NSW DPE State Significant Development Proposal No. 6367: Revised Bylong Coal Project - Response to EDO NSW brief

Expert Report | 14 November 2018

Groundwater

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Report prepared for Environmental Defenders Office NSW on behalf of the Bylong Valley Protection Alliance

1 Introduction

1. My name is Mr Doug Anderson. I am Principal Engineer for Groundwater and Modelling at the Water Research Laboratory (WRL), School of Civil and Environmental Engineering at UNSW Sydney. WRL is located at 110 King St, Manly Vale, NSW, 2093.
2. This expert report has been prepared to advise on the hydrological aspects (primarily groundwater but also connected surface water) of the revised project proposal for the Bylong Coal Project, a proposed open cut and underground longwall mining operation.
3. The Bylong Coal Project would be located in the headwaters of the Goulburn River catchment near the Wollemi National Park (WNP), a World Heritage Area (WHA), and Goulburn River National Park. The underground mine would be situated below Bylong State Forest (Cyprus Pine) and agricultural land that utilises groundwater and surface water for primary production. The project would also have some influence on the Tarwyn Park Homestead which is being considered for Heritage listing (Document 37).
4. The NSW Department of Planning and Environment (DPE) State Significant Development (SSD) application number for the project is 6367. The development proponent is the Korean miner, KEPCO. The development proposal has already been subject to an Environmental Impact Assessment (EIA) process, has been revised as part of this process, and is now before the NSW Independent Planning Commission (IPC) for review and determination. The revised proposal is for an open cut mining pit of a reduced size and an underground longwall mine.
5. I have been retained to provide my expert report by the Environmental Defenders Office (EDO) NSW on behalf of the Bylong Valley Protection Alliance (BVPA).
6. My brief which is detailed at Appendix A is to provide expert advice to the NSW IPC on the hydrological aspects of the revised project. I have been instructed that I am not an advocate for the BVPA and that I am to prepare an independent report that assists the decision maker.
7. As detailed in Appendix A, my scope of works for this report is to:
    a. Review the referenced documents, consider the review findings by Pells Consulting (Document 35) and examine issues that should be considered by the IPC;
    b. Provide advice on groundwater issues in relation to: agricultural soil and water impacts, potential impacts on the adjacent World Heritage Area of Wollemi National Park (WNP), interactions with the *NSW Aquifer Interference Policy 2012* (AIP), and possible groundwater dependent ecosystems;
    c. Provide any further observations or opinions which I consider relevant.

8. Appendix A lists the primary documents that I considered in the preparation of this report. I have numbered these documents 1-33. I have not read all these reports in detail; they are voluminous and there has been insufficient time. I have conducted a high level review of issues.

9. Appendix B lists the additional documents that I have considered and relied upon in this report.

10. This report makes reference to presentation slides that accompanied my presentation to the NSW IPC on the matter of SSD 6367. The slides provide a graphical description of some of the matters presented below. This includes:

    a. geological cross-section figures extracted from EIA reports;

    b. plan view maps of maximum drawdown impacts from the different EIA computer models;

    c. illustrations of why it is important to provide time-series predictions of water budget components of mining activity after the mining activity ceases;

    d. an extract of the project geology maps showing structures mapped in adjacent and nearby national parks (my review did not explore this matter further);

    e. a seven (7) point summary of key issues; and

    f. a presentation on numerical modelling of specific storage issues in the context of the latest available, peer-reviewed, accepted and published science.

11. I have read, understood and complied with Division 2 of Part 31 of the Uniform Civil Procedure Rules 2005 (UCPR) and the Expert Witness Code of Conduct contained in Schedule 7 of the UCPR and agree to be bound by the code of conduct. My opinions expressed in this report are based wholly on the specialised knowledge mentioned in the report.

12. I adopt a pragmatic approach to engineering water and groundwater practice. I am neither for or against coal mining development. Under the *Environmental Planning and Assessment Act 1979 (NSW)*, I understand the Minister or his/her delegate(s) will consider the best knowledge available to them and then either approve an SSD application if it is assessed in the best interests of NSW, or reject the application if it is not. Section 2 of this reports describes my qualifications to inform on matters of water and water-related impacts.

2 Qualifications

13. I am an Environmental Engineer who specialises in the solution of groundwater, hydrology and earth-science problems. Environmental engineering practice, which is my discipline, conserves and maximises the value of water resources and environmental assets while enabling social and economic development, e.g. mining.

14. I hold undergraduate and postgraduate qualifications in environmental engineering (BE Environmental Hons. 1) and groundwater studies (M.Eng. Sci) from UNSW Sydney. I am a member of Engineers Australia and the International Association of Hydrogeologists.

15. I have accumulated 17 years of technical experience in groundwater and surface water resource assessment, impact assessment and management both locally and internationally. This includes groundwater modelling.

16. During my career I have worked as a consultant for resource development companies, science advisory groups, community groups and local, state and federal governments alike. I regularly provide advice to the NSW Department of Planning and Environment on tunnelling projects as an independent groundwater reviewer and on other matters. I regularly review groundwater impact assessments for coal mining projects for community. I have experience developing groundwater flow models in a range of geological environments including alluvial, porous and fractured rock systems. I have investigated and reported on failures of environmental monitoring and management in respect of underground mining activity in the Southern Coalfields and provided recommendations for improvement.

17. I have reviewed numerous Groundwater Impact Assessments (GIA) in NSW since 2012. I have a good understanding of the state of practice, the limitations of current practice and leading practice as it relates to water resource characterisation, impact assessment, uncertainties in knowledge and prediction of impacts and decision making.

18. My CV is attached at Appendix C.

3 Summary

19. In the Response to Submissions (RtS), AGE (Document 10, Figure 19, p. 41) presented literature values of aquifer specific storage (Ss) that were utilised in their groundwater model to predict the groundwater and connected surface water impacts of SSD 6367. The Ss values for layers 1, 2, 3, 7, and 8 of their model are much larger than the limits allowed by poroelastic theory. Limits on values of Ss were confirmed recently by Rau et al. (2018) from geophysical methods and first principles. This work has been peer-reviewed and published in an esteemed international journal. The theoretical limits described by Rau et al. (2018) are consistent with the experiment work of other groundwater practitioners in Australia, e.g. Evans et al. (2015).

20. Independently, Pells Consulting has also identified that the values of Ss utilised for modelling are not appropriate. In their submission on SSD 6367 (Document 35, p. 9 - 10) they contrasted the modelled values of Ss with typical geotechnical properties of the geology that those layers were reported to describe. They found that most specific storage values in the model were mathematically impossible.

21. The observations that the modelled Ss values are inconsistent with both poroelastic theory and typical engineering properties of rock and sediments is highly concerning. It implies that the basis for model conceptualisation is unreliable, transient model calibration incorrect and that the predictions reported throughout all of the EIA documents are not accurate in the context of the latest peer-reviewed and accepted science.

22. This is a critical issue. Specific storage influences how quickly groundwater levels fall when groundwater discharge exceeds groundwater recharge. It also influences how quickly drawdown effects travel from a source of aquifer interference to a nearby water user or ecological receptor. Consequently, with unrealistic and artificially high values of Ss being used within the SSD 6367 groundwater flow model, there is a real risk that all the model predictions presented to date substantially under-predict the speed at which mining impacts move through the subsurface, the rate and magnitude of groundwater drawdown at water assets and ecosystems, and the groundwater capture (impact) zone of the proposed development.

23. In my opinion, the very high, and unrealistic values of specific storage assigned to the coal seam subject to mining (model layer 8) and the overlying bedrock (model layer 7) are not appropriate. This issue will limit the model from predicting sufficient propagation of drawdown from mining activity away from the coal seam.

24. Consequently, in my opinion, for all the reasons stated above, I am concerned that the Environmental Impact Assessment (EIA) is not predicated on a correct and/or clearly stated understanding of groundwater flow. I request this matter be resolved and key stakeholders are provided with opportunity to comment on and review the responses on this matter at an appropriate time so the predictions of the groundwater model provided to date can be placed in the appropriate context.

25. In my opinion, resolving the issue described above will require further data collection and/or analysis and recalibration of the predictive model to determine more appropriate choices of hydraulic conductivity and recharge using realistic, measured values of specific storage. Then all the model predictions will need to be remade.

26. The impacts of mining activity can last for many decades or even hundreds of years after mining is complete. In the materials I have examined, for the latest groundwater modelling assessment report presented by the proponent (Document 30), the water balance on the last page does not satisfy the request of the *NSW Aquifer Interference Policy 2012* to provide information about the changes in flows and volumes after mining is complete. The reporting of water balance impacts stops at year 25. It should be established whether all the required information from the revised model has also been received, reviewed and considered by NSW DI Water.

27. In my opinion, the community should be afforded the opportunity to review and comment on the revised, predicted future water balance impacts of the proposed development from the latest groundwater model. Without this revised information, the community may not fully appreciate the uncertainty surrounding what might happen to the water entitlements currently held by KEPCO once mining ceases. These considerations are particularly important in the event that KEPCO relinquishes their land title in part, or in full, shortly after mining (while groundwater impacts are still occurring).

4 Response to the brief – detailed comments

28. My response is structured as follows:

4.1 Matters of SSD 6367

29. During the EIA process the mine plan has been revised, the model software and model setup has been revised, some of the input data and assumptions to the models were changed, and various types of uncertainty analysis were undertaken. There are now multiple numerical models being used for a variety of purposes. This is not necessarily a bad thing; such practice can be best practice if it is planned from the beginning, the model inputs are sound, and all crucial environmental processes have been considered, simulated and assessed. Multiple conceptual models (often at different scales and/or locations) are required in groundwater studies to predict different types of impacts.

4.1.1 Trading risk

30. If the project is approved, the state of NSW receives revenue in various forms (e.g. royalties, salaries for workers etc.), however, it will also incur costs. Some of these costs are economically easy to quantify, while others are more difficult to quantify.

31. The costs that should be straightforward to compute with research based on experience at other mines in relation to subsidence and mine-water impacts across NSW, include:
    a. costs to repair infrastructure from subsidence cracking;
    b. potential loss of revenue from NSW State Forest – potential loss of Cyprus Pine due to ground movements from subsidence and any associated shallow groundwater table impacts;
    c. increased costs of water supply due to any decreased volume of water flowing into downstream reservoirs for the life of the mine (which may be about 20-30 years);
    d. increased costs of water supply due to the same impacts after the mine is closed while the mined-out voids and subsidence fractures capture water from both elsewhere in the ground and from the surface (this may take decades or centuries until a new equilibrium condition is achieved – our understanding of the time this takes depends on numerous factors including ground conditions, climate, and methods of mining, rehabilitation and modelling);
    e. the total cost of undertaking EIA and water management for a project in accordance with the *Environmental Planning and Assessment Act 1979* (NSW), *Water Management Act 2000* (NSW) and the *Mining Act 1992*, and their related / derivative instruments, policies and technical guidelines.
    f. “planned” reductions in GDP due to NSW primary producers utilising water to value add to the economy, decreasing their productivity either:

i. directly on account of that water being provided to the owner of the proposed development for increased value adding; or

ii. indirectly through pre-acknowledged and accepted “interference” which results in water costing more to access (e.g. increased pumping costs or deeper pumping wells) or possibly being unavailable at certain times because of cumulative impacts (e.g. drought of a certain duration coinciding with peak development impacts);

g. “unplanned” reductions in GDP due to NSW primary producers utilising water to value add to the economy, suddenly decreasing their productivity because there has been some unanticipated “interference” with water availability. Such interference can occur for several reasons.

32. In practice, unplanned interference chiefly occurs when potential impacts were not predicted or communicated to decision makers and/or environmental managers prior to developing plans of management or determining a project. Quantification and simulation of all environmental processes and impact mechanisms helps to support successful planning and environmental management practice.

33. The costs of development that are more difficult to quantify are the visual, social, and ecological externalities of about three (3) metres of subsidence. It has been contended in various assessments and/or submissions in response that these impacts will or may include: the collapse of some aesthetic cliff lines, fractures in the ground and steep slopes, damage to trees and ecosystem function in State Forest, and possibly even National Park (Goulburn River) and World Heritage Area (Wollemi National Park).

34. These impacts will or would occur directly as a result of conventional or non-conventional ground movement or “indirectly” through water-related movements and water quality changes. These would be brought about either by subsidence or depressurisation and/or flow of groundwater and surface water into or towards the mined-out voids (which may or may not be backfilled on account of future market fluctuations and technological advancements). Balancing the needs of present and future generations in respect of climate change impacts, standards of living and right to enjoyment of environment and protection of ecosystems is also a complex consideration.

4.1.2 Stakeholder concerns

35. Stakeholders appear concerned about various project impacts and risks which include:

a. The NSW DPE Preliminary Assessment Report (Document 11) which expresses an opinion that the underground mining operation would represent a negative $89 million Net

Present Value (NPV) loss to KEPCO (Document 11, p. 3, paragraph 3), requiring the impacts of a further open cut coal mine to justify the benefits of the project.

b. The magnitude of the development and the magnitude of the longwall mining subsidence (about 3m) which will result in:

   i. Shallow groundwater, streamflow and forestry impacts in the overlying NSW State Forest - NSW DPI Water has stated an integrated model could have been developed (Document 11, p. 57).

      This is a sensible suggestion for predicting near surface impacts – such impacts have been observed from one metre of subsidence in the Southern Coalfield (Document 53, Section 2, p. 2); in MODFLOW modelling software this process is often not represented for various reasons such as some of those described in Section 4.2.8.

   ii. depressurisation impacts of agricultural aquifer systems during and, most likely, for a considerable duration after mining finishes when KEPCO may sell the land. This may decrease the future economic productivity of that land until the aquifer is restored. During drought, when water is required, there may be a risk that some neighbouring properties might not be able to access water, or need to pay more to access water when it is required.

c. The features of the built and natural environment at Bylong, which include Tarwyn Park, adjacent Goulburn River National Park and World Heritage Areas (Wollemi National Park) just 2.5km away – edge effects are of concern to NSW OEH.

   In my opinion, this is a reasonable consideration as geological structural features if unmapped could potentially cause some localised water impacts in National Park or World Heritage Area; I am not a subject expert in the mapping of geological structures or non-conventional subsidence prediction and could not comment further in the context of SSD 6367, although I have observed in public environmental management plan annual reporting the environmental water quantity and quality outcomes of unpredicted subsidence from failure to consider such factors in the Southern Coalfields.

36. In relation to water and water-related impacts, in my opinion, the concerns of key stakeholders can be grouped under a number of general themes:

    a. Concerns about the magnitude of water impacts and the uncertainty in predicted impacts in respect of surface water and groundwater being available at the appropriate times (e.g. especially during drought) both now and in the future when KEPCO has finished mining and may sell the land.

    b. Comprehensiveness of site conceptualisations and geological mapping and modelling to demonstrate and communicate the understanding of both geology and hydrogeology to facilitate informed decision making and environmental management, e.g. any unassessed impacts from non-conventional and far-field subsidence and non-conservative modelling assumptions that might result in unrealised ecological and water impacts in adjacent Goulburn River National Park and the Wollemi National Park World Heritage Area located 2.5km away;

c. Untested data assumptions taking prominence over measured data in models, e.g. assuming that local landowners have been pumping their full groundwater entitlements, when local landowners state they had not (as stated to me on the date of my presentation to the NSW IPC); (see also Section 4.1.5)

d. Appropriateness and lack of justification of various other environmental process simplifications in modelling;

e. Selection of fit for purpose modelling tools given the nature of the project impacts, e.g. no application of an integrated, distributed surface water – groundwater model (Document 11, p. 57) to simulate and understand the water balance impacts of near-surface subsidence induced fracturing on surface water – groundwater interactions and water availability in NSW State Forest, Bylong River and underlying alluvium. The adopted MODFLOW models are normally focussed and/or biased towards predicting deep depressurisation impacts rather than shallow surface-water groundwater interaction processes and leakage impacts;

f. KEPCO's interpretation of NSW Environmental Law and the NSW Aquifer Interference Policy 2012 (e.g. Document 35, Section 2, p. 3). In my opinion, KEPCO has a duty as a responsible miner to inform on, and ensure protection of, the long-term viability of water sources and ecosystems on land they currently own from "more than minimal harm", especially after mining is complete;

g. Likely errors in modelling and misunderstandings of how confined groundwater flows, e.g. Document 35 Section 7, p. 9 highlights the Specific storage (Ss) values for confined aquifers were inconsistent with geotechnical engineering knowledge noting; methods for avoiding this were described in Pells and Pells, 2015 (Document 35 Section 7, p. 9);

37. In terms of specific issues, the Pells Consulting Submission (Document 35) prepared by two experienced engineers, provides a succinct 13-page summary of some of the critical assessment issues that I can relate to as an engineer. These issues were raised in response to KEPCO's Response to Submissions (RtS) and include (p.2):

a. "Impacts of expected subsidence on Bylong Valley Way

b. Impacts of subsidence and cracking on regional farmland

c. Stability of cliffs

d. *Impacts of cracking on Dry Creek and limitations of proposed rectification measures*

e. *Assessment of post-mining flow frequency in the Bylong River*

f. *Consideration of uncertainty in borefield yields and impacts to the alluvial aquifer*

g. *Incorrect storage values used in groundwater modelling*

h. *Inadequate consideration of groundwater modelling*

i. *Inadequate representation of groundwater in upper 200 m of strata"* (i.e. below the NSW State Forest above the proposed longwall mine)

38. The Pells Consulting Submission (Document 35, Section 8, p. 10-11) discusses uncertainty in model predictions and noted "*Groundwater impacts (and drawdown mapping) asserted within the main text of the EIS were declared on a single model outcome alone. This is inappropriate, and we request that determination of the project is done on the basis of the predicted range of impacts rather than a single 'mean' model run*".

39. Some of the above matters have been considered as part of the supplementary RtS and PAC review process. However, in my opinion, not all matters have been considered, or considered properly by addressing the technical study limitations and/or errors.

40. I discuss some of these issues and additional matters below. Dr Steven Pells (now of PSM) who jointly prepared Document 35 referenced above would be better qualified to comment on various geotechnical aspects of subsidence and whether his concerns have been satisfactorily addressed in response or by conditions.

41. I have not considered the matter of impacts to agricultural soils further, however, I noted that the Gateway Panel, expressed some concern in this regard at the beginning of the EIA process (Document 8, Section 3.1.1, p. 19).

4.1.3 Matters of inaccurate specific storage

42. See slides 13-16. Specific storage (Ss) is a property of both earth and water that describes how much water is released from storage in a pressurised (confined) aquifer for each metre decline in hydraulic head. Specific storage forms part of the hydraulic diffusivity term in the transient groundwater flow and transport equation:

$$\nabla h^2 = \frac{dh}{dt}\frac{Ss}{K} + R - D \qquad (1)$$

Where:

- ∇ is the Laplace operator;

- h is the piezometric (hydraulic) head (or pressure) at a location;
- t is time;
- K is the hydraulic conductivity of the earth to a fluid. It may help to think of K as a conductance term that describes how easily water can move through the ground because of the size and connectedness of the water filled pore spaces in the earth;
- Ss is the specific storage, which is a property of both earth and water that describes how much water is released from storage in a pressurised (confined) aquifer for each metre decline in hydraulic head;
- R is the combination of all sources of groundwater recharge into the aquifer; and
- D is the combination of all sources of groundwater discharge out of the aquifer.

43. Being part of the hydraulic diffusivity term of the groundwater flow equation, Ss has a significant influence on how quickly groundwater levels fall in response to groundwater abstraction and how quickly groundwater levels rise in response to recharge, or the cessation of groundwater abstraction. Similarly, Ss also significantly influences how quickly a pressure disturbance (e.g. groundwater drawdown) propagates away from an aquifer interference activity (e.g. pumping / injection well, mine) to a more distant groundwater user, surface water body or groundwater fed ecosystem.

44. According to a recent peer-reviewed publication in an esteemed international journal (Document 45, Rau et al., 2018) specific storage cannot be larger than approximately 1.3×10^{-5} m^{-1} since this is the upper limit of Ss accommodated by poroelastic theory (see attached copy of Rau et al. 2018 in Appendix D and illustrations in slides 17-19 of attached presentation)

45. See slides 20-23. The specific storage values presented in Document 10, Figure 19, p. 41, of the Response to Submission by AGE for layers 1, 2, 3, 7, and 8 of the AGE groundwater model are larger than the upper limit of poroelastic theory mentioned above. This EIA reporting figure is reproduced in this report with overlays as illustrated in Figure 4.1. If these parameters were the basis for modelling and model calibration, then the modelling predictions reported throughout all of the EIA documents are not accurate in the context of the latest peer-reviewed and accepted science. It is also very important to note that the specific storage values in layers 7 and 8 are critical for establishing the propagation of drawdown from mining activity both laterally and vertically away from the coal seam. Unrealistically large values of Ss in these model layers could lower the magnitude of the drawdown impacts predicted to be caused by the proposed development

46. Consequently, the validity of the proponent's understanding of groundwater flow processes at the site must be questioned or at least very strongly qualified. In my opinion, the model calibration and predictions must be completely reworked to test this uncertainty, however, this has considerable implications. Therefore, I request that this matter be referred to the IESC for consideration and advice, if it has not been dealt with already in the context of Rau et al. (2018).

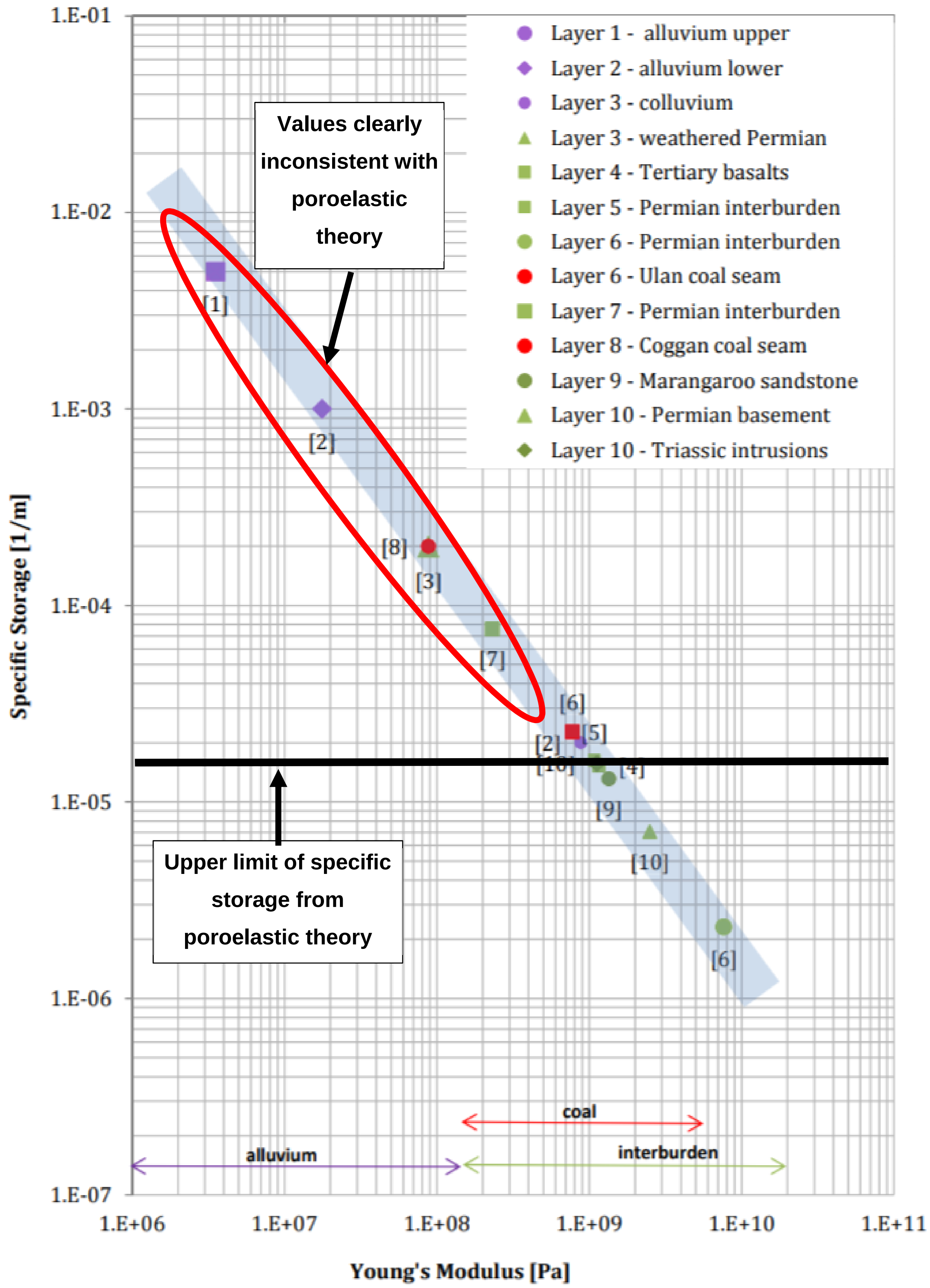

Figure 4.1: Limit of specific storage from Rau et al. (2018) (Document 45) overlain on Figure 19 from Appendix H of the Response to Submission (Document 10)

4.1.4 Matters of sensitivity to specific storage

47. As can be seen from Equation 1, the value of specific storage applied in the model is important for correctly calculating the drawdown that occurs in the aquifer system. All of the following factors which influence the availability of water determine how fast groundwater falls when there is no, or below average rainfall:

    a. changes in groundwater discharge caused by natural discharges (i.e. transpiration and baseflow to streams, rivers and springs);

    b. irrigation activity;

    c. capture of water by mining activity in voids and various mine water storages; and

    d. Movement of groundwater and surface water into and through subsidence fractures.

48. My opinion is that the model predictions are sensitive to the chosen values of specific storage can also be verified by reviewing the linear uncertainty analysis results presented by the proponent in Document 10 (section 5.4, p. 67). I pose some of my opinions and statements as questions as I do not have access to the computer model files to check:

    a. The simulation results presented in their Figure 40 on p. 72 (reproduced as Figure 4.2 in this report) demonstrate that the borefield yield is sensitive to the Ss parameters in the alluvium (ss01 and ss02) and Tertiary Basalts (ss04). I have not reviewed why the borefield yield is completely insensitive to parameters ending in "03", which I presume are in model layer 3. It may be because there is no thickness of this model layer or observation data in this model layer near this location. It would be interesting to know how sensitive the results are to specific storage in deeper bedrock layers given the observations made in respect of the inconsistency with the latest accepted science as stated at 45.

    b. The simulation results presented in their Figure 42 on p. 74 (reproduced as Figure 4.3 in this report) clearly demonstrate that maximum drawdown variance is sensitive to the Ss parameters in the bottom layer of alluvium (ss02). I have not investigated why the modelled drawdown predictions are completely insensitive to the values of specific storage adopted for the other zones. Given equation 1, and because the borefield yield is sensitive this would be a good point of further discussion. It would also be interesting to know how sensitive the drawdown results are to the specific storage values in all model layers (especially models layers 5, 6, 7 and 8).

