DWLBC REPORT

Preliminary estimates of farm dam development in the Northern and Yorke NRM region

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Government of South Australia
Department of Water, Land and Biodiversity Conservation

Preliminary estimates of farm dam development in the Northern and Yorke NRM region

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Knowledge and Information
Department of Water, Land and Biodiversity Conservation

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FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Rob Freeman
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Information on the sustainability of existing water resource development levels in the Northern and Yorke (NY) Natural Resources Management (NRM) region lags behind much of the state, where catchment management boards have been developing such understanding for over ten years. The Northern and Yorke NRM Board has, over recent years, initiated a range of assessment work in order to develop a baseline understanding of the current risk to water resources from over-development. Excessive farm dam development is a key risk facing water resources, and has been shown to have significant impacts on streamflow in many parts of the state.

Outside of the Clare Valley very limited published information on farm dam development levels for the Region existed prior to this point in time, and this study aimed to fill this gap across the four major river systems of the region. This report provides baseline estimates of the extent of farm dam development in these river systems, and highlights sub-catchment areas where dam development may be at or beyond sustainable levels. In addition a hypothetical modelling exercise was undertaken to evaluate the effectiveness of existing state policies in protecting streamflow regimes under semi-arid climatic conditions, which prevail across much of the region.

Data limitations were a considerable constraint on the study, and results should be seen as being preliminary and in need of refinement. For example, the most recent imagery available for this work was collected in 2002, and development in the period 2002–07 is unknown. Additional work to refine estimates both of farm dam storage, catchment runoff responses, and the interaction between surface and groundwaters is critically important to future water resource management in the region.

Farm dam storage, distribution and sustainability

Over 8800 dams were identified from the most recent available imagery, captured in 2002. These represent a total potential storage of around 22 000 ML. Over 90% of dams have an estimated full supply volume of less than 5 ML, however the remaining 8% of dams hold almost 50% of the total storage volume. The median size of all dams across the four catchments was 1.6 ML (mean = 2.6 ML), illustrating the dominance of small storages.

Hotspots (high storage density areas) of farm dam development were located within and adjacent to prescribed areas in the Clare and Barossa Valleys. Other areas of high levels of development were found in southern Willochra Creek, Rocky River and Upper Light River sub-catchments.

Limited time-series data were available to determine rates of new dam development, but increases appear to have occurred within at least the Light River and Willochra catchments where such comparisons were possible. Although apparently largely for stock and domestic uses, the estimated total storage capacity of all dams in the Light River catchment increased by 69% between the years of 1999 and 2002. Increases in the number of dams within southern Willochra Creek sub-catchments was around 10% per annum over the same period, but volumetric increases could not be determined.

Definitive comparisons of observed development against existing sustainable use threholds were difficult due to data limitations. The ratio of total sub-catchment dam storage capacity

(as a surrogate measure of use) and estimated median sub-catchment runoff was calculated to determine relative development levels at this scale. For the purposes of this report, a value of this ratio that exceeds 25% is suggested as a conservative indication that development levels are likely to be impacting on streamflow. While 50% of median runoff has been used in higher rainfall areas of the state, use of this lower threshold accounts for the age and quality of the data, and is conservative in light of climatic uncertainties. Against this benchmark more than 40% of the sub-catchment areas assessed (14 out of 34) were found to be at risk of over-development. Identifying impacts in an assessment of this nature is strongly scale dependent, and small areas within all sub-catchments reviewed are likely to be developed beyond State NRM guidelines.

Farm dam development in the region to date has been largely unregulated and in some areas is likely to be disrupting natural streamflow regimes, particularly at local scales. Uncertainties in this work may also have resulted in the risk to resources being under-estimated. Actual development levels might be considerably higher than indicated by this analysis owing to the following factors:

- The most recent imagery available was five years old and the rate of farm dam construction over the period 2002–07 cannot currently be ascertained.
- Climatic conditions over recent years have been less conducive to reliable runoff, with further reduction in catchment yields predicted in future under climate change scenarios.
- Streamflow volumes in the region have decreased during recent years in excess of that predicted by models for the observed changes to rainfall patterns – a circumstance usually attributed to the widespread uptake of improved land management practices which increase infiltration of rainfall.
- Sustainable yield estimates from published data used in this report were up to ten years old and based on models calibrated to streamflow data that would not include the effect of the reductions described above.

The findings of this report may well represent ‘best case’ scenarios. An improved understanding of the impact of farm dams on catchment hydrology in the region should be acquired as soon as possible, focussing intially on more highly developed catchments identified within this report.

Farm dam policy

Policy instruments used to limit farm dam development in South Australia are effective in areas of high rainfall where runoff is reliable, but have not been evaluated for use in semi-arid environments. Two such policies were assessed in terms of their effectiveness at protecting natural flow regimes in high variability environments through a simple modelling approach. The policies evaluated in the hypothetical analysis were:

1. Permissible farm dam storage equal to 30% of average winter runoff
2. Permitting use of up to 25% of median adjusted annual runoff (where ‘use’ herein was equated to total dam capture volume).

These policies were applied to a model of a small sub-catchment and the effects on the flow regime were assessed. Runoff modelling based on a 117–year simulation suggest that policy seeking only to control the total dam storage volume will not protect flow regime characteristics. Even volumes of storage permissible under the most conservative existing policy removed all flows below the 40th percentile of naturally observed flows, increasing the

average between-flow and maximum no-flow periods by between two and ten times those predicted under a no dams scenario. Such increases in no-flow periods are highly likely to impact on the condition of water dependent ecosystems, if not water resources more generally. Simulations retaining a percentage of the catchment as free-to-flow greatly reduced the impacts on the natural flow regime for any given storage volume.

Overall, modelling indicated that because runoff generated during the majority of years was of a modest volume, even small dams are capable of capturing most, if not all, of the resulting streamflow. This suggests that policies based only on specifying a maximum allowable proportion of mean or median annual runoff to be captured are, in isolation, not adequate to ensure protection of natural flow regimes in semi-arid environments where high variability in runoff is observed.

Consideration should be given to developing policies to guide surface water development in a manner appropriate for conditions in the region. To be effective at protecting streamflow regimes, the impact of stock and domestic farm dams should be included. Such a policy framework could potentially be established under the provisions for Water Affecting Activities within the *Natural Resources Management Act 2004*. Criteria would need to consider not only the total storage of dams, but also the placement of dams with respect to both the watercourse itself and the distribution of dams within the catchment more broadly. Options to address the impacts on natural flow regimes include:

- Identifying and maintaining adequate free-to-flow areas
- Locating all farm dams off-stream and diverting water only during adequate flow events
- The installation of low-flow bypasses.

Finally, the potential impacts of farm dams on the water balance of aquifers in semi-arid zones was not assessed in this work, but remains a critical question. The lack of information regarding the likely magnitude of any decrease in groundwater recharge lower in the catchment as a result of over-development of surface water is an impediment to the development of sustainable management policies. This understanding is required not only in order to ensure that groundwater resources are maintained for human use, but also to protect groundwater dependent ecosystems present in river catchments throughout the region.

1. INTRODUCTION

1.1 GEOGRAPHICAL SCOPE

The geographical focus of this project was limited to the four main river catchments present in the Northern and Yorke NRM region: the Light, Broughton and Wakefield Rivers, and Willochra Creek. Owing to existing processes to manage development within prescribed areas such as the Clare Valley, these were not considered within the scope of this project, however, these dam storages are included in regional totals and used for comparative purposes.

Areas outside of these relatively major river systems may also be subject to excessive levels of dam development, but preliminary analysis suggested that the highest development levels, and therefore priority for assessment, is associated with the main river catchments. Other areas outside of these may be the subject of future farm dam assessments where considered necessary. The conclusions with regard to appropriate levels of development apply generally across the region and semi-arid areas of the state.

1.2 THE NEED FOR INFORMATION ON FARM DAMS

Small surface water storages including simple earthen dams are a critical component of water management at the farm scale. Historically, individual landholders have constructed farm dam storages according to their needs for water, governed by the quantities and spatial distribution of runoff generated on their properties.

The most cost effective method of creating a farm dam is generally to utilise existing drainage lines, constructing earthen walls to capture all of the streamflow until the storage fills. This approach inevitably has an impact on the volume and timing of streamflow below the dam. If there is no consideration of the water needs of the lower catchment when determining the total volumetric capacity or spatial distribution of dams, there is the potential for impacts to occur on downstream users. Impacts must be managed to ensure that the ability of downstream users—including the environment—to access sufficient water for their own needs is not compromised. To achieve this, information is required on the total storage and distribution of farm dams, as well as the volumes of rainfall and runoff, to allow for impacts to be quantified. The level of development is usually compared with some benchmark figure to ensure that surface water development is within sustainable limits.

Beyond the volumetric impacts, a further consideration for resource managers in semi-arid regions is the frequency of dams filling to capacity and allowing flow to pass. The existing policy framework for the control of farm dam development relies on the fact that reliable runoff will occur during the majority of years. This results in farm dams filling to capacity and allowing flow to pass most years—a situation where the dam is effectively ‘transparent’ and no longer affects the nature of passing flow. However, in semi-arid areas such as much of the Northern and Yorke NRM Region, runoff is by no means predictable. This raises the potential for significant impacts to occur on streamflow frequency at much lower levels of development. As demonstrated in Section 5, even small dams may remove all of the runoff generated in many, if not most years, highlighting the need for areas of catchments to remain free of dam development.

Where large areas of a catchment are controlled by farm dams, the reduction in flow frequency is likely to be imposing a high level of hydrological stress on water dependent ecosystems. Occasional freshening flows from surface runoff, although unpredictable, are critical in semi-arid environments to improve water quality and support ecological processes.

The interaction between surface and groundwaters is now well appreciated, and this understanding has led to recognition of the need to consider impacts on any phase of the hydrological cycle as potentially effecting other phases. This highlights the need for climatic variability to be considered in resource management decisions. From a whole-of-resource perspective, reductions in streamflow through surface water runoff captured in farm dams is not available for water dependent ecosystems, nor to recharge alluvial aquifers. This latter aspect may be especially important in semi-arid areas where stream losses may contribute a significant component of the overall recharge budget.

The need to ensure sustainable management of surface water in semi-arid areas has been recognised by the NY NRM Board, particularly in light of increasing climatic variability. This study was initiated to determine whether current development levels are sustainable, and to begin to address some of the technical issues associated with the creation of policy that would ensure sustainable farm dam development in semi-arid areas.

1.3 ENVIRONMENTAL IMPACTS OF EXCESSIVE FARM DAM DEVELOPMENT

The impacts of farm dams on water resources and water-dependent ecosystems are conceptually and quantitatively quite well understood. Conclusions to date however, have largely been based on findings from studies in higher rainfall catchments within South Australia.

Studies on the impacts of small farm dams on the hydrology of semi-arid catchments more generally are extremely limited world-wide. From a South Australian perspective, this lack of information is compounded by the limited amount of streamflow and biological data that are available, with which to undertake meaningful assessments—for example to compare pre-impact conditions with the current conditions.

The impact of farm dams on streamflow have been identified through work in higher rainfall areas of South Australia and are well documented in other reports (MREFTP 2003, Savadamuthu 2002 and 2003, Heneker 2003, Teoh 2002, 2007, Champion et al 1999) and the reader is referred to these for a more detailed discussion. Generally speaking, the key impacts identified in those studies are as follows:

- A reduction in the volume, number and duration of streamflow events—particularly in ephemeral and intermittent streams
- Delays in the seasonal onset of continuous streamflow
- Reductions in the number of streamflow events.

From the perspective of aquatic ecosystems, these flow impacts have the effect of decreasing either the extent or the amenity of aquatic habitat. This aspect of the influence of farm dams within a semi-arid setting is explored in Section 5 through a simple modelling exercise.

2. AIM

This project has two aims:

1. To provide information for resource managers and the community on the spatial distribution of farm dam storage density, and to identify any areas where the levels of storage may be problematic from the perspective of sustainable resource use and environmental water requirements.
2. To review existing policies for farm dam control for applicability in drier regions of the state, and investigate quantitative changes to streamflow resulting from a simple modelling approach.

The spatial extent of project work was restricted to the four major river catchments within the NY NRM region.

3. METHODOLOGY

3.1 OVERVIEW

The main aim of this assessment was to provide an indication of the spatial distribution of farm dam development and determine any areas at potential hydrological risk across the four main catchments within the Northern and Yorke NRM Region. A simple ratio of the estimated total dam storage and median runoff were used to estimate hydological risk. An additional aspect of the work was a review of the adequacy of existing farm dam development policies available for application in the region, supported by a simple surface water modelling study considering a range of scenarios.

The project required three separate analyses:

- Mapping and volumetric estimation of farm dam development
- Estimation of runoff volumes at sub-catchment scale
- Surface water modelling of differing farm dam development scenarios.

3.2 MAPPING OF FARM DAMS

In the Clare Valley Prescribed Water Resources Area (PWRA) farm dams have been mapped and volumes are relatively well known. These values were obtained from the Clare Valley Water Allocation Plan (WAP) at sub-catchment scale. Additionally Deane (2005) mapped farm dams in the Rocky River sub-catchment, and this dataset was used as is, except for the addition of one extra watercourse dam found recently through ground truthing by NY NRM Board staff. Although farm dam volumes were estimated in Risby et al (2003) for the Willochra Creek, more recent imagery was used to develop new estimates.

Outside of those areas where prior work provided good estimates of farm dam development, farm dams were determined by use of aerial photography. Once obtained, imagery was imported into a GIS and the outline of identified (or suspected if imagery was unclear) farm dams were digitised. Once digitised, the surface area was determined and volumes were derived by use of a previously published formulae for farm dams within the region (McMurray 2004).

Farm dam summary statistics were calculated at three scales—being regional, catchment and sub-catchment. For each of these scales a range of statistics and figures are presented.

Farm dams were firstly distributed into size classes, allowing for any dominant size class to be determined. This is effectively a surrogate measure of the type of use that water is intended for, with dams greater than 5 ML total storage considered to be the minimum size capable of supporting high volume uses such as irrigation. Mean dam size was also calculated as well as two different measures of farm dam storage density.

- Mean density – defined as the total storage divided by the total area of the sub-catchment, intended to allow for comparison between sub-catchments.

- A density surface (raster grid) – calculated using the Spatial Analyst extension in ArcMAP. In this analysis the density of storage is represented as a continuous grid and the density determined for each 100 m^2 grid cell based on a 5 km interpolation radius. As with the above measure of density, the resulting units are again defined as megalitres of storage per square kilometre. A density surface was determined for each sub-catchment. This type of analysis is of use in highlighting any areas of localised high density development within sub-catchments.

To assess the sustainability of observed development, total sub-catchment farm dam storage was compared to mean annual runoff using published data or sub-catchment scale mean annual flow estimates as described below.

3.3 ESTIMATIONS OF SUB-CATCHMENT RUNOFF

Where available, estimates of adjusted median runoff were obtained from prior published data. The sources of this information are shown in Table 1. Where this information was not available, it was necessary to develop a rainfall–runoff relationship based on the Tanh function (described further in App. B).

The function was calibrated for use within each catchment by adjusting the two loss parameters through a combination of manual iteration and least squares optimisation. In the case of the Hill River and Mingays catchments both loss parameters were minimised through least squares. To reduce over-estimation in the low-flow range for Baroota and Rhynie sub-catchments, it was necessary to specify a value for the initial loss parameter (see App. B), and use least squares optimisation to fit the continuing loss parameter.

Table 1. Sources of runoff estimates for NY rivers

Catchment	Sub-catchments	Source
Light River	All sub-catchments	Tanh – Mingays
Wakefield River	Eyre Ck, Skillagolee Ck	Cresswell (1999)
	All other catchments	Tanh – Rhynie
Broughton River	Hutt, Hill	Cresswell (2000)
	Rocky River	Deane (2005)
	Mid Broughton, Booborowie, Freshwater, Baldry, Yackamoorundie, Bundaleer, Crystal Brook	Tanh - Hill
Willochra Creek	Southern Willochra	Tanh – Baroota
	Lower Willochra	

Rainfall–runoff data was calculated using group means for values of all data occurring within 50 or 100 mm increments (depending on replication) in annual rainfall and the corresponding mean runoff for the same years. This reduced the dispersion in the data and provided increased certainty that average catchment behaviour was modelled.

Rainfall data for the calibration were from regionalised annual rainfall volumes for the gauged catchment, derived using modelled rainfall data obtained from the Bureau of Meteorology (BoM)—SILO Patched Point Dataset. SILO rainfall data was subsequently obtained to model rainfall representative of each of the sub-catchments for the period 1889–2005.

Four regionalised functions were required to develop estimates for all sub-catchments assessed (Table 1). The rainfall–runoff curves are shown in Appendix B. Each of these were based on data recorded within the catchment itself with the exception of Willochra Creek, which was based on flow data from the adjacent Baroota Creek Reservoir.

Comparison of the values for mean and median runoff values derived using the rainfall–runoff function with actual observed data suggest that the method consistently over-estimated mean rainfall by around 7% and median by around 25% (see section 6.2.2). Although this will help to offset reductions due to existing development that was present in the catchment during the gauging period, this over-estimation was incorporated into the decision to use capture proportions over 25% as an indication of potential hydrological stress.

3.3.1 CHOICE OF A SUSTAINABILITY BENCHMARK

The default sustainability benchmark outlined in the *State Natural Resources Management Plan 2006* (DWLBC 2006) is defined as a proportion of median runoff, adjusted to have the impacts of farm dams removed. A figure of 25% total use of resource is considered to be the maximum sustainable level of development. It was not possible to directly apply this threshold in this work for three reasons:

1. The work is intended to cover a very large geographical region, and insufficient resources were available to develop the surface water models necessary to remove the impacts of farm dams and generate an adjusted volume and water use.
2. The coverage of streamflow gauges was not adequate to provide the necessary data to calibrate models in order to be able to determine the adjustment volume.
3. Even where gauges are present, the majority of these outside the Clare Valley are of a short duration, and a reliable value for median annual flow requires a long-term flow gauging record.

An operational policy applied in higher rainfall areas of the state in the absence of adjusted median runoff allows for a maximum dam size that does not exceed 50% of median annual runoff. However, given the uncertainties around the estimates in this report, this value was considered to be too high.

An alternative benchmark was adopted for the unique circumstances of this assessment where total dam storage which exceeds 25% of the estimated median runoff was considered to represent a level of development that warrants additional investigation. Rationalisation of this benchmark and a discussion of the issues around sustainability of farm dam development in the region appears in Section 6.

As with any benchmark applied at a relatively large scale, there is the potential for local impacts to be masked by averaging storage over the whole sub-catchment area. This potential, and the applicability of existing farm dam policy generally is examined in Section 5.

3.4 SURFACE WATER MODELLING

A simple daily time step surface water model was constructed using the WaterCress modelling platform and WC-1 rainfall–runoff model. Detailed information on model operation can be found in many recent Department of Water, Land and Biodiversity Conservation

(DWLBC) surface water assessments (e.g. Heneker 2003, Savadamuthu 2002, Teoh 2002) and the interested reader is referred to these.

The WC-1 model used optimised parameters obtained by calibrating a basic representation of the Mingays Waterhole gauging station (A5050532), and using regionalised rainfall from the BoM (SILO Patched Point Dataset). Model parameters can be seen in Appendix D. Although only fairly limited calibration results were obtained for the data (see Table 2), this was considered adequate as the representation is intended to evaluate scenarios rather than establish exact volumes. Generally speaking, the model reproduced patterns and volumes of annual and monthly flow well, but had a tendency to over-estimate the frequency of small runoff events, resulting in over-estimation of flow volumes and poor daily correlation statistics. As a result, the frequency of surface flow events appears larger than would generally be expected, but the relative reduction in streamflow responses is considered to be indicative of actual impacts (see Section 6.2.2).

Table 2. Calibration results for the Mingays Waterhole model

Time step	Coefficient of determination	Coefficient of efficiency	% difference in flow
Annual	0.95	0.89	13
Monthly	0.84	0.71	13
Daily	0.65	0.38	13

The model, consisting only of a single catchment node and two off-stream dam nodes, was designed to simulate the response of a small catchment area of 804 ha in the Upper Light River that controls runoff to a series of permanent pools located on a fourth order stream. Rainfall input to the model was a 117–year modelled record for the Light River region obtained from the BoM (SILO Patched Point Dataset). Results of the modelling can be found in Section 5, and Appendix D shows the model parameters.

4. RESULTS – FARM DAM DEVELOPMENT

4.1 INTRODUCTION TO RESULTS SECTION

The farm dam findings are divided into three categories of summary data for the area covered by the four river catchments and are reported at three scales—regional; catchment, and sub-catchment. Statistical descriptions of the farm dams present at each scale are provided including a break down of storage by size class. The distribution of farm dams is also reported using two measures of storage density as described in Section 3.2. Finally, in order to evaluate whether existing development is likely to be within sustainable use limits, farm dam storage was compared to mean annual runoff using published flow data or sub-catchment scale mean annual flow estimates. An indicative threshold of 25% of estimated mean annual flow is used as a sustainability benchmark, and this is discussed further in Sections 3 and 5.

4.2 REGIONAL LEVEL FINDINGS

4.2.1 SIZE AND STORAGE CAPACITY OF DAMS

There are estimated to be over 8800 farm dams located within the runoff generating catchment areas of the four main rivers within the Northern and Yorke NRM Region, with a combined storage volume of around 22 000 ML. Averaged over the whole area of the assessment the mean density of farm dam development—defined as total storage volume divided by the total area—is 1.6 ML/km^2.

Compared with other areas in the state, this level of development density is at the low end and indicative of the majority use for surface water in the region, which is the provision of stock waters or for domestic uses.

An indication of the widespread use of smaller storages can be seen in Figures 1 and 2. Over 8000 dams in the region have a total estimated storage volume of less than 5 ML. This comprises over 90% of the total number of dams. These dams however, only store a little over half of the total capacity potentially held within all dams in the region, meaning that only 10% of farm dams hold over 50% of the total potential storage volume.

Dams of a volume greater than 5 ML are generally considered to be the minimum size capable of supporting higher water use activities such as irrigation. Across the region there are thought to be 705 dams above this threshold. These dams hold almost 47% of the total estimated storage, despite comprising only 8.2% of the total number of dams. For the largest dams this volumetric dominance is further emphasised where the 1.1% of dams larger than 20 ML hold over 20% of the total storage volume.

