Review of the assessment of reliabilities for licences in the Tindall Limestone and Oolloo Dolostone Aquifers based on potential impacts on Daly River streamflows

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Review report

This report has been prepared under the DHI Business Management System certified by Bureau Veritas to comply with ISO 9001 (Quality Management)

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Executive Summary

Background

This report has been prepared in response to the Department of Land Resource Management (DLRM) request for an independent review of its reliability assessment of the most recent groundwater licence applications in the Daly River catchment.

The reliability of licences in the Daly River depends on dry season discharge limit-of-change thresholds at key gauging stations on the Daly River. These thresholds are based on environmental water requirements determined from environmental flow and they are specified as maximum allowable percentage discharge decreases.

The original reliability evaluation process relied on an integrated surface water – groundwater model to accurately simulate these gauging station discharges with and without groundwater and surface water extractions in place. DLRM has recently identified that the model is overestimating dry season discharges at the key gauging stations. This has led to an overestimate of the licence reliability of existing licences in the system.

To improve the accuracy of the licence reliability estimation DLRM have developed a new licence reliability methodology. This still uses the absolute change in discharge calculated by the model, but evaluates it as a percentage of the observed discharge rather than the modelled natural discharge. This approach and inputs and the outputs to it are the subject of this review.

Key Findings

The terms of reference required that the review address specific objectives, and that the review scope should include specific considerations. The conclusions against each of the review objectives and scope are presented in below, with further detail in the body of the main report.

Scope Item 1: Assess the suitability of the current Feflow and Mike11 connected modelling package used by DLRM to describe the potential impacts on Daly River stream flows associated with granting applications for water extraction licences

1. The review concludes that the FEFLOW / MIKE 11 model is suitably aligned with the objective of describing the potential impacts on Daly River streamflows for the purpose of assessing water extraction licences.

2. Methods of estimating recharge are based on earlier application of water balance hydrograph analysis (Jolly, 2002), a Soil Moisture Deficit Model (Knapton, 2005, 2006) and later a physics based MIKE SHE model. These approaches represent the current and best practice model packages available for determining recharge processes.

Scope Item 2: Assess the suitability of the input data provided for the connected modelling package; the output data delivered by the modelling package; and the streamflow monitoring data used for the most recent licence applications being processed by DLRM

3. The development of the model and input data for the scenarios are considered suitable for the stated objectives.

4. Rainfall inputs are point time series extracted from SILO data used to form subcatchment Mean Area Rainfall series. Using this approach may not accurately reproduce the historical spatial rainfall distribution given the large subcatchment area and sparsity of the rainfall stations. This issue was considered in previous work (Knapton, 2011) and is unlikely to be significant at the seasonal timescales of most relevance to the licence reliability assessment. SILO data may change as the algorithms used to derive the rainfall and evaporation series are updated, however, it is unlikely that changes to SILO data would result in significant changes to modelled outcomes. It would be prudent to document any changes to the SILO data and any implications of subsequent model performance.

5. It is understood that there is only one model run undertaken in assessing licence applications. Based on knowledge that a single true model cannot be constructed (Barnett et al, 2012) the current industry practice is to provide quantitative estimates of uncertainty associated with model outputs to be used in decision making. The estimate of uncertainty provides an understanding of the level of confidence in the modelled outputs. This review was not able to source any assessment of uncertainty of the model outputs and implications for the licence assessment. **[Note additional work undertaken by DLRM satisfies the Reviewers recommendations. Further details are at the Addendum in Section 7 of this report].**

6. It is recommended that uncertainty analysis is undertaken to test the robustness of model outputs and new licence methodology in determining licence reliability. This assessment would require some additional modelling, where model parameters are changed and model outputs compared against the base model outputs to indicate the level of error. In the first instance it is suggested to undertake a further 10-20 model runs and to document the level of uncertainty. **[Note additional work undertaken by DLRM satisfies the Reviewers recommendations. Further details are at the Addendum in Section 7 of this report].**

7. Input observed streamflow records at the key gauging stations of Mt Nancar and Dorisvale Crossing appear to be reliable with rating error typical of good long-term sites. There have been no recent gaugings in the low flow range since the mid-2000's, probably due to wet catchment conditions. This suggests some uncertainty about the accuracy of low range discharges since then. This is unlikely to affect the licence reliability assessment process given the relatively wet conditions over this period.

Objective 1: Confirm the approach taken and model data outputs used to derive reliability for the most recent ground water extraction licence applications in the Tindall Limestone – Flora Aquifer and the Oolloo Dolostone Aquifer based on potential impacts on Daly River stream flows

8. This review has found that the model and model outputs produced are generally satisfactory, and suited for the purpose of licence reliability evaluation.

9. Both the current and previous superseded reliability assessment approaches calculate the modelled streamflow impacts as the difference between the modelled licence extraction scenario and the modelled natural scenario. They then calculate the licence reliability as follows:

    - In the previous approach the modelled streamflow impact was compared against the *modelled* natural flow to determine whether environmental water requirements are satisfied. This approach was superseded as error in the modelled natural series led to an overestimate of the licence reliability.

    - In the current approach the modelled streamflow impact is compared against the *observed* natural streamflow record. This approach attempts to correct for the error in the modelled natural series by comparing the modelled impact to the observed discharges instead.

10. The modelled streamflow impact series is a model output and will have inherent error regardless of how well the model is calibrated. Uncertainty is reduced compared to the previous approach, as the current approach uses the difference of two model results. However, the current approach still relies on a single modelled impact series to evaluate licence reliability. It does not consider the range of uncertainty in that single modelled series, and how that translates into uncertainty in the licence reliability calculation outcome. Additional model runs to test and document uncertainty (as per point 6) would provide an evidence base to test the assumption that there is little or no uncertainty in the model outputs. **[Note additional work undertaken by DLRM satisfies the Reviewers recommendations. Further details are at the Addendum in Section 7 of this report].**

11. The integrated assessment approach to assessing individual licences should be documented. This document should summarise the principles behind the assessment approach, how it relates to the Water Allocation Plans and environmental water requirements, how licence security is determined from the process, what the key assumptions in the assessment are, and the modelling and analysis steps in the assessment process.

12. The observed (measured) streamflow is used as the natural (unmodified by extraction) streamflow in the assessment process. Past aquifer pumping has potentially affected streamflows although this is less likely in the Oolloo Dolostone Aquifer. The observed series may therefore underestimate the natural discharge series which could lead to an underestimate of reliability. However, as the climate has been wet since the mid-2000's with few restricted years this assumption is unlikely to have affected the licence scenarios being considered in this review.

13. The assessment assumes licence extraction at full entitlement continuously throughout the scenario simulations. It does not take into account annual allocation restrictions and the reduced drawdown of the aquifer associated with this. This assumption of full allocation extraction in all years is a conservative approach likely to overestimate impact.