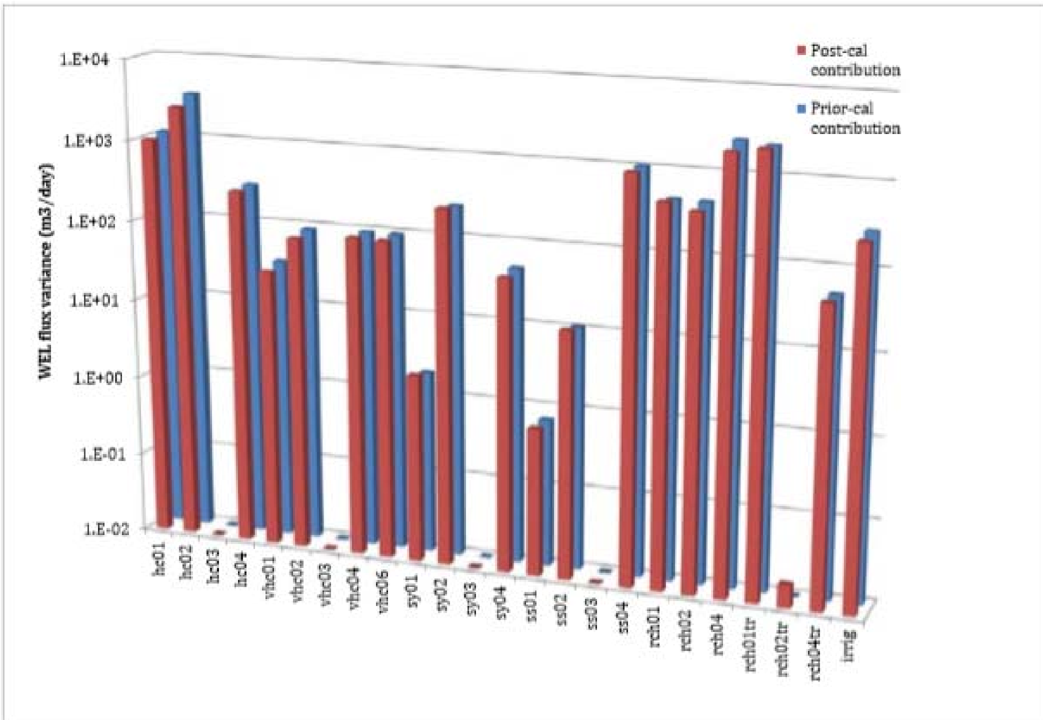

Figure 4.2: Parameter contribution to uncertainty in borefield yield **(source: Document 10, p. 72)**

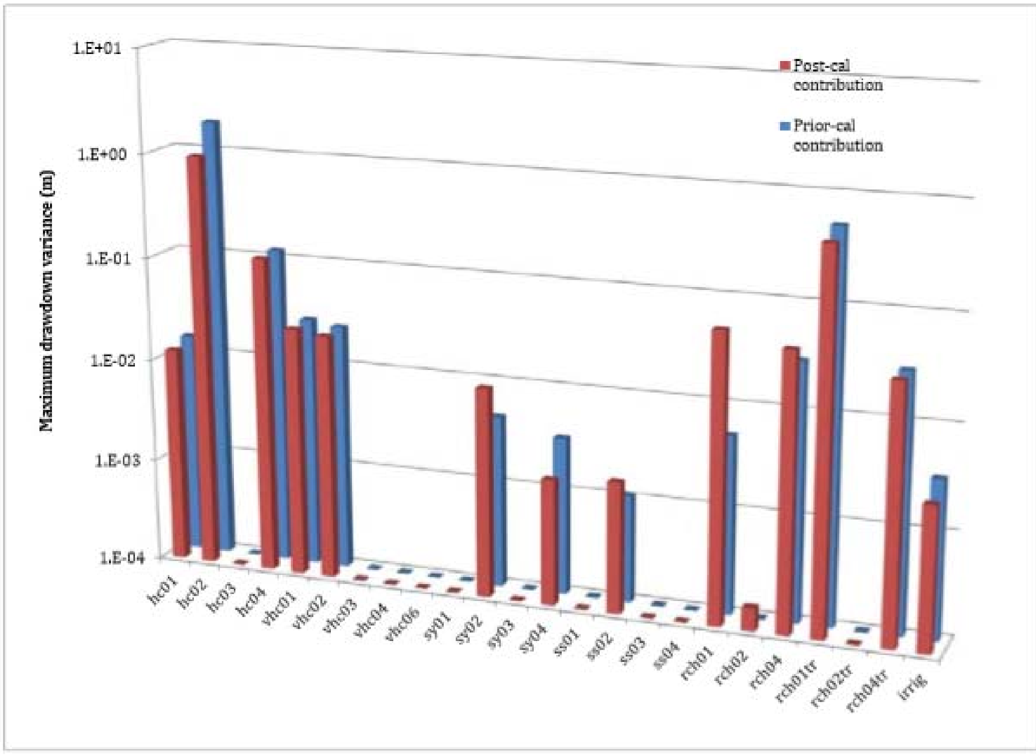

Figure 4.3: Parameter contribution to uncertainty in drawdown (Source: Document 10, p. 74)

a. In my opinion, the lack of sensitivity to specific storage to some model zones described above may, in part, be due to all the values of specific storage in the linear uncertainty analysis being above the limit imposed by poroelastic theory as stated already at 44. Figure 4.4. demonstrates why models with values of specific storage above the limit of poroelastic theory could appear insensitive to small adjustments in specific storage.

b. Given equation 1, and because bore yield is reported sensitive to zone ss04 (Tertiary Basalt) but drawdown is not, it may be that in the model that the hydraulic conductivity and/or the specific storage of the basalts is very high. In Document 35 (p. 10, Figure 3) it has been suggested that the modelled specific storage value for the basalt is slightly too high compared to geotechnical considerations. Consequently, to maintain the same hydraulic diffusivity value the specific storage and hydraulic conductivity values for the basalt aquifer would need to be reduced and recharge increased to maintain model calibration.

49. Figure 4.4. presents the drawdown simulated in a computer model of a homogenous 45m thick, confined sand aquifer with hydraulic conductivity of 1 md^{-1}, confined by 30m of groundwater pressure and subject to a single aquifer interference activity pumping groundwater continuously at 8.68 L/s for 5-years during a drought. Drawdown predictions are shown for a range of assumed values of specific storage. Note that cool colours represent realistic values of specific storage consistent with the limits of poroelastic theory. Warm colours represent incorrect values that are too large.

50. While this example in Figure 4.4. does not represent the geometry or conditions of the aquifer at Bylong, it does highlight several important facts, for drought conditions in confined aquifers which are:

a. Models utilising large, unrealistic values of specific storage predict very little drawdown;

b. Models utilising large, unrealistic values of specific storage could be mistaken in uncertainty analysis to be largely insensitive to the specific storage value in respect of drawdown;

c. Model predictions are sensitive to the adopted values of specific storage until such time as the capture of water by the pumping well is balanced by flow from surrounding boundary conditions (this is called steady-state conditions);

d. Models utilising realistic values of specific storage may predict significantly more drawdown than the models utilising large, unrealistic values of specific storage;

e. Models utilising realistic values, rather than large values of specific storage may predict greater baseflow impacts (reductions) to connected surface water systems;

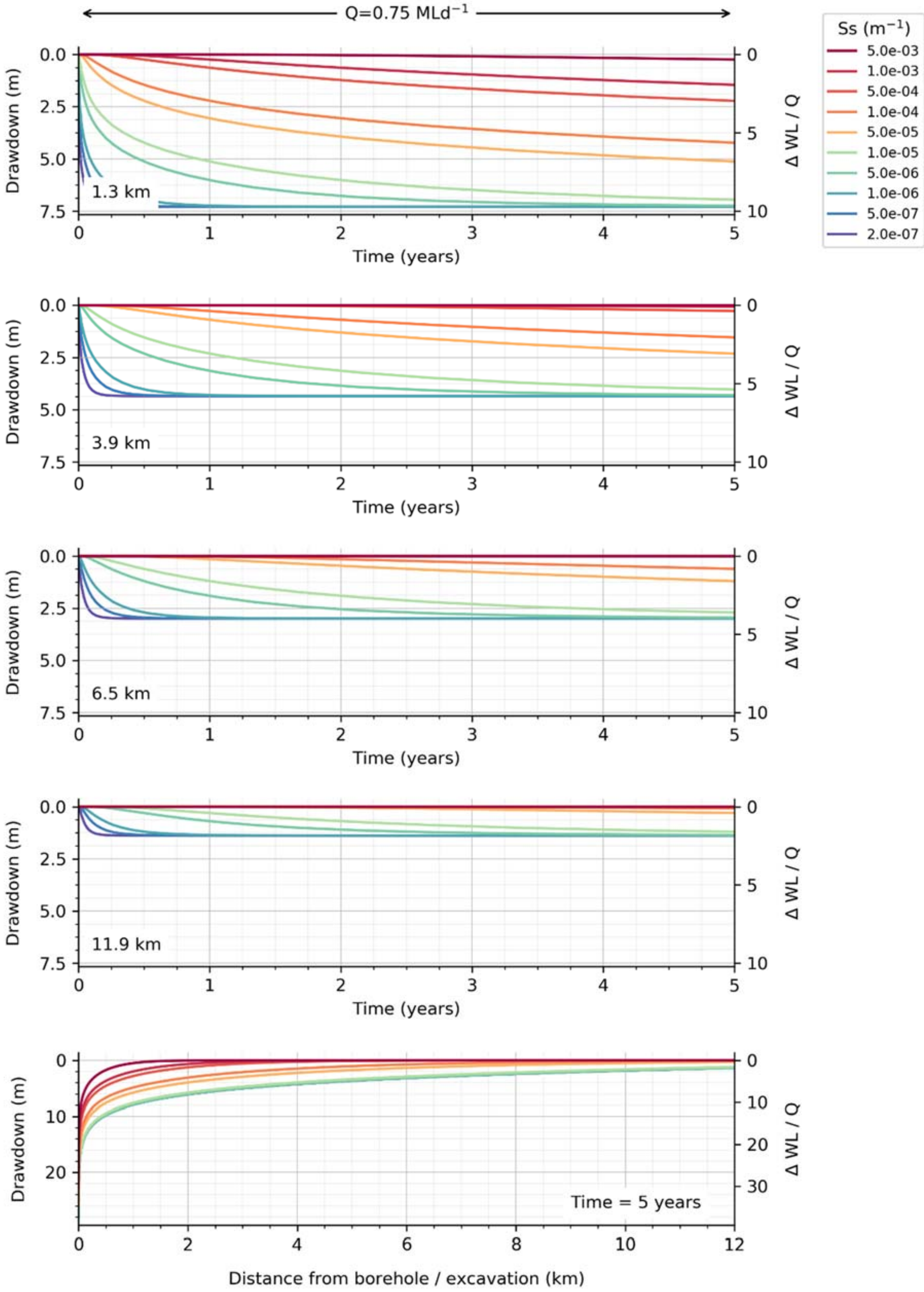

Figure 4.4. Drawdown predictions for hypothetical aquifer K=1.0 m.d^{-1}, Q=0.75 ML.d^{-1} for 5 yrs

f. Models utilising realistic values of specific storage (or geological units with smaller values of specific storage) predict that drawdown travels away from the pumping well much more quickly than models utilising unrealistic values of specific storage.

g. For the example presented in Figure 4.4, which is not a model of Bylongaquifers, decreasing the specific storage from 1 x 10^{-3} m^{-1} (equivalent to layer 2 of the EIA model) to 1 x 10^{-5} m^{-1} (equivalent to about the maximum value allowed by poroelastic theory) changes drawdown from less than two (2) metres after five years of pumping to:

   i. About 7.5 m at distance of 1.3 km from the pumping well after just three (3) months;

   ii. Almost 4.3 m at a distance of 3.9 km after just three (3) months; and

   iii. Just over 3.0 m at a distance of 6.5 km after just three (3) months.

h. Utilising unrealistic values of specific storage in numerical models can be the difference between a computer model that predicts no more than minimal harm under the NSW Aquifer Interference Policy 2012, and a model that predicts more than minimal harm.

i. Baseline monitoring might not be possible once ground disturbance works have commenced because pressure disturbances can move quickly.

51. Designing a groundwater monitoring program and a water management plan on the predictions of a model based on unrealistic values of specific storage may lead:

    a. to inadequate safeguards, a failure to protect water assets, ecosystems and primary producers from aquifer interference impacts, and

    b. a failure to recognise when it is time to make good as per the requsts of the *NSW Aquifer Interference Policy 2012*.

52. Consequently, in my opinion, for all the reasons stated above, I am concerned that the EIA is not predicated on a correct and/or clearly stated understanding of groundwater flow. I request this matter be resolved and key stakeholders are provided with opportunity to comment on and review the responses on this matter at an appropriate time so the predictions of the groundwater model provided to date can be placed in the appropriate context.

53. I continue the discussion of this matter in Section 4.2

4.1.5 Other matters of data

54. Matters of site investigation, monitoring, complex numerical modelling, groundwater and connected surface water assessment and reporting have been ongoing for SSD 6367 for approximately seven (7) years (Document 23, their Figure 2-1; reproduced as Figure 4.5 in this report).

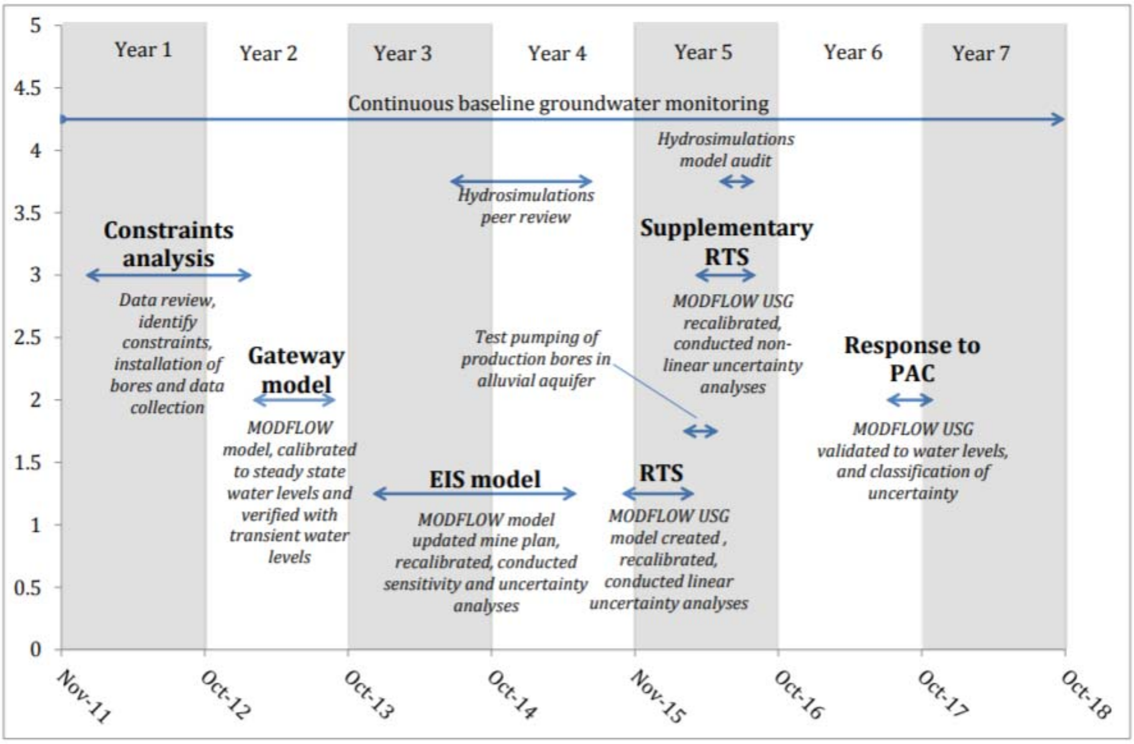

Figure 2-1 Timeline showing evolution of numerical model

Figure 4.5: Timeline of groundwater impact assessment (Source: Document 23)

55. The amount of field investigation and hydrological and hydrogeological data analyses from first principles described in Figure 4.5 appears minimal in comparison to the complex numerical modelling work that has been undertaken. This view is also stated in more technical detail in the various technical submissions on the EIS and RTS by various agencies of government and community stakeholders (as listed in Appendix A and B). Figure 1 which was produced in response to the PAC review report.

4.1.6 Matters of drought, aquifer interference and aquifer sensitivity

56. From the materials I have considered to date, which include some of the geological cross sections (see slides 4 and 5 of my presentation) that show a single measured groundwater level and layered unconfined and confined alluvial sediments and the conceptual model (see slides 24-26) I have formed the following opinions based on my skills and experience:

    a. The groundwater pressures in the Bylong alluvial aquifers will be very sensitive to the cumulative effects of climate and aquifer interference, whether this be from groundwater or surface water takes by agricultural or mining activity for the following reasons:

i. The aquifer appears to be recharged by leakage from surface water bodies such as the Bylong River. Therefore river flow is important for maintaining aquifer levels.

ii. Since the longwall mine may cause near surface subsidence fracturing (or seam to surface subsidence fracturing as was reported by MSEC engineers in the Gateway Panel report – Document 39) there is some risk that stream flows from NSW State Forest may be reduced at some points in time. These reductions would be in addition to those streamflow reductions simulated to be caused by depressurisation effects from groundwater inflows into the mined-out voids. Therefore it is important to check how reliably near surface subsidence was fracturing simulated in the EIS groundwater model. Such processes were not simulated in the EIS numerical model of the Metropolitan Coal Mine in the Southern Highlands);

iii. The clean sand aquifers shown beneath the Bylong River are thin and do not store significant quantities of water as compared to other sites I have worked at;

iv. These aquifers are underlain by more silty and sand clay materials that may drain relatively quickly compared to the overlying cleaner sands when there is competing water demand (this layering would be challenging to represent in a computer model);

v. In some locations there appears to be a confined clean sand aquifer above weathered bedrock. Pressure disturbances from water use travel much more quickly through confined aquifers than unconfined aquifers. This may be challenging to represent in a computer model;

vi. Coal seams presumably containing confined groundwater subcrop (almost reach the surface) near the alluvial aquifers. Measuring the hydraulic properties of coal seams is not always undertaken in detail;

vii. There is, therefore, good reason to believe that during a drought the groundwater levels could fall quickly towards the bottom of the alluvial aquifer due to:

    1. the combined effects of pumping from groundwater wells,
    2. decreased runoff from harvestable rights and mine storages,
    3. induced recharge into near surface subsidence fractures,
    4. depressurisation from long-wall and open cut mining,
    5. shallow groundwater movements deeper underground on account of groundwater capture by mined-out voids and subsidence fractures;

viii. The modelling works as summarised (see also slide 6 of my presentation) demonstrate that small changes in modelling software, modelling approach and assumption result in substantially different predictions of drawdown in the alluvial aquifer and elsewhere.

4.1.7 Matters of groundwater management, equity and making-good

57. During my examination of the documents listed in Appendix A and B, I have not identified any costing of the water and water-related impacts of the development.

58. Similarly, I have not identified any commitment from NSW Government or KEPCO that existing landowners will be compensated if licenced surface water or groundwater entitlements near the proposed mine suddenly or gradually reduce or become unavailable. The only commitments provided so far are to consider how this might happen after the project has been approved. Based on past practice, this has been problematic. Section 4.2.4 provides further details.

59. In my opinion, while calculations of aquifer interference and reductions in pressure or water levels are useful indicators of system state and inform discussions about how to make good, the amount of water in any one locality is finite. Therefore, whenever there is uncertainty about the structure of the subsurface and all its properties of hydraulic conductivity, specific yield and specific storage in the X, Y and Z directions, and consequently the reliability of predictive models, the presence or absence of water at a borehole that used to pump groundwater is usually a good indicator that an aquifer interference impact has occurred.

4.1.8 Matters of policy and practice

60. The impacts of mining activity can last for many decades or even hundreds of years. More presentations of impact should be provided at different times. Slide 7 of my presentation to the NSW IPC presented a graph prepared by an international hydrogeologist, J. Bredehoeft of a hypothetical aquifer system subject to a pumping disturbance with observations of baseflow changes to a spring (Document 50). His graph highlights that the impacts of aquifer interference continue to increase for many years after pumping stops and that it takes centuries for the flow to the spring to recover to baseline conditions. This highlights the importance of being provided with sufficient predictions of post mining impacts, especially when mine voids will continue to capture water after the mine has stopped operating and the voids fill with water.

61. In the materials I have examined, for the latest groundwater modelling assessment report presented by the proponent (Document 30, last page), the water balance on the last page does not satisfy the request of the *NSW Aquifer Interference Policy 2012*, reproduced in this report on p. 24 in Section 4.2.2 at 75. The request is to provide information about all changes in flow,

including after mining is complete (as these impacts can last decades or up to a century). The information provided in Document 30 stops at year 25.

62. Therefore, in my opinion, there needs to be some consideration of how to apply NSW Water law to fully assess and cost the impacts to the State's water resources beneath KEPCO's vast land holdings. This is especially important if they relinquish their land title in part, or in full, shortly after mining. Related issues are noted in Document 35, p.3, Section 2. I provide additional context in reply to these issues at Section 4.2.3 and discuss this matter further below.

63. In my opinion, the community should be afforded the opportunity to review and comment on the revised, predicted future water balance impacts of the proposed development from the latest groundwater model. Without this revised information, the community may not fully appreciate what might happen to the water entitlements currently held by KEPCO once mining ceases. I also request that the NSW IPC confirm with NSW DI Water that that sufficient predictions of water balance impacts, groundwater level predictions and baseflow impacts through time have been provided from the available models to the end of mining activity, to support both groundwater impact assessment and management.

64. The Proponent has not posted the historical groundwater level fluctuation data on the detailed geological cross-sections or similar long section figures that I have seen. This presentation would provide information that can be clearly and reliably understood by decision makers and environmental engineers to facilitate their decision / design work to achieve the best outcomes e.g. design of a robust monitoring and groundwater management program. In my opinion, this information is required to clearly communicate system understanding of the how the system responds to climate and the risks of the project in terms that decision makers, water management plan, and make-good plan developers can understand.

65. In my opinion, the above cross-sections should also be presented additionally showing the groundwater model predictions of drawdown from all available models during clearly defined droughts of various durations, based on appropriate starting water table conditions, and consultations with landowners to established their actual groundwater use (if not done already). KEPCO and NSW Government and landowners need to have access to this information to make reliable predictions and prepare reliable management and business plans for the future. In my opinion, the project should not be allowed to break ground until NSW DI Water is satisfied this has occurred and the impacts of the project can be managed without significant economic consequences.

4.1.9 Matters of precaution

66. In my opinion, based on all of the above, it would be precautionary to assume that impacts from SSD 6367 could be either larger or smaller in various locations than the model predictions presented to date, simply because the modelling work contains limitations and demonstrates sensitivity to data and assumptions. If the project is approved, very careful consideration needs to be given to how potential aquifer interference might impact water users, especially during drought.

67. The models developed for this project have limitations and the predictions of these models appears to arise from incomplete system understanding. The project will place additional surface water and groundwater demand into the Bylong Valley. Given the sensitivity described above, and to avoid unnecessary conflict, there needs to be certainty that the risks and consequences of all these matters are not placed onto existing water uses, when the revenue from the mine is shared all across NSW.

4.1.10 Conditions

68. The draft conditions request a detailed site water balance and some necessary inclusions are specified. However, there are some ambiguities, e.g.:
    a. What is the complete definition of ‘detailed’?
    b. The extent of site is not defined. Will the definition of site extend all the way from the development to encompass at least the entire groundwater capture zone of the development?
    c. Will a quantified, conceptual model diagram of the water balance be required on cross-section and in plan-view figures at different locations and spatial scales?
    d. Will the site water balance include all aspects of hydrology and hydrogeology? I provide some examples of conceptual water balance models of a hypothetical longwall mining impacted inflow and groundwater dependent ecosystem in the attached presentation (see slides 24-26).

69. In my experience, on many past developments, ambiguities with regard to what constitutes a ‘detailed’ water balance are a principal source of assessment uncertainty, consequential environmental management issues and problematic aquifer interference outcomes. A thorough understanding of water balances is required to understand where, when and how impacts will be observed. These conceptual models and water balances should be prepared at the very beginning of an assessment from data and revised throughout the assessment process.

4.2 General matters for consideration

4.2.1 Data and analyses supporting complex modelling

70. Comprehensive collection and analysis of hydrological and hydrogeological field data and preparation of detailed geological models (outside of groundwater flow models) is critical for developing conceptual and environmental process understanding of baseline, mining and post-mining conditions. Complex modelling should not be attempted without this work, unless accompanied by comprehensive uncertainty analysis and full testing of all modelling assumptions and limitations by highly experienced practitioners.

4.2.2 "Complex" modelling assessment "requirements"

71. The *NSW Aquifer Interference Policy 2012* (NSW AIP 2012) which requests "complex" modelling in assessment and management of aquifer interference impacts from SSD, does not objectively define minimum standards of supporting data and data analyses to minimise predictive uncertainty and achieve quality groundwater management outcomes.

72. The NSW AIP 2012 is a derivate policy of the *Water Management Act 2000 NSW* (WMA 2000). It is designed to help avoid and/or manage the local scale impacts of competing developments that cannot be managed by catchment or basin scale water accounting systems.

73. The NSW AIP 2012 is not a yet a statutory instrument under the WMA 2000 because the "*more than minimal harm*" licencing provision for protection of water sources and ecosystems has not been activated.

74. Nonetheless, the policy is still "*NSW Government policy for the licensing and assessment of aquifer interference activities.*" In my opinion, therefore, the policy was created by the then NSW Office of Water (now Department of Industry (DI) – Water) to give effect to its obligation to manage water sources to promote economic production (by ensuring security of supply) whilst also balancing these considerations with the principles of Ecologically Sustainable Development (ESD). ESD is defined in the *Protection of the Environment Administration Act 1991 NSW* (POEA 1991). An object of the *Environmental Planning and Assessment Act 1979 NSW* (EP&A Act 1979) under which SSD is assessed is to promote ESD in the planning process.

75. For SSD projects assessed under Part 4, Division 4.1 of the *Environmental Planning and Assessment Act 1979* (NSW), the NSW AIP states the following minimum requirements for proponent's "complex" model estimations of "*all quantities of water taken from any water source during and following cessation of the activity and all predicted impacts associated with the activity*" are:

a. "*Calibrated and validated (where practical) to the available baseline data that has been collected at an appropriate frequency and scale and over a sufficient period of time to incorporate typical temporal variations*";

b. "*In instances where an activity has a high likelihood of causing more than minimal harm to a "reliable water supply", at least 2 years of baseline data is required*";

c. "*Consistent with the Australian Groundwater Modelling Guidelines*";

d. "*Independently reviewed and determined to be robust and reliable, and deemed fit-for-purpose to the satisfaction of the Minister*"

4.2.3 Concepts of "minimal harm" and "long-term viability"

76. The NSW AIP states (p.12):

> *"The Water Management Act 2000 includes the concept of ensuring "no more than minimal harm" for both the granting of water access licences (see Section 2) and the granting of approvals. Aquifer interference approvals are not to be granted unless the Minister is satisfied that adequate arrangements are in force to ensure that no more than minimal harm will be done to any water source, or its dependent ecosystems, as a consequence of its being interfered with in the course of the activities to which the approval relates.*
>
> *While aquifer interference approvals are not required to be granted, the minimal harm test under the Water Management Act 2000 is not activated for the assessment of impacts. Therefore, this Policy establishes and objectively defines minimal impact considerations as they relate to water-dependent assets and these considerations will be used as the basis for providing advice to either the gateway process, the Planning Assessment Commission or the Minister for Planning."*

77. The objective minimal impact considerations specified in the policy relate to fixed water assets that take water on privately owned land and also identified and defined groundwater dependent ecosystems considered to be important. Future (new) groundwater works that may need to take water in the locality to support economic activity and unidentified, sensitive inflow or groundwater dependent ecosystems that may be impacted by the groundwater and associated surface water impacts of development are not explicitly protected by the NSW AIP 2012. In my opinion, these protections are best provided at an economic level through improved valuation, pricing and incentive mechanisms; the final principle of ESD defined in the POEA Act.

78. p. 12 and 15 the NSW AIP 2012 state:

    a. When certain water pressure levels and thresholds are exceeded the Minister must be satisfied that "*the decline will not prevent the long-term viability of the affected water supply works unless make good provisions apply*"; and

    b. "*The NSW Officer of Water's assessment will determine the potential level of impact […] and will identify where further mitigation, prevention or avoidance measures would be necessary […] or […] what further studies are necessary to assess whether the project will not prevent the long-term viability of a relevant dependent ecosystem or significant site*"

4.2.4 Limitations of the NSW Aquifer Interference Policy

79. The AIP does not define and provides no guidance on how to calculate the long-term viability of a water source or asset. It also does not define what make-good provisions must be, nor objectively quantify how, when and why they must be triggered.

80. In practice, in my experience to date, with the exception of the Hume Coal Project, the above definitions tend to be made by consultants employed by mining companies, or the mining companies themselves with review by NSW DPE and NSW DI Water. These definitions tend to get developed post-approval at the Water Management Plan development stage sometimes without any input from or consultation with the stakeholders who are actually at risk of the aquifer interference activity.

81. For the Hume Coal Project, large impacts were predicted during the EIS. Concerns about make-good were raised by the community and considerable effort has been made by all parties upfront during EIA to define what make-good means, how it is measured, how uncertainty in models, knowledge and climate should be managed to decide when make-good should occur, how quickly it should happen and who should pay if a landholder has lost access to water and all parties cannot agree the reasons why.

82. In my experience reviewing historical management plans, the approved definitions of performance measures, trigger levels, and the definition of how a more than "minimal harm impact" is quantified are highly subjective, if defined at all. This places all the risks of limitations in knowledge and the understanding of aquifer interference impacts onto the stakeholders (water users and environment) at risk of aquifer interference. Consequently, when aquifer interference impacts do occur, and/or when they do occur but are not properly understood, long-lasting and costly dispute entails which is unhelpful for the water user that cannot access water.

