THE UNIVERSITY OF WESTERN AUSTRALIA

Review of Wattle Grove Water Balance, Environmental Review Document, and District Water Management Strategy

Sally Thompson

The University of Western Australia
M004 Perth WA 6009 Australia

Executive Summary

The Wattle Grove South area lies in proximity to the ecologically valuable Greater Brixton Street Wetlands (GBSW) and is proposed to be rezoned from rural to urban.

This review covers 3 hydrological management documents for the proposed rezoning / development: the Water Balance Assessment (WBA, Emerge Associates (2024)), District Water Management Strategy (DWMS, hyd2o Hydrology (2024)), and Environmental Review Document (ERD, Coterra Environment et al. (2024)).

Comments are firstly general and then address details of hydrological assumptions and conclusions reached in the WBA, DWMS and ERD. The study site is referred to as the Amendment Area or AA.

No.	Finding	Recommendation
General Comments		
1.	Standard urban water planning methods, applied to specific project areas, risk failing to protect the GBSW. This comment is general, not specific to the Wattle Grove South rezoning.	Consider creating, testing and adopting GBSW-centric management tools. A 2 or 3 dimensional, fully distributed surface x groundwater and nutrient/solute transport model of the GBSW, in conjunction with vegetation mapping and vulnerability assessments, would be especially valuable.
2.	Hydrological processes sustaining the GBSW, their temporal and spatial heterogeneity and connection to GBSW environmental values (esp. biodiversity) remain incompletely understood.	Avoid strong assertions about GBSW hydrology. Strong assertions made about GBSW processes in the WBA, DWMS and ERD are not supported by consensus understanding of the GBSW hydrology and its relation to the wetland's ecological values. Continue and extend hydrological monitoring of GBSW and surrounding areas under supervision of a specialist hydrologist. Develop a conceptual model of GBSW processes and function to guide decision-making, with relevant agencies and stakeholders.

3.	The groundwater catchment for the GBSW is not understood, which means that investigations of groundwater flow are truncated by the boundary of the AA, not by an analysis of whether flow from the AA could travel to the GBSW once it leaves the AA.	Consolidate all recent monitoring datasets in the GBSW region and build a single regional groundwater surface map. Use this map to trace flow nets and define the GBSW groundwater catchment.
4.	Hydrological fluxes (groundwater or surface water) entering GBSW should not be evaluated as a % of total GSBW water budget, due to the distributed and heterogeneous nature of the GSBW and the risk that localized changes could impact biodiversity.	Evaluate the importance of hydrological fluxes and changes to these fluxes for GSBW in terms of how GSBW processes and biodiversity depend on those surface or groundwater fluxes. This dependence could be highly localized due to the heterogeneous nature of the GSBW. A quantitative and distributed model (point 1) would best facilitate such evaluation.
Comments on WBA and DWMS assumptions/methods		
5.	The assumption that the existing groundwater mound below the turf farm should be maintained merits further consideration	Evaluate impact to groundwater flow if mound not maintained, and how this influences risks / impacts to GBSW. Back of the envelope calculations suggest throughflow would increase by an approximate factor of 4 if mound were not maintained (see responses to Table 1 questions for calculation details). Consider alternative hydrological futures for GBSW, e.g. restoration of surface flows via previous Crystal Brook tributary.
6.	Groundwater calculations use static groundwater levels and gradients, which may misrepresent groundwater throughflow in a seasonally dynamic environment	Repeat WBA throughflow analysis with temporally resolved groundwater levels. Include assessment of changing shape and gradient of the groundwater mound if seasonally maintained through stormwater infiltration. Back of the envelope calculations suggest that seasonal fluctuations in water level would change from approx.

		20% to approx. 80% under proposed seasonal infiltration (see responses to Table 1 questions for information about approach used, noting that it is a very preliminary calculation used only to broadly assess sensitivity).
7.	No uncertainty / sensitivity analysis has been undertaken	Undertake a sensitivity analysis with respect to uncertain hydrological parameters, e.g. K_{sat}, initial losses (IL), continuing losses (CL), recharge estimates.
8.	Minor issues with rainfall dataset and recharge estimates identified	Check consistency between Jandakot and Gosnells rainfall data for 2010-2019 period. Re-estimate recharge using latest data from Gelsinari et al 2024 (and Recharge Estimation Collaboration / Recharge in a Changing Climate project outcomes, available from DWER, see https://www.wa.gov.au/service/natural-resources/water-resources/recharge-estimation-collaboration-project), not solely PRAMS estimates.
Comments on conclusions regarding environmental impacts		
9.	The small proportion of the whole GBSW water balance derived from the AA does not imply that changes to fluxes from the AA have a negligible impact on the GBSW.	See point 3 above.
10.	While urban development is likely to reduce nutrient inputs to the AA, the conclusion that it will reduce nutrient loading to the GBSW is speculative.	No action needed as development is unlikely to worsen loadings. Monitoring and adaptive management as recommended in the DWMS are appropriate responses.
11.	Installation of water treatment measures (e.g. bioswales) to improve surface water quality, and opportunities to supplement GBSW inflows with water derived from the AA under a drying climate are valuable and welcome additions to the DWMS.	No action needed.
Comments on sufficiency of environmental mitigation measures		

12.	Excluding the questions re. maintenance of the groundwater mound and dependencies between the GBSW and offsite areas, the environmental mitigation measures proposed are likely to be sufficient to manage onsite waters and minimise offsite impacts.	Implement the monitoring plan and best practice Water Sensitive Urban Design principles within the AA.
Additional mitigation measures		
13.	Develop a model of GBSW function that can be used to better evaluate offsite impacts on wetland function, biodiversity and health.	As per points 1 and 8.
14.	The groundwater flow direction south-west of the AA is poorly documented in the ERD, WBA and DWMS, but may impact understanding of groundwater connectivity between the amendment area and GBSW.	Extend groundwater data in the analysis to the area down-gradient of the AA.
15.	The information presented about the perched groundwater is confusing and may require further elaboration.	WBA figure 9 is confusing – contours seem unrelated to groundwater depths, and locations of bores used to form contours are not shown. Consider clarification of the assumptions and understanding of the perched system.
16.	The GBSW is a prime candidate for hydrological adaptation measures to support biodiversity in a drying climate. One option would be to restore flow in the former Crystal Brook tributary, which passes through the AA.	Develop a GBSW working group to consider hydrological futures for the wetland and how DWMSs can be devised that maintain flexibility for different hydrological restoration options.

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1 Introduction

This report was prepared for the Department of Water and Environmental Regulation (DWER) by Associate Professor Sally Thompson based on a review of the Water Balance Assessment (WBA, Emerge Associates (2024)), District Water Management Strategy (DWMS, hyd2o Hydrology (2024)), and Environmental Review Document (ERD, Coterra Environment et al. (2024)) and supporting technical reports, for the proposed rezoning of the Wattle Grove South area (the Amendment Area, AA).