Scope Item 3: Assess the validity of the determinations made by DLRM for expected licence reliabilities for the most recent licence applications being processed by DLRM.

Objective 2: Verify and confirm the reliability calculations for those licence applications

14. The spreadsheet used by DLRM to carry out the assessment has been reviewed and confirmed to be consistent with the intended licence reliability assessment process, and no calculation errors were found.

15. It is currently assumed that there is insignificant variability in model outputs and therefore, the reliability calculations are not influenced by any of the model parameters. There has been no documentation presented to the Review Team testing and confirming this assumption. An uncertainty analysis is being recommended as outlined in point 6 earlier, to test this assumption in a valid an accepted manner. Without this analysis, it is not possible to verify and confirm the reliability calculations per se. What can be confirmed is that the Departmental process has been followed and there are no process errors apparent in the calculations. **[Note additional work undertaken by DLRM satisfies the Reviewers recommendations. Further details are at the Addendum in Section 7 of this report].**

Conclusions

Overall, this review has found that the modelling package, the input and output data used in this process are suitable and satisfactory for the purpose of assessing water extraction licences. No process errors were identified in the reliability calculations for the new licence applications, which are the focus of this review.

It is clear that the assessment team has excellent knowledge of the hydrogeology and hydrological processes of the system. Based on this understanding, assumptions have been made in relation to the level of uncertainty of model outputs without documentation or validation. It is recommended that a small number (minimum of 10) of additional model runs are undertaken as an initial test of the robustness of the assumptions made and to document this uncertainty.

In response to the recommendations by the Independent Peer Reviewers, DLRM undertook predictive sensitivity analysis to investigate the potential range in estimated licence reliabilities resulting from alternative model parameterisations for the Daly water resource assessment model.

DLRM provided to the reviewers the stream flow forecasts and reliability calculations based on 5 Natural (no pumping) and Scenario 10 (Sc10) models (a total of 10 models). These have varying parameter sets, described as the minimum, 25th percentile, median, 75th percentile and maximum ranked average flows. Further details are included in the **Addendum at Section 7** of this report.

This additional work undertaken by DLRM adequately addresses the issues raised by the reviewers in Conclusions 5, 6, 10 and 15 above. The Reviewers confirm that the investigation of predictive uncertainty (sensitivity analysis approach) is adequate and appropriate and accept the outcomes of the work undertaken. On this basis, the reviewers can confirm the reliability assessment and that the objectives of this report are confirmed by this review.

CONTENTS

1 Introduction

1.1 Overview

The Northern Territory Department of Land Resource Management (DLRM) actively manages water resource allocation in the Daly River catchment through a water allocation planning and licensing system. DLRM aims to sustainably allocate water abstraction for consumptive use by ensuring that environmental and cultural values are maintained. Excessive surface water and groundwater abstraction would potentially reduce baseflow supply within the Daly River which may impact on water dependent ecosystems. The water allocation planning and licensing system allocates at least 80% of flow at any time in the Daly River for environmental and other public benefit water in the absence of science.

Management of the water resource in the Daly River catchment is complex due to the highly interconnected surface water – groundwater system. The Tindall Limestone Aquifer and the Oolloo Dolostone Aquifer are karstic, characterised by cavities, cave systems and high variability in subsurface features. While there are high localised variations, these karstic aquifers are considered to behave as equivalent porous media at a regional scale. Determining suitable limits on licence allocation within the system depends on having a good understanding of the seasonal streamflow and aquifer recharge processes, and on having a licence determination methodology that uses this understanding to set appropriate boundaries on extraction.

The Integrated Daly River Surface Water and Groundwater Model embeds the understanding of the catchment, streamflow, aquifer recharge and extraction impact processes. It was originally developed by URS Australia in 2008 for the purpose of assessing impact of water resource development scenarios on existing water resource users and the environment. The model is a coupled MIKE11 – FEFLOW model.

In the past the model has been used to estimate the impact of additional licence entitlements on baseflow by comparing entitlement model scenario discharges against natural model scenario discharges. However recent comparison of the model outputs against the recorded discharge has shown that the natural scenario model consistently overestimates dry season baseflows at two key monitoring stations (Dorisvale Crossing and Mount Nancar). This has led to an overestimate of the system reliability when the model is referenced against recorded streamflows.

To address this shortcoming, DLRM have developed a new licence assessment methodology. This uses the difference between the entitlement model scenario discharge and the natural model scenario discharge, but then evaluates this against the observed discharge record (instead of the modelled natural scenario discharge). DLRM requested independent validation that this proposed methodology for evaluating licence applications is appropriate and suitable. This validation will consider the model, its inputs and outputs, hydrometric data used in the process, and the process which applies the model outputs to evaluate licence reliability.

1.2 Review objectives and scope

This project seeks to establish whether the methods used to determine the reliabilities attached to the licences in the Daly River system are valid

Objectives

A. Confirm the approach taken and model data outputs used to derive reliability for the most recent ground water extraction licence applications in the Tindall Limestone – Flora Aquifer and the Oolloo Dolostone Aquifer based on potential impacts on Daly River stream flows; and
B. Verify and confirm the reliability calculations for those licence applications

Scope

1. Assess the suitability of the current Feflow and Mike11 connected modelling package used by DLRM to describe the potential impacts on Daly River stream flows associated with granting applications for water extraction licences;

2. Assess the suitability of the input data provided for the connected modelling package; the output data delivered by the modelling package; and the streamflow monitoring data used for the most recent licence applications being processed by DLRM; and

3. Assess the validity of the determinations made by DLRM for expected licence reliabilities for the most recent licence applications being processed by DLRM.

DLRM has also indicated that the review needs to focus on both the model and the method used to assess reliability. The review is not intended to be an exhaustive review of the simulation modelling, and relies on the available model development and calibration reports to confirm the accuracy and correct operation of the models.

