Potential Impacts of Reducing Groundwater Abstraction from the Southwestern Great Artesian Basin:
Modelled Aquifer Pressure and Spring Flow Response

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Goyder Institute for Water Research
Technical Report Series No. 2024/01

www.goyderinstitute.org

Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725

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Partington D, Love A, Wohling A, Keppel M (2024) *Potential Impacts of Reducing Groundwater Abstraction from the Southwestern Great Artesian Basin: Modelled Aquifer Pressure and Spring Flow Response.* Goyder Institute for Water Research Technical Report Series No. 2024/01.

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Respect and reconciliation

Aboriginal people are the First Nations people of South Australia. Aboriginal peoples' spiritual, social, cultural, and economic practices come from their lands and waters, and they continue to maintain their cultural heritage, economies, languages and laws which are of ongoing importance.

Executive Summary

This report examines the likely impact that a reduction in groundwater abstraction from the main aquifer of the Great Artesian Basin (GAB) will have on hydraulic head of the aquifer and spring flow rates. A numerical groundwater flow model developed by the Department for Environment and Water (DEW) for the southwest region of the GAB (Far North model) was used to simulate six groundwater abstraction scenarios and subsequently assess aquifer (hydraulic head or pressure) and spring discharge responses over a hundred-year period.

Our analysis demonstrated that system dynamics are transient owing to historical abstraction (declining heads) and capping and piping programs (recovering heads) as well as a myriad of other drivers. For the five scenarios that implemented abstraction reductions, hydraulic heads increased over time across the whole study area, with the most pronounced rise in head occurring near the two wellfields. The change in total water balance fluxes stabilised after 2040 with only minor gradual changes thereafter.

Changes to groundwater abstraction were modelled at two wellfields (referred to as Wellfield A and Wellfield B) and not other users, near the southwestern spring zone. However, hydraulic head and spring discharge responses were assessed across the whole model domain. On average, the model predicted hydraulic heads to increase with reductions in abstraction, with the largest increase in hydraulic head occurring at spring complexes close to Wellfield A and B. Importantly, all scenarios tested varying abstraction from Wellfield A and/or B only and were carried out deterministically in order to gain insight into head and spring responses due to abstraction change, they are not related to any proposed operational changes. As maximum modelled abstraction related to mining activities represents approximately 25% of the total groundwater abstraction from the GAB within the model domain, additional spring flow benefits may occur if the proposed desalination and piping option were available to other industries (energy, pastoral) and/or to supplement community supplies. Model scenario results showed that at the spring complex level, there were both declining and increasing hydraulic head levels, as well as both increasing and declining spring discharge rates. This occurred even under the continued 100% abstraction rates. This most likely occurs due to the residual head recoveries owing to the capping and piping programs.

The model assumes a linear relationship between hydraulic head and spring discharge. Intuitively a reduction in the abstraction from the GAB aquifer close to the GAB springs would have a positive impact on spring flow rates. However, a linear and positive response isn't always guaranteed. Further assessment of the hydraulic head to spring flow relationship is recommended to understand this relationship.

Additionally, because of the modelled linear relationship, the modelled spring fluxes are assumed to represent the maximum spring discharge possible at the given modelled hydraulic head. However, again, this may not be the case as a non-linear aquifer head-spring flux relationship likely occurs at the aquifer–spring conduit(s) interface and through the spring conduit(s) or fault and/or fracture zones. Regardless of these representations, when abstraction rates at both Wellfield A and B are reduced from 100% abstraction (case, A100_B100) to zero abstraction (case A0_B0), modelled spring flux (i.e., total modelled spring discharge) only increases by less than 5% over the 100-year prediction period.

The model did not attempt to replicate the phenomenon of spring switching. This occurs when a particular spring ceases to flow and aquifer head must find an alternative pathway to discharge either by a new spring emerging or diffuse discharge. The opposite occurs when the spring that has ceased to flow switches back to flowing after a period of time. An example of this occurs at Wabdu Kadabu. This phenomenon has important implications for First Nations people and needs to be researched further.

Regardless of the potential model limitations including how the drain package may not accurately represent the interplay between hydraulic head and spring flow, it remains the best tool available for this large regional scale assessment. Future work is recommended to understand the behaviour between aquifer head, spring architecture and flux at a smaller scale, for example spring group and individual spring vent. This work would include both modelling and field work.

In this report we conclude that a reduction in pumping from the GAB aquifer will result in an increase of aquifer head pressure. Despite the above limitation we cannot automatically assume that this modelled increase in pressure head in the aquifer will be transferred to an increase in spring flow.

Recommendations

The proposed key recommendations are as follows:

1. Review timeseries hydraulic head vs spring flow data to inform the conceptual understanding that underpins the numerical model. Specifically, review spring flow and head data from 2019-2023 to comment on appropriateness of the DEW model to make these predictions including assessing the assumed 1:1 relationship.
2. Re-calibrate the DEW model to new data (from the assessment in Recommendation 1)
3. Undertake a detailed sensitivity and uncertainty analysis of spring flow predictions to improve confidence in results and indicate areas for future parametrisation.
4. Develop and implement bore and spring monitoring strategies.
5. Obtain a greater understanding on First Nation people's knowledge of springs in particular in regard to spring emergence and cessation and spring wetland extent.
6. The most important recommendation is to implement field studies to obtain a greater hydrogeological understanding of the relationship between hydraulic head and spring flow rate. This would include but is not limited to a study on spring switching as well as a small-scale field trial with associated numerical modelling experiments to improve our understanding of the architecture of spring discharge including spring flow and hydraulic head. These are key knowledge gaps that when addressed will provide more reliable outputs and reduce the risk associated with spring switching to the environment and First Nation people.

Acknowledgements

The authors extend their gratitude to the project advisory committee for their contributions to this report, including the provision of background information, knowledge, and expertise. Members included representatives from BHP, Infrastructure SA, Jacobs, and the South Australian Department for Environment and Water.

The authors would also like thank Saskia Noorduijn, CSIRO/Flinders University and Travis Gotch, South Australian Department of Environment, Water and Natural Resources for their peer review and Bryony Cotterall from the Goyder Institute for Water Research for her project management support

1 Introduction

1.1 Context

Groundwater from the Great Artesian Basin (GAB) provides water for pastoral, mining, and petroleum industries, as well as community/town water supplies. The total amount of groundwater extracted from the modelled SA portion of the GAB is estimated to be 180 ML/day (DEW 2023, Vol 7) of this approximately 45% is used for pastoral and town water supplies, 30% for the petroleum and gas industries and 25% for mining.

The South Australian Government established the Northern Water Project, via Infrastructure SA, to investigate a new coastal desalination plant and pipeline to treat and transport water to the north of the state to support current and potential future mining, energy, and agricultural activities.

This sub-project has aimed to investigate the potential impact and/or benefit of reduced groundwater abstraction from the main Southwestern Great Artesian Basin (GAB) aquifers in the vicinity of the GAB springs. This project team used the SA Department for Environment and Water's (DEW) Far North model to implement six experimental abstraction scenarios and examine the response of aquifer pressure (hydraulic head) and spring flow rate (Figure 1).

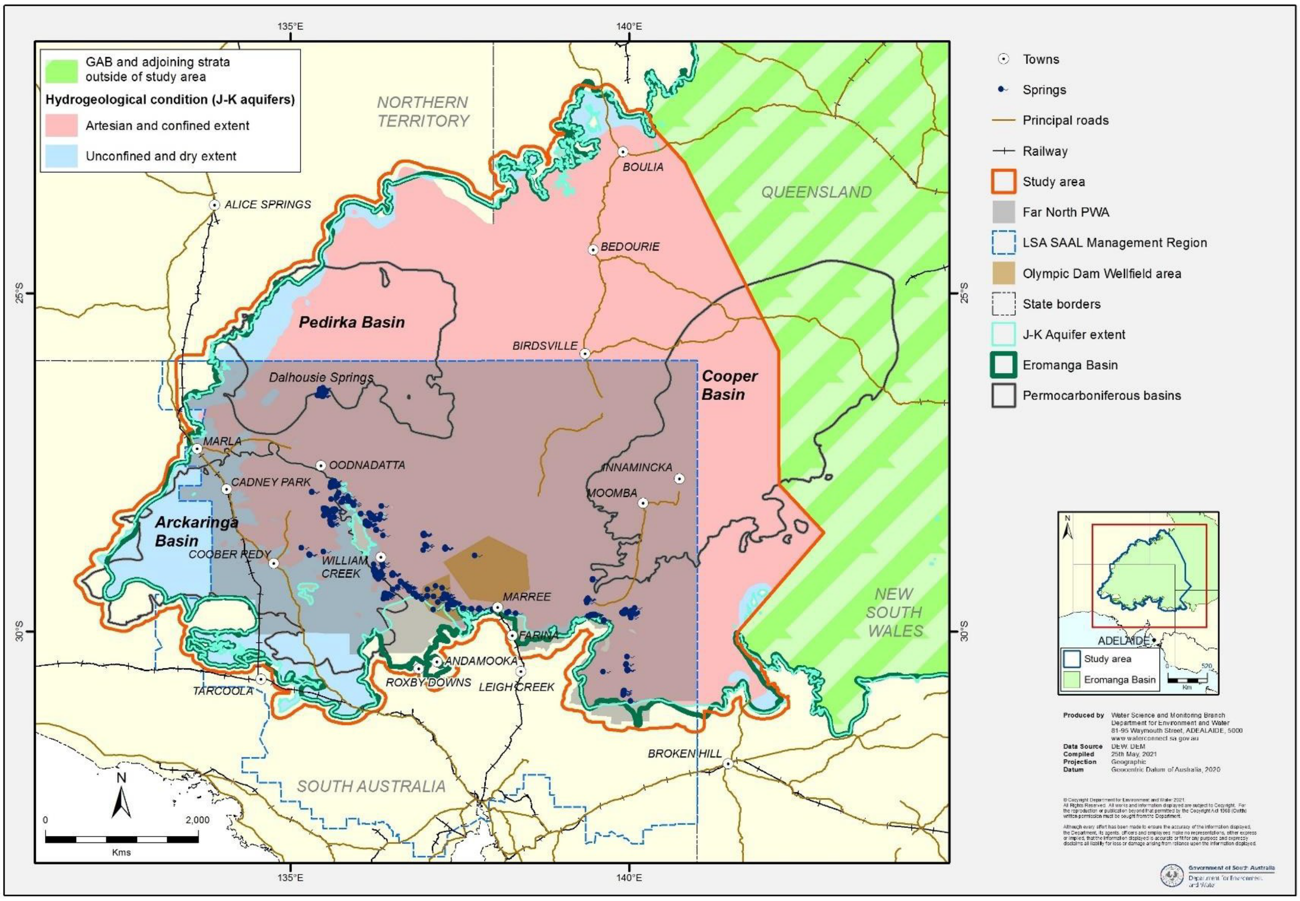

Figure 1. Location of the study area showing extent of the Eromanga Basin and the deeper Permo-carboniferous basins, as well as spring locations in SA and the numerical model domain (DEW, 2023g).

This work included a literature review of the status of GAB springs. Due to data limitations, a planned review of the relationship between observed aquifer pressure and spring flow data was not possible and therefore the project team was unable to assess the appropriateness of the model for predicting the relationship between hydraulic head change and spring flow response.

1.2 Objectives

The planned objectives of this sub-project were as follows:

1. Literature review including hydrogeological conceptualisation of the GAB in South Australia, history of groundwater abstraction and available spring and bore monitoring.
2. Examine the relationship between aquifer pressure and spring flow rate using field measurements.
3. Analyse the relationship between aquifer pressure and spring flow rates using the Far North Groundwater Model.
4. Discuss limitations of the Far North Groundwater Model to represent aquifer head and spring flow and suggest areas for improvement.
5. Provide recommendations for future work.

2 Literature Review: Hydrogeological Conceptualisation and Springs

2.1 GAB conceptualisation current model

The following is a brief review and summary of the history and hydrogeological conceptualisation of the GAB in South Australia (SA) from the late 19th century until 2023.

The first mention of the GAB in SA dates to the late 1870's and early 1880's where subterranean water was discovered and recognised in SA (Rawlinson, 1878; Tate, 1882). One of the first comprehensive studies of the GAB was conducted by Jack (1923) who recognised the potential for long groundwater flow paths based on the distribution of groundwater chemistry as well as dividing the basin into eastward and westward flowing groundwater systems.

Since this time several seminal pieces of work on the hydrogeology of the GAB have been completed including works by the Commonwealth Government (Audibert, 1976; Habermehl, 1980). In fact, the conceptual and numerical model that forms the basis for groundwater management in the western GAB was largely derived from the pioneering work of Audibert (1976) and Habermehl (1980). This model assumes the hydrogeology of the GAB is relatively simple. The main features of this model were that there is continuous porous medium flow in sandstone aquifers contiguous across the basin, with limited to zero interactions with other geological units above or below the main GAB units. This model implies simple groundwater flow paths with groundwater age increasing along the flow path. Groundwater flow from western margin springs was assumed to originate from the GAB outcropping units on the eastern side of the Great Dividing Range. Importantly the groundwater system was considered to be in steady state where groundwater recharge is equal to groundwater discharge.

While the work of Audibert (1976) and Habermehl (1980) provided an important baseline of geological units and hydraulic units, it did not provide a detailed hydrogeological understanding of the flow of water in the GAB. A far more detailed understanding of the basin wide GAB was beginning to emerge as presented in another seminal piece of work on the hydrochemistry and hydrodynamics of the basin (Radke *et al*., 2000). While this work provided an increased awareness of the complexity of the system it did not provide any new knowledge on the understanding and quantification of groundwater fluxes in the western margin. Considerable improvements in the hydrogeological understanding in the western margin has occurred in more recent times through the GABWRA project (Smerdon *et al*., 2012), NWC project (Keppel *et al*., 2013; Love *et al*., 2013a, 2013b; Lewis *et al*., 2013; Green *et al*., 2013) and continuing work by DEW (DEW, 2023a, 2023b, 2023c; 2023d, 2023e) (Figure 2).

The GAB is a non-marine to marine Triassic-Jurassic-Cretaceous hydrogeological super basin (Krieg, 1995) that underlies approximately 22% of Australia including large areas of SA, New South Wales, Queensland, and the Northern Territory (Audibert, 1976). In SA, the GAB is coincident with the large epi-continental Eromanga Basin which is the focus of this study. Major geological units are the Cadna-owie Formation and the Algebuckina Sandstone (and lateral equivalents). These are treated as a single hydrogeological unit (Radke *et al*., 2000; Welsh, 2000) and form the focus of this report as they hold the primary groundwater resource of managerial and regulatory focus. The Cadna-owie Formation and Algebuckina Sandstone are overlain by an aquitard composed of shaly mudstone units of low permeability that are known as the Bulldog Shale and Oodnadatta Formation in SA. The Bulldog Shale and Oodnadatta Formation outcrop extensively near the western margin of the GAB. Underlying the major aquifer in SA are several Permian aged basins such as the Cooper Basin, Pedirka Basin and Arckaringa Basin.

The dynamics of the system are controlled by climate change on a geological time scale, and it is unlikely that the GAB has ever been in steady state with respect to recharge and discharge (Love *et al.,* 2013a).

Groundwater recharge along the western recharge boundary of the GAB is currently negligible, with the majority of recharge occurring previously in the late Pleistocene (Wohling *et al*., 2013). Any recharge today is a result of rainfall in the Pleistocene that slowly percolates through the thick unsaturated zone and ephemeral river recharge along the Finke and Plenty rivers (Fulton *et al*., 2013). Groundwater recharge is several orders of magnitude less than discharge (Love *et al* 2013 a and b).

Groundwater discharge along the southwest margin of the GAB in SA occurs via two mechanisms namely diffuse discharge and preferential discharge. The clearest example of preferential discharge happens through springs. Diffuse discharge from the GAB occurs via slow upward leakage through thick competent regional aquitards and by rapid preferential flow through faults and fractures. These mechanisms discharge water to the water table aquifer and ground surface. These discharge zones are readily identified by salt encrusted areas. Many of these form dry playas in the region. Diffuse discharge as preferential leakage through faults and fractures has been estimated to be three orders of magnitude greater than diffuse discharge via slow leakage through the regional aquitard (Love *et al*., 2013b).

The groundwater flow system is complex, consisting of recharge on the western flank of the Great Dividing Range travelling thousands of kilometres to be discharged in the southwest margin of the basin. Along its flow path inter-aquifer and intra-basin leakage occurs. This leakage including downward flow to the GAB aquifer as well discharge to the surface appears to be dominated by preferential flow and not by slow diffuse leakage through the various confining units in the system (Love *et al*., 2013a and b, Smerdon *et al*., 2013).

The high geothermal gradient in parts of the western margin raises questions about the dominant mechanism of groundwater movement. In large sections of the western margin the forces of buoyancy dominate those of advection, which indicates that theoretically density driven flow is a plausible mechanism for groundwater movement. While the work to date has provided a far more comprehensive understanding of the system much more work is required in the quantification of the various components of the system including both spatial and temporal fluxes into and out of the system.

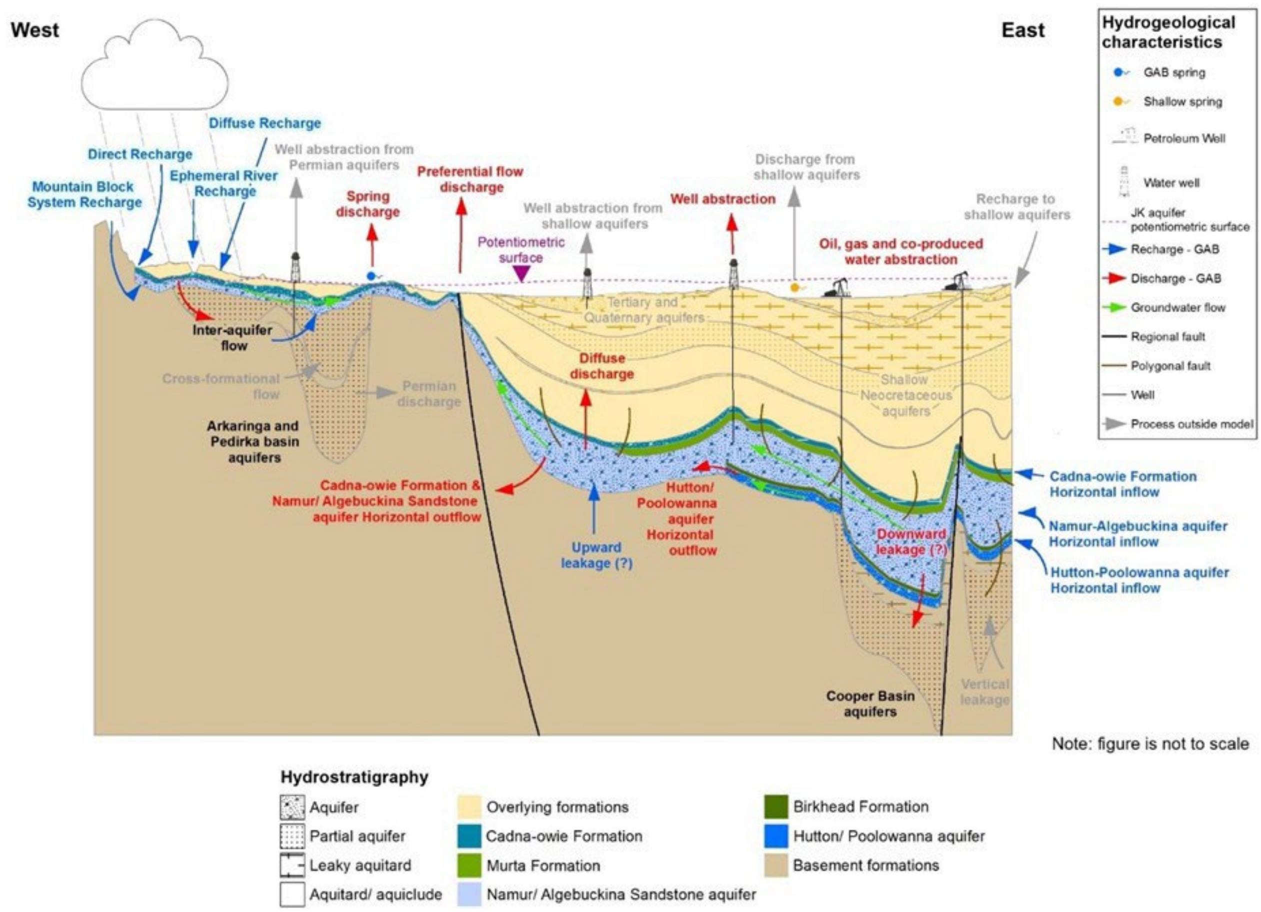

Figure 2. Key features of the hydrogeological conceptualisation (DEW, 2023a). The Cadna-owie Formation and Namur-Algebuckina aquifer are considered as one hydrostratigraphic unit which is the main aquifer of managerial and regulatory focus.

