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Donnelly River model review

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1 Executive summary

The Donnelly River Model was prepared for the Department of Water and Environment Regulation (DWER) by an external consultant (Hydrology and Risk Consultants) in 2018. The purpose of this model was largely to evaluate the feasibility of a proposed irrigation development centred on diversions from the Middle Donnelly near Chappel's Bridge into a reservoir in the nearby Record Brook catchment. Model methods and simulation results including future climate scenarios are outlined in HARC (2018).

As a part of the model build and reporting process, the HARC report was reviewed by Eco-Logical Australia (2018) against the model specifications outlined in the document DWER100418. ECL concluded that the model was ”fit for purpose”, but made many recommendations, for example *”in future updates to the modelling, further investigation into the surface water - groundwater interaction within the Basin should be undertaken and incorporated into the modelling”*. Since report release, concerns have been raised related to model methods and predictions under future climate scenarios. As a result, the CSIRO was contracted to undertake a further model review to address these concerns as outlined in the terms of reference (see Section 2).

Model future climate data used a baseline historical period of 1961 - 1990, and these data were scaled using GCM information as outlined in Department of Water (2015). The baseline period used was particularly wet in the Donnelly catchment and featured a significant trend, both of which created issues for future climate data. Due to continued reductions in rainfall across the catchment over the period since the end of the baseline historical period, some of the future climates have higher mean rainfall than recent observed rainfall. Given that all future climates were intended to represent a drier future, these future climates time-series are not appropriate and should not be used.

Hydro-climate ”non-stationarity” in the south west of WA has been acknowledged in academic publications for over 10 years. This phenomenon relates to the drastic reduction in runoff with declining rainfall. Moreover, the proportion of rainfall returned as runoff falls such that even in wetter years, runoff does not return to proportions once experienced. These processes are related to the depth to groundwater. Examination of available data strongly suggests that these processes are occurring at least in the forested portions of the Donnelly River catchment. This means that the chosen model, GR4J, is very likely to over-predict runoff in conditions drier than those experienced in calibration. This was particularly apparent in the Middle Donnelly where, under the ”Dry 2050” scenario, mean runoff coefficient was greater than 4% , with no obvious reduction of runoff in the driest years. Similarly, over-prediction was apparent in the Record Brook catchment.

It is recommended that:

1. The DRM use a model capable of predicting reliably in conditions of ”non-stationarity” e.g. LASCAM, GR7/8J, as opposed to GR4J
2. Climate future time series be updated using the latest GCM outputs available (probably CMIP5), and update the baseline period to as recent as reasonably possible.
3. The use of loss functions in the DRM should be abandoned or at least applied uniformly. They were not applied in key locations such as the Middle Donnelly where water is to be diverted for the SFIS
4. ”Split sample” calibration - validation should not be used in non-stationary situations, but

rather all possible data be used

5. A review of available stream gauge data be conducted to act as a reference with which to judge what might be expected in various future climate scenarios
6. Any estimated streamflow from future climate scenarios be analysed with reference to the review of data recommended above
7. Where possible re-instate monitoring at sites with historic streamflow and/or groundwater data. Consideration should be also given to improved monitoring in cleared areas.

2 Background

The West Australian Department of Water and Environmental Regulation (DWER) commissioned an external consultant (Hydrology and Risk Consultants - HARC) to build and calibrate a hydrological model in the Donnelly River area in South - West Western Australia. The primary intention of the model was to evaluate the viability of a development proposal that aims to improve water security and water distribution to irrigators in the Manjimup area. HARC outlined details of the construction and calibration of this model in a report published in December 2018 (HARC, 2018). Additionally, the model was reviewed by Eco-Logical Australia, who concluded the model was ”fit for purpose” (Eco-Logical Australia, 2018). Subsequent to public release of the model report, concerns were raised regarding model methods and streamflow predictions under future climate scenarios. As a result, the West Australian Department of Primary Industries and Regional Development (DPIRD) contracted the CSIRO to conduct a review of the model, the results of which this report documents. The terms of reference for consideration in this review were as follows:

1. Suitability of the monitoring data used and its applicability to support model assumptions with suggestions for improvements where appropriate
2. Commentary on the suitability of current climate data, and value and likely impact of applying revised (updated) data, to current forecast flows
3. Likelihood and the degree of any predicted changes in catchment rainfall runoff processes (non-stationarity) would affect yields and reliability of irrigation supplied from the proposed Record Brook Dam
4. Comment on the estimated future flows under historical climate, median dry and wet scenarios, the 30 year sequence used, with particular reference to the calculated reliability of 2030 Dry and 2050 Dry scenarios
5. Advise alternative approaches (if applicable) to derive forecast volumes for reliability of flows
6. Comment on assumptions made in the model that may affect quantification of the amount and reliability of flows
7. Suggest improvements to the data and model to inform future decisions where appropriate including the likely impacts/merits of doing so

2.1 Site details and brief model description

The location for model application and selected features of the the Donnelly River area are shown in Figure 2.1. However, for further details of the site, readers are directed to HARC (2018).

One of the main purposes of the Donnelly River Model (DRM) is to assess the feasibility of surface water diversion from the Donnelly River near the outlet of the Middle Donnelly subcatchment. This proposed diversion would pump water across the watershed to a reservoir located within the Record Brook sub-catchment. Stored water could then be re-distributed to irrigators via a pump and pipeline network. This proposal is referred to hereafter as the Southern Forest Irrigation Scheme (SFIS). Portions of the Upper Donnelly, Mid Donnelly and Manjimup Brook sub-catchments are largely cleared of forest and presently satisfy irrigation demand using on-farm storages and runoff capture. Most of the catchment area contributing to the outlet of the Middle Donnelly is uncleared, and the premise of the proposed irrigation development is that some of the additional runoff from the forested area could be harvested and used for irrigation. In addition to this, the DRM could also be used to assess the effect of water harvest on down