The following points regarding the scope of the review are noted:

- the models were not run as part of the review process, and consequently model outputs provided by DLRM are assumed to be as described
- as the model has not been run, it has not been confirmed that the model has been correctly operated and is numerically stable
- the model is assumed to be as reported in the various development and calibration reports, i.e. that data used to develop the model, the configuration of the model, and the calibration performance, is as reported
- the licence reliability assessment process is not documented, and this was determined by inspection of the calculation spreadsheet and through discussions with DLRM staff
- the review has focused on evaluating the process with regard to the licences currently under consideration, and does not consider whether the process is well-suited to future applications
- the review has not considered whether the definition of licence reliability is appropriate, the nature of the environmental flow requirements, the adequacy of the 30 year timeframe of historical climate used for the assessment, or the initial conditions of the modelling period; these are taken as starting points for the review
- the review is intended to make conclusions about the current process rather than recommend alternative approaches

1.3 Structure of this review

This review includes the following sections:

- **Overview of the licence evaluation process**: An outline of the process to evaluate the prospective licenses, including how it relates to defined environmental flow thresholds, the available datasets, the current licence entitlements, and the simulation models.
- **Scope Item 1: Assessing the suitability of the current FEFLOW and MIKE11 model**
- **Scope Item 2: Assessing the suitability of model input, model output and streamflow data**
- **Scope Item 3: Assessing the validity of the determinations for licence reliabilities**
- **Summary**: Conclusions regarding the review objectives and scope

2 Overview of the license evaluation process

2.1 Rules for managing licence take

The level of protection of surface water minimum flows are based on the recommendations made in *Environment Water Requirements of the Daly River – Revision of Recommendations of Erskine et.al. 2004* (Erskine, 2004). This report specified criteria for environmental water requirements relating to minimum streamflows at Dorisvale Crossing and Mt Nancar gauging stations, and these are currently used to evaluate prospective future licences.

These requirements are stated in terms of a maximum permissible impact to *natural* dry season flows at the two gauging station. The form of these requirements is (DLRM, January 2016):

- Consistent with the environmental water requirements of the Daly River (2004), the combined effect of all groundwater and surface water extractions should not reduce natural flows in the Daly River:

(a) at Dorisvale Crossing gauge station G8140067 by

(i) >8% whenever natural flow is ≤6.2 cubic metres per second; or

(ii) >20% whenever natural flow is >6.2 cubic metres per second

(b) at Mount Nancar gauge station G8140040 by

(i) >8% whenever natural flow is ≤12 cubic metres per second; or

(ii) >20% whenever natural flow is >12 cubic metres per second

Tindall Limestone Aquifer

The Tindall Limestone Aquifer -Katherine annual allocation is based on the forecast flow at Katherine Railway Bridge on the 1st November. The surface water – groundwater model is used at the end of the wet season to estimate the future flow. Table 3 of the Tindall Limestone Aquifer Water Allocation Plan specifies the extraction limit on the aquifer, based on the expected flow.

2.2 Licences currently under evaluation

DLRM considers new licence applications as these applications are validated and finally lodged. DLRM is currently considering a number of applications for licence entitlements in the system. These are summarised in Table 1 below

Table 1 Modelling Undertaken for Licence Applications

MODELLING FOR OOLLOO & TINDAL LIMESTONE FLORA LICENCE APPLICATIONS	
Model Run 1	All unlicensed and licensed water entitlements prior to licence applications under consideration
Model Run 2	Run 1 + Application for licence on NT Portion 2978
Model Run 3	Run 2 + Application for licence on NT Portion 2530
Model Run 4	Rune 3 + Application for licence on NT Portion 709
Model Run 5	Rune 4 + Application for licence on NT Portions 1166 & 4305

2.3 Reliability definition

Based on the National Water Initiative (NWI) definition; DLRM defines reliability as *the frequency with which a water extraction licence is able to be allocated its maximum water entitlement (ML/yr)* (National Water Commission, 2004).

This reliability measure indicates how often all Oolloo Dolostone Aquifer licences (High, Medium and Low security) can be supplied without any restriction on their allocation being required. It does not provide any information about how much allocation each of the High, Medium and Low security category licences would receive when the annual extraction limit is smaller than the maximum entitlement (i.e. the available resource is smaller than the granted licences at 100% allocation).

2.4 The licence evaluation process

The process for working out licence reliabilities for the most recent licence groundwater extraction applications in the Tindall Limestone Aquifer and Oolloo Dolostone Aquifer is as follows:

1. **Estimate natural (no extraction) discharge series**: Simulate natural streamflow discharges using the surface water – groundwater model for the period 1960 to the current day
2. **Estimate Tindall Limestone Licence extractions**: Based on the simulated natural discharges at Katherine Railway Bridge, calculate the annual allocations for the Tindall Limestone Aquifer as per the Tindall WAP Table 3; restrict each licence according to these annual allocations to get a time series of Tindall Aquifer extractions
3. **Prepare a current licence entitlement model simulation**: Set up and run a model with all licences in place for the full simulation period (1960 onwards); this will include:
    - Extractions by Tindall Limestone Aquifer licences as per Step 2 (i.e. restricted according to estimated annual allocation)
    - Extractions by Oolloo Dolostone Aquifer licences to their maximum entitlement for every year (i.e. not restricted according to annual allocation)
4. **Estimate pre-existing Oolloo Dolostone Aquifer licence reliability**: From the simulation in Step 3, for the last 30 years of the simulation calculate the reliability (this is percentage of years that all existing licences of all securities can be supplied without breaching the criteria in Section 2.2)

5. **Prepare a new licence entitlement model scenario**: Set up and run a model with all existing and the prospective new licence in place, with all Oolloo Dolostone Aquifer licences extracting at maximum entitlement
6. **Estimate the Oolloo Dollostone Aquifer reliability with the new licence in place:** Perform the same reliability calculation as Step 4 but using model results with the prospective licence in place

2.5 Licence reliability value

Section 2.4 outlines the process of determining the licence reliability. The reliability calculation stated in Step 4 and Step 6 is reviewed in more detail in this section.

The environmental water requirements (Section 2.2) specify limits to the impact of the extractions in terms of a *maximum percentage change to the natural flow.* These criteria are used to determine whether all licences receive full allocation in a particular year

To determine the reliability using these criteria for the pre-existing licences:

1. The discharge time series at Mt Nancar and Dorisvale Crossing gauging stations are taken from the simulated natural scenario (S) and the pre-existing licence scenario (E)
2. The impact of the pre-existing licence scenario on streamflow is calculated as S – E (m^3/s)
3. The actual observed discharge time series for Mt Nancar and Dorisvale Crossing gauging stations is now taken to be the natural flow (N)
4. The percentage change to the natural flow is calculated for every day in the 30 year period; for the pre-existing licence scenario this is (S - E)/N
5. The number of days that fail the maximum percentage change criteria are added up for each water year
6. If no single day fails the criteria in a year, that year is considered reliable
7. The pre-existing licence reliability is then the number of reliable years as a percentage of 30 years

The same process is used to calculate the prospective licence scenario reliability, i.e. the discharge time series from the prospective licence scenario run is P, the impact is estimated as S – P (m^3/s), and percentage change for every day is calculated as (S – P)/N.

This section of the review will look at two aspects of this reliability calculation: the definition of reliability and its use; and the assumptions regarding natural flow. The next section (surface water – groundwater model review) will look at the impact calculated by the model (S - E and S - P), and consider the assumptions and uncertainties in these values.