2.2 GAB Springs

GAB springs are listed under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) given the ecological importance of the springs, which support rare flora and fauna species with a high degree of endism while they are culturally significant for both indigenous and European communities. However, there have been significant impacts on important cultural, economic, environmental, and social values of some of the GAB springs due to groundwater extractions, as well as degradation by cattle and feral herbivores (Gotch *et al* 2013).

Large scale groundwater abstraction in NSW and Queensland at the turn of the century resulted in large drawdowns and an estimated extinction of some 50% of springs in the eastern GAB (Cox and Barron, 1998). During this time, it was recognised that a reduction in aquifer pressure was related to a reduction in spring flow rates until an extinction of the spring vent occurred. A similar situation did not occur in SA at the turn of the 19th to 20th century due to significantly less widespread groundwater extraction.

Since the late 1970s, and particularly from 1999 when the GAB Sustainability Initiative program was implemented, significant action has occurred to reduce the impact of water extractions on the spring's environments through Commonwealth, State, and pastoralist investment (Brake, 2019). These investments have included bore remediation/decommissioning as well as stock water piping systems to reduce water wastage and improve water efficiency to recover artesian water pressures. Further, regulation and management aimed at judicious use is underpinned by the Far North Prescribed Wells Area Water Allocation Plan (WAP).

The most obvious manifestation of spring discharge in SA occurs in the Lake Frome and Lake Callabonna region as well as along an arcuate line from Maree to Dalhousie in the north of the state (Figure 1).

While GAB springs in the region are largely the result of faulting and fractures, springs can also occur to a lesser degree by thinning of the confining units and abutments adjacent to geological basement (Keppel *et al*., 2015; 2016; 2019; 2023). It is unlikely for a spring vent to be a single conduit from the confined aquifer to discharge at the surface, and more likely comprise a damage zone of multiple fractures and faults through the confining layer that may split into several connecting branches (Bense *et al.,* 2013, and as reported in Keegan-Treloar *et al*., 2022; Keppel *et al*., 2023). Within these conduit branches, upward moving water may be blocked by closure of the conduit aperture by physical or chemical means. Also, there are likely to be physical discontinuities in these pathways, such as where a conduit through the aquitard interfaces with overlying sedimentary material. At this interface, water flowing upward through the conduit may again separate into more than one pathway, such that a proportion of the flow may continue to the spring discharge point at the surface, while the remainder flows to unconfined groundwater overlying the aquitard and may ultimately discharge to the surface diffusely via capillary rise and evapotranspiration. An understanding of the complexities of each spring vent can only be achieved through detailed hydrochemical and geophysical field studies applied to individual springs. This is a key knowledge gap in our understanding.

Groundwater abstraction from the Cadna-owie Formation and Algebuckina aquifers causing aquifer drawdown is well documented with a reduction in aquifer pressure close to a spring resulting in anything from a reduction of flow to a total cessation of spring flow. (Mudd and Currell, 2023) However, there can also be a reduction of spring flow due to natural conditions. Many of the reasons for this have never been fully explored or understood. However, one mechanism that is well documented is that changes in the potentiometric surface in the main aquifer over time have resulted in cessation of spring flow. These changes in the potentiometric surface over time are a result of changes in the boundary conditions of the system over time due to geological climate change (Rousseau-Gueutin *et al*., 2013). Evidence of this comes from ancient spring complexes like Warburton Hill that stands approximately 45 m above the current landscape respectively and is testament to much larger pressure in the past. Dating the carbonate sediments of this ancient limestone platform indicates much wetter conditions at Warburton Hill 100 – 187 kyr BP (Priestley *et al*., 2013).

There are over 5,000 spring vents within 22 spring complexes (Gotch, 2013; Keppel *et al*., 2016). Of these mapped spring vents, approximately 40% have partially or completely ceased to flow (as reported in Keppel *et al*., 2023). This can be ascribed to two main mechanisms in the Cadna-owie Formation and Algebuckina aquifers, namely: 1) abstraction induced groundwater drawdowns or 2) natural processes such as long-term decline in the potentiometric surface due to change in boundary conditions on geological timescales or spring switching.

Here we "coin" the term spring switching to be when a spring vent will cease to flow, and flow will either reappear from a new vent or discharge occurs via diffuse mechanisms through the overlying confining unit nearby. Alternatively, the spring that ceases to flow may with time reinitiate via the same vent. Spring switching can occur over both long- and short-term time periods. Over longer-term time scales throughout indigenous history springs have ceased to flow and reappeared elsewhere (Travis Gotch, Dean Ah Chee pers comm 2012). An example of short-term time periods is shown in the Wabdu Kadabu National Park (Figure 3). Both spring switching and changes in wetland extent can be observed at different times. Figure 3 shows that by February 2024, 3 springs in the middle of the panel may have disappeared. Furthermore, there appears to be spring switching from December 2018 to September 2022. As highlighted by the spring swapping caption in Figure **3**, we assume from the wetland extent that a single spring or cluster of springs transition from flowing to either non-flowing or minimum flow, while a single spring or cluster of springs to the south shows increasing spring flow with time.

This phenomenon has occurred throughout both indigenous and European history but is not fully understood. We suggest that natural spring switching may be attributed to actual changes in the spring aperture. This may be a result of physical or chemical changes. Physical changes such as blockage and wind-blown sand may cause springs or a spring vent to cease to flow. Geochemical variations may cause changes in chemical saturation and precipitation or undersaturation causing dissolution at or near the spring vent. Both physical and/or chemical changes can also occur within the aquifer which also has the potential to cause the springs to cease flowing. Blockage of the spring vent for whatever reason will result in the groundwater trying to find another outlet. As discussed previously it appears that at Wabdu Kadabu both closing and opening of the spring vent appears to be occurring. Field validation in addition to satellite imagery is required to confirm this. Other examples of spring switching occur at West Finnis and Frog Dreaming in Dalhousie springs. This is of particular importance to First Nations people as it is possible that a spring of significance could cease to flow.

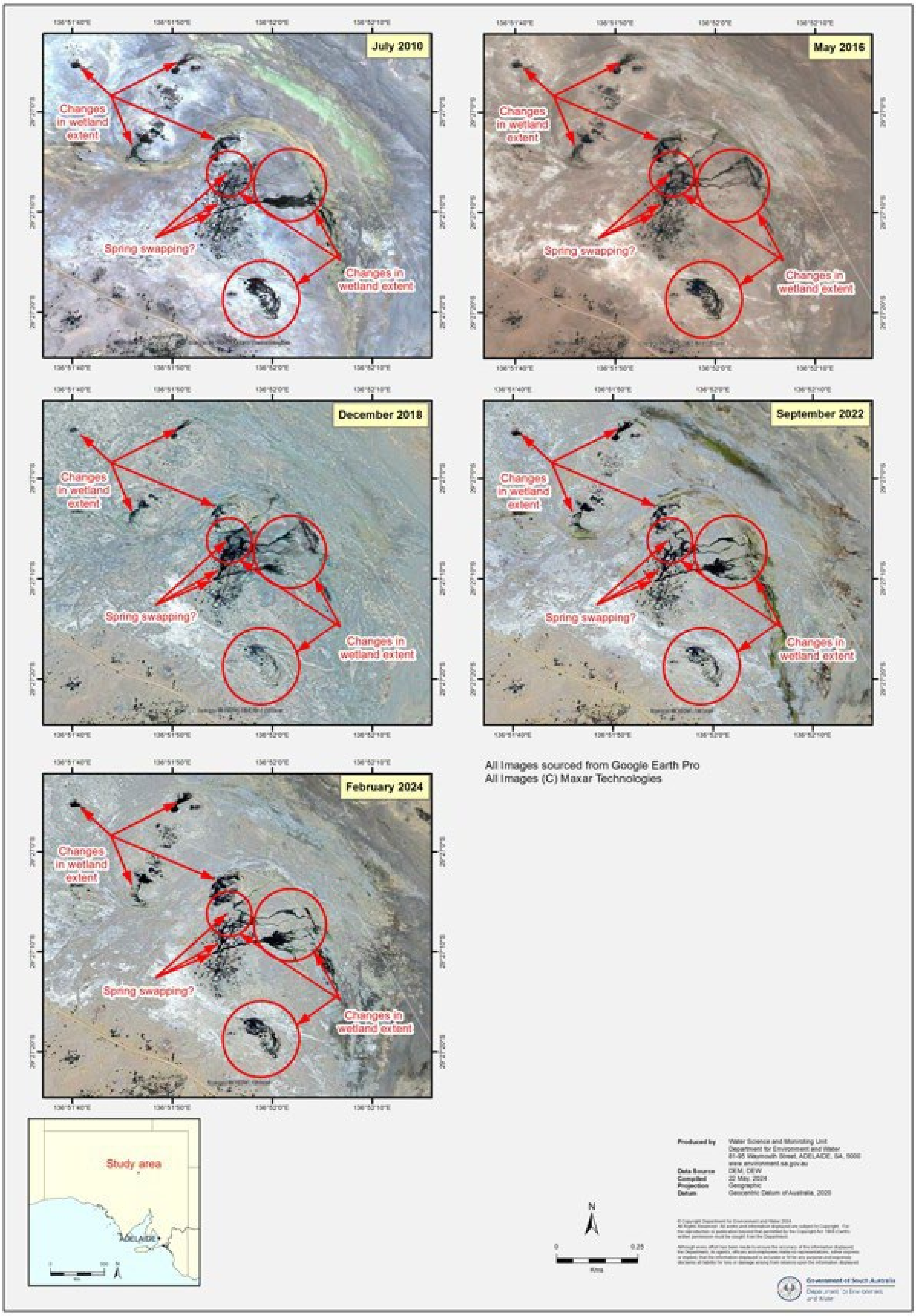

Figure 3 Google Earth images showing an example of spring switching and changes in wetland extent in the Wabdu Kadabu National Park GAB. For reference the Bubbler spring is to the northwest and Blanche Cup is to the west.

Green and Berens (2013) compared variations in flow rates with variations in excess head, at the Freeling Spring Group. Freeling Springs comprise a group of approximately 98 springs occupying a relatively narrow north-south swath over approximately out one kilometre. The study concluded that there is no direct correlation between spring flux and pressure head (Figure 4). Further studies such as these are required and would benefit from long term monitoring for aquifer pressure and spring flow.

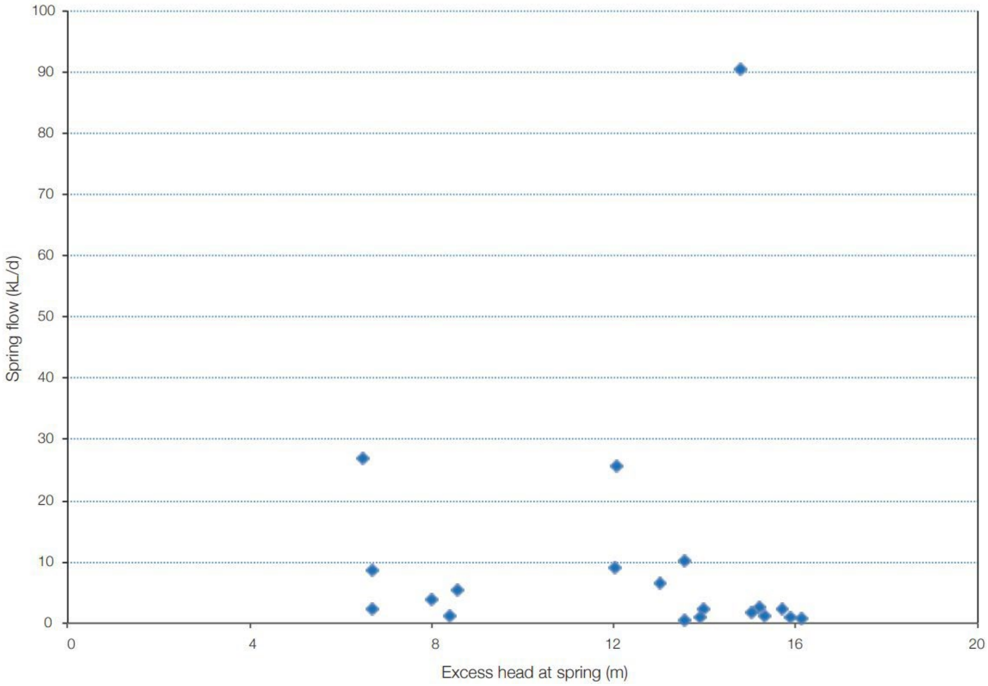

Figure 4. Excess head versus spring flow from the Freeling spring group showing that there is no apparent relationship between the variables (Green and Berens, 2013).

2.3 History of groundwater extraction and spring behaviour /monitoring

In the Far North Water Allocation Plan (FNWAP) region, DEW have established 87 monitoring bores (Sibenaler, 2010; Keppel, 2023) (Figure 5). Bores in this network are currently monitored once or twice a year, a larger network consisting of all GAB bores (approximately 300-400 bores) are monitored every 3-4 years. Figure 5 shows the distribution of this network along with 5-year trend analysis and selected long term hydrographs.

The network is reviewed approximately every 5 years. The current data shows that approximately 50% of bores have a stable distribution of hydraulic heads, while the remaining bores show either a rising or declining trend. The reasons for the declining and rising trends have not been articulated, but stable and inclining trends are likely to be related to capping uncontrolled bores and/or piping infrastructure.

The development of the Olympic Dam mine resulted in the establishment of a wellfield in 1984 where groundwater abstraction reached a maximum rate of 15 ML/day in 1995. A second wellfield was established in 1995/96 to reduce the impact of the original wellfield on nearby spring complexes. Leading up to the peak abstraction from the original wellfield, there has been a decrease in aquifer pressure as well as spring flow (Mudd and Currell, 2023) and two springs, one in the Wangianna complex (Priscilla) and a second in the Hermit Hill complex (Venables), ceased to flow. As a result of the reduction in abstraction from the original wellfield post 1995/96, aquifer pressure and spring flow rates recovered at nearby springs including those within the Hermit Hill and Lake Eyre South spring complexes. However, spring flow at Priscilla and Venables springs did not recover, inferring that previously active flow pathways were not reactivated, or aquifer pressure had not responded near those springs.

Unfortunately, there is no long-term, reliable spring monitoring network recorded by DEW. DEW records indicate that occasional spring flow monitoring data has been collected but this has occurred typically on a piecemeal basis. BHP conducts routine spring flow monitoring in the southwest spring zone, however these data were not available to the project team.

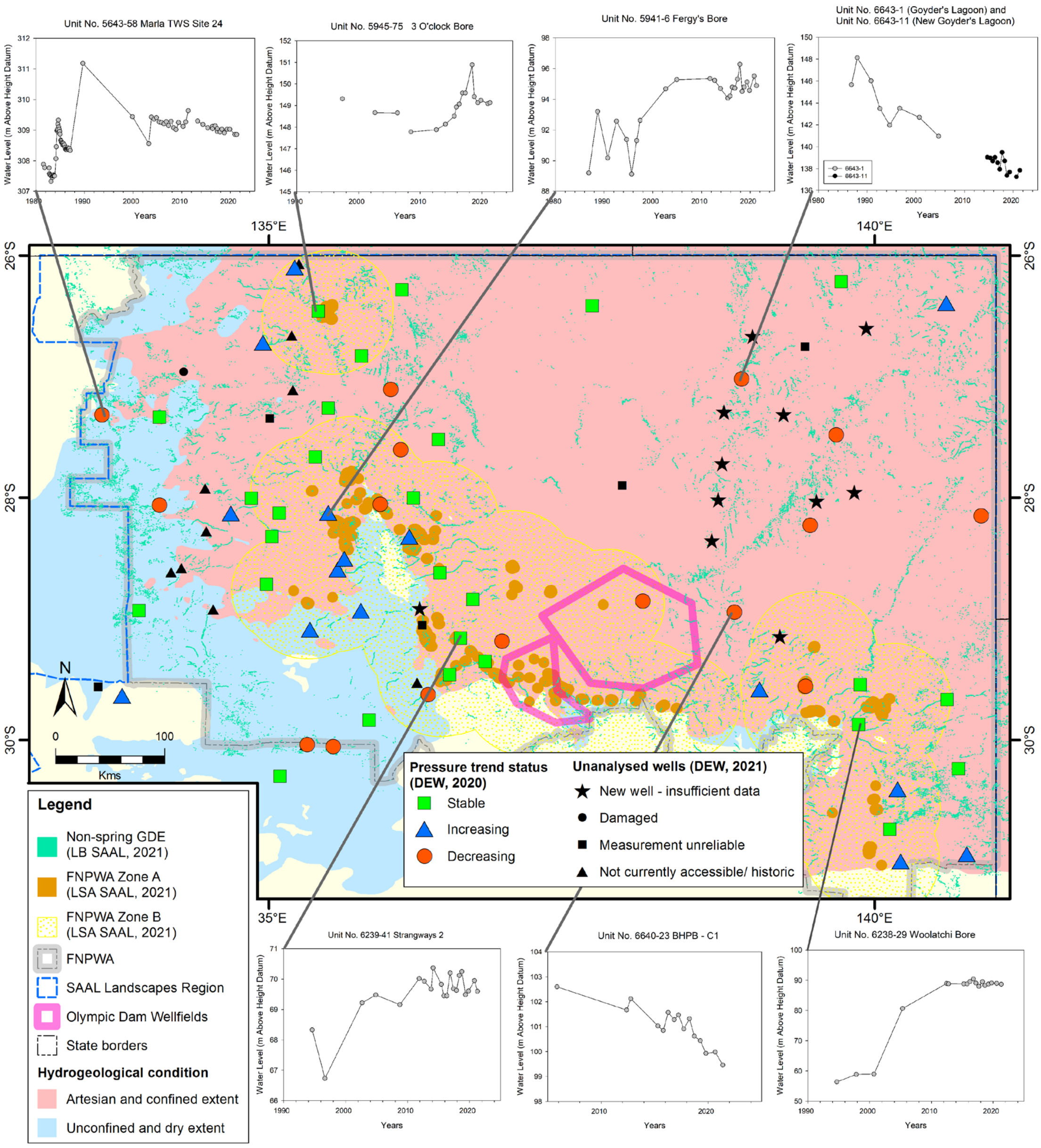

Figure 5. Monitoring network for the FNPWA (Keppel *et al*. 2023).

3 Modelled Abstraction Scenarios using the Far North Groundwater Model

3.1 Model Background (Key Features of the Far North Groundwater Model)

The model domain covers all the Eromanga Basin in South Australia and the Northern Territory, including a buffer area, but also extends part way into southwest Queensland and New South Wales (Figure 6). The model area covers approximately 721,000 km^2. Model capabilities and limitations are summarised below.

3.1.1 Model capabilities

- The model is the only South Australia-specific numerical groundwater model available that covers the entire Eromanga Basin in South Australia and the NT. Whilst there have whole-of-basin numerical models built previously, these do not have nearly the same level of vertical or horizontal discretisation available and therefore cannot provide the same level of precision. Other models that have similar levels of detail largely only focus on the artesian component of the South Australian GAB and may use the GAB springs as a boundary condition, rather than as a central focus.
- The model is currently the only South Australian-specific, non-proprietary tool available to assess large, regional scale, cumulative drawdown impacts and pressure recoveries within the South Australian portion of the GAB. Consequently, the model represents the best tool available to examine the impacts of cumulative drawdown, as well the benefits of groundwater saving measures across the entire GAB in South Australia.
- The model represents the latest attempt to incorporate or respect all the latest GAB-related groundwater science.
- Currently, the model is the most optimised numerical groundwater model available to investigate the groundwater hydrology of GAB springs at the complex and supergroup level and the possible impacts caused by one primary vector for risk, being cumulative changes in groundwater pressure within the main supplying aquifer.
- The model is stable in both steady and transient states and is therefore mathematically optimised to provide reliable output data. This was achieved by undertaking a much finer grid discretisation than what was originally planned to account for the highly complex basin architecture found within the South Australian portion of the GAB.
- The incorporation of a basement layer of nominal thickness across the entire model domain provides the opportunity to examine groundwater flow relationships between the Main Eromanga Aquifer sequence and strata below the GAB. Consequently, it is one of very few GAB numerical models that explicitly acknowledges groundwater migration to and from underlying strata as critical and as a conservative conceptual approach.
- The model is one of few that attempts to vertically discretise the Main Eromanga Aquifer Sequence into intra aquifer units of differing hydraulic property. This was undertaken with close consultation with the Energy Division within the South Australian Department of Energy and Mining, who prepared the structure surfaces for incorporation into the model.
- The model can replicate changes in groundwater levels with reasonable precision, particularly around the Kai Thanda- Lake Eyre South region.