The vast majority of these larger dams are found within the high rainfall zones of the region, notably within the Clare Valley, where rainfall and runoff is relatively reliable. As dams are likely to capture significant volumes during most years, the cost of building and maintaining such large storages is justified. For the same reason however, these high rainfall zones are

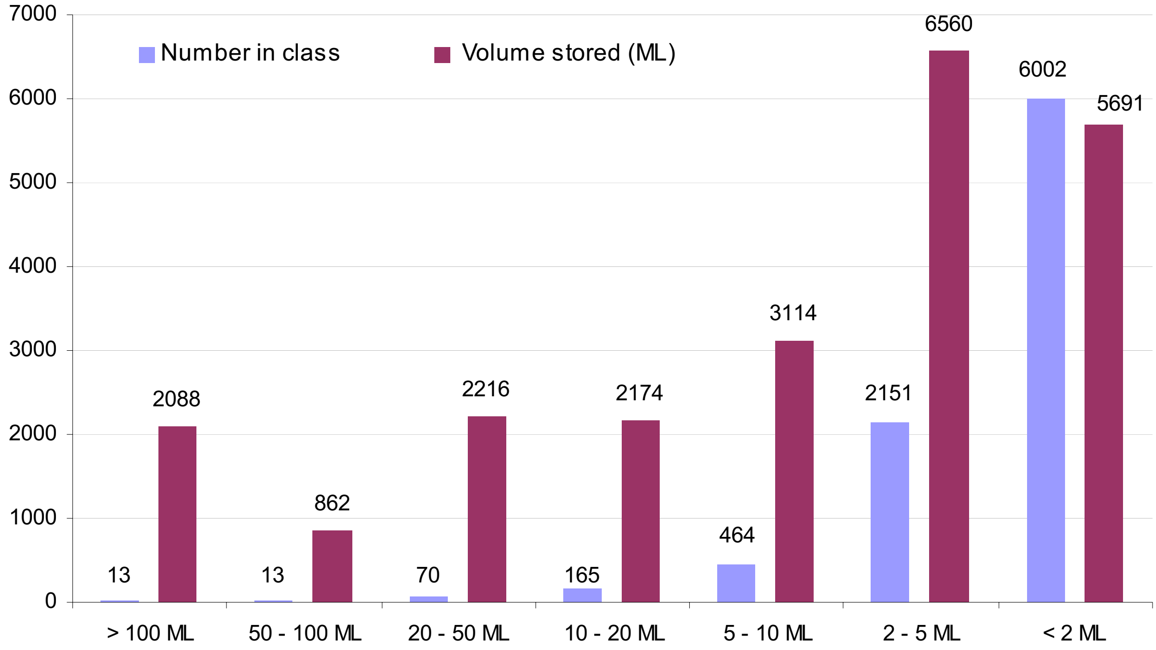


Figure 1. Classification of farm dam sizes for the NY rivers catchments

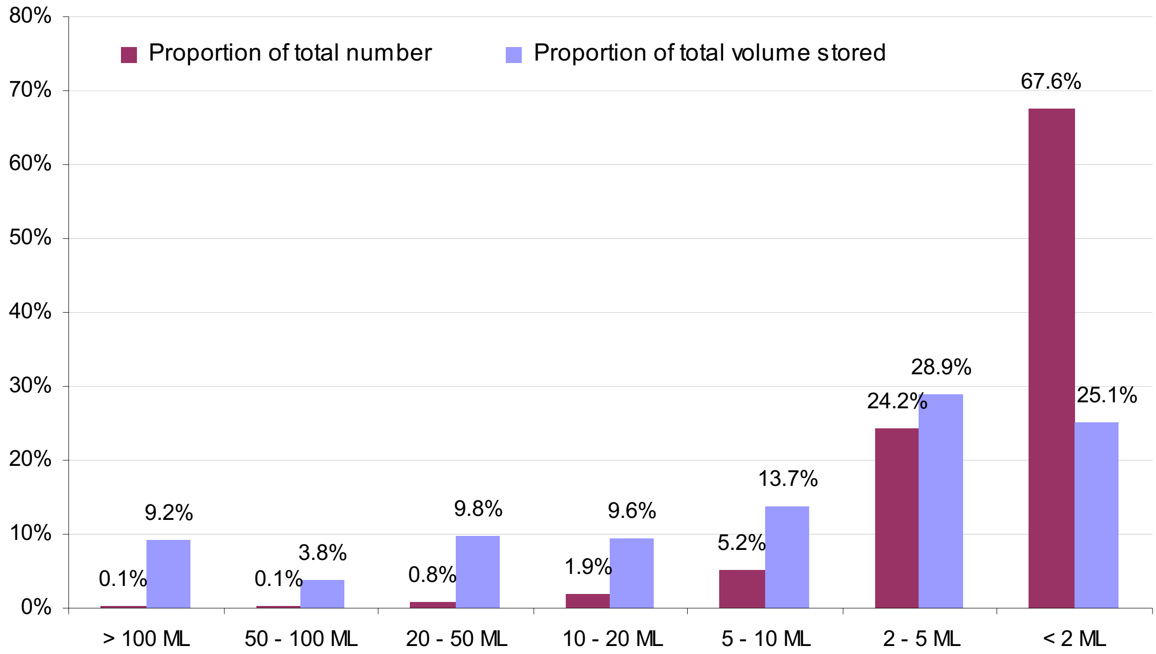


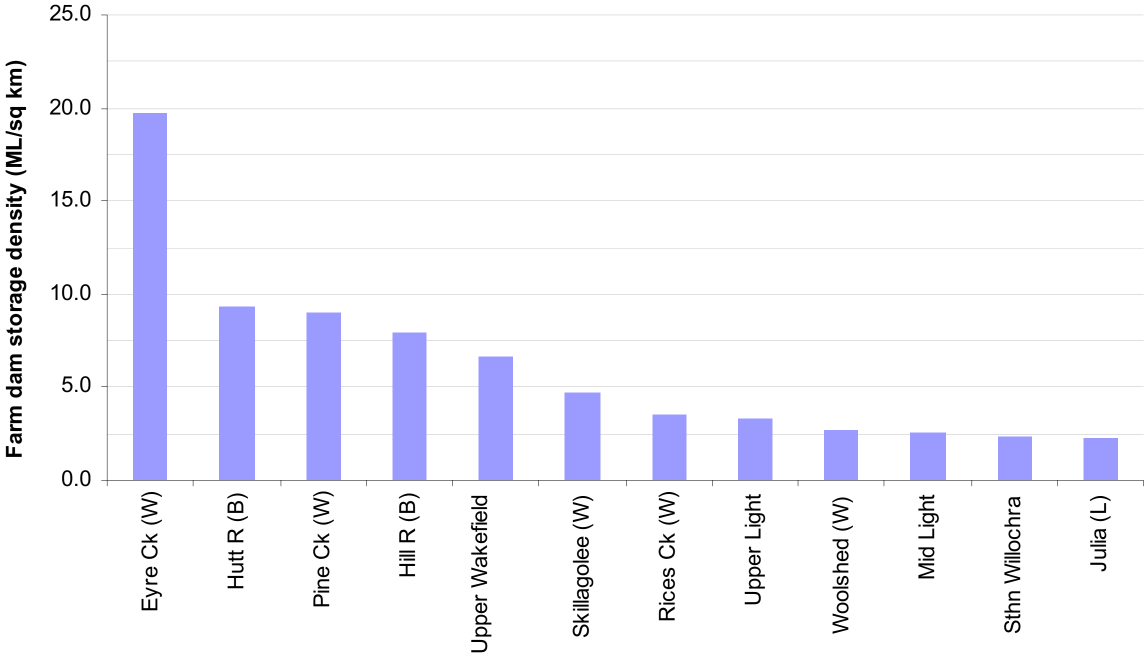
Figure 2. Proportional distribution of dams in size classifications: NY rivers

of disproportionate importance to the river system as a whole. Seasonally reliable flows that serve critical ecological functions in less reliable areas further downstream are generated in these zones of a catchment. Managing dam development in the areas of reliable runoff generation to maintain riverine processes at catchment scale is a critical aspect of sustainable water resource management. Topics relating to farm dam development and water resource management in the region are discussed further in Section 6.

4.2.2 DISTRIBUTION OF FARM DAM DEVELOPMENT

While collation of data at this regional scale is of value in characterising surface water use and in tracking changes in storage volume over time, it provides little indication of the level of hydrological impact across the four catchments. To gain an appreciation of this, it is necessary to examine the distribution of farm dams throughout each of the catchment areas. Two measures of farm dam storage density have been analysed to provide an indication of the high density areas.

The simplest measure of farm dam density can be obtained by calculating the ratio of total farm dam storage volume for each catchment or sub-catchment and the corresponding total area. This provides a low resolution means of assessing the relative development levels of individual catchment areas both within the NY NRM Region and also with higher rainfall areas to the south. Sub-catchments from within the four river catchments that have the highest storage densities are shown below in Figure 3.



River catchment in brackets after sub-catchment name: W = Wakefield; Br = Broughton; L = Light

Figure 3. Sub-catchments with highest farm dam densities: all NY rivers

Although sub-catchment storage density comparisons provide an indication of areas of widespread development, this does not allow for fine-scale variations in development to be assessed. To gain an improved overall picture of the distribution of relative hydrological stress in the region, the density surface of farm dam storage across the region is shown in Figure 4. Areas of low density are indicated by light blue shading, with higher densities indicated by darker shading. Although a region-wide mean storage density is of the order of 1.6 ML/km^2, the figure suggests that much of the area has a density of less than 1 ML/km^2.

As it is based on assessing density over a relatively small area, Figure 4 provides a clearer indication of fine-scale variations in storage density due to localised areas of high development. The density surface clearly demonstrates how high density sub-catchments are mostly located within prescribed areas or those already under a Notice of Intent to Prescribe. Areas of very high storage density can be seen in Figure 4 within the Clare Valley PWRA and the adjacent Upper Wakefield River Notice of Intent to Prescribe area. As previously mentioned, reliable seasonal runoff generally encourages increased usage of surface water runoff, including high levels of dam development.

Other areas of high density are found in the southern Light River catchment, within the Mid Light sub-catchment, and adjacent to the Barossa Valley PWRA. This is likely to be evidence of the boundary development that often occurs in response to the proclamation of a resource in zones adjoining the boundary by landholders who perceive their rights to take water may also be regulated.

Areas of slightly less density, but still clearly above the ambient levels indicated by the lightest shading level in Figure 4 are apparent in the central Rocky River and southern Willochra Creek catchments. In parts of the region, darker areas can be seen indicating isolated 'hot spots' of farm dam concentration. In many instances closer analysis showed this to be due to the presence of individual large dams rather than clusters of smaller dams.

More detailed discussions on the distribution of farm dam density in the four river catchments and their component sub-catchments are found in the following sections corresponding to each catchment.

4.2.3 HYDROLOGICAL IMPACTS

Although farm dam density statistics can provide an indication of absolute levels of development and their spatial distribution, it does not provide any measure of whether observed developments can be considered sustainable. The best manner in which to achieve this is through the development of a surface water model capable of reproducing spatial patterns of runoff and farm dam distribution. This method is capable of representing the interception of surface water runoff by farm dam storages across the range of conditions present in a given landscape and under various climatic conditions. This is however, a highly intensive approach and was beyond the scope of this report.

As a preliminary indication of the level of hydrological stress across different catchments, the estimated total volume of farm dam storage within each sub-catchment has been compared to an estimate of the annual runoff for the same sub-catchment area. Calculation of the ratio of farm dam storage to estimates of annual runoff then allows for comparison with existing sustainability criteria. This can also help to inform the development of new criteria more applicable to the conditions and available data, which is the subject of Section 6.

For the purposes of this assessment, a surrogate threshold of sustainability is proposed that was quantifiable using available data, and adequately reflects uncertainties in the runoff and farm dam estimates as well as the findings of the scenario modelling presented in Section 5.

Given these limitations, where farm dam volumetric capture exceeds 25% of the estimated median annual runoff, this is considered likely to represent a significant enough level of development to warrant further investigation. This value should be recognised as being a preliminary indication of development levels that are likely to exceed sustainability guidelines, and is not consistent with existing state farm dam policy. The applicability of this policy to semi-arid parts of the state along with uncertainties associated with the methods employed in this study however warrant a more conservative approach. These issues are discussed further in Section 6.

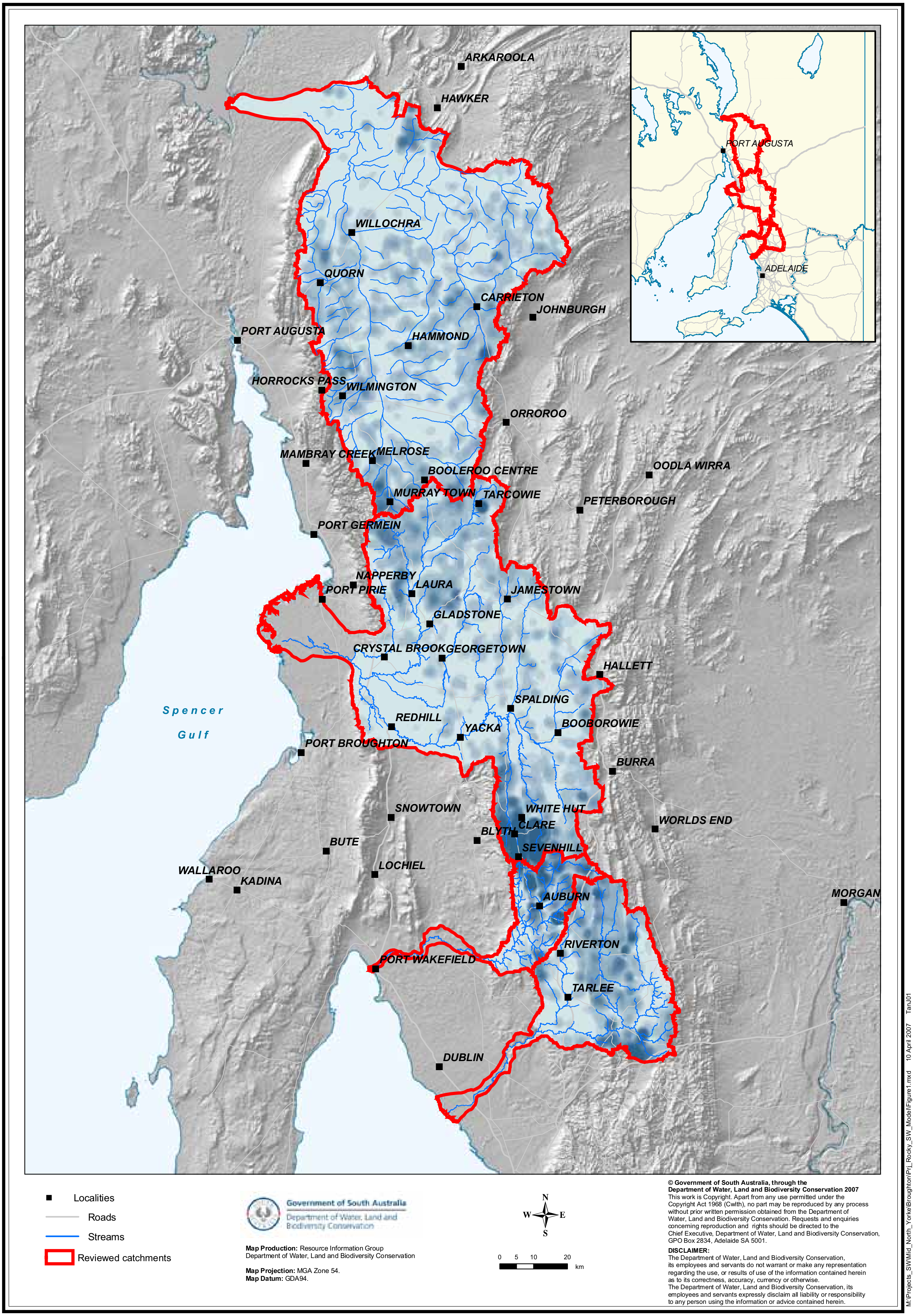
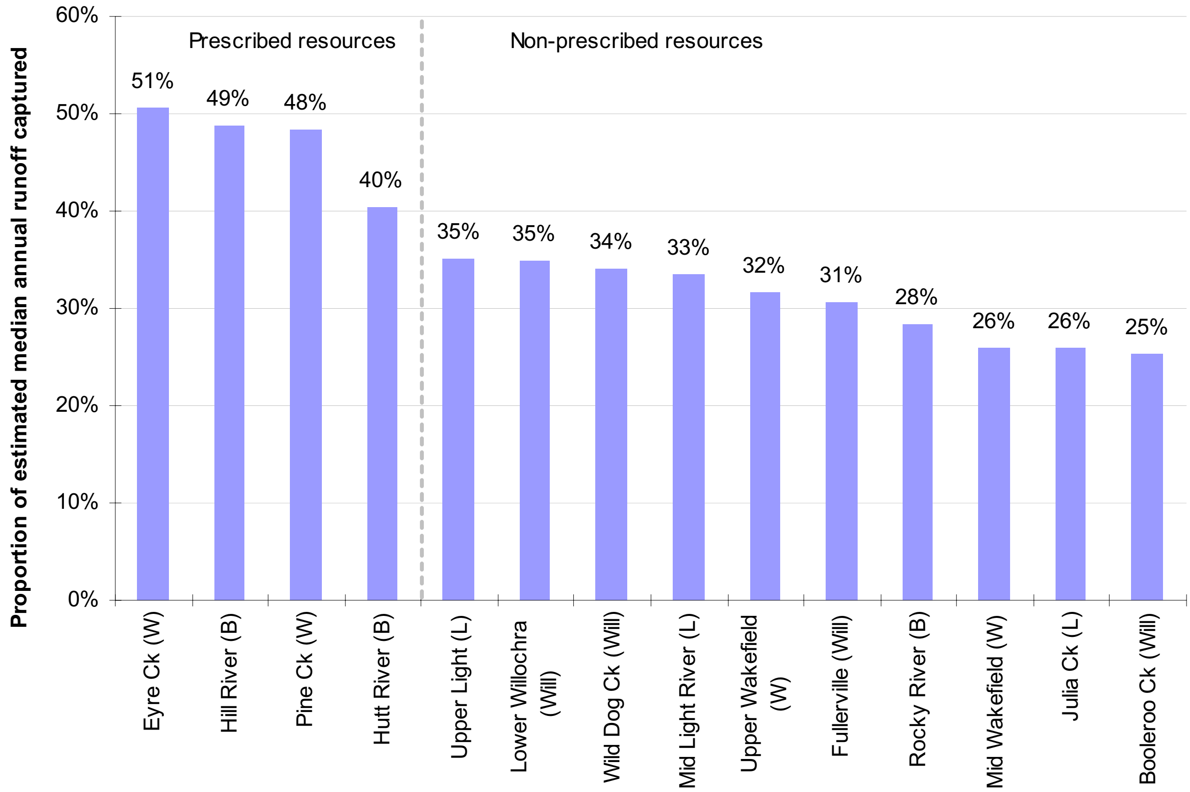


Figure 4. Farm dam storage density by NY river catchment

Figure 5 below shows sub-catchments where total farm dam storage volumes exceed the nominated sustainability threshold, deemed to be 25% of estimated annual runoff. This indicates that areas within all river systems of the NY region may currently exceed sustainable levels of farm dam development. The high water use areas within the Clare Valley have the highest development levels, but a number of non-prescribed sub-catchments have very similar use ratios. Even some catchments where use is limited to small dams also have total storage capacities that exceed 25% of estimated annual runoff. A clear example of this is the fact that the highest level of proportional capture observed outside of prescribed areas corresponds to the upper Light River (35%) and Lower Willochra Creek (35%). Watercourses in the Wild Dog Creek sub-catchment of the southern Willochra have added streamflow impacts as a result of diversions for episodic flood irrigation, which increases the level of risk to the resource (see Section 4.6.3).



River catchment in brackets after sub-catchment name: W = Wakefield; B = Broughton; L = Light; Will = Willochra

Figure 5. Sub-catchments in the NY region where farm dam capture exceeds 25% of estimated annual runoff

The estimates for prescribed areas in this report are intended to provide relative levels of development for comparative purposes. These are however only indicative, and should not be seen as having equal veracity as estimates appearing in water allocation plans (WAPs). For the most accurate estimates of current development, the values in the Clare Valley WAP should be referred to. Inclusion of the prescribed area estimates does provide an indication of the relative closeness of impacts as determined under this study and allows for benchmarking these levels with non-prescribed areas.

4.3 LIGHT RIVER CATCHMENT

4.3.1 INTRODUCTION

The Light River Catchment is the most southerly of the four main river catchments found within the region. The catchment has an area of around 1750 km^2, and the river discharges into Gulf of St Vincent around 40 km north of Adelaide.

Prior work on catchment hydrology is largely unpublished and includes an assessment of farm dam impacts undertaken by Greenwood (2000), and an assessment of environmental water requirements completed two years later (Murdoch 2002). The latter work was a background report to the Mid North Rivers Management Planning Project (Vanlaarhoven et al 2004), which is the major published work on the catchment.

For the purposes of this analysis five previously identified component sub-catchments of the Light River were used. Statistics relating to the impacts of farm dam development for these sub-catchments are shown in Appendix A, Table A1, with their locations shown in Figure 9. The sub-catchments are Gilbert River, Upper Light River, Pine Creek, Julia Creek, and Mid Light River. The Lower Light River effectively had no farm dam development, being coastal plain, and was not included in this analysis.

4.3.2 SIZE AND STORAGE CAPACITY OF DAMS

A total of over 2100 dams were identified within the Light River Catchment, with a combined storage volume of almost 4000 ML. The mean size of dams was 1.9 ML, which was the lowest of the four river systems. Over 80% of dams had a storage capacity of less than 2 ML. While no data were available on water use from surface water dams in the catchment, the great majority would appear to be used only for stock waters.

As shown in Figures 6 and 7, the number of larger dams is small in comparison with higher rainfall areas. Only 100 dams were estimated to have a capacity that exceeded 5 ML. Although only representing around 5% of farm dams, this small number of dams represents over 40% of the estimated storage held in the catchment.

4.3.3 DISTRIBUTION OF FARM DAM DEVELOPMENT

The mean farm dam storage density for the Light River Catchment was the second highest of all catchments at 2.5 ML/km^2, but was still less than half of the maximum value of 5.0 ML/km^2 for the Wakefield River. Farm dam densities throughout the Light River were moderate and generally above the regional mean of 1.6 ML/km^2. Densities of dams varied considerably between sub-catchments as shown in Figures 8 and 9. The Upper Light River has the highest storage density, at 3.3 ML/km^2, followed by the Mid Light at 2.6 ML/km^2. Pine Creek sub-catchment had very low levels of development with a storage density of only 0.2 ML/km^2.

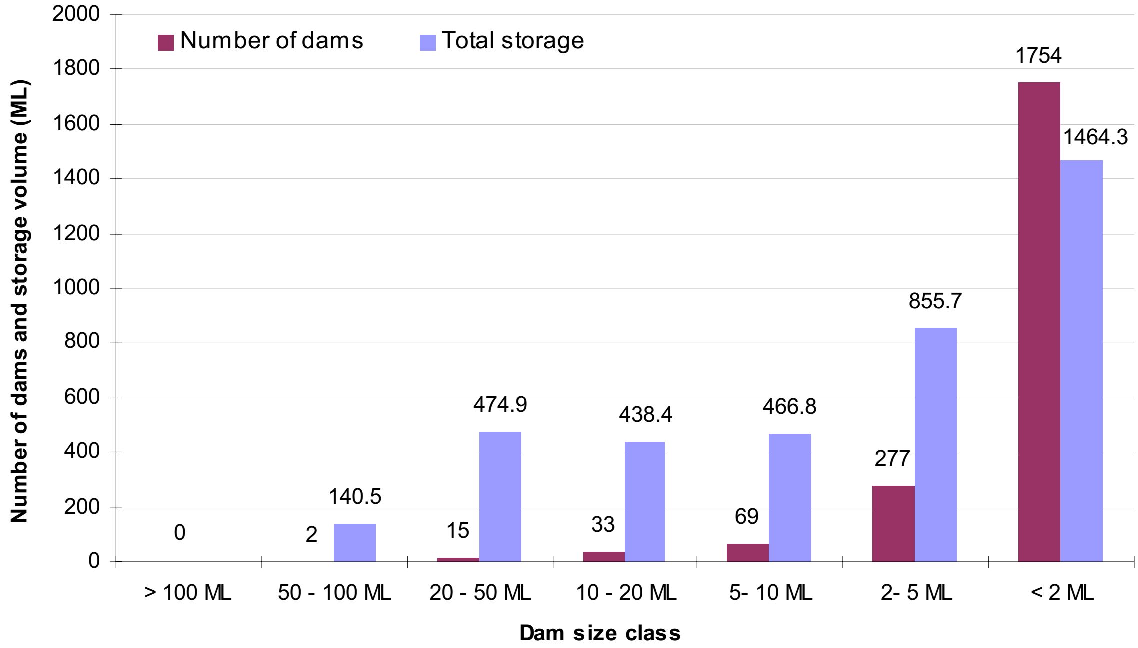


Figure 6. Farm dam size class distribution for the Light River

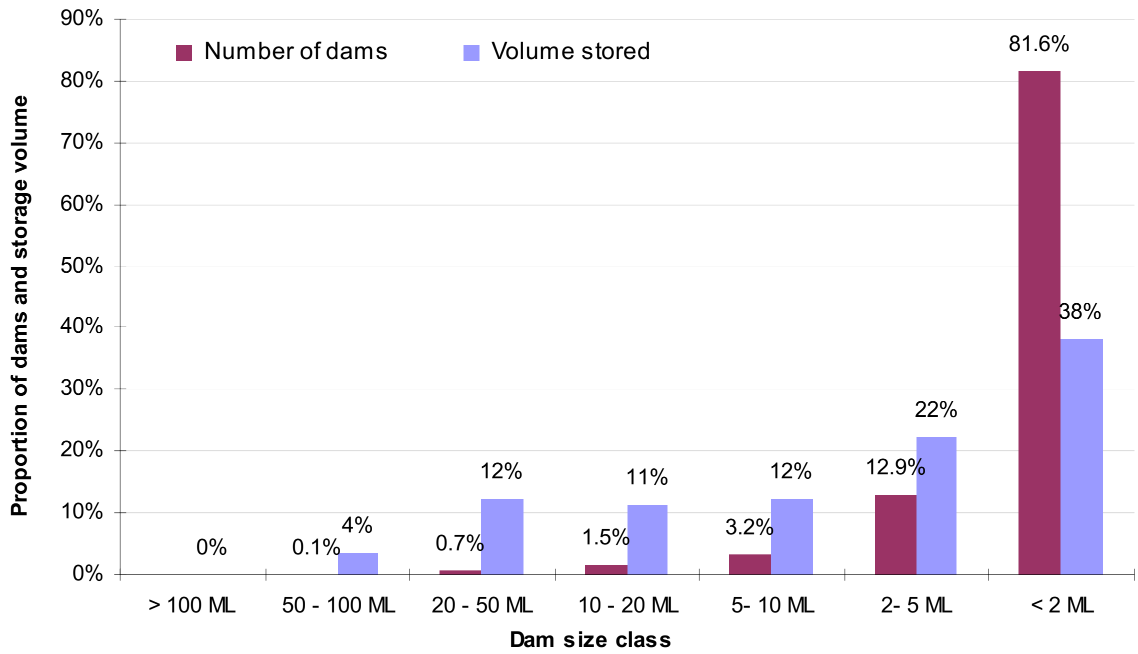


Figure 7. Proportional distribution of dams by size class: Light River

Within sub-catchments, the density surface (Fig. 9) indicates a number of 'hot spots' of dam development. As discussed above and shown in Figure 4, there is extremely dense development in the south-central areas of the Mid Light sub-catchment. Although some of this is attributable to the Barossa Valley PWRA, which actually extends slightly into the Light River Catchment (Fig. 4) the highest densities appear to be to the west of the PWRA boundary. Dam densities in this area exceed 10 ML/km^2, almost four times the sub-catchment average—and comparable with densities in the Clare Valley. Accelerated development levels have been observed in areas adjacent to prescribed resources in other parts of the state, including the Clare Valley. For example, the Upper Wakefield River was prescribed in response to perceived increased pressure in this region following prescription of the original Clare Valley PWRA.