83. In my opinion, the capital and operational costs of pumping water from deeper below ground and the lost economic production due to entitled water not being available at the right time for any party, is the responsibility of the owner and the manager of the groundwater source (i.e. NSW Government). NSW Government charges fees for groundwater and surface water.

84. Under Australian Consumer Law there are consumer guarantees associated with the purchase of goods and services and the right to compensation for damages and loss if there is a problem with a product or service when the supplier could have reasonably foreseen the problem.

85. Large mining operations can take significant quantities of both runoff and groundwater which are then evaporated or stored in mine-voids, possibly deep underground. Any subsidence and depressurisation impacts associated with a development will also redistribute water within the catchment, typically resulting in surface water and shallow groundwater migrating deeper underground or elsewhere in the catchment, bypassing some surface water features.

86. When a large coal mine is added close to existing groundwater water users, there will be competition for groundwater. In good times when water is plentiful, no impacts may be observed, or the impacts may be acceptable. However, during droughts when everyone is taking their share of water that they purchased, then there may not be enough water to go around (without spending extra money to obtain that water). Consequently, some water users may be disadvantaged by needing to spend, or being unable to afford or obtain finance, for additional labour and materials and/or electricity to obtain water from deeper underground and/or from an alternate source (if available).

87. NSW Government currently earns substantial revenue from mineral leases and revenue from mining. This revenue is obtained by selling rights to resources that have predicted water impacts, which may be larger or smaller than reality. When impacts (or any perceived impacts) do occur, the direct and indirect costs of water – energy conflicts reduces the productivity of all parties, but those stakeholders without or with less water may be disadvantaged more than others.

4.2.5 A more efficient business model for making-good

88. NSW Government could establish an “aquifer interference fund” for each development project which is set equal to:

    a. the value of the water predicted to be used and otherwise diverted or wasted by mining operations, plus

    b. the value of electricity, materials and labour required to pump existing entitlements from deeper underground based on the model predictions accepted by NSW Government when approving development, plus

    c. some risk weighted allowance for compensation in the event that water entitlements which have been purchased cannot be provided in an appropriate amount of time and it can be demonstrated that primary production has been lost and/or fixed assets have become stranded as a consequence.

89. A model of this nature would be best practice and help reduce water – energy conflicts by not placing all the direct risks of bad outcomes onto existing water users located near or beside new development. Similarly, when bad outcomes do occur, the business model would limit the indirect economic costs associated with conflict between miners, government and other primary producers.

90. Deciding when to make good would then be a matter (and I simplify for brevity) of:

    a. requiring the landowners at risk of aquifer interference to keep records of their water use with a cheap water metering device and share this data freely – thereby solving the water metering problem that is the bane of every groundwater modellers existence and which creates so much uncertainty and debate in the predictions of groundwater models; and

    b. using those improved models of groundwater flow to determine the buffer distance from a mining development where any loss of water supply, e.g. during a drought, would be immediately and automatically compensated for by the aquifer interference fund in the form of an interest free loan (a suitable buffer distance for Bylong might be about 7 km); and

    c. NSW Government then undertaking an investigation (if it were deemed cost effective) to review water balances, check metered water use data, reliability of model calibrations and predictive uncertainty at their leisure (rather than in urgency) to decide if there was enough scientific certainty in understanding not to discharge the loan and/or prosecute any particular party for meter-tampering and/or theft of water.

91. In my opinion, this proposed business model has the following advantages:

    a. Businesses can get on with business;

    b. Governments can get on with governance;

    c. Engineers can get on with engineering projects that create revenue for NSW; and

    d. Mining companies get on with mining and spend less money on:

        i. tackling the complexities of defining performances measures, trigger levels for investigations and make-good arrangements in Water Management Plans that, in my opinion, currently do not work and create conflict (and equally more work through conflict);

        ii. developing and maintaining complex models that are not supported by enough field data;

        iii. some forms of monitoring (to improve reliability in water balance monitoring and modelling so the models that are developed are more reliable)

4.2.6 Appropriate assessment practice

92. In my opinion, as a general principle, when key EIA requirements in respect of water related impacts have not been met or poor quality work is presented, EIA should not be accepted, marked as incomplete, and returned to the development proponent for revision so risk based decision making is evidence based and in the interests of the people of NSW. The basis for my opinion is that failure to do this does not encourage the development of best practice.

93. In my opinion, good quality water work enables good quality project design, and appropriate monitoring and environmental management that provide economic, social and environmental prosperity. In contrast, poor quality water work may lead to poor quality project designs and inappropriate monitoring and environmental management plans. When that happens undesirable social, environmental and economic externalities may result in the form of “unplanned” or “non-agreed” aquifer interference as described already.

4.2.7 The technical basis for stakeholder concern

94. In my experience, stakeholders have a good understanding of their land and water from many decades of observation and they generally have a good idea of when something unusual is happening to the water source(s) they use.

95. Through attendance at university courses on groundwater, or their own private study, many agricultural stakeholders often have a good working knowledge of the various technical aspects of groundwater flow, monitoring and modelling. Consequently, when they read groundwater impact assessment reports and express concern there is usually an underlying technical basis, which is usually a modelling assumption or limitation that does not accord with their understanding and experience. Therefore, when stakeholders perceive a risk of something bad happening to them because of untested assumption or limitation, they naturally express concern.

4.2.8 Some limitations of modelling practice, that place statements that models are fit, reliable and built for purpose in context

96. A groundwater model that is stated during EIS to conservatively (over) predict groundwater drawdown at one location (e.g. around a mine) must intentionally (or by necessity) misrepresent certain conditions and environmental processes to achieve this. Therefore, “conservative” models must underpredict groundwater drawdown impacts at other locations, e.g. much further away from the development in deeper aquifers and somewhat further away in shallower aquifers, if the development is deep underground. Alternatively, or in doing so, that same model may underestimate the groundwater recharge, or overestimate the groundwater pumping rates to provide the “conservative” prediction. In this case, the model misrepresents the water balance and understanding of the local scale impacts of the project and water management are distorted.

97. Consequently, during conceptualisation or calibration, to try and constrain these limitations, the modellers may then, for example, over-estimate the aquifer specific yield and/or specific storage parameters in an attempt compensate for the lack of recharge that really does occur during transient simulation (or to account for the land subsidence that does occur). The modellers may then fail to appreciate the true magnitude of the surface water – groundwater connectivity that does exist and/or the consequences of ground subsidence. Subsequently, or separately, the modellers may then under-estimate the hydraulic diffusivity of the aquifer and the speed at which the pressure disturbance travels away from the aquifer interference activity during a drought. In such examples all the drawdown and water predicted to enter a mine might be predicted to originate from very close to the proposed aquifer interference (e.g. from “fake”

specific storage) when in fact more water comes from further away or from directly above (which has implications for connected surface water – groundwater management). There are of course other possible combinations of assumptions, limitations and outcomes; this is only one example.

98. The above limitations highlight the fundamental importance of analysing groundwater levels and water quality data for recharge-estimation and metering groundwater takes. Therefore NSW Government needs to ensure metering can take place and landowners must meter their bores and be prepared to share their water use data. If they do not do this, they risk placing themselves at a distinct disadvantage from aquifer interference simply because engineers and groundwater modellers have no way of understanding or simulating their water use.

99. However, the engineers and groundwater modellers themselves are not without fault if they make no attempt to undertake fundamental hydrogeological analysis of groundwater level and water chemistry relationships to estimate the relationships between rainfall, groundwater recharge and specific yield from monitoring data and pump testing. Large groundwater impact models do not typically resolve the knowledge contained in such data-sets in the data calibration process. This is because such models typically operate at large temporal and spatial scales and do not simulate geochemistry or high frequency climatic variations for practical reasons of cost and numerical efficiency.

100. Therefore, while modelling simplifications are usually carried out in good faith or out of necessity, problems do result if additional conceptual and numerical models are not created to address the limitations of the modelling simplifications and assumptions, e.g.:

    a. The highly localised impacts that might occur at specific locations when unmapped geological structures or known geological structures exert a significant influence on groundwater flow because they are not represented reliably in the model (either because this is difficult or takes a lot of time). Consequently, these impacts might not be observed (e.g. in a National Park or World Heritage Area) or might be dismissed as some anomaly until the existence of the geological structure was identified and studied in more detail.

    b. The administrative, adaptive management, social-justice and economic issues when one or more parties in a position of power attach 100% confidence to the prediction of a model when it is known that all models are uncertain and it was stated that the model impacts were conservative in some respect. Therefore while one party may assert the extent of drawdown impact is one small number, the reality may be that it is a larger number and there is no evidence to prove either opinion.

    c. When the focus of one model is to predict depressurisation impacts of deep aquifers from groundwater seepage into mined-out voids, then that model may not have been constructed or may not be able to (either technically or on account of limited observation data and analysis) to predict the integrated groundwater and surface-water impacts of near-surface subsidence induced fracturing. These fractures re-route surface water and groundwater to greater depths underground and different locations in the catchment, changing the water quality in process. Groundwater in general, and in subsidence fractures, is usually anoxic and mineralised. When discharging back to the surface it then reacts with oxygen to deplete dissolved oxygen essential for the survival of aquatics ecosystems. In the past, MODFLOW modellers have not, or have not been able to, simulate such surface – water groundwater interactions. When it is considered that such processes are important, they are best examined from first principles or in an integrated surface water – groundwater model such as MikeSHE, Hydrogeosphere or COMSOL.

101. Therefore, while modellers and managers like to make use of predictions based on comprehensive data and models, there are practical limits and multiple models are often required to answer all the important questions.

102. In support of my above opinions on the above matters, I have relied on experience and:

a. the equation of transient groundwater flow.

b. the statements of the esteemed international hydrogeologist, Bredehoeft (2005):

“*Limited empirical data indicate that surprises occur in 20–30% of model analyses. These data suggest that groundwater analysts have difficulty selecting the appropriate conceptual model. There is no ready remedy to the conceptual model problem other than (1) to collect as much data as is feasible, using all applicable methods—a complementary data collection methodology can lead to new information that changes the prevailing conceptual model, and (2) for the analyst to remain open to the fact that the conceptual model can change dramatically as more information is collected. In the final analysis, the hydrogeologist makes a subjective decision on the appropriate conceptual model. The conceptualization problem does not render models unusable. The problem introduces an uncertainty that often is not widely recognized. Conceptual model uncertainty is exacerbated in making long-term predictions of system performance*.”

5 Declaration

103. I have made all the inquiries that I believe are desirable and appropriate and that no matters of significance that I regard as relevant have, to my knowledge, been withheld.

6 Signature

Douglas John Anderson
Principal Engineer – Groundwater and Modelling
Water Research Laboratory
School of Civil and Environmental Engineering
UNSW Sydney

14 / 11 / 2018

Appendix A EDO NSW Brief

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1 November 2018

Dr Doug Anderson
Principal Engineer - Groundwater & Modelling
UNSW Water Research Laboratory

By email: d.anderson@wrl.unsw.edu.au

Dear Doug,

Bylong Coal Project

We act for Bylong Valley Protection Alliance (**BVPA**) in relation to the proposed open cut and underground coal mine by KEPCO's Bylong Coal Mine for the Bylong Coal Project (**Project**). Our client is concerned about any environmental impacts arising from the proposed Project.

The Project has previously been on public exhibition through an Environmental Impact Statement (**EIS**) and Planning Assessment Commission (**PAC**) Review process. As a consequence of the assessment undertaken to date, KEPCO has modified the proposed Project to reduce the size of the open cut pit (**Revised Project**). The Revised Project has now been referred to the Independent Planning Commission (**IPC**) for determination.

Our client wishes to engage you to provide expert advice to the IPC Determination meeting in relation to hydrological aspects of the Revised Project.

Purpose of your expert report

We note as a preliminary matter that our primary purpose in briefing you to prepare your report is to assist the decision maker for the Project. We do not ask you to be an advocate for our client. You are requested to prepare an independent report that is clear and well-written.

In this respect, we draw your attention to Division 2 of Part 31 of the *Uniform Civil Procedure Rules 2005* (**UCPR**), and the Expert Witness Code of Conduct (**Code of Conduct**) contained in Schedule 7 of the UCPR, both of which govern the use of expert evidence in the Court. We enclose copies of the Code of Conduct and relevant UCPR provisions.

In particular, we note that clause 2 of the Code of Conduct states that:

> "An expert witness is not an advocate for a party and has a paramount duty, overriding any duty to the party to the proceedings or other person retaining the expert witness, to assist the court impartially on matters relevant to the area of expertise of the witness."

Your expert report must contain an acknowledgment that you have read the Expert Witness Code of Conduct in Schedule 7 of the UCPR and that you agree to be bound by it.

Your expert report will be used as evidence in chief of your professional opinion. Information which you believe the decision maker should be aware of must be contained in your expert report.

In providing your opinion to the decision maker you must set out all the assumptions upon which the opinion is based. This may include, for example, facts observed as a result of fieldwork or 'assumed' facts based on a body of scientific opinion. If the latter, you should provide references which demonstrate the existence of that body of opinion.

Your expert report must also set out the process of reasoning which you have undertaken in order to arrive at your conclusions. It is insufficient for an expert report to simply state your opinion or conclusion reached without an explanation as to how this was arrived at. The purpose of providing such assumptions and reasoning is to enable the decision maker and experts engaged by other parties to make an assessment as to the soundness of your opinion.

Overview of work requested

We request that you undertake the following work:

(1) review the documents listed below;
(2) prepare a written expert report that addresses the issues identified below ('Issues to address in your expert report'), and ensure that the work is prepared in accordance with Division 2 of Part 31 and Schedule 7 of the UCPR; and
(3) appear as an expert witness at the IPC public hearing for the purpose of giving oral evidence.

Documents

All documents for the Project are located here:
http://majorprojects.planning.nsw.gov.au/index.pl?action=view_job&job_id=6367.

Hyperlinks to the key documents relating to the Project are provided to assist you in preparing your expert report. Please note that the documents have been provided in the order that they were produced but later documents may replace earlier ones.

Environmental Impact Statement

[1] • Executive Summary;
[2] • Appendix L Surface Water Part 1;
[3] • Appendix L Surface Water Part 2;
[4] • Appendix M Groundwater Part 1;
[5] • Appendix M Groundwater Part 2;
[6] • Appendix M Groundwater Part 3;

[7] • Appendix N Groundwater Peer Review; and
[8] • Appendix B Regulatory Correspondence (including the Secretary's Requirements, the NSW Office of Water, and the Gateway Panel's report).

Response to Submissions

[9] • Main Report
  - Surface Water (p 339)
  - Water Licences (p 345)
  - Groundwater (p 348)

[10] • Appendix H – Responses to Submissions on Groundwater
  - Bylong Coal RTS - Appendix H Part 1.pdf
  - Bylong Coal RTS - Appendix H Part 2.pdf
  - Bylong Coal RTS - Appendix H Part 3.pdf

Preliminary Assessment Report

[11] • Main Report
  - Project Changes (pp 11-15 of 146)
  - Water Resources (pp 58-77 of 146)

[12] • Appendix E - Supplementary Response to Submissions (Part 1)
  - Summary of submissions and responses (pp 14-64 of 346)
  - Main Report: Appendix A Hypothetical Scenario Water Balance (pp 107-123 of 346)

[13] • Appendix E - Supplementary Response to Submissions (Part 2)
  - J Response to Department of Primary Industries -Water Submission (pp 4-169 of 412)
  - L Groundwater Model Audit (p 204-407 of 412)

[14] • Appendix F – Additional Information
  - F5 KEPCO response to DPI Water request for clarification groundwater issues –Sep 2016 (pp 11-144 of 182)
  - F8 DPI advice on Supplementary Response to Submissions, Nov 2016 (pp 155-158 of 182)
  - F9 KEPCO response to DPI Water, Nov 2016 (pp 159-177 of 182)

[15] • Appendix G: Peer Review Reports and Response from KEPCO
  - G1 Groundwater Review, Kalf & Associates, Nov 2015 (pp 1-8 of 192)
  - G2 Groundwater Review, Kalf & Associates, May 2016 (pp 9-14 of 192)
  - G3 Groundwater Review, Kalf & Associates, Aug 2016 (pp 15-24 of 192)

[16] • Appendix H: IESC Advice

PAC Review

[17] • Commission Review Report
  - Executive Summary (pp 3-4 of 53)
  - Water and Agricultural Resources (pp 10-20 of 53)

[18] • Commission Review Report _Appendix 6
  - Groundwater Assessment (pp 27-29 of 128)
  - Response to Stephen Pells (pp 47-51 of 128)

[19] • Bylong Coal Project _Commission Review Report _Appendix 9.pdf
  - Water Resources (pp 5-6 of 45)

Response to PAC Review Report

[20] • Kepco Response to PAC Review - Main Report
  - Executive Summary (pp 2-5 of 106)
  - Water and Agricultural Resources (pp 30-57 of 106)

[21] • Appendix F - Bylong Water Management Plan-part A

[22] • Appendix F - Bylong Water Management Plan-Part B

[23] • Appendix K - Groundwater Response to Planning Assessment Commission

[24] • Appendix L - Letter to DPI-Water

[25] • Appendix M - Surface Water Response

[26] • Appendix N - Water Balance Peer Review

DPE Final Assessment Report

[27] • Bylong Final Assessment Report
  - Executive Summary (pp 3-16)
  - Water Resources (pp 37-51 of 122)

[28] • Supplementary Information _ Main Report
  - Groundwater and Surface Water (pp 34-40 of 85)

[29] • Appendix A DPE Revision of Mine Plan Letter

[30] • Appendix G Review of Groundwater Impacts

[31] • Appendix H Updated Surface Water and Flooding Impact Assessment

[32] • Advice from AGE _ Drawdown due to mining only

[33] • Recommended Conditions to IPC

Please let us know as soon as possible if you require further information for the purpose of giving your expert opinion.

Issues to address in your expert report

We ask that your report address the following issues:

(1) A review of Revised Project documentation, including consideration of the review findings by Pells Consulting, and identify and examine other issues that should be considered by the IPC when determining the Project, including modelled recharge and aquifer storage properties;

(2) Groundwater issues related to the Revised Project particularly as they relate to:
  a. Agricultural soil and water impacts;
  b. Potential impacts on adjacent World Heritage Areas (WHA);
  c. Interactions with the Aquifer Interference Policy, including how the long-term viability of an aquifer should be assessed;
  d. possible groundwater dependent ecosystems; and

(3) Provide any further observations or opinions which you consider to be relevant.

Key dates

The IPC meeting will be held in Mudgee on 7 November and in Sydney on 9 or 12 November 2018. We confirm that our client would like to engage you to attend the IPC meeting in Sydney and provide a verbal presentation to the IPC.

Written submissions to the IPC are due on Wednesday **14 November 2018**. We would appreciate receiving a draft of your expert advice by no later than 6 November 2018 to assist our client to finalise their own submission to the IPC.

Duty of confidentiality

Please treat your work as strictly confidential until your expert report is provided to the IPC, unless authorised by us.

Fees

Thank you for agreeing to provide expert advice in this matter at a capped rate of $10,758 (inc GST). Our client will also cover any reasonable travel expenses associated with you attending the IPC determination meeting. Please discuss these costs with us before incurring them.

We are grateful for your assistance in this matter.

If there are any matters that you would like to discuss please do not hesitate to contact me on ph: 02 9262 6989 or by e-mail nadja.zimmermann@edonsw.org.au.

Yours sincerely,
EDO NSW

Nadja Zimmermann
Solicitor

Our Ref: 1522462

Appendix B Supplementary Documents

Doc. No.	Document Category	Prepared by	Author(s)	Prepared for	Document Title	Document Section	Year	Date
[34]	Supplementary Reference	Bylong Valley Protection Alliance Inc		NSW DPE	Submission to the NSW Department of Planning and Environment KEPCO-Bylong Coal Project		2015	November 2015
[35]	Supplementary Reference	Pells Consulting	Phillip Pells, Steven Pells		Consideration of Responses to submissions		2017	May 2017
[36]	Supplementary Reference	Hansen Bailey	James Bailey	Bylong coal Project	Bylong coal Project Environmental Impact Statement		2015	September 2015
[37]	Supplementary Reference	AECOM		Hansen Bailey	Bylong Coal Project Historic Heritage Impact Assessment		2015	April 2015
[38]	Supplementary Reference	Advisian		Water NSW	Literature Review of Underground Mining Beneath Catchments and Water Bodies		2016	December 2016
[39]	Supplementary Reference	MSEC		NSW DPE	Subsidence Ground Movement Predictions and Impact Assessment	Appendix H	2015	May 2015
[40]	Supplementary Reference	Hansen Bailey		Cockatoo Coal Limited	Bylong Coal Project, Gateway Certificate Application		2014	January 2014
[41]	Supplementary Reference	SLR		Hansen Bailey	Bylong Coal Project, Soil Assessment and Site Verification	Appendix D	2013	December 2013
[42]	Supplementary Reference	SLR		Hansen Bailey	Bylong Coal Project, Preliminary BSAL Rehabilitation Strategy	Appendix J	2013	December 2013

[43]	Supplementary Reference		Evans, R., Campbell, L., McKelvey P		Determining realistic specific storage input values for groundwater flow models: a case study from Surat Basin, Queensland		2015	November 2013
[44]	Supplementary Reference		Pells, S. and Pells, P.		Hydrogeologists and Geotechnical Engineers – Lost without Translation		2015	November 2013
[45]	Supplementary Reference		Rau, G. C., Acworth, R. I., Halloran, L. J. S., Timms, W. A. Cuthbert, M. O		Quantifying compressible groundwater storage by combining cross-hole seismic surveys and head response to atmospheric tides		2018	July 2018
[46]	Supplementary Reference		Barnett, B., Townley, L.R., et al.		Australian groundwater modelling guidelines		2012	June 2012
[47]	Supplementary Reference		John Bredehoeft		The conceptualization model problem – surprise		2005	February 2005
[48]	Supplementary Reference	AGE		Hansen Bailey	Bylong Coal Project Response to Planning Assessment Commission	Appendix K	2017	December 2017
[49]	Supplementary Reference	AGE		Hansen Baily	Bylong Coal Project Response to Submissions on Groundwater	Appendix H	2016	March 2016
[50]	Supplementary Reference		J. Bredehoeft, T. Durbin		Ground water development—The time to full capture problem		2009	July 2009
[51]	Supplementary Reference	Cockatoo Coal Limited		Hansen Bailey	Bylong Coal Project Geology Report	Appendix C	2014	August 2014
[52]	Supplementary Reference		R. Evans, L.Campbell, P. McKelvey	Australian Groundwater Conference	Determining realistic specific storage input values for groundwater flow models: a case study from the Surat Basin, Queensland.	Afternoon Keynotes	2015	November 2015
[53]	Supplementary Reference		J. Jankowski, et al.		Surface Water-Groundwater Connectivity in a Longwall Mining Impact Catchment in the Southern Coalfield, NSW, Australian		2008	April 2008

Appendix C CV

UNSW SYDNEY Australia's Global University

Water Research Laboratory
Doug Anderson
Principal Engineer

Doug has 17 years of technical experience in groundwater - surface water resource and impact assessment. He designs and manages field investigations and groundwater monitoring programs in addition to undertaking environmental process and modelling studies. Doug delivers environmental assessment results and strategic environmental management advice. He helps his clients tackle challenging water issues to achieve their environmental and engineering objectives.

Doug maintains a strong background in hydrogeological site characterization, data management automation, numerical modelling, programming and geo-spatial data analysis. Doug is an expert groundwater modeller with several years of FEFLOW modelling experience. His expertise is complemented by background skills in civil engineering hydraulics and physical modelling. Doug employs a considered and practical approach to projects, working in a team environment to deliver quality project outcomes. His eye for detail in flow system conceptualisation provides decision makers with appropriate assessments of project risk and uncertainty.

Qualifications

BE Hons 1 (Environmental Engineering), UNSW, 2000
MEngSc (Groundwater Studies), UNSW, 2001

Professional history

2013-:	Principal Engineer, UNSW WRL
2010-2013:	Groundwater Modelling Specialist, AquaResource/Matrix Solutions Inc. (Canada)
2001-2009:	Project Engineer, UNSW WRL

Expertise

- Hydrogeological site characterisation
- Groundwater flow and transport modelling
- Water resources management and protection
- Geo-spatial data analysis
- Information management and computer programming
- Coastal imaging (machine vision)
- Civil engineering hydraulics

Summary of relevant experience

Doug has worked as a consultant for a range of industry and government clients to support environmental impact assessment, mineral resource development and site closure planning. He has accumulated groundwater resources expertise in fractured rock, coastal sand aquifers, moraines and salars in Australia, Argentina, Canada and the United States. Doug's experience includes all aspects of hydrogeological site characterization, e.g. conceptual model development, monitoring program design, drilling supervision, field data collection, data analysis, groundwater flow and transport modelling, environmental impact assessment and peer review.

Doug has worked at a number of waste disposal sites where contamination risks to groundwater and surface water must be investigated, modelled and managed with great care. This includes the radioactive waste disposal facilities at Ranger Mine in the Northern Territory and Little Forest Legacy Site at Lucas Heights. Doug's project experience also includes: the design and commissioning of effluent reuse monitoring programs; the assessment of groundwater contamination from urban and industrial landfilling; groundwater modelling for water protection studies; peer review of groundwater models; resource and reserve assessment for mineral brine projects; and the feasibility assessment of municipal extraction projects, wastewater disposal and effluent reuse.

Summary of relevant experience

Groundwater resources management and protection

- Site investigations, data analysis, groundwater modelling and closure planning for a low-level radioactive waste facility at Little Forest Legacy Site, Lucas Heights (2016-).
- Groundwater monitoring at John Fisher Park legacy landfill site for Northern Beaches Council (2016).
- Aquifer test analysis and peer review of contamination monitoring for Burra Rd, Gundagai Landfill (2016).
- Measurement of landfill clay cap permeability by gas permeameter and UNSW geotechnical centrifuge (2016).
- Measurement of drill core permeability by geotechnical centrifuge for WA Department of Water Perth Confined Aquifer Capacity Study (2015).
- Confidential groundwater desktop and numerical model study for Newcastle City Council (2015-2016).
- Groundwater Impact Assessment adequacy review for Lynwood Quarry (2015).
- Groundwater and surface water flow modelling to support Ranger Mine Pit #1 and Pit #3 closure plans (2009, 2014).
- Groundwater modelling for the Municipality of Waterloo in Ontario to establish well head protection areas to help plan secure drinking water supplies for 500,000 residents (2010).
- Updated Lake Conjola Groundwater Monitoring Program and Response Plan for the NSW Public Works (2008).
- Groundwater investigations and modelling to assess the feasibility of a horizontal collector well system and desalinisation plant proposed as an emergency solution to drought-proof the for Wyong Shire Council supply (2004-05).

Managed aquifer recharge (MAR)

- Entry level assessment of MAR for Sydney Water for the townships of Galston and Glenorie (2013).
- Site selection, borehole drilling and groundwater monitoring program to assess the operational performance of the Moree Plains Shire Council effluent reuse scheme (2006).
- Groundwater investigations, numerical modelling and concept designs for EGIS Consulting and Department of Commerce to support the feasibility assessments for the effluent reuse scheme at Iluka (2001-2005).
- Groundwater modelling of virus transport in coastal sand aquifers for DLWC for the proposed effluent reuse scheme at Hat Head (2002).

Mining and coal seam gas – studies

- Measurement of drill core permeability by centrifuge for OGIA's Walloon Interconnectivity Research Project (2014).
- Background paper on groundwater resources and CSG for the NSW Office of the Chief Scientist and Engineer (2013).
- Measurement of drill core permeability by centrifuge for a coal mining / CSG client (2013).
- Technical advice and support to the United States Forestry Service, ERO and mining company groundwater groundwater modellers to developed an EIA model of the Rock Creek underground Copper Mine Prospect (2012).
- Hydrogeological characterization and groundwater modelling of brine deposits to support a NI-43101 reserve estimation for TSX / Lithium Americas Corp (2010-2012).
- Groundwater modelling for Tier II source water applications for proposed SAGD oil shale projects in Alberta (2012).

Mining and coal seam gas – peer review

- OWS science and literature review to identify coal seam gas and coal mining knowledge gaps (2014).
- Peer review of Shenhua's groundwater model for the proposed Watermark Coal Prospect (2014).
- Peer review of the SHCAG's groundwater model of the Hume Coal Prospect (2013).
- Technical review of OWS's critical science review on coal seam gas and aquifer connectivity (2013).
- Technical review of OWS's critical science review on coal seam gas and groundwater modelling (2013).