3.1.2 Key model limitations

- The model does not attempt to replicate density driven flow. The amount of technical knowledge required to numerically describe and constrain the computational requirements to replicate convective flow was too great to attempt incorporation during a Stage 1 model build, particularly given the design objectives of the model that emphasised third party use using commonly available software. Whilst not currently replicated, DEW is very supportive of continued research, including smaller scale modelling, that will enable properly described and constrained replication of convective flow in future model iterations.
- After extensive analysis, it was necessary to use a simple method for groundwater density correction, as using multiple, smaller scale density correction constants across the model domain proved to be

too difficult to accomplish. Consequently, density correction favours accuracy near springs, as this is a key risk receptor the model was designed to help manage.

- There was insufficient information to accurately describe the initial conditions and so this has been approximated for the purposes of this model. This is a common problem for GAB numerical models as there is very little, to no historical information collected prior to groundwater extraction. This may lead to systematic misreporting of hydraulic heads across the model domain. Further, this problem is exacerbated by the very slow response times between recharge events experienced by the hydrogeological system, which are best described using paleoclimatic cycles.
- Grid discretisation could not be completed to a sufficiently fine scale to permit every spring and well to be individually replicated. In some areas, spring and well locations required aggregation to allow model stability. Consequently, at more localised scales model predictions become less accurate. As before, this is not a unique problem for regional-scale GAB numerical models.
- Whilst the model provides some flexibility for inter-aquifer flow, this was only accomplished in a very approximate manner.
- Faults are not represented in the current model. Whilst their importance in spring conduit formation, inter-aquifer relationships, preferential flow development, and definition of sub-basinal groundwater systems is recognised, numerically replicating the impact of faults without any specific hydrogeological information to constrain this was considered too onerous.
- Most hydrograph data across the model domain used to calibrate the model is sourced from dual purpose wells. Whilst every care is taken during monitoring to collect a representative sample, the potential of error cannot be confidently removed.
- There is very little reliable monitoring information to constrain spring flow. Further, the groundwater source for springs is assumed to be entirely from the Main Eromanga Aquifer Sequence, with possibly some contribution from the basement layer where inferred. Furthermore, the model is not designed to explore the complexities of groundwater flow through individual spring conduit architectures and all the strata through which they occur; smaller scale localised models would be better able to accomplish this.
- Water use data for stock and domestic use is estimated using a simple formulation in the absence of sufficient metering data. Whilst the formulation is considered conservative for risk assessment purposes, in the context of numerical model calibration, overestimating water use may lead to overcompensation in other hydraulic parameters, such as hydraulic conductivity, during calibration.

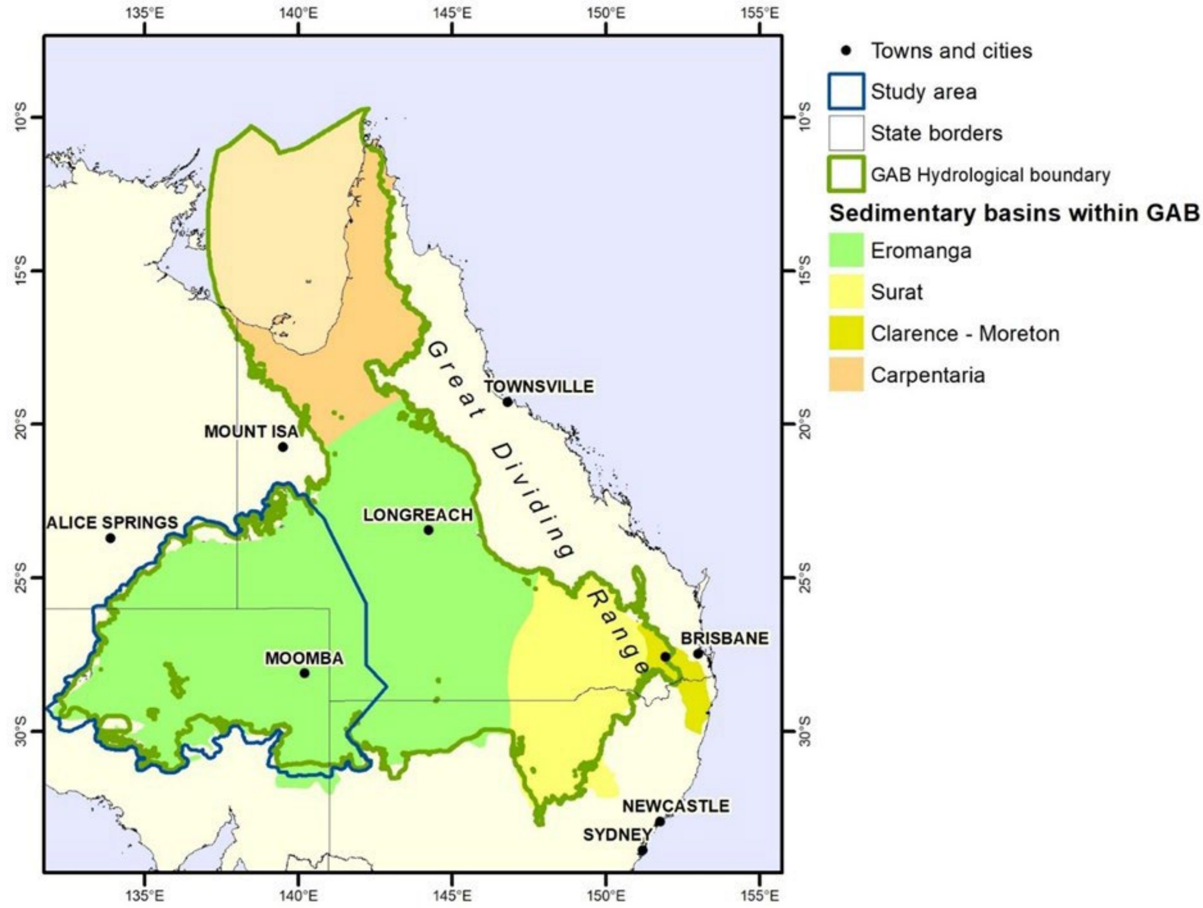

Figure 6. Location of the DEW Far North model extent within the larger GAB.

The Far North model was built in MODFLOW-USG (Panday, 2022; Panday *et al.,* 2013). The version used to run the model is 1.10.0 which is built and maintained by GSI Environmental (Panday, 2022). Full details on the development and purpose of the Far North model can be found in DEW (2023g). Herein we focus on the representation of the springs within the model. A review of the Far North model was out of scope and as such not conducted.

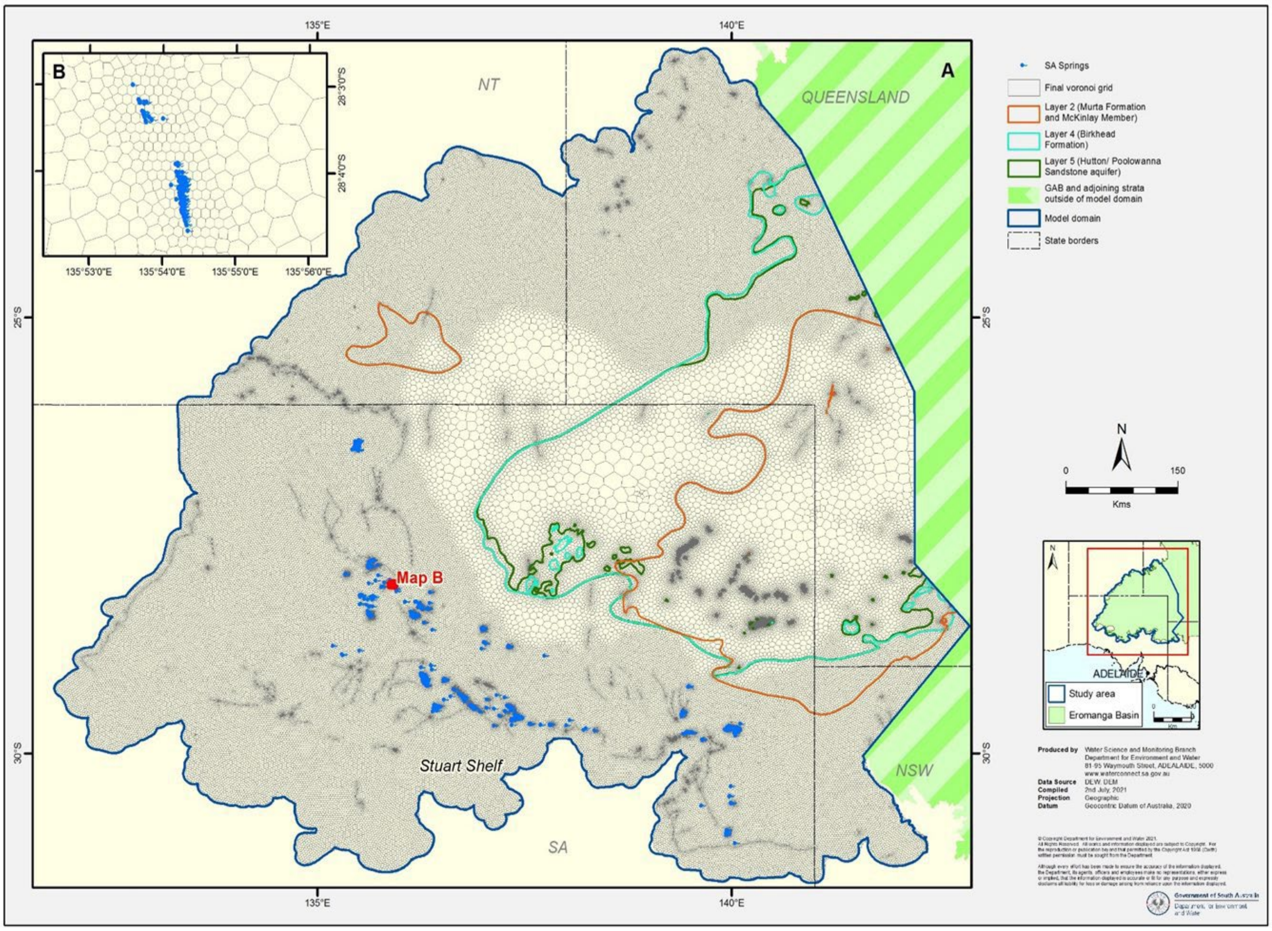

Figure 7 A) Final Voronoi grid used in model construction. B) Detailed example of assigned minimum cell size in areas where many spring vents occur (DEW, 2023g).

The components of the conceptual hydrogeological model included in the numerical model are:

1. Diffuse rainfall recharge, diffuse discharge near springs, and flooding recharge from the Finke River (see Figure 8);
2. Lateral inflows and outflows through general head (see Figures 9-12) and specified gradient (Figure 13) boundaries and flow barriers with no-flow boundaries;
3. Point discharge through extraction wells (see Figure 14) and point discharge at springs (through drain boundaries, Figure 16).

The model is transient and is represented by annual stress periods, each with 6 steps.

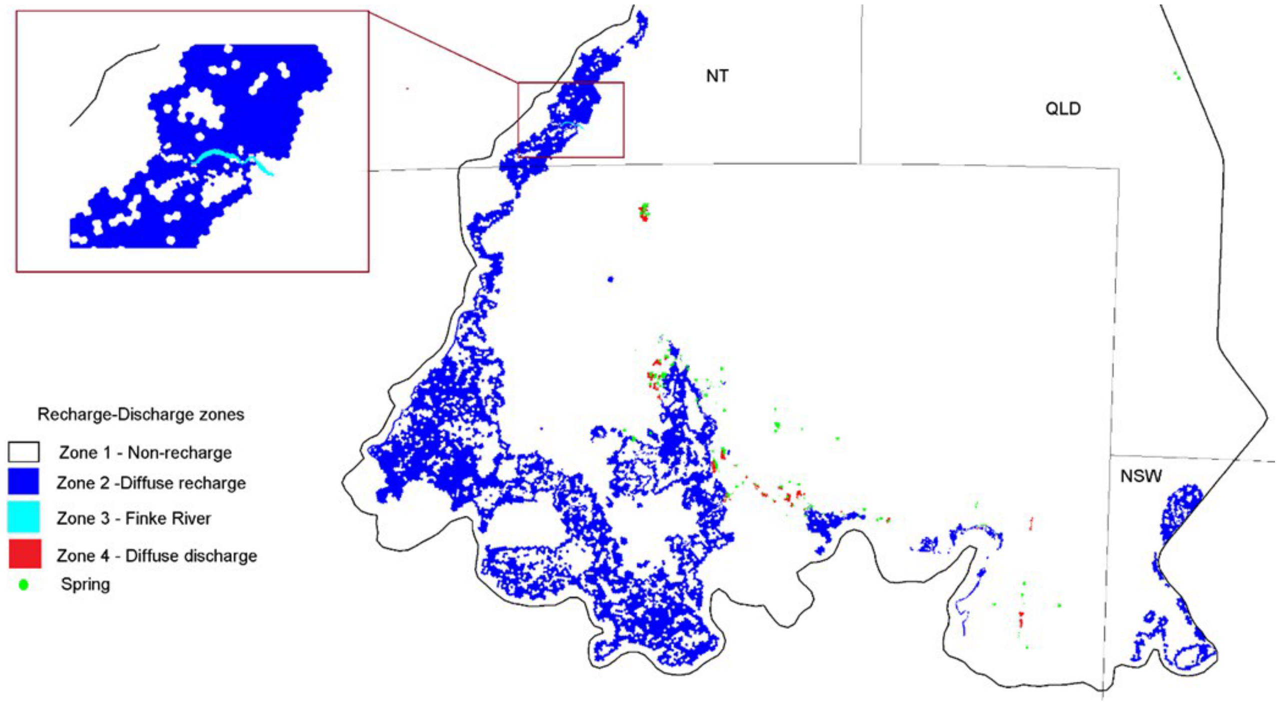

Figure 8. Diffuse recharge, ephemeral recharge and diffuse discharge zones (DEW, 2023g)

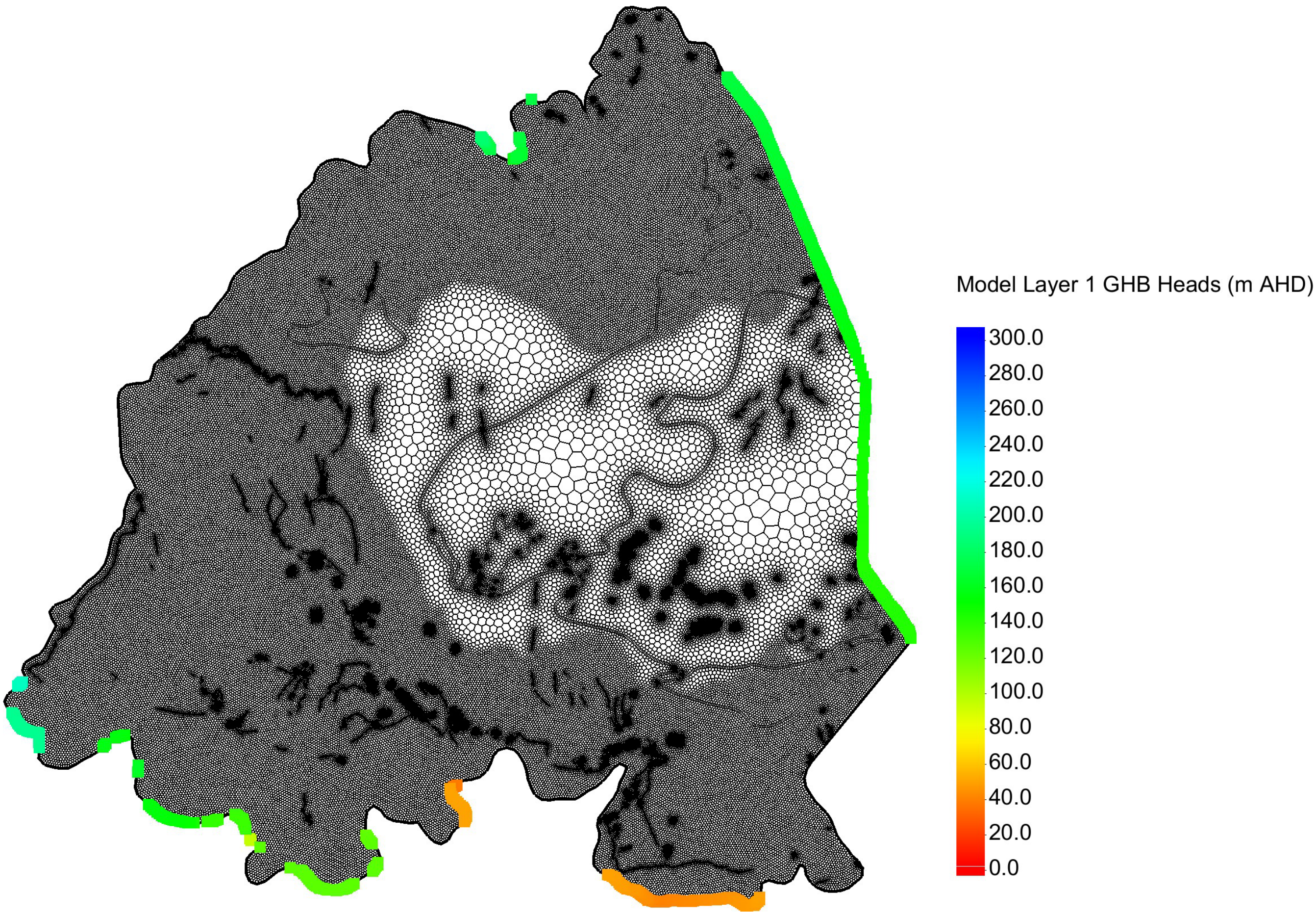

Figure 9. Model layer 1 (Cadna-owie) GHB cell location and hydraulic heads (DEW, 2023g)

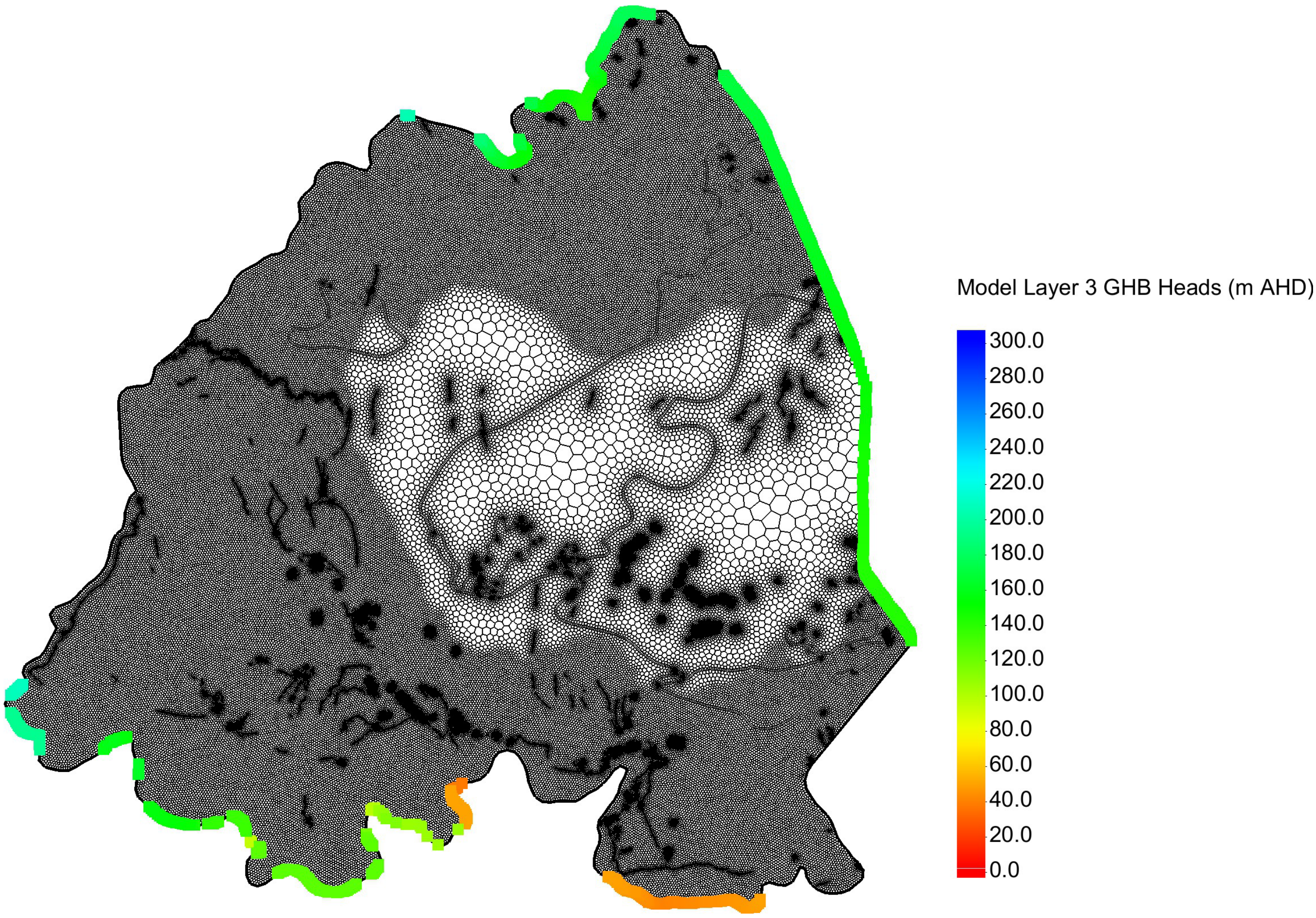

Figure 10. Model layer 3 (Namur/ Algebuckina) GHB cell location and hydraulic heads (DEW, 2023g)