Other 'hot spots' of farm dam development shown in Figure 9 can likely be attributed to the presence of individual large dams such as can be seen in the upper reaches of the Upper Light and Gilbert River sub-catchments. The high density but relatively low mean dam size for the Upper Light sub-catchment demonstrates that many smaller dams can result in similar hydrological impacts as fewer, larger dams.

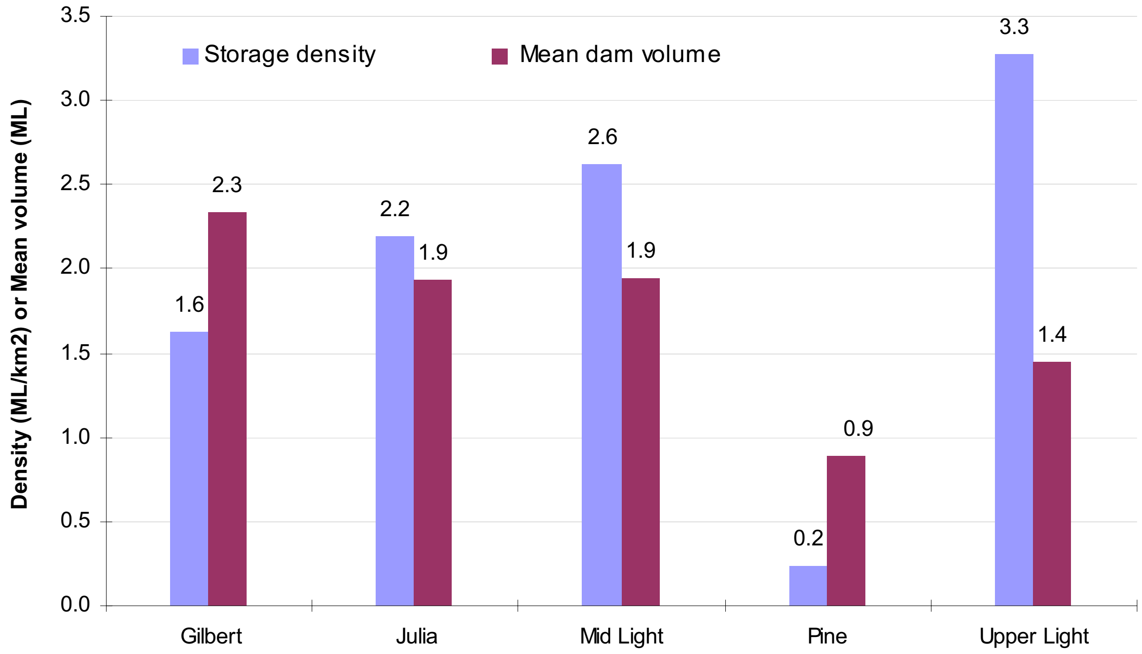


Figure 8. Storage density and mean dam size by sub-catchment: Light River

4.3.4 HYDROLOGICAL IMPACTS

Figure 10 shows the total farm dam storage capacity as a proportion of estimated median annual runoff. The data indicates that, as suggested by the density mapping, the highest level of hydrological stress currently appears to be within the Upper Light and Mid Light sub-catchments. Both of these sub-catchments have dam storage capacities that exceed 30% of the estimated annual runoff and must be considered to be at risk. Streamflow within Julia Creek sub-catchment would also be impacted with a storage capable of holding 26% of mean annual yield. The remaining sub-catchments appear to have been at low levels of development at the time the imagery were captured. Owing to the low volumes of runoff generated there is still potential for isolated impacts to occur, and Section 5 examines the potential impacts of even small dams in semi-arid areas where these are located in on-stream locations.

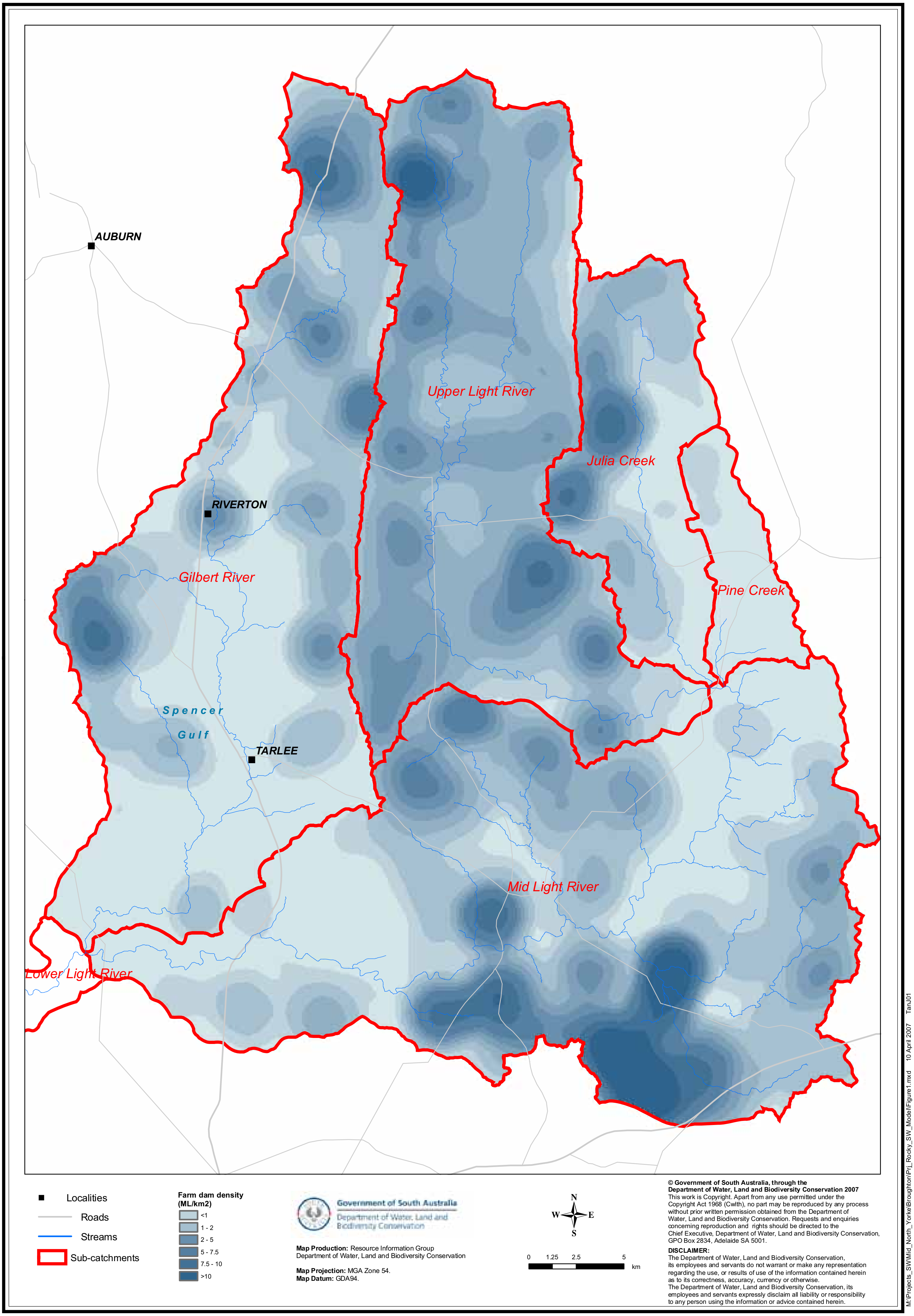


Figure 9. Farm dam density by sub-catchment: Light River catchment

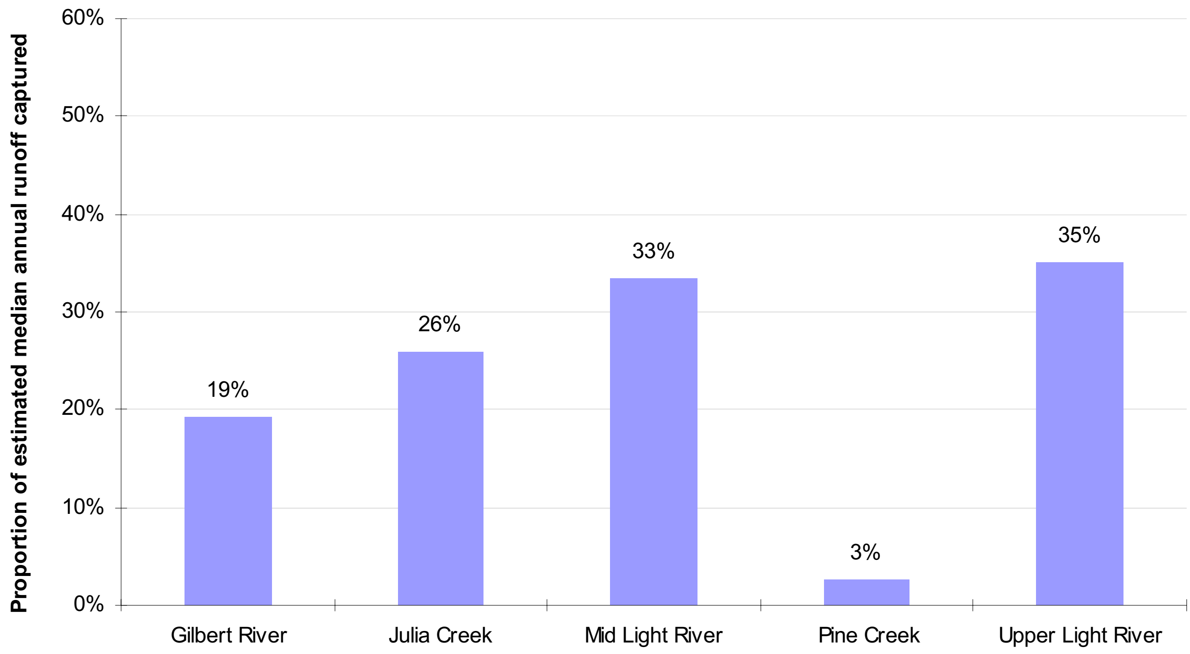


Figure 10. Estimated capture of annual runoff by sub-catchment: Light River

4.3.5 RISK ASSESSMENT: LIGHT RIVER CATCHMENT

Historically farm dam development levels in the Light River Catchment have not been considered to be of a level likely to be unsustainable (Murdoch 2002). In more recent years, concerns have been raised in the southern-most areas of the catchment over increasing development of surface and groundwater. Landholders from areas around the Barossa PWRA in particular have voiced concerns over declining water resources. Evidence in this report would support the fact that development levels in this area are easily of the highest density throughout the catchment, and well above comparable levels away from the boundary of the PWRA. Clearly further investigation of this is warranted.

The indicator of potential stress to the resource of 25% of mean annual runoff or greater is exceeded in the Upper Light, Mid Light and Julia Creek sub-catchments. With the exception of the Pine Creek and Gilbert River it would appear that farm dam development throughout the catchment has reached levels where future sustainability may be at risk.

There is also a prior estimate of total farm dam storage available for the Light River catchment. This has enabled a rate of increase to be determined. Greenwood (2000, cited in Murdoch 2002) estimated total dam storage from imagery captured in 1999 at 3000 ML. Before relevant comparison could be made with the current work it was necessary to adjust for slight differences in the methods used to estimate dam volume in the earlier work. Greenwood (2000) used the same surface area digitisation technique employed in this study, but used a different surface area to volume conversion formula, which was developed in Billington and Kotz (1999). Applying the Billington and Kotz (1999) formula to the surface areas determined in the current work from 2002 imagery results in an estimate for total current storage of 5350 ML, compared with 3829 ML reported above.

Comparing the two figures developed using the Billington and Kotz formula indicates an increase in total dam storage of 69% over the three–year period. Raw data from this assessment were not available, and although sub-catchment boundaries used in that assessment did not align directly with those used in this assessment, some comparison of farm dam statistics was possible. These were limited to the relative number of dams and are presented in Table 3. At catchment level the number of dams appears to have roughly doubled, producing the 69% increase in estimated storage.

Table 3. Change in farm dam numbers 1999–2002, Light River Catchment

Sub-catchment	Number of dams 1999	Number of dams 2002	% change in number
Julia, Pine and Upper Light combined	492	1017	107
Gilbert River	200	312	56
Mid Light	385	885	109

These figures suggest that the observed increase is not due to concentrated high volume development adjacent to the Barossa Valley PWRA, much of which may have been developed prior to 1999. Rather, the increases seem to be due to new small dams being implemented across the catchment. Some misidentification may have occurred for the 2002 imagery, which was of a lower standard, but this source of error can also result in dams not being identified. The rate of increase cannot be further assessed as the source data for the 1999 report is not available. Additionally, it should be recognised that the imagery used in this assessment was already almost five years old. If the same trend has continued to the year 2007, the total farm dam storage volumes in the Light River catchment would be over 9000 ML. Further investigation on the rate of increase in and current farm dam storage in the catchment needs to be undertaken as a matter of urgency.

Flow estimates were also presented in Greenwood (2000, cited in Murdoch 2002), which reported that the mean and median flow volume, with the impacts of farm dams removed totalled 24 300 and 16 730 ML/y, respectively. These values exceed the estimate in this report of 19 000 and 13 500 ML/y respectively, and may reflect inclusion in this study of rainfall since 1998 which has been below the long-term average. The affect of dams at 1999 levels (3000 ML total storage) was to reduce the annual flow volume by around 1900 ML/y, representing around 11% of median adjusted flow, or 45% of the state benchmark for the sustainable development limit. Given the increase in farm dam storage observed during 1999–2002, and the fact that this trend may actually have continued to the present day, the sustainability of current development levels must be questioned. Even if development levels have not increased by any great amount in the period 2002–07, the modelled scenarios in Section 5 indicate that development levels are likely to be having an impact on streamflow.

The above finding of an 11% reduction in streamflow being attributable to dams led Murdoch (2002) to conclude that the impact of farm dams on annual flow at that time were minimal and unlikely to be compromising environmental water requirements at catchment scale. The same author however, did not rule out the possibility for localised impacts to be occurring. Modelling reported in Section 5 suggests that even small stock dams are capable of removing all of the streamflow received in many, if not the majority of years in semi-arid areas.

4.4 WAKEFIELD RIVER CATCHMENT

4.4.1 INTRODUCTION

The Wakefield River rises in the northern Mount Lofty Ranges (MLR), flowing westerly to drain into the north of Gulf of St Vincent. The western catchment consists of coastal plains of low elevation and accordingly low rainfall. However, much of the upper catchment is within a high elevation and therefore high runoff zone, and as a result is heavily developed. With a total catchment area of only around 690 km^2 it is easily the smallest of the four river systems.

For the purposes of this analysis the lower reaches of the Wakefield River catchment, which do not have any farm dams capturing surface runoff, were excluded. The high rainfall in the sub-catchments assessed—particularly those within the Clare Valley—contribute almost all of the runoff to the Wakefield River system as a whole. This is an important consideration for management as excessive development levels in upper catchments can exert a large impact on the flow regime of the river system as a whole. Summary statistics relating to the impacts of farm dam development for these sub-catchments can be found in Appendix A, Table A2, and their locations can be seen in Figure 14.

Areas of the Wakefield River catchment that are assessed in this study are all either currently, or shortly will be, included in the Clare Valley PWRA. Both the Eyre Creek and Skillagolee Creek sub-catchments, as well as parts of all remaining sub-catchments with the exception of Woolshed Creek, are already protected under the existing Clare Valley WAP.

For the purposes of this report, which aims to gain some appreciation of the level of development at sub-catchment level, it has been necessary to include both currently prescribed, and non-prescribed areas. Any indication of non-sustainable development that may be implicit in the findings of this report will be addressed through investigations under the Notice of Intent to Prescribe that will occur over the coming years. This process will be of a more technically detailed nature than this assessment, and the findings of this report may not be directly applicable to those investigations.

4.4.2 SIZE AND STORAGE CAPACITY OF DAMS

A total of 839 farm dams were identified within the Wakefield River sub-catchment, with a combined storage volume of around 3050 ML. The mean size of dams was 3.6 ML, the highest value for this statistic of all river catchments in the NY region. The larger mean dam size reflects the widespread use of surface water for high volume activities such as irrigation in the catchment and the relatively small catchment areas concerned.

Figures 11 and 12 show the distribution of dams by volumetric size class, as totals within each class and as a proportion of total use in the catchment, respectively. Although only comprising around 10% of the total number of dams, 68% of total storage is contained within dams exceeding 5 ML capacity (2100 ML within 84 dams). The number of large dams is much greater than in other parts of the region and only ten dams exceeding 50 ML hold over 35% of the total capture volume for the entire catchment.

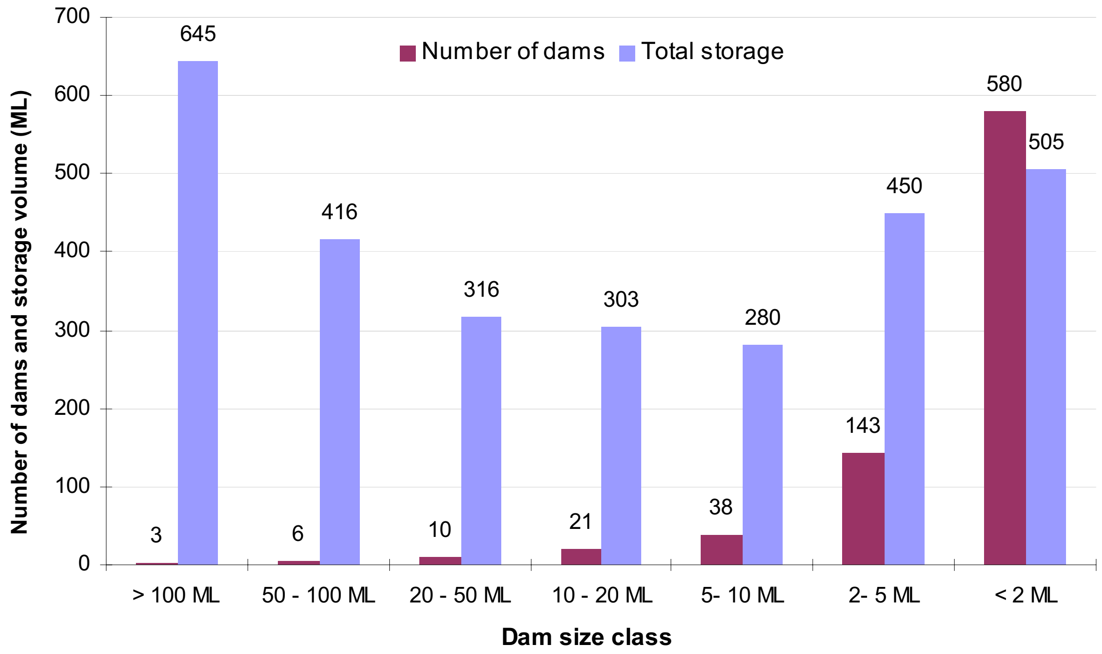


Figure 11. Farm dam size class distribution for the Wakefield River

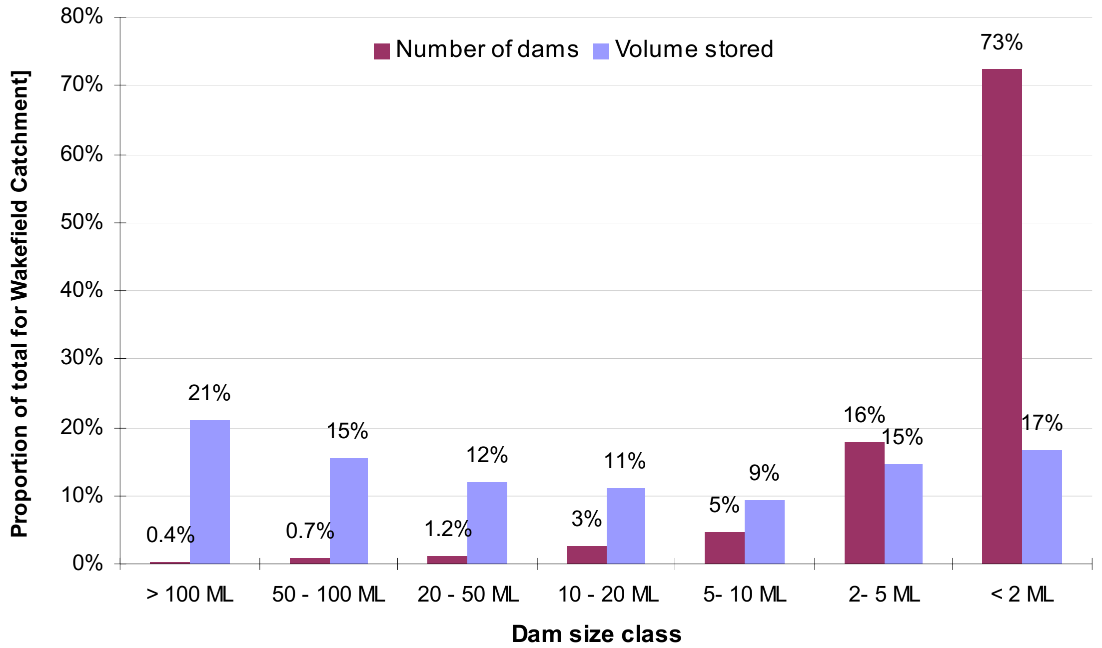


Figure 12. Proportional distribution of dams by size class: Wakefield River

Dams smaller than 5 ML comprised 89% of the total number of dams, and clearly small stock and domestic dams are a major contribution to overall water resource development. Dams in this size class had a storage capacity totalling less than 32% of the total storage held however, and the volumetric impact is accordingly proportionally lower.

4.4.3 DISTRIBUTION OF FARM DAM DEVELOPMENT

The mean farm dam storage density for the Wakefield River Catchment was by far the highest of all catchments at 5.0 ML/km^2. Figure 13 shows the farm dam storage density and mean dam size by sub-catchment. Again, the highest dam densities in the NY NRM region were found in sub-catchments of the Wakefield River. Eyre Creek has a farm dam storage density of almost 20 ML/Km^2 stored, which was clearly the highest of all sub-catchment level values assessed. Mean dam size for this catchment was also the largest for the region at 9.8 ML.

Other sub-catchments with high density and mean storage volumes include the remaining three sub-catchments—Upper Wakefield, Pine Creek and Skillagolee Creek—within which dams with a capacity of greater than 50 ML are located. This reflects the influence of these large storages on farm dam statistics in the small sub-catchments areas, as are found in the Wakefield River.

The density surface shown in Figure 14 provides further insights into the distribution of farm dams in the catchment. Although the Clare Valley PWRA includes the majority of the more highly developed sub-catchments, Skillagolee Creek is still relatively dam free by comparison. To maintain a natural hydrology within the river system as a whole, maintenance of this area as free-to-flow is critical.

Additional areas of high storage density can be found in Pine Creek sub-catchment which is largely due to a single high volume dam of around 250 ML. Outside of the areas adjacent to the Clare Valley PWRA farm dam development in the Mid Wakefield sub-catchment is low, reflecting the lower volumes and reliability of runoff.