3 Scope Item 1: Suitability of FEFLOW and MIKE 11 connected modelling package

This section of the review focusses on assessing the suitability of the current FEFLOW and MIKE 11 connected modelling package used by the DLRM to describe the potential impacts on Daly River stream flows for purpose of assessing water extraction licences.

The review references the best practice guidelines for groundwater model development and review (Barnett et al, 2012).

Comments are provided for the purpose of communicating DHI views on the suitability of the model for the intended purpose and recommendations for addressing limitations.

DHI has reviewed the modelling based on the primary documentation supplied by DLRM, including:

- Preliminary Groundwater Modelling of the Oolloo Dolostone (Knapton, 2005)
- Regional Groundwater Modelling of the Cambrian Limestone Aquifer System of the Wislo, Georgina and Daly Basin (Knapton, 2006)
- Integrated Hydrologic Modelling of the Daly River Catchment and Development of a Water Resource Monitoring Strategy (URS, 2008)
- An Investigation into the effects of Climate Change and Groundwater Development Scenarios on the Water Resources of the Daly River Catchment using and Integrated Groundwater/Surface Water Model (Knapton, 2010)
- Recalibration of a Coupled Surface Water – Groundwater Model to the Low Flows in the Daly River Catchment (Knapton, 2011)

The overarching objective for development and application of the model is stated by DLRM as being to quantitatively describe the potential impacts on Daly River stream flows for purpose of assessing water extraction licences. The significance of the model results for the purpose of making decisions regarding licence approvals is considered high.

The model confidence classification (Barnett et al, 2012) refers to a semi-quantitative assessment of the degree of confidence with which a model prediction can be used. The confidence level classification takes into consideration the availability of data (for conceptualization and calibration), calibration procedures and currency, the consistency between the calibration and predictive analysis and the level of stress applied in predictive simulations (compared to calibration).

Limited documentation synthesizing all available hydrogeological data and the conceptual model available for this review. As with all model the FEFLOW model is a simplified representation of the groundwater system. For example the model represents the unconfined portion of the Oolloo Dolostone and Tindall Limestone with exclusion of confined portions. The hydraulic parameterization of the Oolloo Dolostone and Tindall Limestone is vertical homogeneity. These simplifications may not represent heterogeneities in the real system and the impact on predicted results should be considered.

Review of model validation, calibration and sensitivity analysis for the period since mid-2011 incorporating new observation points (if available) would further inform model confidence level.

However, the review of factors relevant to assessing model confidence classification indicates the model has a Class 2 confidence level classification, with some elements achieving Class 3. While being qualitative, this classification indicates the model has been developed in a manner that aligns with the objective for development of the model.

4 Scope Item 2: Suitability of input and output data from FEFLOW / MIKE 11, and measured stream flow data

In this section the suitability of model input data and model output data from the FEFLOW and MIKE 11 connected modelling package are considered.

Model scenario input data includes:

- Rainfall and NAM inputs
- MIKE SHE recharge estimates
- Pumping schedules

FEFLOW/MIKE 11 outputs include:

- Simulated natural groundwater levels and stream discharges (natural scenario)
- Simulated groundwater levels and stream discharges under prescribed pumping scenarios (pumping scenario).
- Calculated difference in average daily stream discharge between the natural scenario and pumping scenario.

Measured stream flow, though not a direct input to the model scenario is the reference for establishing threshold values for acceptable change in baseflow and the reference level for calculating the percentage change in base flow. The validity of the measured stream flow is also commented on in this section.

4.1 Suitability of Rainfall and NAM inputs

The river basin catchment is represented using a NAM lumped conceptual rainfall runoff model. The conceptual structure of NAM distinguishes surface, shallow (root zone) subsurface and deep subsurface (groundwater) components. The total runoff from the model is partitioned into surface runoff, interflow and baseflow components.

The NAM model uses point time series at rainfall stations from SILO data. This SILO data is used to derive Mean Area Weighted subcatchment rainfall and potential evapotranspiration time series as input to the model. This is a common approach used to develop long-term hydrological time series inputs, especially where the rainfall records are not continuous or stations are sparse. It may produce poor results when trying to reproduce runoff from short duration storms, when trying to reproduce the short term water balance from a storm, or when estimating longer term runoff from subcatchments with strong rainfall gradients or orographic effects.

Attempts were made as part of the Northern Australia Sustainable Yields project (2010) to improve the calibration by trialling the use of spatially distributed rainfall data instead of point estimates. This was reported as not having improved model performance (Knapton, 2015).

However the NAM model schematisation has to be considered in terms of its intended use. The licensing application of the model is focused on simulating dry period discharges at lower river gauging stations. These discharges are unlikely to be sensitive to the model's ability to reproduce short-term events. In order to accurately model dry season flows it is more important that the NAM model simulates the overall wet season-scale water balance, the wet season net groundwater recharge, and dry season baseflow discharge.

It is noted that SILO datasets are updated from time to time, as new data becomes available or when changes are made to the algorithm used to derive the gridded series. When the later of these occurs this may lead to changes in the historical rainfall and evaporation series that are extracted for use in the model. DLRM have not identified this as an issue in any model documentation however it is understood this was raised during discussions with the Science Review of Environmental Water Requirements for the Daly River expert panel (Cox et. al., 2015). It is recommended that any inconsistencies arising from past changes to SILO data are documented, and that the sensitivity of the licence reliability process to these changes investigated.

4.2 Suitability of MIKE SHE recharge estimates

The MIKE SHE integrated modelling system is used to generate recharge rates used in the FEFLOW / MIKE 11 model scenarios. Recharge is applied consistently for the natural scenario and pumping scenario's. Processes controlling recharge are inherently complex. Previous method of estimating recharge using a soil moisture deficit model have been updated with application of MIKE SHE model. MIKE SHE is a fully integrate catchment model capable of simulating infiltration taking into account many physics based processes. The selection of MIKE SHE has been based on suitability to represent major recharge processes including recharge through macro-pores which bypass the unsaturated zone.

The development of the MIKE SHE model is not described in the reports however discussion in the reports of comparisons with data driven recharge estimates including hydrograph analysis and chloride mass balance provide some validation for the MIKE SHE model recharge estimates as does overall calibration of the model.

The development of recharge estimates for the FEFLOW model are considered appropriate and consistent with the objectives.

Uncertainty associated with recharge estimates and impact on FEFLOW / MIKE 11 model outputs should be assessed.

4.3 Suitability of Pumping schedules applied in FEFLOW / MIKE 11 Model

The pumping schedule assigned to the FEFLOW / MIKE 11 model pumping scenarios represent the full allocation under each scenario. Pumping begins in 1960 through to the present day, with the last 30 year period being the focus of analysis.