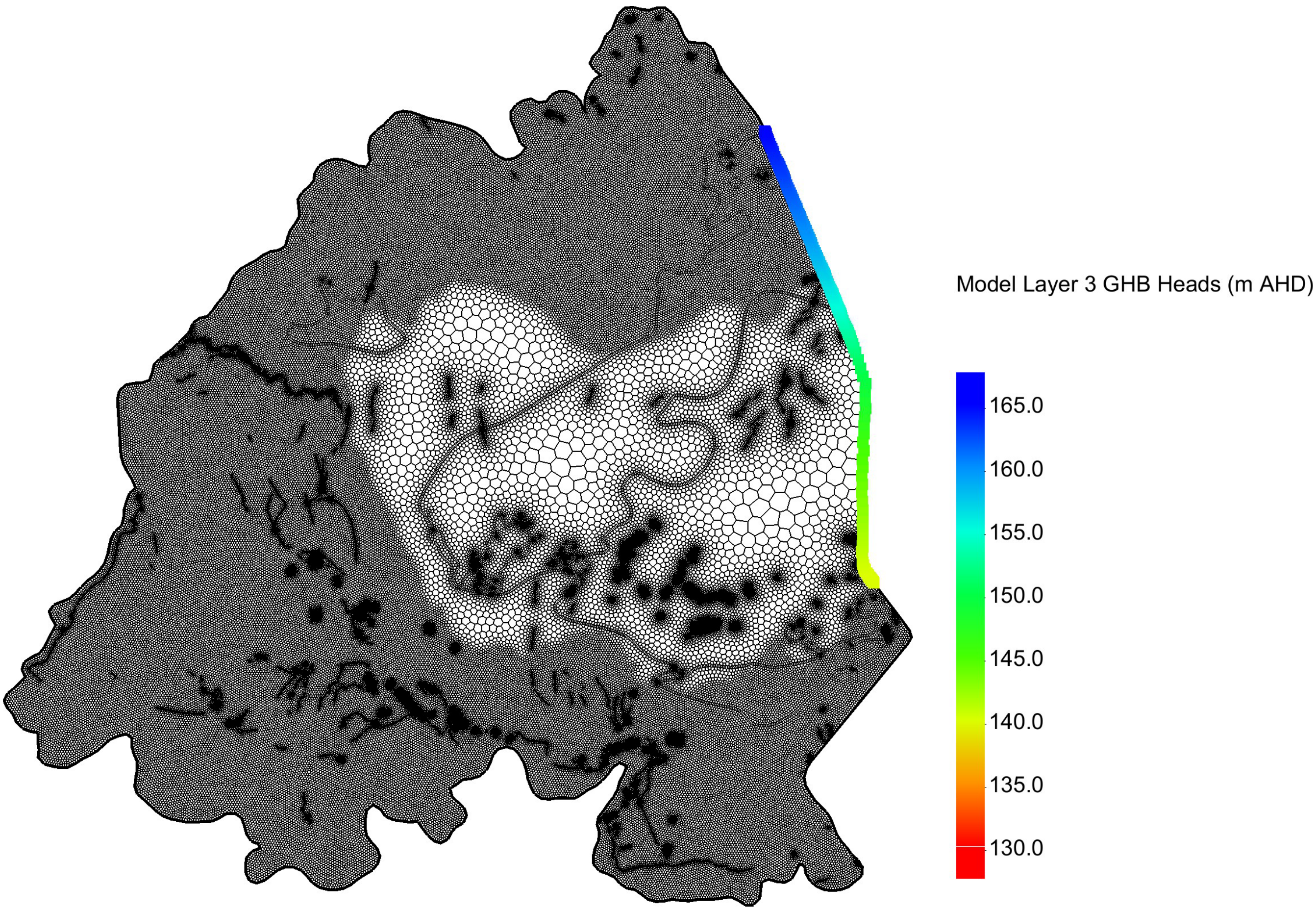

Figure 11. Model layer 5 (Hutton/ Poowlowanna) GHB cell location and heads (DEW, 2023g)

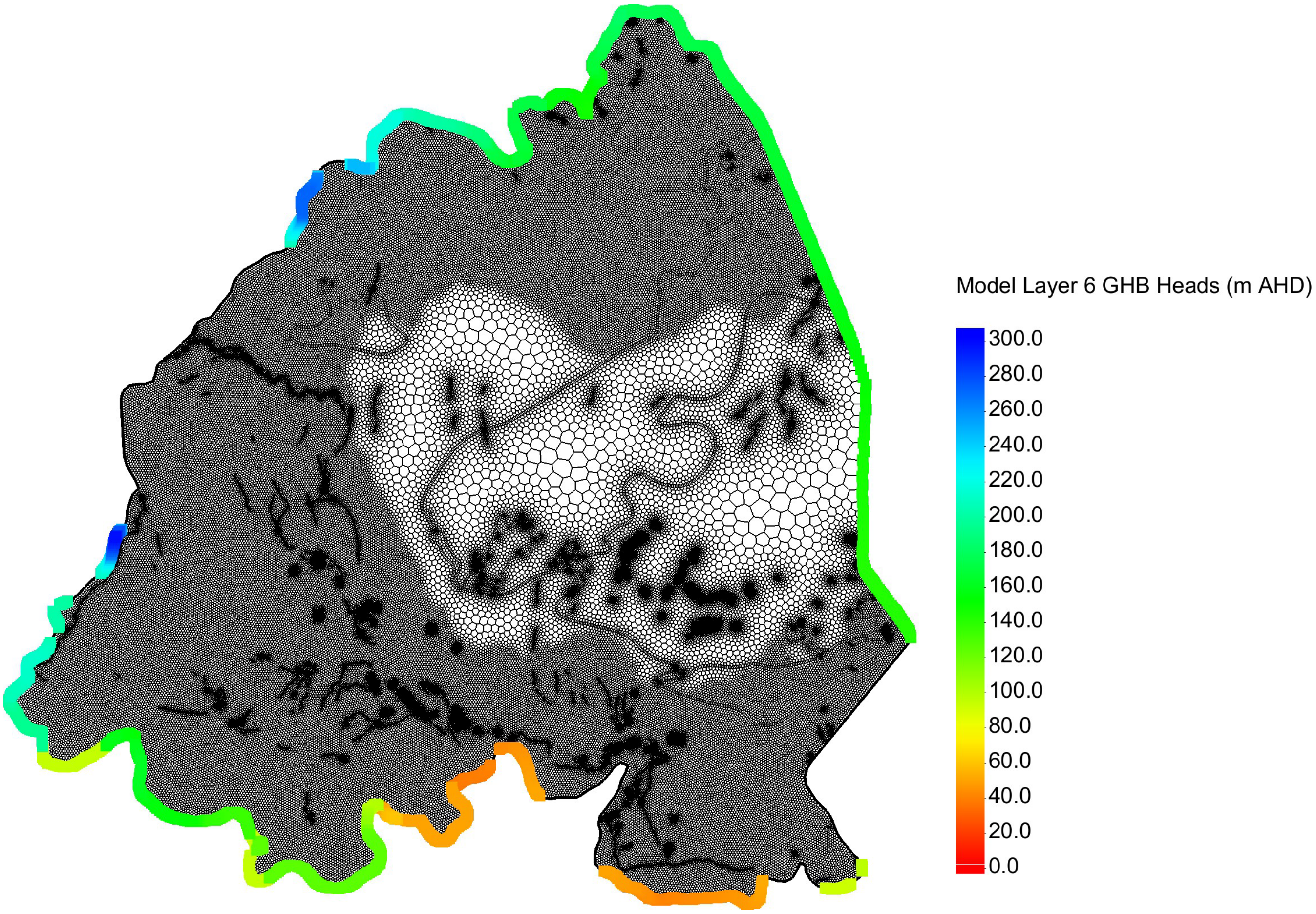

Figure 12. Model layer 6 (Basement) GHB cell location and hydraulic heads (DEW, 2023g)

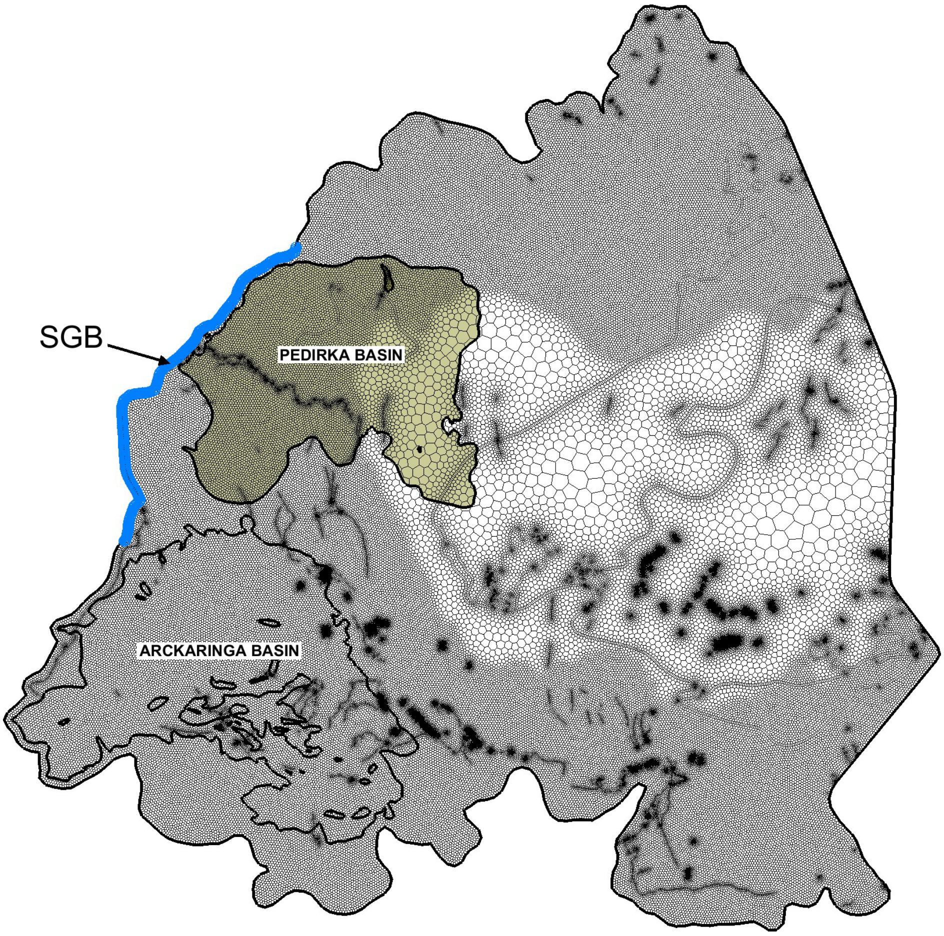

Figure 13. Specified Gradient Boundary (SGB) assigned to model layer 6 (Basement) (DEW, 2023g)

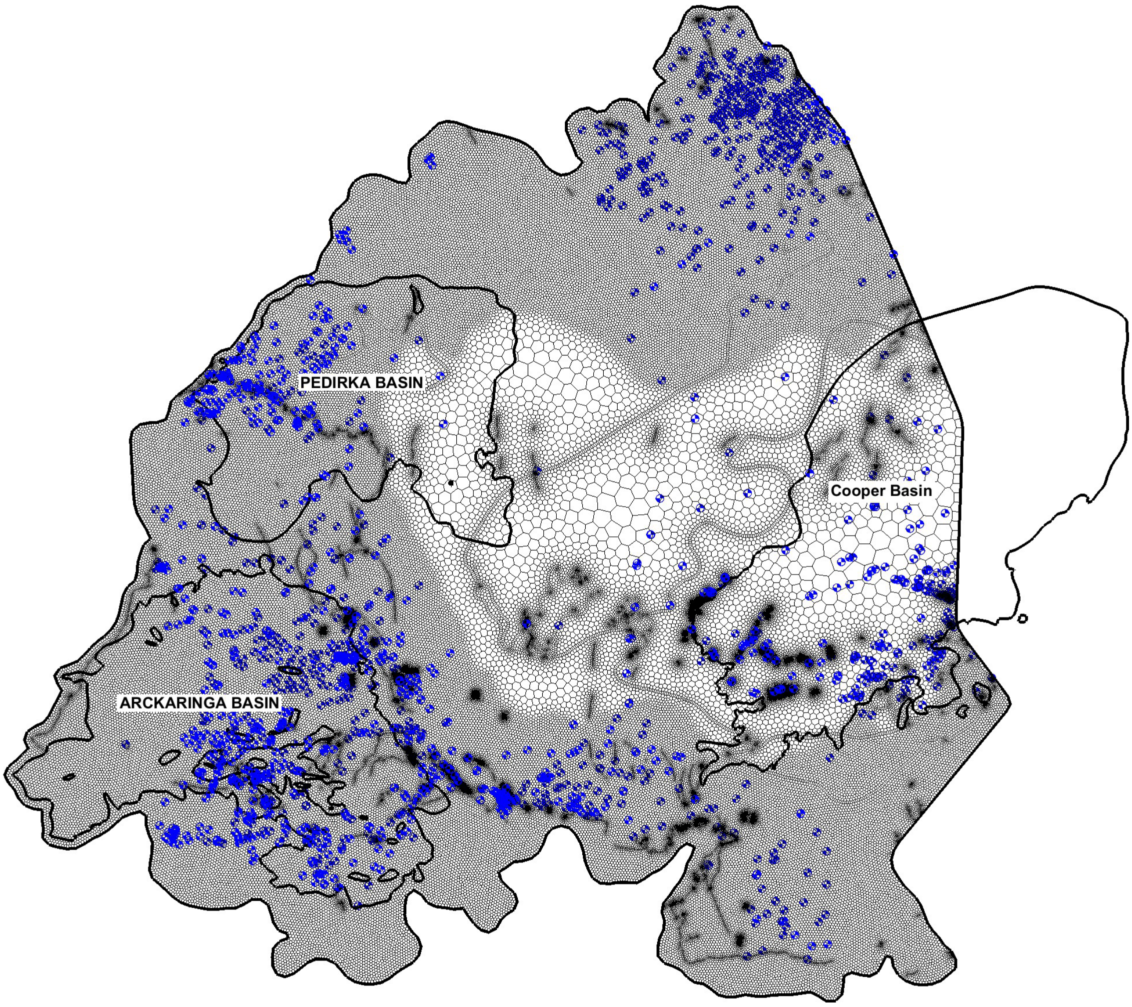

Figure 14. Location of extraction wells (DEW, 2023g)

3.2 Extraction wells

This model represents over 400 extraction wells, with this study focussed on Wellfields A and B, shown below in Figure 15. Wellfield A is comprised of 9 extraction wells at an average depth of 175 m, and Wellfield B is comprised of 3 extraction wells at an average depth of 797 m. Historical and forecast extraction rates from these wells are discussed in Section 3.5.

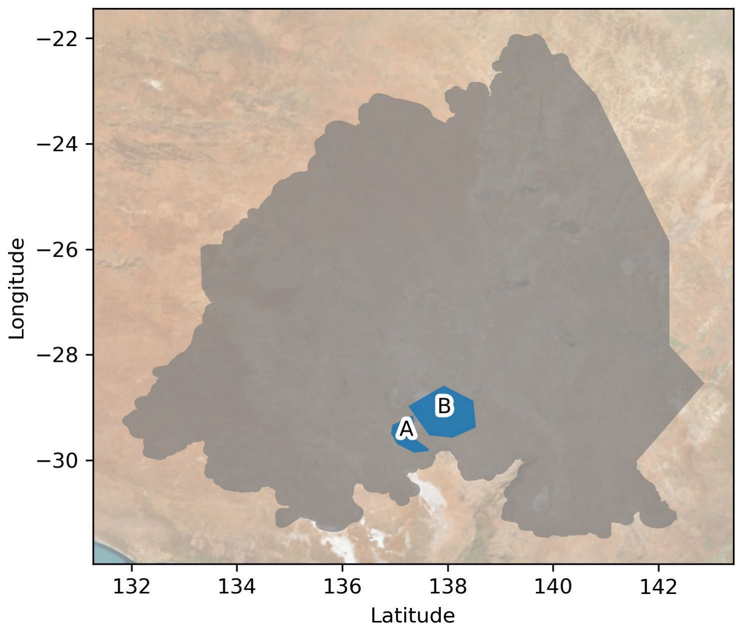

Figure 15. Location of Wellfield A and Wellfield B related to mining activities within the study area.

3.3 Spring discharge

The Far North model represents springs using the drain package (DRN) from MODFLOW-USG. Individual spring vents are not modelled due to the model resolution; however, collections of springs are modelled using the drain package. The drain package allows for discharge from a given cell if the hydraulic head is above the drain bottom elevation which is specified by the user and using a specified conductance. The equation for discharge from a model cell with a drain boundary condition is:

$$Q_{drain} = \begin{cases} CD \times (h_{drain} - h_{cell}) & if\ h_{cell} > h_{drain} \\ 0 & if\ h_{cell} < h_{drain} \end{cases}$$

Where Q_{drain} is the outflow to the drain in the cell [L^3/T], CD is the drain conductance [L^2/T], h_{drain} is elevation of the bottom of the drain, and h_{cell} is the hydraulic head in the cell. This conceptualisation assumes that there is a linear relationship between the hydraulic head in the aquifer and spring discharge.

Within the Far North model, there are a total of 5,356 unique drain boundary conditions applied at 1,273 unique nodes (multiple drain boundary conditions are often applied at the same node as part of a spring vent collection). Of the unique nodes, 1,228 are considered (comprising 5,140 drain boundaries) for detailed analysis as part of the named spring complexes in Figure 7.

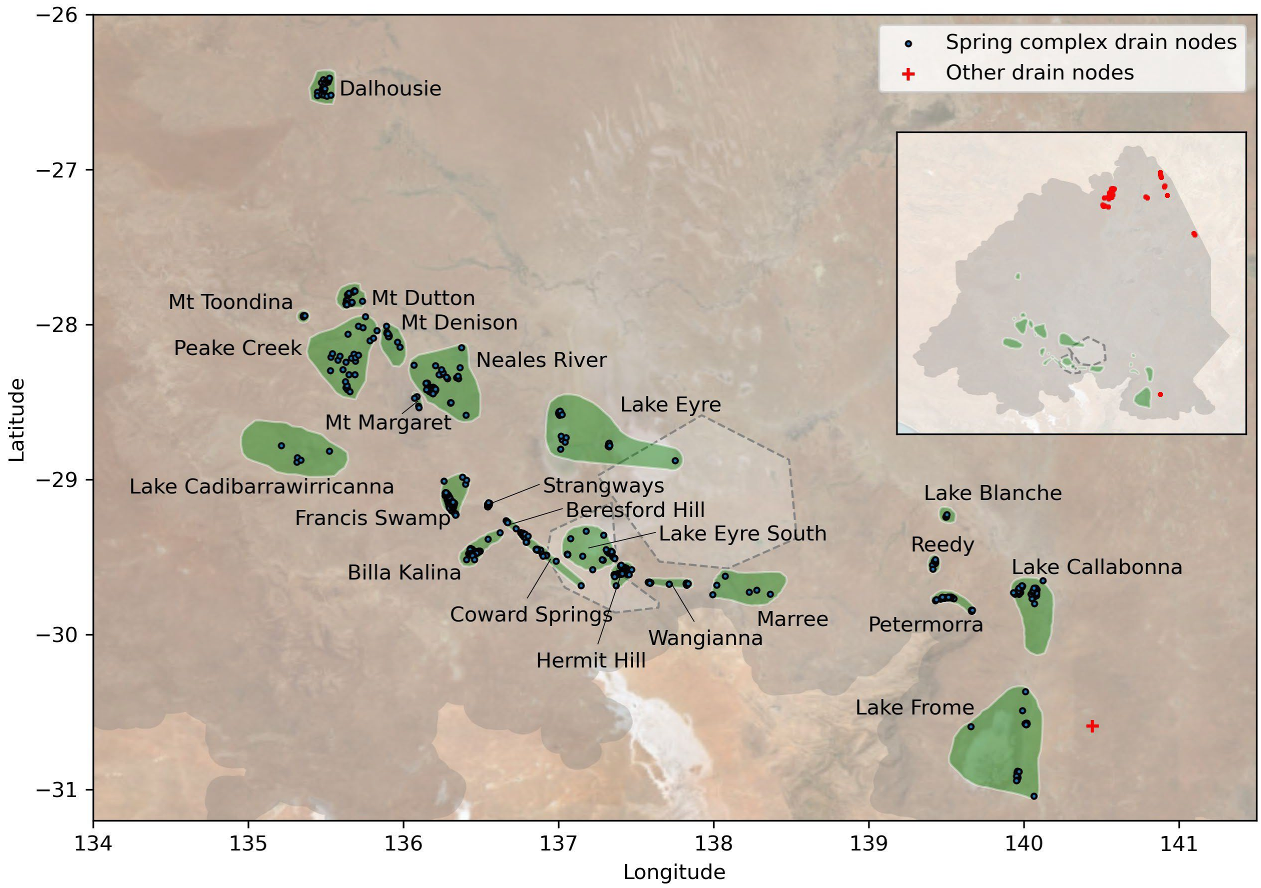

Figure 16. Location of the drain nodes representing springs in the Far North model. Drain nodes are shown in the context of the spring complexes (green polygons) and other drain nodes (unclassified).

