plausible (Webb, 2015). GHD and Adani Mining (2013b) did not explore scenarios in which some element of spring flow is sourced from preferential pathways through the Rewan Formation, and therefore, their modelling of impacts is not valid for studying these latter scenarios.

The cross-examination of expert witnesses during the court proceedings did not resolve this issue. In a joint report by all groundwater experts prior to proceedings, it was agreed that: *"the source of the Doongmabulla Springs is inconclusive and that there are two potential sources that need to be considered; one a source below the Rewan Formation, the other a source from above the Rewan Formation. Methods such as isotope sampling, in conjunction with analysis of existing data (water chemistry, water level, geology) would potentially assist in resolving the question."* (Webb et al., 2015).

However, Adani relied heavily on the absence of positive physical evidence of faulting at the Doongmabulla Springs, and the hypothesis that the springs are inherently coupled to the existence of faulting was dismissed due to the lack of field data. No seismic survey or drilling to investigate faulting had been conducted in the immediate vicinity of the springs, despite such surveys having been undertaken to the east within the mining lease. As shown in Fig. 3, those surveys indicated significant offset of bedding planes through the Rewan Formation in at least one location, consistent with the presence of a major fault. Adani disputed that this evidence could be applied to infer faulting as a potential source of groundwater flow at the Doongmabulla Springs. Other evidence that faults are important controls on the hydrogeology of the Galilee and Eromanga Basins, allowing flow from hundreds of meters depth to the surface in some cases (e.g., Moya et al., 2014; Smerdon and Turnadge, 2015) was also not considered significant in the Land Court's decision. Thus, limited previous attempts to characterise the Doongmabulla Springs and a lack of data served to obviate what were considered by all the expert witnesses to be possible scenarios for the springs' occurrence. There was agreement by the experts that if the excluded scenarios were correct, mining would potentially lead to springs disappearing (Land Court of Queensland, 2015a).

4.2. Modelling the impact of mining on spring flow

The hydrogeological study conducted by GHD and Adani Mining (2013b) predicted that peak mine-induced drawdown within the Triassic Clematis Sandstone aquifer (i.e. above the Rewan Formation, modelled as a competent aquitard) would be 0.19 m, or up to 0.3 m accounting for model parameter sensitivities (Merrick, 2015b). The model presumed this was the source aquifer of the Doongmabulla Springs, and therefore the drawdown in this aquifer was taken to be the same as the drop in driving head for the springs. However, there was disagreement as to: (a) whether this was indeed the most likely drop in driving head for the springs, and (b) if so, how this amount of drawdown (or a greater amount) would affect the number, area and flow rates of the springs (Land Court of Queensland, 2015a).

In regard to the head drop applicable to the springs, there was disagreement as to the source aquifer (described above), which has direct bearing on the relevant drawdown prediction. Other issues contribute to uncertainty in the prediction by GHD and Adani Mining (2013b). Firstly, there was no representation of the Doongmabulla Springs within the model. The spring discharge was not simulated and no physical mechanism for upward flow to the surface at the location of the springs was embedded into the model. Only flow to the nearby Carmichael River was represented, through the simulation of river-aquifer interaction with shallow aquifers. Given that the numerical model did not simulate groundwater discharge at the springs, it lacked inherent capability to simulate any decrease in spring flow. Subsequently, the applicability of the model to the prediction of spring flow impacts, and indeed the study area's water balance more generally, were brought into question (Land Court of Queensland, 2015a).In lieu of this lack of capability within the numerical model, a relationship between the drop in driving head and spring flow was developed by Merrick (2015b), upon which Adani relied on during the case, using a simple Darcy's Law analysis, as follows: The objective was to obtain the spring flow reduction (ΔQ) as the difference between spring flow before (Q_B) and after (Q_A) mining. It was presumed that spring flow can be represented by Darcy's Law ($Q = KA(\Delta H/\Delta z)$), where Q is spring flow, K is vertical hydraulic conductivity representing the resistance of upward groundwater flow to the spring, ΔH is the 'driving head difference', and Δz is the elevation difference. Darcy's Law was used to show that $\Delta Q/Q_B = DD/\Delta H_B$, where DD is drawdown in the source aquifer (estimated at between 0.16 and 0.3 m) and ΔH_B is the difference between the source aquifer head and the spring 'threshold elevation'. This was defined by Merrick (2015b) as "ground surface for discharge of water to pools", but would be at "a higher elevation (the lip of the mound or other overflow elevation or pipe invert level) for water that is transferred from the mound pool to an associated wetland". This theory, albeit simplified, was not disputed in the hearing.