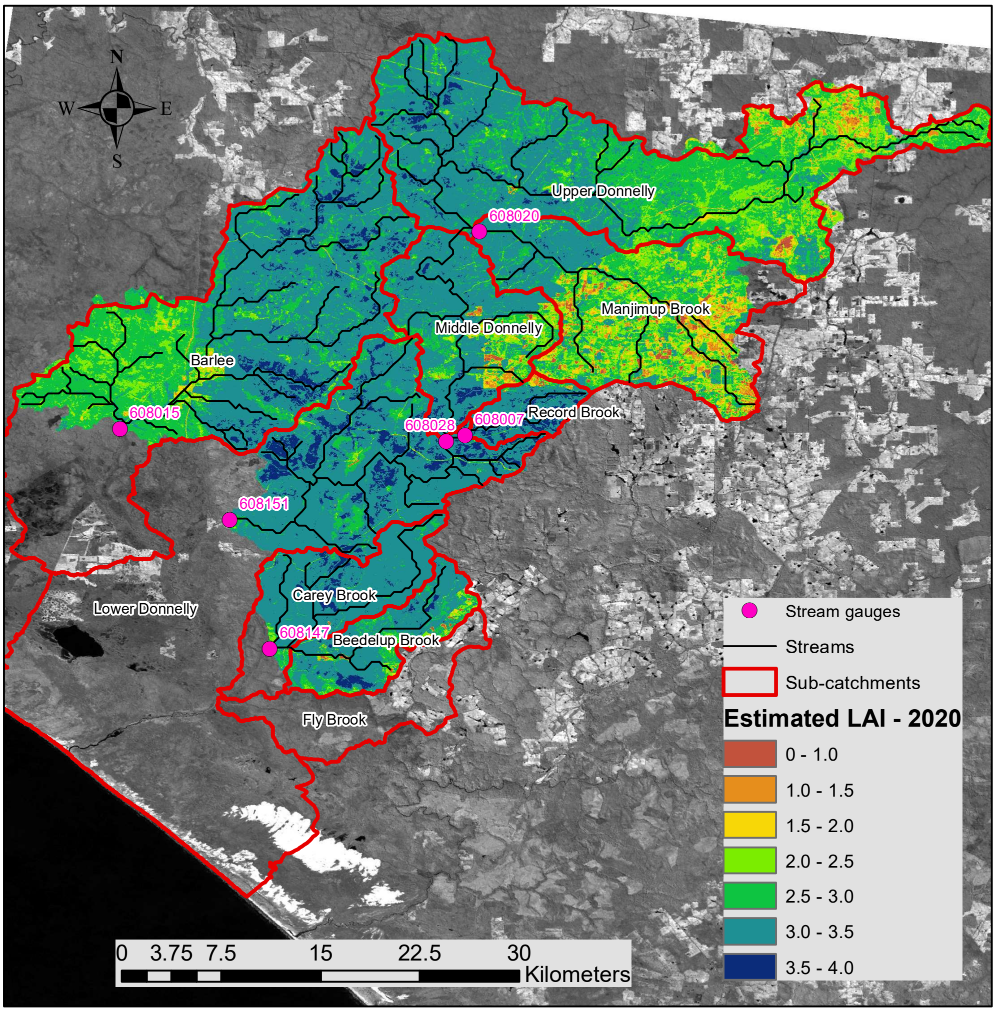

Figure 2.1: The Donnelly River model subcatchments showing selected gauge locations and estimated Leaf Area Index for the year 2020

stream flows. In most respects therefore, the DRM falls into the ”River system model” category, although it is described as ”Rainfall-runoff model” by HARC (2018). However, one of the most important components of the DRM, in terms of this review, was the rainfall-runoff model and its use within the DRM.

For the purpose of this review, analysis and discussion are restricted largely to the areas upstream of the Strickland gauge (608151), since this is the area from which either model parameters are derived, or simulations are used for estimation of yields from the SFIS. Observations and recommendations from these areas are generally applicable to the areas within the DRM since model methods are similar for all sub-catchments.

Model construction and calibration relied heavily on observation from four stream gauges; Strickland (608151), Record Brook (608007), Manjimup Brook (608020) and Chappels Bridge (608028). Of these, the Strickland gauge is by far the most important, both for model calibration and for the detection of ”non-stationarity” issues since the data is continuous from 1952 till present. Both the Chappels Bridge and Manjimup Brook gauges commenced observations since 2010 and, while useful, their records are quite short in the context of this review.

The DRM is constructed using the eWater Source framework and utilises the GR4J rainfall-runoff model (Perrin et al., 2003) to generate runoff with in each sub-catchment, with parameter sets assigned to cleared and uncleared portions of each sub-catchment separately. Additionally, a ”farm dam” sub-model was included in areas where farm dams were used to capture runoff for consumptive use (e.g. Manjimup Brook sub-catchment). For SFIS scenario modelling, pumping from the Middle Donnelly was simulated using constraints such as a pump start threshold and pump rates. Diverted water was transferred to a reservoir model within the Record Brook sub-catchment for yield analysis.

Sub-catchment calibration was necessarily complicated by the lack of long-term data at most model locations, along with confounding factors such as farm dam construction and management, forestry operations and the hydrological behaviour of cleared and uncleared land. For example, at Manjimup Brook observed flow data was ”impacted” by farm dams and their management. An un-impacted time series was estimated via the use of the Manjimup Brook farm dam models. Subsequently cleared area runoff parameters were estimated using the unimpacted time series along with forested parameters calibrated in the Record Brook catchment. A similar process was necessary to estimate uncleared parameters in the Upper, Middle and Lower Donnelly sub-catchments. Model construction and calibration methods for the DRM were stipulated by DWER in the document DWER100418, which in turn references Vaze et al. (2011) as a guide to methods.

Future climate scenarios were developed from the Coupled Model Inter-comparison Project 3 (CMIP3) data. General circulation models (GCM’s) and emission pathways were selected from the CMIP3 outputs for suitability according to the methods outlined by Department of Water (2015). From the range of future climate estimates, three scenarios that covered the range of estimates (wet, median and dry) were selected. These were used to develop climates anomalies for each region, and, using a baseline period of 1961 - 1990, scaling was applied to produce future climate time series. For the DRM, wet, median and dry time series for 2030 and 2050 horizons were used to estimate a range of future climate runoff and SFIS yield.

Table 3.1: Mean annual rainfall for the historical baseline period, recent historical period, and future climate scenarios in the Middle Donnelly sub-catchment

Period	Mean annual rainfall (mm)	Difference relative to historical baseline (%)	Difference relative to recent historical (%)
Historical baseline (1961-1990)	1068	0	+10.6
Historical recent (1998 - 2017)	966	-9.6	0
Dry 2050	847	-20.7	-12.3
Dry 2030	946	-11.4	-2.0
Median 2050	900	-15.7	-7.0
Median 2030	976	-9.0	+1.0
Wet 2050	1016	-4.8	+5.2
Wet 2030	1036	-3.0	+7.2

3 Analysis

3.1 Future climate data

Review terms of reference (points 2 and 4) specified examination of the suitability of future climate scenarios. Accordingly, future climate and historical climate time series were compared. An example of this (for the Middle Donnelly sub-catchment) is shown in Figure 3.1. Additionally, mean annual rainfall for the historic baseline (1961 - 1990), recent historical (1998 - 2017) and future climates is given in Table 3.1.

Examination of Figure 3.1 shows the 10-year moving average of future climate data as bold coloured lines. These show an obvious trend that are a reflection of the same trend in the baseline period (1961-1990). Such large trends can be problematic for applications since the sequencing of hydrological yields can significantly influence viability of projects, particularly those assessed on an economic basis. Similarly, it is easy for users of these data to interpret the trend as a property of future climates when this is not the case. The Department of Water and Environmental Regulation's future climate method document (Department of Water, 2015) concedes that trends in the baseline period should be avoided if possible. The authors state:

> *The IPCC (2001) recommended that there should be no significant trend in climatic variables during the baseline period. This is difficult to achieve using a single baseline across all of WA. In the South-west there was an observable trend in rainfall during most of the last century, and it is impossible to select a baseline that includes a period of stationary rainfall and an adequate historical rainfall record.*

The second and more concerning observation is that the recent climate is significantly drier than the baseline period. Practically, this means that some of the future climates are actually wetter than recent climate when they were all originally assessed to be drier than baseline. In an application such as that intended for the DRM this has serious consequences. Combined with large trend in the baseline data, this means that the earlier part of the future climate is substantially wetter than recent climate. Assuming that futures climates are likely to be drier than present, the suite of future climates used in DRM cannot be considered ”fit for purpose”.

It is recommended that future climates based on CMIP3 GCM's and the 1961-1990 baseline not be used for the DRM since many of these time-series are wetter than recent observed climate when a drier future is expected. Perhaps the simplest remedy to this is to use more recent GCM's (CMIP5 or later) and a more recent baseline period with a less obvious trend in rainfall. Ironically,