Linear infrastructure

- NSW Department of Planning Groundwater Peer Reviewer for Westconnex and Northern Beaches Hospital road upgrade (2015-)

Civil engineering hydraulics – wastewater

- Monitoring of Warriewood STP secondary clarifiers (2005-06).
- CFD modelling of FL2000 wastewater separator (2002).
- WA setting tank desktop assessments (2003).
- Modelling for Christchurch ocean outfall (2003).

Education and training

- Federal Office of Water Science Surface Water Training Course on Large Coal Mines and Coal Seam Gas (2015).
- FEFLOW Training Course (LAC, 2012; UNSW, 2002).
- Sydney Coastal Councils' Groundwater Workshops (2007).
- Australian Cotton CRC's Groundwater Workshops (2007).

Civil engineering hydraulics – flooding and coastal

- Eidsvold Weir physical model, QLD.
- East Arm Port ship interaction physical model, NT (2002-03).
- Penrith Lakes desktop, numerical and physical modelling (Penrith Lakes Development Corporation, 2003-2009).

Information management and coastal imaging

- Real-time web based coastal monitoring (Gold Coast City Council, Tweed River Entrance Sand Bypassing Project, Warringah Shire Council, 2001-2008,2013-).
- Hong Kong North Western Waters Database, Warringah Council Water Quality Database, Australian Councils' St Sweeping Database, ACO Polycrete Scheduling Software (2001 - 2003).

Publications

Timms, W A, Crane, R, **Anderson, D J**, Bouzalakos, S, Whelan, M, McGeeney, D, Acworth, R I, 2016, 'Accelerated gravity testing of aquitard core permeability and implications at formation and regional scale', *Hydrology and Earth System Sciences*, *20*(1), 39-54. doi:10.5194/hess-20-39-2016

Timms, W A, Crane, R, **Anderson, D J**, Bouzalakos, S, Whelan, M, McGeeney, D, Acworth, R I, 2014, 'Vertical hydraulic conductivity of a clayey-silt aquitard: accelerated fluid flow in a centrifuge permeameter compared with in situ conditions', *Hydrology and Earth System Sciences Discussion*, *11*(3), 3155-3212. doi:10.5194/hessd-11-3155-2014

Anderson, D J, Timms, W A, and Glamore W C, 2009, 'Optimising subsurface well design for coastal desalination water harvesting', *Australian Journal of Earth Sciences*, 56, 53-60.

Turner, I L, and **Anderson, D J**, 2007, 'Web-based and 'real-time' beach management system', *Coastal Engineering*, 54, 555-565.

Glamore, W C, Timms, W A, and **Anderson, D J**, 2007, 'Injection or release: Innovative technologies for disposing recycled water in coastal environments', *Proc. 16th NSW Coastal Conference*, Yamba, NSW, 7-9 November.

Turner, I L, and **Anderson, D J**, 2006, 'CZM applications of Argus Coastal Imaging in Eastern Australia', *Proc. 15th NSW Coastal Conference*, Coffs Harbour, NSW, 7-9 November.

Glamore, W C, **Anderson, D J**, and Timms, W A, 2006, 'Coastal groundwater intakes: Numerical modelling of coastal wells for desalination source water', *Proc. 30th International Conference on Coastal Engineering*, San Diego, USA, 3-8 September.

Anderson, D J, Timms, W A, and Glamore, W C, 2005, 'Optimising subsurface well design for coastal desalination water harvesting', *Proc. NZHS-IAH-NZSSS Conference*, 28 November-3 December, Auckland (CD rom).

Anderson, D J, Frazer, A, Jancar, T, and Miller, B M, 2004, 'The implementation of PIV-PTV techniques for measurement of velocities in large scale physical models', *Proc. 8th National Conference on Hydraulics in Water Engineering*, Gold Coast, 13-16 July.

Anderson, D J, Turner, I L, Dyson, A, Lawson, S, and Victory, S, 2003, 'Tweed River Entrance Sand Bypassing Project: 'real-time' beach monitoring and analysis system via the world-wide-web', *16th Australasian Coasts and Ports Conference*, Auckland, 9-12 September.

Appendix D Rau et al. (2018)

ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Earth Surface

RESEARCH ARTICLE

10.1029/2018JF004660

Key Points:

- Cross-hole seismic surveys and tidal head analysis can be combined to improve estimates of specific storage
- We have developed an upper bound for specific storage for unconsolidated materials with low adsorbed water fractions
- Derived values of specific storage larger than this upper bound imply inappropriate use of oversimplified hydrogeological conceptual models

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Citation:
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Quantifying Compressible Groundwater Storage by Combining Cross-Hole Seismic Surveys and Head Response to Atmospheric Tides

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Abstract Groundwater specific storage varies by orders of magnitude, is difficult to quantify, and prone to significant uncertainty. Estimating specific storage using aquifer testing is hampered by the nonuniqueness in the inversion of head data and the assumptions of the underlying conceptual model. We revisit confined poroelastic theory and reveal that the uniaxial specific storage can be calculated mainly from undrained poroelastic properties, namely, uniaxial bulk modulus, loading efficiency, and the *Biot-Willis* coefficient. In addition, literature estimates of the solid grain compressibility enables quantification of subsurface poroelastic parameters using field techniques such as cross-hole seismic surveys and loading efficiency from the groundwater responses to atmospheric tides. We quantify and compare specific storage depth profiles for two field sites, one with deep aeolian sands and another with smectitic clays. Our new results require bulk density and agree well when compared to previous approaches that rely on porosity estimates. While water in clays responds to stress, detailed sediment characterization from a core illustrates that the majority of water is adsorbed onto minerals leaving only a small fraction free to drain. This, in conjunction with a thorough analysis using our new method, demonstrates that specific storage has a physical upper limit of $\lessapprox 1.3 \cdot 10^{-5}$ m^{-1}. Consequently, if larger values are derived using aquifer hydraulic testing, then the conceptual model that has been used needs reappraisal. Our method can be used to improve confined groundwater storage estimates and refine the conceptual models used to interpret hydraulic aquifer tests.

1. Introduction

Groundwater compressible storage has always been difficult to quantify with high certainty using field techniques. Pumping-test analysis can be used to derive the aquifer properties of transmissivity and storage for a confined aquifer, but the degree of accuracy achieved for storage is often less than that achieved for transmissivity (Kruseman & de Ridder, 1990). Theoretical approaches (Narasimhan, 1979; Narasimhan & Kanehiro, 1980) shed some light on the concept of storage and led to further discussion (Bredehoeft & Cooley, 1983; Narasimhan, 1983), with Hsieh et al. (1988) concluding that it was only possible to estimate S_s to within $\pm$50%. Wang (2000) reviewed the field of poroelasticity with applications from the geotechnical field and from hydrogeology. Specific storage is now recognized as one of the fundamental coefficients of poroelastic theory (Green & Wang, 1990), along with Young's modulus (E), the shear modulus (G), and Poisson's ratio (μ). Its value can also vary with time due to human activity (David et al., 2017). The subject area has been overly complicated by the use of a variety of definitions and specialized terminology.

The response of a groundwater system to pumping, such as a decrease of hydraulic head or the development of land subsidence in aquitards, can only be predicted to any degree of accuracy if compressible storage properties are known at some reasonable vertical resolution (Alley et al., 2002). Although aquifer test analysis, taking account of leakage factors (Hantush, 1960, 1967a, 1967b) and using multiple piezometers (Kruseman & de Ridder, 1990), may permit the estimation of storage properties at multiple depths, in practice, these methods are not used due to the time and expense required to establish a site and the great length of time (weeks to months) required to obtain representative responses in lower hydraulic conductivity layers. Traditionally, characterization at $\lesssim$1-m scale could be achieved through expensive sediment coring using sophisticated drilling equipment and laboratory assessment, but the validity of laboratory measurements over in situ measurements has also been questioned (Clayton, 2011). The accelerating depletion of global groundwater resources (Gleeson et al., 2012; Wada et al., 2013) necessitates development of accurate and low-cost methods to routinely establish profiles of specific storage so that the accuracy of predicted drawdowns and aquitard settlement can be assessed.

Acworth, Halloran, et al. (2016) described a new method to quantify in situ barometric efficiency (BE) using the hydraulic head response to atmospheric and Earth tides. We refer to this as *tidal analysis* from here onward. Data for three different BE values across the possible range from 0 to 1.0 (Acworth, Halloran, et al., 2016) and for a profile of 10 different depths at a single site were described (Acworth et al., 2017). Acworth et al. (2017) used the BE analysis to predict specific storage using the formulation of Jacob (1940). However, Van Der Kamp and Gale (1983) and Domenico (1983) noted (independently) that the approach of Jacob (1940) was based on a one-dimensional analysis that neglects the possibility of horizontal movement and also assumes that the compressibility of individual grains is insignificant. Van Der Kamp and Gale (1983) proposed a more extensive analysis that required consideration of the compressibility of individual components of the material (β_s) and also whether the elastic coefficients used represented drained or undrained systems. Their analysis requires further data on the elastic properties, including the bulk modulus (K), the shear modulus (G), and Poisson's ratio (μ) of the material. They noted that estimation of specific storage would be possible if these parameters were available. Wang (2000) provides a comprehensive overview of the theory of poroelasticity.

The cross-hole seismic method is well established in the geotechnical industry (Mathews et al., 1994) where it is routinely used to determine profiles of Poisson's ratio (μ), shear modulus (G), and bulk modulus (K). It is a recommended investigation technique (ASTM Method D 4428/D 4428M) when carrying out design work in unconsolidated materials for foundation or tunneling design. The methodology has changed little from early work by Davis and Taylor-Smith (1980) and Davis (1989). Despite the success and essential simplicity of the method, application to inform groundwater resource investigation appears limited (Clayton, 2011; Crice, 2011). The cross-hole seismic method presents an opportunity to measure the variation of elastic moduli over depth. A complete profile at any vertical interval $\lesssim$ 1 m, or less, is possible, allowing for realistic visualization of actual lithological variation of these moduli with depth. In addition, as the testing is of the ground between two boreholes, it is completely in situ, undrained, and not subject to the inaccuracies due to sampling, sample recovery, and stress changes before laboratory testing.

We present a new method to quantify profiles of specific storage in unconsolidated formations in situ using a rigorous interpretation of poroelastic theory (Green & Wang, 1990; Wang, 2000; Van Der Kamp & Gale, 1983). We combine loading efficiency derived from groundwater response to atmospheric tides in piezometers at multiple depths with elastic parameters derived from cross-hole seismic surveys. This interpretation is further strengthened by comparison with detailed laboratory data on formation water content and bulk density, derived from previously reported measurements on core material data previously reported (Acworth et al., 2015). Two sites with contrasting lithology, representing the end-members of sand- and clay-dominated deposits, illustrate the usefulness of combining two geophysical techniques to provide reasonable bounds for compressible subsurface properties and demonstrate its implications for groundwater resource investigations.

2. Methodology

2.1. Poroelastic Drained and Undrained Terminology in Hydrogeology

Quantifying specific storage relies on the assumption that subsurface poroelasticity is linear. This has seen separate development in the areas of geomechanics, petroleum engineering, and hydrogeology (Wang, 2000) that has caused a wide variety of definition and terminology. For reference, definitions of all variables used in this paper are listed in Table A1. In our analysis it is assumed that the subsurface system remains saturated and confined at all times.

The elastic coefficients involved in poroelastic coupling vary depending upon the time taken for a load to be applied and stress to dissipate (Domenico & Schwartz, 1997; Wang, 2000). While two end-member conditions, undrained and drained, can be distinguished, it should be recognized that real field conditions may exist anywhere on the continuum between these end-members depending on the relationship between the timescale of the applied stress changes, the hydraulic properties of the formation, and the distance to hydraulic boundaries. First, for rapid loading, as occurs with the passage of a seismic wave or the response to atmospheric tides at subdaily frequency, there may be insufficient time for water to flow in response to the increased stress and pore pressure. Therefore, the loading occurs at constant mass ($\mathrm{d}\zeta/\mathrm{d}t = 0$ where ζ is the mass of fluid) and poroelastic coefficients represent *undrained* conditions. Second, and by contrast, if the loading occurs slowly and fluid has the opportunity to redistribute, the loading occurs at constant pore pressure ($\mathrm{d}p/\mathrm{d}t = 0$ where p is pore pressure) and represents *drained* conditions. In this work undrained parameters are explicitly denoted with the superscript u, drained parameters have no subscript, or (u) if a relationship can be used interchangeably for undrained and drained values. Note here that the term drained should not be confused with the interpretation that subsurface pores are drained of water, that is, when the hydraulic head in a confined aquifer is lowered below the confining layer causing unconfined conditions, as is a common interpretation in hydrogeology. In our analysis it is assumed that the subsurface system remains saturated and confined at all times.

2.2. Subsurface Poroelastic Coefficients

Over the small range of pressure changes caused by tides and acoustic pulses, we assume that the matrix exhibits a perfectly elastic (i.e., *Hookean*) response. If such a material is subjected to a uniaxial compression or tension, a linear relationship exists between the applied stress σ and the resulting strain ϵ expressed as

$$\sigma = E^{(u)}\epsilon, \tag{1}$$

where E is a constant of proportionality known as *Young's Modulus*. The value of the strain ϵ is the ratio of the change in line length in its deformed state l_f to its initial state l_o

$$\epsilon = \frac{l_f - l_o}{l_o} = \frac{\Delta l}{l_o}. \tag{2}$$

If a Hookean solid is subject to uniaxial compression, it will shorten in the direction of compression and expand in the plane at right angles to the direction of compression. If $\epsilon_\parallel$ represents the shortening in the direction of compression and $\epsilon_\perp$ represents the expansion in the plane at right angles to the compression, then the ratio of these two quantities is referred to as *Poisson's ratio*

$$\mu^{(u)} = \frac{\epsilon_\parallel}{\epsilon_\perp} \le 0.5. \tag{3}$$

A solid can also be deformed by means of a shear causing shear strain (ϵ) in response to the shear stress (σ). The ratio of these quantities is the shear (or rigidity) modulus

$$G = \frac{\sigma}{\epsilon}. \tag{4}$$

The shear modulus G is related to the Young's modulus E and Poisson's ratio μ by

$$G = \frac{E^{(u)}}{2(1 + \mu^{(u)})}. \tag{5}$$

In an isotropic material subject to a change in pressure, a change in volume will occur. This is described by the *bulk modulus*

$$K = -V\frac{\mathrm{d}p}{\mathrm{d}V} = \rho\frac{\mathrm{d}p}{\mathrm{d}\rho}, \tag{6}$$

where p is pressure, V is volume, and ρ is material density. Further relationships for K are

$$K^{(u)}_{(s)} = G\frac{2\left(1 + \mu^{(u)}_{(s)}\right)}{3\left(1 - 2\mu^{(u)}_{(s)}\right)} = \frac{E^{(u)}_{(s)}}{3\left(1 - 2\mu^{(u)}_{(s)}\right)}. \tag{7}$$

Note that these relationships apply for solid materials (indicated as (s)) as well as interchangeably for drained or undrained (indicated as (u)) conditions, with exception of the shear modulus G, which remains the same (Wang, 2000). In the case of a homogeneous, isotropic, elastic materials, values for any two of the shear modulus G, Young's modulus E, bulk modulus K, or Poisson's ratio μ (or, additionally, the longitudinal modulus or Lamé's first parameter) are sufficient to define the remaining parameters for drained or undrained conditions (Wang, 2000).

2.3. Confined Groundwater Storage in a Poroelastic Formation

Wang (2000) provides a detailed analysis of poroelastic theory for both drained and undrained conditions, and Van Der Kamp and Gale (1983) develop expressions for the analysis of atmospheric and Earth tides, which are normally considered as undrained phenomena in groundwater level time series. The developments build on the coupled equations for stress and pore pressure derived by Biot (1941) for very small deformations, typical of those that occur with the passage of seismic waves or in response to atmospheric tides. In the most general case, it is necessary to consider a fully deformable medium in which all components are compressible. Besides the bulk formation compressibility $\beta = 1/K$, which is the reciprocal of the bulk modulus $K = 1/\beta$, two more components require consideration. The water compressibility is expressed as

$$\beta_w = \frac{1}{K_w} \approx 4.58 \cdot 10^{-10}\mathrm{Pa}^{-1}. \tag{8}$$

The solid grain (or unjacketed) compressibility can be stated as

$$\beta_s = \frac{1}{K_s} \tag{9}$$

assumes homogeneous solids and is not well defined for mixtures of different grain types (Wang, 2000).

The volume of water displaced from a sediment is always less than the change in bulk volume whenever grain compressibility is included (Domenico & Schwartz, 1997). To take account of this change, the *Biot-Willis* coefficient is used (Biot, 1941; Wang, 2000)

$$\alpha = 1 - \frac{\beta_s}{\beta} = 1 - \frac{K}{K_s}. \tag{10}$$

Note that if $\beta_s \ll \beta$ then there is relatively little, if any, change in volume of the grains when compared to the total volume change and therefore $\alpha \rightarrow 1$.

Van Der Kamp and Gale (1983) and Green and Wang (1990) presented a comprehensive relationship for specific storage that assumes only uniaxial (vertical) deformation (zero horizontal stress) and includes solid grain compressibility

$$S_s = \rho_w g \left[\left(\frac{1}{K} - \frac{1}{K_s} \right) (1 - \lambda) + \theta \left(\frac{1}{K_w} - \frac{1}{K_s} \right) \right], \tag{11}$$

where the density of water $\rho_w = 998$ kg/m^3, the gravitational constant is $g = 9.81$ m/s^2, θ is total porosity, and

$$\lambda = \alpha \frac{2}{3} \frac{(1 - 2\mu)}{(1 - \mu)} = \alpha \frac{4G}{3K_v}. \tag{12}$$

Here K_v is the drained vertical (or constrained) bulk modulus and expressed as (Green & Wang, 1990; Wang, 2000)

$$\frac{1}{K_v^{(u)}} = \beta_v^{(u)} = \frac{1 + \mu^{(u)}}{3K^{(u)} \left(1 - \mu^{(u)}\right)} = \left(K^{(u)} + \frac{4}{3}G\right)^{-1}. \tag{13}$$

If the solids are incompressible ($\beta_s = 1/K_s \rightarrow 0$), then equation (11) reduces to the well-known formulation (Cooper, 1966; Jacob, 1940)

$$S_s = \rho_w g \left(\frac{1}{K_v} + \frac{\theta}{K_w} \right) = \rho_w g (\beta_v + \theta \beta_w), \tag{14}$$

We note that if $\mu^{(u)} = 0.5$, then it can be seen from equation (13) that $K_v^{(u)} = K^{(u)}$. Note, however, that this will only be the case for very unconsolidated silts or clays.

To summarize, specific storage values derived from equations (11) and (14) represent vertical and isotropic stress only and are therefore smaller compared to the case where horizontal stress and strain is allowed to occur (Wang, 2000). However, this is a reasonable and common assumption, which suffices to represent the conditions encountered in a hydrogeological setting. For example, equation (14) is widely used in hydrogeology (Van Der Kamp & Gale, 1983), particularly for the analysis of head measurements obtained from aquifer testing (e.g., Kruseman & de Ridder, 1990; Verruijt, 2013).

2.4. Elastic Moduli From the Propagation of Seismic Waves

Two fundamental wave motions can transmit energy through a formation. The first is a compressional, or primary wave (*P* wave) whose speed is a function of the undrained uniaxial bulk modulus

$$V_p = \sqrt{\frac{K_h^u}{\rho}} = \sqrt{\frac{K^u + \frac{4}{3}G}{\rho}}, \quad (15)$$

where K_h^u is the undrained bulk modulus (Wang, 2000, Page 60). We have used the notation K_h^u to recognize that the wave front spreads out spherically from the source but is monitored in the horizontal plane. The geophone that is aligned in the horizontal direction and pointing to the source detects the primary wave arrival after the wave has progressed horizontally through the formation. Hence, the appropriate bulk modulus derived from this velocity (equation (15)) is an undrained uniaxial (horizontal) bulk modulus (K_h^u).

Due to the short distances between the source and receiver and the assumed homogeneity of unconsolidated deposits, we assume isotropic conditions and therefore that $K_v^u = K_h^u$. It is noted that it would be possible to investigate anisotropy in K^u by analyzing the arrival times of the primary wave for the other two (one horizontal and one vertical) geophone components.

For sand and water mixtures, bulk density and total porosity of the formation are related through a simple volumetric mixing model (Jury et al., 1991)

$$\rho = \rho_s(1 - \theta) + \rho_w \theta, \quad (16)$$

where ρ_s is the density of the solid phase (sand particles) generally assumed to be 2,650 kg/m^3 and the density of water $\rho_w \approx 998$ kg/m^3.

The second wave motion is a shear wave (*S* wave) that progresses through a material by motion normal to the direction of propagation

$$V_s = \sqrt{\frac{G}{\rho}}. \quad (17)$$

Conveniently, the ratio of the compressional and shear wave velocities can be used to determine the undrained Poisson's ratio μ^u directly (Davis & Taylor-Smith, 1980)

$$\mu^u = \frac{V_p^2 - 2V_s^2}{2V_p^2 - 2V_s^2} \leq 0.5. \quad (18)$$

Note that $V_s < V_p$.

2.5. Combining Cross-Hole Seismic Surveys and the Groundwater Response to Atmospheric Tides

Specific storage has previously been calculated from *BE* estimates. Acworth, Halloran, et al. (2016) developed an accurate method to quantify *BE* using the groundwater response to atmospheric tides when influences at frequency of 2 cpd. The method is given as

$$BE = \frac{S_2^{GW} + S_2^{ET} \cos(\Delta\phi) \frac{M_2^{GW}}{M_2^{ET}}}{S_2^{AT}}, \quad (19)$$

where S_2^{GW} is the amplitude of the hydraulic head, S_2^{ET} is the amplitude of the Earth tide, and S_2^{AT} the amplitude of the atmospheric tide; $\Delta\phi$ is the phase difference between the Earth tide and atmospheric drivers (both at 2 cpd frequency); M_2^{GW} is the amplitude of the hydraulic head and M_2^{ET} the amplitude of Earth tides at 1.9323 cpd frequency. The required amplitudes and phases can be obtained using the *Fourier* transform of atmospheric and head records which require a duration of ≥16 days with frequency of ≥12 samples per day (Acworth, Halloran, et al., 2016).

We note that an estimate of specific storage for a formation comprising incompressible grains can be made if the value of porosity is estimated (Acworth et al., 2017)

$$S_s = \rho_w g \beta_w \frac{\theta}{BE} \approx 4.484 \cdot 10^{-6} \frac{\theta}{BE}. \quad (20)$$

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Estimating porosity can be problematic when dealing with fine-grained materials and, especially, smectitic clays where it is never clear what value of porosity exists due to the uncertainty regarding the volume of adsorbed water (i.e., hygroscopic water bound to the surface of the grains via molecular forces). This is due, in part, to the extreme values of surface area per volume characteristic of clays, which render the proportion of water molecules that are adsorbed rather than absorbed non-negligible.

In this paper, we develop a new method to quantify confined groundwater specific storage depth profiles in situ by combining cross-hole seismic measurements of elastic coefficients with the groundwater response to atmospheric tides. From Wang, (2000, equations (3.84) and (3.81)), a uniaxial specific storage equation can be derived as

$$S_s = \rho_w g \frac{\alpha}{K_v^u LE(1 - \alpha LE)} \tag{21}$$

where *LE* is the uniaxial loading efficiency (or tidal efficiency), which can be calculated from *BE* as (Domenico & Schwartz, 1997; Wang, 2000)

$$LE = 1 - BE. \tag{22}$$

Equation (21) allows calculation of uniaxial specific storage mainly from undrained parameters, which are readily measured using field techniques, for example, seismics and tidal analysis. A discussion of α follows later.

Wang (2000) further shows that *Skempton's* coefficient can be calculated from undrained parameters as

$$B = 3LE\frac{1-\mu^u}{1+\mu^u} = \frac{1-K/K^u}{1-K/K_s} \tag{23}$$

which can be reformulated to arrive at a relationship between undrained and drained bulk modulus

$$K = \frac{K_s K^u(1-B)}{K_s - BK^u}. \tag{24}$$

To quantify specific storage using our new method of combining cross-hole seismic surveys and tidal analysis (equation (21)), K_v^u, G, and μ^u are obtained from seismic velocities (equations (15), (17), and (18)) and *LE* stems from tidal analysis (equations (19) and (22)). To estimate the drained formation compressibility (24), B is calculated from seismically derived μ^u (equation (18)) and tidally derived *LE* (equations (19) and (22)), whereas K^u is calculated from seismically derived K_v^u and G (equations (15) and (17)). In both cases, values for K_s can be found in the literature and are discussed below.

2.6. Quantifying Compressible Groundwater Storage at Two Field Sites: Fine Sands Versus Clays

We investigate and contrast the subsurface conditions at two field sites in Australia (Figure 1) with different lithology.

2.6.1. Sand-Dominated Site at David Philips Field

David Phillips Field is located on top of the Botany Sands Aquifer in Sydney, NSW (Figure 1a). During the last glacial epoch, sand has been blown from Botany Bay and now fills deep-sided valleys in the Permo-Triassic Hawkesbury Sandstone (Acworth & Jankowski, 1993; Webb et al., 1979). The sands provide an important water resource that, for a time, served Sydney. Webb and Watson report a very detailed pumping test at this site that determined There is an unconfined aquifer to approximately 7.5 m at the site, below which a thin layer of peat and silt acts to confine the underlying aquifer to approximately 17 m. Below this, a further silty sand separates a deeper confined aquifer (Webb et al., 1979). The depth to the water table was approximately 7 m at the time of testing. Acworth (2007) reported the results of manometer board testing from the same field that included geophysical logs and detail on lithology. The sands are very well sorted with a median grain size of 0.3 mm and a typical porosity of $\theta \approx 0.35$ (Acworth & Jankowski, 1993).

Three bores were installed in the southwest corner of David Phillips Field (Figure 1a). The first bore penetrated Hawkesbury Sandstone (Permo-Triassic) at 31 m using a combination of rotary auger and rotary mud drilling. The bore was completed at 36 m with 80 mm PVC casing. Cement gout was placed at the base of the sands, and the formation above allowed to collapse back onto the PVC casing (Borehole G1 in Figure 1a). A second bore was installed using hollow-stem augers to a depth of 28 m (Borehole G2 in Figure 1a), while a third bore

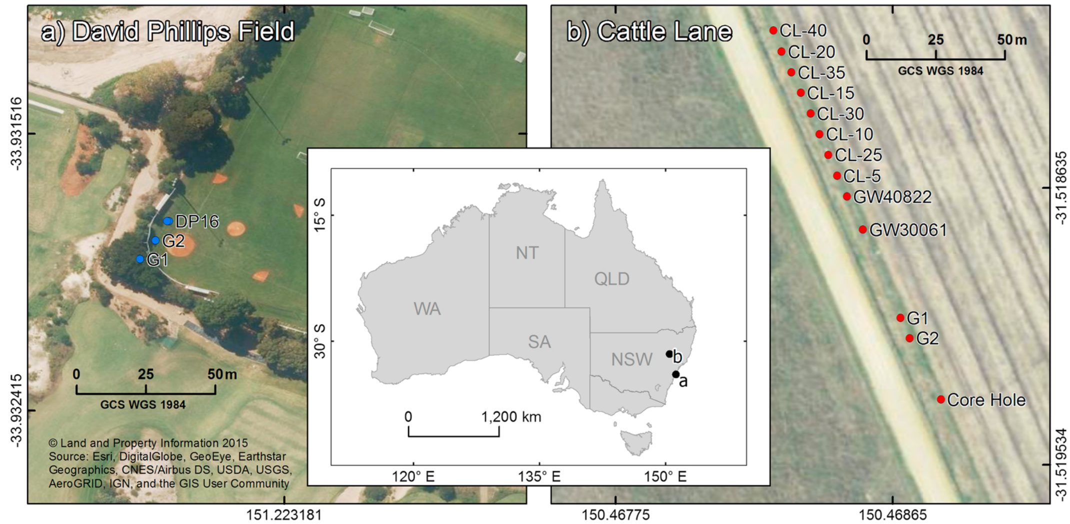

Figure 1. Map showing the locations of boreholes at David Phillips Field (aeolian sand; a) and Cattle Lane (clay; b) in New South Wales, Australia (inset map with locations).

was installed to 16-m depth (DP16 in Figure 1a). Both these bores were completed using 50-mm PVC with a 1-m screen set at the base.