However, Werner (2015) argued that the application of the theory was flawed, leading to a potential order-of-magnitude underestimation of impacts of spring flow. A schematic diagram of the key parameters in the theory of the relationship between water levels and spring flow is provided in Fig. 4.

Spring flow requires that the source aquifer (Aquifer 2 shown in Fig. 4) must have a head (h_2) greater than the spring land surface (h_s) or the ponded water level at the spring ($h_s + \Delta h_p$), whichever is higher, resulting in upward flow. Depending on the conceptualisation, Aquifer 2 could represent either Permian or Triassic sediments, and is intended only as a schematic of the general spring flow mechanism. Limited measurements of the shallow aquifer head (h_1) close to the spring showed that the head was lower than land surface (Merrick, 2015b), and therefore Aquifer 1 in Fig. 4 is clearly not the springs' source aquifer. The application of the simple relationship $\Delta Q/Q_B = DD/\Delta H_B$ by Merrick (2015b) presumed that ΔH_B is equal to $h_2 – h_1$, i.e., the head difference between the source aquifer and the overlying unconfined aquifer. Merrick (2015b) adopted $\Delta H_B = 5$ or 6 m in estimating spring flow reduction, on the basis that the overlying unconfined aquifer has a water level 2–3 m below ground surface, and Joshua Spring has a small dam raised some 3 m above ground surface. This however does not accord with the definition of 'threshold elevation' above, which should be based on the spring's surface elevation, not the unconfined aquifer head. If the correct threshold elevation ($h_s + \Delta h_p$) is adopted, where Δh_p is only a few centimetres above the land surface in situations of the many seeps and other less prominent discharge features that characterise the Doongmabulla Springs Complex, then the reduction in flow to these features due to mining would be much greater (i.e., 100%, on the basis of the range of predicted drawdown of h_2 of 0.19 to 0.3 m in GHD and Adani Mining (2013b) and Merrick (2015b)). Thus, decline in the flow from Doongmabulla Springs, even adopting GHD and Adani's (2013b) predicted source aquifer drawdown of 0.19 m, is plausibly a significant or complete loss of the springs complex.

In spite of the disagreement among experts, and the lack of field data required to resolve the issue conclusively, the Court accepted Merrick (2015b)'s proposed model of the springs and predicted reduction in spring flow due to mining of between 3 and 6%, consistent with GHD and Adani Mining (2013b)'s modelling. This was in spite of the admission by Dr. Merrick, under cross examination, that a reduction in driving head on the order of 5 cm would lead to a number of the smaller springs within the Doongmabulla Springs Complex drying up completely. This evidence was addressed by LSCC in its submissions (Land Court of Queensland, 2015b), but was not ultimately reflected in the Court's decision. In the federal approval conditions designed for the project, 20 cm was considered to be an acceptable level of water level drawdown to safeguard the springs from adverse impacts (Department of the Environment, 2015).

A lack of site-specific field data once again prevented a clear resolution of the uncertainty about the impacts of reduction in hydraulic head in the modelled aquifers on spring flow. There were no basic quantitative hydrological data for the springs - no gauged outflow rate (only a visual estimate of ~5 L/s at Joshua Spring) and no hydraulic head measurements from nested piezometers in the direct vicinity of the springs available at the time. As noted above, the water surface in the 'turkey's nest' dam at Joshua Spring is 2–3 m above the surrounding plain, however the height of the water level in the dam has not been surveyed accurately, and the actual hydraulic head is unknown. This was also identified by LSCC in its submissions to the Court (Land Court of Queensland, 2015b).

The ecological value of the Doongmabulla Springs Complex is directly linked to the rates of discharge from spring vents, which support a large wetland complex in the otherwise semi-arid setting (Fensham, 2015). Therefore, determining the hydrogeological setting of the springs (as discussed in Section 4.1) and linking spring flow to the projected influence of mining on groundwater levels in different aquifers (discussed in Section 4.2) are critical to understanding the likely ecological impacts of the mine. The Land Court acknowledged the remaining uncertainty with respect to these matters in its decision, stating:

"Given the exceptional ecological significance of the DSC (which is detailed further below) I consider that the lack of direct investigation or modelling is concerning." (Land Court of Queensland, 2015a).