The report firstly summarizes known information about hydrology of the Greater Brixton Street Wetlands (GBSW) and the relationship between the environmental values of the site and that hydrology. It then reviews the documents above and their conclusions, before presenting responses to specific questions posed by DWER.

2 Greater Brixton Street Wetlands

The Greater Brixton Street Wetlands are recognized as one of the most important sites for biodiversity remaining in the Swan Coastal Plain and Greater Perth area. Their key environmental value lies in the diversity of vegetation within the wetlands, with over 650 species identified, among multiple different, often hydrologically and geomorphologically differentiated, vegetation communities (Environmental Protection Authority, 2022).

The hydrological functioning of the wetlands underpins both the diversity and distribution of vegetation communities, as well as providing specific conditions for individual species to thrive. The connection between hydrology and ecological function remains poorly elucidated across the range of conditions and species present in the wetlands. Examples include that most, possibly all, vegetation communities present in the wetlands are considered to have some level of groundwater dependence (Tauss et al., 2019); and the specific dependence of Spider Net Grevillea on high calcium concentrations within soil, with the high calcium levels that control its distribution likely provided from the superficial aquifer (Gao et al., 2020).

Considering the importance of the wetlands and the importance of wetland hydrology to their key environmental values, the hydrological processes that sustain the Greater Brixton Street Wetlands are distressingly opaque. Limited monitoring provides only weak constraints on understanding hydrological processes in the wetlands (Bourke, 2017) and their importance for maintaining biodiversity. Consequently, different reports consider the same datasets and make divergent conclusions, and often explicitly note that there is not enough data available to test and validate those conclusions.

This leaves a difficult environment for decision-making.

Examples of conflicting interpretations include:

(i) Connectivity between the Leederville aquifer and the superficial aquifer in the wetlands. Geological cores from nearby sites indicate that the Leederville is confined by shales and clays in the Osborne Formation (located 10 – 20 m below ground level, depending on surface dune-swale topography) (Bourke, 2017). Regional DWER mapping also suggests there is no connectivity in this region (Department of Water and Environmental Regulation, 2021). However, surveys identified an active mound spring in the area (Tauss, 2010), and the elevated salinity in the superficial aquifer in the region is consistent with connection with the Leederville (Environmental Protection Authority, 2022).

(ii) The degree of surface-groundwater connectivity within the wetlands. Many interpretations suggest the wetland blocks function as isolated surface watersheds, with perching of water on clay pans produced by surface flows (Bourke, 2017). Authors have interpreted rapid groundwater rise after rain as being due to perching over calcrete rather than rapid recharge of the superficial aquifer (Endemic Pty Ltd, 2012). Equivalence of water levels in surface and groundwater bores during wet periods, however, suggests some degree of connectivity, which more recent reports describe as being likely to be "substantial" (Bourke, 2017; Environmental Protection Authority, 2022).

(iii) The importance of lateral groundwater flow through the wetlands. The degree to which road construction around the wetlands has isolated the shallow groundwater systems within the wetlands from their surroundings has been conceptualized as nearly complete (Emerge Associates, 2024), through to sufficiently incomplete that the wetlands could be considered flow-through groundwater systems (Environmental Protection Authority, 2022).

These distinct interpretations lead to radically different interpretations as to how development in areas around the wetlands could impact the wetland hydrology.

For instance, in a "least connected" scenario, if the wetlands are disconnected from the Leederville aquifer, there is little surface-groundwater interaction, and surface and shallow subsurface flows are laterally disconnected by road construction, then each wetland bloc (separated by roads and surface drains from its surroundings) would effectively be an isolated catchment, with little hydrological dependence on its surroundings.

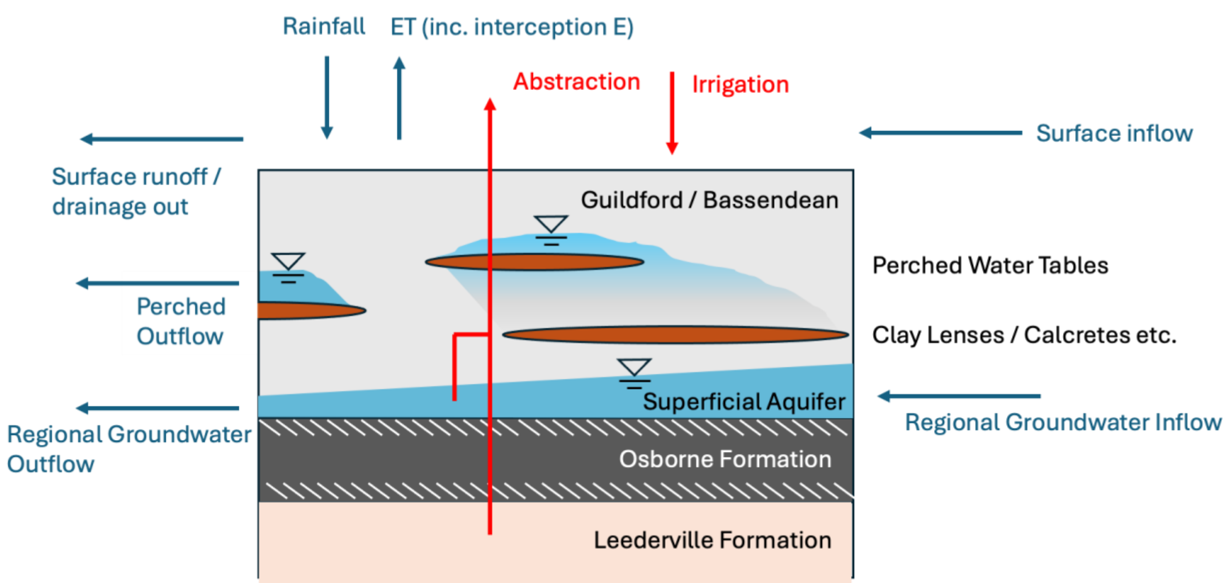
Conversely, in a "most connected" scenario, the wetlands may be substantially influenced not only on regional groundwater flow and quality, but also on local abstraction from deeper aquifers and the pressures achieved within them.

Beyond the difficulty of immediate planning decisions regarding the wetlands, it may be useful to observe that the high value of these wetlands makes them an attractive target not only for protection, but potentially for hydrological restoration (e.g. to maintain winter water levels and quality in a drying climate). Options for such restoration – which could e.g. include restoring the former Crystal Brook tributary to introduce surface flow to the wetlands – could be significantly curtailed by development in the surrounding areas.