3.4 Model conversion

An initial part of the modelling process in this study was the conversion of the model from the commercial Groundwater Vistas (GWV) GUI (ESI, 2023) modelling platform to the open source FloPy (Hughes *et al.*, 2023). As part of this conversion, it was necessary to ensure matching of the historical simulation between platforms. The GWV generated MODFLOW model files were handled by FloPy with the exception of the Specified Gradient Boundary (SGB) package which is not currently supported by the United States Geological Survey (USGS) version of MODFLOW-USG. The SGB was handled by writing a Python function to allow reading and writing SGB files. After conversion the results, historical GWV model output files and FloPy output files were compared to ensure minimal difference. The difference in target heads and residuals (Figure 17) and the difference in cumulative volume from each of the boundary conditions (Figure 18) demonstrate a very good match with the largest notable difference being in storage out with a difference near 0.001%.

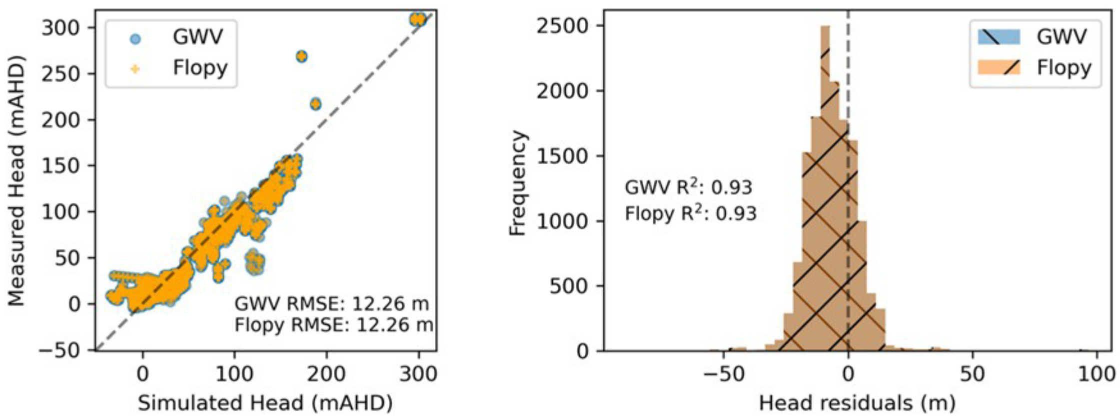

Figure 17. Comparison of calibration target heads between the GWV and FloPy models demonstrating sufficient match between models.

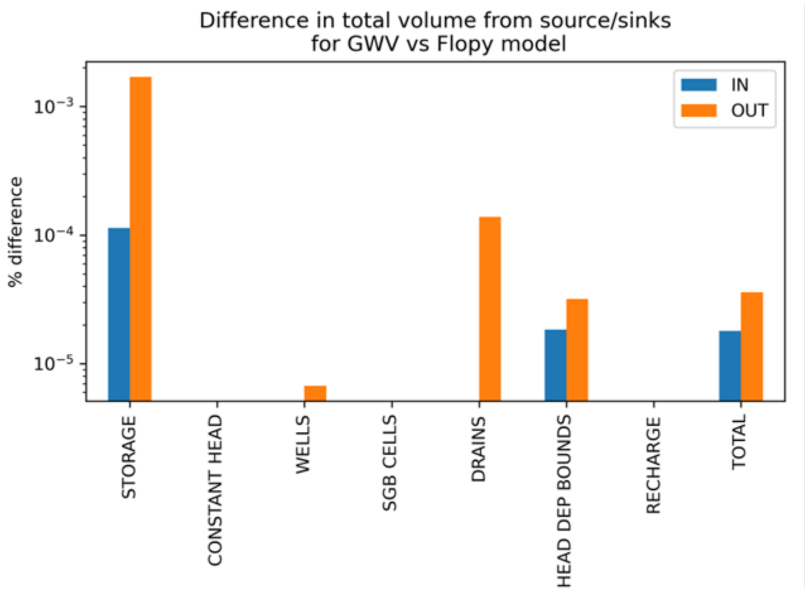

Figure 18. Cumulative differences in total volumes as a percentage for key water balance variables after 120 years of simulation.

3.5 Output From the Modelled Scenarios

Six experimental abstraction scenarios were proposed by Infrastructure SA to provide a spectrum of stimuli to assess the responsiveness of the aquifer to a change in abstraction volumes. The future abstraction rates from Wellfield A and B have not been confirmed, however there has been public commitment to cease abstraction from Wellfield A if water from the Northern Water project is available (see Olympic Dam Context-Based Water Targets). These scenarios are not indicative of established or foreseen abstraction patterns; rather, they offer substantial alterations in water extraction to evaluate the aquifer's reaction.

The selected experimental abstraction scenarios are provided as percentages of total abstraction in two wellfields, Wellfield A and Wellfield B (Figure 15,

Table 1). For each scenario it was proposed that changes would take effect in 2028 and each scenario should run for 100 years, i.e., to 2128.

Table 1. Scenarios for Far North model.

Scenario No.	Scenario Description	Wellfield A (% of abstraction)	Wellfield B (% of abstraction)
1	**A100_B100 (Base)**	100%	100%
2	**A50_B100**	50%	100%
3	**A0_B100**	0%	100%
4	**A50_B50**	50%	50%
5	**A100_B0**	100%	0%
6	**A0_B0**	0%	0%

Each scenario begins at the start of 2020, with Wellfield A and B abstraction assumed to be the same as in 2018 and carried forward to the end of 2021. Abstraction rates from 2022 to 2028 are linked to forecast abstractions acquired from published forecasts from mining companies. From 2028, the proposed abstraction scenarios are applied in Wellfields A and B as per Table 2. For all boundary conditions (CHD, GHB, DRN, SGB, RCH) except for abstraction (WEL), the boundary conditions are applied statically (i.e. they don't change across the scenarios from 2022 to 2128) as per the final stress period (2019) of the historical model.

Table 2. Forecast abstractions from Wellfields A and B

Year	Wellfield A (ML/d)	Wellfield B (ML/d)
2022	3.9	28.0
2023	3.5	30.0
2024	2.4	32.0
2025	3.4	32.0
2026 – 2032	3.9	32.0
2033 – 2128 *	3.9	32.0

*** For the purpose of model scenarios, assumed consistent with 2032 abstraction.**

Scenario changes to abstraction in Wellfield A and B are applied evenly across the production bores within each wellfield. All scenarios are established by modifying the historical model which is carried out in Jupyter Notebooks with FloPy. The resultant time series of total abstraction from all groundwater extractions (not just those in Wellfields A and B) in each of the six scenarios is shown in Figure 19.

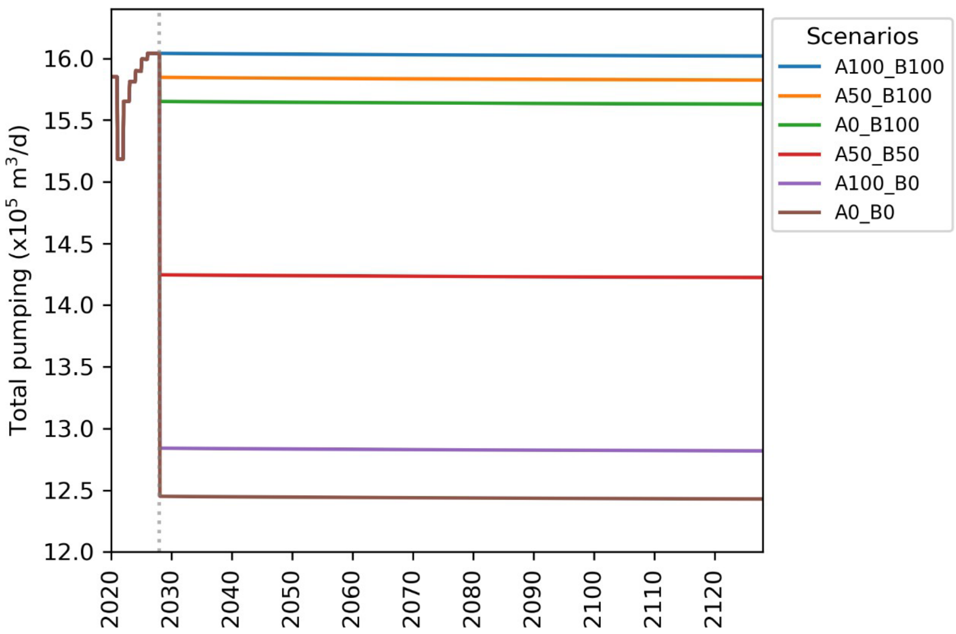

Figure 19. Total abstraction scenarios over time with changes to Wellfield A and B abstraction in each scenario beginning in 2028.

For each scenario, modelled head and cell by cell outputs were written at the end of each year for the entire simulation from 2020 to 2128.

3.6 Post-Processing Model Outputs

Global (whole of model) analyses were conducted for each of the six scenarios simulated to explore the evolution of: a) spatial head distribution, and b) the water balance of the aquifer system and how it responds to changes in abstraction. This analysis was done from using the "*.hds*" and "*.list*" output files from MODFLOW-USG that were used to calculate:

2. Absolute changes in fluxes and volumes between base case (BC) and each scenario for each BC.
3. Relative change of cumulative volume and instantaneous fluxes (%) between base case and each scenario for each BC.

Spring complex analyses were also conducted in each of the six scenarios over the simulation period to highlight the range of changes to the underlying heads and discharge for each of the 23 spring complexes shown in Figure 16.

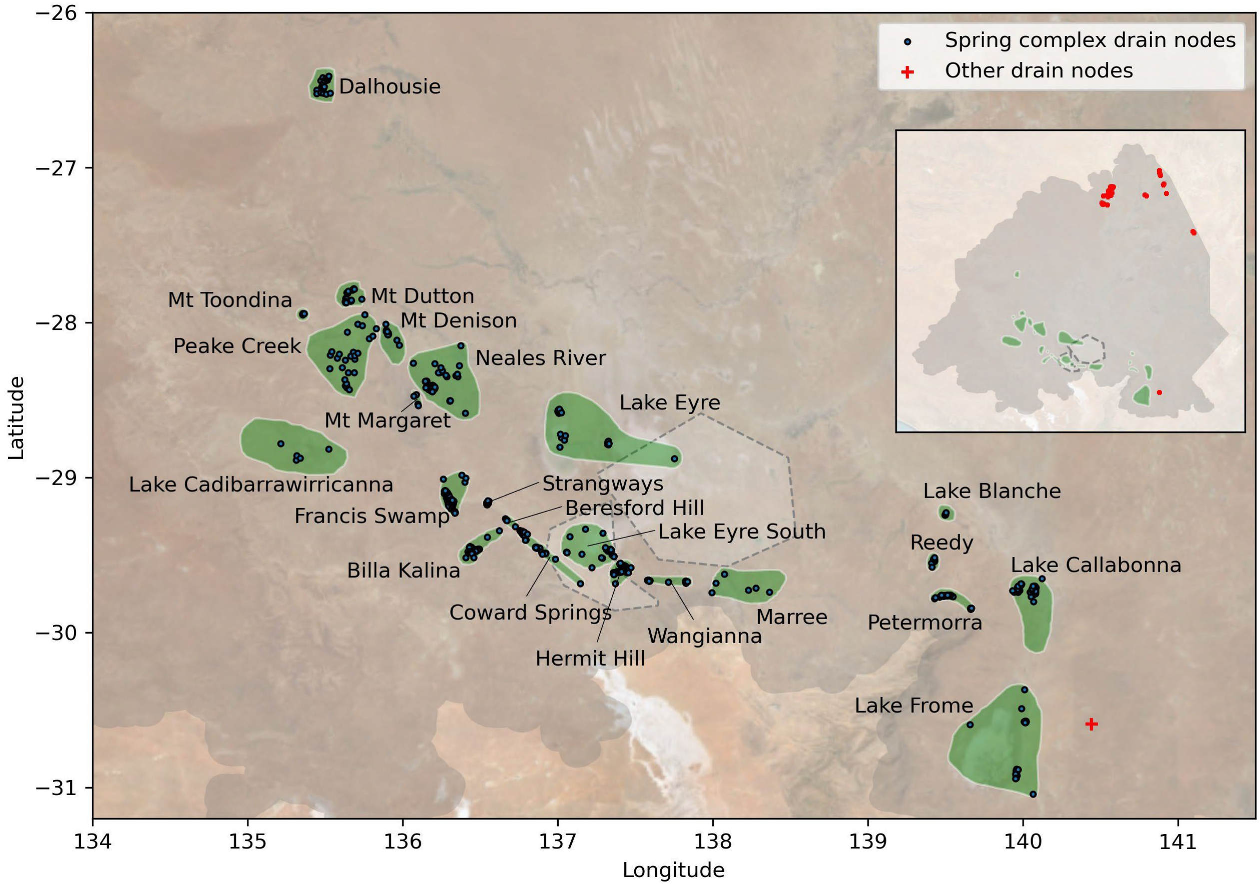

Figure 16. Location of the drain nodes representing springs in the Far North model. Drain nodes are shown in the context of the spring complexes (green polygons) and other drain nodes (unclassified).

3.7 Model Scenario Results

3.7.1 Global Analysis

The base case (A100_B100) initial head and its evolution over the 108-year simulation is shown in Figure 20. Only the first layer is used to visualise the spatial distribution of head in 2020 and subsequent changes in head at select times (Figure 20). The display of only the top layer was used as the vertical collection of most model cells was found to have near zero variance in head across the three top layers (where most wells are located) of the model. For most of the model area across at the select times, decreases in head are seen. However, the model shows head increases around the western and the south-eastern spring complexes, mostly likely the result of capping uncontrolled flowing bores and/or piping infrastructure. Up until 2058, there is a slight recovery in the Wellfield A region, but then a decline is seen up to 2128. The strongest decreases in head (up to 8 m) are simulated in Wellfield B. The entire northern region of the model shows continued decline over the 108 years.

The water balance for the historical (1900 – 2020) and current/future (2020 – 2128) periods are provided in Figure 21. The historical water balance that derives from simulations from previous work (DEW, 2023) is shown to give context to changes in the current modelling work as the model is still in a clearly dynamic state with effects from relatively large total abstraction still carrying through to the current simulations from 2020 – 2128. The base case from 2020 – 2128 shows that most inflow to the model comes from the head dependent boundary condition (HEAD_DEP_BOUNDS_IN) with the specified gradient boundary

(SGB_CELLS_IN) and release from storage (STORAGE_IN) also providing large contributions and a small amount of inflow comes from the areal recharge to the top of the model (RECHARGE_IN). The major sources of outflow are spring discharge (DRAINS_OUT), abstraction (WELLS_OUT), and through the head dependent boundary (HEAD_DEP_BOUNDS_OUT), with a small amount going into storage (STORAGE_OUT). The error (IN-OUT) is shown to be relatively small enough to demonstrate suitable convergence of the flow solution in the model. The most significant dynamics can be seen between 2020 and around 2035 in response to changes to the forecast abstraction in the first 8 years. The system response to changes in abstraction appears to be absorbed by releases in storage (STORAGE_IN) and a slight increase in inflow from the head dependent bounds (HEAD_DEP_BOUNDS_IN).

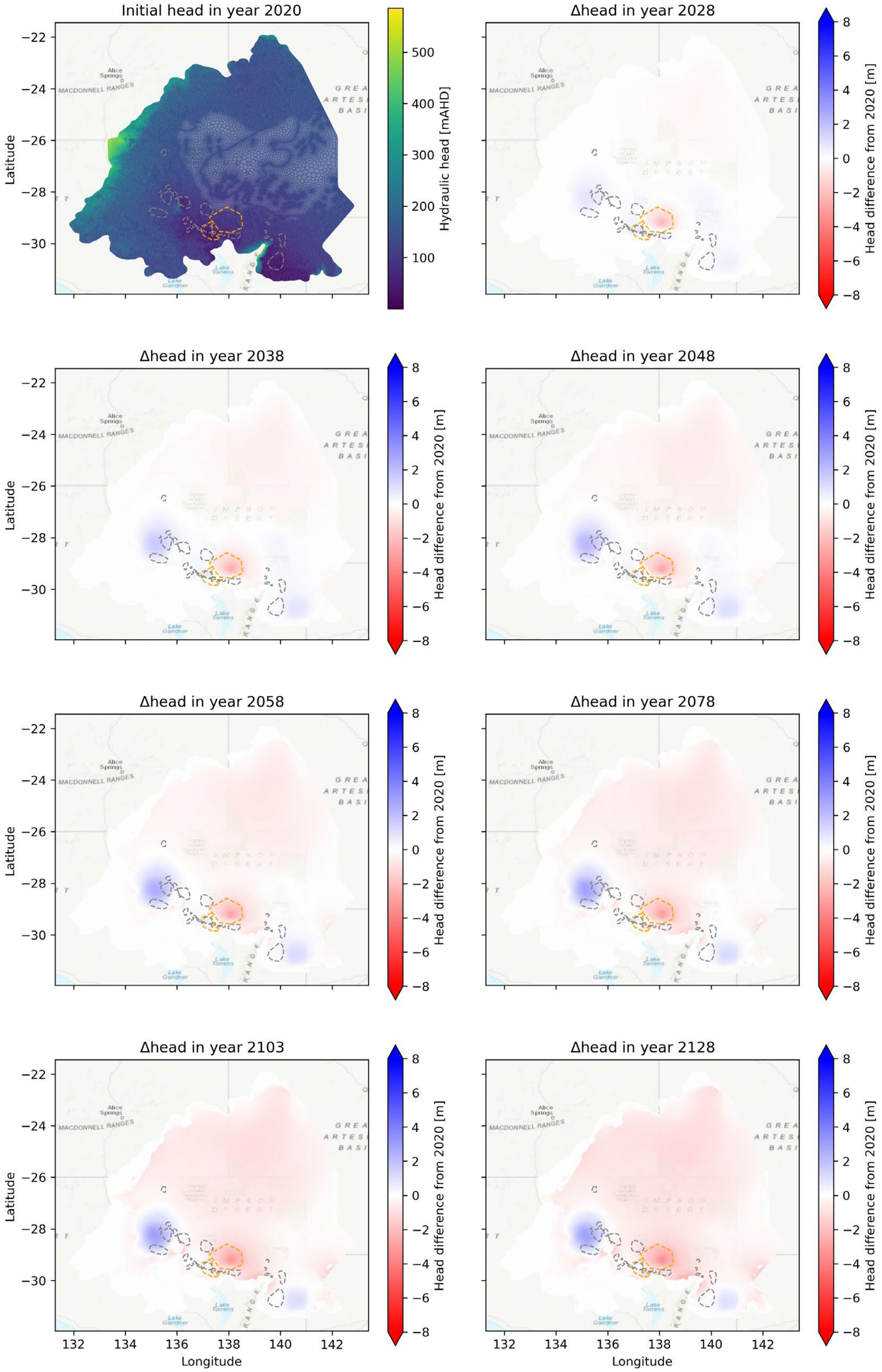

Figure 20. Initial spatial head distribution in the top layer of the model for the base case (A100_B100) and subsequent changes in head at specified times of interest. For reference wellfields A and B are indicated in the orange dashed lines and the spring complexes are indicated by the grey dashed lines.