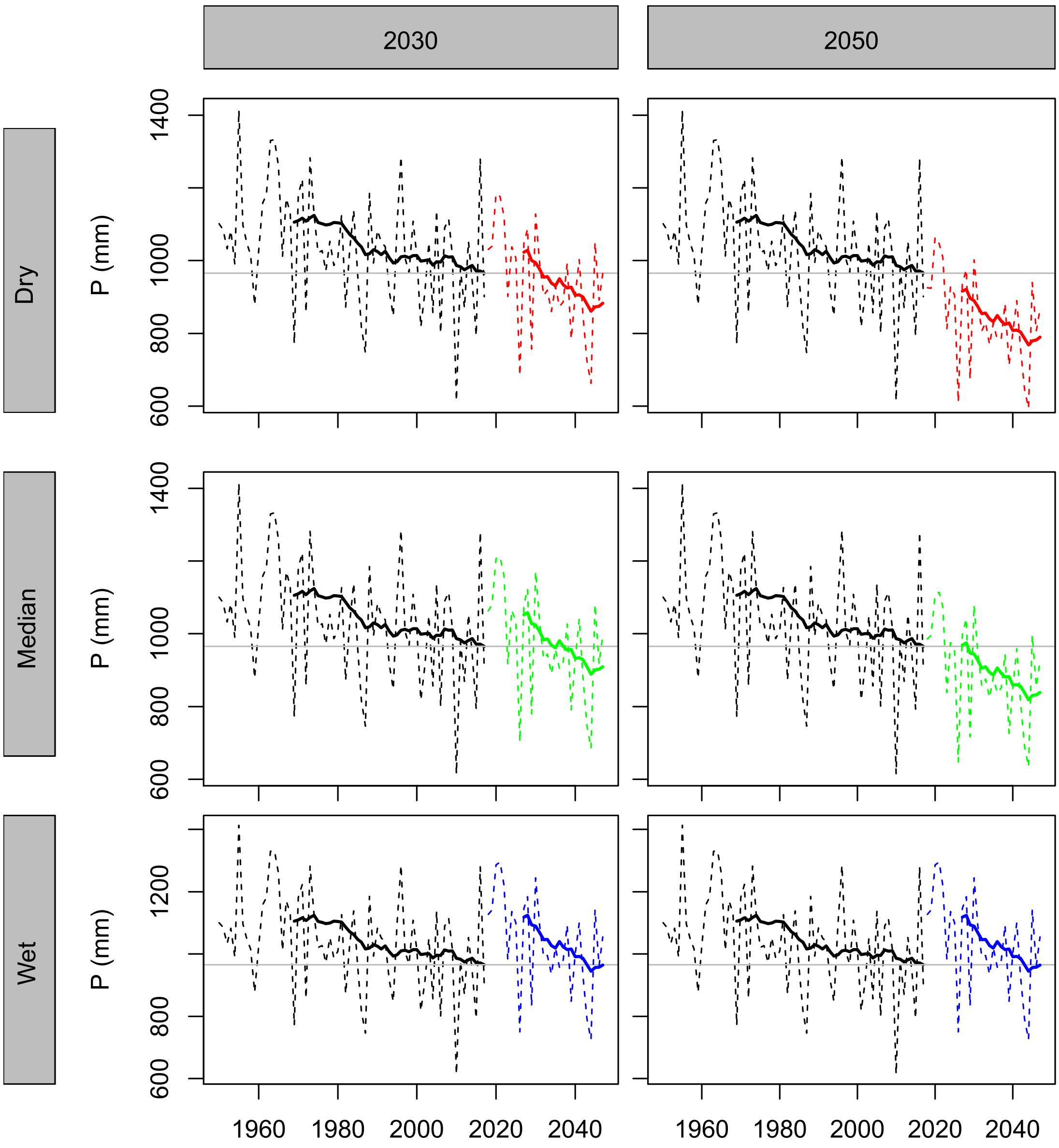

Figure 3.1: Historical and future rainfall time series for the Middle Donnelly sub-catchment

The broken black line represents historical rainfall, while the bold black line represents 20 year moving average rainfall. The bold coloured line represents 10 year moving average future rainfall. The horizontal grey line represents mean historic rainfall for the 1998 - 2017 period the use of scaled historical data for future projections can become outdated in a changing climate such as experienced in the South-west of Western Australia. For this reason a baseline period as recent as possible is needed. Given more time, other options may be used. For example, dynamic downscaling with a regional climate model (RCM) may be worth investigation as it does not have such a strong reliance on historical data, and some of the problems that brings.

3.2 Non-stationarity issues and model prediction

A ”stationary” time series is one in which the probablistic behaviour of any sub-set is identical to another. However in the context of hydrology and, in particular, south-western Western Australia, non-stationarity is often associated with large reductions in runoff with declining rainfall. These changes are usually evident in annual rainfall vs annual runoff plots, where new relationships are evident with continued reductions in rainfall. Examples of this can be seen in studies in the Northern Jarrah Forest (Petrone et al., 2010; Hughes et al., 2012; Grigg and Hughes, 2018; Kinal and Stoneman, 2012) and in South-eastern Australia (Saft et al., 2015; Petheram et al., 2011). An example of this is shown for the Del Park catchment in Figure 3.2. Throughout the 1980’s the Del Park catchment would produce approximately 150 mm of runoff from 1000 mm of annual rainfall. In more recent times this has fallen to less than 20 mm. These observations are not restricted to experimental catchments and have already seen the yield of Perth’s water supply reservoirs decline to the point where they cannot be relied upon (Raiter, 2012; Smith and Power, 2014).

Examination of groundwater and surface water data in the Northern Jarrah Forest (Hughes et al., 2012; Kinal and Stoneman, 2012; Grigg and Hughes, 2018; McFarlane et al., 2020) indicates that stream flow decline with declining rainfall is amplified by substantial falls in water table elevations, particularly in the catchment riparian zones. Such falls reduce direct groundwater movement into streams, but also substantially reduce saturated over land flow and shallow through-flow from the near stream area. The strong link between catchment surface saturated area via groundwater and runoff generation has been demonstrated in in multiple studies (Grigg and Kinal, 2020; Ruprecht and Schofield, 1989).

Runoff non-stationarity has also exposed deficiencies in rainfall-runoff models. Rainfall-runoff models form the foundation of many surface hydrological applications as they do for the DRM. These models are very adaptable, and parameters can be optimised to reproduce observed runoff very well in most circumstances. It should be recognised that many of these models were formulated in more humid environments, and in some applications are not well suited. In the south-west of Western Australia, many of the the common rainfall-runoff models have been shown to be incapable of simulating the type of catchment response shown in Figure 3.2 (Silberstein et al., 2013; Grigg and Hughes, 2018).

Briefly, one of the main issues is that as model storage (a model state or states that are related to the amount of water stored in a catchment) falls, runoff also begins to fall, as it should. However, the modelled rate of evapo-transpiration also falls so that the rate of storage depletion also falls with drying. This makes it impossible for these models to reproduce runoff where drying/droughts are longer than a few years, and cannot simulate the persistent effect of drought on runoff in subsequent years (Hughes and Vaze, 2015). In a humid environments where catchment evapo-transpiration is generally energy limited, this type of phenomenon is not likely and most rainfall-runoff models will perform well. Similarly, in environments where evapo-transpiration is water limited, most rainfall-runoff models will perform at least adequately. In environments where there is a transition from energy to water limited (or vice-versa), most rainfall-runoff models will not

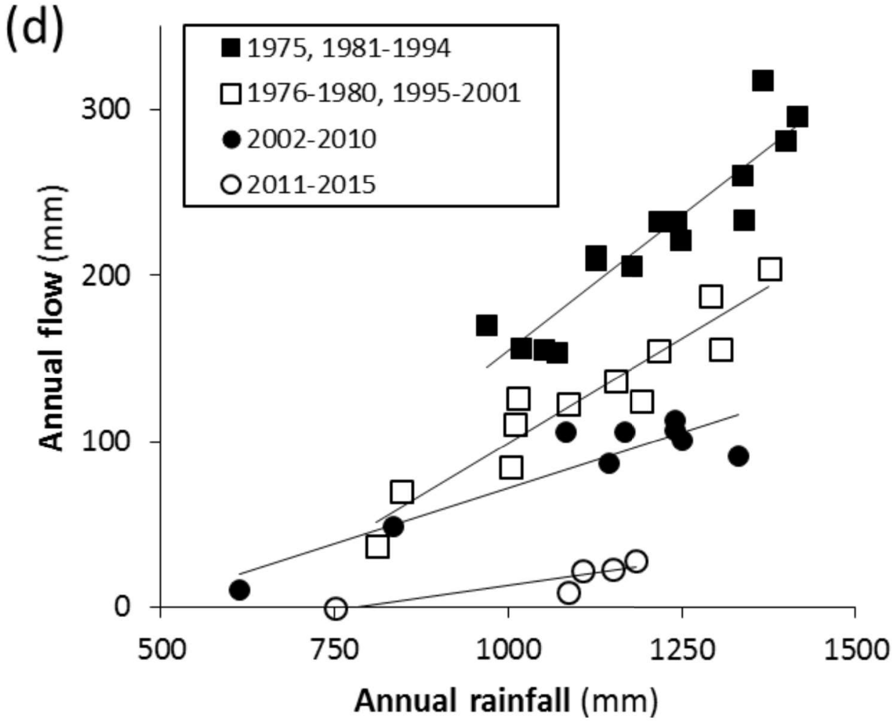

Figure 3.2: Annual rainfall and runoff relationships for the DelPark catchment [†]

[†] Reproduced from Grigg and Hughes (2018)

perform adequately.