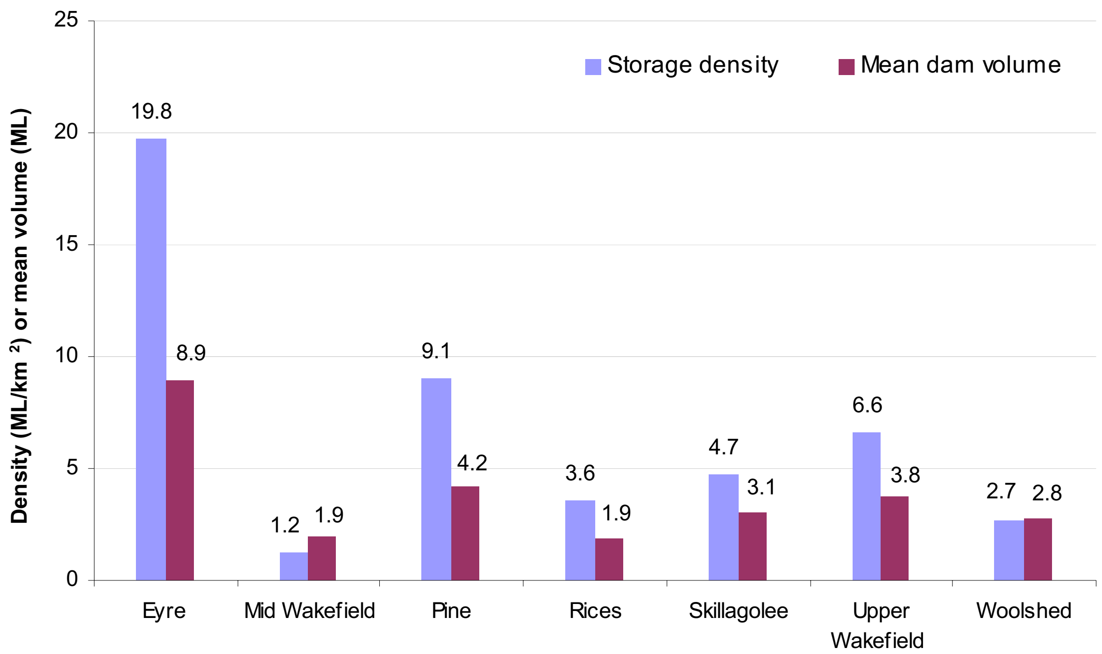


Figure 13. Farm dam density levels for Wakefield River sub-catchments

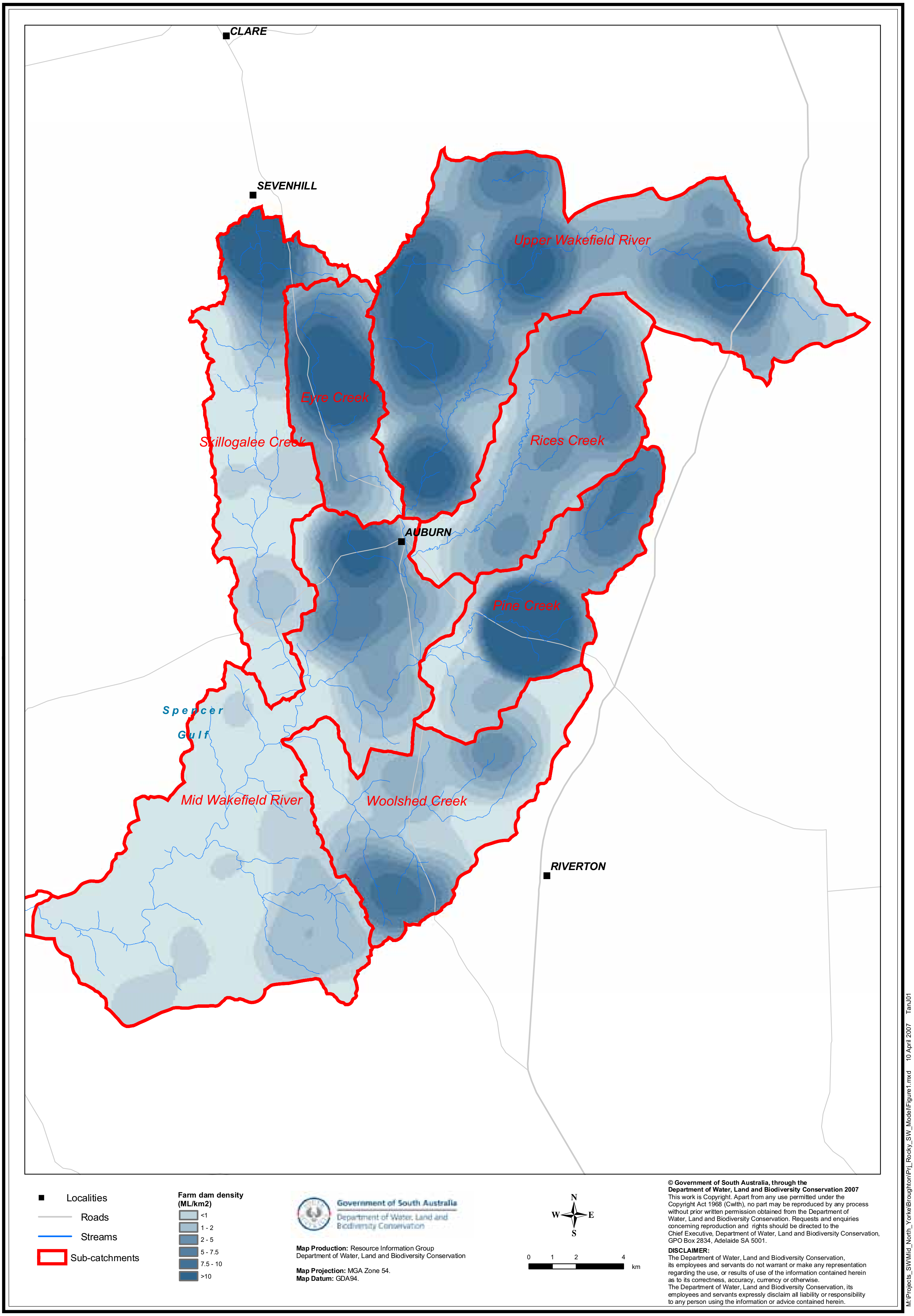


Figure 14. Farm dam density by sub-catchment: Wakefield River catchment

4.4.4 HYDROLOGICAL IMPACTS

Although considerable prior modelling and assessment has been undertaken in the Clare Valley catchments, this has focussed on the boundaries of the prescribed area. No previous data were identified that was directly applicable at sub-catchment scale outside of this area. Estimates of annual runoff were derived using published data where available, or alternatively developed specifically using the Tanh function described in Section 3 and Appendix B.

Figure 15 suggests that, with the exception of Rices and Skillagolee Creek, all sub-catchments in the Wakefield River system are currently under potential hydrological stress. The relatively undeveloped Skillagolee Creek sub-catchment is an important streamflow generating zone from a whole-of-river perspective. The free-to-flow areas in this sub-catchment are of critical importance to the maintenance of a relatively natural hydrology for downstream areas. The preservation of this area as remaining free of further dam development has been recognised in the water allocation plan for the area.

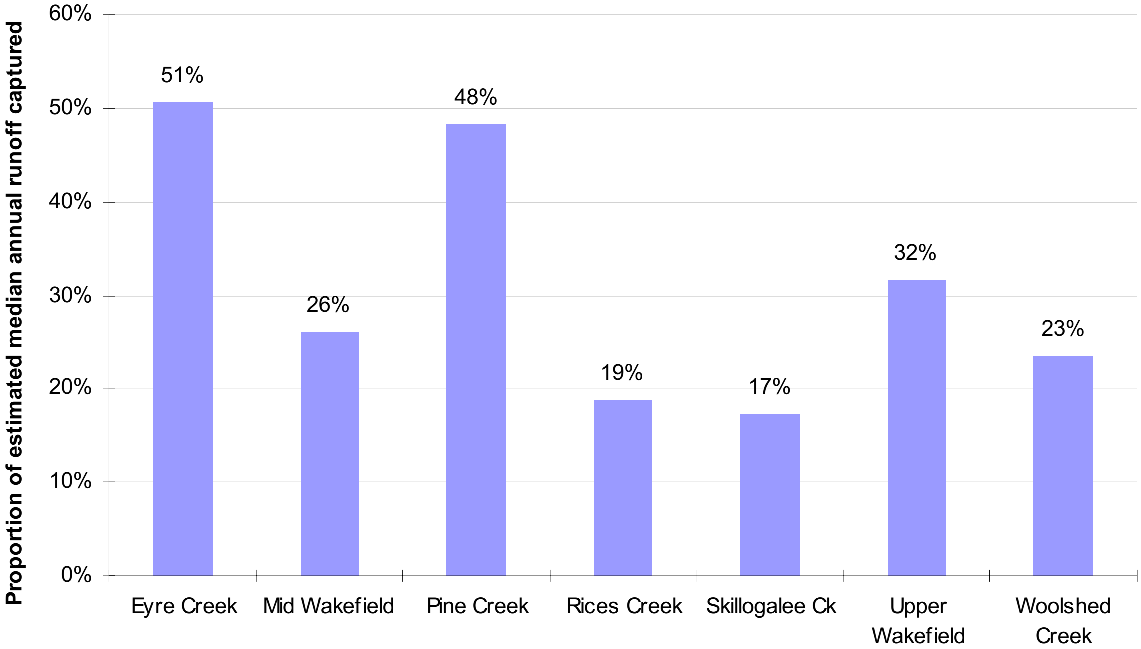


Figure 15. Estimated capture of annual runoff by sub-catchment: Wakefield River

Figure 15 indicates that Pine Creek, Eyre Creek, and the Upper Wakefield River sub-catchments in particular are highly developed, and likely to be beyond sustainable limits at sub-catchment scale. Any issues of unsustainable development for the Wakefield River will however be addressed through future water allocation planning as part of the Clare Valley PWRA and are not considered further in this report.

4.4.5 RISK ASSESSMENT: WAKEFIELD RIVER

The Wakefield River is unique among the catchments considered, owing not only to it's small area, but also the fact that the majority of the catchment area is found within high rainfall areas. Only the Mid Wakefield sub-catchment has a mean rainfall of below 500 mm/y. These high elevation areas generally also have a relatively high slope and represent relatively productive farm dam catchment areas.

All of the measures of development used in this study returned the highest value for sub-catchments in the Wakefield River. By all measures farm dam development is high—summary statistics for sub-catchments of the Wakefield River were consistently up to twice the next highest value recorded in the region. These values compare with not only other catchments within the NY NRM region, but also other areas of South Australia such as the Onkaparinga and Marne River (Teoh 2002, Savadamuthu 2002). Statistical analyses in this report suggest that the Wakefield River is likely to be experiencing the highest impact from farm dam development in the region.

Excessive water resource development has however long been recognised in this catchment, and as a result of protective actions already taken to address this, farm dam proliferation is now able to be managed. Management actions must now turn to ensuring that current development is sustainable and any issues of over-development of farm dams—if confirmed in future technical assessments—will be addressed through the development and review of water allocation plans.

In terms of the future sustainable management of the river system, the importance of Skillagolee Creek as an area of limited development, and therefore a reliable source of runoff, cannot be overstated. The level of development should be maintained at current low levels into the future, as the importance of maintaining this relatively natural hydrology has been well appreciated by water allocation planners for the region.

4.5 BROUGHTON RIVER CATCHMENT

4.5.1 INTRODUCTION

The Broughton River Catchment is the major river system of the Northern and Yorke region, with the highest mean and median flow volume. The Broughton River Catchment has a total area in excess of 5500 km^2. For the purposes of this assessment the catchment has been considered from the perspective of a number of sub-catchments of varying size. Key statistics relating to the impacts of farm dam development for these sub-catchments are shown in Appendix A, Table A3, and their locations can be seen in Figure 20. The Lower Broughton River sub-catchment is not considered within this assessment as it is effectively coastal plain and no farm dam development was identified within this area.

The mean annual rainfall for the catchment overall is estimated at around 474 mm/y and sub-catchment means range from around 415 mm/y to almost 550 mm/y. The Hutt and Hill River sub-catchments receive the highest annual rainfall, with mean totals in excess of 500 mm/y.

4.5.2 SIZE AND STORAGE CAPACITY OF DAMS

A total of 3641 dams were identified within the catchment, and are estimated to represent a combined storage capacity of around 9670 ML. The mean dam storage capacity for all dams in the Broughton River Catchment was 2.7 ML. Figures 16 and 17 present summary information for all farm dams in the catchment within the size classifications used in this assessment.

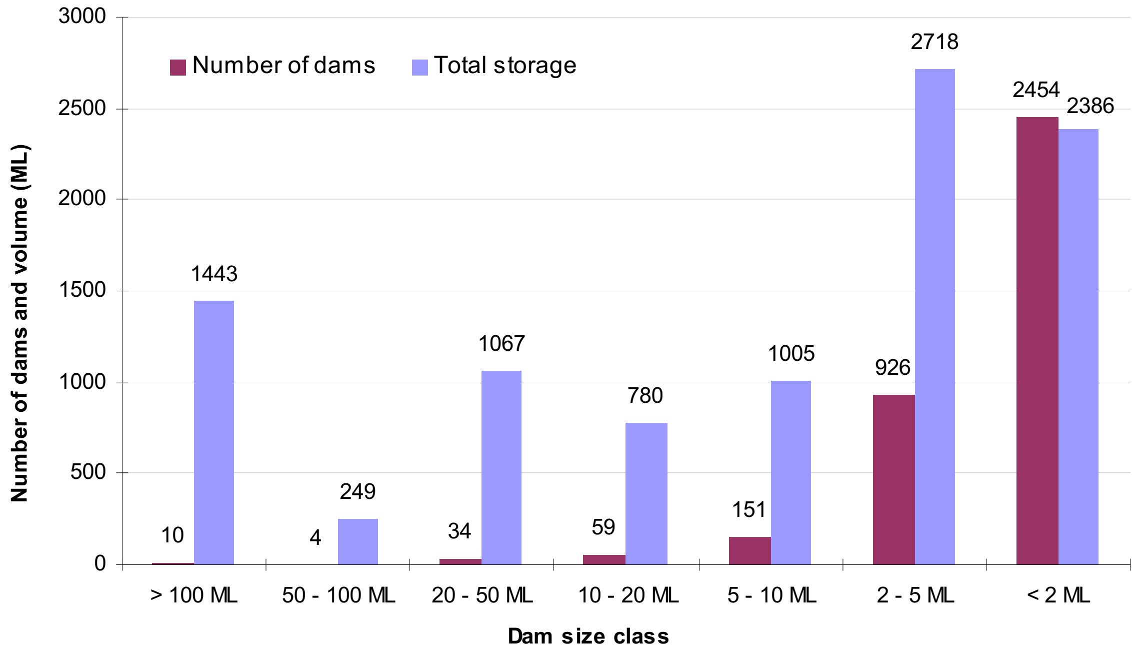


Figure 16. Farm dam size class distribution for the Broughton River

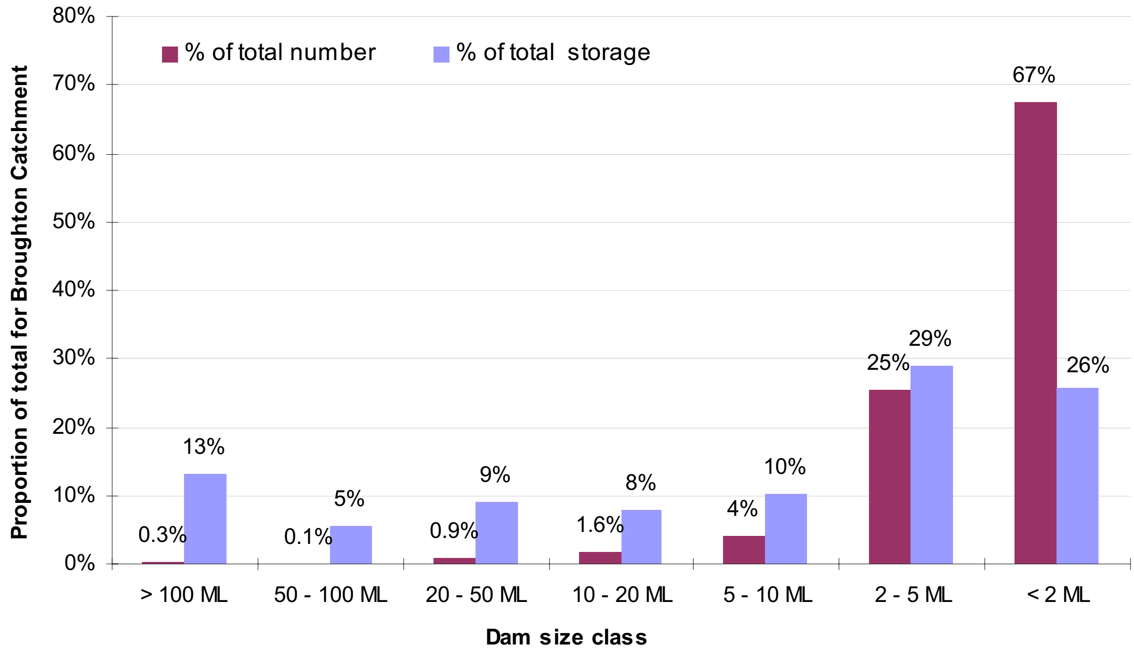


Figure 17. Proportional distribution by farm dam size class: Broughton River

Farm dams within all size classes are found in the Broughton catchment, reflecting the broad range of climatic conditions and land uses that are found. Of the total storage volume represented by farm dams in the Broughton River Catchment, 45% is contained within the 7% of dams with a capacity exceeding 5 ML. This also means that more than half of the total volume stored is used for stock and domestic purposes, which comprise over 90% of dams present.

4.5.3 DISTRIBUTION OF FARM DAM DEVELOPMENT

The mean farm dam storage density for the Broughton River Catchment was 1.9 ML/km^2. Figure 18 shows farm dam density and mean farm dam size calculated for each sub-catchment as a whole. As would be expected, farm dam development is greatest in the high rainfall Clare Valley sub-catchments of the Hutt and Hill Rivers. Dams with a capacity exceeding 50 ML for example, are all found in the Hutt and Hill River sub-catchments, with one exception, which is located in the upper Rocky River sub-catchment.

The marked difference between the density and size distribution in the high rainfall sub-catchments of the Hutt and Hill Rivers, compared with the rest of the Broughton River system, is shown in Figure 18. The Hutt River sub-catchment has the highest mean storage density (9.3 ML/km^2), but the largest mean dam size is found in the Hill River (5.3 ML). With the exception of these catchments, plus the Rocky River, and parts of the Mid Broughton, Figure 18 suggests that both the storage density and mean size of dams is low.

It should be noted however, that no allowance has been made for the presence of Beetaloo and Bundaleer Reservoirs. Beetaloo Reservoir captures all of the surface runoff in the high rainfall upper Crystal Brook catchment. Although not currently in operation, Bundaleer Reservoir diverts or captures runoff from several sub-catchments of the Broughton including Freshwater, Booborowie and Bundaleer Creeks.

The presence of the reservoirs has a profound influence on catchment hydrology, effectively removing all streamflow above the location of the dam wall or weir in all but the most extreme years. All catchments where reservoirs are located should be considered to be fully developed and have environmental release programs to ameliorate any impact on the environment resulting from capture of all surface water runoff.

The density surface map of the Broughton River Catchment (Fig. 20) as expected, shows that the highest densities are located in the Hutt and Hill River sub-catchments, in particular within the zone forming part of the Clare Valley. Rocky River sub-catchment also shows areas of high dam density, and small areas within this sub-catchment have been found to be at or above sustainable development guidelines (Deane 2005).

4.5.4 HYDROLOGICAL IMPACTS

In the case of the Broughton River sub-catchments, Cresswell (2000) evaluated the available gauging record and determined the mean and median yield for sub-catchments where this was possible. The same author used a surface water model to remove the impacts of farm dams from the Hutt and Hill River sub-catchments. Surface water modelling has also been used to determine permissible levels of dam development for each sub-catchment within the Clare Valley PWRA.

In sub-catchments where no-flow data were available, Cresswell (2000) made estimates based on surface water models, and those median flows are used in this assessment with the exception of Rocky River and Mid-Broughton. Estimates for the Rocky River were obtained from Deane (2005), and the Mid-Broughton was estimated using the Tanh function approach described earlier in this report and shown in Appendix B.

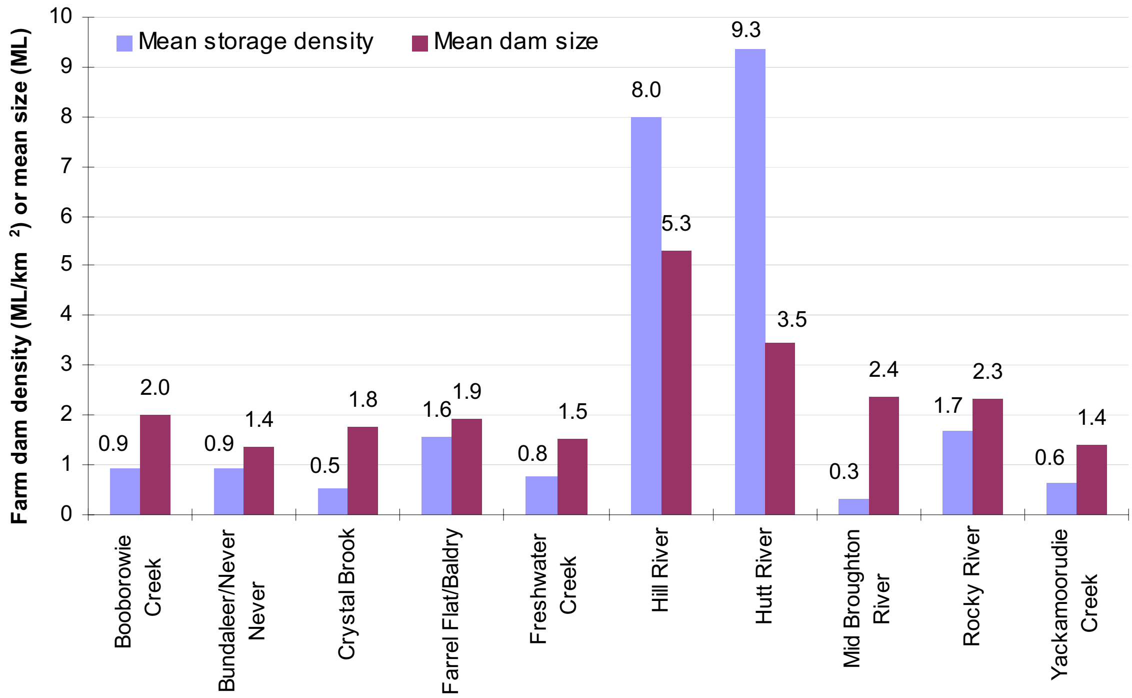


Figure 18. Sub-catchment storage density and mean dam size: Broughton River

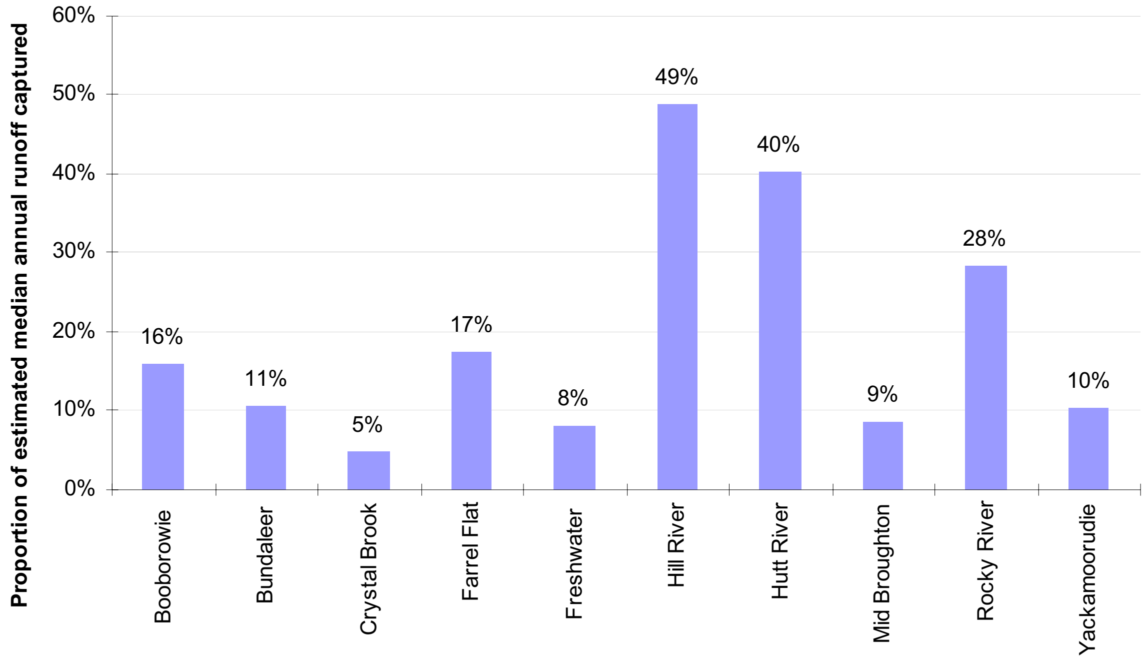


Figure 19. Estimated capture of annual runoff by sub-catchment: Broughton River

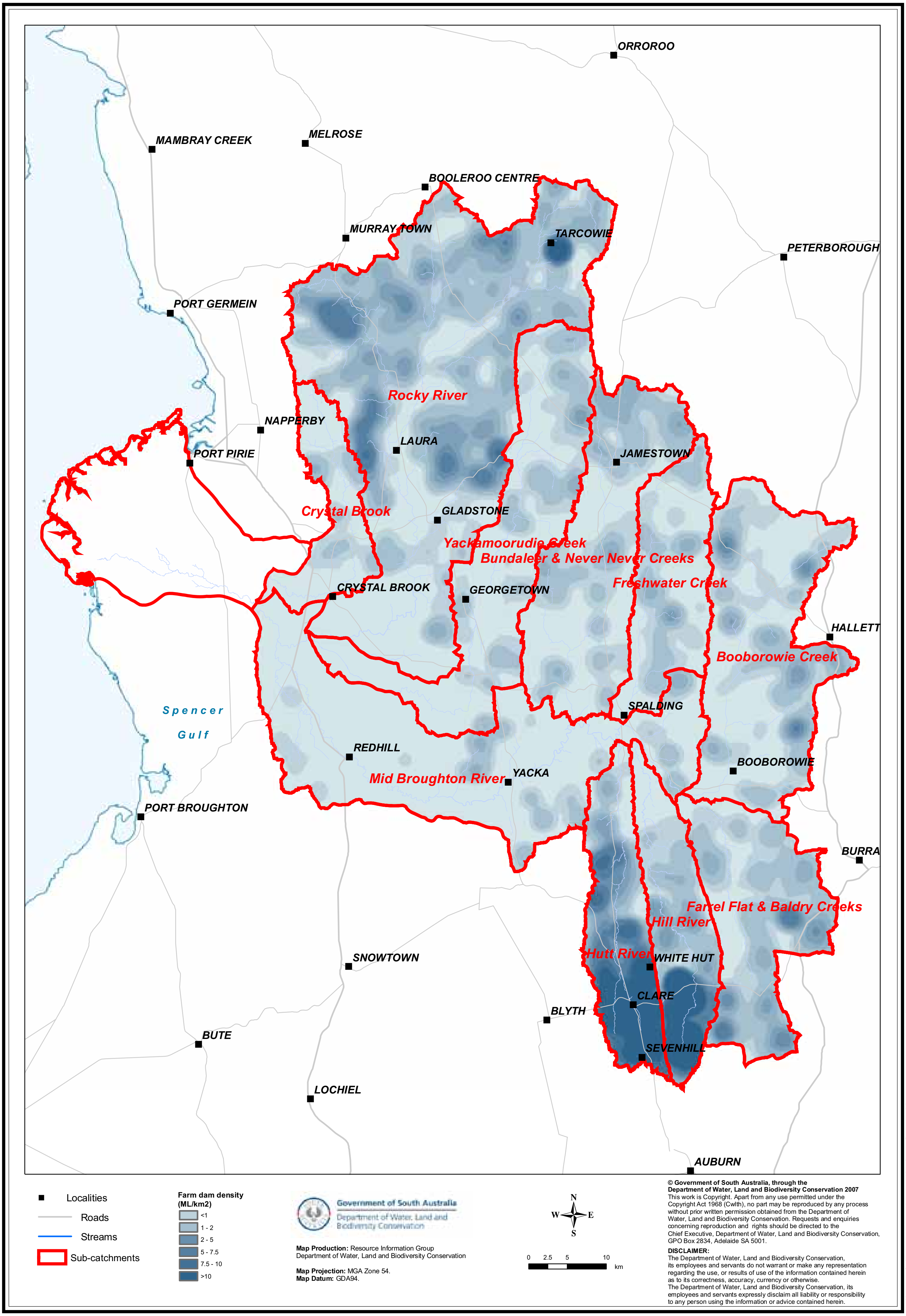


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Figure 20. Farm dam density for by sub-catchment: Broughton River

Figure 19 shows a comparison between the total estimated farm dam storage for all sub-catchments and the median streamflow values obtained as described above. The Hill and Hutt River sub-catchments are closely managed through the Clare Valley WAP. The Rocky River sub-catchment, which exceeds the 25% capture ratio, is not currently under any form of management control.