The effect is to create a quasi steady state condition representing ongoing pumping at the allocation level prior to the assessment period. It is likely that this approach reduces storage in the aquifer prior to the period of the assessment and therefore the magnitude of the change in base flow (when compared to the natural scenario at equivalent points in time) would be different to starting the model pumping scenario with present day groundwater levels. It is probable that the approach is conservative with respect to predicting the change in baseflow between the natural and pumping scenarios in the sense that reduction in base flow is over estimated.

4.4 Suitability of FEFLOW / MIKE 11 outputs

Decision making regarding licence allocation is primarily based on the calculated difference in stream discharge. This approach is consistent with best practice guidelines (Barnett, et al, 2012).

The development of the model and inputs for the scenarios are considered suitable for the stated objectives however, based on knowledge that a single true model cannot be constructed (Barnett et al, 2012) the current industry practice is to provide quantitative estimates of uncertainty associated with model outputs to be used in decision making. Uncertainty can arise from a number of sources including error in field measurement (used in development of the model) and the simplifying assumptions made in development of the models (structural error).

While considerable effort has gone into calibrating the model, with particular focus on the intended outputs of the predictive scenarios (stream flows) the outputs of the FEFLOW/ MIKE 11 model are generated with a single set of model parameters and input data and thus no estimate of uncertainty is provided. The implication for model outputs of noted variability in stratigraphic and lithological characteristics, in regions of the model domain that have increased sensitivity (with regards to model outputs) should be evaluated.

DHI recommend that quantitative assessment of uncertainty associated with current model outputs is undertaken and considered in assessing the licence application.

4.5 Suitability of measured stream flow data

The assessment methodology relies on measured streamflow series at Mt Nancar (8140040) and Dorisvale Crossing (8140067). These measured series are used as an estimate of the natural historical discharge at the gauging stations.

The impact at Dorisvale Crossing is assessed relative to the threshold discharge of 6.2 m^3/s. Figure 4 compares gauged discharges against the equivalent discharge calculated from the rating curve for the site, from 1984 onwards. There are no recent gaugings of a similar magnitude to the Dorisvale threshold. Older values indicate an average error of approximately 11% for discharges within the range 4-8 m^3/s, which is a typical level of error for a long-term site with a stable rating which is updated on a regular basis. There was no bias towards over or under prediction within this discharge range. This indicates that rating curves have generally been accurate in the past within this range, and the site is reliable as an estimate of discharges in the historical period.

However it is noted there have been no gaugings at the site below 8 m^3/s since 1997, and a review of older gaugings indicates that the site has had different low flow – water level characteristics in the past. Figure 5 shows gaugings since 2004 (green), all older gaugings including those prior to 1984 (grey) and the current rating. While the current rating is consistent with the gaugings of 8 m^3/s or above, there is no gauging confirming that the current rating below 8 m^3/s is still valid. This is probably due to the wet climatic conditions in the catchment since the mid-2000's, meaning flows within this low range have been relatively rare anyway. However given the site has some history of variation in the rating at lower water levels, it is highly recommended that low flow ratings are carried out.

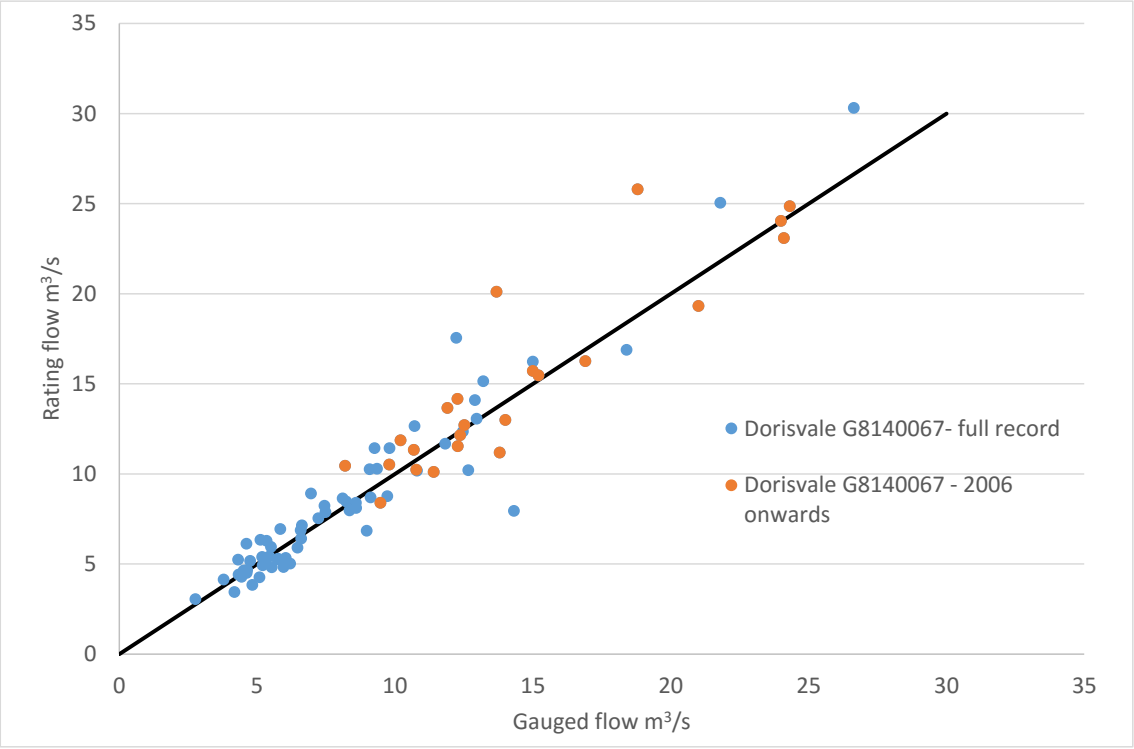

Figure 4 Comparison of gauged and rated discharge at Dorisvale Crossing G8140067 (calculated using ratings relevant to the selected gauging period)

Figure 5 Comparison of all gaugings for Dorisvale Crossing G8140067 against the current rating (Bureau of Meteorology Water Info website, 11 March 2016)

Similarly, the impact at Mt Nancar is assessed relative to the threshold discharge of 12.0 m^3/s. Figure 6 compares gauged discharges against the equivalent discharge calculated from the rating curve for the site. As was seen for the Dorisvale Crossing site, there are no recent gaugings of a similar magnitude to the threshold. Older values indicate an average error of approximately 7% for discharges within the range 8-16 m^3/s, which is a good level of error for a long-term site with a stable rating. There was a small bias (on average 5%) towards over-prediction by the rating curve within this discharge range. This indicates that rating curves have generally been accurate in the past within this range, and the site is reliable as an estimate of discharges in the historical period.