Nonetheless, the Court accepted Adani's conclusions about these matters ahead of those reached by LSSC's groundwater experts.

5. Approval decisions and conditions for the Carmichael Mine

Prior to the Land Court case, the Queensland Coordinator-General reviewed the project EIS and Supplementary EIS and recommended approval of the mine subject to a number of conditions (State of Queensland, Department of State Development and Infrastructure and Planning, 2014). In 2015, following the hearing of the evidence from the groundwater expert witnesses, the Land Court ruled in favour of Adani, also recommending approval of the mine. Following the court hearing, the federal Minister for the Environment approved the mine and released an updated list of operating conditions for the mine (Department of the Environment, 2015). In the light of the discussion above regarding

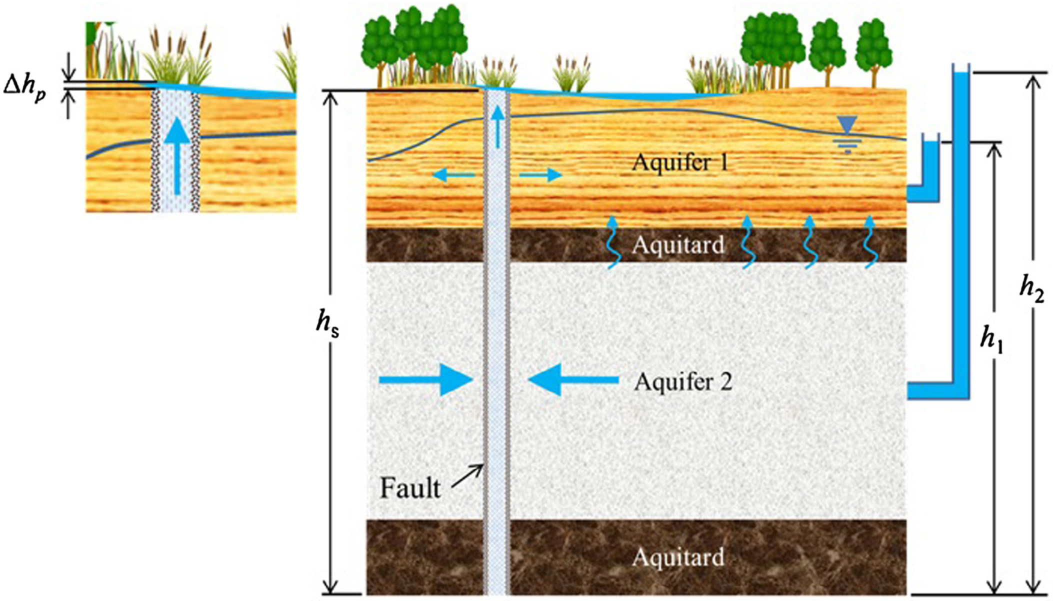

Fig. 4. Schematic of a spring used in estimating the mine-induced spring flow reduction to the Doongmabulla Springs.

the uncertainties surrounding the hydrogeological impact of the mine, particularly the effect of dewatering on Doongmabulla Springs, these decisions are discussed further, in order to understand how the approving bodies reconciled the uncertainties and believed they could be overcome.

It was acknowledged in all the approval decisions that considerable uncertainty existed regarding the impact of the mine on the Doongmabulla Springs. For example, the Land Court judgement stated:

"... after considering the evidence as to the source aquifer of the DS...I was concerned at the lack of direct investigation by the applicant of the area of the DS to determine the likelihood of faulting in the area. While I considered that on balance, it is unlikely that there was a continuous preferential pathway from the Colinlea Sandstone through the Rewan Formation, there was evidence to the contrary which raised some uncertainty as to the existence of faulting. There was also uncertainty as to the source aquifer of at least the Little Moses Spring and Dr. Webb's evidence about the groundwater flow directions in the Colinlea Sandstone also raised further uncertainty as to the source aquifer of the DS." Nevertheless,"As discussed at length above, I concluded that, on balance, the DS are not fed by the Colinlea Sandstone." (Land Court of Queensland, 2015a).

More than a year before the court case, the IESC had pointed out that the evidence base for conceptualising the Rewan Formation as a regional aquitard was poor:

"The current groundwater model assumes the Rewan Formation will respond uniformly as an aquitard. However, the Committee questions this assumption based on variability in the hydraulic conductivity field data. Further data collection and assessment of the Rewan Formation is necessary...Information on the degree of groundwater connectivity between the coal seams and the GAB is essential to understand the potential impacts of this project" (IESC, 2013).