Water level data for the Botany Site at David Philips Field were measured in piezometer DP16. A Diver data logger was used with a sampling interval of 1 hr. The atmospheric pressure was compensated using the record from Sydney Airport (≈4 km from the field site). There is only a single value of *BE* (*BE* = 0.151) available for David Phillips Field from Piezo DP 16 (Figure 1a).

2.6.2. Clay-Dominated Site on the Liverpool Plains

The second field site, Cattle Lane, is located on the Liverpool Plains, NSW (Figure 1b). Deposition of clay derived from the nearby Liverpool Ranges has occurred onto the Liverpool Plains (south to the north). The saturated zone at this site is typically within a meter or two of the ground surface. Clay deposition has been dominant during drier periods, with silt and clay deposited during colder periods and gravels and sands during periods of higher rainfall. This sequence has been proven by coring (*Core Hole* in Figure 1a) to 31.5-m depth and the lithology is given by Acworth et al. (2015). Note that the subsurface is very homogeneous in the horizontal direction (150 m between CL40 and the core hole, Figure 1) as determined by surface-based geophysics across the site (Acworth et al., 2015).

To conduct the cross-hole seismic survey (Crice, 2011) at Cattle Lane, two boreholes were drilled to 40-m depth adjacent to the cored hole (G1 and G2 shown in Figure 1). The boreholes were lined with thin-walled PVC casing that was grouted in place using a weak cement/mud slurry forced out of the base of the casing and allowed to overflow back to the surface outside the casing, ensuring that no air gaps were present. Good continuity was achieved between the formation and the casing with no air gaps to ensure unrestricted passage of seismic waves.

Bulk densities were measured on the clay samples recovered from the core nose of the triple-tube core barrel (Acworth et al., 2015) immediately after sample collection. Densities corresponding to the depths of the cross-hole measurements were calculated by interpolation of measurements at known depths. Samples were also dried and weighed to obtain total moisture and bulk density data (Table 1). Essential data for the core measurements at the site are presented in Table 1.

There are a total of nine piezometers screened at 5-m intervals between 5- and 55-m depth exist at Cattle Lane. Water levels were measured in these piezometers using vented pressure transducers (LevelTroll, InSitu Inc., United States). We note that the subsurface processes at this site are relatively well understood and have been reported in a number of previous papers. For example, in prior studies, the lithology was sampled by obtaining minimally disturbed 100-mm core followed by extensive laboratory testing and analysis (Acworth et al., 2015) and the BE and degree of confinement over depth established (Acworth, Halloran, et al., 2016; Acworth et al., 2017). We extensively make use of this existing data set in order to add context to the cross-hole seismic survey and further improve our understanding of the unconsolidated subsurface.

Table 1
Depth Profile of Moisture Content and Density for Core Samples (Acworth et al., 2015) and BE Values From Piezometers (Acworth et al., 2017) at the Cattle Lane Site

Core sample depth z (m BGS)	Water content θ (%)	Natural density ρ (kg/m^3)	Free water porosity θ_{free} (%)	Piezo depth z (m)	BE (-)
2.68	64.71	1659	0.015	5	0.010
4.35	31.25	1907	0.010	10	0.007
5.85	43.48	1926	0.007	15	0.032
7.35	46.43	1864	0.007	20	0.039
10.35	52.94	1721	0.007	25	0.042
11.85	47.37	1707	0.005	30	0.042
13.35	36.36	1997	0.020	35	0.059
14.85	58.57	1763	0.018	40	0.121
16.40	48.44	1664	0.018	55	0.138
17.35	47.37	1748	0.020		
19.35	52.38	1721	0.023		
20.85	55.56	1821	0.023		
22.35	45.45	1807	0.020		
23.85	52.63	1815	0.020		
26.85	36.17	1924	0.020		
28.35	34.29	1940	0.020		
29.85	44.99	1756	0.022		
31.35	25.00	2075	0.023		

Note. Estimates of free water porosity (θ_e) are based upon the analysis of density developed in section 3.1.2. BGS = below ground surface. BE = barometric efficiency.

2.7. Cross-Hole Seismic Survey Procedure

At both sites, a seismic source (Ballard borehole shear wave source) was lowered into the borehole and clamped to the casing using an inflatable bladder expanded using air pressure. Upward and downward polarized shear waves were generated by either dropping a weight onto the clamped frame or pulling the weight upwards so that it struck the clamped frame. *P* waves were generated by both upward and downward blows on the clamped frame. Seismograms were recorded using a submersible three-component geophone (Geostuff wall-lock geophone). The geophone had two horizontal and one vertical element and was locked in place using a mechanical arm (steel spring) that was activated from the surface. The horizontal components were configured so that one component was normal to the source bore and the second at right angles using an on-board magnetometer element to sense direction.

Seismograms were recorded by a multichannel seismograph using image stacking to improve the signal-to-noise ratio. In general, six upward and six downward blows provided a clear indication of the shear wave arrival. Data were collected either at 0.5- or 1.0-m intervals, but the station interval was arbitrary. Data collection required between 2- and 3-hr work. The distance between the shot and receiver bores at different depths was established by running borehole verticality logs (Geovista verticality sonde) in each bore. The verticality-distance relationships were combined to calculate the distance between the source and receiver at each required depth. Wave arrival times were estimated using the vertical component for the shear waves and the beginning of the phase difference between the upward and downward blows. Similarly, the compressional wave arrivals were estimated using the horizontally orientated geophones. Wave velocities were established using the horizontal distance between the sensors established from the verticality survey

3. Results and Discussion

3.1. Combining Cross-Hole Seismic Surveys and Tidal Analysis Reveals Subsurface Properties

Example primary and shear wave measurements are shown in Figure 2 to illustrate the data collected from the three-component geophones. The *P* wave arrivals are noticeably in phase, whereas the *S* wave arrivals are 180° apart. As the vertical component presents the clearest arrival time, it is used in the investigation of shear wave anisotropy.

We calculate the drained and undrained poroelastic parameters from undrained measurements using values for grain compressibility provided in the literature. Further, two different specific storage depth profiles

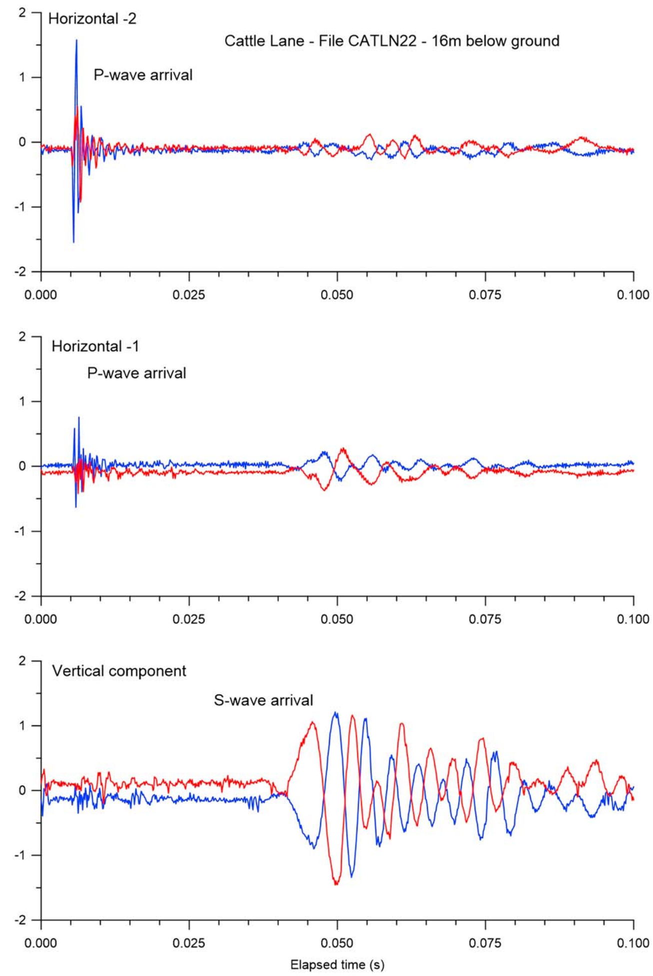

Figure 2. Example output from the three-component geophone showing the arrivals from upward (red) and downward (blue) polarities measured at 16 m BGS at Cattle Lane (Figure 1b).

are calculated and compared: (1) equation (20): This approach assumes a porosity as well as incompressible grains ($K_s = 0$); (2) equation 21: In this new method, the required parameters are obtained by combining cross-hole seismic surveys and tidal analysis. Here it is noteworthy that the bulk density ρ is required instead of porosity. Further, the influence of compressible grains can be explored by taking K_s values from the literature. This mathematically constrains the poroelastic parameter space so that K values can be obtained from equation (24).

3.1.1. Sand-Dominated Site: David Phillips Field

The seismic waveforms (Figure 3) measured during the cross-hole survey at David Phillips Field are shown along with the gamma ray activity and bulk electrical conductivity logs to provide a lithological comparison.

The water level in the sands at the time of measurement was ~7 m below ground surface. Both P and S wave arrivals were detected above this depth. Elevated bulk electrical conductivity levels between 7 and 15 m represent contaminated groundwater moving laterally from an old waste fill and the elevated gamma ray activity at 23 m is considered to be an old interdune wetland that may have trapped dust (Acworth & Jorstad, 2006).

The shear wave results for the David Phillips Field (Figure 3) indicate that there is significant variation in signal amplitude with depth, although the source signal was produced manually, that is, by pulling up or letting the shear source weight drop down. This suggests that the shear wave amplitude could be used to indicate lithological variability. The sedimentary sequence at this site was examined during drilling to comprise uniform sands to 22-m depth with a black silty ooze at 23 m before a return to uniform sands. Samples were not kept as the sequence appeared so uniform.

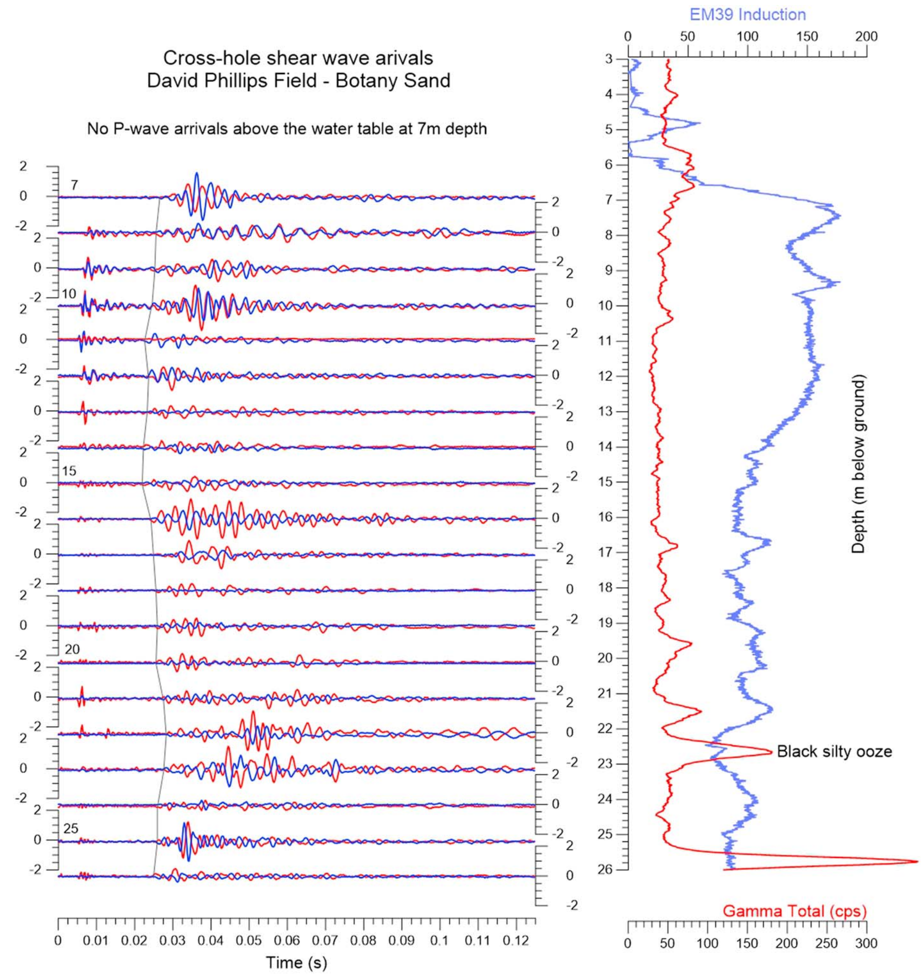

Figure 3. Profile of the vertical component cross-hole survey results from bore G2 at David Phillips Field (Figure 1a) vertically colocated with an EM39 induction and gamma depth survey.

Shear wave amplitudes suggest that considerably greater variability is present that may indicate differences in consolidation or protosoil development due to a break in sand accumulation. The sequence is undated although tree remains from approximately 30 m at a site in the sands 800 m to the southwest give an uncorrected radiocarbon date of $\sim$ 30,000 BP. Variability in sediment accumulation rate and type would have occurred through the last glacial maximum at this site.

The results derived from the cross-hole survey at David Phillips Field are shown in Figure 4a. In the absence of depth-specific information, a density of $\rho = 2,072$ kg/m^3 was determined using equation (16) with a total moisture content $\theta = 0.35$ (Acworth & Jankowski, 1993). As a first approximation, porosity, density, and loading efficiency were not considered to vary with depth. Fine-grained sands with thin beds of silt/clay at the site were reported by Webb et al. (1979). The BE measured in the piezometer installed at 16 m ($BE = 0.151$) was used to calculate the loading efficiency ($LE = 0.849$, equation (22).

Richardson et al. (2002) report a solid grain modulus for Ottawa Sand in the range of $30 \leq K_s \leq 50$ GPa using 95% confidence limits, which they consider to be consistent with values for polycrystalline quartz found in the literature ($36 \leq K_s \leq 40$ GPa) and also for glass beads. The Ottawa Sands had a fractional porosity of 0.373, a mean P wave velocity of 1, 775 m/s, a bulk density of 2, 080 kg/m^3, and a grain density of 2,670 kg/m^3. As the physical properties of the Ottawa Sand sample closely match those from David Phillips Field, we have selected the midpoint of the solid grain modulus range ($K_s = 42$ GPa), which represents a $\beta_s \approx 2.632 \cdot 10^{-11}$ Pa^{-1}, for our poroelastic analysis.

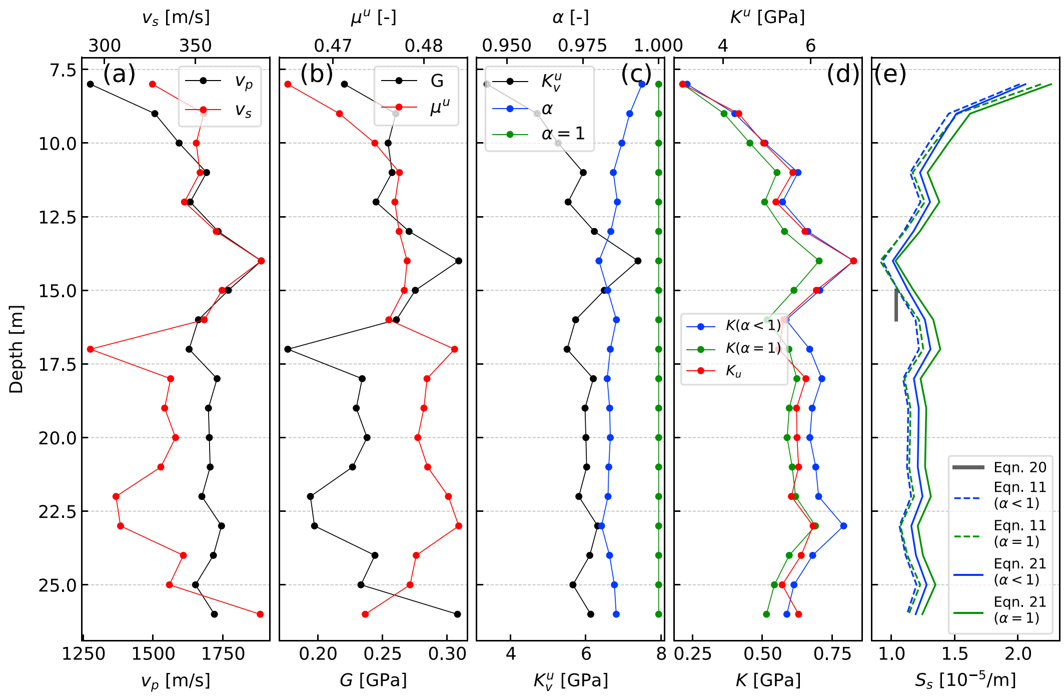

Figure 4. Results for the David Phillips Field Site. (a) Primary and shear wave velocity data. (b) Undrained Poisson's ratio and shear modulus. (c) *Biot-Willis* coefficient (α) and undrained (vertical) bulk modulus (K_v^u). (d) Drained (K) and undrained (K^u) bulk moduli. (e) Specific storage estimates using parameter ranges as described in the text.

The results of the poroelastic calculations are summarized in Figure 4. Figures 4b–4d show the calculated depth profiles for the poroelastic coefficients. Figure 4e compares the three specific storage estimates calculated using

1. Equation (20) (for the single value of *LE* at 16-m depth). This is the conventional analysis that is based upon Jacob (1940) and is implemented in Acworth et al. (2017).
2. Equation (11) with values calculated for $K_s = 42$ GPa ($\alpha < 1$) as well as $K_s \to \infty$ ($\alpha = 1$). This is a fully developed poroelastic solution where knowledge of parameters are required, that is, estimates for porosity, drained bulk modulus K, solid grain modulus K_s, and shear modulus G or Poisson ratio μ.
3. Equation (21) with values calculated for $K_s = 42$ GPa ($\alpha < 1$) as well as $K_s \to \infty$ ($\alpha = 1$). This is the new poroelastic approach presented in this paper which requires density estimates.

We note the agreement between the three specific storage calculations (Figure 4e). The values of specific storage decrease from $S_s \approx 2 \cdot 10^{-5}$ m^{-1} to $S_s \approx 1.2 \cdot 10^{-5}$ m^{-1} over depth. We note also that bulk density and porosity are related (equation (16)), an observation that we will return to below.

3.1.2. Clay-Dominated Site: Cattle Lane

The seismic waveforms recorded during the cross-hole survey by the vertically orientated geophone at Cattle Lane are shown in Figure 5. The depth of each seismogram is arranged so that the zero amplitude is adjacent to the depth below ground level used for the geophysical logs.

A detailed lithological characterization for this site has previously been published (Acworth et al., 2015; Acworth, Halloran, et al., 2016) and provides physical data and observations that we draw upon for the poroelastic analysis in this work. *S* wave variability was significantly higher at this site than at David Phillips Field. It is therefore assumed that the observed variability is a function of lithology and not a measurement artifact. The shear wave data were collected to 38 m, a depth that correlates to an age of approximately 150 ka (Acworth et al., 2015) and covers the start of the penultimate glacial, the interglacial, and the last glacial stages of the Ice Age.

It is not the intention to fully interpret the correlations between the shear wave arrivals and waveforms but to note that there appear to be relationships between shear waveforms and the past climate variations that cause the different lithologies observed. For example, the clear change in shear waveform at 14- and 15-m

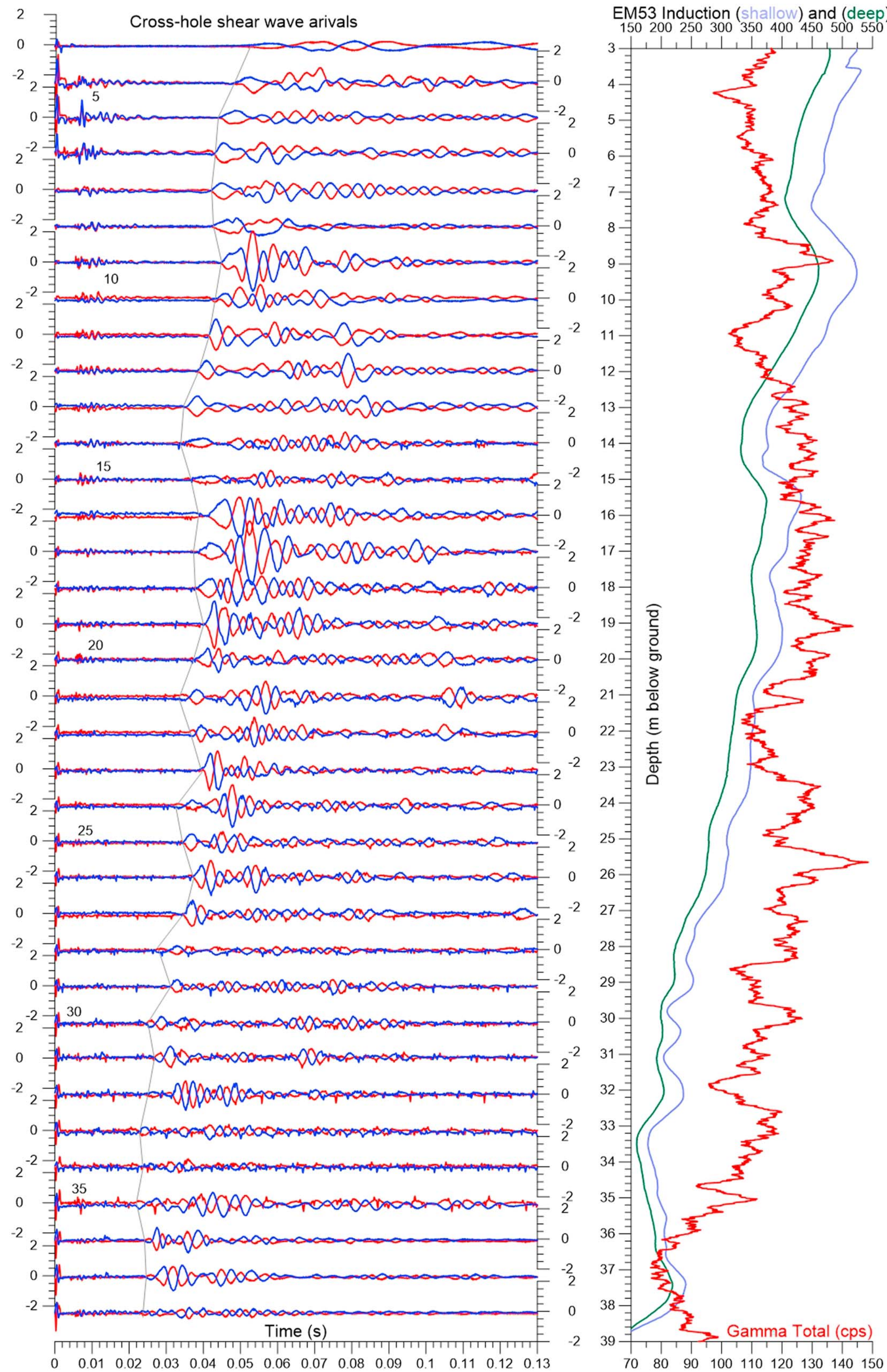

Figure 5. Profile of the vertical component cross-hole survey results at Cattle Lane arranged alongside with the gamma ray activity and electromagnetic borehole logs.

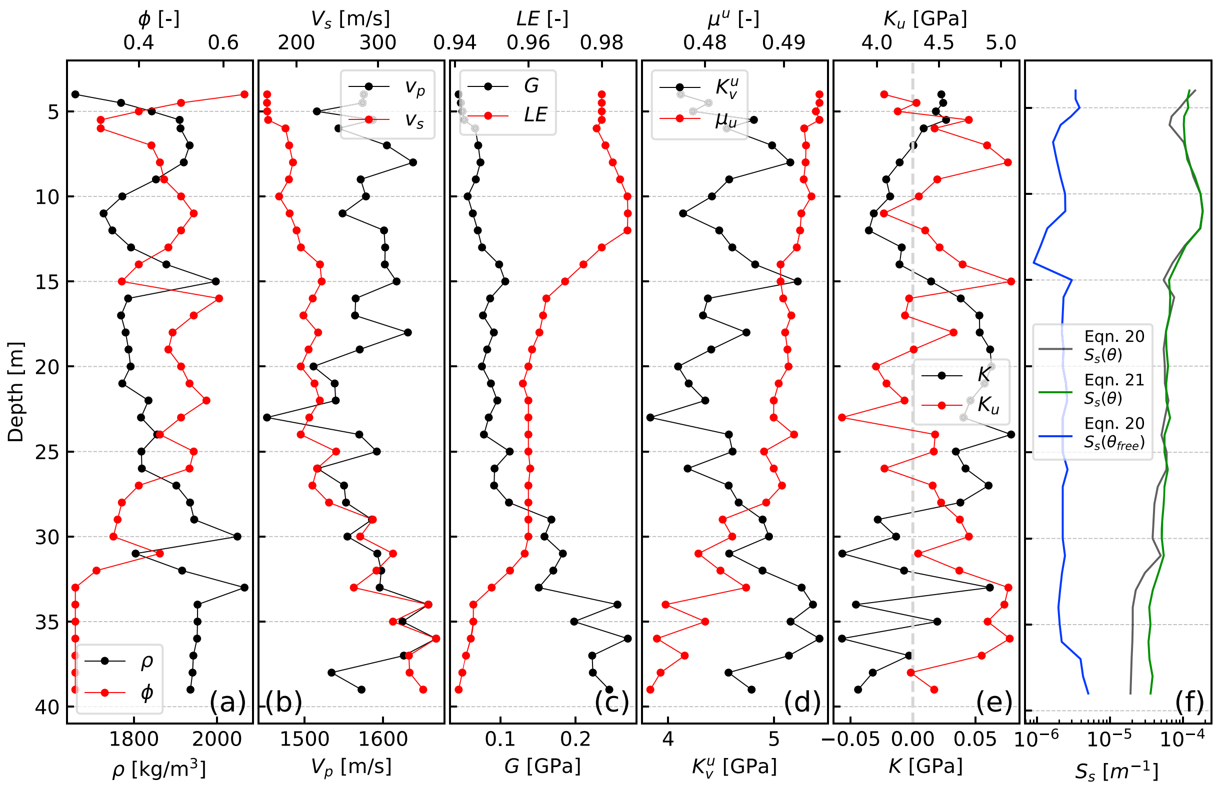

Figure 6. Depth profiles of the poroelastic parameters at the Cattle Lane Field Site. (a) Porosity and density. (b) Seismic velocities. (c) Loading efficiency and shear modulus. (d) Poisson's ration (undrained) and bulk modulus (vertically constrained and undrained). (e) Undrained vertical bulk modulus and undrained bulk modulus. (f) Specific storage, quantified using equation (20) assuming a measured bulk moisture content as total porosity θ (black line) and using equation (21) with measured formation densities (green line). For smectite clays we assumed that $\alpha = 1$. For comparison, S_s calculated from the free water fraction $S_s(\theta_{\text{free}})$ is shown.

depth (much reduced amplitude and lower frequency) shown in Figure 5 correlates with the depth at which Acworth et al. (2015) observed a sandy layer in the bore during construction. Core recovery over this interval was very poor, and good core only recommenced at 16.5 m. The age of sediments at this depth is approximately 55 to 60 ka (Acworth et al., 2015) and correlates with *lake full* conditions across eastern Australia (Bowler, 1990) as well as a period of increased dust concentration in Antarctic ice cores (Petit et al., 1999). Shear waveforms remain stronger between 16- and 21-m depth (65 to 80 ka) during a time of reduced dust and higher temperatures. It is evident that the seismic shear waves could be further analyzed for an improved correlation with lithology.

A solid grain modulus for the smectite-dominated clay at the Cattle Lane Site is also required to mathematically constrain the poroelastic relationships. However, no data are available for Cattle Lane and we have not found values for smectite-dominated clay in the literature. This is not surprising as the parameter is intrinsically difficult to measure given the fact that a high proportion of the water associated with the clay is adsorbed. Separating the clay from the water changes the material matrix. Prasad et al. (2001) directly measured Young's modulus and Poisson's Ratio of clay minerals and found values of $E_s = 5.9$ GPa and $\mu_s = 0.3$. These values can be converted to a clay solid gain modulus $K_s \approx 4.9$ GPa (equation (7)). However, this result leads to negative and therefore physically unrealistic values of K when equation (24) is used. We hypothesize that the assumed linearity inherent to poroelastic theory breaks down for clays, a fact that has been noted before (Bathija, 2000). We therefore make the reasonable assumption that $K_s \gg K$ and that the *Biot-Willis* coefficient $\alpha = 1$ for smectite clays.