Again, as was seen at the Dorisvale Crossing site there have not been low flow gaugings since 2006, probably due to the wet climatic conditions and higher dry season flows since the mid-2000's. Consequently it is unknown whether the current rating curve is accurate for low flows and this should be investigated.

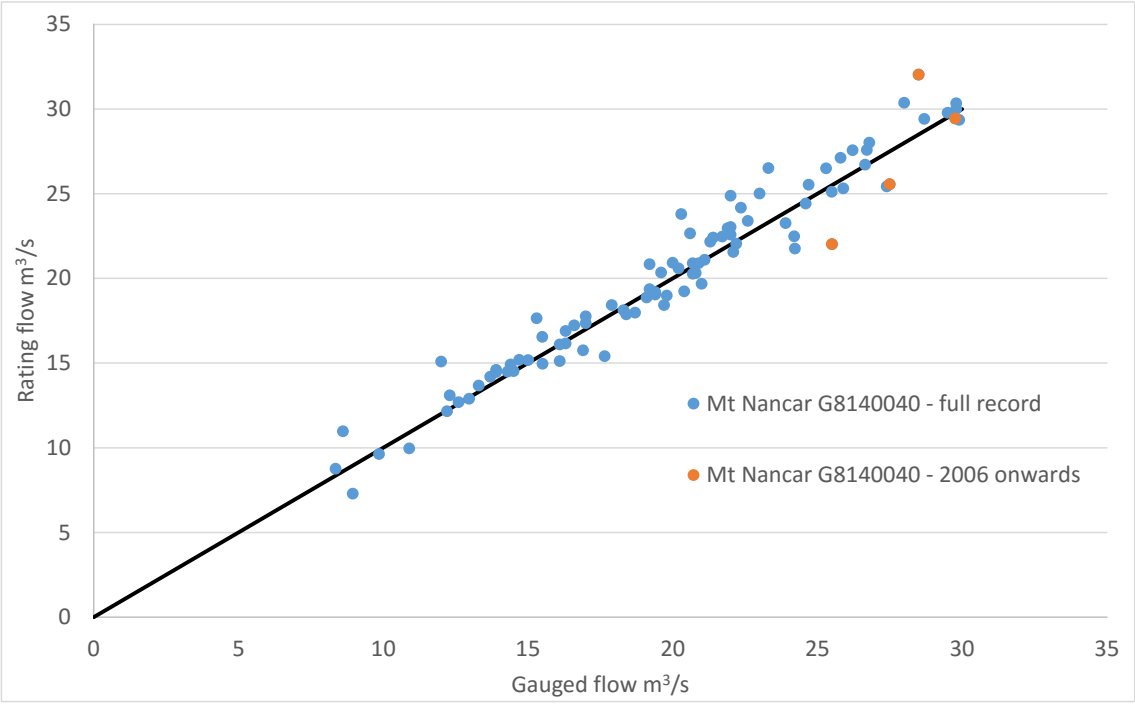

Figure 6 Comparison of gauged and rated discharge at Mt Nancar G8140040

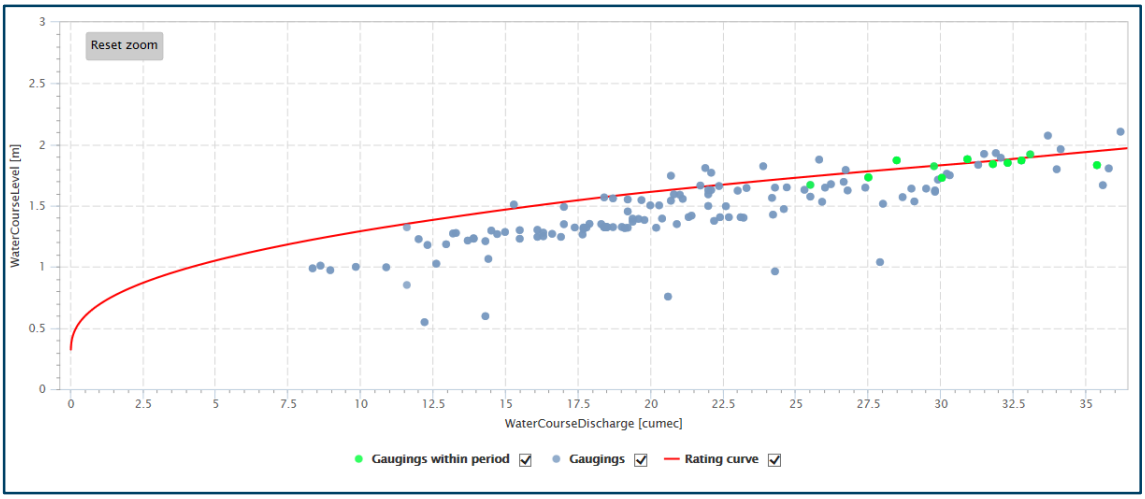

Figure 7 Comparison of all gaugings for Dorisvale Crossing G8140067 against the current rating (Bureau of Meteorology Water Info website, 11 March 2016)

In summary, the accuracy of the two gauging station site discharge records appears to be relatively good, when discharges calculated by historical ratings back to 1984 are compared against their simultaneous gauged discharges. Overall the records are sufficient for the purposes of this reliability assessment, especially when it is consider the thresholds themselves are likely to have calculated based on the discharge records. However there are no low flow gaugings in the range of the discharge thresholds at the sites since the mid-2000's, probably due to relatively wet catchment conditions. This means there is greater uncertainty in the accuracy of those low discharges that did occur in that period.

5 Scope Item 3: Assessment of validity of determinations for most recent licence applications

The licence determination process is outlined in Section 2. This includes the definition of the licence reliability applied by DLRM (Section 2.3), the licence evaluation process (Section 2.4) and the licence reliability calculation (Section 2.4). This section reviews how DLRM have implemented this process to determine licence reliability. It considers how the inputs, assumptions or processes of each of the following affect the outcome:

- The application of model outputs to the calculation
- The natural flow series used in the calculation
- The DLRM spreadsheet used to make assess reliability
- Documentation of the process

5.1 Application of modelled impacts to the calculation

5.1.1 Streamflow impact uncertainty

As outlined in Section 2.4, two time series outputs from the model are used in the reliability calculation. These are the modelled gauging station discharges for the *licensed extraction model scenario* and the *model natural scenario*. The impact of the combined extractions is the difference between these two modelled time series. This impact time series is the only model information used in the reliability calculation.