While such considerations are not normally part of the water management strategy for urban development, the high value accorded these wetlands may justify taking a long-term view. Such a view would consider trends towards increasingly valuing urban greenspace and biodiversity and adopting climate-informed planning to protect such a biodiversity asset by maintaining flexibility in land use options in their vicinity.

3 Assumptions that underpin the Water Balance Assessment and District Water Management Strategy

An attempt to conceptually depict the water balance as developed for the AA visually is provided below. Black text refers to lithological/geological/hydrogeological features; blue text to non-anthropic water inflows and outflows included in the water balance, and red to anthropic flux terms.



The water balance is then conceptualized as the sum of all inflows minus all outflows being equal to the net change in storage (recharge) to the superficial aquifer.

3.1 Assumptions underpinning the DWMS

Most of the assumptions that underpin the DWMS are mirrored in the WBA or are addressed in the review of conclusions regarding environmental impact. However, the DWMS makes some additional assumptions, importantly:

3.1.1 Key hydrological mechanisms supporting GBSW

"The DWMS recognizes the key hydrological mechanisms supporting the GBSW area as detailed in previous hydrological studies are incident rainfall on the wetland itself and surface water flows."

This statement presumes greater certainty about the GBSW hydrological functioning than can be inferred from the current state of knowledge. As noted previously, there are indications of significant surface-groundwater interactions within the GBSW, and there is a lack of clarity as to the importance of regional groundwater flows for the GBSW hydrology.

Throughout the DWMS, GBSW hydrological sensitivity is viewed in the DWMS in a lumped sense – as if the wetland were a single bucket, where water inputs in one location can be treated as equivalent to those in another location. Two considerations mean this assumption should be questioned:

(i) The inputs being considered from the AA are at the upgradient end of GBSW wetlands, and may represent the major and only sources of inflow to those immediate localities, and
(ii) The GBSW is so highly biodiverse and ecologically heterogeneous, that changes to the hydrology in a localized area may have an outsized impact on environmental values.

3.1.2 The existing groundwater mound below the former turf farm should be regarded as the pre-existing hydrological condition and be maintained

While this assumption is in keeping with the wording of the EPA guidance, it is not necessarily in keeping with the *spirit* of such guidance. This assumption merits scrutiny, on the grounds that:

(i) The pre-existing condition is anthropic and based on imports of water from the Leederville.
(ii) The impact of the pre-existing condition on the GBSW, relative to a 'natural' condition, is unknown

Additionally, this assumption does not lead to the most low-risk approach to water management in the area. While it is possible that the proposed stormwater management could maintain the mound, is nonetheless speculative. Concerns arise, for example, how robust is the strategy to:

- Errors in assumptions,
- Climate change,
- Willingness to persist in the same management strategy long term, especially if e.g. pumping from the Leederville is required
- Large changes in seasonality of water inputs to the groundwater mound

It is recommended that further evaluation should consider:

(i) What would occur if the mound were not present? Specifically, how would flow volume and direction change, and would this alter evaluation of the impacts of AA water management on the GBSW?

(ii) How will large seasonal difference in water inputs at the location of the mound under pre- and post-development scenarios alter timing and volumes of groundwater flow away from the mound?

(iii) How will the change in water source in the mound, from the Leederville to stormwater, potentially alter the quality of water in the mound and water flow from the mound to the GBSW?

3.2 Assumptions underpinning the WBA

3.2.1 Inclusions/Exclusions

The terms included in the water balance are all reasonable.

Two terms are omitted from the water balance: perched water inflows to the AA, and any possible exchange (recharge or upflow) between the Leederville and superficial aquifer.

The exclusion of perched water inflows is based on the only evidence of perched layers occurring at the northwest of the AA (downgradient), with no evidence of perching at upgradient AA boundaries. This is *reasonable*.

Consensus in previous studies has not been reached regarding the likelihood or otherwise of connectivity between Leederville and Superficial aquifers in this area. While a confining unit is certainly present in the form of the Kardinya Shales, the potential that this unit thins or is bypassed, resulting in the springs observed by Tauss and the elevated salinity in the region, remains plausible. The complexity of the deep soil profiles obtained from geophysics offers little clarity about the nature of the subsurface. Thus, the reasonableness of excluding exchange between the Leederville and superficial aquifer *cannot be determined*.

3.2.2 Uncertainty

Computing any urban water balance is an uncertain task (Claydon et al., 2020). Physical data are often not available to describe the pre-development conditions. Models used are generally simplified, meaning that physical data that are available are usually not directly translatable into model parameters. Validation data are usually absent, particularly for difficult-to-measure properties like sheet runoff or evaporation. Future projections are necessarily best-estimates. These uncertainties apply to all urban water balance assessments and should be acknowledged in general. In this situation in particular, the uncertainties are potentially relevant to the risk that development of the AA would impact the GBSW and further investigation of the sensitivity of the findings to the specifics of parameter choices would be valuable.

It would be helpful to check the sensitivity of the findings to the specific values chosen. Below, specific terms that should be checked through sensitivity analysis are identified.

3.2.3 Quantification of water balance terms

3.2.3.1 Rainfall

Ten years (2010-2019) of half hourly rainfall data were used from the Jandakot aero weather station, in preference to the nearby Gosnells weather station which only offers daily data. Long-term climatology suggests very similar rainfall totals at each station. However, a comparison for 2010-2019 is difficult because of missing data and quality control issues. For those years where data are available, annual rainfall differs between Gosnells and Jandakot by as little as 3.8 mm/year in 2010 and as much as146 mm/year in 2019. For all years 2010-2019 where a comparison can be made, the Jandakot station overestimates annual rainfall relative to Gosnells by ~10%.

Recommendation: *Consider rescaling the Jandakot ½ hourly rainfall data for application to the study area and time.*

3.2.3.2 Rainfall interception

Interception estimates used are *reasonable* – e.g. recent measurements of interception in native banksia woodland indicate that the median event-based interception losses had an upper limit of 14% of rainfall (Gelsinari et al., 2024).

3.2.3.3 Irrigation

The water balance assumptions are that all allocated water in the study area is abstracted and reapplied to the study area, with the water allocation from the turf farm being sourced from the Leederville aquifer (i.e. outside the water balance control volume), and other allocated water being sourced from the superficial aquifer.

These assumptions are reasonable. In particular, the reasoning that suggests the turf farm is abstracting from the Leederville aquifer, based on the presence of an observed groundwater mound, is *reasonable*.

3.2.3.4 Upstream inflows

The delineation of upstream catchments through topographic analysis of LIDAR observations, and mapping of surface drainage and culvert features is *reasonable*.

The methodology used to compute the inflows is *standard*. It is, however, a nonlinear methodology. This can make the results quite sensitive to IL and CL values.
IL and CL are candidates for *sensitivity analysis*.

3.2.3.5 Surface water outflows

The same comments as for inflows.