4.5.5 RISK ASSESSMENT: BROUGHTON RIVER

No prior work was available on which to base comparisons of development levels within this catchment, although anecdotal evidence reported in Deane (2005) suggests that farm dam development had been occuring during the period 2002–05 in the Rocky River sub-catchment. It is reasonable to conclude that increases in sub-catchments of this river system are likely to have mirrored the increases in other adjacent rivers, although it is not possible to quantify this.

As with the Wakefield River, the high rainfall and runoff sub-catchments that are within the Clare Valley PWRA have by far the highest development levels, yet contribute runoff volumes to the river system disproportionate to their relative areas. As with the Wakefield River however, these sub-catchments are currently managed under the Clare Valley WAP and any issues of excess farm development that were to be identified could be managed.

The sub-catchment most at risk is the Rocky River sub-catchment, where no management controls currently exist. This area was the subject of a prior investigation (Deane 2005), and although having no identified high volume use of surface water, was found to have areas that are likely to be beyond sustainable development levels.

A final source of uncertainty for this river system, although outside the scope of this report is the future management of the two water storage reservoirs, Beetaloo and Bundaleer. It is important that future management of these Reservoirs reflect their influence on catchment hydrolgy, and that environmental release programs are developed for both reservoirs to reduce any impacts on water dependent ecosystems.

4.6 WILLOCHRA CREEK CATCHMENT

The Willochra Creek is one of the largest river systems within South Australia with a catchment area of more than 6400 km^2. All but the lowest reaches of the northerly flowing Creek are included in the NY NRM region, although the actual terminal body, Lake Torrens, and a short section of the Creek are officially within the South Australian Arid Lands NRM Region.

Statistics relating to the impacts of farm dam development for Willochra Creek sub-catchments are shown in Appendix A, Table A4, and their locations can be seen in Figure 24. Although largely subject to semi-arid to arid climatic conditions, areas of rainfall in the upper catchment exceed 650 mm (Risby et al 2003). This includes the catchment areas for streams entering the Creek from the south-west which rise in the Southern Flinders Ranges. The relatively high and reliable rainfall within the southern most of these sub-catchments exerts a major influence on the hydrology of the catchment as a whole.

These higher rainfall sub-catchments of the Southern Willochra Creek system were the subject of a recent investigation by Risby et al (2003), and the catchment divisions and runoff estimates used in this assessment are based on work presented in that report. Farm dam volumes in that report were from data thought to be collected during the 1990s and for the purposes of this report farm dam data was re-evaluated using imagery from 2002. It should be noted that a number of dams are known to have been installed in the higher rainfall catchments of the upper Willochra since 2002, but no data were available to include these in this current assessment.

For the majority of the catchment area climatic conditions or soil type limit land use to grazing (mainly in the north), and cereal cropping (Magarey and Deane 2005). Limited volumetric information on surface water use is available for the Willochra Creek Catchment. It is thought that some farm dams capable of supplying irrigation activity are found in the relatively high rainfall foothills of the Southern Flinders Ranges, however Risby et al (2003) and Magarey and Deane (2005) were unable to identify any actual irrigation activity dependent upon farm dams. Risby et al (2003) did identify a number of sites where flood irrigation of paddocks through opportunistic diversion of streamflows was occurring. This was estimated to use 2000–3000 ML, but clearly can only occur during years where sufficient streamflow is available for diversion. This additional use of surface water confined to a limited number of catchments where conditions are suitable is estimated to exceed farm dam storage for the entire southern Willochra. This contributes considerably to the overall pressure on the resource. Further consideration of this activity in terms of the overall impact on surface water can be found in Section 4.6.3.

4.6.1 SIZE AND STORAGE CAPACITY OF DAMS

An estimated 2251 dams were identified in the Willochra Catchment, with a combined storage volume of almost 6200 ML. The mean storage capacity of dams is 2.7 ML. Figures 21 and 22 show summary information about the distribution of dams within the size classes. It is notable that no dams in the catchment were identified as having a capacity exceeding 50 ML, as all other river systems assessed in this study had at least one dam in excess of 100 ML.

Figure 22 provides an indication of the dominance of small stock dams in the catchment. Almost 90% of the total number of dams are estimated to hold less than 5 ML when full, and these store 63% of the total volume of all dams. There is a proportionately higher level of 2–5 ML size class dams in the Willochra Catchment, which holds 41% of the total volume stored. This suggests that stock dams may on average be constructed to have a larger capacity in this catchment, possibly to counter the high evaporative rates and less reliable rainfall. This point is emphasised when compared with the Light River Catchment (Fig. 7), which also has around 90% of dams holding less than 5 ML. In contrast with the Willochra where only 52% of dams are smaller than 2 ML capacity, in the Light River this size class constitutes 82% of the total number. It is this increased proportion of dams in the 2–5 ML class in the Willochra that leads to the higher mean dam size of 2.7 ML, which is considerably larger than the mean size of 1.9 ML for dams in the Light River Catchment.

4.6.2 DISTRIBUTION OF FARM DAM DEVELOPMENT

The mean farm dam storage density for the Willochra Creek Catchment was the lowest of all catchments at 1.0 ML/km^2, reflecting the largely arid and semi-arid nature of the catchment.

Figure 23 shows the mean storage density and dam size for all sub-catchments for Willochra

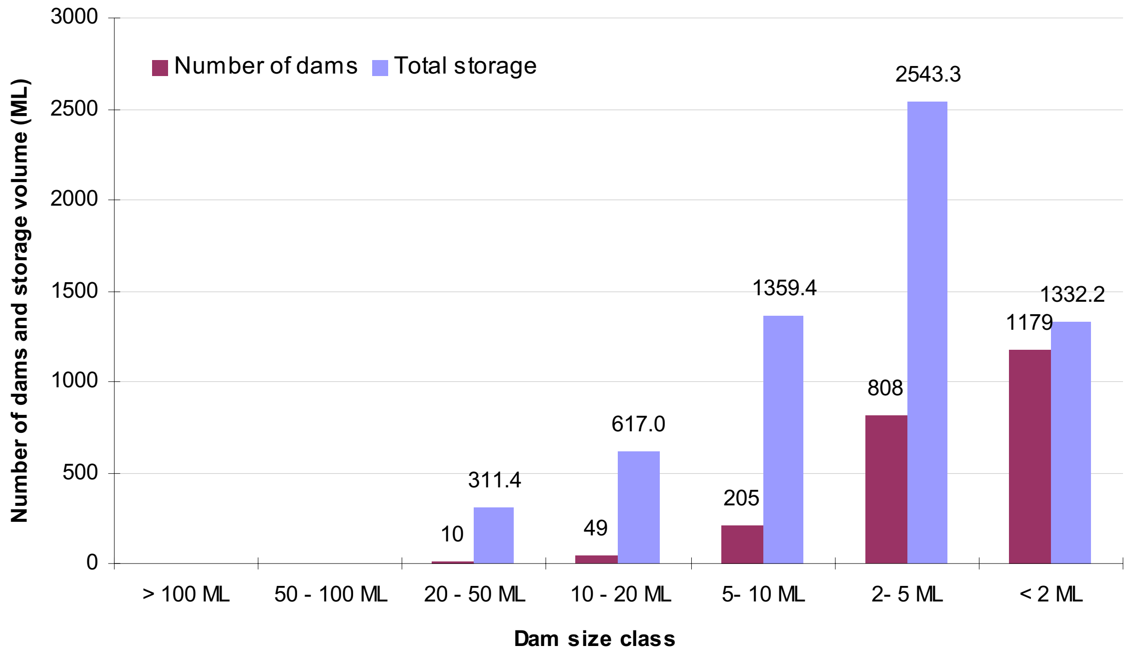


Figure 21. Farm dam size class distribution: Willochra Creek

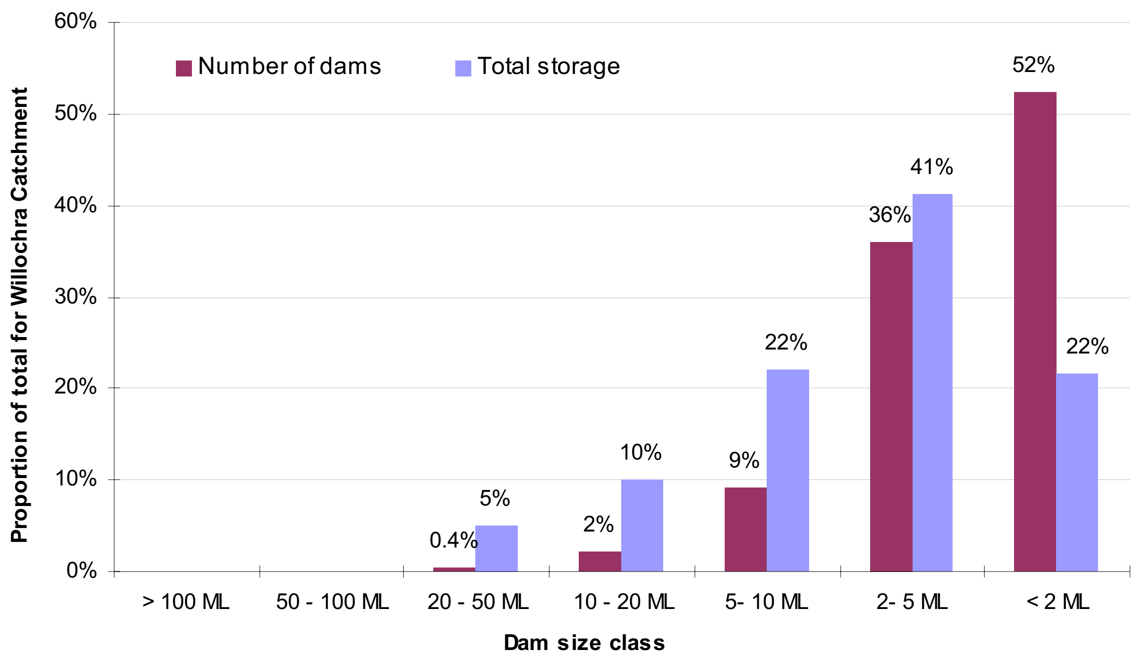


Figure 22. Proportional distribution of farm dams by size class: Willochra Creek

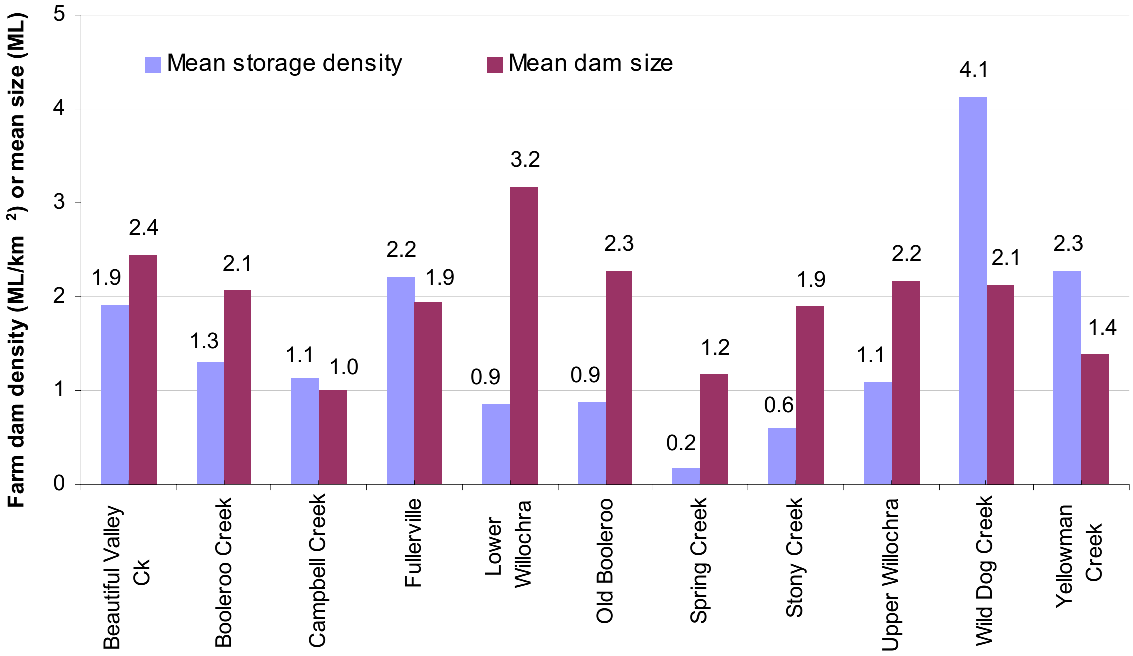


Figure 23. Farm dam density levels for Willochra Creek sub-catchments

Creek. As is to be expected, higher rainfall sub-catchments tend to have higher densities, and this generally relates to the south-western catchment. The exception to this is the Spring Creek sub-catchment, which as a water supply catchment is a water protection area proclaimed under the *Environment Protection Act 1993* and land use is restricted to protect water quality.

The highest sub-catchment storage densities are found within Wild Dog Creek, which has almost twice the density of the next most developed. The mean density for the southern sub-catchments was 2.4 ML/km^2, whereas for the arid Lower Willochra sub-catchment this value was 0.9 ML/km^2.

The density surface (Fig. 24) shows farm dam density calculated for each sub-catchment using a 5 km search radius to interpolate the value for each 100 m^2 grid cell. Areas of high development can be seen mostly within the Wild Dog Creek sub-catchment. This catchment is also the most heavily impacted by flood irrigation, and the combined effects on the hydrology of the creek are discussed in Section 4.6.3.

Isolated high density areas found in the more arid parts of the catchment to the east and north are likely to be due to single, high volume farm dams. These are often constructed at the confluence of two low order watercourses in order to maximise the catchment area for the dam. Unless fitted with flow bypasses for low-flow volumes, even modestly sized dams in arid or semi-arid areas have the potential to remove all streamflow generated across large areas in the majority of years. This may potentially create elevated stress levels for water dependent ecosystems downstream of the location of the dam. Section 6 includes further discussion on this aspect of farm dam management in areas of less reliable runoff.

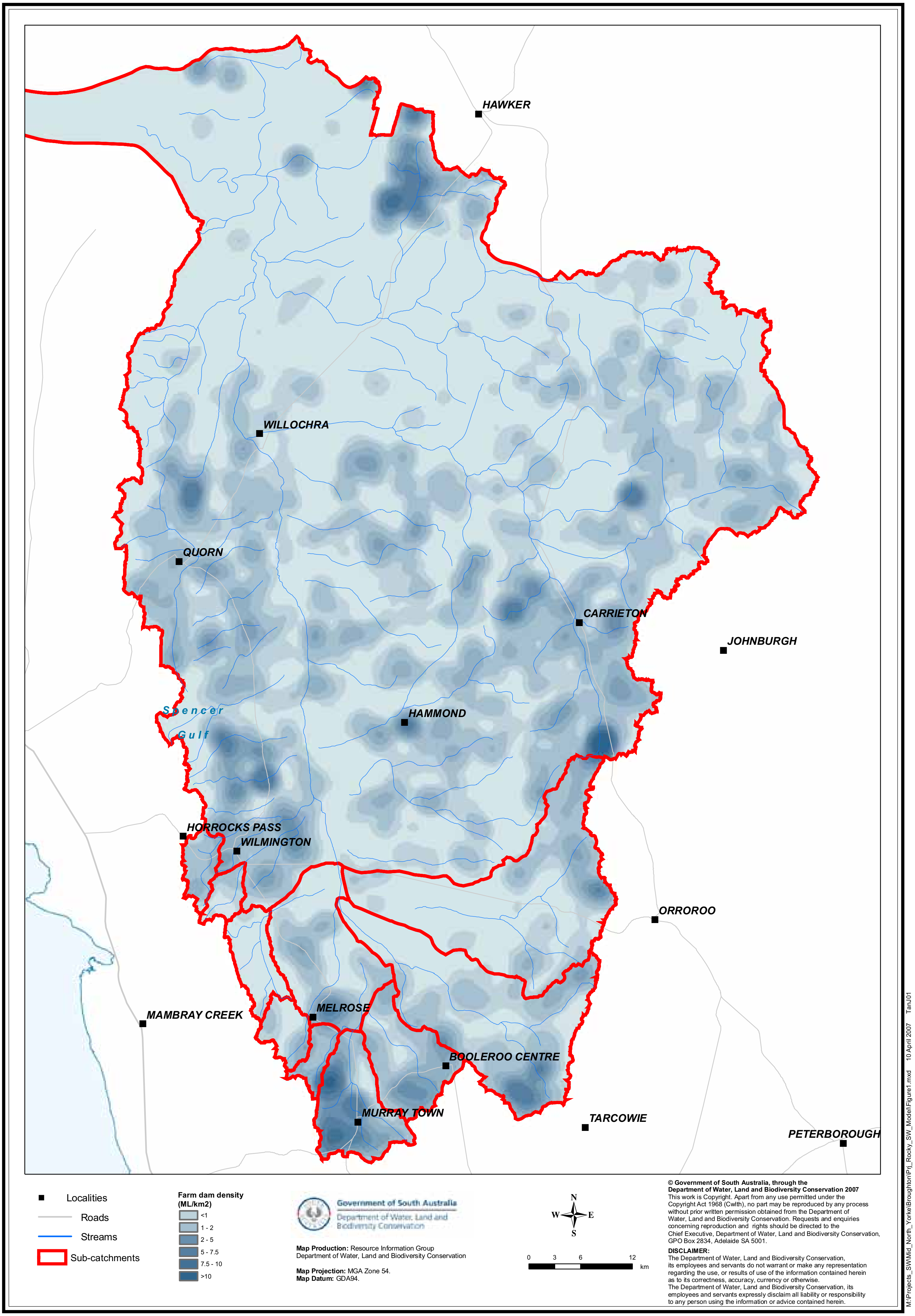


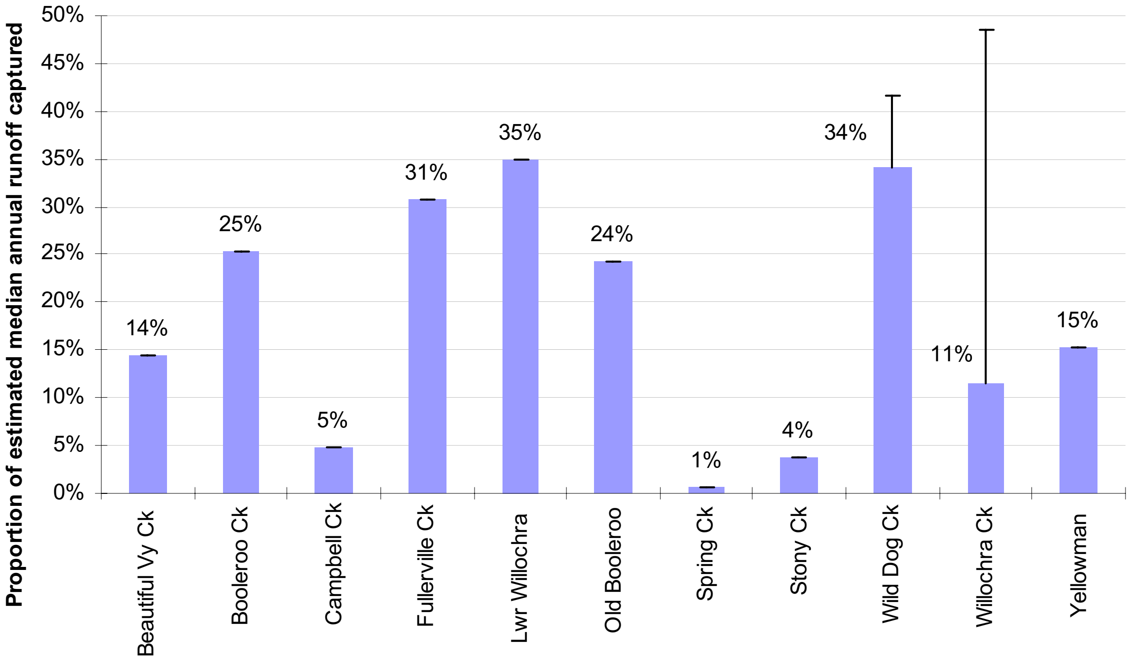
Figure 24. Farm dam density by sub-catchment: Willochra Creek Catchment

4.6.3 HYDROLOGICAL IMPACTS

Estimates of mean annual runoff for the southern Willochra sub-catchments were revised from those obtained in Risby et al (2003) through the use of long-term rainfall records. This is a more robust approach, enabling improved estimates of median annual runoff through incorporating the variability of rainfall over time. Comparison of values determined using this method suggests that the estimated runoff volumes used in Risby et al (2003) over-estimated the available resource.

Runoff from the remainder of the Willochra Creek Catchment, here considered as a single sub-catchment and referred to as the Lower Willochra (Fig. 25), was also estimated. The methods employed in this approach assume a uniform runoff rate, and the size of this catchment places additional constraints on the estimates. Hence, these are likely to underestimate runoff along the ranges, but over-estimate runoff in valley floors.

The proportion of estimated median runoff able to be held in farm dam storage in each sub-catchment is shown in Figure 25. Four sub-catchments, Booleroo Creek, Fullerville, Wild Dog Creek and the Lower Willochra exceed the 25% threshold.



Error bars on the values for Wild Dog and Willochra Creeks include the impact of flood irrigation withdrawls

Figure 25. Estimated capture of annual runoff by sub-catchment: Willochra Creek

The additional impacts of flood irrigation are also shown in Figure 25 for the sub-catchments where this activity is known to occur. Shown as error bars, the additional impact of these extractions elevates the proportion of runoff removed by development in the Willochra and Wild Dog Creek sub-catchments to 48% and 42% respectively.

4.6.4 RISK ASSESSMENT: WILLOCHRA CREEK

Figures reported in Risby et al (2003) suggest there has been a 30% increase in the number of dams since that work was undertaken. Direct comparison was not possible, as the spatial data used in that assessment were not available, and the source digital dataset is continually updated. It is probable that the farm dam statistics were derived from imagery recorded during the late 1990s.

The increase in the number of dams reported is considerably higher than the estimated increase in volumetric storage of 17%. Risby et al (2003) did not digitise dam outlines as was done in this report and this probably overestimated the volumetric storage represented at that time. Although direct comparison beyond the number of dams is speculative, it is reasonable to assume that farm dam development levels increased by around the same proportion as the number of dams. This corresponds to a 10% annual increase in storage during the years 1999–2002.

Anecdotal reports from landholders and NY NRM board members suggest that new dam construction in the catchment has continued over recent years. If the estimated rate of development has continued during the period 2002–07 it is likely that dam storage in southern Willochra Creek sub-catchments now exceeds 2700 ML, or 4700–5700 ML including the flood diversions. This would represent a storage and diversion volume that would very likely exceed the sustainable development threshold for surface water estimated by Risby et al (2003) at 4000–4500 ML. This is particularly so given the uncertainties associated with climate change.

Moreover, this sustainability threshold was based on 50% of the estimated median catchment runoff, which is the default value prescribed by current state policy. As discussed in Sections 5 and 6, this policy was developed to control farm dam storage in high rainfall areas and it is demonstrated in Section 5 that this probably over-estimates the level of development that can be sustained in semi-arid areas if natural flow regimes are to be maintained. Runoff estimate techniques used in Risby et al (2003) did not provide a means to estimate median runoff, and as a result the estimates of sustainable development limits for surface water presented in that report could hardly be considered to be conservative.

Given the lack of information on farm dams constructed in the period 2002–07, further farm dam development in the southern sub-catchments should ideally be avoided until more reliable information is available.