The cross-hole survey results for Cattle Lane are shown in Figure 6b. Note that this is accompanied by existing depth-specific total moisture (porosity) and bulk density provided by laboratory measurements in Figure 6a (Acworth et al., 2015). Again, the depth profiles of specific storage were calculated using equations (20) and (21) with measured and estimated (interpolated) values of θ and ρ.

Our new method for calculating specific storage (equation (21)) relies on an estimate of the formation bulk density, whereas equation 20 necessitates knowledge of the total porosity. The excellent match between both results confirms the accuracy of our laboratory based measurements from the core reported in Acworth et al. (2015). These density and moisture content profiles were interpolated between field laboratory measurements for the clays at Cattle Lane to estimate values at the depths of the seismic measurements. An extended density formulation was required for the clay sites as it was not possible to use equation (16) to replicate the higher bulk densities measured in the core samples. In recognition of the fact that much of the total moisture (θ) is adsorbed into the clay matrix, equation (16) was extended to include a fraction of the total moisture as adsorbed moisture with a higher density (Martin, 1960; Galperin et al., 1993) as follows

$$\rho = \rho_s(1-\theta) + \rho_{\mathrm{ads}}\theta_{\mathrm{ads}} + \rho_w\theta_{\mathrm{free}}, \tag{25}$$

where θ is the field measured moisture content, θ_{ads} is the adsorbed moisture fraction, and $\theta_{\mathrm{free}} = \theta - \theta_{\mathrm{ads}}$ is the free water fraction; ρ_s is the solid density (between 2,000 and 2,700 kg/m^3 based upon published values), ρ_{ads} is the adsorbed water density (between 1,000 and 1,400 kg/m^3; Martin, 1960; Galperin et al., 1993). We note that the value of θ_{free} represents the water that can freely drain from the formation and is considered similar to the specific yield S_y value that would occur when the system becomes unconfined. With this approach, predicted values of density could be found that matched the observed natural densities by using an adsorbed water density of 1,400 kg/m^3. The intervening depths were then estimated using the determined range of values.

Water adsorbed onto clay minerals is recognized as having physical properties more akin to the solid than the fluid with considerable viscosity, elasticity, and shear strength (Galperin et al., 1993). Considerable uncertainty concerns the physical properties of adsorbed water in the literature and its implications for groundwater resources or geotechnical understanding are unknown. Our results demonstrate that the response of clays and adsorbed water to stress can be fully explained by poroelastic theory using the total moisture content. This is to be expected because seismic waves and the loading efficiency stresses must act upon the total mass present. However, predicted specific storage values calculated using poroelastic theory assuming porosity is equal to the total water content will likely lead to large overestimates. This is because, as equation (25) indicates, only a very limited proportion of the water present in the clays—that which is not adsorbed to the clay mineral structure—will be free to flow in and out of the pores and therefore contribute to the specific storage value. We calculate this quantity from the theoretical analysis of density (equation (25)). We note that the very low values of free water porosity are corroborated by the field observation that the cores were almost dry to touch with little free water noted (Acworth et al., 2015).

Our estimates of the free water in the clays (θ_{free}) are shown in Table 1 and have been used to reevaluate the possible range of specific storage values via equation (11). The results are shown by the blue line in Figure 6f and demonstrate that realistic values of specific storage for smectite clays are approximately $2 \cdot 10^{-6}$ m^{-1} consistent with previous work by Acworth et al. (2017, Table 1).

3.2. Analysis of the Poroelastic Parameter Space for Specific Storage and Its Limits

We analyze the influence of the parameters involved in predicting specific storage using equation (21) while aiming to better understand the interplay of the various components across the spectrum of consolidation found in real environments. Equation (21) relies only on three parameters, the undrained vertical bulk modulus K_v^u, the loading efficiency *LE*, and the *Biot-Willis* coefficient α. We also investigate the sensitivity to *LE* and α when equation (21) is made independent of physical constants, that is, $S_s^n = S_s \cdot K_u^v \cdot g \cdot \rho_w$.

We used the published poroelastic parameters for marble ($\alpha = 0.19$ [-]; $K = 40$ GPa; $K_u = 44$ GPa, and $G = 24$ GPa) reported in Wang (2000, Table C.1), which represents the most consolidated conditions measured in the literature. The undrained vertical bulk modulus K_v^u was derived using equation (13). To represent unconsolidated conditions, we used the results presented earlier (section 3.1). In our analysis, we assume that the loading efficiency can be calculated with good accuracy using the objective method of the groundwater response to atmospheric tides developed by Acworth, Halloran, et al. (2016) and we allow values to vary between $0 \le LE \le 1$.

Figure 7a shows theoretical values of specific storage calculated using equation (21) and the aforementioned parameter combinations, whereas Figures 7b and 7c illustrate the sensitivity of specific storage to changes in loading efficiency and the *Biot-Willis* coefficient, respectively. Note that only parts of this parameter space are reflective of real-world conditions, as is discussed in the following.

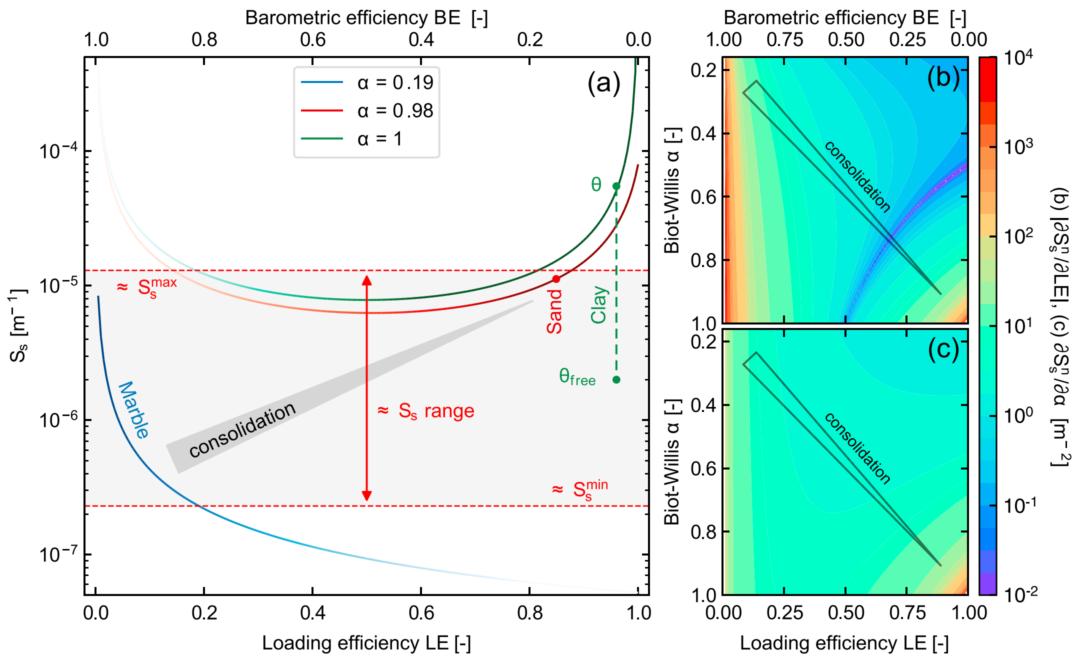

Figure 7. (a) Theoretical values of specific storage S_s as calculated using equation (21) with literature values representative for the most consolidated system as well as our results representative for unconsolidated cases. (b) Sensitivity of specific storage to the loading efficiency *LE*, and (c) to the *Biot-Willis* coefficient α.

It is interesting that S_s is most sensitive to *LE* (Figure 7b) when this parameter assumes very high or very low values. For LE→ 0 the specific storage values obtained from equation (21) diverge and are infinitely sensitive to loading efficiencies that are either very small ($LE \rightarrow 0$) or large ($LE \rightarrow 1$). Because diverging values of S_s are physically impossible, it can be deduced that a lower bound for loading efficiency must exist such that $LE > 0$ ($BE < 1$), and for values of $\alpha \rightarrow 1$ also $LE < 1$ ($BE > 0$). The sensitivity of specific storage to α appears to change for high values of loading efficiency (Figure 7c), such as is characteristic of water-saturated clays (Figure 7a). As such, elastic clay represents the most unconsolidated end-member with $\alpha = 1$.

While measurements of K_v^u exist in the literature for different materials (Domenico & Schwartz, 1997; Palciauskas & Domenico, 1989; Wang, 2000), little is known about how *LE* and α relate to real-world conditions. The *Biot-Willis* coefficient α describes the inverse of the ratio between bulk compressibility and grain compressibility (Wang, 2000). Here values of the bulk compressibility are correlated with the ability of the formation to reduce in volume when stressed, and the microscale mechanism is attributed to a rearrangement of individual grains (Wang, 2000). It is interesting to note that under consolidated conditions, that is, when the grains are locked together by chemical precipitate, the possibility of this rearrangement is much smaller compared to unconsolidated conditions, for which potential grain movement depends on the degree of packing. This is reflected in literature values of α, for example, for marble the ratio of solid grain compressibility is high in relation to that of the formation ($\alpha = 0.19$), whereas for clay this is very small ($\alpha = 1$).

The loading efficiency describes the sharing of stress induced by the weight acting on a confined groundwater system. *BE* and loading efficiency *LE* describe the relative share of stress supported by the matrix and the groundwater (Domenico & Schwartz, 1997; Wang, 2000). To date, relationships between its value and field conditions have not been well described in the literature. It is interesting to note that in consolidated systems (e.g., marble or limestone) the stress can be absorbed mainly by the solid matrix and therefore $LE \rightarrow 0$ ($BE \rightarrow 1$). Such formations are thought to act as a barometer where the pore pressure is negatively correlated with the atmospheric pressure (Domenico & Schwartz, 1997; Jacob, 1940; Meinzer, 1928). Contrarily, in unconsolidated systems where the stress is shared between water and matrix, the loading efficiency $LE \rightarrow 1$. Interestingly, Acworth, Halloran, et al. (2016) found that $LE \approx 0.02$ ($BE \approx 0.98$) in a clayey-sand formation that existed beneath overconsolidated clays of Tertiary age at Fowlers Gap in western NSW (Acworth, Rau, et al., 2016). Again, this points to the fact that both LE and α can depend on how well grains are packed. An optimum packing will result in less individual grain movement and vice versa. It is therefore very difficult to determine a definitive relationship between all parameters involved. However, there appears to be an interrelated correlation for consolidation, here defined as optimum packing or grains locked in place by chemical precipitate, where $\alpha \rightarrow 0.2$ and $LE \rightarrow 0$ reflect more consolidated environments (see annotation in Figure 7). Further evaluation of *BE* and α for different environments will lead to improved understanding of these relationships.

We further apply these considerations to finding realistic bounds for specific storage. From Figure 7a, a hypothetical minimum specific storage value can be deduced for the poroelastic parameters that characterize marble by following the blue line. However, the required loading efficiency of $LE \rightarrow 1$ is unrealistic as *LE* must remain toward the lower end. While a realistic bound is difficult to determine, we assume that for marble or limestone $LE \lesssim 0.2$. This results in a lower bound of $S_s^{\min} \approx 2.3 \cdot 10^{-7}$ m^{-1} but which must be prone to considerable uncertainty.

On the other end, clays are generally thought of as having the highest values of specific storage due to their high compressibility (e.g., Domenico & Schwartz, 1997; Fetter, 2001). Our results demonstrate that the total moisture content responds to stress and that poroelastic theory is able to quantify parameters for unconsolidated conditions. While this allows hypothetical estimates of $S_s^{\max}$, our results further demonstrate that such values may not be meaningful to predict the quantity of water that is freely expelled from the clay, as is the case during groundwater pumping. It is well known that a large proportion of the total moisture content associated with a swelling clay is adsorbed water that is not readily released by simple drainage (Galperin et al., 1993; Jury et al., 1991). The complicated nature of the interaction between water and clay minerals may also thwart the assumption of linearity inherent to poroelastic theory (Bathija, 2000). It is therefore questionable whether poroelastic theory can determine an absolute upper bound $S_s^{\max}$ that is meaningful for water resources.

For our smectite clays, we estimate a maximum $S_s^{\max}(\theta_{\text{free}}) \approx 1 \cdot 10^{-6}$ m^{-1} from values that are quantified in Figure 6, and a previous description by Acworth et al. (2017). However, it appears that fine sands can have higher S_s values compared to clays (compare Figures 6 and 4). While it is difficult to estimate an upper limit for extractable water, this must be based on the free water fraction and we estimate this value to be maximal at $S_s^{\max}(\theta_{\text{free}}) \approx 1.3 \cdot 10^{-5}$ (Figure 7a) for silts or kaolinitic-dominated clays where the adsorbed water fraction is lower than in smectite-dominated clays (Jury et al., 1991).

Notably, both cross-hole seismic and tidal analysis yield coefficients representative of undrained conditions. The specific storage equations (11) and (21) contain the drained bulk *K* and solid grain moduli K_s. Because both these parameters are unknown, the poroelastic system remains mathematically unrestrained; that is, not all parameters can be quantified by combining cross-hole seismics and tidal analysis. However, the unknown moduli occur as the *Biot-Willis* coefficient α (equation (10)) in equations (21) and (24). As discussed here, values for unconsolidated bulk moduli are generally much lower compared to consolidated formations (Domenico & Schwartz, 1997; Wang, 2000). This means that $K \ll K_s$ and therefore $K/K_s \rightarrow 0$ hence $\alpha = 1$, which leads to the following simplification of equations (21) and (24) (Wang, 2000)

$$S_s = \rho_w g \frac{1}{K_v^u LE(1 - LE)} \tag{26}$$

and

$$K = K^u(1 - B) = \left(K_v^u - \frac{4}{3}G\right)\left(1 - 3LE\frac{1 - \mu^u}{1 + \mu^u}\right). \tag{27}$$

Equations (26) and (27) mathematically constrain the parameter space and can therefore be used to approximate the poroelastic properties of unconsolidated formations using cross-hole seismic surveys and the groundwater response to atmospheric tides.

We note here that our analysis also produces a value of the drained bulk modulus (*K*) from equation (24) or (27), although, for the sake of brevity, the value of these estimates for geotechnical investigations will be described in a subsequent paper.

3.3. Implications for Groundwater Resource Analysis and Modeling

The uncertainty and lack of groundwater storage properties on a global scale (Richey et al., 2015) has meant that groundwater models generally use crude estimates of this parameter and also relegated it to a second-order importance. Even in aquifer testing interpretation, an order of magnitude estimate is often considered satisfactory (e.g.,Kruseman & de Ridder, 1990). This is despite the fact that this also implies a high degree of uncertainty in the derived transmissivity value since these parameters appear together in commonly used *Well Functions* via the relationships for aquifer hydraulic diffusivity, $D = T/S = K/S_s$. Thus, the accuracy of transmissivity and storage terms are inextricably linked.

Hsieh et al. (1988) consider the accuracy of specific storage values calculated theoretically to only $\pm$50%. Such difficulty in obtaining representative aquifer storage values has meant that groundwater modeling has focused far more on transmissivity when trying to achieve satisfactory model calibration. The significance of variation in storage is almost always overlooked, despite the fact that variation in storage can have just as great an impact on predicted groundwater elevations.

From the perspective of hydrogeology, which is mostly concerned with the continuous extraction of water from the subsurface, the poroelastic definitions drained and undrained (see section 2.1) change over time. As water is removed from a bore, clearly there is a change in mass occurring and $d\zeta/dt = Q\rho_w$, where Q is the volume of water abstracted. However, after a long time period of pumping from a confined aquifer, the system reaches steady state (Kruseman & De Ridder, 2000) and is at constant pore pressure ($dp/dt = 0$) as well as mass ($d\zeta/dt = 0$). By the poroelastic definitions given in section 2.1, stress conditions become drained as soon as extraction starts but transition into undrained conditions when steady state is reached. Drained and undrained elastic parameters can therefore be thought of as bounds for the poroelastic conditions encountered as a result of pumping.

A more complete consideration of poroelastic theory, as was undertaken in this paper, illustrates that the specific storage is limited to the range of $2.3 \cdot 10^{-7}$ m^{-1} $\lessapprox S_s \lessapprox 1.3 \cdot 10^{-5}$ m^{-1} with the lower limit derived from the poroelastic parameters of marble and the upper limit for materials where the grain size is smaller than that of fine sands but where the adsorbed water fraction is small compared to the total water content.

The uncertainty in S_s is substantial for estimating the drawdown caused by pumping. To illustrate the maximum possible drawdown difference due to our range in specific storage, Figure 8 shows the drawdown normalized by pumping rate and aquifer thickness for discrete pumping durations and realistic aquifer hydraulic conductivities ($\langle K\rangle$ = 0.01, 0.1, 1, 10 m/day) estimated using the standard Theis (1935) solution. Interestingly, it appears that the difference in normalized drawdown across the range of S_s is independent of the distance to the pumped well for high conductivities (Figures 8j–8l) or long extraction periods (Figures 8f, 8i, and 8l).

Where a groundwater model has performed a satisfactory mass balance using a very high storage coefficient, but we accept that such a value is not realistic based upon the known properties of the formation and the poroelastic theory described earlier, then we are forced to recognize that a large proportion of the water delivered cannot come from storage changes within the formation. This must lead to a reevaluation of the conceptual model of an aquifer and the inclusion of effective leakage into the modeled space, for example, either from upward or downward leakage through bounding aquitards or from lateral movement from channels associated with rivers or other recharge boundaries.

At our field sites, especially on the Liverpool Plains, uncertainty regarding specific storage persists in modeling groundwater resources where new coal mines are proposed, and there is a possibility of future coal-seam gas extraction. As very few, if any, measurements of specific storage in the low permeability units are available from pumping test studies, values of specific storage in the range of $1 \cdot 10^{-6}$ m^{-1} $\leq S_s \leq 5 \cdot 10^{-4}$ m^{-1} have been used to allow groundwater level calibration (McNeilage, 2006; Price & Bellis, 2012). While the lower end is similar to values we have calculated from poroelastic analysis (an average of $\approx 2 \cdot 10^{-6}$ m^{-1}), the upper value is at least an order of magnitude too high. The worst-case difference in drawdown resulting from lowering S_s to the upper bound determined here would be $\Delta s \approx 25$ m at a distance of 10 m from the extraction bore, assuming a hydraulic conductivity of $\langle K\rangle = 1$ m/day, constant rate pumping $Q = 50$ L/s, and aquifer thickness of $b = 50$ m (Figures 8g–8i). Our analysis supports the observations of rapid downward leakage in response to pumping on the Liverpool Plains (Acworth & Timms, 2009; Timms & Acworth, 2004).

Our findings have global implications wherever groundwater models have been calibrated using values of specific storage that are unrealistically high ($\gg 1.3 \cdot 10^{-5}$ m^{-1}). We should of course add the caveat that our poroelastic analysis is based upon the theory of linear poroelasticity and assumes perhaps an unwarranted degree of material homogeneity. However, use of the assumption that the *Biot-Willis* coefficient is unity will address this uncertainty. We anticipate that our results will help improve conceptual models that are used to quantify aquifer parameters for groundwater resource estimates and management.

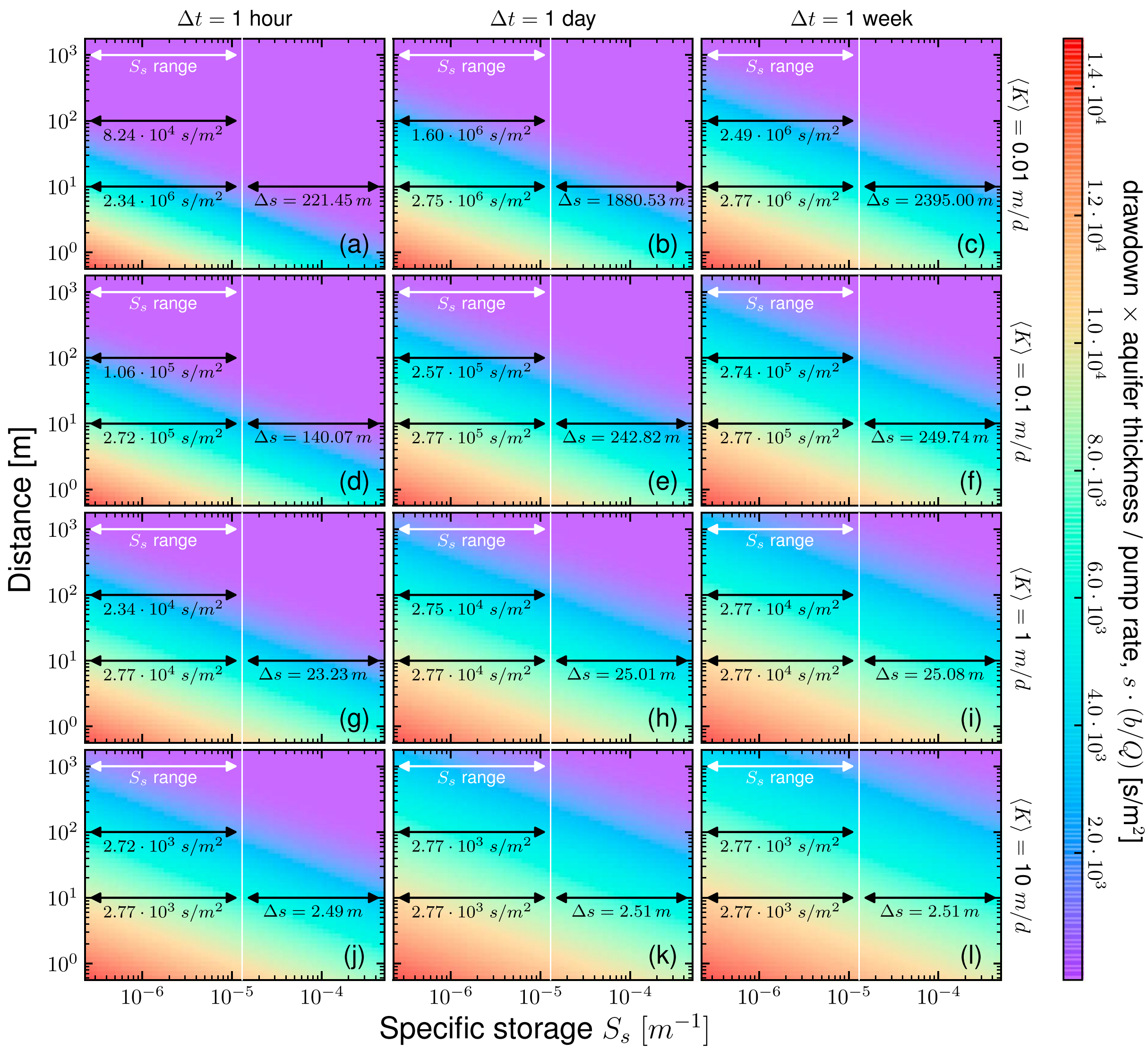

Figure 8. Normalized drawdown (s/m^2; i.e., groundwater head drawdown [*s*] × aquifer thickness [*b*] / pump rate [*Q*]) for a confined aquifer as calculated using the solution by Theis (1935). To convert to drawdown in meters, multiply the values by Q/b. Notation on the left shows generic drawdown differences across the possible specific storage values of $2.3 \cdot 10^{-7}$ m^{-1} $\lessapprox S_s \lessapprox 1.3 \cdot 10^{-5}$ m^{-1}. Notation on the right illustrates our field example (Δs) across the possible specific storage values assuming our upper limit of S_s for discrete times, distances, and hydraulic conductivities as well as a pumping rate of $Q = 50$ L/s and an aquifer thickness of $b = 50$ m.

4. Conclusions

We have derived new equations which relate the drained and undrained poroelastic parameters governing specific storage in consolidated materials, incorporating the effects of both solid grain and bulk compressibility. We have shown how the necessary parameters can be derived from a combination of cross-hole seismic surveys and high-frequency groundwater level measurements, reducing the large uncertainty that is normally inherent in storage estimates using a priori estimations of such parameters. Our new method for quantifying specific storage relies on an estimation of formation density. However, this is relatively easy to constrain in comparison with the assumptions inherent in other methods, for example, reliance of porosity values for tidal analysis (Acworth, Halloran, et al., 2016) or the conceptual or numerical simplifications applied during pumping test inversion (Kruseman & De Ridder, 2000).

We have presented field data and analysis to demonstrate the applicability of the new method in the context of two contrasting lithologies (sand and smectite clay), and the results show excellent agreement with those derived from an alternative method. Our results yield a new constraint of $S_s \lessapprox 1.3 \cdot 10^{-5}$ m^{-1} for the physically

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plausible upper limit of specific storage for unconsolidated materials, applicable as long as the adsorbed water fraction is small compared to the total water content. For clay-rich formations with substantial adsorbed water, specific storage will be much lower than this value (as shown in Figure 6) but in a range that is only as certain as the estimation of the free water content will allow. This occurs because the adsorbed water significantly contributes to the compressibility of the formation, but because it cannot flow under an imposed hydraulic gradient, it does not contribute to groundwater storage that is actually available.

It is common for literature values of specific storage of aquifers to be above the theoretical maximum we present here. Where this is the case, a reappraisal of the conceptual model and data that have been used to derive such values is needed. This is critical to ensure more robust management of groundwater resources from confined aquifers or to predict the possible subsidence due to continued groundwater abstraction, issues of increasing importance worldwide.

Appendix A

Table A1 provides a quick reference for the mathematical symbols used in this paper.

Table A1
Definitions of Variables Used

Variable	Definition and SI units
ads	(subscript) Adsorbed water
free	(subscript) Free water
s	(subscript) Solid matrix
w	(subscript) Water
v	(subscript) Vertical
h	(subscript) Horizontal
u	(superscript) Undrained
$< none >$	(superscript) Drained
B	*Skempton* coefficient (-)
BE	Barometric Efficiency (-)
$E^{(u)}$	Young's Modulus (Pa)
g	Acceleration due to gravity (m/s^2)
G	Shear (or rigidity) modulus (Pa)
$K_{(s)}^{(u)}$	Modulus of elasticity (Pa)
$K_{(h,v)}^{(u)}$	Uniaxial (horizontal or vertical) or confined modulus of elasticity (Pa)
l	Length (m)
LE	Uniaxial loading efficiency (-)
M_2^{ET}	M_2 Earth tide amplitude[a] (m/s^2)
M_2^{GW}	M_2 Groundwater amplitude[a] (m H_2O or Pa)
p	Pressure (Pa)
h	Groundwater head (m)
S_s	Specific storage (m^{-1})
S_y	Specific yield (-)
S_2^{AT}	S_2 Atmospheric tide amplitude[a] (m H_2O or Pa)
S_2^{ET}	S_2 Earth tide amplitude[a] (m/s^2)
S_2^{GW}	S_2 Groundwater amplitude[a] (m H_2O or Pa)
V	Volume [m^3]

Table A1 *(continued)*

Variable	Definition and SI units
V_p	Seismic *P* wave velocity (m/s)
V_s	Seismic *S* wave velocity (m/s)
α	*Biot-Willis* coefficient (-)
$\beta^{(u)}_{(v,s)}$	Compressibility (Pa^{-1})
$\Delta\phi$	Phase shift (rad)
ϵ	Strain (Pa^{-1})
$\lambda^{(u)}$	Lamé's modulus (-)
$\mu^{(u)}$	Poisson's Ratio (-)
ρ	Bulk density (kg/m^3)
σ	Stress (Pa)
θ	Total porosity (= water content in saturated zone; -)
z	Depth (m)
s	Change in head with pumping (drawdown; m)
b	Aquifer thickness (m)
$\langle K\rangle$	Hydraulic conductivity (m/s)
Q	Pumping rate (m^3/s)

[a]See Acworth, Halloran, et al. (2016).