Error in the licensed extraction model and natural model outputs propagates into the modelled streamflow impact, which is calculated as the difference between these two series (Section 4 discusses the uncertainty in the model outputs). DLRM's current approach does not appear to consider the uncertainty in the modelled outputs or how this impacts the modelled streamflow impact. Past calibration reports have assessed the sensitivity of individual model run outputs to changing input parameters (Knapton, 2012). But there is no evidence that the uncertainty in the streamflow impact time series has been assessed (i.e. the uncertainty in the difference between two model outputs).

Uncertainty is reduced compared to the previous approach, as the current approach uses the difference of two model results (Barnett, 2012). However the current approach still relies on a single modelled impact series to evaluate licence reliability. It does not consider the range of uncertainty in that single modelled series, and how that translates into uncertainty in the licence reliability calculation outcome.

A preferable approach would be to test the effect model output uncertainty has on modelled streamflow impact, and then look at the range of possible licence reliability outcomes this produces.

5.1.2 Licence scenario extraction assumption

The reliability indicates how often all Oolloo Dolostone Aquifer licences (High, Medium and Low security) can be supplied without any restriction on their allocation being required. It does not provide any information about how much allocation each of the High, Medium and Low security category licences would receive when the annual extraction limit is smaller than the maximum entitlement (i.e. the available resource is smaller than the granted licences at 100% allocation).

The scenario models are set up to continuously extract at the maximum entitlement rate for each licence, regardless of whether the streamflow falls below the thresholds for allocation restrictions or not. This approach is relatively conservative, as it if in a dry year the Oolloo Dolostone aquifer is

depleted by the assumed maximum extraction, and groundwater levels are drawn down, then the aquifer will be lower at the start of the next dry season. This may lead to failure to supply the second year, when restrictions in the first year may have been sufficient to avoid this. Consequently this approach may lead to an underestimate of reliability.

5.2 Use of observed (recorded) stream flow

The new methodology for the licence reliability analysis uses the observed discharge record as the natural discharge at the Mt Nancar and Dorisvale Crossing gauging stations. The modelled impact (modelled licence extraction streamflow – modelled natural streamflow) is then subtracted from the observed discharge to calculate the impacted discharge.

This approach assumes that historical extractions have had little impact on the observed discharge records at the gauging stations, and that the observed (monitored) flow is an accurate measurement. Whether this assumption regarding natural discharge affects the current licence determination depends on:

- whether the aquifer has already been affected significantly by increased extractions; and
- whether the years in which this has occurred have been relatively dry, and whether the observed discharges get as low as the minimum gauging station discharges.

It is difficult to determine directly from observations whether the aquifer levels and dry season streamflows have already been affected by extractions. In this system both borehole and gauging station observations are strongly affected by inter-annual and inter-decadal scale variability in the hydrology, making it difficult to detect trends solely due to increased pumping.

Furthermore, the allocation system only restricts extractions in years when the resource is constrained (i.e. the extraction limit determined for that year is less than the total licensed volumes). If such limits were being applied in years when pumping had historically been happening, then any impact this existing pumping had on the observed flow (i.e. assumed natural flow) would have affected the estimated reliability of the new licence.

Licensed entitlements in the aquifers are summarised in Table 2. In the Oolloo Dolostone aquifer, these increased from 2,900 ML/yr in 2004 steadily to 24,636 ML/yr in 2013, and then jumped to 65,970 ML/yr in 2015. In the Tindall Limestone Aquifer (Katherine) entitlements increased from 22,468 ML/yr in 2003 to 27,029 in 2005, and jumping to 35,324 ML/yr in 2009 and reducing slightly to 35,237 ML/yr in 2015. Both aquifers have seen significant increases in entitlements since the late 2000's.

Table 2 Aquifer licensed entitlements

Year	Tindall Limestone Aquifer (ML/yr)	Oolloo Dolostone Aquifer (ML/yr)
2003	22468	N/A
2004	23923	2900
2005	27029	4635
2006	27029	6785
2007	27029	10550
2008	27029	16501
2009	35324	23760
2010	35324	23760
2011	35309	24636
2012	35283	24636
2013	35272	24636
2014	35237	56604
2015	35237	65970

In the Oolloo Dolostone Aquifer, the increase in licence entitlement and the associated increased historical extractions (which are likely to be considerably less than the maximum licence entitlement) have coincided with years of above average rainfall. At the Mt Nancar gauging station modelling by DLRM has indicated no need for licence allocation restriction from 2005 onwards in any of the new license scenarios. At the Dorisvale Crossing gauging station the DLRM modelling does indicate some restrictions on licences in years coinciding with or after the increase in entitlements.

The licences in the Tindall Limestone – Katherine Aquifer were 22,468 ML/yr in 2003. Given the length of time these licences have been present, there is the potential for the observed discharge record to have been affected by the extractions from the aquifer. If this is the case then the observed record underestimates the natural discharge.

5.3 The DLRM licence reliability spreadsheet

DLRM uses Excel spreadsheets to determine the licence reliabilities for the different licence scenarios, at the Dorisvale Crossing and Mt Nancar gauging stations. These spreadsheets use the modelled impact time series and the natural (observed) discharge as inputs, in order to calculate the number of years in which licensed extractions can occur without reducing streamflows below the environmental water requirement thresholds.

The spreadsheets work as follows:

- Model results are imported for the natural model and each licence scenario
- The scenario impact is converted to a percentage (model scenario – model natural)/observed discharge

- The permissible percentage change in the threshold is calculated based on the observed discharge
- The scenario percentage change is compared against the permissible percentage change; if the scenario exceeds the permissible percentage, the day in which this occurs is marked as unreliable (using a flag value of 1)
- A pivot table is used to sum all days in each year when a flag value of 1 occurs
- The number of restricted years is the count of all years where >0 flags occur
- The number of unrestricted years is the count of all years where no flags occur
- The reliability is the number of unrestricted years as a percentage of all years evaluated (30 years)

Formulas in the spreadsheets were reviewed, confirming that they are consistent with the intended licence reliability assessment process, and that there are no apparent calculation errors.

5.4 Documentation of the licence reliability assessment process

In some cases additional documentation is required, or documentation relevant to the scope was unavailable for review. This includes:

- Current documentation synthesising all available hydrogeological data and the conceptual model;
- Reporting of Feflow / MIKE11 model sensitivity analysis that has been carried out in the past;
- Reporting of Feflow / Mike 11 model calibration and sensitivity analysis for the 2011 to 2015 period.
- A detailed account of DLRM's integrated assessment approach, including how it relates to the declared and draft Water Allocation Plans and the environmental water requirements;
- Documentation of the current licence reliability assessment methodology, including preparing historical input data series, setting up model inputs and model initial conditions, extracting model results, and analysis of the model results to produce the reliability assessment; this documentation should include a step-by-step account of how the assessment is carried out;
- Documentation of key assumptions in the reliability assessment process such as the assumed pumping rates in the model, the initial conditions chosen for the model run, the time frame for the model run and the period chosen for the assessment

6 Conclusions

Scope Item 1: Suitability of FEFLOW / MIKE 11 model

- **Conclusion 1:** The review concludes that the development of the FEFLOW / MIKE 11 model is suitably aligned with the objective to describe the potential impacts on Daly River streamflows for the purpose of assessing water extraction licences.
- **Conclusion 2:** Methods of characterising recharge are based on earlier application of water balance hydrograph analysis (Jolly, 2002), a Soil Moisture Deficit Model (Knapton, 2005, 2006) and later a physics based MIKE SHE model. These approaches represent the current and best practice approaches. It is acknowledged that the mechanisms of recharge in a karstic system are not fully understood and that these approaches may not represent adequately all recharge processes.