The high rainfall areas of the southern catchment are vitally important to streamflow in the Willochra system as a whole, as much of the catchment is semi-arid and generates little runoff or recharge. The levels of existing groundwater development exacerbate the water resource sustainability challenges faced in this catchment. Given the importance of streamflow for recharge in the area (O'Driscoll 1956), it is likely that excessive surface water capture will increase the pressure on groundwater resources, which are already considered to be at high risk. This catchment, and in particular the southern high rainfall areas, should be seen as a key priority for management action if sustainable resource use is to be achieved in future.

5. RESULTS – SCENARIO MODELLING

In order to assess the magnitude of any alteration to the flow regime downstream of farm dams in semi-arid areas, a simple daily timestep surface water model was developed. The model was based on the dimensions and storage levels found within a small area in the Upper Light sub-catchment headwaters. The mean annual rainfall of the dataset used in modelling was 417 mm, thus representing a drier area of the Light River catchment. The study area selected is shown in Figure 31, and has a runoff contributing area of 804 Ha. The model used parameters obtained from a lumped model of Mingays waterhole gauged catchment, calibrated against flow data for the period 1985–2000. More information on model construction and parameters can be found in Section 3 and Appendix D.

Observed farm dam development had a total estimated storage volume of 34.9 ML. As can be seen in Figure 31, dams controlled the entire study area and a series of permanent pools are present on the fourth order stream draining the catchment immediately below the final dam. The selection of this point was intentional, as a key question to be evaluated in the scenario modelling was the relative effectiveness of farm dam policy in semi-arid areas.

There are two scenarios explored below, each seeking to determine impacts across the full flow range to a user located downstream of a dam controlled area of a semi-arid catchment. The first scenario compares the effectiveness of different benchmarks in a fully dam controlled catchment to preserve the flow regime passing as a good reflection of natural conditions, and the second evaluates the effectiveness of preserving free-to-flow areas for the same purpose. The two available policies for permissible volumes of dam storage are 25% of the median adjusted annual catchment yield (State NRM Plan policy—see Section 6 for a full description), and 30% of the long-term runoff generated between the months of May–November (SA Murray-Darling Basin [MDB] NRM Board farm dam policy—see Section 6 for a full description).

5.1 POLICY SCENARIO 1: LIMITING PERMISSIBLE STORAGE IN A FULLY CONTROLLED CATCHMENT

The model was used to firstly estimate the annual runoff statistics necessary to establish permissible limits for farm dam development under the two criteria discussed above. The model was run without any farm dam storage represented to provide a surrogate measure of a natural catchment response. Although this clearly is not representative of pre-European flow, it is the basis upon which current allocation decisions would be made.

Median modelled annual flow from the study area for the 117–year rainfall record in the absence of farm dams was 62.4 ML, and mean annual flow was 96 ML. This gave a runoff coefficient for the study area of 0.029, which although low, is comparable to other studies from the region in semi-arid catchments (Risby et al 2003, Deane et al 2008).

The mean runoff for the months of May to November inclusive was 89.3 ML, resulting in a permissible storage volume under the SA MDB NRM Board 30% rule of 26.8 ML. The median streamflow allowed for a value of 15.6 ML of storage using the State NRM Plan 25% of median adjusted runoff rule (note that strictly speaking this benchmark applies to use – for the purposes of this study, storage is used as a surrogate for use). The three development levels were input to the model as the amounts of dam storage held within the catchment, with the dam surface areas adjusted according to the ratio observed in the full dataset for the study area. Results of the modelling were analysed for the changes they introduce to the flow regime leaving the controlled area through flow duration and spell analyses.

The daily flow duration curve for the four scenarios can be seen as Figure 26. The curves can be interpreted as the inflows and their likely annual durations to the first permanent pool seen in Figure 31, although no indication is given as to the distribution of flows across the year (see Figs 27 and 28). The X-axis represents the average expected number of days in a given year that a flow of a volume read from the Y-axis would be expected at the pool based on the 117–year record. The four curves represent the modelled average catchment flow for the four farm dam development scenarios over a year. The levels of development were: (1) no dams, simulating natural flow regimes, (2) existing development (34.9 ML), (3) storage volume allowable under the 25% of median rule (15.6 ML), and (4) allowable under the 30% of winter rule (26.8 ML). As was the case for the observed real world catchment, no free-to-flow area was incorporated into the model for this evaluation.

The results clearly indicate that substantial reductions in flow duration occur for all of the farm dam scenarios evaluated. The estimated natural flow would see a flow to the pool on average 160 days every year. Under the observed development level the number of days where flow would reach the pool has been reduced by 75%. While reduced development under sustainability guidelines decreases the impact to a 56% reduction in flow duration, as the catchment is totally controlled by dams, low-flows are effectively removed from the system.

To analyse this further, a daily time series of modelled flow data was analysed for spell durations over the 117–year period. This was to allow for assessment of the difference between the mean and maximum periods without flow downstream of the dams under the four scenarios.

As shown in Table 4, the average period between flows has increased from 22 days with no dams present, to 85 days under the current development level. The maximum between flow period has increased from 335 days under a no-dams scenario to 3537 days under current levels, an increase of almost 1000%. The mean total number of inflows to the pool has more than halved under current development. The data in Table 4 support Figure 26 in suggesting that the available benchmarks are incapable of protecting the low-flows to pools, and substantial increases in the inter-flow period statistics are seen for all development levels.

Table 4. Flow duration summary statistics for the study area under different farm dam development scenarios

	No of dams	Allowable: 25% median runoff rule	Allowable: 30% winter runoff rule	Current
Total storage volume of farm dams	0	15.6	26.8	34.9
Average number of days per year with flow to pool	160	71	52	42
Average number of days between inflow	22	52	70	85
Maximum number of days between inflow to pool	335	991	1351	3537
Average number of inflow events per year	10	6	5	4

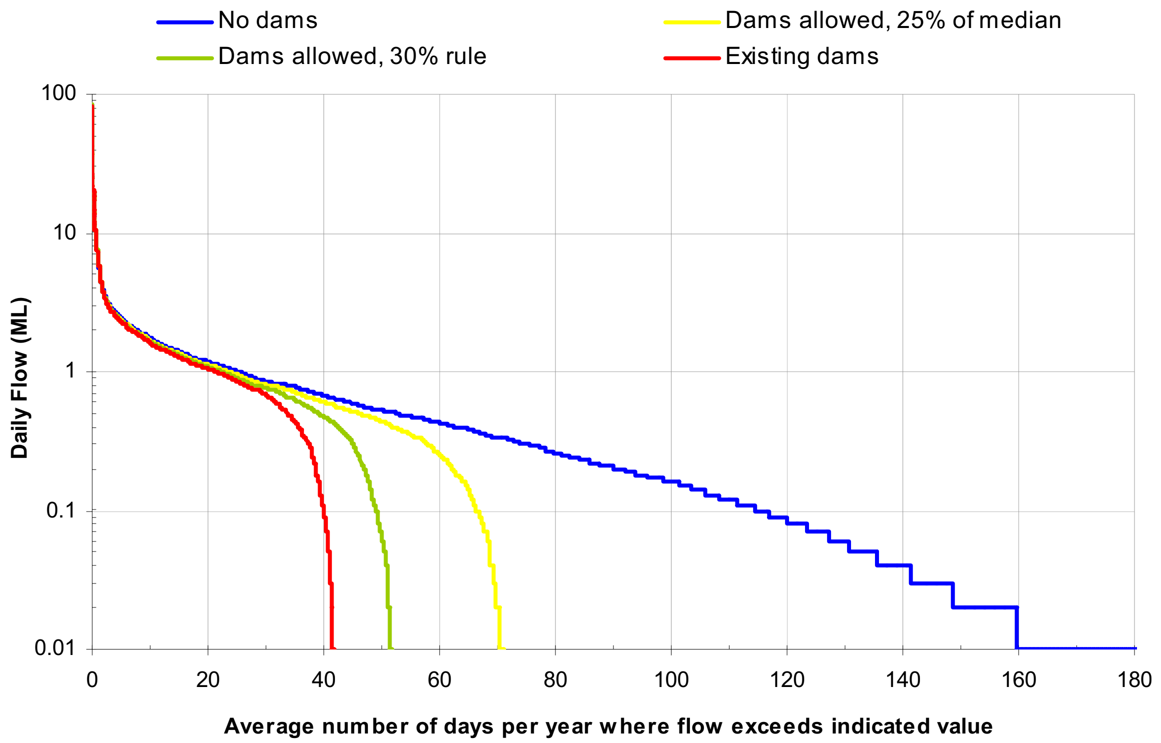


Figure 26. Modelled daily flow duration curve for the study area showing comparison between the natural flow and that under three levels of development

Figures 27 and 28 illustrate the difference in the annual distribution of flow events by presenting the modelled flow for the last 30 years of the record. In this daily time series, a flow event of any magnitude is indicated by a blue line. It is clear from comparison between the figures that the existing farm dam development level is capable of removing virtually all of the low-flows that occur over summer periods. While the core flow period during the late winter and early spring months is evident in Figure 28, which shows the existing situation, the duration of flow periods has been greatly reduced. This would be a time of the year where dams would be expected to be near to capacity and therefore exerting a relatively minimal impact on flow regimes. This suggests that dams are rarely filled to capacity and exert an influence year–round on flow volumes leaving the catchment.

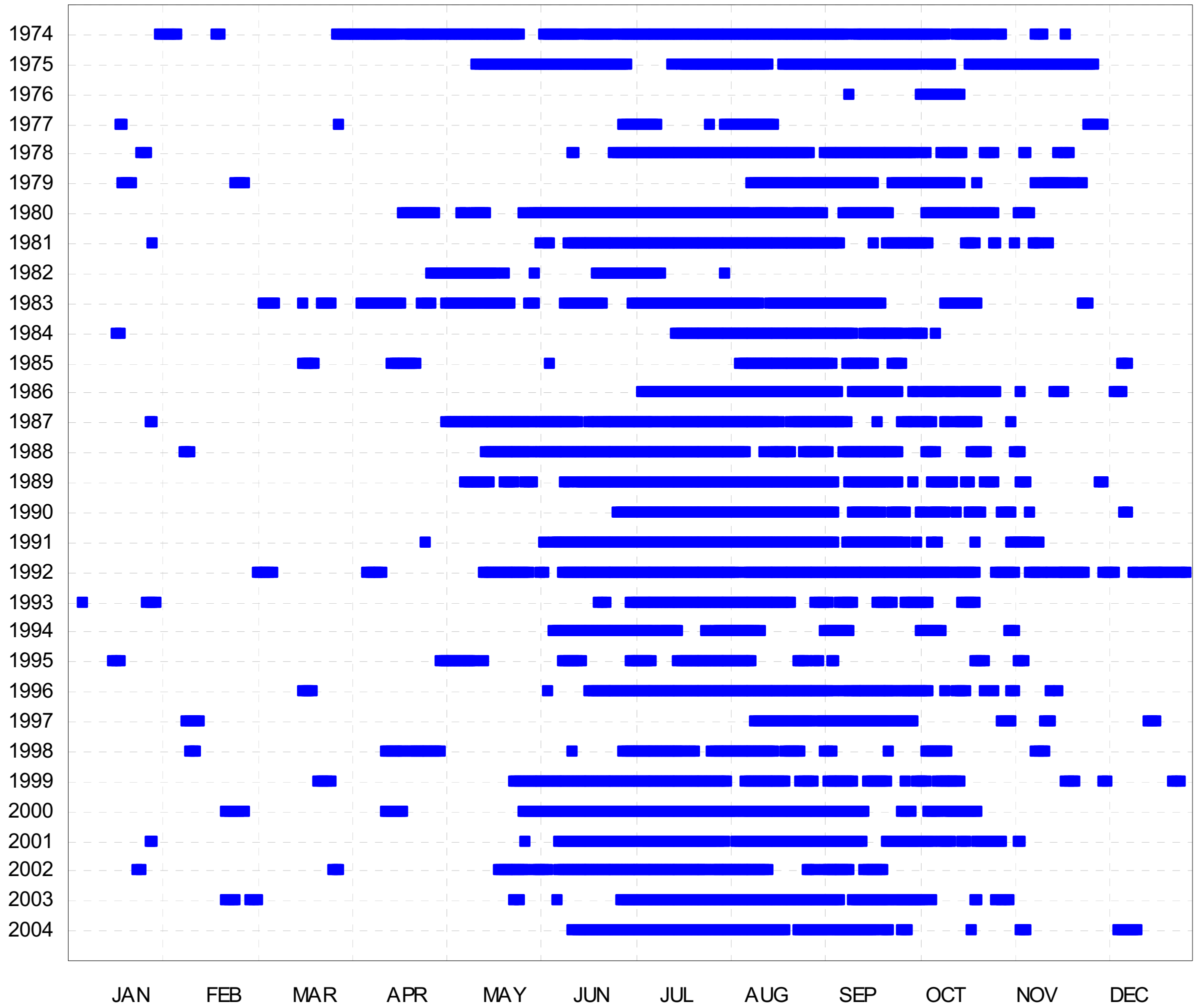


Figure 27. Daily flow to downstream pools under no-dams scenario: Light River study area 1974–2005

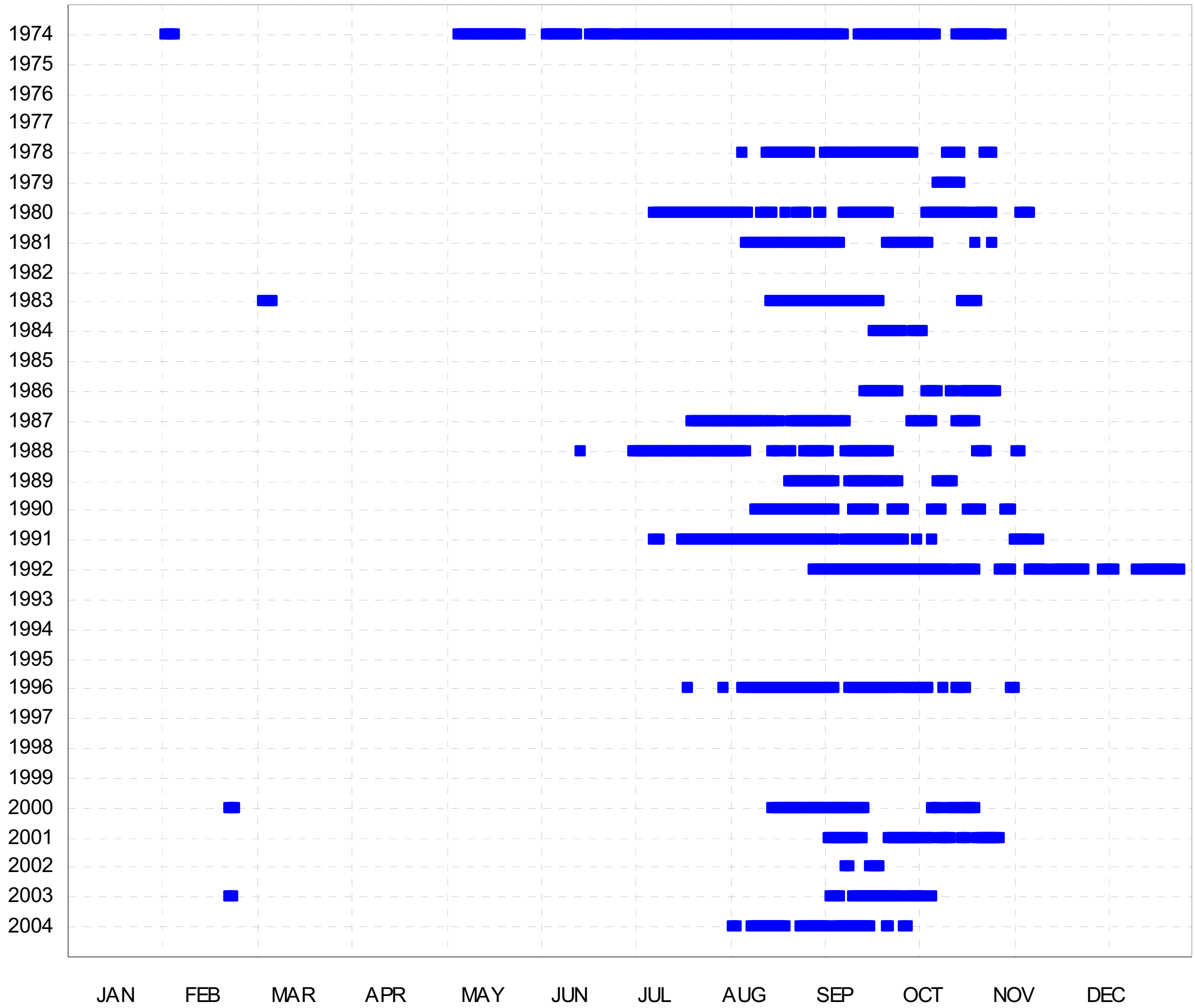


Figure 28. Daily flow to downstream pools under current development: Light River study area 1974–2005

5.2 POLICY SCENARIO 2: MAINTAINING CATCHMENT FREE-TO-FLOW AREAS

To assess the ability of free-to-flow areas in providing security of low-flows to the pool, a second scenario was undertaken. In this analysis farm dam volume was kept constant, as was the surface area of the dams, but in each iteration a percentage of the catchment area was not controlled by farm dams—that is, it remained free-to-flow. Conceptually, this scenario represents the difference between a number of shallow dams distributed across the catchment and the same number of deeper dams that only collect runoff from half of the area.

Figure 29 again shows the average yearly flow duration curve for the no-dams scenario, but also the curve representing the same volume of dam storage with 50% and 30% of the study area remaining free-to-flow. The model predicts that the concentration of the same volume of storage within smaller areas of the catchment begins to influence the flow duration curve at higher flow levels. This would be predicted intuitively, as larger storage for a given area will be capable of storing higher flows without passing flow downstream. In a higher rainfall area similar patterns could be expected, but the impact would only become evident on lower volume flows. However it is clear that even providing 30% of the catchment as free-to-flow greatly increases the low-flow component to downstream areas.

The preservation of the low-flows is also clearly indicated in Figure 30, showing flow spell incidence. This indicates that although some of the flow event durations are reduced in length (and although not apparent in the Figure, the volume is also reduced), the majority of events do appear downstream. In particular the small, short duration events typical of summer months and likely to be ecologically important for improving water quality are present (compare with Fig. 28 for current flow events).

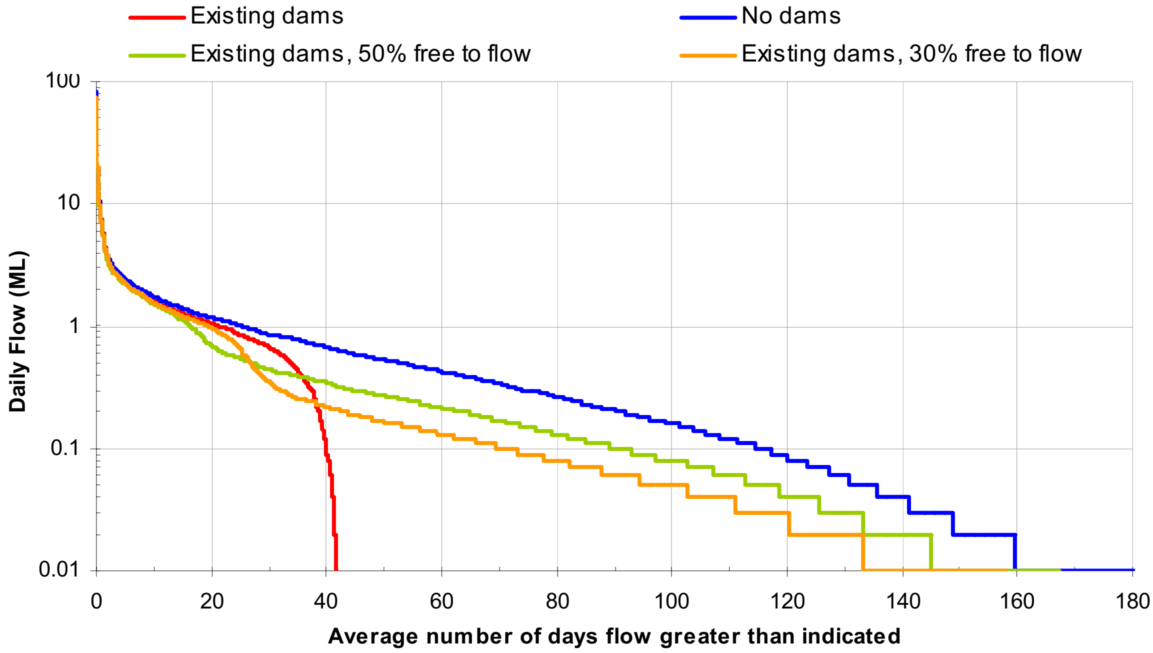


Figure 29. Modelled daily flow duration curve for the study area showing comparison between the natural flow and that under three levels of development

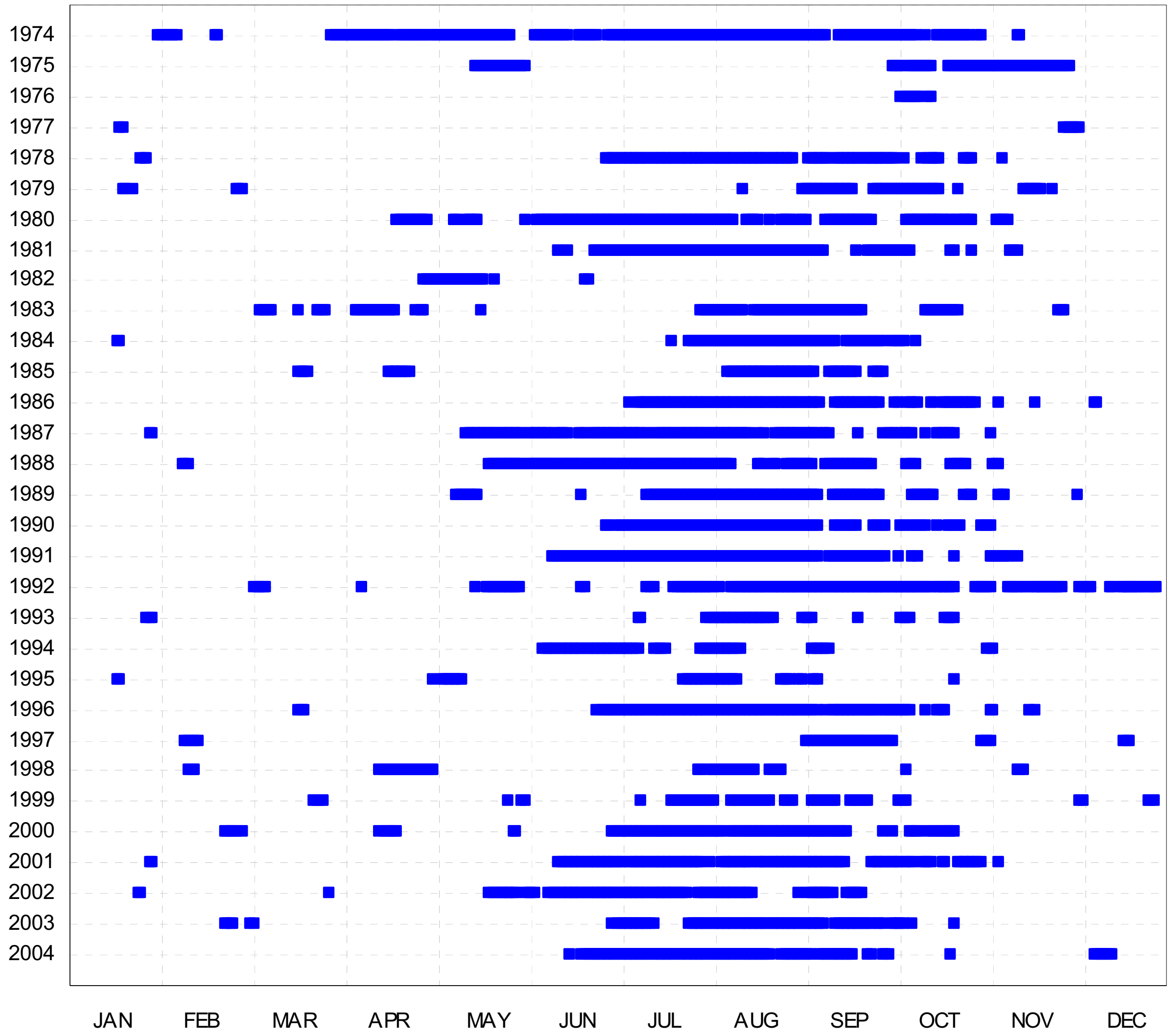


Figure 30. Daily flow to downstream pools from a 50% free-to-flow catchment (compare Fig. 27): Light River study area 1974–2005

5.3 TRADE-OFFS IN FARM DAM STORAGE VOLUMES

By changing the distribution of farm dams there is likely to be an impact on the storages themselves in terms of the amount of water they are capable of capturing and holding. Analysis of the dam storage data from the model yields the comparative statistics shown in Table 5.