The terms of reference item 3 states *”Likelihood and the degree of any predicted changes in catchment rainfall runoff processes (non-stationarity) would affect yields and reliability of irrigation supplied from the proposed Record Brook Dam”*. The best direct evidence for the occurrence of non-stationarity issues in the Donnelly catchment comes from streamflow observations at the Strickland gauge. This is a valuable data source in the context of this study, since the record of observations covers the period 1952 till present, and it’s contributing area encompasses the source areas for the SFIS proposal.

When the annual catchment rainfall is plotted against annual runoff, it can be seen that there is a shift in the rainfall-runoff relationship following the 2001 drought (Figure 3.3). It is also possible that a new relationship may have formed post the 2010 drought year (as can be seen in the lower panel of Figure 3.3). This classic non-stationarity behaviour and mimics the behaviour seen in catchments of the Northern Jarrah Forest. The important difference between this site and others in the Northern Jarrah Forest is the timing of these changes in response. In the northern catchments, many of the catchments exhibited response changes in the 1990’s and some post the dry years of the late 1970’s (Petrone et al., 2010). Although in all cases, declines in runoff coefficient continued following significant droughts years, e.g. 1994, 2001, 2010. Another point worth noting is that the Strickland gauge catchment area contains areas of cleared land where, due to lower evapo-transpiration, groundwater levels and runoff coefficients would be higher than forested areas. This may serve to ”buffer” runoff at Strickland against declines to some, unknown degree.

Changes in rainfall-runoff coefficient would be expected to be driven by falling groundwater levels

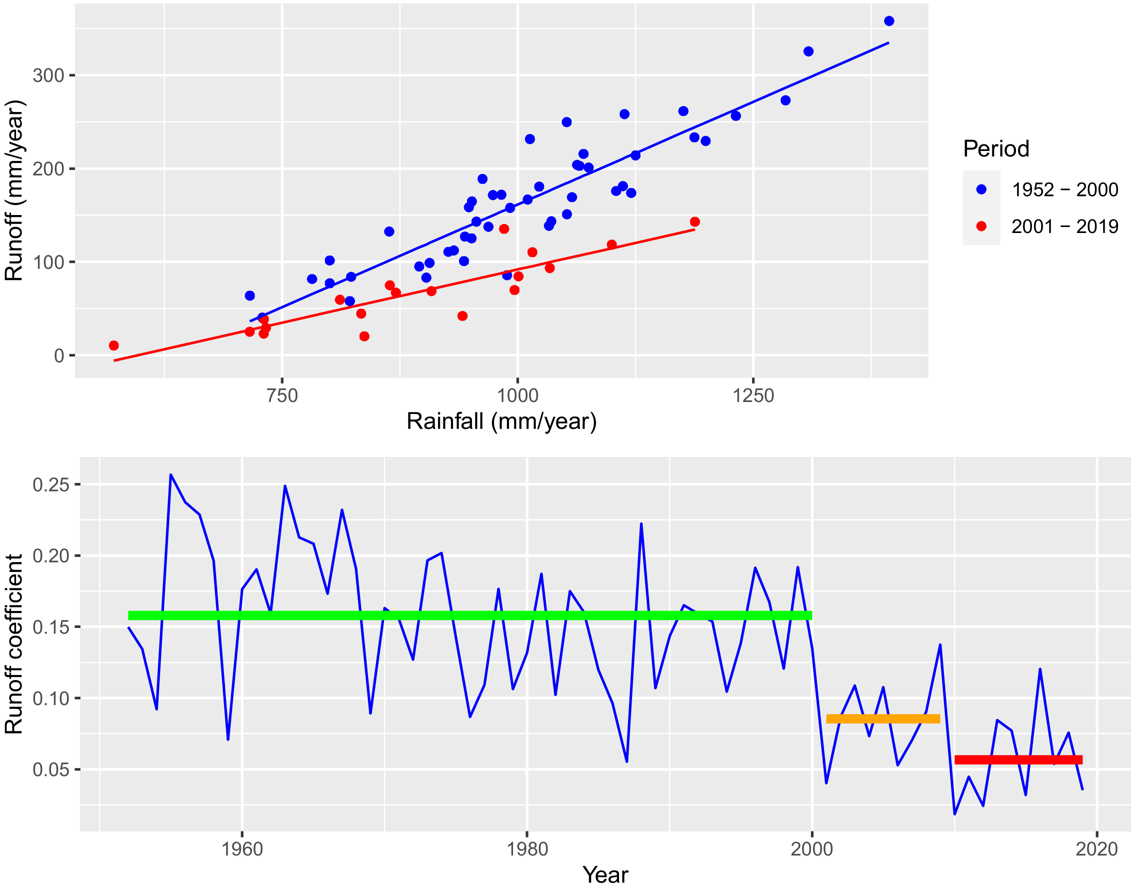

Figure 3.3: Annual rainfall and runoff observations at the Strickland gauge (608151). The lower panel shows runoff expressed as runoff coefficient

Figure 3.4: Groundwater observations from Southern Forest experimental catchments

Data supplied by DBCA. For catchment locations see Borg et al. (1987b) and Borg et al. (1987a)

as mentioned above. There are no known groundwater data available from within the Strickland gauge contributing area. However, there are numerous research catchments within the Southern Forest area, that offer a source of groundwater information. Unfortunately most of the monitoring (streamflow gauging and groundwater) ceased in the 1980's and 1990's. In some of the catchments, groundwater data has been collected in more recent times, some of which to support this review. A sample of these data is shown in Figure 3.4. The falls in groundwater level (increase in depth to water) are large, even relative to Northern Jarrah Forest observations, and would be expected to accompany drastic reductions in streamflow. Unfortunately, stream gauging at these sites had ceased by 2001.

The evidence presented above strongly suggests that non-stationarity issues as experienced and documented in the Northern Jarrah forest are also apparent in the Southern Forest. To address the terms of reference of this review, the obvious question is can the DRM predict reliably under these conditions? The chosen rainfall-runoff model, GR4J, has been demonstrated in the Northern Jarrah Forest to be unsuited to such conditions (Hughes et al., 2013; Grigg and Hughes, 2018). The model is incapable of simulating long-term storage changes and concurrent reductions in streamflow. Practically, this means that the model is almost certain to over-predict during drier periods in environments experiencing non-stationarity. GR4J can reproduce observations well enough if calibrated to a short period of observations where non-stationity is evident, but will not predict well outside of that period. When calibrated to a longer time series of observations experiencing non-stationarity, the model will not reproduce the calibration data adequately. For example when calibrating GR4J to the Del Park stream gauge data (4̃0 years), Grigg and Hughes (2018) found that the model under predicted during the wetter period and over predicted the drier portions of the time series.

3.2.1 Lower and Middle Donnelly model

For the DRM, the majority of the area above the Strickland gauge used a common GR4J parameter set calibrated to the Strickland gauge across the 2001 - 2017 period. Calibration took place subsequent to Manjimup Brook sub-catchment calibration, but is described first since the techniques used apply across the model domain.