The uncertainty around these issues was also acknowledged in the conditions applied to approval of the lease by the Federal Minister for the Environment. Adani must carry out research that includes "geological and geochemical surveys to inform the source aquifer(s) for the DSC" and characterises the Rewan Formation within the area impacted by the mine "to determine the type, extent and location of fracturing, faulting and preferential pathways....and an examination of the hydraulic properties.....to better characterise the Rewan Formation and the contribution of fracturing, faulting and pathways to connectivity..." (Department of Environment, 2015).

These conditions emphasise the data gaps and the importance of addressing them prior to any effective management or mitigation strategy being implemented. To our knowledge, there has still been little geochemical/isotopic sampling of the groundwater from the aquifers and springs, which could provide more conclusive evidence as to the source aquifer, e.g., if the major element and/or isotopic signature of spring water is indicative of a deep source (or component thereof). Similarly, to our knowledge there has been limited additional investigation of the hydraulic properties of the Rewan Formation aquitard, no monitoring of the flow or hydraulic head of the springs, and no geophysical survey of the area of the springs to determine if they are fed by a fault from depth. The approval conditions for the project require Adani to fill these data gaps in order to resolve the uncertainty, and these mandated research programs are clearly a valuable and warranted step. However, we argue that much of this investigation could (and should) have been conducted during the Environmental Impact Assessment, following which they could be assessed by the public and made subject to expert review and technical assessment, for example in objection hearings in the Land Court.

It was acknowledged during the approval process that the new information gathered would be likely to require revision of the modelling of the hydrogeological impact of the mine. Thus the Coordinator-General's report states that "review of the collated data should continue throughout all stages of the project life (including post mine rehabilitation) and the predictive groundwater model should be reviewed and updated at regular intervals" (State of Queensland, Department of State Development, Infrastructure and Planning, 2014). However, the conditions governing future operation of the mine need not be subject to any revision if the updated modelling produces different results to the original modelling. Furthermore, neither the Coordinator-General nor the Land Court judgement mentioned any requirement to develop detailed mitigation strategies to overcome any unforseen negative impacts to the springs (impacts which, in the absence of conclusive field data, cannot be ruled out at this stage).

The approval by the Federal Minister for the Environment stipulates that a groundwater management plan must be established that sets trigger values for detecting impacts on groundwater levels at and around Doongmabulla Springs, and which specifies "corrective actions and/or mitigation measures to be taken if the triggers are exceeded where caused by mining operations, to ensure that groundwater drawdown does not exceed an interim threshold of 0.2 m at the Doongmabulla Springs Complex". The plan must also give details of "potential mitigation activities, such as but not limited to, re-injection to the groundwater source aquifer to maintain pressure head, flows and ecological habitat at the Doongmabulla Springs Complex" (Department of Environment, 2015).

The presence of mitigation/remediation plans in the approval conditions is an advance on the previous conditions set by the Coordinator General that required only monitoring to determine if adverse impacts appeared. However, the conditions do not specify what will occur if remediation is not successful or if the Doongmabulla Springs dry up as a result of the mine. Once a mine is approved, it is in our experience highly unlikely that the mine's operating conditions will be modified or revoked, notwithstanding the fact that decision makers under the relevant State and Federal legislation are afforded the power to do so.

The conditions released by the Federal Minister for the Environment set a drawdown threshold of 0.2 m for the Doongmabulla Springs Complex. However, the approach of applying a drawdown threshold at a spring or stream is problematic, as discussed in detail in Currell (2016). Drawdown at a set of springs is unlikely to be a good predictor of changes to spring flow rates, and is a poor 'early warning' indicator because a change in water level will typically only reach springs after the groundwater flow direction has reversed towards the region being pumped/dewatered. Such a change can take place with minimal drawdown occurring where the springs emerge at the surface, but it could still significantly reduce (or eliminate) the flow. Due to the high level of inertia (time-lag) in groundwater systems, impacts such as reduction in discharge can be 'locked in' by a water balance change in advance of the detection of a drawdown response (Bredehoeft and Durbin, 2009). Subsequent mitigation actions may then be of limited effectiveness.