There is a consistent pattern across all capture volumes, where the larger the free-to-flow area of the catchment retained, the greater the loss of storage. The mean daily storage and the average number of days per year where dams hold usable volumes of water are both reduced by restricting capture to smaller areas of the catchment. For the observed level of development, this reduction is up to around one third for the half free-to-flow scenario. Where only 30% of the catchment is free-to-flow, the reduction is 17%. Arguably of more impact on

Table 5. Farm dam storage statistics for the different free-to-flow modelled scenarios in the study area

Total storage	Statistic	Proportion of free-to-flow		
		100% capture	50% free-to-flow	30% free-to-flow
34.9 ML (current development)	Mean daily storage held (ML)	18	13	15
	Average number of days per year storage is below 10%	36	85	62
	Average number of days per year storage is above 90%	82	45	64
15.6 ML	Mean daily storage held (ML)	10	8	9
(allowable under 25% of median annual runoff rule)	Average number of days per year storage is below 10%	16	38	25
	Average number of days per year storage is above 90%	118	77	96
26.8 ML	Mean daily storage held (ML)	15	11	13
(allowable under 30% of mean winter runoff rule)	Average number of days per year storage is below 10%	25	67	43
	Average number of days per year storage is above 90%	90	55	70

landholders is the increase in the average number of days where the dam is at less than 10% of total capacity. For the half free-to-flow scenario the average number of days per year below this threshold is increased from the current 36 days to 85 days.

As the total farm dam capacity is reduced, the difference between the 100% controlled and free-to-flow scenarios also reduces. This is due to the decrease in the proportional measure—the fact that smaller volumes held in storage will represent 10 and 90% of the lower total volume.

This simple study does not assess the impacts occurring within the dam controlled study area, treating the storage as a single large dam, rather than the actual distributed network of small dams. However, in general the findings apply equally to the farm dams of downstream landholders as they do to water dependent ecosystems. Multiple dams on single watercourses greatly increase the duration between downstream flows, as indicated by the modelling. The inflows to successive downstream farm dams positioned ‘in series’ (on the same watercourse) will be greatly reduced in duration, frequency and volume, each dam in turn having to fill to provide flow to the next. The lack of resources to review the impacts of multiple farm dams occurring on the same watercourse is a weakness of this study and future investigations would ideally allow for more accurate spatial representation and quantification of inter-dam impacts.

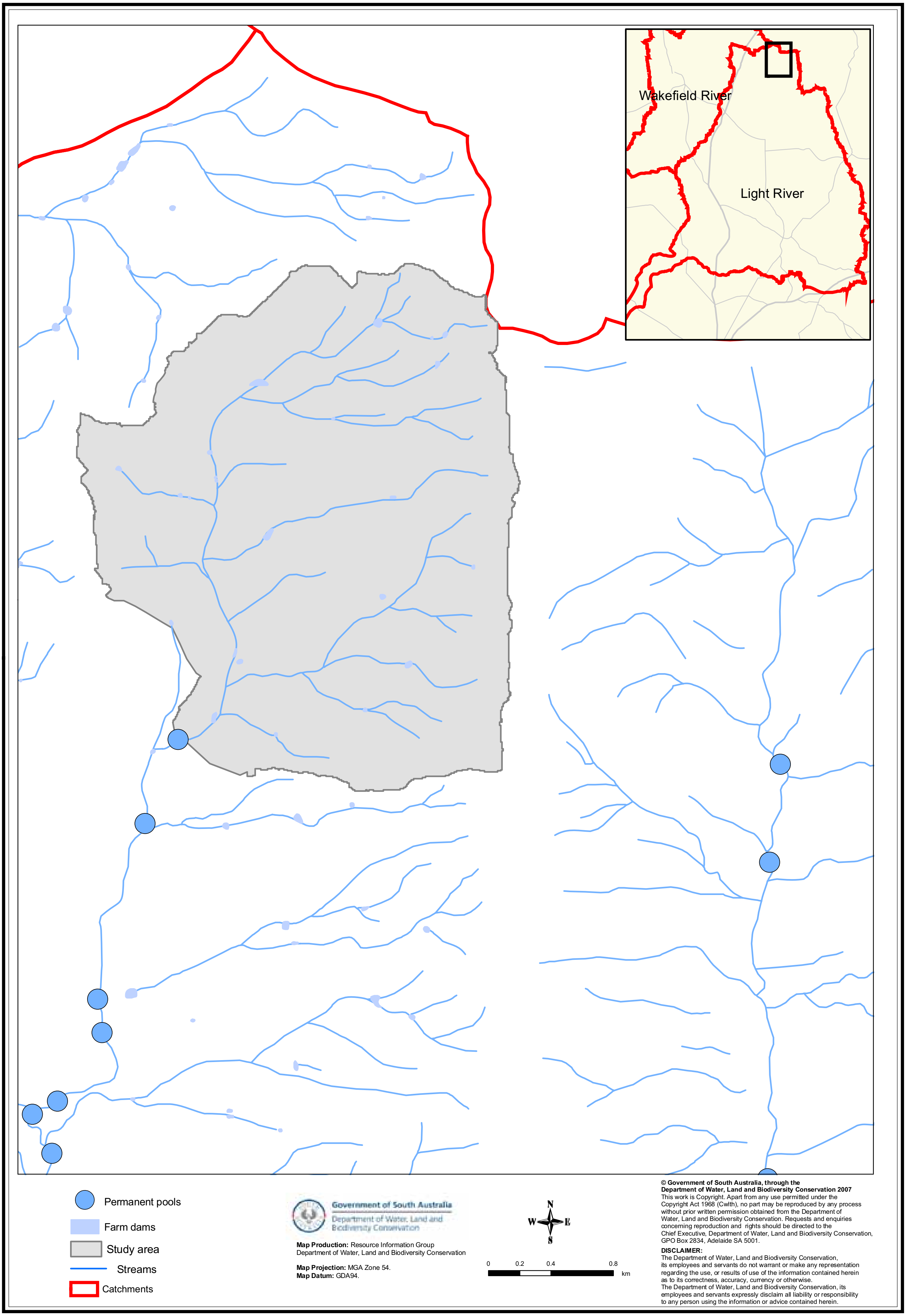


Figure 31. Scenario modelling study area – Upper Light River sub-catchment

5.4 CONCLUSIONS

The key point that can be taken from this exercise is that even if they were to be enforced, permissible storage volumes in isolation cannot guarantee that there will be no impact on downstream users from farm dams. The most serious consequences in the changes in flow regimes are likely to be to water dependent ecosystems. The impacts are also greater in low rainfall areas, where even small on-stream storages can capture all streamflow during most years.

Conversely, the maintenance of even relatively small areas of a catchment free of dams does provide a good degree of protection of the water regimes of dependent ecosystems. Although some reduction does occur to streamflow events in the low to mid range, the duration and frequency of flow events are much closer to predicted natural conditions.

By manipulating both the area remaining free-to-flow, as well as the permissible storage volume, resource managers should be capable of ensuring that relatively natural flow regimes to water dependent ecosystems are maintained.

Any farm dam control policy is likely to result in some reduction in the availability of water for consumptive use. For a given storage volume, modelling suggests that retaining areas of a catchment as free-to-flow will result in an increase in the amount of time that dams are empty each year. Further study is required to determine what proportion of any water returned to the system may enhance groundwater recharge. If shown to be the case, there is the potential that some trade-offs in increased groundwater access could be made to compensate for any loss of availability of surface water experienced by upstream landholders.

If combinations of these two control mechanisms prove unrealistic technically or practically, managers may be forced to draw upon other policy tools including compulsory locating of dams off-stream, or the installation of low-flow bypasses, to retain all flow components.

An ideal policy would be flexible enough to allow adjustment of storage or free-to-flow areas, according to the situation within the catchment. Clearly, a high conservation value ecosystem would demand a more conservative approach, best achieved by a combination of securing free-to-flow areas and restricting total storage. Ideal policy would also need to be adaptive enough to respond to reductions or changes to the patterns of surface water availability resulting from climate change.

6. INTERPRETATION OF FINDINGS

6.1 APPLICABILITY OF EXISTING FARM DAM POLICIES

Outside of highly regulated prescribed water resources, policy on farm dam development is limited in South Australia. Guidance is provided in the *State Natural Resource Management Plan 2006*, which states:

> *Outside prescribed areas, and until there is additional information, 25% of median annual adjusted catchment yield should be used as an indicator of the sustainable limit of the catchment surface water and watercourse water use. 'Adjusted' is defined as the annual catchment discharge with the impact of dam storage removed.*

The policy refers to adjusted catchment yield, which requires a surface water modelling approach in order to estimate the current volumes removed by dams. Once this is achieved, the removed portion is added to the observed volumes to provide the adjusted yield. Where flow modelling is not available in order to estimate the adjusted catchment yield, a storage volume of 50% of estimated adjusted median annual runoff has been applied in higher rainfall areas. This approach is referred to within agencies as the '50% rule'.

An alternative approach to farm dam policy was developed by the then River Murray Catchment Water Management Board (RMCWMB), which now forms part of SA MDB NRM Board water resource development policy. Essentially, the policy divides relevant areas of the catchment into management zones, where within each zone the maximum permissible total storage volume for all dams is limited to 30% of the estimated long-term mean runoff generated between the months of May and November. Runoff is estimated from the product of the long-term mean rainfall and a runoff coefficient, which has a default value of 0.1.

These policies rely on the assumption that imposed storage thresholds will be exceeded and adequate runoff will pass from the catchment to meet the environmental and downstream user requirements. For this approach to be successful in protecting natural flow regimes, the majority of flow events must generate adequate runoff to fill all dams so that subsequent flow will then pass downstream of the dam storages. Even in higher rainfall areas of the state however, this is not the case, and farm dam impacts—which include delays in the onset of seasonal streamflow, as well as loss of summer 'freshes'—have been well documented.

Clearly, in an area such as the Northern and Yorke region (which has an average annual rainfall of around 350 mm), the applicability of policies developed for use under relatively high and reliable seasonal rainfall conditions is debatable. One of the defining characteristics of low rainfall areas is that runoff is extremely unpredictable. Systems in semi-arid and arid climatic zones have highly non-linear rainfall–runoff (and recharge) relationships. Effectively, there is no meaningful definition of a 'typical' streamflow year, with many years having almost no-flow and others experiencing extremes of flood. From a purely volumetric perspective, the great majority of groundwater recharge and surface runoff occurs during those extreme years, at unpredictable intervals. Although much of this water effectively can not be utilised, under a typical assessment these volumes would still be incorporated into calculations for permissible storage, greatly elevating allowable storage above what could be expected in the majority of years.

In a generally low yield hydrological setting such as described above, farm dams potentially have the impact of greatly increasing the period of time between any streamflow reaching users downstream of their locations. Where all major tributaries have dams, and perhaps multiple storages are encountered on individual tributaries, there is the potential that dams will capture the majority of runoff that occurs during the majority of years. In this scenario streamflow may only reach downstream low rainfall and runoff areas—where most water dependent ecosystems such as permanent pools are located—in extreme years.

Extreme years contribute the vast majority of the volume for a semi-arid water resource averaged over time and are critical to both groundwater and surface water systems. A recent study in the Mallee region of Victoria for example (Zhang et al 1999) found that 85% of recharge volume occurred in only 10% of events. Data presented in a review of the water resources of Burra Creek Catchment (Deane et al 2008) showed that 66% of the surface runoff recorded at the gauge occurred in only three years, from a 31–year period of record.

Surface runoff and streamflow events also contribute significantly to groundwater recharge in semi-arid areas where low water tables and losing streams are the norm. An Israeli study of transmission losses from ephemeral streams estimated that the mean annual contribution of streamflow to groundwater recharge was of the order of twice gauged surface water flows (Shentsis et al 1999). Although that particular work was based in an arid system, ephemeral streams in the mid-west of the United States have been estimated to lose on average around 44% of total flow via infiltration through their bed and banks (NCHE 2004). Although not at this stage quantified, surface water is a known recharge source in the NY region, particularly in areas that streams cross zones of faulting. Such situations are known for streams in the Willochra Basin, such as Spring Creek.

These types of interactions between surface and groundwater clearly illustrate the importance of managing the resources conjunctively, so policy on farm dam development must consider any potential decrease in groundwater recharge that may result. The volumetric dominance of episodic events and extreme years however, suggests that the interception of small volumes of streamflow is perhaps unlikely to exert a major influence on the water balance of the resource, when considered over averaging periods typically used to determine sustainable yield volumes. The main impact of farm dams in a hydrological setting where runoff is unpredictable, and mostly of only modest volumes, lies in the major alteration that even small storages create in the flow regime.

Any change in flow characteristics, such as increases in the duration of no-flow periods, is likely to have a major impact on aquatic ecosystems. The ecological benefit of small volume and duration freshening flows in semi-arid zones is well known, and any increase in the period of time between these inflows must be considered to comprise a source of stress to dependent ecosystems. Permanent pool refugia, sedge communities and phreatophytic vegetation such as river red gums, will all benefit from even small flow events that will increase soil moisture levels and help ameliorate decreased water quality associated with evapo-concentration over seasonal and inter-annual drought periods. These are the flows that are also most likely to be totally contained within farm dam storages, and thereby removed from the system.

6.2 UNCERTAINTIES WITH THIS ASSESSMENT

In considering the apparent risks to the resource presented in this report it is appropriate to re-iterate the major uncertainties associated with this work.

6.2.1 IMAGERY AVAILABILITY AND QUALITY

The methods employed in this assessment were the best possible given the data and resources that were available, but a number of major uncertainties are inherent in the approach. The farm dam mapping suffered from the available imagery in two main regards:

- The resolution for much of the region was 1:40 000 whereas 1:20 000 is the minimum generally recommended for the digitisation of full supply level surface areas as required in the method.
- The imagery was captured at a time when most dams were close to empty, and in fact had not been at full supply for a number of years. This limited the ability of the GIS operator to delineate the full supply level precisely, and no doubt introduced errors that were exacerbated by the poor resolution of images.

Despite these uncertainties, the level of accuracy from this assessment at regional level exceeds any prior work. The farm dam dataset developed at least provides a baseline for future assessments. As demonstrated in the Light River Catchment, prior benchmarks add considerable value to the interpretation of farm dam levels, allowing trends to be examined.

6.2.2 RUNOFF ESTIMATION AND SUSTAINABILITY THRESHOLD

The other factor contributing to the uncertainty of results herein relates to the use of the Tanh function and annual rainfall data to develop estimates of sub-catchment yields. Although much could be written with regard to the accuracy and precision of the method, for the available data and resources to conduct an assessment over such a broad area, there was little alternative.

The Tanh method was applied to a 120–year time series of annual rainfall to enable estimates of both mean and median runoff. The function was calibrated using mean values at 50–100 mm increments in annual rainfall, and the corresponding mean runoff for the same years. This is effectively a data smoothing approach, and provides more certainty in the estimates, which can be difficult to determine simply using raw annual data.

Once calibrated, the Tanh method was applied for periods where actual data were available to enable a comparison of the method. The results of this analysis are shown in Table 6. All mean and median estimates using the Tanh method are higher than the gauged data. Mean runoff is estimated well for the Light River and Rhynie data, and reasonably well for the Hill River. Error values in the median runoff are consistently above 25%, with the Tanh estimates used in this analysis all higher than observed data. This information suggests that runoff estimates can be considered to be higher than would actually be found. Partly as a result of this analysis, the 25% threshold was adopted as an indication of potential hydrological stress.

Table 6. Comparison of observed and Tanh estimates of annual runoff for the Hutt and Hill Rivers and Rhynie gauged catchments

Catchment	Mean runoff			Median runoff		
	Tanh	*Observed*	*Error*	*Tanh*	*Observed*	*Error*
Hill	5137	4307	16%	3834	2872	25%
Mingays	9021	8895	1%	5427	3943	27%
Rhynie	6193	5820	6%	5386	3714	31%

6.2.3 AFFECTS OF LAND USE AND CLIMATE CHANGE ON RUNOFF ESTIMATES

As a final comment on the uncertainties associated with the proposed benchmark of sustainability, it is worth considering the observations over recent years of a dramatic decline in the availability of surface water throughout the NY NRM region. Quite apart from the impacts of farm dams there are also two other processes thought to have decreased catchment yields:

- Improved land management practice
- Changes in rainfall patterns.

The consequences of improved land management for surface water yield

Awareness has increased over recent decades of the need to manage properties in order to maximise the infiltration of water into the soil. This has resulted in greatly improved land management practice such as minimum tillage, contour banking, and decreased stocking rates. The response of catchments to this behavioural change has been greatly reduced runoff volumes.

The decrease in flows is dramatically illustrated in the draft *Clare Valley PWR Water Allocation Plan* (NYNRMB 2006), which indicates that the average annual flow for all rivers over the past ten years has decreased by between 32 and 70%, compared with the period 1969–84. Rainfall did not show a similar trend, falling by a maximum of only 5%, and in the case of the Wakefield River actually increasing. Although the non-linear nature of the rainfall–runoff relationship suggests that declines in runoff would be greater than the relative decline in rainfall, this still leaves considerable reduction to explain.

In a recent review of the declines in streamflow volumes leaving the Clare Valley, Clark (2007) found that flows had reduced by over 50% over the period described above. Only around half of this could be explained by surface water development. The most likely explanation offered for this ‘missing’ volume was considered to be the effect of improved land management.

The implication of this analysis is that sustainable use limits have been established based on historical gauged streamflow data indicating catchment response to the observed rainfall. As catchment yields would have been dramatically reduced since the data were collected, there is a need to ensure that this reduced yield is accounted for in planning.

The impact of observed changes in rainfall patterns on surface water yield

A number of recent reports have shown similar changes in rainfall over recent years across much of South Australia (Clark 2007, Deane 2005, Deane et al 2008, Heneker 2003, Risby et al 2003). Although a very slight decrease is often observed, these have not generally resulted in a major shift in the mean annual rainfall. They have however, suggested a decrease in the amount that annual rainfall can be expected to be above or below this value. Until around the mid–1970s observed annual rainfall demonstrated much greater variability, with extremes of both wet and dry relatively common. The last three decades have shown a shift towards rainfall closer to the long-term mean—that is, a decrease in variability.

Rainfall in South Australia generally does not produce significant runoff until it reaches around 400–450 mm/y (Murdoch 2002, Clark 2007, Risby et al 2003), and is generally unreliable until annual totals of around 600 mm/y are reached. Owing to this effect, areas that on average receive below these thresholds will rely on above-average years for significant runoff. Decreases in the frequency of these more extreme years will result in disproportionately high decreases in mean streamflow, as the relationship is not linear. Future predictions of climate change suggest that variability is likely to increase, with longer dry spells, and this situation can be expected to worsen.

A later break in the season has also been observed in a number of studies (e.g. Risby et al 2003, Heneker 2003, Deane 2005), meaning that rainfall is commencing later than has been the case historically. This trend also leads to a proportional decrease in water availability as losses to evapotranspiration increase greatly in later months.

Consequences for resource users and managers

As a result of the above two processes it is to be expected that annual means based on the historical gauging record will continue to decrease for the foreseeable future, as more data are collected reflecting the current drier than previous conditions, as well as the generally reduced catchment yield due to improved land management. Both of these processes acting to decrease catchment yield, have become more widespread and apparent over the past 30 years, which is also the period of most gauging records. Existing estimates of available runoff based on historical gaugings are therefore highly likely to show an over-allocation of water resources, as more information on contemporary climatic cycles and catchment responses become better known.

It is critically important that any new benchmarks of sustainability developed factor in a conservative approach to counter this historical artefact, and that sustainable limits are regularly reviewed in order to ensure they are not misleadingly high. The additional uncertainty around climate change needs to be built into any review process so that likely future scenarios are evaluated in the new benchmarks.

6.3 KNOWLEDGE GAPS

In general, aquifers in arid and semi-arid regions are relatively reliant on streamflow for recharge (Dingman 2002). This applies to both confined and unconfined aquifers, and the reliance of, for example the Willochra Basin, on streamflow has previously been documented (O'Driscoll 1956). It is unclear to what degree the use of numerous distributed small farm dams decrease the amount of runoff and to what extent this impacts on the available groundwater resource by intercepting potential recharge. As shown above in Section 5.2, in many years in semi-arid zones, available streamflow may be entirely controlled by even a modest amount of dam storage, relative to higher rainfall areas where streamflow volumes are much higher. The reliance of these systems on the recharge occurring during the rare extreme events may mean that the volumes held in storage by small dams does not represent a significant proportion of the total available resource. What has not as yet been tested is the degree to which these small volumes of flow may help to replenish groundwater stores, or at least assist in ameliorating salinity levels, which can be expected to increase in the periods between episodic recharge events.

Over recent years, awareness of the need to consider surface and groundwater interactions in developing sustainable use criteria to avoid ‘double accounting’, has increased. Many of the policy responses that are commonly employed to limit farm dam development were designed for use in higher rainfall areas where runoff is more predicable. The usefulness of these policies in higher variability environments has not been tested, and nor has the potential impact of dam capture on the water balance of aquifers in semi-arid zones.

Optimal use of streamflow in semi-arid parts of the region may well involve the use of surface impoundments located to enhance groundwater recharge, rather than simply collect surface water for use in situ. The challenge for water resource managers and landholders may then become the equitable sharing of available resources across property boundaries. If such an approach were to occur, there will be a need to consider how upstream landholders that retire or relocate dams to enhance recharge volumes, can share in any additional availability of the resource.

Nevertheless, this is an example of the type of approach that may become necessary under climate change scenarios. It is also consistent with a landscape scale resource management philosophy, as required under the *State Natural Resources Management Plan 2006*.

To date, no work has considered the impacts of farm dams in semi-arid catchments from a water balance perspective that includes an assessment of the decreases in groundwater recharge lower in the catchment. This is seen as an important knowledge gap, not only in order to ensure that groundwater resources are maintained for human uses, but also to protect the groundwater dependent ecosystems present in the rivers catchments.

6.4 TOWARDS A POLICY FRAMEWORK

The modelled scenarios demonstrate the potential for even modest levels of storage to fundamentally alter streamflow patterns in watercourses of semi-arid areas. Owing to the dominance of episodic extreme events, long-term runoff statistics are arguably not in isolation a sound basis for decisions about a sustainable use limit for surface water capture. Consideration of the factors involved suggests that policy should be developed around the following principles:

- The majority of recharge and runoff volumes are delivered episodically during extreme events, and farm dams are unlikely to exert a detectable impact on the quantum of these. From the perspective of surface water capture and use, only a minute fraction of these events is accessible, and inclusion of the total volume across all flow ranges in calculating permissible storage volumes is therefore to some extent misleading.
- More frequent flows of small to medium size and short durations are heavily influenced by farm dam storages including stock dams, which are capable of capturing the majority of these flows in many years. Conversely, these smaller flows are also likely to be critical for the maintenance of water dependent ecosystems.

- Hence, to protect ecosystem needs for water, some proportion of all runoff events must be allowed to pass. Policy options to achieve this include maintaining free-to-flow areas within catchments, ensuring all dams are located off–stream (and only diverting water once an agreed threshold of flow is exceeded), and the installation of low-flow bypasses.
- An acceptable deviation from the natural flow regime may vary depending on the assets being protected. The proportion of flow that is required to be alllowed to pass should be informed by criteria such as the value of the ecosystem from a conservation perspective and its known water requirements.
- Maintenance of free-to-flow areas is likely to be the best defence against unsustainable development of surface water resources, and provides increased landscape scale resilience.
- In semi-arid systems streamflow is likely to be an important source of recharge to groundwater systems, and there is a need to quantify this relationship across the range of expected and predicted climatic variations, and to take account of this interaction when developing policy for surface water storage.

These principles raise a number of questions for future research before responsible policy can be developed for stock and domestic dams. Foremost among these:

- Is the loss of small streamflow events in the years between the large episodic events likely to impact on the integrity of the groundwater resource, or is it only of significance to ecosystems and other downstream users that benefit from these?
- What is the frequency of events for a particular area of interest that result in flow, and what level or spatial distribution of dam development can be sustained without compromising these flows?
- Is the use of small, distributed stock dams the best use of rare surface water flow events, or would an alternative approach—such as collecting this water to enhance recharge to groundwater—provide an improved benefit to users and the resource as a whole?
- If the latter option is more effective, how can the water that is saved be equitably shared among all users, including those who would presumably forfeit their small surface water storages to enhance the overall resource volumes?

7. CONCLUSIONS

In undertaking this work four distinct issues have emerged:

- Stock and domestic dams likely present at least some level of threat to ecologically sustainable development of surface water resources in semi-arid areas. Modelling indicates that even the most conservative existing policy is not capable of protecting the flow regime across the full flow range for such regions. Where on-stream dams appear on all watercourses draining a given catchment, periods of no-flow to downstream water dependent ecosystems may on average be increased by up to a factor of ten. In addition to environmental benefits, these flows could potentially be important in replenishing groundwater supplies in periods between major episodic runoff and recharge events, in particular where streams cross highly faulted or jointed zones.

- Existing policy approaches to the control of farm dam development are not as effective outside of high rainfall (and therefore reliable runoff) zones. In future it will be necessary to, if not regulate, at least control the density of farm dams in all areas. This will need to be of a form that incorporates guidance on both dam siting (either imposing a minimum acceptable free-to-flow zone of a catchment or enforcing off-stream dams and low-flow bypasses), as well as the size of individual and total storage within allowed development zones.

- Available data presents significant obstacles to detailed assessment of hydrological stress in semi-arid areas—this means that assessment work is associated with a high degree of uncertainty. Increasingly, the inherent climatic variability particularly under predicted climate change scenarios, can be expected to exacerbate the effects described.

- All river systems of the mid-north have probably experienced significant growth in the volume of farm dam storages, and flow regimes should be considered to be under pressure from the levels of farm dam development. Available information suggests that the highest levels of risk are associated with the Willochra Creek and the Light River, but some non-prescribed areas of the Broughton River could also be close to sustainable limits. Currently, highly developed sub-catchments of the Wakefield River are potentially suffering the greatest hydrological stress, but it is assumed that this will be addressed in future through water allocation planning processes.