Additionally, the choice to increase catchment-wide initial losses to account for infiltration within surface drainage infrastructure is questionable. The direction of this change – which will reduce runoff and increase infiltration – is appropriate. However, the timing and magnitude of resulting changes will be applied based on occurrence of storm events (rather than e.g. duration of inundation in stormwater infiltration basins), and will be applied across the whole catchment (rather than to the area of the catchment where stormwater infiltration occurs). Thus, the post-development IL parameter selection is also a useful candidate for *sensitivity analysis* – simply by re-running runoff computations across a reasonable range of plausible IL values and determining if the conclusions about the water balance are robust to the parameter choice.

A comparison of the effect of changes in runoff from the changes in IL to a back-of-the-envelope estimate of the infiltration fluxes from stormwater infrastructure would also be appropriate.

3.2.3.6 Evaporation

The WBA uses of PRAMS parameters for evaporation assessments. PRAMS is a valuable tool and using PRAMS parameters maintains consistency with regional modeling. However, PRAMS and the VFM, are currently under reassessment in terms of recharge predictions through the Recharge Estimation Collaboration and Recharge in a Changing Climate projects, bringing new information to light. For example, recharge of 38% below native vegetation may be too high for contemporary conditions – see Gelsinari et al. (2024), and also evaporation data from Banksia woodlands available through TERN Australia (https://portal.tern.org.au/metadata/TERN/b66d399a-8d40-4e68-a820-c2e06689ac8b). These data suggest ET from a banksia woodland varies from 466 mm/year – 667 mm/year, with annual recharge varying from 0 to 29% of precipitation, and the 2011-2024 average recharge as a fraction of precipitation being 0.4%. This is very different to 38% of rainfall and may influence the water balance.

In irrigated landscapes, the WBA assumes that 70% of applied irrigation water is evaporated/transpired, and 20% recharged. These values may be reasonable but depend heavily on irrigation technologies and scheduling used. This value is candidate for *sensitivity analysis*. Reasonable values to consider using in the sensitivity analysis for irrigation can be sourced from e.g. Connellan (2013).

Overall, the evapotranspiration methods are *reasonable*, but parameters would benefit from *re-evaluation in light of new research and observations*, which should be used to inform further *sensitivity analysis*. Sensitivity analysis would involve identifying the plausible **range** of recharge values for the different land uses, repeating the water balance analyses across these ranges of values, and identifying how robust the findings are to changes in the parameter assumptions made.

3.2.3.7 Lateral groundwater flow

Lateral groundwater flow was subdivided in the WBA into a separate treatment of a localized perched and regional superficial system.

The water balance computed lateral groundwater fluxes on boundaries of the development area that ran near parallel with water table contours using Darcy's Law:

$$Q = -A\,K_{sat}\,\frac{dh}{dl}$$

Here h is the local head, l is the distance in the direction of groundwater flow, A is the area perpendicular to the flow and K_{sat} is the lateral hydraulic conductivity.

3.2.3.7.1 Estimating K_{sat}

Although there are numerous permeability measurements made at the AA, estimating effective K_{sat} is clearly problematic due to the tremendous heterogeneity indicated by cores and geophysics across the soil profile. The WBA estimates K_{sat} as a mean of that measured in 3 representative bores, and then halves this value to represent K_{sat} on the Tonkin Hwy boundary.

The first choice is *reasonable*, while the subsequent choice to halve the conductivity along the Tonkin Hwy boundary seems *arbitrary*. There are good reasons to consider that Ksat will be distinct in that location from the rest of the AA due to the change in soil type and emergence of perching, but there is no obvious reason to assume it's 50% of that measured elsewhere.

Due to the subsurface heterogeneity present, K_{sat} will always be difficult to pin down accurately at the AA. It is thus a good candidate for *sensitivity analysis*. A "scenario" analysis may also be appropriate considering scenarios of high, moderate and low connectivity across the Tonkin Hwy, for instance. Such exploratory analysis could inform whether further work to identify groundwater through flows in that area is needed by covering a range of possibilities that are hard to discriminate with available data.

3.2.3.7.2 Estimating A

The cross-sectional area of flow in the regional superficial system is computed across the boundaries as the area between the underlying confining layer and the AAMGL (regional aquifer) or MGL (perched aquifer). The confining layer used is respectively the base of the regional aquifer or the location of clay layers above which perching has been observed. Flow in the perched aquifer is considered for a 5-month period only, May – September.

The validity of using AAMGL/MGL for these estimates is questionable. AAMGL likely over-estimates the cross-sectional area of flow by assuming that the average *maximum* groundwater level can represent a level that in practice fluctuates over time and is usually lower than the maximum value (e.g. the DWMS quotes seasonal fluctuations between 0.8 and 2.4m for 3 of the bores in the area). The impact of using MGL is likely to be greater for the perched aquifer than the regional aquifer.

If average values are to be used, a long-term average using all available data in the AA and its vicinity would be more appropriate than the AAMGL /MGL.

Alternatively, and preferably, a time-resolved computation of groundwater flow would be suitable, allowing for seasonal fluctuations in both cross-sectional area, hydraulic gradient and direction. This would also allow for the formation / loss of the measured perched water table to naturally determine when outflows from the perched region started / stopped.

Ideally, consideration of how stormwater infiltration might alter the seasonality and gradients in the southern groundwater mound should be included in these assessments.

3.2.3.7.3 Estimating dh/dl

AAMGL and MGL contours were used to estimate dh/dl.
The validity of this choice is questionable. This choice assumes both that the gradients associated with the maximum groundwater level are representative of conditions throughout the year, and also neglects interactions between seasonal variations in gradient and cross-sectional area.

Robust alternatives are to use a time-averaged dh/dl estimate[1] in conjunction with a time-averaged A estimate, or to use time resolved estimates of both A and dh/dl. Since dh/dl will need to be computed over time to obtain a time average anyway, I would recommend working with time-resolved variables.

[1] Note that this is not the same as a dh/dl estimate made from the average groundwater surface. There is something called the "commutation error" and it means that taking the average of a set of derivatives is not the same as taking the derivative of the averages. It pops up a lot in fluid mechanics, and it could be relevant here too.

4 Conclusions regarding potential environmental impacts

The overall argument in the DWMS is that:

(i) There is limited connectivity between the AA and the GBSW, and therefore there can only be a limited impact of changing hydrology in the AA on the GBSW
(ii) Development in the AA will improve water quality of inflows to GBSW
(iii) Opportunities for water treatment and future water diversion into the GBSW from the AA could provide opportunities for climate change adaptation and protection of the GBSW hydrology.

I *disagree* with the first conclusion, find the second conclusion *speculative* and *strongly endorse* the third conclusion, while noting that such opportunities are not necessarily dependent upon development of the AA.