For the forested areas of the Lower, Middle and Upper Donnelly, calibration used the Strickland gauge data. Calibration of GR4J was restricted to the period 2001 - 2017. These parameters were then used for the upper, Middle and Lower Donnelly areas. In the Lower Donnelly upstream of the Strickland gauge, a loss function was also applied as part of the calibration process (Table 3.2. This was not applied in the Middle or Upper Donnelly. Goodness of fit in calibration was very good with an index of agreement of 0.9 and bias of 0.2%. When these parameters and the loss function were used in validation (1952 - 2017) bias was -33%. This means that the calibrated parameters are unsuitable for prediction in wetter climates. For a dry future this may not present a problem *per se*. However, it is also indicative of GR4J's inability to respond to long-term changes in catchment storage as discussed above. Only two years of validation data was available for the Middle Donnelly at Chappel's Bridge (2016-2017). Index of agreement was good at 0.87, however bias was +25%.

For prediction in drier climates, the use of a loss function as shown in Table 3.2, may be a means of reducing over-prediction, since, as initial estimates of flow reduce with falling rainfall, the loss function ”deletes” progressively higher proportions of initial flow estimates. This was examined using simulations of historical and ”Dry 2050” climate sequences at both Lower Donnelly above Strickland and Middle Donnelly (Figure 3.5). The most notable difference between the two model simulation points is the behaviour of runoff under the drier climate future. As indicated in Table 3.1, the Dry 2050 climate is quite extreme and runoff would be expected to decline substantially under such conditions. In the Lower Donnelly US of Strickland, the future climate rainfall- runoff relationship is visibly different to the simulated historical relationship. However, using the same parameter set, *without* a loss function at Mid Donnelly indicates that dry future climate is similar to the historical relationship, except that at lower annual rainfall, the model is predicting higher runoff. Mean runoff coefficient for the Dry 2050 at Middle Donnelly is 4.2 % while at Lower Donnelly it is 2.8 %, despite slightly higher rainfall. The use of the loss function in this way ensures a good calibration fit and a more reasonable prediction (though probably still over-predicting) into dry climates at the Strickland gauge, while over-predicting in the middle Donnelly where water is diverted for the SFIS.

An important question for future climate simulation, is what would be a reasonable runoff depth or runoff coefficient to expect from a future climate such as the Dry 2050? It is vital for the hydrologist to have some information with which to ”reality-check” the veracity of future forecasts. A good, or at least defendable method, would be to examine the behaviour of gauged Jarrah forest catchments as their behaviour has changed in response to rainfall reductions. Even knowledge of what kind of runoff coefficients could be expected for given mean annual rainfall in the Darling Range would be very informative to at least check what might be the reasonable bounds on future climate runoff. For example, the mean Dry 2050 rainfall at Middle Donnelly is 847 mm

Table 3.2: Loss function applied in the Lower Donnelly upstream of Strickland

Initial flow (ML/day)	Applied loss (ML/day)
0	0
4	4
6	4
10	5
15	6
20	7
30	9
35	12
40	14
50	20
60	25
70	30
90	35
100	40
99999	40

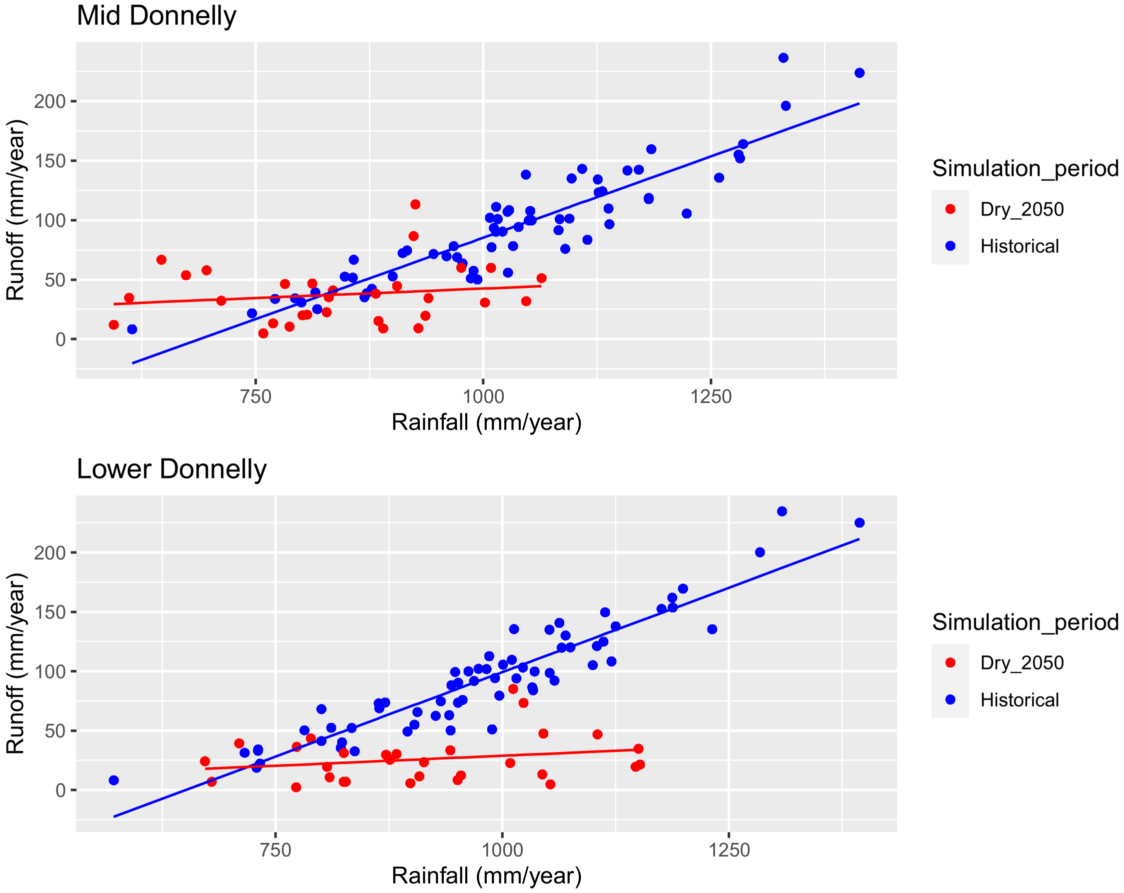

Figure 3.5: Simulated historical (1952 - 2017) and Dry 2050 streamflow and rainfall for Middle Donnelly and Lower Donnelly upstream of Strickland gauge

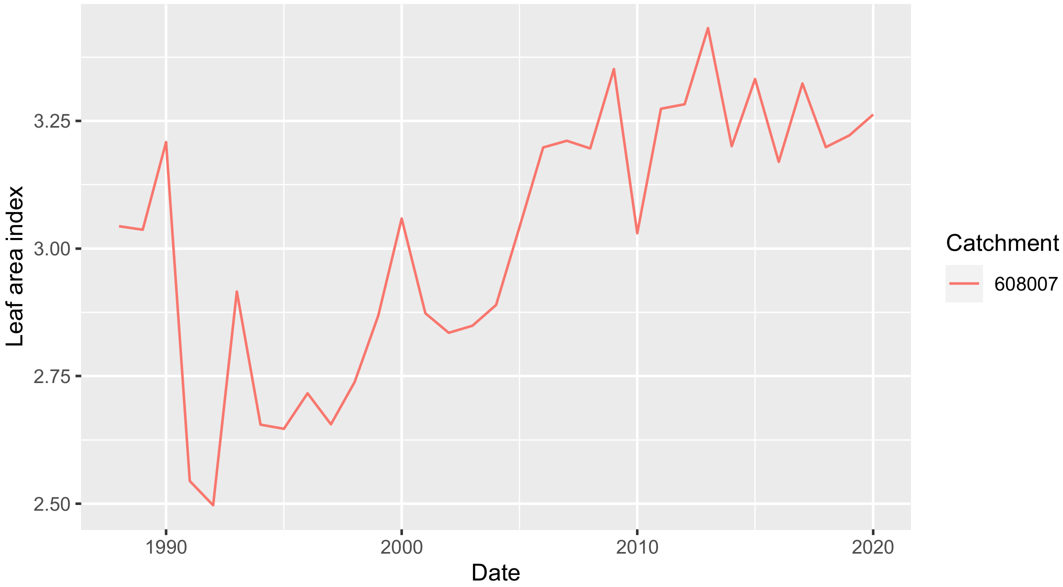

Figure 3.6: Estimated catchment mean leaf area index time series for the Record Brook catchment

(Table 3.1). Examination of data from Hughes et al. (2012) and Kinal and Stoneman (2012) indicate that, at a mean annual rainfall of around 850 mm, mean runoff coefficient may expected to be less than 1 %. Variation in forest cover/type, antecedent effects and regolith/location would require a more thorough tabulation of observed runoff data to have a confident estimate of runoff expectations.