What is more important than monitoring drawdown at a spring is to establish, through rigorous pre-development hydrogeological field work and modelling, the relationships between water levels in key aquifer(s) and flow at the springs (neither of which has been precisely gauged to date at the Doongmabulla Springs), and the likely water balance changes that will occur during mining, including the amount of discharge 'captured' (e.g. Bredehoeft and Durbin, 2009; Konikow and Leake, 2014). Such an assessment should be based on identification of the source aquifer (using multiple lines of evidence such as flow maps and geochemistry), hydraulic properties of relevant units, and a robust conceptual model. As discussed and acknowledged in the Court's decision (see Sections 4.1 and 4.2), these key pieces of scientific information were still absent at the time of the decision to recommend the mine's approval, notwithstanding that data gaps may be filled by future mandated research programs.

6. Recommendations and conclusion

The scientific uncertainties and misconceptions accepted by decision makers and reflected in the approval conditions for the Carmichael project highlight an urgent need to better bridge the gaps between science and policy with respect to groundwater and mining projects. Because the problems are currently unresolved, we argue that there remains considerable uncertainty about the environmental impacts of the Carmichael Mine on areas of high conservation value, to the degree that approval should have been deferred until the data gaps responsible for the uncertainty were filled. Furthermore, only in the federal approval conditions (publicised as the "the strictest conditions in Australian history") are there provisions for corrective actions to be taken if mining activity has a more serious impact on groundwater than is currently modelled; all previous reports and assessments for the mine omitted mention of remediation/mitigation strategies altogether. This omission is typical of mine approval conditions in Australia, and we argue that it is a major oversight that should not be allowed to continue.

On this basis, we contend that even with the current system of checks and approvals, there remain fundamental problems with the way hydrogeological science is incorporated into environmental decision making for mining projects in Australia, an issue with significant national and global ramifications. Casey and Nelson (2012) pointed out that a key aspect of the overall challenge for groundwater management is improving communication between scientists and policy makers. We propose that additionally, there are some simple steps that could help to bridge the science-policy divide and ensure that future decisions about projects with potential impacts on high-value GDEs (such as the Doongmabulla Springs) are based on the best possible scientific evidence:

1. Greater emphasis should be placed on identifying and resolving scientific uncertainties relating to groundwater during the upfront environmental impact assessment (EIA), as argued by Lee (2014). The EIA is the most transparent part of the approval process for mining projects, and it is where deficiencies such as data gaps, competing conceptual models and points of potential scientific conjecture can be identified and resolved through additional/supplementary work. Such an emphasis would reduce the chances of uncertainties and scientific misconceptions carrying through to approval decisions and designing of project conditions, and of subsequent conflicts emerging.
2. There needs to be a stronger role for independent scientific opinion in the approvals process. The IESC is an example of one body in Australia which currently provides advice on mining projects. However, their advice is only sought for coal mining and CSG projects. Also, their advice is not binding, and mining companies are not strictly required to resolve all technical and scientific issues identified in the committee's advice (such as those identified in this case) prior to project approval.
3. Monitoring criteria and proposed mitigation strategies should be available for public review and scrutiny prior to project approval, rather than being deferred to a post-approval process (Lee, 2014; Slattery, 2016). After approval, monitoring and management plans are generally overseen by mining companies and the relevant government department(s), but need not involve public consultation. Monitoring the compliance with environmental conditions in jurisdictions such as the state of Queensland, Australia (where our case study is situated) is hampered by a lack of resources and expertise (e.g. Queensland Audit Office, 2014), and this is likely true in other jurisdictions also. A greater degree of transparency and upfront effort in the design of monitoring criteria and proposed mitigation plans would thus allow the public and technical experts to provide input, helping to ensure environmental objectives will be effectively monitored and met.

This case study has emphasised the universal need for rigour by hydrologists to understand the uncertainty of modelling relating to major projects. It also emphasises the perceived significance of this uncertainty in formal and legal decision making among different stakeholders (Liu et al., 2008). As demonstrated, what are seen as acceptable risks may vary between different hydrologists and others such as project proponents, ecologists, lawyers and politicians. It is thus important to acknowledge that the traditionally defined roles of hydrologists may be inadequate to positively affect decision making, unless their role is carefully planned within the decision-making system (Syme, 2012). In some cases, this may mean that well intentioned hydrological professionals end up on opposite sides of an argument when disputes occur, such as in this case. However, this is a challenge that must be seen as a priority if hydrologists are to contribute to improving our current environmental decision-making. We believe that the recommendations derived from this study provide a necessary step in that direction and would enhance the prospects for an environmentally sustainable mining industry – a major global challenge.

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