4.1 Limited Connectivity

The argument about limited connectivity between the AA and GBSW is based on diversion of regional groundwater flows by the groundwater mound, limited volumes of water flowing from the perched system in the north west into the GBSW area, and limited surface water connectivity between the AA and GBSW.

If the groundwater mound is present this assessment of limited connectivity is reasonable. However, back-of-the-envelope calculations suggest that flow across the south western boundary of the AA could increase by a factor of approximately 4 if the mound were not present, meaning that the 'natural' (pre-mound) connection between this AA and the GBSW may be more substantial than it is at present (see responses to Table 1 for calculations).

Even if there are only limited connections between the AA and the GBSW, however, it is inappropriate to assume that such connections are insignificant.

The GBSW should not be viewed in a lumped "bucket" type fashion, where the importance of any one hydrological input can be assessed in terms of how large it is relative to input fluxes to the whole wetland system.

It is known, for example, that there are individual endangered species in the GBSW whose range is confined to areas as small as 0.1 ha. Were those species located where perched shallow flow from the AA enters the GBSW, or where locally damp conditions were supported by the incoming water from the AA, it is possible that there could be significant local impacts of hydrological changes that are small compared to the overall water balance of the wetlands.

I would suggest that it is very difficult to assess the environmental importance or otherwise of current inflows to the GBSW. Thus, the conclusion that development will not impact the GBSW hydrology in a meaningful way *cannot be supported* based on the current state of knowledge of GBSW function.

4.2 Development of the AA will reduce nutrient loading on the GBSW

It is quite plausible that nutrient inputs to the AA will decline with development. However, this does not imply that exports, particularly exports through groundwater, will decline. Anecdotally there is very mixed evidence about the trends in nutrient export pre- and post-development across Perth, and good evidence that high nutrient levels in pre-development groundwater may be exported post development due to altered hydrology. It would be helpful to review post-development nutrient export rates from other sites around Perth to benchmark expectations in addition to using tools such as UNDO.

While development is unlikely worsen current nutrient loading, to argue that it will improve nutrient loading is *speculative*.

4.3 Development of the AA offers opportunities to improve water quality of surface inflows to the GBSW, and climate resilience

Improvement of water quality of surface inflows to GBSW through water quality management control measures would be desirable and are a welcome component of the DWMS.

Additionally, the opportunity to use water generated in the development area as a potential additional water source to support the GBSW if climatic drying threatened the wetlands, is also a welcome component of the DWMS, although it is unclear whether this would be feasible in addition to maintaining the groundwater mound. See responses relating to the groundwater mound maintenance in Table 1, which consider how climate change might affect the water needed for mound maintenance.

The degree to which these opportunities require development of the AA, however, is unclear. Most of these opportunities could presumably be realized through other actions by regulators, LGA or the community.

5 Sufficiency of mitigations (including post-development mitigations) in ERD, WBA and DWMS to manage hydrological impacts on GBSW

The key hydrological mitigation measures proposed in the ERD, WBA and DWMS are:

(i) Implementation of water sensitive urban design within the development area (e.g. infiltration infrastructure, bioswales, onsite infiltration)
(ii) Long term monitoring and adaptive management program
(iii) Maintenance of the existing groundwater mound

Given the assumptions within these documents, all these measures are reasonable and sufficient to manage most hydrological impacts.

The open question is the extent to which adaptive management can effectively be implemented to manage the existing groundwater mound – if there is enough onsite water, power and infrastructure to vary stormwater infiltration over the mound area to increase/decrease mounding as needed.

6 Additional mitigation measures

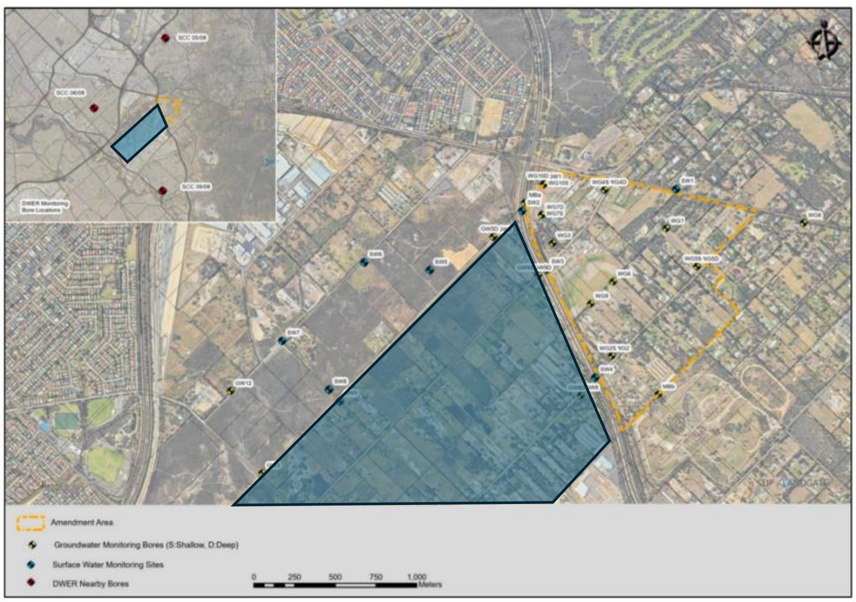
6.1 Model of GBSW function

Developing a working quantitative model of the GBSW, testing it and using it to assist in evaluating likely impacts of changing hydrological conditions in its environment would be of great value to ongoing adaptive management, to facilitate informed cumulative impact assessments, and to test hypotheses and claims about the impacts of offsite management measures on the GBSW.

Such a model should be at least a 2D groundwater – surface water model, and it may need to be 3D to adequately represent all processes. It would need to capture solute and nutrient transport as well as hydrological dynamics. It would also need to be related to vegetation community distribution (as well as distribution of priority species) and any known dependencies between vegetation and either water or solutes/nutrients, so that it could be used to assess the vulnerability of communities/species to change.

6.2 Additional groundwater level data

The local groundwater monitoring on the AA is now quite detailed but considering the relevance of offsite impacts of changing hydrology, there is little information presented in the ERD, WBA and DWMS about the groundwater depth and gradient offsite – particularly in the area south-west of the AA. As this is the expected direction of groundwater flow, and as any diversion of the flow northwards would cause the flow to intersect the GBWS, it would be valuable resolve groundwater flow in this region. I've sketched out an approximate area of interest. Monitoring undertaken for separate scheme amendments (e.g. https://www.epa.wa.gov.au/city-gosnells-local-planning-scheme-6-amendment-169) may provide a useful source of such information.



6.3 Hydrological restoration of GBSW

As noted in the ERD, the surface hydrology of the GBSW has been substantially altered by diversion of existing streams, and the groundwater hydrology at least potentially altered by groundwater use and irrigation in the region. Reversing hydrological modifications – for example by removing obsolete drainage infrastructure – can assist in rehydration and protection of valuable landscapes.