Observed runoff at Strickland will in some way be modified by runoff generated from cleared areas, although from the available data from within the model domain, this is difficult to estimate.

3.2.2 Record Brook/Manjimup Brook calibration

Record Brook was calibrated between 1987 and 2000, which was thought to be the period of all the available observations [1]. As the authors of HARC (2018) point out, this was a very wet period and probably results in over-prediction in the post–2000 period. It is also likely that, using this parameter set in future climates, over-prediction will result. A further complicating issue is the degree of forest management throughout the calibration period. To examine this, Landsat data was obtained from Geoscience Australia. Normalised Difference Vegetative Index (NDVI) was calculated for each year from Landsat data and converted to a Leaf Area Index (LAI) using the following formula from Macfarlane et al. (2018):

$$LAI = 4.45 * NDVI^{1.42} \tag{3.1}$$

LAI estimates were then aggregated to each catchment. It should be noted that no normalisation between Landsat scenes/satellites was conducted, and, therefore accuracy could be improved. Nonetheless data indicates that throughout the 1990's , significant forest clearing and re-vegetation occurred in Record Brook (and other areas of the model domain). These data can be seen in Figures 3.6 and 3.7.

Future climate over-prediction of runoff from the Record Brook is very likely, although given data availability it is difficult to estimate by how much. Mean observed runoff coefficient was

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[1] it has come to the authors attention that some data post 2000 is available

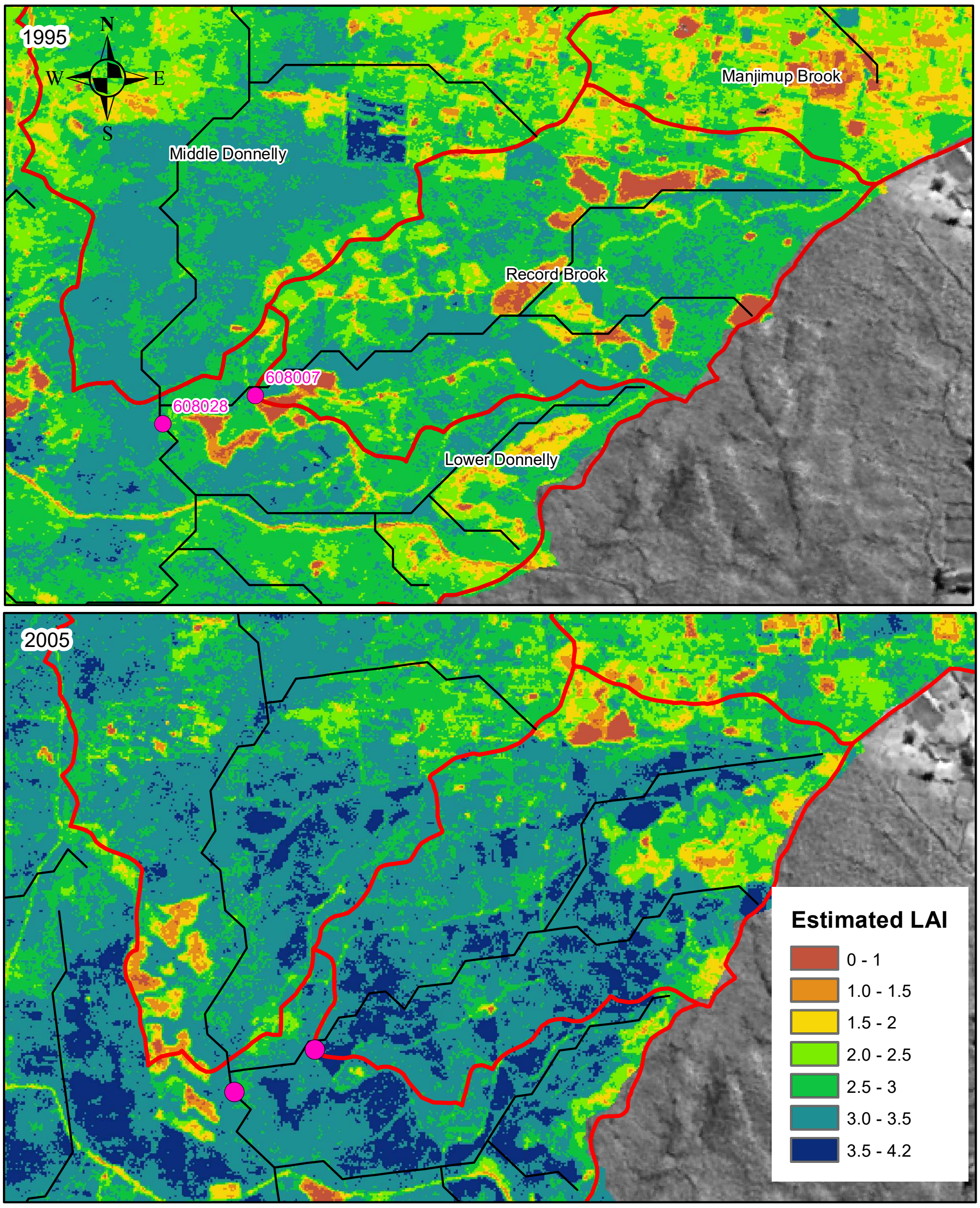

Figure 3.7: Estimated leaf area index for the Record Brook catchment in 1995 and 2005

approximately 15 % during calibration (mean annual rainfall for this period is approximately 1100 mm). For the simulated Dry 2050 future, mean annual rainfall at Record Brook is 886 mm, and mean runoff coefficient during this period is 8.6%. This is very unlikely (too high) and should be reviewed.

The Record Brook catchment makes a small contribution to the yields from the SFIS proposed development although the parameters from the Record Brook calibration are used for estimation of uncleared area runoff in Manjimup Brook. It is very difficult to follow these effects through to Manjimup Brook runoff estimates for a number of inter-related factors. Firstly, the Manjimup Brook Gauge, at present, has less than 10 years of data, secondly there are no independent observations of runoff from cleared or uncleared portions of the catchment, thirdly, consumptive water use on cleared land occurs within the catchment (incorporating significant volumes of on-farm storage of runoff), and lastly, a loss function is used in the DRM to improve goodness of fit. It is possible that over-prediction from the uncleared portions of Manjimup Brook is balanced out by either under-prediction from the cleared portions of the catchment and/or over-prediction of farm dam water use and/or ”deletions” of runoff from the applied loss function.

Observed flow at Manjimup Brook gauge indicates that runoff coefficient varies between 4 and 17 % in the years 2012 to 2018 with a mean coefficient of 9.7 % from a mean annual rainfall of 866 mm. Comparing runoff coefficient for Strickland and Manjimup Brook for the overlapping period of observations (full years 2012 - 2018), it is possible to estimate the runoff coefficients from the cleared and uncleared portions of the catchment knowing the proportional areas of cleared and uncleared land contributing to each gauge. Cleared area makes up 55% of the Manjimup gauge area, while cleared areas make up 25% of contributing area to the Strickland gauge. Knowing the runoff coefficients for both areas for the 2012 - 2018 period gives;

$$\begin{cases} 0.55c + 0.45u = 9.7 & (3.2) \\ 0.25c + 0.75u = 6.7 & (3.3) \end{cases}$$

where u and c are the runoff coefficients from uncleared land and cleared land respectively. Equation 3.2 and 3.3 are relationships for the Manimup and Strickland gauges respectively. Solving these equations simultaneously gives an uncleared area runoff coefficient of 4.2% with cleared land equating to 14.2%. These relationships will change given the changing climate but these estimates highlight the large differences in runoff coefficient with land treatment, and also mean that the runoff from forested areas has already declined to quite low levels. Assuming 31% of the area contributing to the Middle Donnelly at Chappels Bridge is cleared, runoff coefficient at this location is estimated to be 7.3% for the same period.