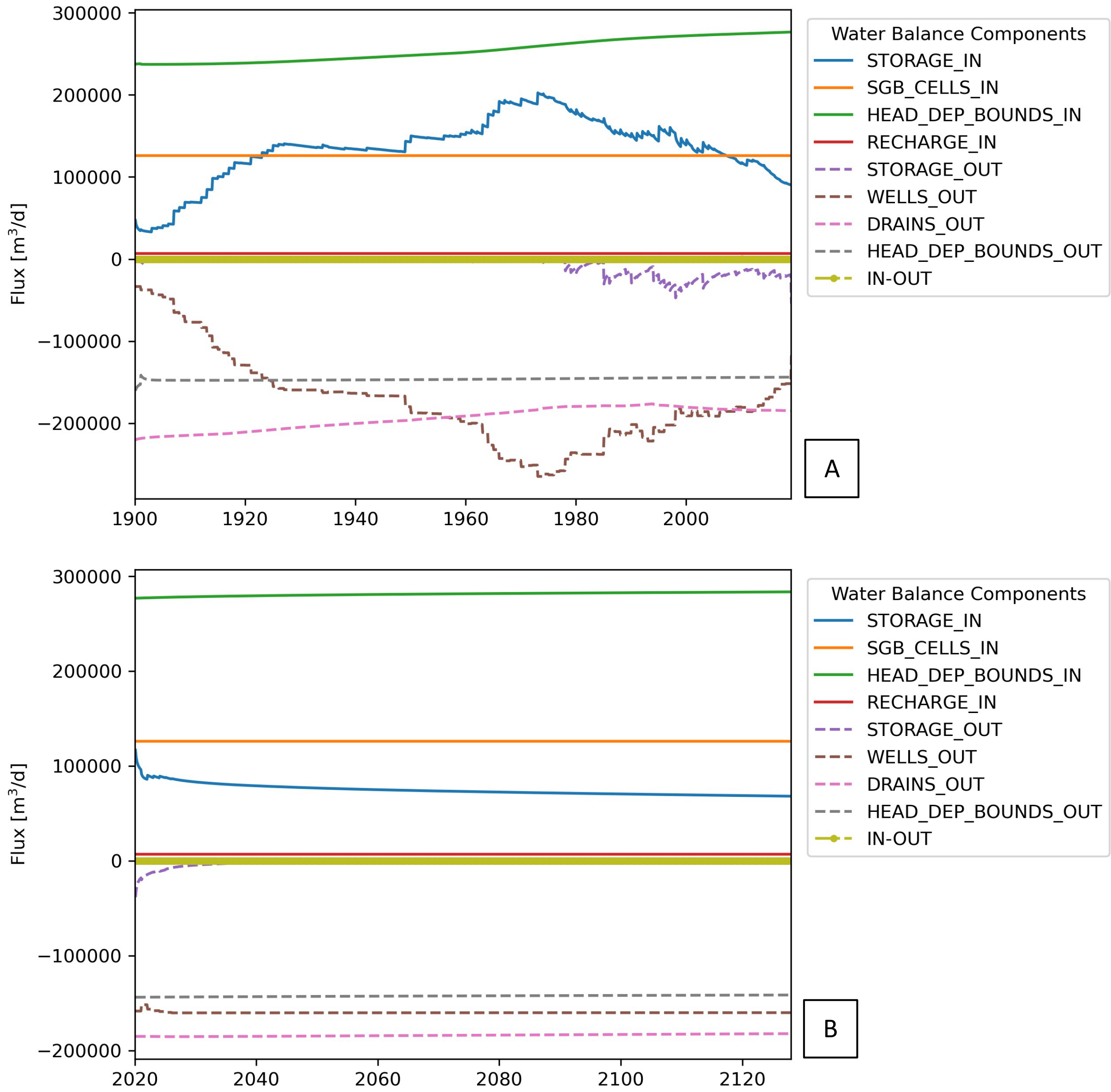

Figure 21. Water balance for the base case (A100_B100) for A) the historical (1900 – 2020) and B) the current/future (2020 – 2128) periods.

A comparison of the instantaneous fluxes for each key water balance component (Figure 22) shows how the model changes in response to the different scenarios. Only components that showed significant differences between scenarios are shown here. The 'WELLS_OUT' fluxes demonstrate that the abstraction imposed on the model could be sustained throughout the simulation, i.e., no significant abstraction cells going dry. For the different scenarios, reductions in releases from storage are clear (STORAGE_IN), with reductions in Wellfield B having the biggest impact and the rate of releases diverging over time. Similarly, with increases in storage (STORAGE_OUT), as the abstraction decreases, the rate at which storage accumulates also increases, but these rates converge slowly over time. The inflow from the HEAD_DEP_BOUNDS_IN increases over time across A100_B100, A50_B100 and A0_B100 scenarios. Meanwhile, inflow under the A50_B50 scenario increases at a lower rate over time than in the previous scenario. Whereas inflow from the A100_B0 and A0_B0 scenarios start decreasing from approximately 2050. Excluding the base case, total spring discharge (DRAINS_OUT) in all scenarios increases in rate initially after 2028, but then those with 100% Wellfield B abstraction show clear declines in discharge rate over time and a smaller decline observed in the A50_B50 scenario. For both scenarios with no abstraction in Wellfield B after 2028 (A100_B0 and A0_B0), the total spring discharge continues to increase over time, and the rate of this increase appears to plateau towards the end of the simulation.

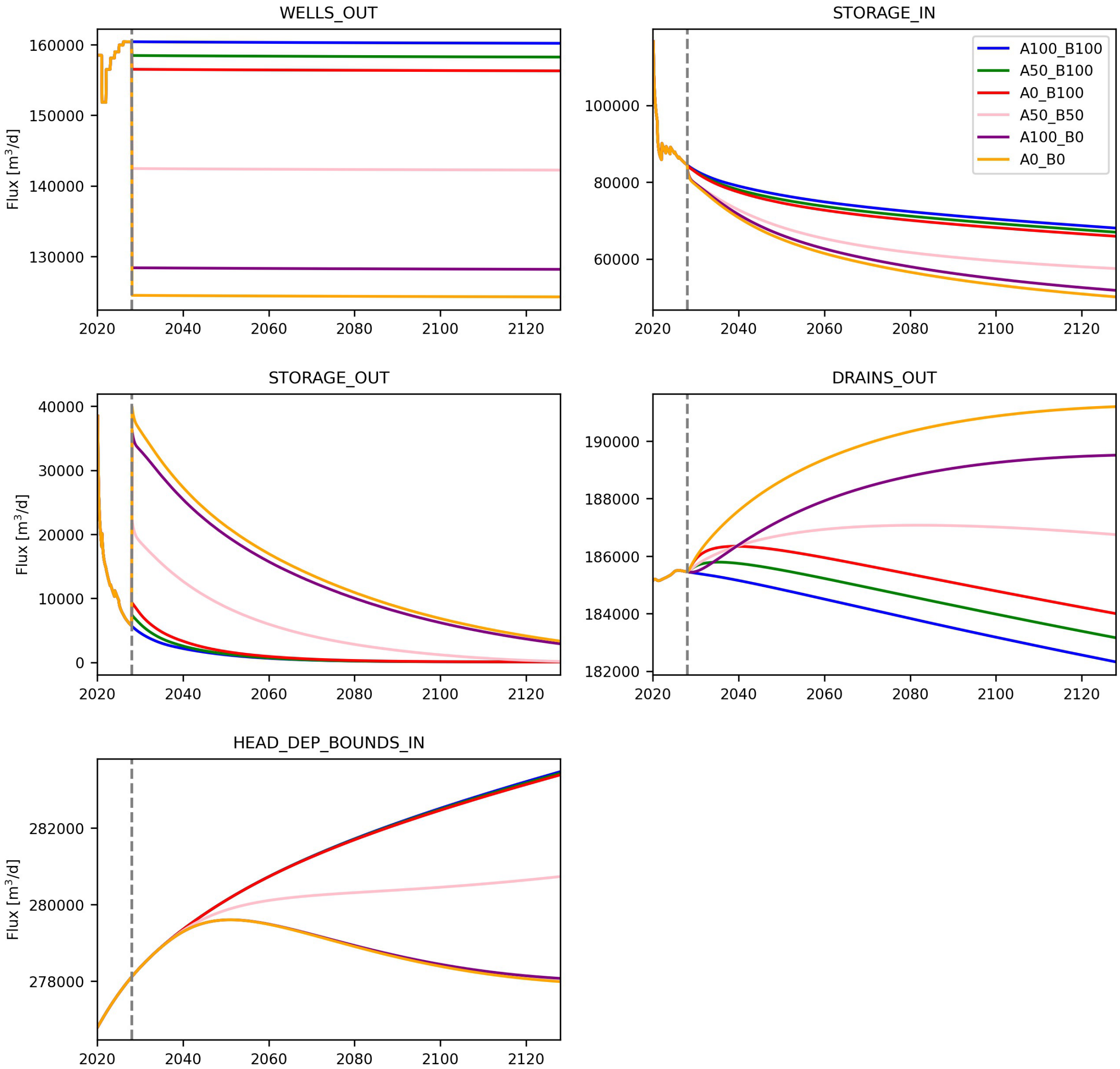

Figure 22. Comparison of the temporal evolution of total fluxes from key components of the water balance

The relative differences for each of the water balance components as compared to the base case are shown in Figure 23. The extremely large relative differences in STORAGE_OUT (~ 6000%) that are seen are due to the base case STORAGE_OUT tending towards zero as can be seen in Figure 13 in the STORAGE_OUT subplot.

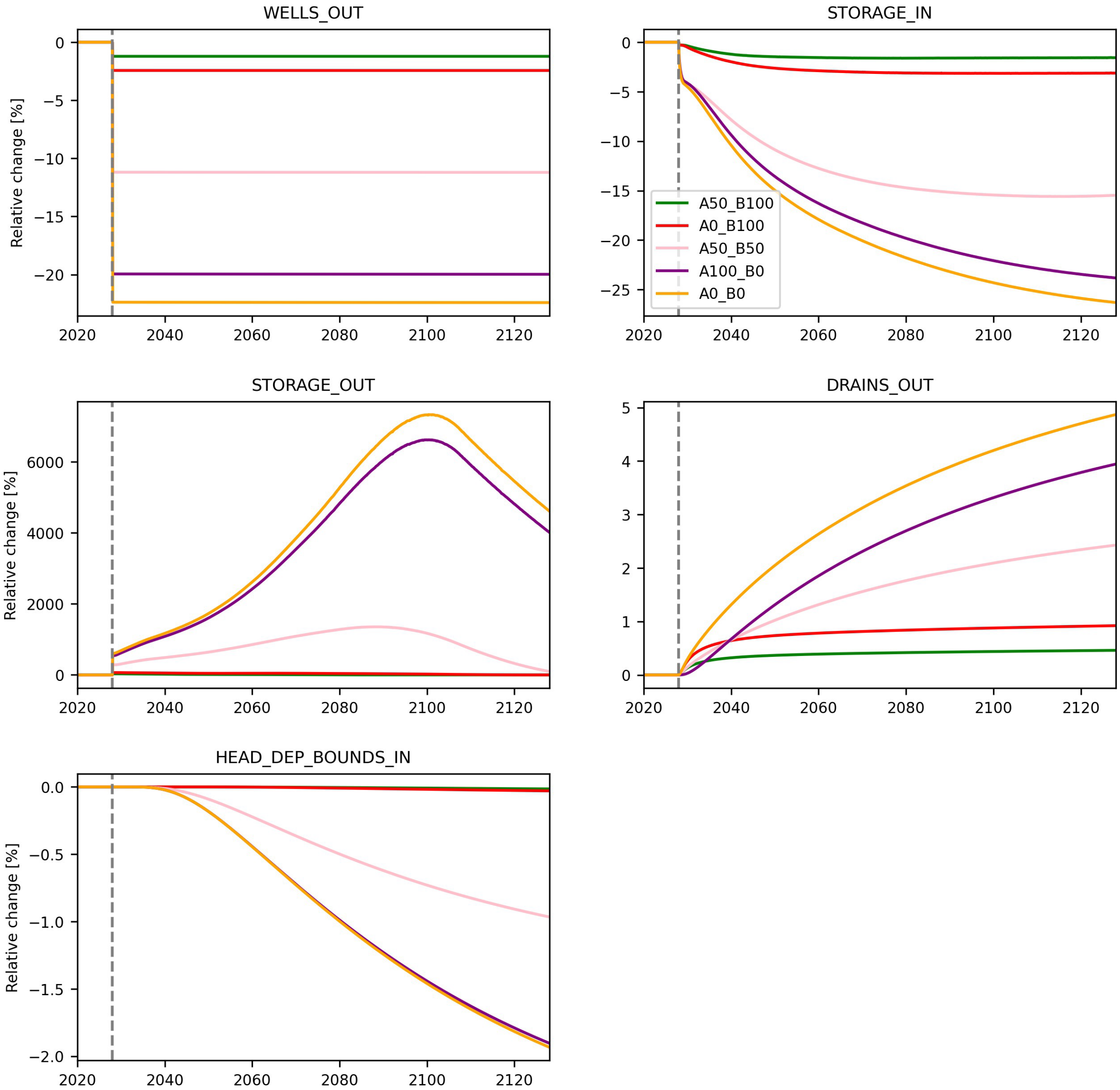

Figure 23. Comparison of the temporal evolution of the relative change in key components of the water balance for each of the scenarios as compared to the base case (A100_B100)

The cumulative volume from major water balance components for each of the six scenarios is shown in Figure 24.

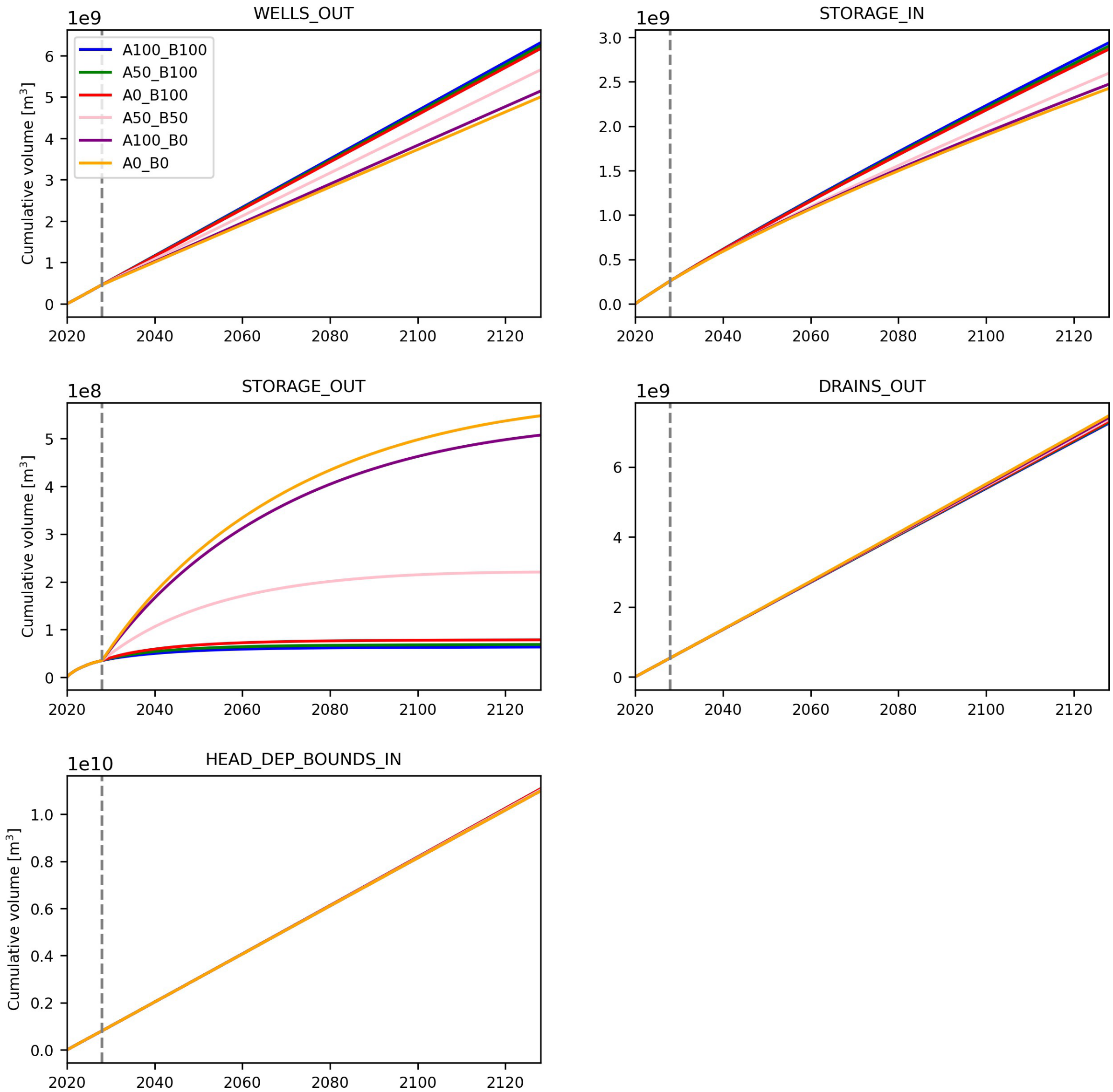

Figure 24. Temporal evolution of cumulative volume associated with major water balance components for each of the six scenarios.

Figure 25 shows the relative changes in cumulative volume from major water balance components for each of the six scenarios.

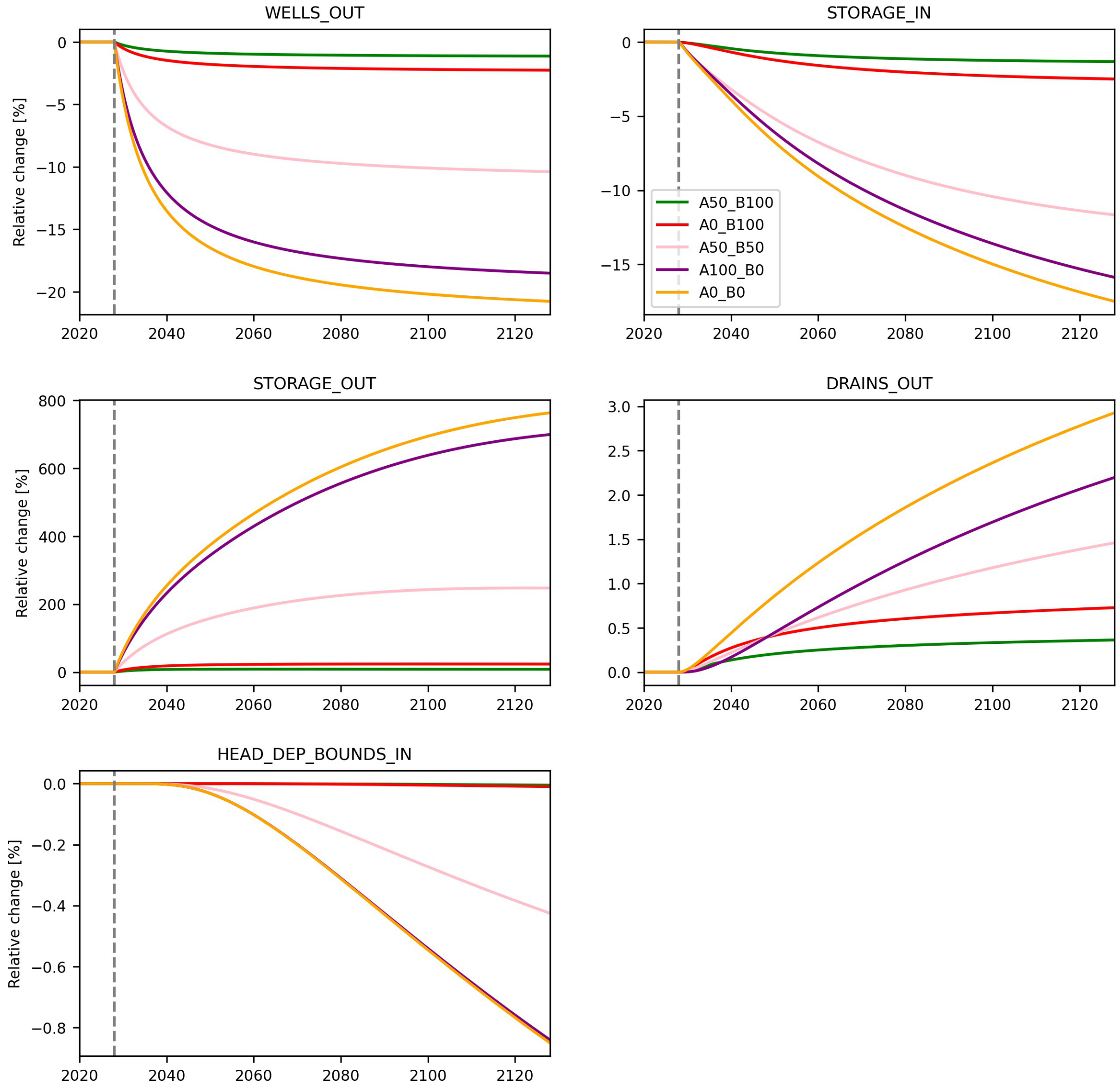

Figure 25. Temporal evolution of relative difference in cumulative volume associated with major water balance components for each of the six scenarios.