There seems to be potential to consider such restoration activities for the GBSW by restoring the historical surface flow connections between the "former Crystal Brook tributary" and the GBSW, subject to appropriate water quality and hydrological regime management. Such restoration would likely impact the north-western corner of the AA.

The University of Western Australia
M004 Perth WA 6009 Australia

7 Response to Specific Questions

Item No.	Response
1.	
(a) Are the DWMS and water balance methodologies including assumptions and data used accurate, reasonable, and sufficient?	A lot of work and effort has gone into the WBA and DWMS. The points below are necessarily focused on areas for potential improvement or outstanding ambiguity. These comments are made with respect for the professionalism and effort represented in the existing documentation. Assumptions and data are *primarily reasonable*. Minor issues are identified in the report. There are two areas where further work could be valuable. There is no uncertainty analysis, which is problematic considering (i) the difficulty in constraining estimates of effective hydraulic conductivity in this complex site, (ii) the nonlinearity in how runoff calculations can depend on IL and CL parameters, (iii) the uncertainty in parameters such as recharge (PRAMS estimates are an excellent baseline to use, but are not a "truth", and disagree with some recent measurements of recharge as a fraction of annual precipitation). Understanding how sensitive the findings are to the assumptions (parameter choices) enables risks associated with these choices to be better delineated. The assessment of groundwater throughflow has been conducted with the AAMGL levels (MGL for the perched aquifer). This is not

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	appropriate given the seasonal fluctuations in the water table level and gradient, and using time-resolved data would be preferable. The assessment of groundwater throughflow has not considered the scenario where the current groundwater mound cannot be maintained. This scenario should be explored in order to understand how risky or otherwise the proposal to maintain the mound is. The assessment of groundwater throughflow has not considered the large changes in seasonality of recharge to the mound that would result from recharging with stormwater. This would presumably alter mound elevation, gradients and seasonality.
(b) Are the data and inputs, methodologies and results/outcomes of technical assessments appropriate and accurate?	Some minor areas and queries around data and inputs to the WBA are noted above. I have not e.g. checked all technical calculations in all technical assessments, however overall methodologies are standard, data provided with the technical assessments are comprehensive and overall I am comfortable with the technical assessments performed. I would not give a lot of weight to the geophysics and ERT results, however, due to the complexity of the subsurface, the lack of sufficient deep drill logs to assist in interpretation, and the multiplicity of potential drivers of changing resistivity. However, as the geophysics is mostly used to claim the subsurface is complex –

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	the details of the interpretation are probably not critical to the technical assessment of the site. At this stage I would not recommend investing further effort in the ERT.
(c) Are the hydraulic conductivity and hydraulic gradient calculations and subsequent values adopted to inform the water balance and DWMS accurate and reasonable?	The hydraulic conductivity adopted for most of the site is reasonable (although results should be subjected to an uncertainty analysis given the variations in measured K_{sat}). Hydraulic conductivity adopted on the Tonkin Hwy boundary has been apparently arbitrarily set to 50% of the main site K_{sat}. As noted in response (a), the gradient computations focus only on current AAMGLs/MGLs.
(d) For each of the above, if answered in the negative discuss both why and what further work is recommended	As noted in response (a), uncertainty analysis and a broader exploration of different seasonal and plausible future conditions associated with the mound management would be valuable future work.
(e) Is there confidence that the hydrogeological/geotechnical studies and assessment provides sufficient information relative to the complexity of groundwater flows and interactions and accurately represents the hydrogeological system underlying the amendment area and surrounds?	Within the amendment area, the hydrogeological and geotechnical investigations are mostly sufficient. They indicate a soil transition from sandy Yoganup soils to the Guildford complex occurs within the AA, consistent with mapping. The complexity of the area's hydrogeology is mostly associated with the Guildford complex where hardpans and clay lenses introduce perching and areas of low transmissivity. This area is a small fraction of the site.

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	There are a few areas where a more resolved understanding of the hydrogeology would be helpful. One of these is around the Tonkin Hwy. There are quite strong assumptions made about the effect of the highway on hydrological connectivity between the GBSW and the AA, which are difficult to assess with the current information. Additional coring along this boundary to delineate the extent of perching or doing a pump test with bores on either side of the highway would help strengthen understanding of how water flows – or doesn't flow – across this boundary. The other area where groundwater flows are unclear is offsite and southwest of the AA. It would be possible for high groundwater levels in this area to alter groundwater contours and incline flows northwards - to the west – which would cause them to intercept the GBSW. Groundwater monitoring in this area is not included in the assessment documents, and it would be helpful to have such data here as it will clarify the assumption that groundwater throughflow from the AA would not encounter the GBSW. I understand that additional data may be available from other investigations e.g. https://www.epa.wa.gov.au/city-gosnells-local-planning-scheme-6-amendment-169
(f) Has sufficient information been provided for the following items to provide certainty for the accuracy of the hydrogeological functioning of the system:	

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Geology • Drill hole stratigraphic logs and provision of the methodology used to interpret stratigraphy (e.g., sediment and groundwater geochemistry, palynology, environmental tracers). • Verified ground geophysical data.	Drill logs and photographs of cores / drill cuttings are provided in Appendix E in the DWMS. Appendix B identifies that interpretation of logs was based on Australian Standard AS1726:2017, Geotechnical Site Investigations. Particle size distribution laboratory results are provided in Appendix B. Tracers, palynology and geochemistry have not been used to interpret stratigraphy. This is not, in my view, a limitation. The report associated with the geophysical data was illegible inn the documentation provided. ERT collection, inversion and visualization are all ok. However, I do not think there has been enough deep drilling done with the ERT to allow robust interpretation of the ERT data and would discourage leaning heavily on the interpretations made.
Hydrogeology • Phreatic aquifer isopaches, saturated thickness, or change in saturated thickness to verify recharge, gradients, or aquifer transmissivities.	This information has been provided. Comment (e) above outlines a few areas of concern with respect to superficial aquifer groundwater flow. I am frankly confused by the perched groundwater interpretation (and particularly Figures 5 & 9 in the WBA). Groundwater contours are provided for the area south-west of the AA, but interpolated water levels are shown in the north west of the AA. How are these data related to each other? Why are they so disjunct?