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Appendix E NSW IPC Presentation 12 November

UNSW SYDNEY | Australia's Global University

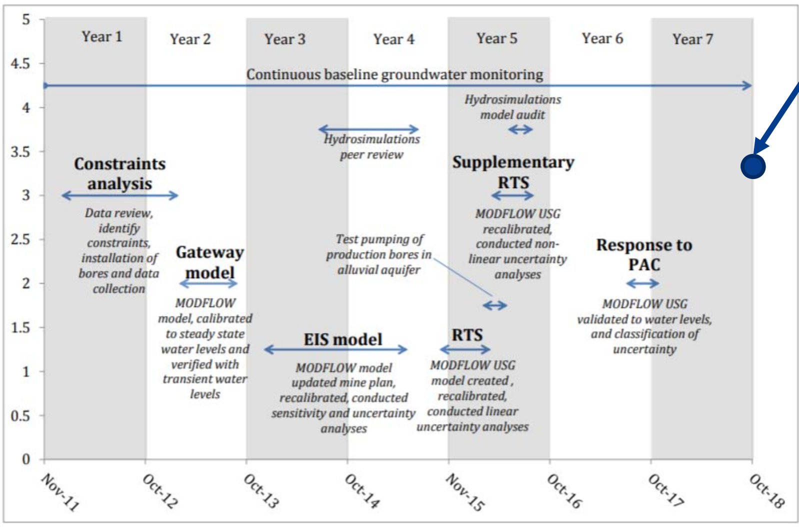
Water Research Laboratory | School of Civil & Environmental Engineering

NSW DPE State Significant Development Proposal No. 6367: Bylong Coal Project (Updated Mine Plan)

Mr Doug Anderson | Principal Engineer – Groundwater and Modelling

12 November 2018

My Terms of Reference



Source: Document 48, Figure 2-1, p. 4

Client: EDO NSW

Funding Body: Bylong Valley Protection Alliance

Brief: Review documents, prepare impartial advice to assist NSW IPC determination, present and write a report (60 hours)

Qualifications

Reviewer: Mr Doug Anderson

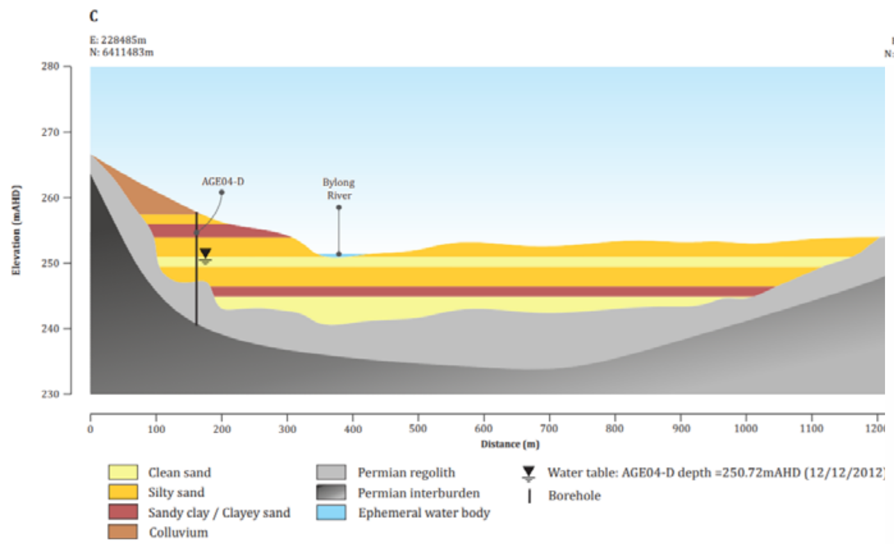
Position: Principal Engineer, Water Research Laboratory, UNSW Sydney (2013 – present)
Groundwater Modelling Specialist, Matrix Solutions, Canada (2010 - 2013)
Project / Senior Engineer, Water Research Laboratory, UNSW (2001 – 2009)

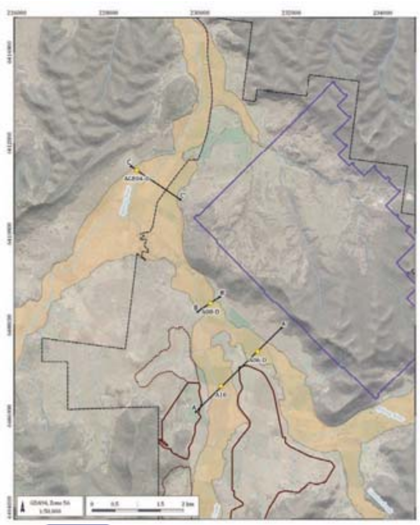
Education: B.E. (Environmental) Hons 1, UNSW 2000
M.Eng.Sci (Groundwater Studies), UNSW 2001

Experience: 17 years of engineering, groundwater conceptualisation and water modelling experience, including development of data management, automated data analysis, decision support and online reporting systems to facilitate engineering and environmental management practice.

Projects Work Examples:

- Groundwater impact assessment peer reviewer: SSD linear infrastructure proposals (for NSW DPE)
- Groundwater impact investigations and assessment review: Various SSD mining and coal mining proposals / proposals (for people of NSW)
- Modelling of water supply impacts of Oil-Shale, Steam Assisted Gravity Drainage Projects in Albrta Canada (development proponents)
- Conceptualisation, modelling, mineral brine resource estimation of Cauchari-Olaroz Lithium Brine Project, Argentina (development proponent)
- Regional model calibration for wellhead protection of Waterloo Moraine Municipal Groundwater Supply, Alberta, Canada (for 500,000 residents)
- Model design assistance for EIA of Rock Creek Underground Copper Mine, fractured rock aquifer, Montana (for United States Forestry Service)
- Numerical modelling of surface water and groundwater for Ranger Uranium Mine Pit No. 1 Closure Strategies, Northern Territory
- Monitoring, modelling, management plan development for effluent reuse projects (Moree, Warren, Lake Conjola, Iluka)
- Numerical modelling feasibility assessment in coastal sand aquifers for desalinisation water harvesting





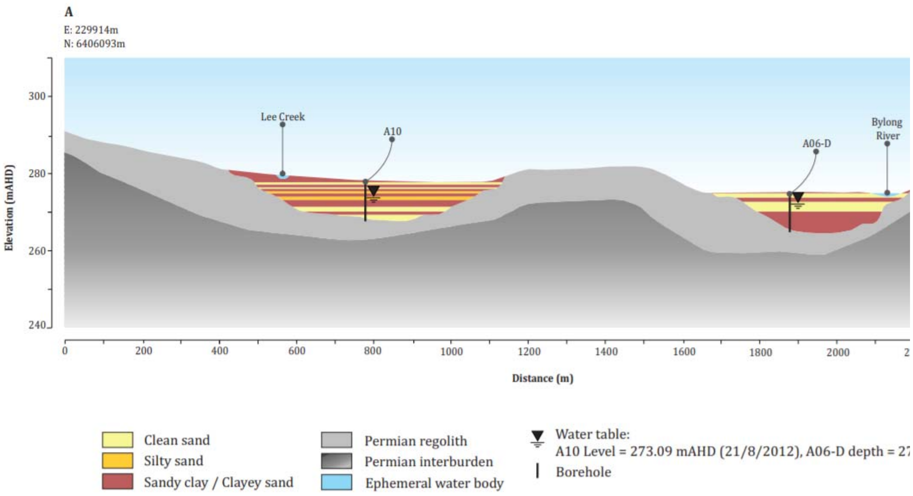
Alluvial cross section C - C'

Figure 7

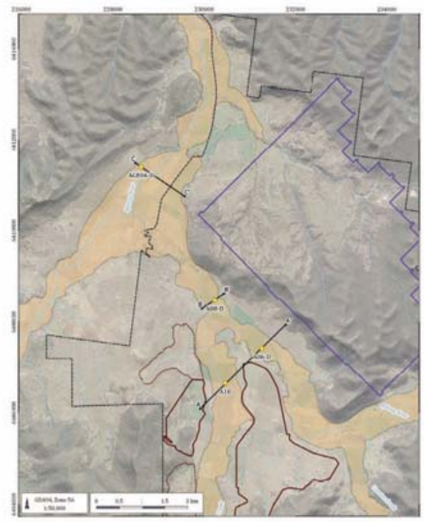
Bylong Coal Project (G1606E)

Source: Document 49, Figure 7, p. 23

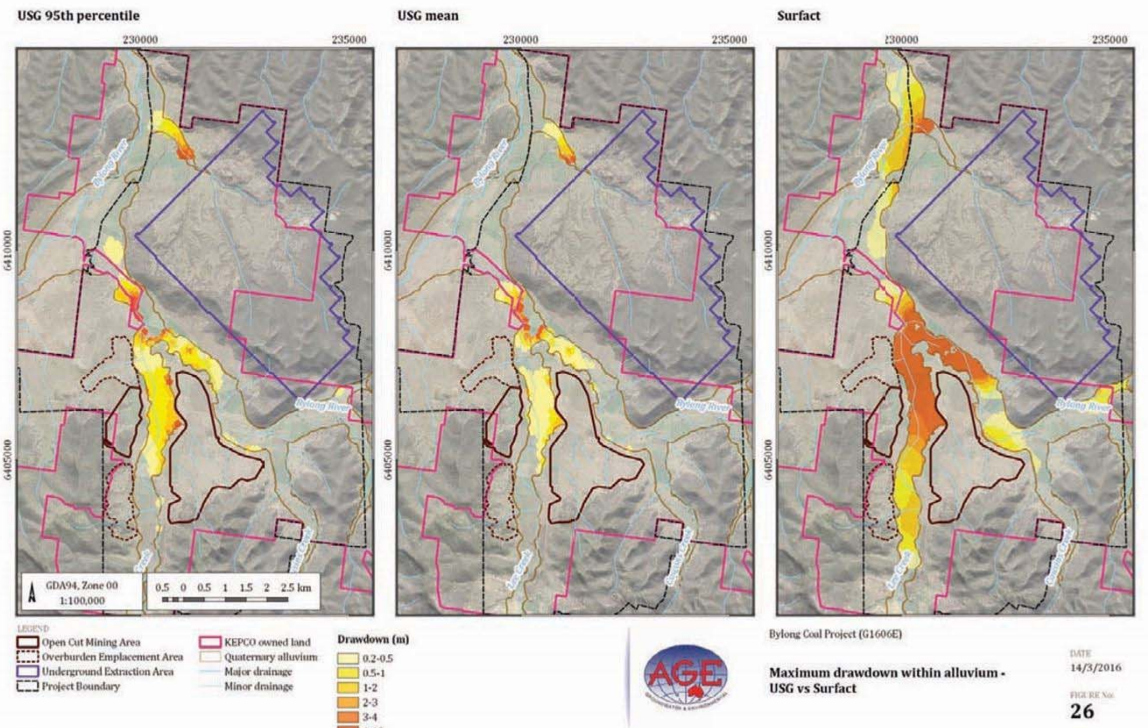
Source: Document 49, Figure 4, p. 20



Source: Document 49, Figure 4, p. 21



Source: Document 49, Figure 4, p. 20



Source: Document 49, Figure 26, p. 50

ground water

Issue Paper/

Ground Water Development—The Time to Full Capture Problem

by J. Bredehoeft[1] and T. Durbin[2]

Abstract

Ground water systems can be categorized with respect to quantity into two groups: (1) those that will ultimately reach a new equilibrium state where pumping can be continued indefinitely and (2) those in which the stress is so large that a new equilibrium is impossible; hence, the system has a finite life. Large ground water systems, where a new equilibrium can be reached and in which the pumping is a long distance from boundaries where capture can occur, take long times to reach a new equilibrium. Some systems are so large that the new equilibrium will take a millennium or more to reach a new steady-state condition. These large systems pose a challenge to the water manager, especially when the water manager is committed to attempting to reach a new equilibrium state in which water levels will stabilize and the system can be maintained indefinitely.

Source: Document 50

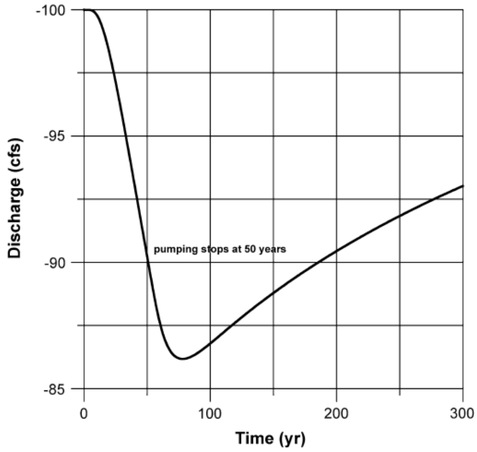
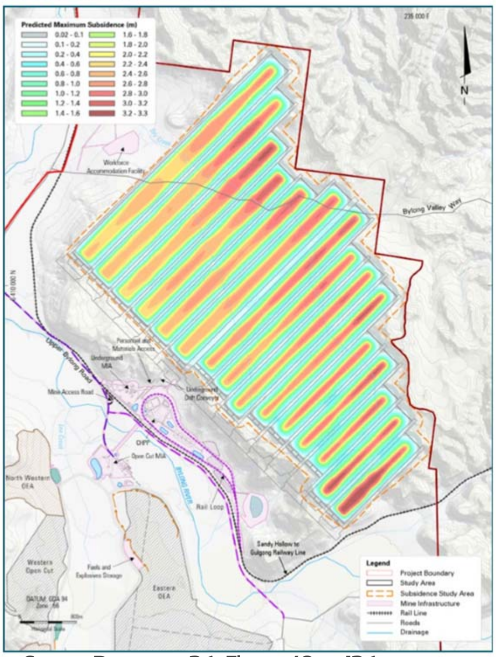


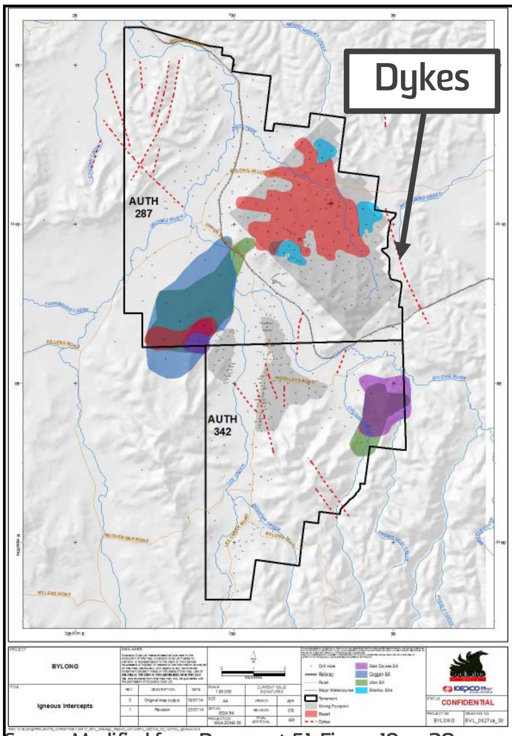
Figure 9. Predicted spring flow from a hypothetical aquifer (Figure 1 with phreatophytes in area 1 replaced by a spring). Pumping ceases after 50 years when the spring flow drops to 90 cfs.

Source: Document 50, Figure 9, p.

FIGURE 40 Predicted Subsidence Contours



Source: Document 36, Figure 40, p. 136



Source: Modified from Document 51, Figure 10, p. 29

Figure 10: Igneous Activity

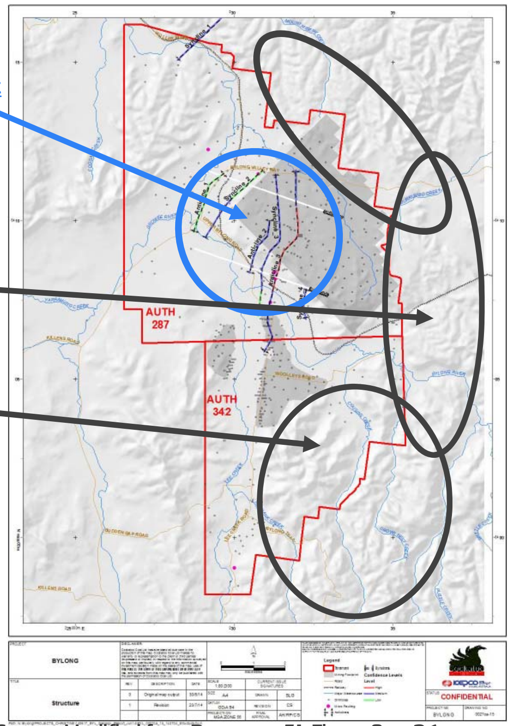
1. Were field geological surveys focused on agricultural land and not National Parks, Heritage Sites or Ecosystems (IDE's and GDE's)?

2. What do geological cross sections showing drawdown predictions in national park look like for different values of Ss?

3. Are there no faults or folds in National Parks and other Forests these area or just no attempts to map faults and folds?

4. Faults represented in prediction model?

5. Consequence of representing faults in model if not already?



Source: Modified from Document 51, Figure 8, p. 26

Figure 8: Structure - Faults and Folds

1. Gateway Panel cited technical reports stating seam to surface fracturing. What changed to allow this conceptual model?

2. Is this diagram an accurate reflection of the concepts constructed in the numerical model?

3. Are the elevated shallow aquifers in State Forest at risk of being slowly drained due to conventional / non-conventional subsidence subsidence movements increasing hydraulic conductivity? How was potential impacts to GDE / IDEs in State Forest calculated / assessed? Was it adequate? Worst case outcome in $ terms is?

4. The open cut coal mine to the south is located ~2.5 km from Wollemi National Park, a World Heritage Area. Is the equivalent hydrogeological conceptual model for that area of project footprint adequate?

5. What do cross-sections of longitudinal drawdown through the alluvial valleys look like at different times for different values of Ss?

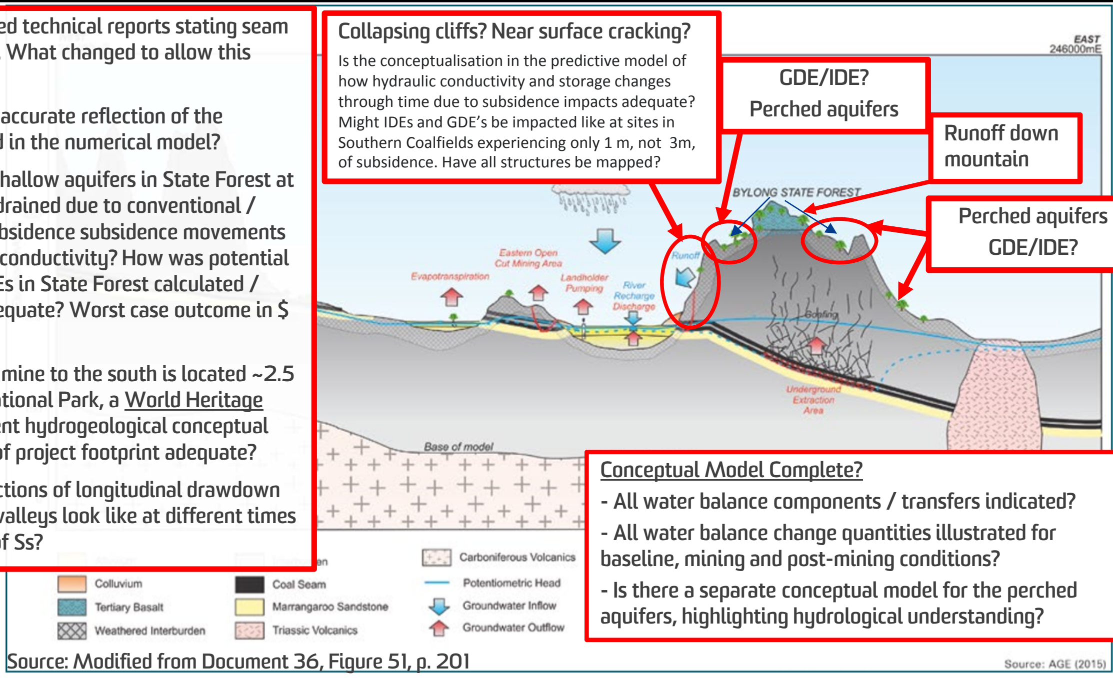
Collapsing cliffs? Near surface cracking?

Is the conceptualisation in the predictive model of how hydraulic conductivity and storage changes through time due to subsidence impacts adequate? Might IDEs and GDE's be impacted like at sites in Southern Coalfields experiencing only 1 m, not 3m, of subsidence. Have all structures be mapped?

GDE/IDE?
Perched aquifers

Runoff down mountain

Perched aquifers
GDE/IDE?



Conceptual Model Complete?

- All water balance components / transfers indicated?
- All water balance change quantities illustrated for baseline, mining and post-mining conditions?
- Is there a separate conceptual model for the perched aquifers, highlighting hydrological understanding?

Source: Modified from Document 36, Figure 51, p. 201

Preliminary opinions

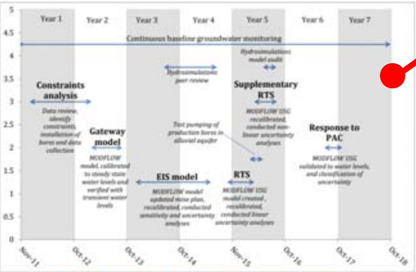


Figure 2-1 Timeline showing evolution of numerical model

1. At least one potentially critical conceptualisation problem in all predictive models reported to date (The specific storage, Ss, values are incorrect).

2. This reduces my confidence that EIS / RTS / RTS v2 models do predict likely impacts everywhere as they will occur. Drawdown impacts may be larger and more extensive in short-term but not last as long after mining. Please check carefully basis for Ss and Recharge, R. Please request strong justification of Ss values. Please request model calibration and new prediction with revised Ss.

3. Please request the historical water level fluctuations and model predictions of water tables (baseline, mining, post mining) on the geological x-sections, including longitudinal cross sections.

4. NSW AIP requirement: Predictions of water take for revised mine plan beyond year 25 (i.e. life of mine) not in public domain? Please publish for stakeholder review.

5. Long-term viability of water sources, assets and 'make-good' currently ill-defined / quantified? Equity, social justice, valuation issues. Please define first.

6. Adaptive management & practice - Design of performance measures, triggers, make-good must be improved to avoid social / economic externalities.

7. If not already, can potential project water-related impacts please be costed?

Thank you for your attention. Questions? (Relevant WRL Reports)

UNSW SYDNEY | Water Research Laboratory School of Civil and Environmental Engineering

Draft

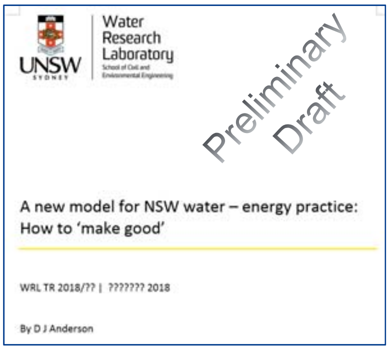
NSW DPE State Significant Development Proposal No. 6367: Revised Bylong Coal Project - Response to EDO NSW brief

Expert Report | 14 November 2018

By D J Anderson (B.E. Environmental, M.Eng.Sci Groundwater Studies)
110 King St
Manly Vale NSW 2093
Australia

Report prepared for NSW Independent Planning Commission on behalf of Environmental Defenders Office NSW and the Bylong Valley Protection Alliance

Expected 14 November 2018



UNSW SYDNEY | Water Research Laboratory School of Civil and Environmental Engineering

Preliminary Draft

A new model for NSW water – energy practice: How to 'make good'

WRL TR 2018/?? | ??????? 2018

By D J Anderson

Available to order

Some history…

Charles Vernon Theis (1900-1987) was the first groundwater hydrologist to develop a rigorous mathematical model of transient flow of water to a pumping well by recognizing the physical analogy between *heat flow in solids* and *groundwater flow in porous media*.

Charles V. Theis

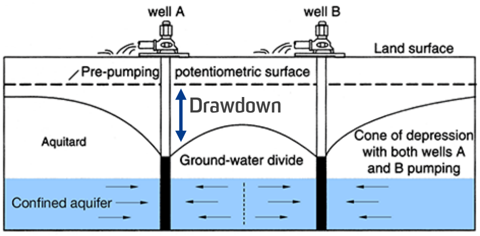
In his final paper, "*Aquifers, Ground-Water Bodies and Hydrophers*", Theis (1987) stated:

> "*Thus, "aquifer" has been used in so many different senses by so many people to express their own particular ideas that it has become an Alice-in-Wonderland word that means just what the author says it means. Worst of all, the author practically never tells us what he means. It has been used in so many different ways that it must be abandoned entirely as a scientific word or alternately to express only the original usage of it without any relation to the water table…*"

Predicting groundwater drawdown – pop quiz

Q1. Have you once heard someone describe groundwater flow in the context of Darcy's Law, i.e. the gradient in water pressure is proportional to hydraulic conductivity?

Q2. Have you once heard someone claim that hydraulic conductivity is the most important / most sensitive parameter for predicting drawdown in a model?

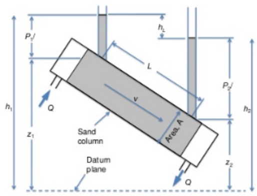


Source: Kansas Geological Survey

Q3. To what extent did you believe that?

Darcy's Experiments

- Discharge is
  Proportional to
  – Area
  – Head difference
  Inversely proportional to
  – Length
- Coefficient of proportionality is
  K = hydraulic conductivity



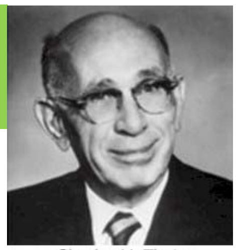
$$Q \propto A\frac{h_1 - h_2}{L} \qquad Q = KA\frac{h_2 \quad h_1}{L} \qquad Q = KA\frac{h}{L}$$

Confined, transient groundwater flow equation:

$$\frac{dh}{dt} Ss = K.\nabla h^2 + R - D$$

- $\frac{dh}{dt}$: Rate of pressure decline (drawdown)
- ∇h^2: Pressure levels through space
- R: Recharge (e.g. rainfall)
- D: Natural discharge (baseflow, transpiration) Aquifer Interference (Pumping, seepage into mines)

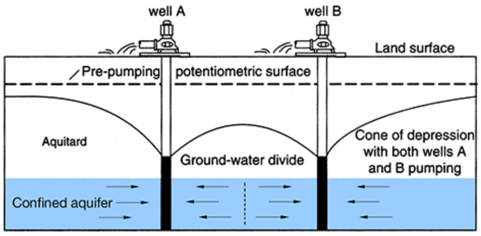
Ss is important too!



Charles V. Theis

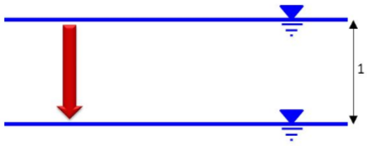
Ss significantly influences how fast water pressure:

- falls in response to water take
- rises in response to water take ceasing
- rises in response to recharge
- impacts (drawdown) travel from an aquifer interference activity to a nearby groundwater user, surface water body or groundwater fed ecosystem.



Source: Kansas Geological Survey

What is Ss ?

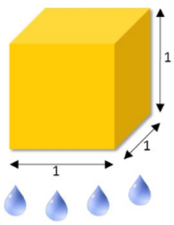


Ss is specific storage; a property of both earth and water

It describes how much water is released from storage in a pressurised (confined) aquifer for each metre decline in hydraulic head.

Ss forms part of the hydraulic diffusivity term in the transient, confined groundwater flow equation along with hydraulic conductivity, K:

Specific Storage



Change in water volume stored in a unit volume of the aquifer per unit change in head.

$$\frac{dh}{dt} = \nabla h^2 \frac{K}{Ss} + r - d$$

In the news: Ss theoretical upper limit is <1.3x10^{-5} m^{-1}

RESEARCH ARTICLE
10.1029/2018JF004660

Key Points:
- Cross-hole seismic surveys and tidal head analysis can be combined to improve estimates of specific storage
- We have developed an upper bound for specific storage for unconsolidated materials with low adsorbed water fractions
- Derived values of specific storage larger than this upper bound imply inappropriate use of oversimplified hydrogeological conceptual models

Correspondence to:
G. C. Rau,
gabriel.rau@unsw.edu.au

JULY 2018

AGU100 ADVANCING EARTH AND SPACE SCIENCE
JGR
Journal of Geophysical Research: Earth Surface

Quantifying Compressible Groundwater Storage by Combining Cross-Hole Seismic Surveys and Head Response to Atmospheric Tides

Gabriel C. Rau[1,2], R. Ian Acworth[1,2], Landon J. S. Halloran[3], Wendy A. Timms[1,4], and Mark O. Cuthbert[1,5]

a thorough analysis using our new method, demonstrates that specific storage has a physical upper limit of $\lesssim 1.3 \cdot 10^{-5}$ m^{-1}. Consequently, if larger values are derived using aquifer hydraulic testing, then the conceptual model that has been used needs reappraisal. Our method can be used to improve confined groundwater storage estimates and refine the conceptual models used to interpret hydraulic aquifer tests.