The change in head in the top layer of the model relative to the base case (A100_B100) in each of the other five scenarios is shown at 30 years (Figure 26) and 100 years (Figure 27) after abstraction changes take place in 2028. As the total abstractions decrease, the increase in heads relative to the base case also becomes greater, as expected. In both the A50_B100 and A0_B100, the zone of influence of head increases is mostly limited to Wellfield A, even at 100 years. In the other three scenarios, the reductions in Wellfield B abstraction are seen to have a larger area of influence on the increased head, which expands into the entire northern part of the model at 100 years.

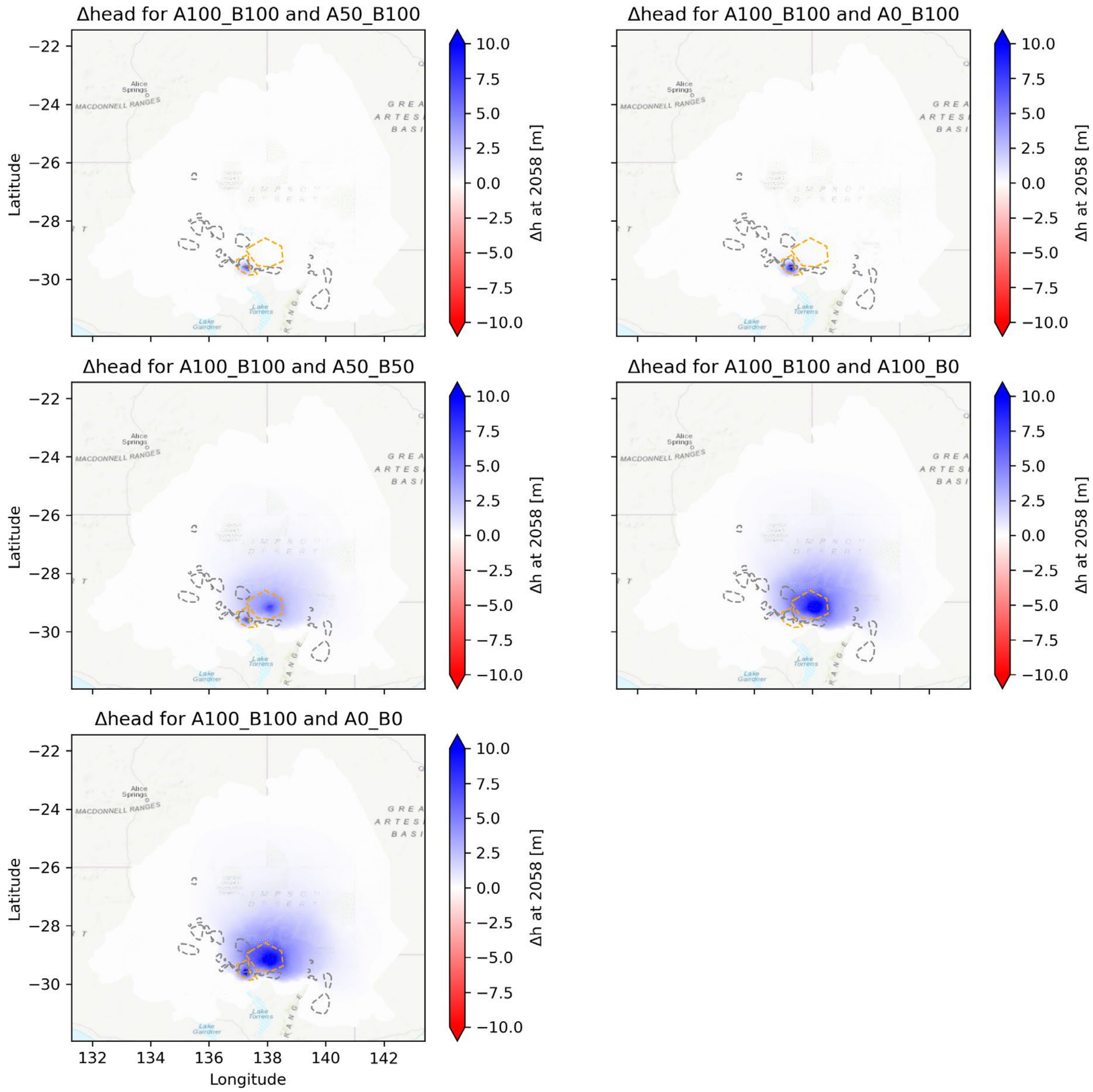

Figure 26. Difference in head between the base case and the five other scenarios 30 years after the abstraction changes in 2028.

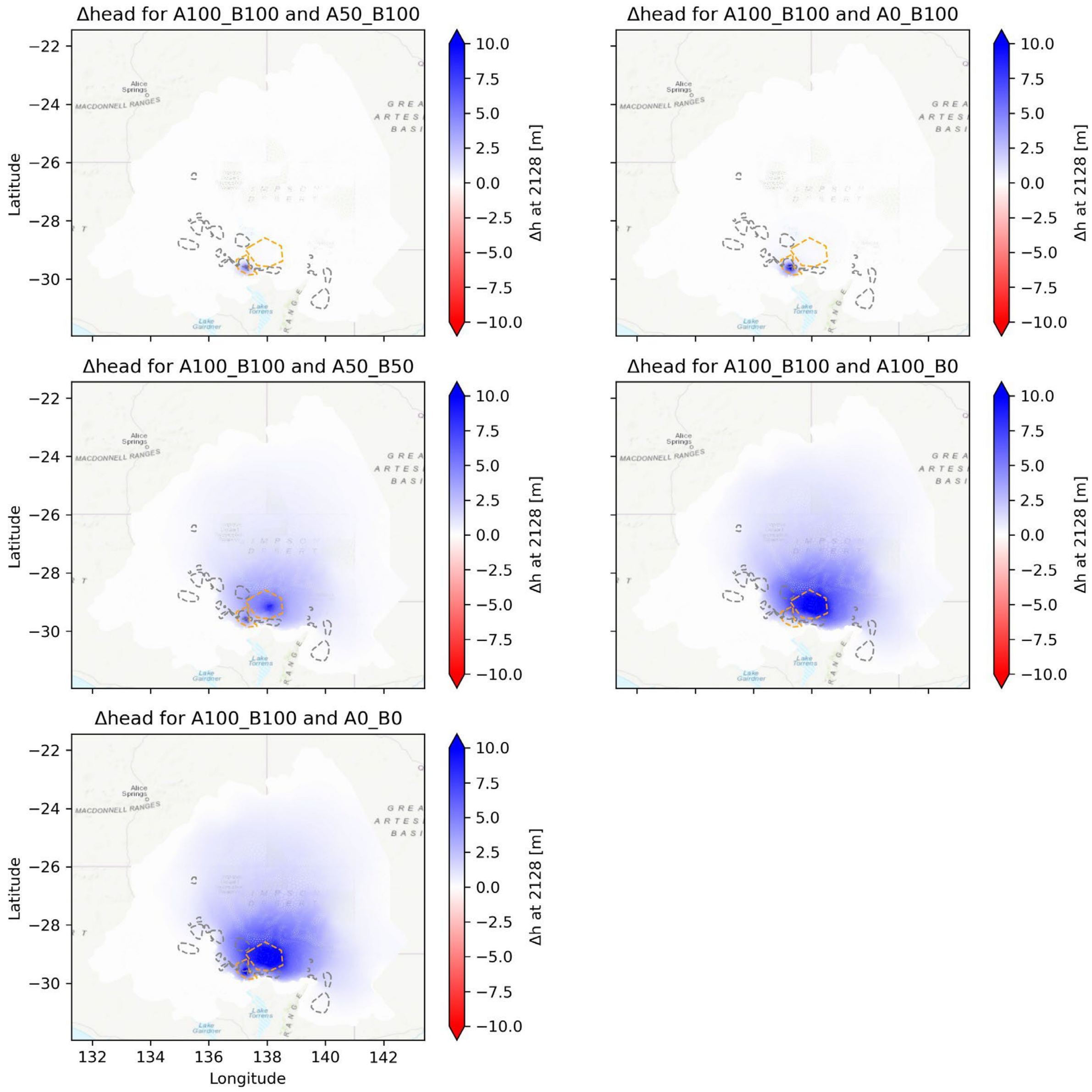

Figure 27. Difference in head between the base case and the five other scenarios 100 years after the abstraction changes in 2028.

3.7.2 Spring complexes analysis

Spring s have been classified into a hierarchy consisting of spring vents, groups, complexes and supergroups. Spring vents are clustered into groups that share similar water chemistry and related to common geological features. These groups then form clusters that share a similar geomorphological setting and are referred to as “spring complexes”. Clusters of spring complexes are referred to as supergroups. The Allocating Water and Maintaining Springs in the Great Artesian Basin (AWMSGAB) Project identified the spring group as the scale for which effective management of springs can take place.

For each of the scenarios the spring complex level of analysis provides a local view of changes to abstraction as compared to the global analysis presented previously. Full time series of mean spring complex head (Figure 28) and total spring complex discharge (based on linear relation of head-discharge assumption, Figure 29) show the divergences in head and associated discharge for each of the spring complexes across the six scenarios (refer to Figure 16 for location of spring complexes).

At the Dalhousie Spring Group, head decreases are seen for all scenarios until around 2040 when divergence of the head response between scenarios is apparent as the effects of changes to abstraction in Wellfields A and B reach this northern spring group. At the point of divergence between scenarios, A100_B0 and A0_B0 show increasing head trends while the other four scenarios all show decreasing trends. A similar pattern to the Dalhousie Spring Group is seen for Neales River, which has a near-neutral head evolution until 2040 for all scenarios.

Similar patterns in head response across scenarios were evident at Francis Swamp, Strangways, Billa Kalina, Beresford Hill and Coward Springs, with a clear separation of head response between scenarios.

Peake Creek, Mt Toondina, Mt Dutton, and Mt Denison have similar head evolutions for each of the scenarios. All scenarios showed an increase in head for the first 20 years, but then in A100_B100, A50_B100, and A0_B100, heads declined for the rest of the simulation. Scenarios A50_B50, A100_B0, and A0_B0 all showed increasing head, with a plateau seen for A50_B50.

Lake Eyre South and Hermit Hill, located in the Wellfield A region, show a response to abstraction changes from Wellfield A with a unique pattern of head changes compared to all other spring complexes. Firstly, in scenario A0_B100, there is the second highest increase in head, and A100_B0 leads to head increases below many other scenarios, only larger than the base case for the first 20 years in Lake Eyre South and for all of the simulations in Hermit Hill.

Marree, Lake Blanche, Reedy, Petermorra, and Lake Callabonna all show similar patterns of head evolution. In scenarios A0_B0 and A100_B0 heads continue to increase but plateau out towards the end. In scenario A50_B50, head gradually declines after an initial increase in the first decades. In scenarios A100_B100 and A50_B100 a clear linear decline in head is seen. Lake Cadibarrawirracanna and Lake Frome spring complexes exhibit minor, centimetre scale, declines in head across all scenarios, while the Mt Margaret spring complex shows no change.

The relationship between the spatial mean of heads and total spring discharge at the spring complex level is shown in Figure 30. For most spring complexes this modelled relationship is linear, which is to be expected if changes in head across a spring complex are similar and the specified drain conductance are the same. Francis Swamp and Marree show slight deviations from a linear relationship, but it is not considered significant. The largest deviations from a linear relationship are seen at Neales River, Lake Eyre South, Hermit Hill and Wangianna, which can be attributed to temporal and scenario variations in the head distribution, e.g., different head distributions across a spring complex can yield the same mean head but owing to drain boundary elevation and conductance differences across a spring complex can yield different total discharge as seen in Neales River spring complex.

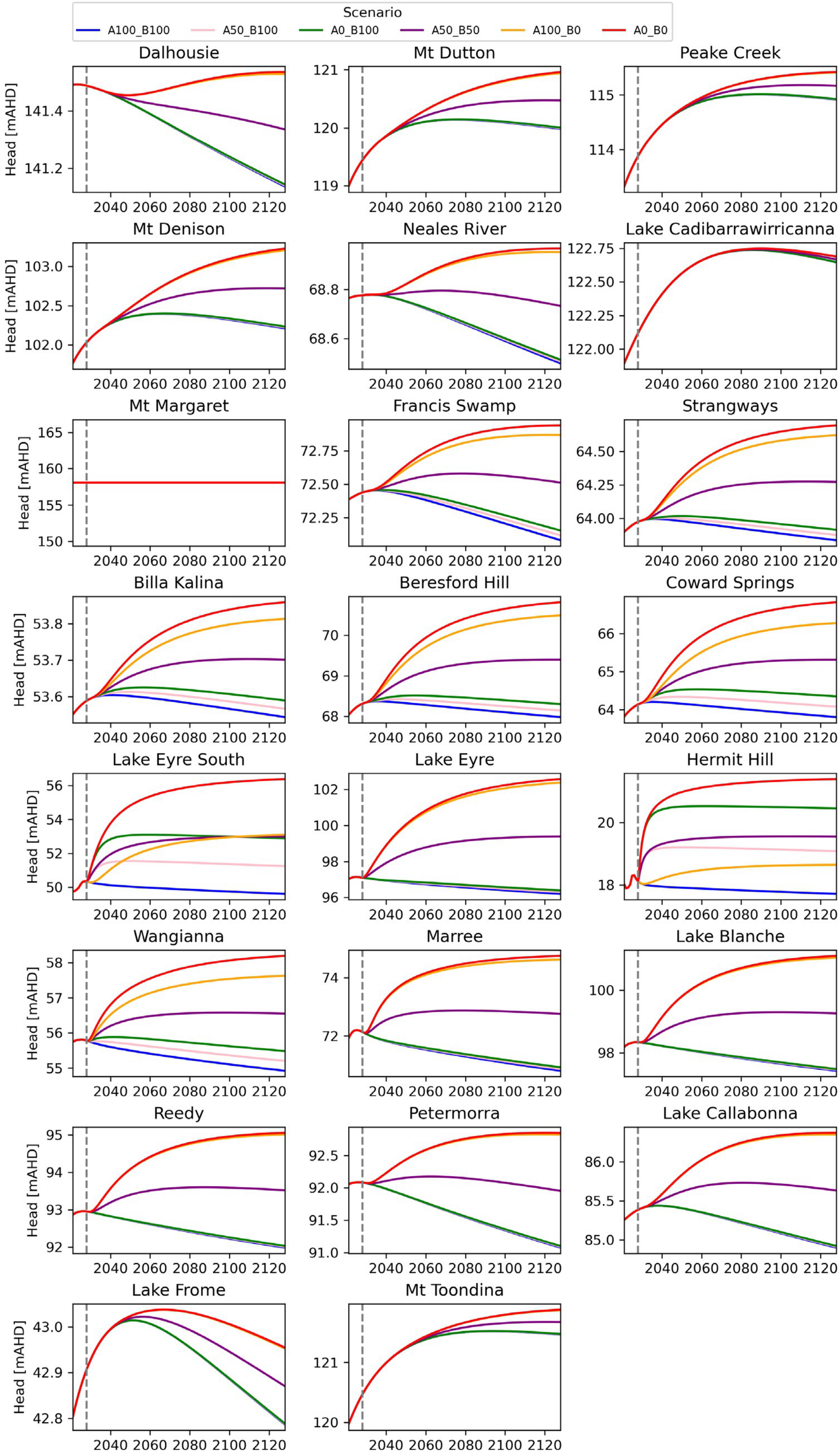

Figure 28. Evolution of the mean head in spring complexes for each of the six scenarios.

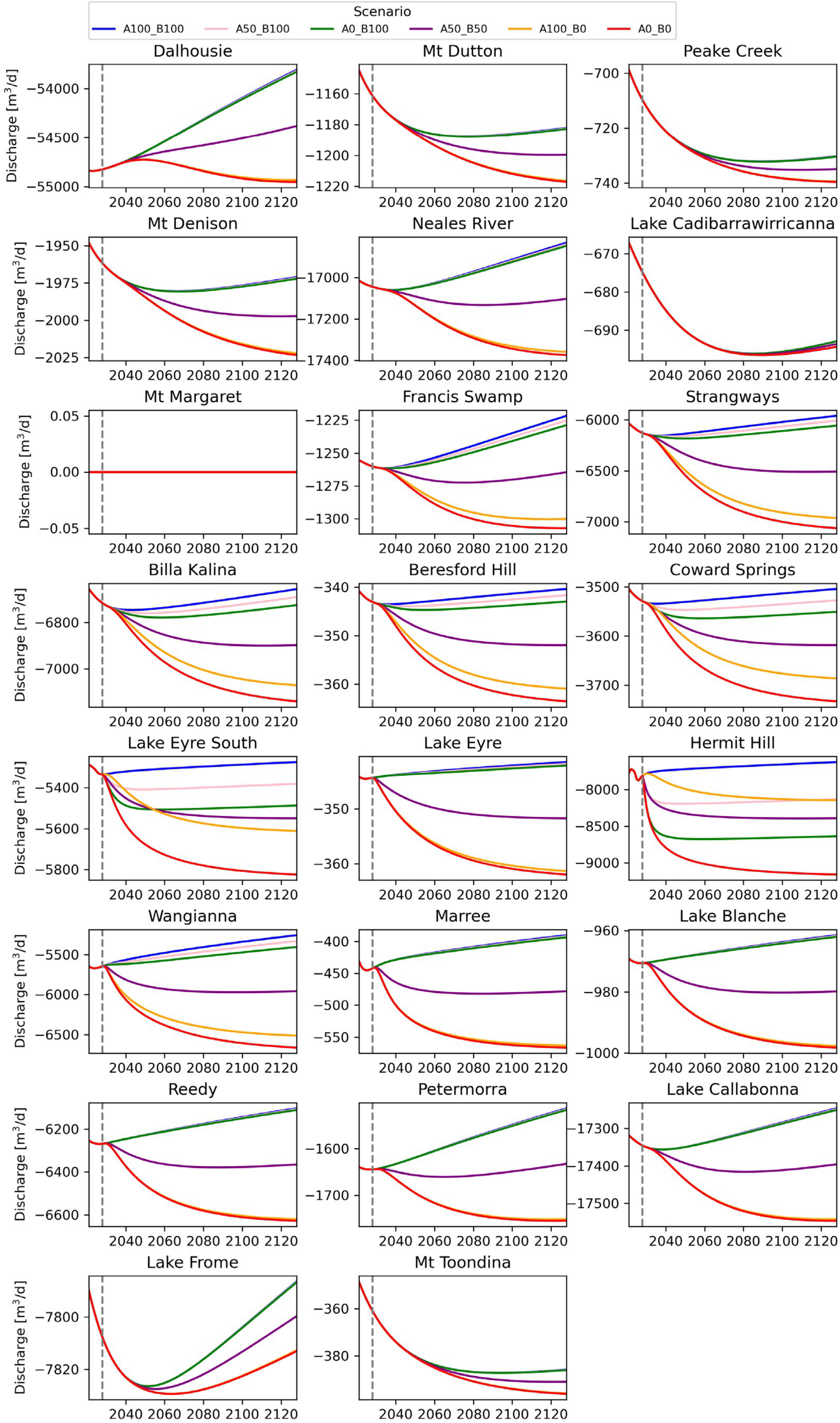

Figure 29. Evolution of the total discharge at spring complexes for each of the six scenarios.