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	The interpolated water levels from the perched system are very spatially localized. It would be helpful to clarify in the mapping which bores are used to generate the contours and interpolated water levels, and whether there is enough information present to infer perching behaviour and flow. It may well be that the data is fine, but I have struggled with its interpretation / communication.
2.	
The ERD states that *post-development groundwater flows will be comparable with pre-development conditions and will continue to flow radially away from the groundwater mound flowing north-west flowing south-east and away from the GBSW area*. (a) Does the technical information provided in the ERD and appendices support this statement?	*Yes* the technical information in the ERD broadly supports this statement, *subject* to previously raised concerns about uncertainty analysis with respect to K_{sat}, and the need to consider additional scenarios (changed seasonality of recharge / absence of mound) with respect to the groundwater mound, and *within the boundaries* of the amendment area. *However*, the statement is in some ways disingenuous, as once southwest of the AA (past the orange dashed line below) the flow from the mound will be to the west/south west (purple arrows below). Since the proposal includes stormwater recharge of the mound, this would result in water from the AA flowing offsite from the mound. While it is perhaps outside the scope of the site specific investigation, a regional groundwater investigation that traces flow paths across site boundaries and establishes the groundwater catchment for the GBSW would greatly assist in evaluating the relations between the GBSW and its catchment.

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	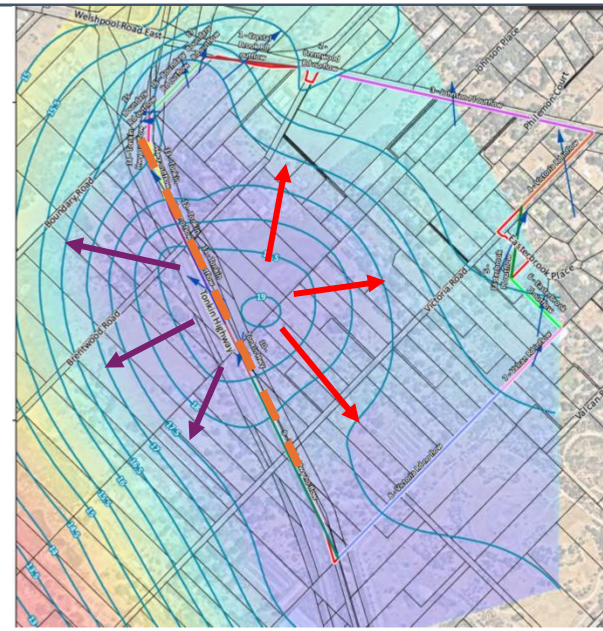
(b) Are the groundwater contours which have been used to inform the water balance and DWMS accurate (noting the differences to DWER groundwater contours)?	The DWER contours are based on regional bores which don't offer a spatially refined picture of water levels around the AA and GBSW. In these circumstances I would tend to consider the locally derived contours as being more likely to be accurate than regional contours. That said, comments about the suitability of using AAMGL/MGL, confusion about the mapping of perched water levels, and the absence of data constraining groundwater levels to the south west of the site mean that there remains some ambiguity about the behaviour of groundwater in the area.

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Is there a view as to whether any further information on the following is required to inform the accuracy of the groundwater contours: • Geological and hydrogeological interpretations of drill hole and geophysical data (in the form of analyses of physical and chemical properties of drill core to map stratigraphy and verify geophysical data). • Drill hole core/chips	I do not think the lithology of the site is the driver of uncertainty. I think using more groundwater observations to delineate the GBSW groundwater catchment would be more informative.
3.	
The water balance states that *The predicted increase in recharge has the potential to increase groundwater depth, however this will not have a significant impact on any of the water balance components, as the Superficial aquifer lies several metres below the natural surface level of the MRS amendment area. The (northerly) localised flow direction of Superficial aquifer in this area does not grade towards the GBSW. Further, the GBSW is predominantly fed by direct rainfall. Therefore, the urbanisation of the MRS amendment area will not adversely impact the existing hydrological regime in the GBSW*. Does the information presented in the ERD and appendices support this statement? If not, please explain why.	To take this statement point by point: *"... this will not have a significant impact on any of the water balance components, as the Superficial aquifer lies several metres below the natural surface level of the MRS amendment area..."* An increase in recharge will increase groundwater levels. I am slightly concerned that the increase may be larger than estimated – for example the recharge estimates for the native vegetation may well be too large, which would tend to lead to an underestimation of the recharge change – and thus, also, the statement above. Similarly, the changes in recharge timing and magnitude in winter over the groundwater mound may invalidate this statement. While this assumption may be reasonable, it would be wise to test it in the context of the recommended uncertainty analyses and future recharge scenarios. "...the *(northerly) localised flow direction of Superficial aquifer in this area does not grade towards the GBSW..."*

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	While true, I find this statement disingenuous, as per comments in 2(a). *"…, the GBSW is predominantly fed by direct rainfall…"* While true in a macroscopic sense, this statement is not an appropriate lens through which to consider potential effects of hydrological change to the GBSW. The heterogeneous and distributed nature of the GBSW and the flow within it mean that the impact of a localized change can't be simply assessed in terms of its magnitude relative to e.g. rainfall inflows. The potential for localized plant species/communities to depend on local conditions that could be changed by changes in fairly small fluxes is quite real in the GBSW. Thus, assessment of impact on the GBSW needs to be based on a more highly resolved understanding of the specific dependencies and vulnerabilities of the GBSW to changes in specific hydrological fluxes. This is likely to require development of consensus conceptual models of the GBSW hydrological functioning and ultimately a quantitative tool (likely a 2/3D water, nutrient and solute model) that can be used for such assessment. *"…the urbanisation of the MRS amendment area will not adversely impact the existing hydrological regime in the GBSW…"* Broadly the DWMS argues that the AA is hydrologically isolated from the GBSW and will therefore not impact the GBSW through urbanization. As outlined above, uncertainties in the dependences and vulnerabilities of the GBSW to small changes in hydrology are substantial. The fate of groundwater exiting the groundwater mound and how it will change under future recharge management – or loss of such recharge management – are not well established. The conditions associated with the Tonkin Hwy boundary are based on assumptions and a still-emerging understanding of the perched groundwater system.

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	Finally, although cumulative impact assessment has considered the upstream catchments of the AA, it has not considered cumulative impacts across the basin of the GBSW. Given the sensitive environment and its value, this would be the preferred lens through which to understand cumulative impacts.
4.	
The ERD asserts that the existing groundwater mound is representative of the local hydrological conditions of the amendment area. Are the assumptions, data, inputs, and modelling and outcomes presented in the ERD, water balance and DWMS sufficient and accurate to support this conclusion?	I interpret the claim in the ERD slightly differently to the way it is presented in this query. I do not believe the ERD claims the existing groundwater mound is "representative" of local hydrological conditions. The ERD and supporting hydrological reports consistently depict the existing groundwater mound as being anthropogenic in origin and due to over-irrigation of the previous turf farm using water from the Leederville aquifer – i.e. a net import of water into the superficial aquifer system that was maintained for many years. This is a very reasonable conclusion. What the ERD does then is consider the EPA's objective of water management in the AA - to maintain "pre-existing" hydrological conditions. It then interprets the "pre-existing" – anthropogenically altered – state of the groundwater as the hydrogeological target to be maintained. (Alternatively, pre-existing *could* have been interpreted as "pre-turf farm" – which would be closer to the "representative" conditions referred to in the query).