Mean Dry 2050 annual rainfall is 776 mm for Manjimup Brook while mean runoff coefficient for the same simulation is 5.8 %. It is difficult to say if this is appropriate given the lack of data on the runoff response of cleared areas with declining rainfall. However at a mean rainfall of 776 mm, forested areas would be assumed to produce little if any runoff.

Given the lower evapo-transpiration from cleared land, groundwater – surface water connection is likely to be maintained for longer into drier conditions relative to forested catchments. This means that overall runoff coefficient is likely to be also higher than forested catchments. However, relative reductions in runoff may be higher per unit decline in groundwater elevation in ”connected systems” (see Hughes et al. (2012)). There are no groundwater data available within the cleared areas of the Donnelly catchment, however some data from a cleared area to the east of the Upper Donnelly sub-catchment are shown in Figure 3.8. These data indicate that depth to

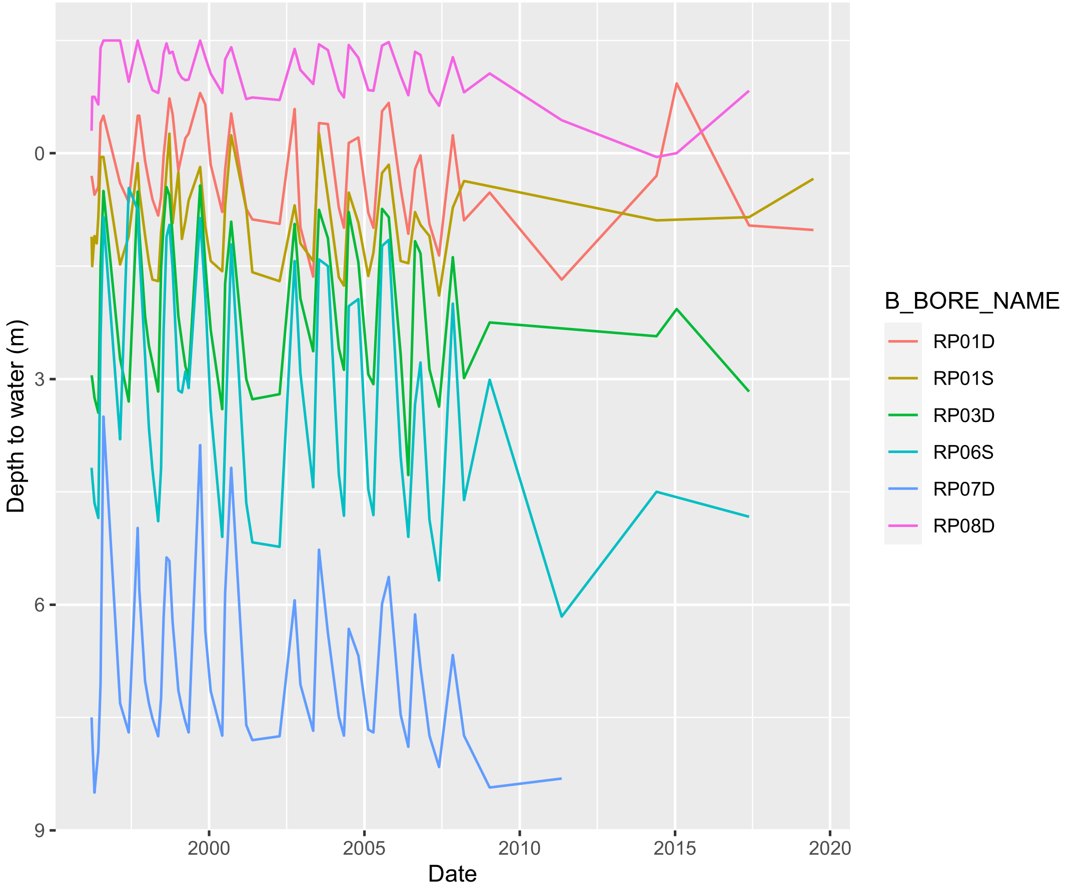

Figure 3.8: Groundwater observations from a cleared area to the east of the Upper Donnelly sub-catchment

Data supplied by DPIRD/Richard George

groundwater may have increased in the area of observation, albeit less dramatically than those in forested area. If groundwater response was similar in the cleared areas of the Donnelly, then it could be also assumed runoff coefficient may decline. This remains unresolved.

3.2.3 An alternative approach

This section is included to stimulate discussion on alternate methods given the identified problems in the current model. It is not intended as a recommendation and it is acknowledged that there may be other ways of improving DRM performance. Also, it should be noted that the while the ”Dry 2050” future climate is a good test of model behaviour, since it is quite dry particularly in the latter half of the time series, it is probably not representative of revised climate forecasts.

The GR8J model has been shown to be able to cope with ”non-stationarity” in the rainfall–runoff relationship (Grigg and Hughes, 2018; Hughes et al., 2021). As a test, the model was calibrated to the observations at the Strickland gauge. The GR8J model is notable in that it requires a forest cover or LAI time series input. This was constructed from the Landsat data, as described above, with values averaged for the entire Strickland gauge contributing area. The model does not explicitly consider cleared and uncleared areas or farm dams but these effects are accounted for implicitly via the model parameters and the catchment LAI time-series inputs, since these factors influence observed runoff at Strickland gauge.

In contrast to the HARC (2018) approach, all observations from the Strickland gauge area used for calibration here. Split sample calibration and validation are often used and promoted as a mean of testing the predictive capacity of the model. However in non-stationary conditions, split sample calibration and validation is not recommended (Vaze et al., 2011). Conceptual rainfall-runoff models are unreliable for prediction outside of their calibration conditions and this is particularly true in the in the Jarrah forests of Western Australia. It is therefore important to use as much data as possible for calibration, covering the maximum possible range of conditions.

The calibration objective function should adequately constrain the model behaviour, and for this test is designed to reduce absolute cumulative error, dry period bias and daily error. Such an objective function ensures the model runoff coefficient falls in line with observations of declining runoff. Also, it is worth including a future climate simulation in the calibration process to further constrain parameters and model behaviour *outside* of observed conditions. This was achieved in this test using a penalty function for Dry 2050 runoff coefficient. The penalty function relies on judgement of what might be reasonable in terms of runoff from forested and cleared areas for the Dry 2050 climate. It was assumed that forested areas would produce a mean of 1 % and cleared areas a mean of 7% runoff coefficient in a Dry 2050 climate, giving a catchment mean of 2.5 %. These values are arbitrary, although influenced by experience, and perhaps a little optimistic, but are included for demonstration purposes only. A review of data is recommended to arrive at these values (or a range of values). The penalty function penalises any parameter sets that simulate Dry 2050 runoff coefficient higher than 2.5 %, with the penalty increasing with simulated runoff coefficient.

Simulation results for GR8J at the Strickland gauge site can be seen in Figure 3.9. The model simulates a changing rainfall-runoff relationship well (top panel) and is well matched to observations (lower panel). The Dry 2050 climate was appended to the historical time series inputs to produce the Dry 2050 simulation post-historical data (and therefore initialising the Dry 2050 simulation with model states from the end of the historical time series). The time series of Dry 2050 simulation shows that initially, simulated runoff is of similar magnitude to recent years, before falling drastically. The future climate baseline period includes the very dry years of the late 1970's, and the ”crash” in runoff is during this period, with little recovery. This is also related to the large trend in the baseline climate data used to produce future climate estimates.

Other models thought to be able to cope with runoff non-stationarity e.g. LASCAM (Viney and Sivapalan, 2000), could be used in a similar way, and indeed may be preferable, since prototype model versions for the area are already available. It should be noted that either model would not be applied as a ”lumped” calibration as was demonstrated in this test, but via sub catchments representing cleared areas as with farm dams distinct from forested areas.