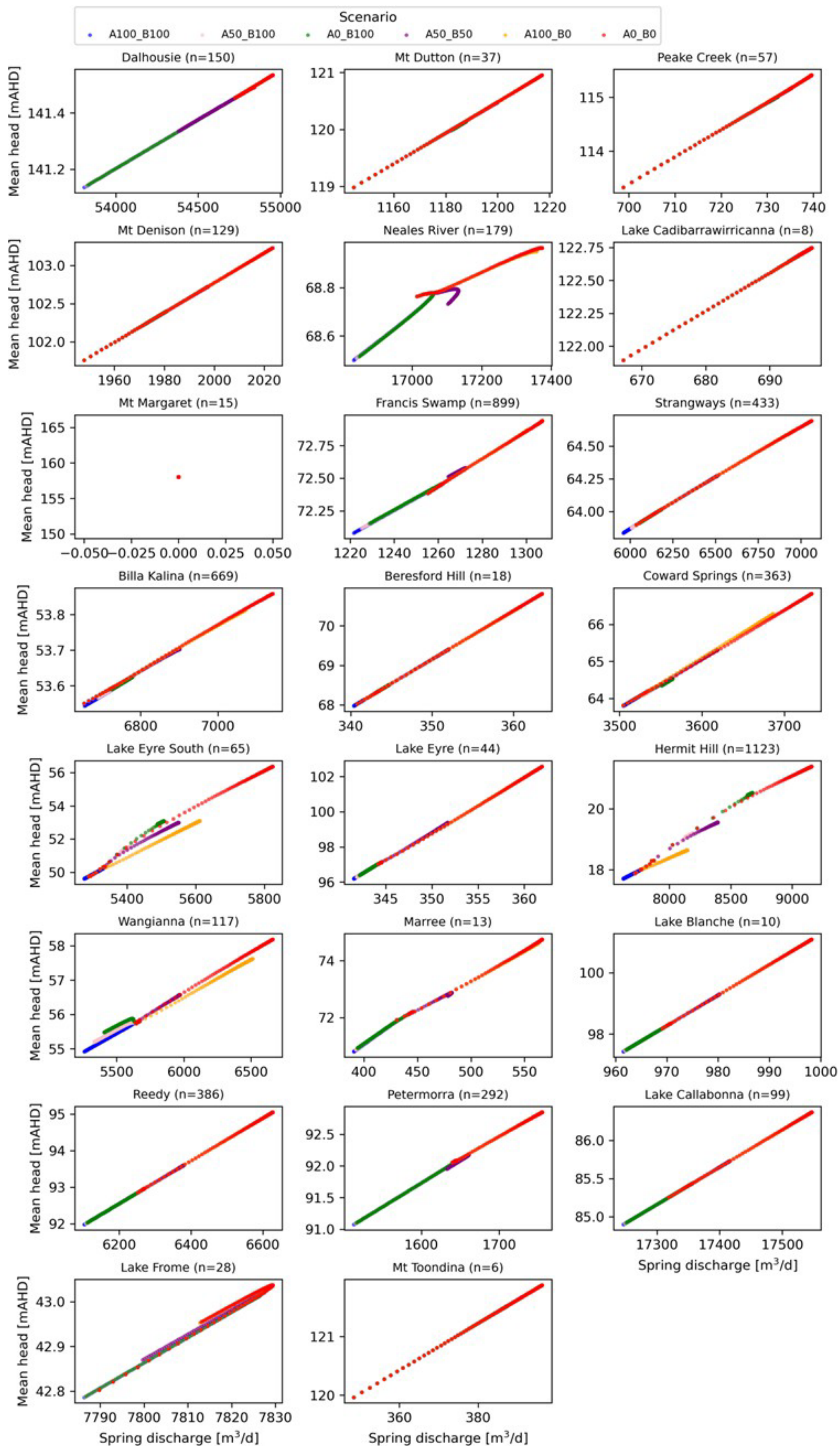

Figure 30 Relationship of mean head to total discharge at the spring complex level for each of the spring complexes and each of the six scenarios.

Figure 31 and Figure 32 demonstrate changes in head and discharge at the spring complexes 10 years after abstraction changes for in the base case (A100_B100) and the biggest reductions in abstraction (A0_B0). The average head changes in the spring complexes show both small increases and decreases (-0.4 to 0.4 m) after

10 years in the base case whereas in the maximum reduced abstraction case of A0_B0, the head appears to be increasing everywhere although a few spring complexes appear neutral, i.e. show very little change.

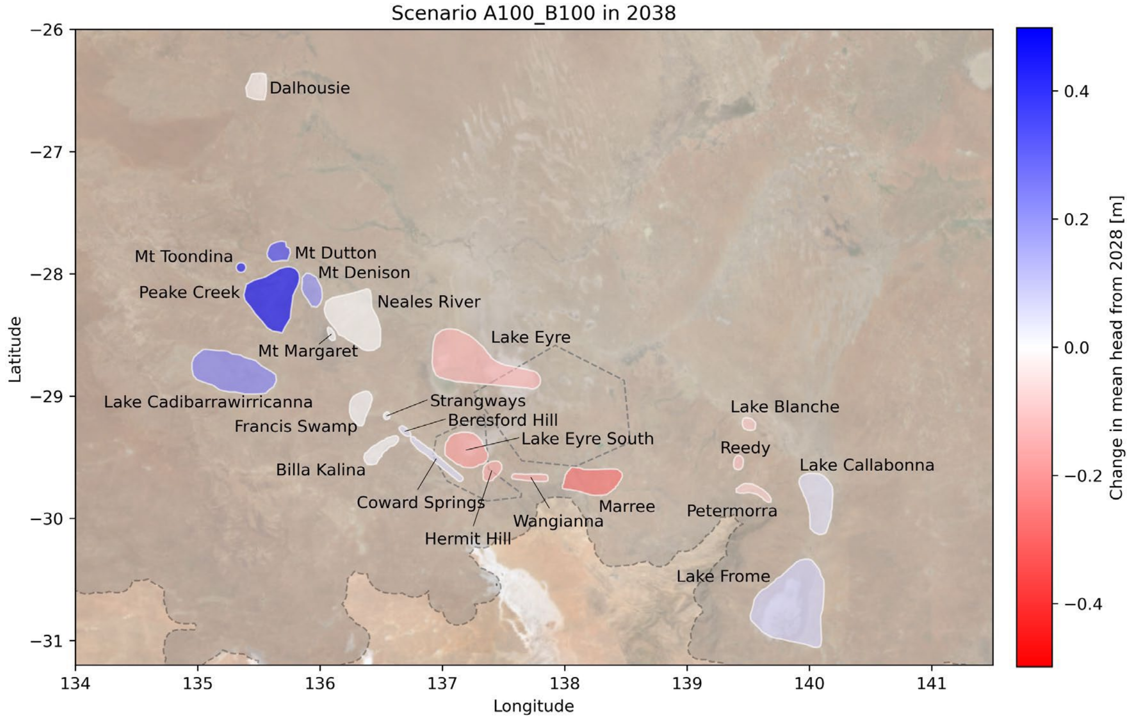

Figure 31. Change in mean head between 2028 and 2038 (10 years after abstraction change) for A100_B100

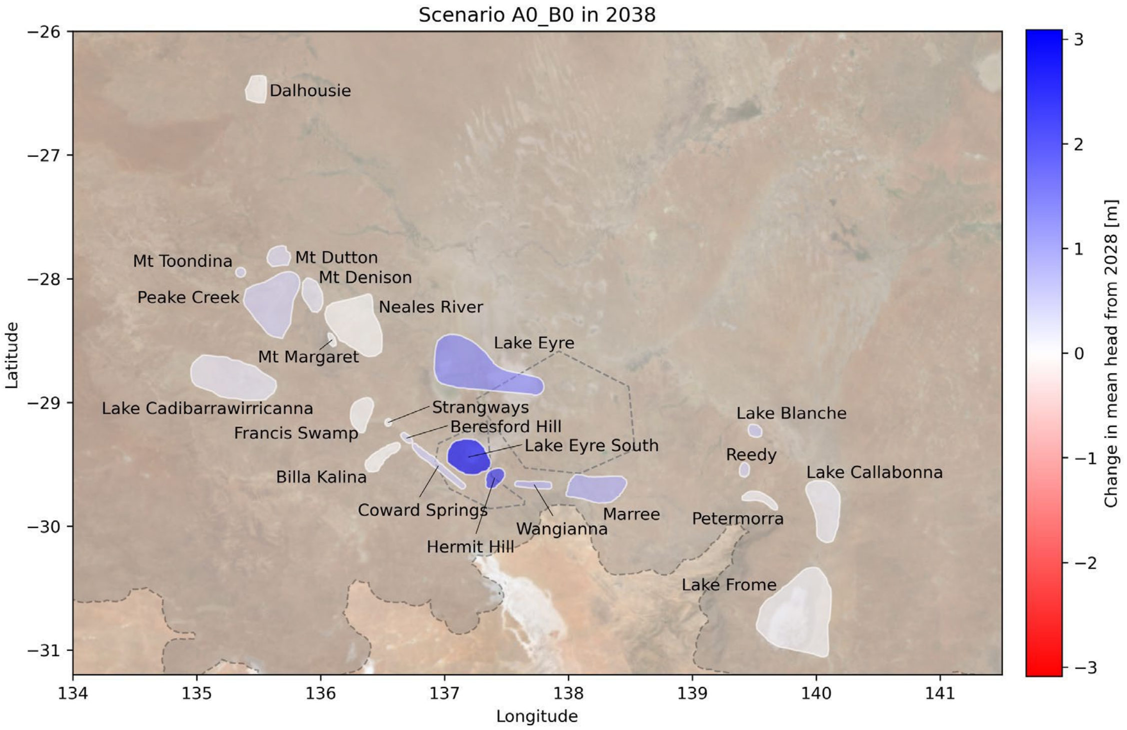

Figure 32 Change in mean head between 2028 and 2038 (10 years after abstraction change) for A0_B0

4 Discussion and Limitations

Previous work has indicated that the groundwater system is in a constant transient state due to climate change over geological time scales (Rousseau-Gueutin *et al*., 2013). Numerical modelling has demonstrated that superimposed on these long-term climate changes that the hydraulics of the groundwater system in more recent time are also in a transient state. This recent perturbation is due to groundwater abstraction (declining heads) and capping and piping programs (recovering heads) as well as a myriad of other drivers.

In all modelling scenarios that involved a reduction in abstraction an observed increase in hydraulic head (aquifer pressure) occurred over time. The largest rise in head occurred near the two wellfields A and B. In terms of water balance fluxes this tended to stabilise after 2040 with only minor gradual changes thereafter.

At the spring complex level there was evidence of both reductions and increases to hydraulic head and spring discharge under differing scenarios. Even under continued 100% abstraction at both wellfields pressure recovery was modelled at several spring complexes. This most likely occurs due to the reduction of uncontrolled bore discharge through capping and piping programs. Owing to the vicinity of Wellfield A to nearby spring complexes, large head and consequent spring discharge increases were modelled for all scenarios that reduced Wellfield A abstraction scenarios. The six scenarios simulated were carried out in a deterministic manner in order to gain insight into head and spring responses due to abstraction change. However, the conceptualisation governing flow through the Far North model are uncertain and as such the simulated head and spring discharge response are also uncertain. While it is beyond the scope of this study, the uncertainty of simulated head and spring discharge could be explored if future access is provided to the PEST control file and outputs produced during the model calibration (DEW, 2023g), especially the model Jacobian which shows the sensitivity of each model output (e.g. spring discharge) to each model parameter (e.g. hydraulic conductivity). The Jacobian matrix along with the PEST control file can be utilised to rapidly explore this uncertainty with linear uncertainty analysis.

Importantly, a review of the relationship between aquifer pressure head and spring flow rate has not been completed for this report. The Far North model assumes a linear relationship between change in the hydraulic head of the aquifer adjacent to a spring and the spring flow rate. However, this may not be the case and requires further investigation. As such, we are unable to provide comment as to whether the model can provide reliable predictions. Additionally, the Far North model was conditioned to historical hydraulic head and spring flow rates up until 2017-2018 and could benefit from an updated calibration with more recent data. There are some limitations on how the model represents springs. The Far North model represents springs using the MODFLOW-USG Drain (DRN) package and varies the head to flow relationship using a conductance term (Darcian flow). The drains were set at the average elevation of spring vents occurring within a model cell. When water gets to this level and above it is simply removed from the system proportionally with the change in head. There are some 5,356 spring vents within the South Australian portion of the GAB that have been represented by 1,270 drainage nodes within the modelled extent, indicating that the drainage nodes have clumped many springs.

However, this is an imprecise representation of GAB springs. As a result, any output from the model in terms of spring flow from individual vents or spring complexes can either be taken as an approximation only with a large degree of variation or to be in some cases in total error. Field work conducted by Green and Berens (2013) showed that there was no correlation between spring flow and excess head. At many spring complexes multiple spring vents occur that have a variety of flows from damp patches to litres per second. This is because the physics of the relationship between aquifer head pressure and spring flow rate is not well understood and is not well represented by a drain package. The spring conduit from the aquifer to the surface is likely to have a coalescing pattern (tortuosity/flow path) with uncertain spring aperture, roughness, and flow velocity. An undetermined amount of these conduits may not obey Darcys Law but instead display non-Darcian flow conditions (Bear *et al.,* 1993; Ni *et al*., 2018) and thus render the modelled spring flow predictions invalid at these locations.

Further, our conceptualisation of system response to increasing aquifer pressure at and near the springs may also limit the accuracy of predictions. We do not understand the behaviour and relative contributions between point and diffuse discharge.

Spring flow data was honoured during the calibration where reasonable and practicable to do so, although such instances where there was sufficient data to enable this were very limited. Key areas where this was undertaken was the Dalhousie Spring complex, where the model was calibrated so the total estimated flow rate from the entire complex was respected, as well as in the Kati Thanda-Lake Eyre South region. Where there was no target flow data, or where springs were required to be treated in aggregate, calibrating the model to spring flow was either impossible or very approximate. Further, where temporal flow data was available, a comparison of measured and simulated flow was undertaken to ensure model outputs were realistic. Finally, the regional scale of the model renders assessment of local spring flow variability impossible.

5 Conclusions and Recommendations

As per the aims and objectives of the project we conclude the following:

The current conceptualisation of the hydrogeology requires further understanding in relationship to the hydraulic behaviour of the aquifer and the emergence and cessation of springs as well as spring flow rate and associated wetland extent. The literature review has highlighted that in some cases that there is not a linear relationship between hydraulic head and spring flow rates. The importance of spring switching was highlighted with an example from Wabdu Kadabu.

This project originally planned to review the relationship between observed hydraulic head and spring flow. Notwithstanding many uncertainties related to how representative individual spring flow observations are for entire spring groups, as well as the potential magnitude of hydraulic head measurement error; a review of the relationship between observed hydraulic head and spring flow would have better informed the appropriateness of the model for predicting head and spring flow under the six (6) scenarios. However, data limitations prevented this review from occurring.

Reducing abstraction from GAB aquifers (i.e., Wellfield A and/or Wellfield B examined here) will result in an increase in aquifer pressures. This increase in hydraulic head will likely propagate to the GAB springs.

As expected, overall, the five proposed scenarios of reductions to abstraction in Wellfield A and B all show benefits in the form of head increases across the model domain when compared to the base case. The extent of those head increases is more pronounced for larger reductions in total abstraction which corresponds to the scenarios reducing abstraction in Wellfield B (A0_B0, A100_B0, A50_B50).

Improved conceptualisation of groundwaters in the GAB will result in more accurate predictions of the hydraulic behaviour of the system. An improved sensitivity analyses to include the model Jacobian from the PEST calibration could be utilised to rapidly explore this uncertainty with linear uncertainty analysis. This will result in not only improved model output but also may show areas where improved field parameterisation is needed.

The model assumes that there is a direct relationship between aquifer pressure and spring flow such that an increase in aquifer pressure will result in an increase in spring flow, both at an individual vent and spring group level. However, this may not necessarily be the case. It is quite plausible that an increased aquifer pressure may result in an increase to the volume and rate of diffuse discharge occurring through the Bulldog Shale, which may or may not express to surface. Higher rates of diffuse discharge express at surface has the potential for increased water logging and evaporation at the surface.

The interaction of pressure change within the general conduit and structural setting of spring complexes is difficult to ascertain. Stability at current flow regimes and supporting pressures may have changed the form and capacity of spring vent conduits such that the change or location of spring flow in reaction to increasing artesian pressure will likely be unpredictable. Pressure increases may result in new springs forming, or widening of spring conduits at some spring complexes, but this may result in a concomitant decrease in flow at other springs. Thus, there may be no guarantee that individual springs with high conservation value (endemic species etc. conservation ranking 1-3) or cultural significance will have improved spring flow outcomes due to reduced abstraction. Likewise, there will be no guarantee that springs that have previously ceased to flow will be reactivated along the same spring conduit. Conversely, at a regional scale, decreasing artesian pressure has long been interpreted as a primary risk to spring environments and thus increasing this supporting pressure may lead to a general increase in the robustness of such environments.

5.1 Recommendations

1. Review timeseries hydraulic head vs spring flow data to inform the conceptual understanding that underpins the numerical model. Specifically, review spring flow and head data from 2019-2023 to comment on appropriateness of the DEW model to make these predictions including assessing the assumed 1:1 relationship.
2. Re-calibrate the DEW model to new data (from the assessment in Recommendation 1)
3. Undertake a detailed sensitivity and uncertainty analysis of spring flow predictions to improve confidence in results and indicate areas for future parametrisation.
4. Develop and implement bore and spring monitoring strategies.
5. Obtain a greater understanding on First Nation people's knowledge of springs in particular in regard to spring emergence and cessation and spring wetland extent.
6. The most important recommendation is to implement field studies to obtain a greater hydrogeological understanding of the relationship between hydraulic head and spring flow rate. This would include but is not limited to a study on spring switching as well as a small-scale field trial with associated numerical modelling experiments to improve our understanding of the architecture of spring discharge including spring flow and hydraulic head. These are key knowledge gaps that when addressed will provide more reliable outputs and reduce the risk associated with spring switching to the environment and First Nation people.

6 Glossary

GAB	Great Artesian Basin
Far North model	Far North Groundwater Model
MODFLOW	Numerical groundwater modelling package
GWV	Groundwater Vistas, commercial GUI for MODFLOW models
FloPy	Python package for MODFLOW models
WEL	Well package for MODFLOW
SGB	Specified Gradient Boundary package for MODFLOW-USG
DRN	Drain package for MODFLOW
RCH	Recharge package for MODFLOW
GHB	General Head Boundary package for MODFLOW
CHD	Constant head boundary package for MODFLOW
RMSE	Root Mean Square Error model fit metric
R^2	Coefficient of determination model fit metric
RECHARGE_IN	Recharge inflow to a MODFLOW model
DRAINS_OUT	Discharge to drains in a MODFLOW model
STORAGE_IN	Inflow release from storage in MODFLOW model
STORAGE_OUT	Outflow of water going into storage in MODFLOW model
WELLS_OUT	Abstraction of water out of MODFLOW model
HEAD_DEP_BOUNDS_IN	Inflow from a head dependent boundary to MODFLOW model
HEAD_DEP_BOUNDS_OUT	Outflow to a head dependent boundary from a MODFLOW model
SGB_CELLS_IN	Inflow from a specified gradient boundary in a MODFLOW model

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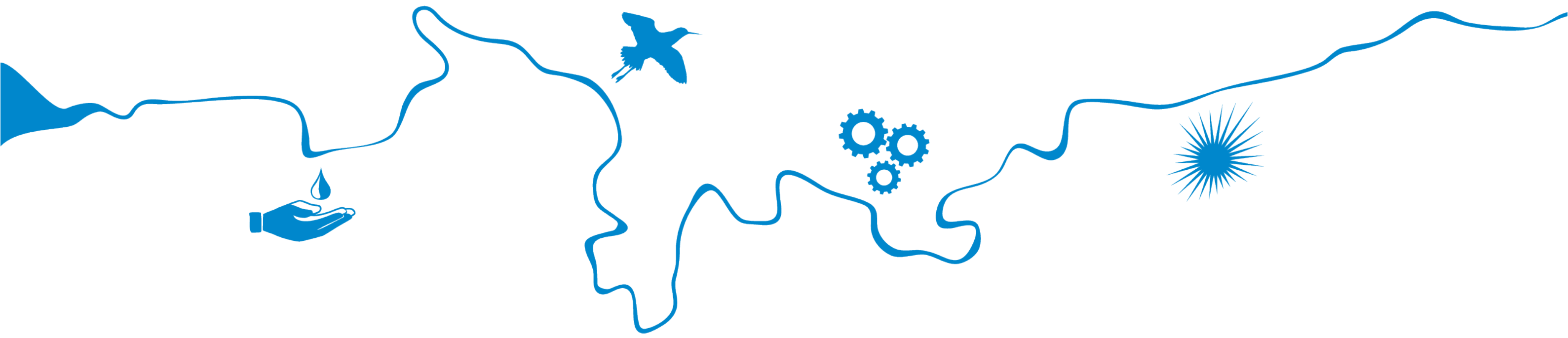

The Goyder Institute for Water Research is a research alliance between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide and the University of South Australia.