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	As noted previously, the proponent's interpretation is in keeping with the letter of the EPA's requirements, but it is not clear to me that it is in keeping with the *spirit* and *intention* of the EPA's requirements. The presence of the groundwater mound on the very boundary of the AA is convenient for the proponents. Its presence means that within the boundary of the AA, groundwater flow is mostly away from the GBSW. This minimizes various risks – for example, any groundwater contamination in the AA would be prevented from flowing into GBSW, or rising water tables in the AA from alter flows to the GBSW by the presence of the mound. Thus, the presence of the mound contributes to the argument that the AA is hydrogeologically disconnected from the GBSW. This argument would be more tenuous if the mound were not present. Absent the mound, groundwater flow would likely follow the DWER regional mapping, and groundwater in the AA would flow to the south west and potentially into the GBSW – rather than the current northerly – north-easterly direction of flow within the AA. The protective barrier between the AA and the GBSW would not be present, and these areas could feasibly be hydrologically connected. Thus from a proponent's point of view, interpreting the EPA's "pre-existing conditions" as meaning "keep the groundwater mound" is attractive. It minimizes risk and allows the proponent to argue that the AA is (largely) hydrologically isolated from the GBSW.

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5	
The ERD asserts that the maintenance of the groundwater mound post development is consistent with the objective of maintaining the existing hydrological regime of the amendment area and surrounds and ensuring the hydrological balance of the GBSW is maintained post development. • Is the data and modelling presented in the water balance and DWMS documents sufficient and accurate to support the above conclusion? If not, what further information may be required?	As per my response to query 4, I do not believe the ERD argues for maintenance of the groundwater mound because of any importance it has for GBSW water balance. Instead, the ERD repeatedly argues that there is very limited groundwater flow on the south-western boundary of the AA, and that this groundwater flow doesn't matter to the GBSW. The current WBA estimates the outflow of water on the Tonkin Hwy boundary (i.e. from the mound) as approximately 125,000 m^3/year. A back of the envelope estimate based on the DWER contours for flow on the same boundary is below – Length of boundary – 1500 m along Tonkin Hwy Approximate height of water table –11 - 13 mAHD (from DWER 2019 contours as shown in Figure 11 in DWMS) Base of water table – 0 mAHD Approximate gradient - ~ 4 m / 1000 m ~ 0.004 (from DWER 2019 contours as shown in Figure 11 in DWMS)

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	Ksat used in WBA – approx. 20 m/day Under these conditions the annual flow would be: $$Q \sim 1500\,m \times 11\,m \times \frac{4\,m}{1000\,m} \times 20\,\frac{m}{day} \times 365\,day$$ =481,800 m3/year (3.85 times predicted flow with the mound in place). Or, if we take the upper value of the water table elevation along the boundary at 13 - $$Q \sim 1500\,m \times 11\,m \times \frac{4\,m}{1000\,m} \times 20\,\frac{m}{day} \times 365\,day$$ =569,400 m3/year (4.5 times predicted flow with the mound in place).
• Will there be any significant adverse impact on GBSW if the existing groundwater mound is or is not maintained?	The calculation above suggests that there is likely to be an increase in groundwater flow to the south west from the AA if the groundwater mound were not maintained. Does the presence of the mound, however, result in higher overall water levels near the GBSW than would occur in its absence?

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• Based on the information provided, does the peer reviewer have a view as to whether the groundwater mound should or should not be maintained in order to ensure the hydrological balance of the GBSW is maintained post development?	Again, I will take the 2019 DWER contours (Figure 11 in DWMS) as a "best bet" as to what the water table might look like without the mound. These contours show the GBSW water table elevation grading from 13m AHD in the north-east to 5mAHD in the south west. In Figure 19 in the DWMS, the regional AAMGLs based on contemporary groundwater mapping – *in the presence of the mound* - are shown, and indicate that the water table elevation grades from 14 mAHD in the north-east to 5mAHD in the south west. So, I would conclude that the mound is *not* increasing water table elevations in the GBSW but IS reducing groundwater inflows that could potentially support the GBSW. In a drying climate this suggests that removal of the mound *might* be beneficial to the GBSW, but I have strong reservations about making any claims as to how hydrological changes would affect the GBSW in the absence of better understanding of the wetland hydrology and a … better than a back of the envelope … calculation of mound impacts on flows.
If the groundwater mound is to be maintained, is the proposed approach for maintenance of the mound presented in the DWMS reasonable and technically sound? (This should include consideration of Appendix Q of the DWMS showing changes to the monthly distribution of recharge across the amendment area)	The proposed approach is (mostly) technically sound but I would characterize it as risky. It relies on replacing Leederville irrigation with stormwater infiltration, with on-lot connections added (rather than allowing for

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	on-lot soak wells) to route some water from outside the turf farm area to infiltration infrastructure in this area. The assumed area of on-lot connections needed at present is small – 4 % of the development area. However, the recharge assumptions for the turf farm irrigation should be considered as estimates and it is useful to consider the implications of these estimates being incorrect. An increase in recharge under the turf to e.g. 30% of irrigation would increase the area where on-lot connections are needed to 12% of the AA. While this might still be technically feasible, it's is surely less economically attractive. Similar concerns arise with climate change – if there is less stormwater produced and less inflows and rainfall to the mound area, then the area of the development where on-lot connections would be needed to maintain the increases to between 20% (if the 20% recharge value were assumed) to 30% (if the 30% recharge of irrigation were assumed) under the 2100 rainfall scenarios. This represents considerable additional piping and stormwater works to future-proof this groundwater mound. The economic viability of this proposal and the likely willingness of developers and landowners to pay for this solution and its upkeep pose a risk that it would not be comprehensively implemented or maintained. Changes in seasonality of recharge are certainly introduced through the proposed stormwater recharge as well. These changes are harder to do a back of the envelope calculation with, but I've attempted to get some intuition about the potential effects using the Hantush Equation, as implemented in a USGS excel based calculator (Carleton, 2010). Running this equation with average

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	summer and winter recharge rates pre- and post- development over the full 14ha Turf Farm Area -- namely Pre. Post Summer. 0.04 m/yr 0.05 m/yr Winter 0.01 m/yr 0.07 m/yr results in the seasonal variation in groundwater mound elevation between summer and winter under current conditions of 20%, and 80% under future conditions – a much more extreme seasonality in the water table level. This is a very crude calculation, but it suggests there is potential for the groundwater mound's elevation and gradient to be sensitive to the timing of recharge. This would have flow-on implications for throughflow and groundwater direction, although I won't speculate on the magnitude of these (this would be pushing a back of the envelope approach too far!).

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