4 Conclusion and recommendations

Model construction and calibration is a challenging task. The challenge increases when data is limited and multi-million dollar developments hinge on model outcomes. These are all factors of influence for the Donnelly River Model. However, in the south west of Western Australia, hydro-climatic non-stationarity issues increase the difficulty to an altogether new level. In such conditions, many of the ”tried and true” methods that hydrologists have become comfortable with are not appropriate and can lead to erroneous predictions. Non-stationarity issues have been reported in many academic publications over the past 10 years, however methods for application of such knowledge to real world applications lags somewhat.

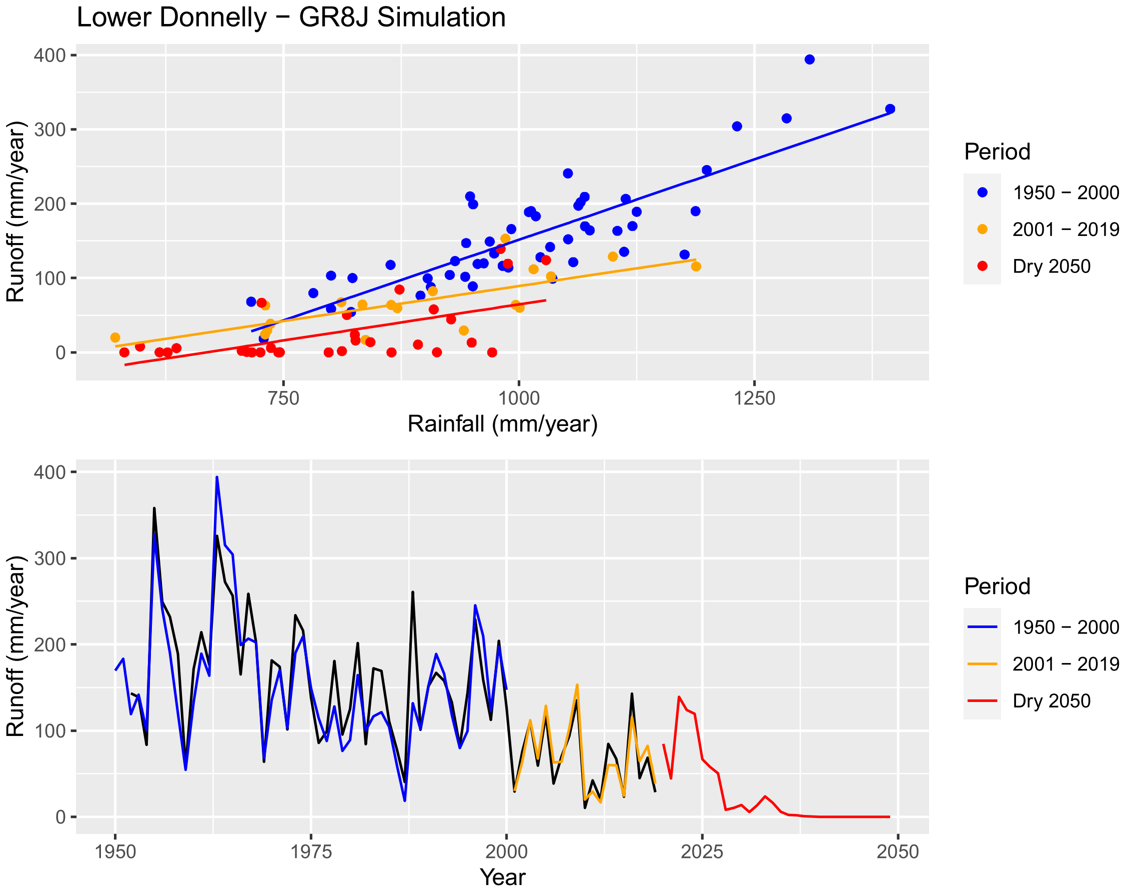

Figure 3.9: GR8J simulation for the Strickland gauge location

The black line in the lower panel represents streamflow observations at Strickland

The DRM, as it stands, has made clever use of limited data, and has been largely built to specifications as outlined in the document DWER100418. In its present format, the model can not be considered ”fit for purpose” however. Firstly, the future climate scenarios are not as dry as intended and, relative to recent data, some are wetter when they are intended to be drier. Secondly, the model itself uses GR4J, which cannot effectively mimic the reductions in runoff observed in the south-west of WA, and therefore will over-predict in conditions that are drier than calibration conditions. Interestingly, the model employs loss functions which ensure a good fit to observed data, but may mask other problems in the model. In particular the model over-predicts in both the Record Brook and Middle Donnelly which are the main supply points to the proposed SFIS.

It is worthwhile commenting here on the availability of data as requested in terms of reference points 1 and 7. It is rare for hydrologists to consider available data excess to needs in any situation. However, in this case, the lack of observations has contributed to the model shortcomings. Longer time series records at more locations within the model domain may have helped to highlight any model issues before calibration was finalised. A more practical question is how should the hydrologist proceed in such situations, which, to be realistic, are more common than not? More particularly, how to proceed when hydrological response is dominated by a drying climate such as south-west WA?

An assumption that creates many problems in non-stationary environments is related to the ability of a calibrated model to predict outside the conditions of the calibration data. In other words, the calibration fit is good, so the prediction should be reliable? This is exacerbated by split-sample calibration-validation procedures that shorten the calibration period. Longer term processes (e.g. catchment storage depletion) require longer calibration data sets to better parametrise the model. To be reliable the model may have to predict in conditions not observed in that region before. Given the general lack of data, what strategies are available to the hydrologist? The best data sources to answer those questions will usually be found outside of the model domain. The hydrologist needs to rely on observations from elsewhere that are similar enough to be useful, but can provide insight into catchment response in the predicted future conditions. In the analysis as a part of this review, runoff coefficient and mean annual rainfall are used regularly to gauge the veracity of catchment response (based on experience and some published data). This could be improved by a ”stocktake” of forested and cleared catchment response to drying in south-west WA. The transition from wet to dry has been gauged in many catchments and these data could constitute a benchmark against which model predictions could be judged. Furthermore, these benchmarks could be incorporated into the model calibration process as they have been in the Section 3.2.3. These data could be used for not only the Donnelly model, but others across the region.

It should be stressed that good modelling relies on good data, not just for the immediate task of model building, but to help answer unforeseen questions that arise and for development of future hydrologists. To that end it would be worthwhile to re-instate some hydrological modelling sites for which historic data is available. For example, monitoring in some of the experimental sites cited here (Borg et al., 1987b,a), largely ceased in the 1990’s. Much of the infrastructure remains in place (e.g. Figure 4.1) and monitoring (surface and groundwater) could be re-instated with relative ease. Data for cleared areas e.g. within Manjimup Brook, is likely to be harder to find, and it may be worthwhile establishing better monitoring in such locations given the paucity of data and the probable needs for this project and others.

Figure 4.1: Lewin North stream gauging weir, looking upstream

To summarise the recommendations scattered throughout this report, they are included below in point form for quick reference.

1. The DRM use a model capable of predicting reliably in conditions of ”non-stationarity” e.g. LASCAM, GR7/8J, as opposed to GR4J
2. Climate future time series be updated using the latest GCM outputs available (probably CMIP5), and update the baseline period to as recent as reasonably possible.
3. The use of loss functions in the DRM should be abandoned or at least applied uniformly. They were not applied in key locations such as the Middle Donnelly where water is to be diverted for the SFIS
4. ”Split sample” calibration - validation should not be used in non-stationary situations, but rather all possible data be used
5. A review of available stream gauge data be conducted to act as a reference with which to judge what might be expected in various future climate scenarios
6. Any estimated streamflow from future climate scenarios be analysed with reference to the review of data recommended above
7. Where possible re-instate monitoring at sites with historic streamflow and/or groundwater data. Consideration should be also given to improved monitoring in cleared areas.

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