Source: Document 45

3. Ss theoretical upper limit confirmed <1.3x10^{-5} m^{-1}

AGU100 ADVANCING EARTH AND SPACE SCIENCE
JGR
Journal of Geophysical Research: Earth Surface

RESEARCH ARTICLE
10.1029/2018JF004660

Key Points:
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Correspondence to:
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Citation:
Rau, G. C., Acworth, R. I., Halloran, L. J. S., Timms, W. A., & Cuthbert, M. O. (2018). Quantifying compressible groundwater storage by combining cross-hole seismic surveys and head response to atmospheric tides. *Journal of Geophysical Research: Earth Surface, 123*. https://doi.org/10.1029/2018JF004660

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Quantifying Compressible Groundwater Storage by Combining Cross-Hole Seismic Surveys and Head Response to Atmospheric Tides

Gabriel C. Rau[1,2], R. Ian Acworth[1,2], Landon J. S. Halloran[3], Wendy A. Timms[1,4], and Mark O. Cuthbert[1,5]

[1]Connected Waters Initiative Research Centre (CWI), UNSW Sydney, New South Wales, Australia, [2]Water Research Laboratory, School of Civil and Environmental Engineering, UNSW Sydney, New South Wales, Australia, [3]Centre d'Hydrogéologie et de Géothermie (CHYN), Université de Neuchâtel, Neuchâtel, Switzerland, [4]School of Minerals and Energy Resource Engineering, UNSW Sydney, New South Wales, Australia, [5]School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK

Abstract Groundwater specific storage varies by orders of magnitude, is difficult to quantify, and prone to significant uncertainty. Estimating specific storage using aquifer testing is hampered by the nonuniqueness in the inversion of head data and the assumptions of the underlying conceptual model. We revisit confined poroelastic theory and reveal that the uniaxial specific storage can be calculated mainly from undrained poroelastic properties, namely, uniaxial bulk modulus, loading efficiency, and the *Biot-Willis* coefficient. In addition, literature estimates of the solid grain compressibility enables quantification of subsurface poroelastic parameters using field techniques such as cross-hole seismic surveys and loading efficiency from the groundwater responses to atmospheric tides. We quantify and compare specific storage depth profiles for two field sites, one with deep aeolian sands and another with smectitic clays. Our new results require bulk density and agree well when compared to previous approaches that rely on porosity estimates. While water in clays responds to stress, detailed sediment characterization from a core illustrates that the majority of water is adsorbed onto minerals leaving only a small fraction free to drain. This, in conjunction with a thorough analysis using our new method, demonstrates that specific storage has a physical upper limit of $\lesssim 1.3 \cdot 10^{-5}$ m^{-1}. Consequently, if larger values are derived using aquifer hydraulic testing, then the conceptual model that has been used needs reappraisal. Our method can be used to improve confined groundwater storage estimates and refine the conceptual models used to interpret hydraulic aquifer tests.

Source: Document 45, https://doi.org/10.1029/2018JF004660, July 2018

Afternoon Keynotes

Determining realistic specific storage input values for groundwater flow models: a case study from the Surat Basin, Queensland.

Richard Evans[1], Lindsey Campbell[2], Patrick McKelvey[2]
1. Jacobs
2. QGC

Specific storage (Ss) values are a key parameter in estimating aquifer response to pumping within confined aquifer systems. Yet limited published specific storage values exist for sedimentary rock aquifers. Recent numerical modelling of QGC's proposed CSG development within the Surat Basin, Queensland, identified that variation in the Ss had the largest influence on predicted impact to the groundwater system. Insufficient historical groundwater monitoring data existed to adequately constrain the Ss values during model calibration, so a broad Ss range (four orders of magnitude) was carried into predictive scenarios. When this broad range of values was simulated, the variations between the predicted impacts were unacceptably large. Evaluation of a more realistic Ss range was then undertaken to reduce the range in values, and thereby improve understanding of potential groundwater impacts. Ss values were derived from three sources – calculation from aquifer pumping test results, reference text values and calculation from geotechnical core test results. Existing reports give typical Ss values within the consolidated formations averaging about 5 x 10-5 m-1. Results using the adopted methods yielded consistent estimates of between 3 x 10-7 m-1 to 1 x 10-5 m-1 with the majority of values occurring within 1 x 10-6 m-1 and 1 x 10-5 m-1. The new values of Ss are considerably smaller than values previously adopted for the basin and hence significantly influence impact predictions. Note that storativity (S) calculated from pumping tests often results in an overestimate of Ss. Ss estimates calculated from reference text values indicate that it may be possible to estimate Ss based on rock type (lithology), providing estimates for porosity were available. Values for porosity across the Surat Basin can be estimated from petrophysical logs. The results of Ss calculated from geotechnical results indicate that the variation in skeletal compressibility with depth may be more important, and thus may exceed the variation due to lithology type.

Source: Document 52, Australian Groundwater Conference, Canberra (3-5 November 2015)

Old literature values of Ss

Not secure | www.aqtesolv.com/aquifer...

UNSW WRL Govt Hydrogeology GIS

AQTESOLV

Representative Values

The following table provides representative values of specific storage for various geologic materials (Domenico and Mifflin [1965] as reported in Batu [1998]):

Material	Units of m^{-1} Min	to	Max
Plastic clay	2.2×10^{-3}	to	1.7×10^{-2}
Stiff clay	1.1×10^{-3}	to	2.2×10^{-3}
Medium hard clay	7.8×10^{-4}	to	1.1×10^{-3}
Loose sand	4.2×10^{-4}	to	8.6×10^{-4}
Dense sand	1.1×10^{-4}	to	1.7×10^{-4}
Dense sandy gravel	4.2×10^{-5}	to	8.6×10^{-5}
Rock, fissured	2.8×10^{-6}	to	5.8×10^{-5}
Rock, sound	<2.8x10-6		

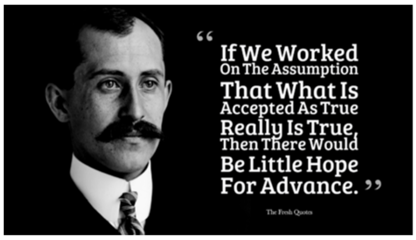
New literature values of Ss

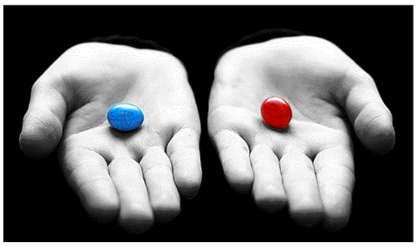
Australian Groundwater Conference, Canberra
(3-5 November 2015)
Evans et al. 2015
Consolidated Formations
$3 \times 10^{-7} < Ss < 1 \times 10^{-5}$ m^{-1}

RESEARCH ARTICLE
10.1029/2018JF004660

Key Points:
- We have developed an upper bound for specific storage for unconsolidated materials with low adsorbed water fractions
- Derived values of specific storage larger than this upper bound imply inappropriate use of oversimplified hydrogeological conceptual models

$Ss < 1.3 \times 10^{-5}$ m^{-1}
July 2018





Why are Bylong Ss > 1×10^{-5} m^{-1} (@ 11th hour)

Australian Groundwater Conference, Canberra
(3-5 November 2015)
Evans et al. 2015
Consolidated Formations
$3 \times 10^{-7} < Ss < 1 \times 10^{-5}$ m^{-1}

RESEARCH ARTICLE
10.1029/2018JF004660

Key Points:
- We have developed an upper bound for specific storage for unconsolidated materials with low adsorbed water fractions
- Derived values of specific storage larger than this upper bound imply inappropriate use of oversimplified hydrogeological conceptual models

$Ss < 1.3 \times 10^{-5}$ m^{-1}
July 2018

Table 4 Linear uncertainty analysis parameter ranges

Parameter	Parameter number	Description	Lower bound	Mean	Upper bound
Specific storage (m^{-1})	ss01	Upper Alluvium parameters	0.001	0.001	0.0125
	ss02	Lower Alluvium parameters	0.005	0.005	0.01875
	ss03	Colluvium parameters	0.0001	0.001	0.01
	ss04	Weathered parameters	0.00002	0.0002	0.002

Values for deeper / older geology are?

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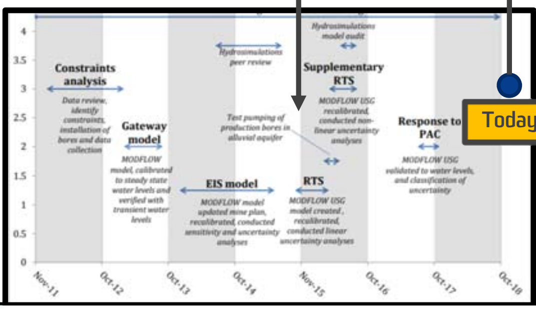
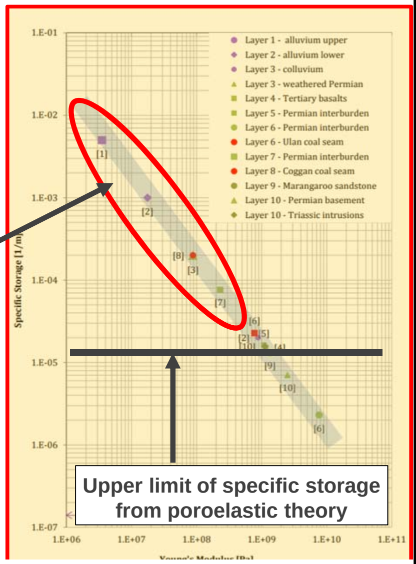
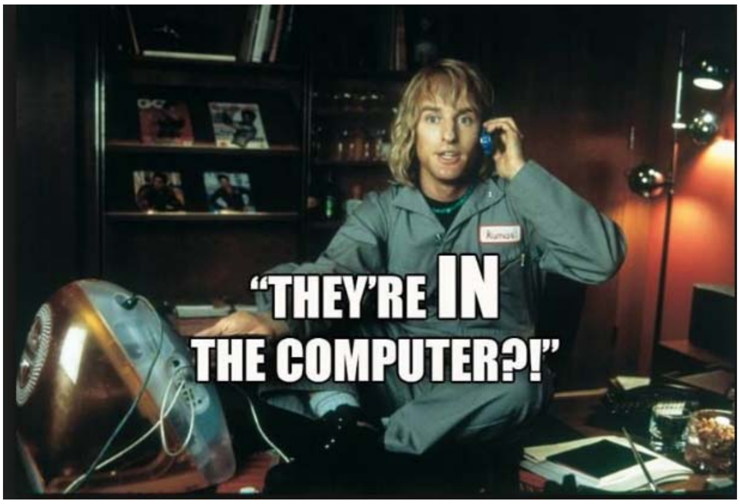
Bylong Coal Project – Response to Submissions on Groundwater (G1606E) | 68

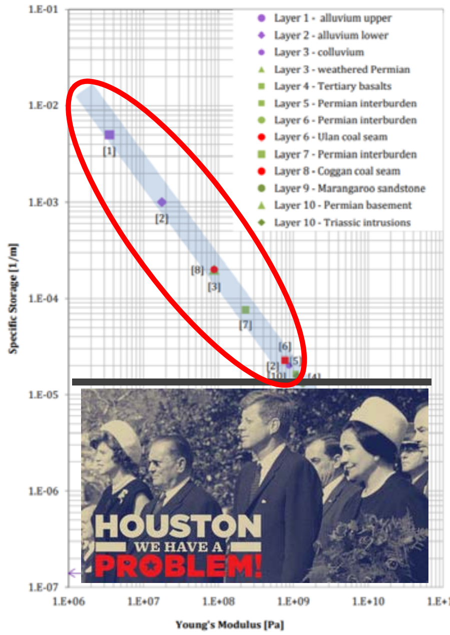
Modelled Ss values mathematically impossible. Why?





Interim Conclusion:
What's that, the Bylong Coal Project computer files have Ss > 1×10^{-5} m^{-1} !!?





Literature values of Ss used in groundwater model from Appendix H of the Response to Submissions

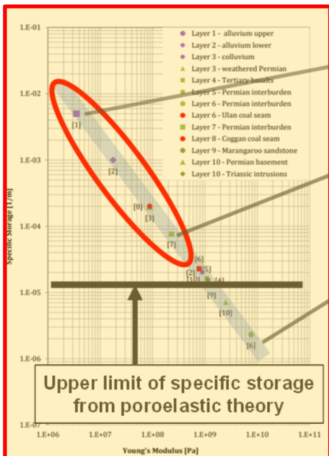
Does it matter Ss > 1×10^{-5} m^{-1} ?

How much does it matter? Sometimes quite a lot

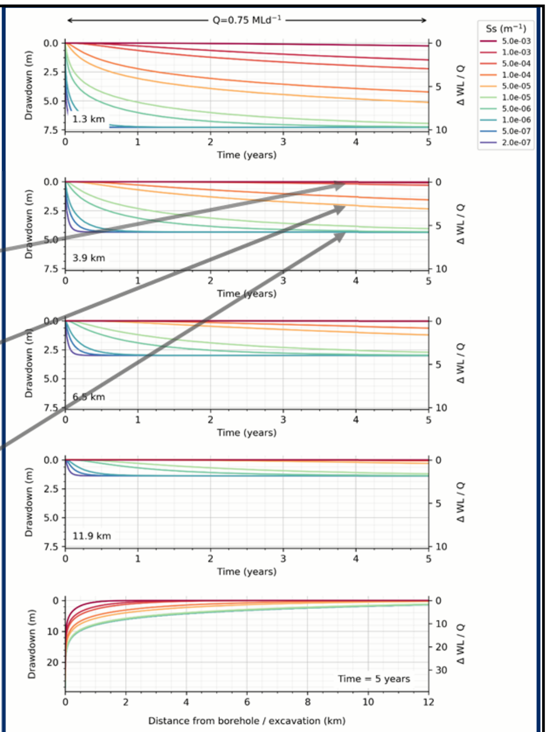
If concerned, please ask IESC if model needs to be re-run

Australian Groundwater Conference, Canberra
(3-5 November 2015)
Evans et al. 2015
Consolidated Formations
3×10^{-7} < Ss < 1×10^{-5} m^{-1}

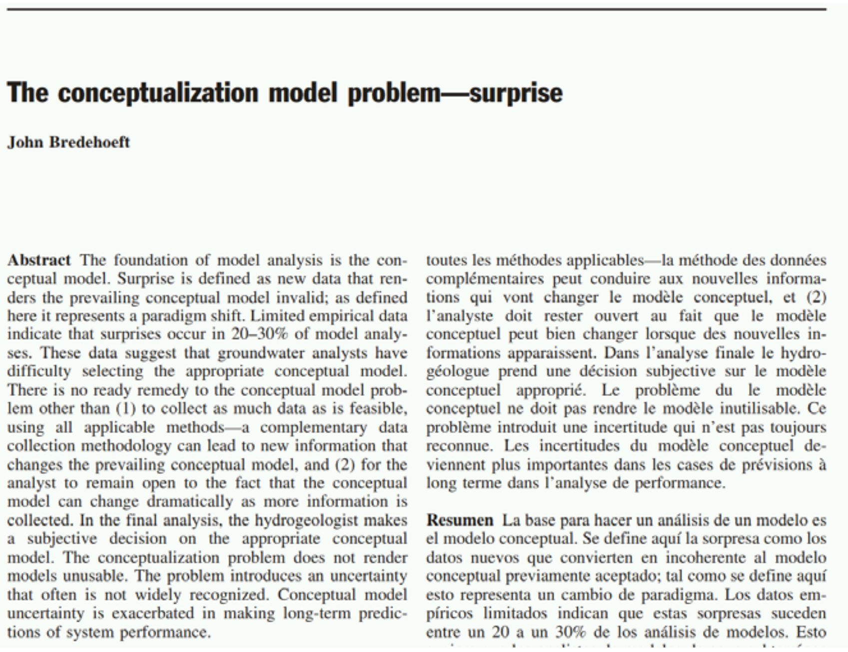
Ss < 1.3×10^{-5} m^{-1}
July 2018



Limit of specific storage from Rau et al. (2018) overlain on Figure 19 from Appendix H of the Response to Submissions



Example Only: Sensitivity of drawdown to Ss



The conceptualization model problem—surprise

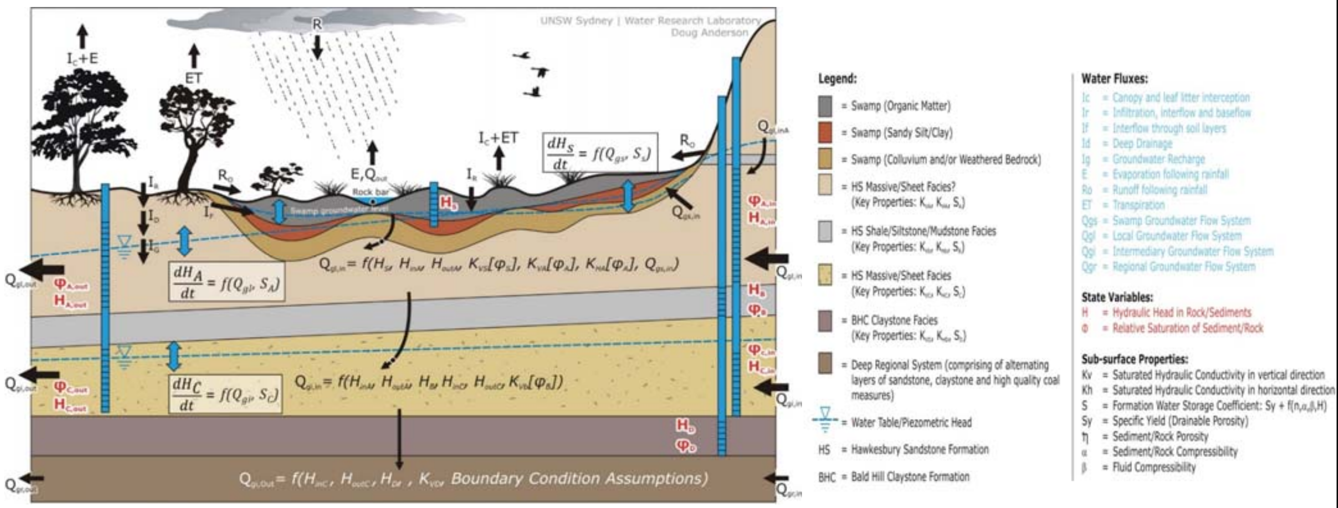
John Bredehoeft

Abstract The foundation of model analysis is the conceptual model. Surprise is defined as new data that renders the prevailing conceptual model invalid; as defined here it represents a paradigm shift. Limited empirical data indicate that surprises occur in 20–30% of model analyses. These data suggest that groundwater analysts have difficulty selecting the appropriate conceptual model. There is no ready remedy to the conceptual model problem other than (1) to collect as much data as is feasible, using all applicable methods—a complementary data collection methodology can lead to new information that changes the prevailing conceptual model, and (2) for the analyst to remain open to the fact that the conceptual model can change dramatically as more information is collected. In the final analysis, the hydrogeologist makes a subjective decision on the appropriate conceptual model. The conceptualization problem does not render models unusable. The problem introduces an uncertainty that often is not widely recognized. Conceptual model uncertainty is exacerbated in making long-term predictions of system performance.

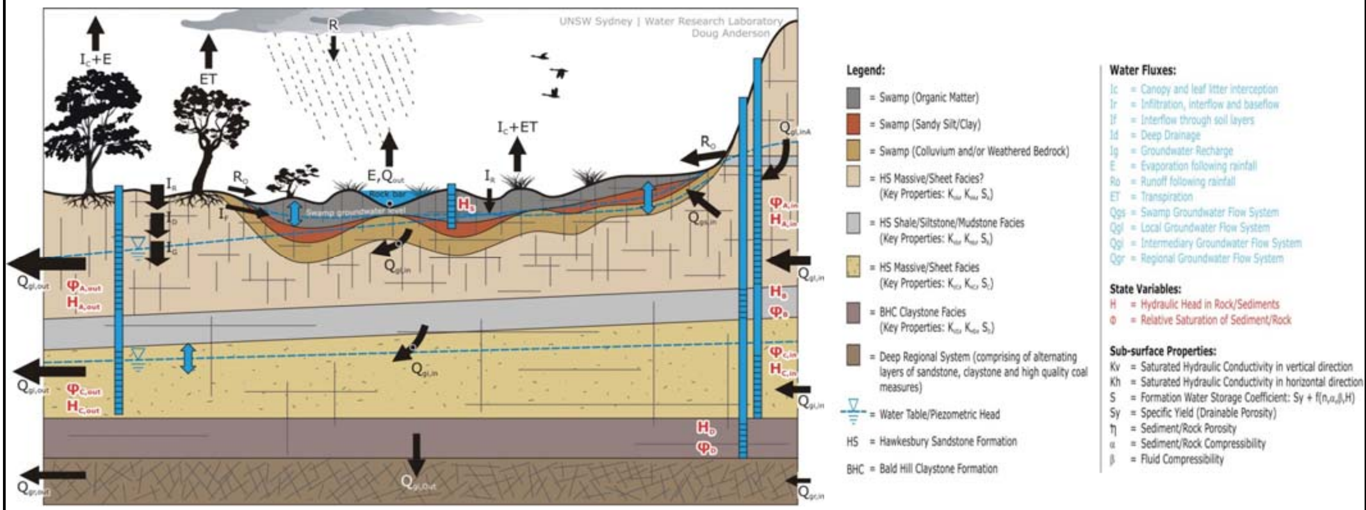
toutes les méthodes applicables—la méthode des données complémentaires peut conduire aux nouvelles informations qui vont changer le modèle conceptuel, et (2) l'analyste doit rester ouvert au fait que le modèle conceptuel peut bien changer lorsque des nouvelles informations apparaissent. Dans l'analyse finale le hydrogéologue prend une décision subjective sur le modèle conceptuel approprié. Le problème du le modèle conceptuel ne doit pas rendre le modèle inutilisable. Ce problème introduit une incertitude qui n'est pas toujours reconnue. Les incertitudes du modèle conceptuel deviennent plus importantes dans les cases de prévisions à long terme dans l'analyse de performance.

Resumen La base para hacer un análisis de un modelo es el modelo conceptual. Se define aquí la sorpresa como los datos nuevos que convierten en incoherente al modelo conceptual previamente aceptado; tal como se define aquí esto representa un cambio de paradigma. Los datos empíricos limitados indican que estas sorpresas suceden entre un 20 a un 30% de los análisis de modelos. Esto

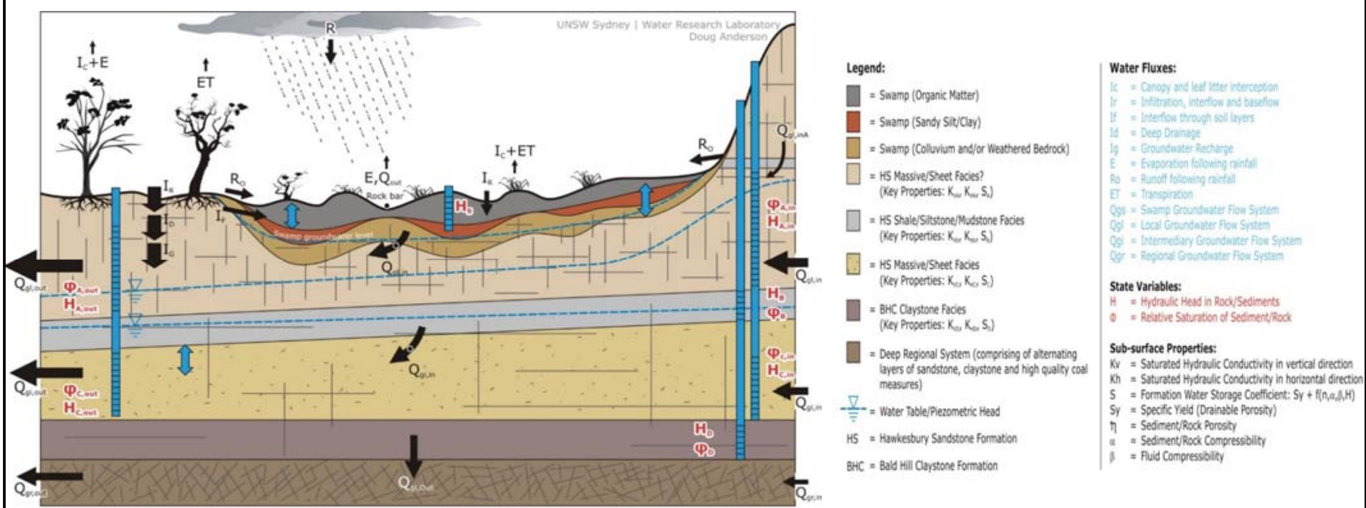
Water Balance Conceptual Model: IDE and GDE Pre-Mining

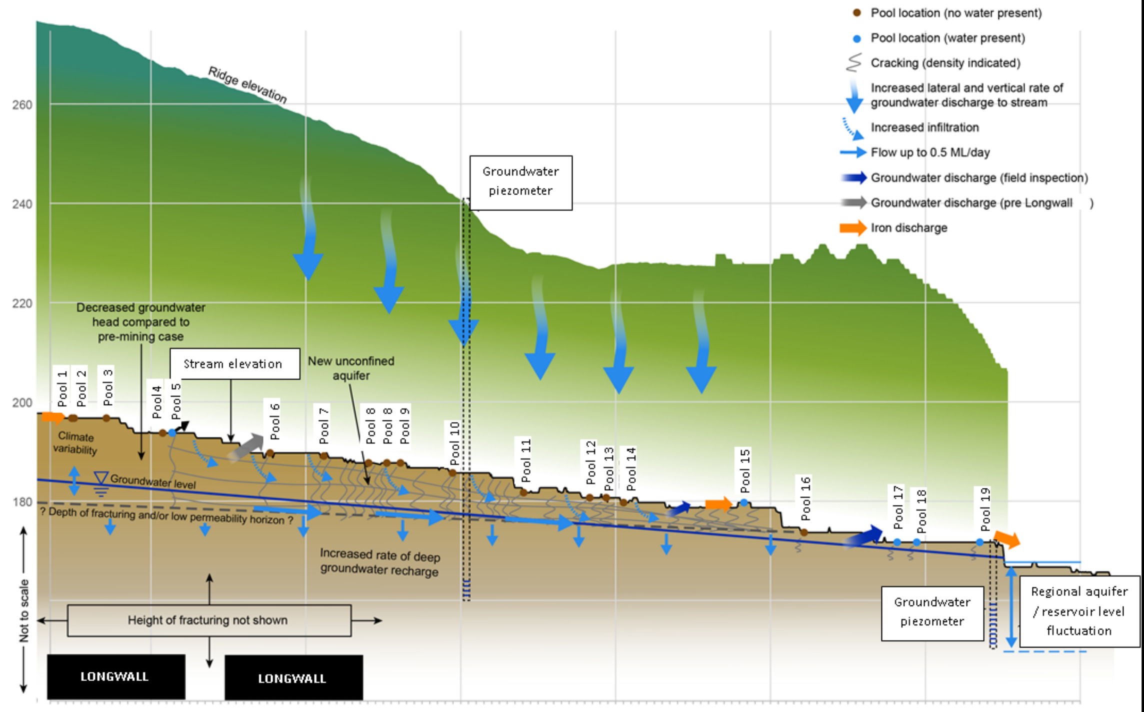


Water Balance Conceptual Model: IDE and GDE Post subsidence cracking (early –time)



Water Balance Conceptual Model: IDE and GDE Post subsidence cracking (late time)





Pool location (no water present)
Pool location (water present)
Cracking (density indicated)
Increased lateral and vertical rate of groundwater discharge to stream
Increased infiltration
Flow up to 0.5 ML/day
Groundwater discharge (field inspection)
Groundwater discharge (pre Longwall)
Iron discharge
Ridge elevation
Groundwater piezometer
260
240
220
200
180
Decreased groundwater head compared to pre-mining case
Stream elevation
New unconfined aquifer
Pool 1
Pool 2
Pool 3
Pool 4
Pool 5
Pool 6
Pool 7
Pool 8
Pool 8
Pool 9
Pool 10
Pool 11
Pool 12
Pool 13
Pool 14
Pool 15
Pool 16
Pool 17
Pool 18
Pool 19
Climate variability
Groundwater level
? Depth of fracturing and/or low permeability horizon ?
Increased rate of deep groundwater recharge
Not to scale
Height of fracturing not shown
LONGWALL
LONGWALL
Groundwater piezometer
Regional aquifer / reservoir level fluctuation