Scope Item 2: Suitability of input data and output data from FEFLOW / MIKE 11 model

- **Conclusion 3**: Rainfall inputs are point time series extracted from SILO data used to form subcatchment Mean Area Rainfall series. Using this approach may not accurately reproduce the historical spatial rainfall distribution, however this is unlikely to be significant at the seasonal timescales of most relevance to the licence reliability assessment. SILO data may change as the algorithms used to derive the rainfall and evaporation series are updated. It is recommended that any inconsistencies arising from past changes to SILO data are documented, and that the sensitivity of the licence reliability process to these changes investigated.
- **Conclusion 4**: Input observed streamflow records at the key gauging stations of Mt Nancar and Dorisvale Crossing appear to be reliable with rating error typical of good long-term sites. There have been no recent gaugings in the low flow range since the mid-2000's due to wet catchment conditions, and this suggests some uncertainty about the accuracy of low range discharges since then. However this is unlikely to affect the licence reliability assessment process given the relatively wet conditions over this period.

Objective 1: Confirm the approach taken and model data outputs used to derive reliability for the most recent ground water extraction licence applications in the Tindall Limestone – Flora Aquifer and the Oolloo Dolostone Aquifer based on potential impacts on Daly River stream flows

- **Conclusion 5**: Detailed documentation of DLRM's integrated assessment approach to assessing individual licences should be produced. This should explain the principles behind the assessment approach, how it relates to the Water Allocation Plans and environmental water requirements, how licence security is determined from the process, what the key assumptions in the assessment are, and what the modelling and analysis steps in the assessment are.
- **Conclusion 6**: This review has found that the model and model outputs produced are generally satisfactory, and suited for the purpose of licence reliability evaluation. However, the overall approach does not adequately consider the potential impact of model error on the licence reliability calculation. The current approach adopts the modelled streamflow impact series without considering the uncertainty in this time series, and without quantifying how this translates into uncertainty in the licence reliability outcome. As stated in the Australian Groundwater Modelling Guidelines: "Because a single 'true' model cannot be constructed, modelling results presented to decision-makers should include estimates of uncertainty" (Barnett, 2012). **[Note additional work undertaken by DLRM satisfies the Reviewers recommendations. Further details are at the Addendum in Section 7 of this report].**

- **Conclusion 7**: The observed (measured) streamflow is used as the natural (unmodified by extraction) streamflow in the assessment process. Past aquifer pumping has potentially affected streamflows although this is less likely in the Oolloo Dolostone Aquifer. The observed series may therefore underestimate the natural discharge series which could lead to an underestimate of reliability. However as the climate has been wet since the mid-2000's with few restricted years this assumption is unlikely to have affected the licence scenarios being considered in this review.
- **Conclusion 8**: The assessment assumes licence extraction at full entitlement continuously throughout the scenario simulations. This is a conservative approach likely to overestimate impact.

Objective 2: Verify and confirm the reliability calculations for those licence applications

Scope Item 3: Assessment of validity of determinations made for expected licence reliabilities for the most recent licence applications being processed by DLRM

- **Conclusion 9**: The spreadsheet used by DLRM to carry out the assessment has been reviewed and confirmed to be consistent with the intended licence reliability assessment process, and no apparent calculation errors were found.
- **Conclusion 10:** The accuracy of the reliability calculations cannot be verified until the effect of model output uncertainty on modelled streamflow impact and licence reliability has been tested and documented**. [Note additional work undertaken by DLRM satisfies the Reviewers recommendations. Further details are at the Addendum in Section 7 of this report].**

7 Addendum – 15 April 2016

Following the recommendations of the Goyder Institute independent review, DLRM undertook predictive sensitivity analysis to investigate the potential range in estimated licence reliabilities resulting from alternative model parameterisations for the Daly water resource assessment model. The uncertainty analysis was submitted to the Reviewers on the 10th April 2016 for evaluation.

Specifically, DLRM evaluated model uncertainty by undertaking a predictive sensitivity analysis. During the 2008 model calibration, sensitivity analysis was undertaken by developing 100 alternative models. These used parameters sets derived from the potential calibration distribution of recharge scaling and hydrogeological properties. From the alternative calibration models, DLRM selected five models from the 100 alternative calibration models, with parameter sets representing the minimum, 25th percentile, median, 75th percentile and maximum ranked average flows. The median model was the model that was used for the December 2015 modelling (and is used for all operational modelling).

It is assumed that these models represent the range of parameters that result in a reasonably calibrated model and/or known variability in the hydraulic parameters. The five parameter sets have an average coefficient of variability for hydraulic conductivity, specific yield, transfer rate and recharge rate of 49%, 36%, 54% and 2% respectively.

DLRM ran Natural (no pumping) and Scenario 10 (SC10) pumping scenarios for each of the five predictive uncertainty analysis models (a total of 10 models). For both Mount Nancar and Dorisvale Crossing gauging stations, the average coefficient of variation between the models for the modelled natural and scenario flows, is around 2% for the period 1984 to 2014, and 5% for the period 2011 to 2014. These results indicate that the predicted streamflows are not sensitive to the variability in the five parameter sets tested.

Furthermore, the reliability calculated at the Mount Nancar gauging station was the same for all of the five model parameter sets tested. The reliability calculated at the Dorisvale Crossing gauging station by each of the models was within a range of 3% of the median model parameter set result.

On the basis of the analysis and results listed above, the Reviewers concluded that the results of the median model parameter set are a reasonable representation of the results of the parameter ranges tested.

Conclusion

This additional predictive uncertainty work undertaken by DLRM adequately addresses the issues raised by the Reviewers in Items 3, 4, 10 and 15 of the Executive Summary, and the corresponding Conclusions in Section 6 of this report. The Reviewers confirm that the predictive uncertainty analysis is adequate and appropriate, and accept the outcomes of the work undertaken. On this basis, the reviewers can confirm the outcomes of the reliability assessment and that the objectives of this report are confirmed by this review.

8 References

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