The most significant question raised in this assessment is seen to be that of what constitutes sustainable development levels for farm dams in areas where runoff is not predictable. In such areas, existing policy approaches cannot be relied upon to ensure levels of development do not adversely impact on water resource users, including the environment. Work is urgently required to ensure that a reasonably natural catchment hydrology is protected into the future, and that the influence of surface water storages in semi-arid areas are better understood in terms of their impact on catchment water balances which include groundwater and water dependent ecosystems.

APPENDICES

A. SUB-CATCHMENT SUMMARY STATISTICS

Table A1. Light River sub-catchment summary statistics

Sub-catchment name	Area (km^2)	Annual RF (mm)	No. of dams (count)	Estimated storage @ full supply (ML)	Mean dam size (ML)	Max dam size (ML)	SD of mean (ML)	Density (ML/km^2)	Mean runoff (mm)	Median RO (mm)	Mean RO (ML)	Median RO (ML)	% capture
Gilbert River	449	495	312	728	2	36	3.8	1.6	12.4	8.5	5558	3801	19
Julia Creek	133	481	149	288	2	43.6	4.9	2.2	11.4	8.3	1511	1109	26
Mid Light River	598	481	805	1564	2	89	5.1	2.6	10.9	7.8	6497	4687	33
Pine Creek	45	483	12	11	1	2	0.5	0.2	11.6	8.8	522	397	3
Upper Light River	378	505	856	1239	1	49	2.3	3.3	13.0	9.3	4906	3527	35

Table A2. Wakefield River sub-catchment summary statistics

Sub-catchment name	Area (km^2)	Annual RF (mm)	No. of dams (count)	Estimated storage @ full supply (ML)	Mean dam size (ML)	Max dam size (ML)	SD of mean (ML)	Density (ML/km^2)	Mean runoff (mm)	Median RO (mm)	Mean RO (ML)	Median RO (ML)	% capture
Eyre Creek	35.1	612	78	694	8.9	79	9.7	19.8	na	39.0	na	1369	51
Mid Wakefield River	169.3	436	110	269	2.4	70	7.5	1.6	8.9	6	1513	1037	26
Pine Creek	52	572	113	471	4.2	251	28.5	9.1	25.0	19	1298	975	48
Rices Creek	61.5	583	114	219	1.9	19	2.9	3.6	26.9	19	1656	1163	19
Skillogalee Creek	67.6	599	108	0	0.0	35	5.5	5.2	na	30.0	na	2028	0
Upper Wakefield River	144.2	594	252	954	3.8	78	9.8	6.6	29.1	21	4201	3011	32
Woolshed Creek	67.2	507	65	179	2.8	27	4.4	2.7	16.1	11	1079	763	23

Table A3. Broughton River sub-catchment summary statistics

Sub-catchment name	**Area** (km^2)	**Annual RF** (mm)	**No. of dams** (count)	**Estimated storage @ full supply** (ML)	**Mean dam size** (ML)	**Max dam size** (ML)	**SD of mean** (ML)	**Density** (ML/km^2)	**Mean runoff** (mm)	**Median RO** (mm)	**Mean RO** (ML)	**Median RO** (ML)	**% capture**
Booborowie Creek	575.0	435.2	263	524	2.0	28	3.2	0.9	11	5.7	6527	3275	16
Bundaleer & Never Never Creeks	498.5	472.5	335	460	1.4	11	1.3	0.9	16	8.7	8079	4319	11
Crystal Brook	189.9	493.3	57	100	1.8	6	1.3	0.5	20	11.2	3875	2122	5
Farrel Flat & Baldry Creeks	394.3	475.4	326	624	1.9	36	2.5	1.6	18	9.1	7023	3582	17
Freshwater Creek	292.6	477.7	150	229	1.5	19	2.0	0.8	17	9.5	5053	2783	8
Hill River	269.0	526.9	405	2150	5.5	216	21.2	8.0	28	18	7443	4400 (1)	49
Hutt River	284.7	542.2	755	2676	3.3	169	9.6	9.4	30	16	8810.0	6600 (1)	41
Mid Broughton River	815.9	415.2	112	266	2.4	13	2.0	0.3	9	3.8	6953	3080	9
Rocky River	1350.0	450.0	968	2274	2.3	104	4.0	1.7	13	6.0	17961	8043 (2)	28
Yackamoorudie Creek	557.4	453.3	256	359	1.4	11	1.6	0.6	13	6.1	7360	3421	10

1. Runoff estimates obtained from Cresswell (2000) , and are modelled estimates with the impacts of farm dams removed (Cresswell 2000).
2. Runoff estimates obtained from Deane (2005).

Table A4. Willochra Creek sub-catchment summary statistics

Sub-catchment name	**Area** (km^2)	**Annual RF** (mm)	**No. of dams** (count)	**Estimated storage @ full supply** (ML)	**Mean dam size** (ML)	**Max dam size** (ML)	**SD of mean** (ML)	**Density** (ML/km^2)	**Mean runoff** (mm)	**Median RO** (mm)	**Mean RO** (ML)	**Median RO** (ML)	**% capture**	**Include flood irrigation**
Beautiful Valley Creek	29	477	23	56.3	2.4	7.4	1.8	1.9	20	13	585	390	14	–
Booleroo Creek	306	361	193	396	2.0	18.8	2.4	1.3	8	5	2430	1570	25	–
Campbell Creek	34	564	39	38.8	1.0	4.0	0.8	1.1	35	24	1206	823	5	–
Fullerville	100	400	114	220.2	1.9	16.4	2.1	2.2	11	7	1082	718	31	–
Lower Willochra	5224	311	1414	4471.7	3.2	39.5	3.2	0.9	5	2	23654	12828	35	–
Old Booleroo	353	344	135	308.3	2.3	12.0	1.9	0.9	7	4	2299	1267	24	–
Spring Creek	53	565	8	9.3	1.2	3.7	1.0	0.2	35	24	1854	1292	1	–
Stony Creek	22	504	7	13.2	1.9	4.0	1.2	0.6	24	16	528	358	4	–
Wild Dog Creek	101	464	197	417.1	2.1	48.2	3.9	4.1	18	12	1832	1221	34	42%
Willochra Creek	166	437	83	180	2.2	11.7	2.1	1.1	15	9	2457	1563	11	48%
Yellowman Creek	24	493	38	52.3	1.4	6.4	1.1	2.2	22	14	521	343	15	–

B. TANH CALCULATION OF MEAN RUNOFF

The Tanh function (Grayson et al 1996) is a standard hyperbolic function and was used by Boughton (1966) as a simple rainfall–runoff relationship.

Calculation

$$Q = (P - L) - F \times \tanh[(P - L)/F]$$

where Q = runoff [mm]
P = rainfall [mm]
L = continuing loss [mm]
F = initial loss [mm].

The equation can be applied to any data, but should be used for data where average storage of soil water is approximately constant—i.e. where the notional loss and infiltration might be expected to be similar. Annual data satisfies this requirement, but monthly data will need to be separated into data for each month or at least for season, and a different L and F derived for each month's (or season's) set. The optimum values of the loss parameters, L and F, are determined by minimising the least squares error, plotting annual flow sets against the associated rainfall, to obtain the estimated depth of runoff for each sub-catchment area.

Regionalised rainfall–runoff curves

As mentioned in Section 3, four regionalised Tanh curves were required to estimate runoff in all of the sub-catchments assessed. These are presented in Figures B1–B4 below.

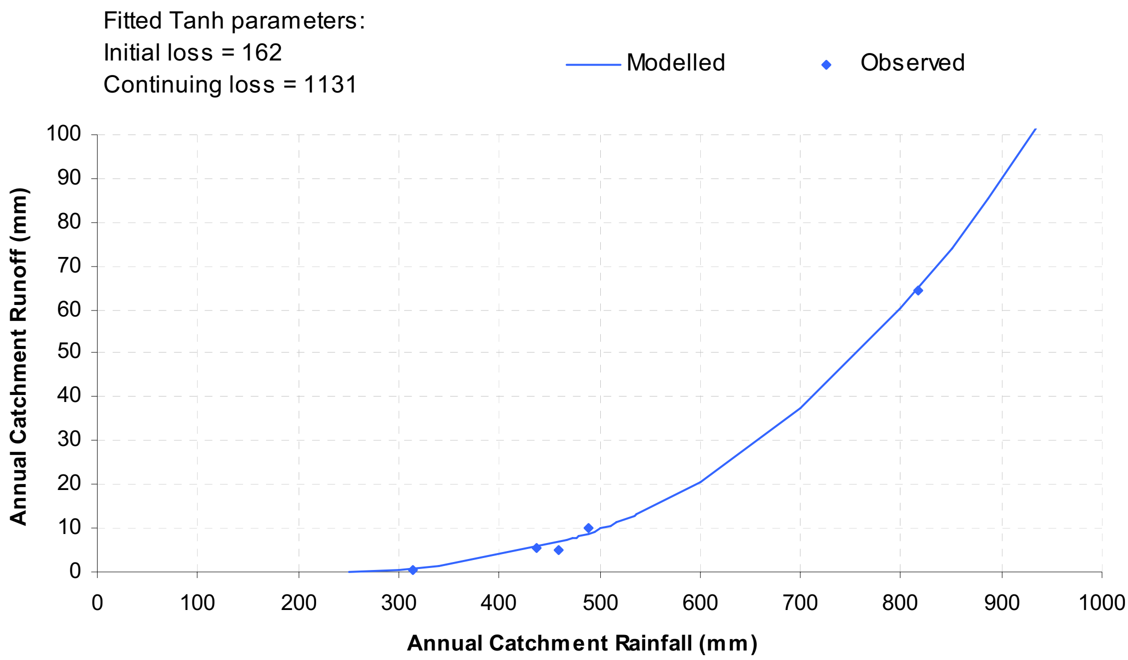


Figure B1. Annual Tanh curve for Mingays Waterhole: 1985–2005

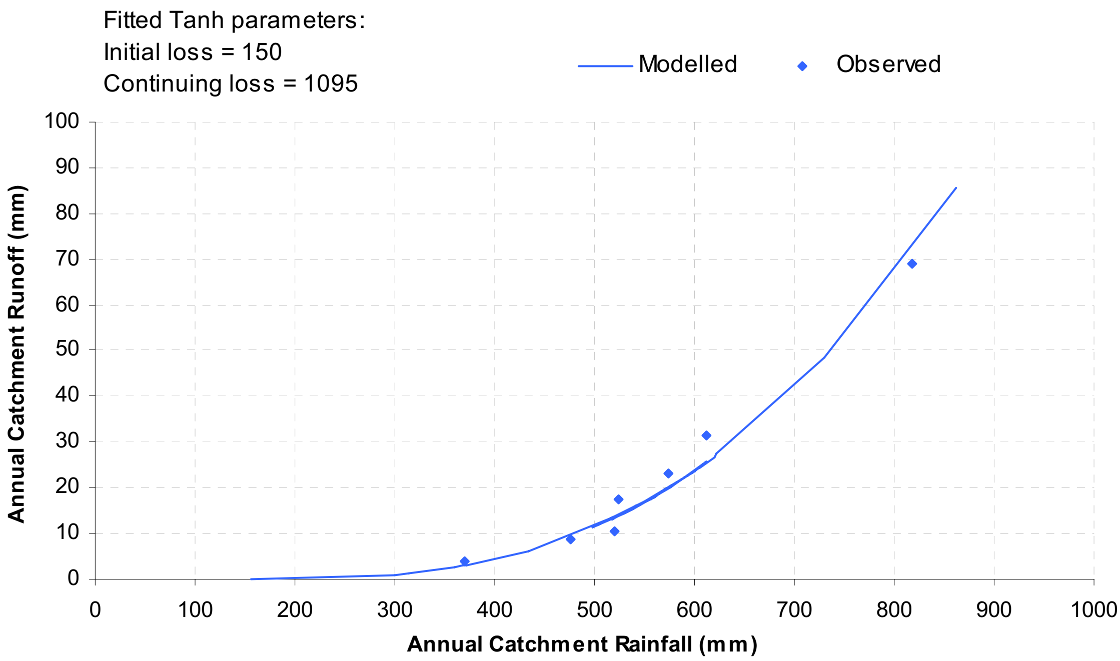


Figure B2. Annual Tanh curve for Rhynie gauging station: 1979–2004

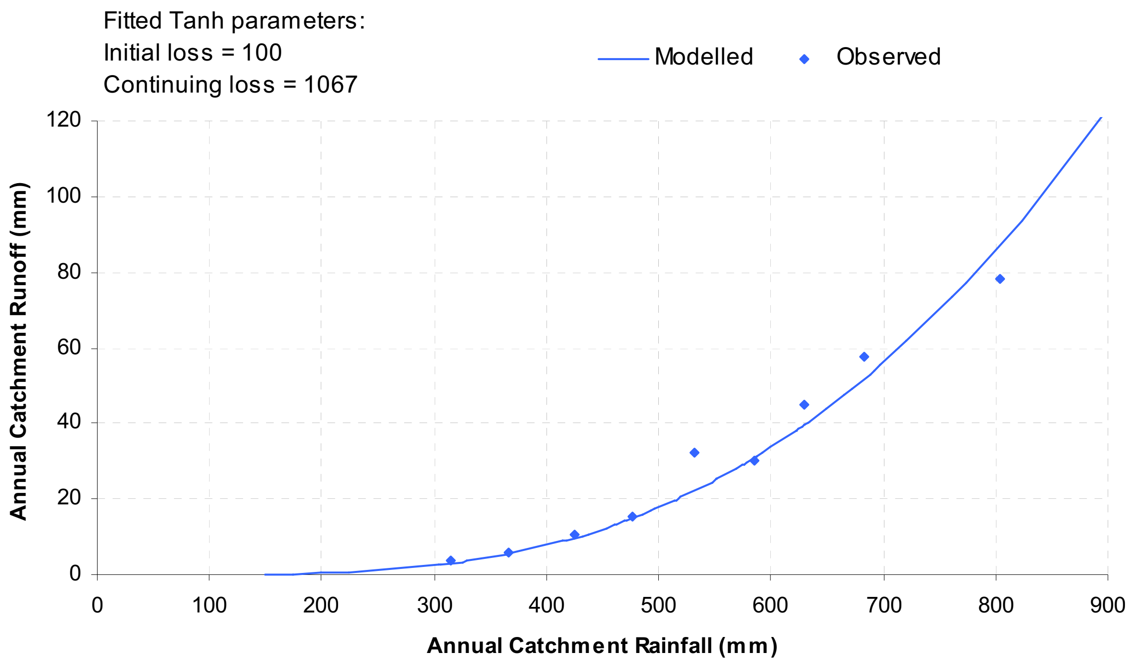


Figure B3. Annual Tanh curve for Baroota Creek Reservoir catchment: 1941–96

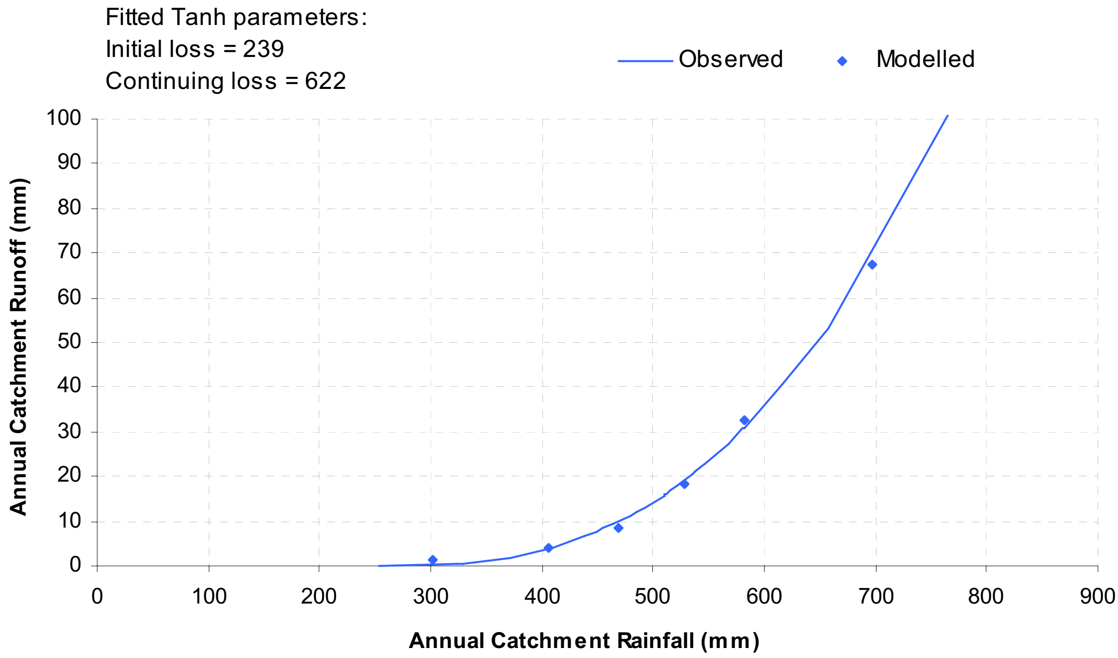


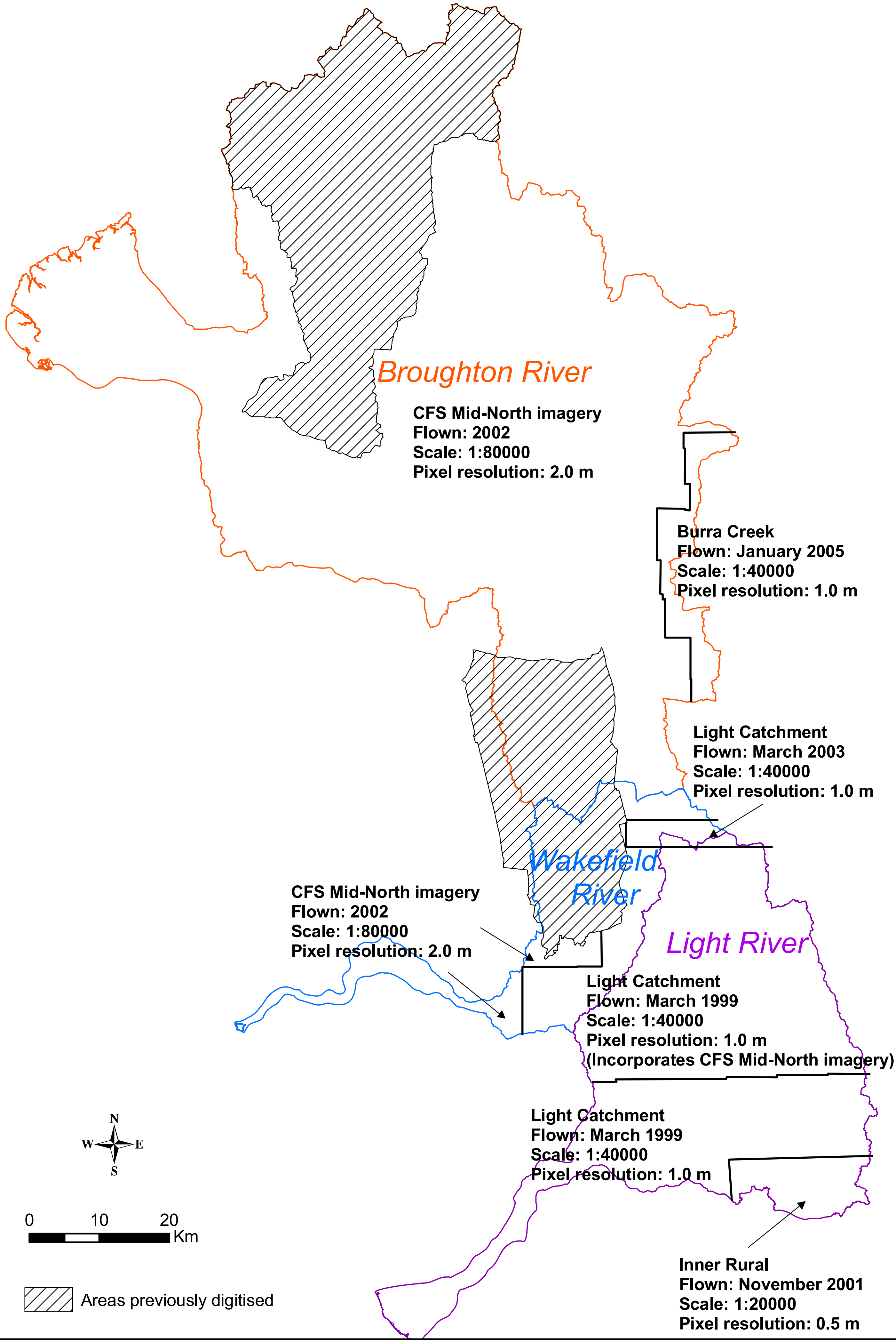
Figure B4. Annual tanh curve for Hill River data: 1979–2005

C. AERIAL IMAGERY USED IN THIS ASSESSMENT

Figure C1 shows the approximate extent and age of the photography used to digitise farm dam outlines in this assessment. Farm dams within the Willochra catchment were all digitised based on 2002 Country Fire Service (CFS) Imagery and this catchment is not shown to improve resolution.

The area of the Light River labelled ‘Incorporates CFS Mid-North Imagery’, combines the CFS imagery & the Light Catchment Orthophotography. Dams in this area, constructed after March 1999, were digitised using the 2002 CFS imagery, and dams that existed prior to March 1999 were digitised using the Light Catchment Aerial Photography, as it was captured at a scale of 1:40 000 as compared to 1:80 000 for the 2002 CFS imagery.

Figure C1. Aerial photography used to digitise farm dam outlines



D. MODEL PARAMETERS

Table D1. WC-1 rainfall–runoff model parameters fitted for use in scenario modelling

Abbreviation	Parameter	Value
MSM	Medium soil moisture	101.85
IS	Interception store	18.0
CD	Catchment distribution	45.0
GWD	Groundwater discharge	0.004
SMD	Soil moisture deficit	0.51691E-03
PF	Pan factor	0.67399
FGL	Fraction groundwater loss	0.10930E-02
SRC	Soil reduction coefficient	0.56182
GWR	Groundwater recharge	0.14936
CL	Creekloss	0.81699E-04

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

GLOSSARY

Act (the) — In this document, refers to the *Natural Resources Management (SA) Act 2004,* which supercedes the *Water Resources (SA) Act 1997*

Ambient — The background level of an environmental parameter (eg. a measure of water quality such as salinity)

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

ASR — Aquifer Storage and Recovery; involves the process of recharging water into an aquifer for the purpose of storage and subsequent withdrawal; also known as aquifer storage and retrieval

Arid lands — In South Australia, arid lands are usually considered to be areas with an average annual rainfall of less than 250 mm and support pastoral activities instead of broadacre cropping

Baseflow — The water in a stream that results from groundwater discharge to the stream; often maintains flows during seasonal dry periods and has important ecological functions

Benchmark condition — Points of reference from which change can be measured

Biota — All of the organisms at a particular locality

Bore — See 'well'

Catchment — That area of land determined by topographic features within which rainfall will contribute to run-off at a particular point

CFS — Country Fire Service

Dams, off-stream dam — A dam, wall or other structure that is not constructed across a watercourse or drainage path and is designed to hold water diverted or pumped from a watercourse, a drainage path, an aquifer or from another source; may capture a limited volume of surface water from the catchment above the dam

Dams, on-stream dam — A dam, wall or other structure placed or constructed on, in or across a watercourse or drainage path for the purpose of holding and storing the natural flow of that watercourse or the surface water

Domestic purpose — The taking of water for ordinary household purposes; includes the watering of land in conjunction with a dwelling not exceeding 0.4 hectares

DWLBC — Department of Water, Land and Biodiversity Conservation (Government of South Australia)

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Ecological processes — All biological, physical or chemical processes that maintain an ecosystem

Ecological values — The habitats, natural ecological processes and biodiversity of ecosystems

Ecology — The study of the relationships between living organisms and their environment

Ecosystem — Any system in which there is an interdependence upon, and interaction between, living organisms and their immediate physical, chemical and biological environment

Environmental water requirements — The water regimes needed to sustain the ecological values of aquatic ecosystems, including their processes and biological diversity, at a low level of risk

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

Estuaries — Semi-enclosed water bodies at the lower end of a freshwater stream that are subject to marine, freshwater and terrestrial influences, and experience periodic fluctuations and gradients in salinity

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

Flow bands — Flows of different frequency, volume and duration

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Intensive farming — A method of keeping animals in the course of carrying on the business of primary production in which the animals are confined to a small space or area and are usually fed by hand or mechanical means

Irrigation — Watering land by any means for the purpose of growing plants

Irrigation season — The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May

MDB — Murray-Darling Basin

MLR — Mount Lofty Ranges

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change

MREFTP — Marne River Environmental Flows Technical Panel

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

NRMB — Natural Resources Management Board

NY — Northern and Yorke

Phreatophytic vegetation — Vegetation that exists in a climate more arid than its normal range by virtue of its access to groundwater

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

Riparian zone — That part of the landscape adjacent to a water body that influences and is influenced by watercourse processes. This can include landform, hydrological or vegetation definitions. It is commonly used to include the in-stream habitats, bed, banks and sometimes floodplains of watercourses

RMCWMB — River Murray Catchment Water Management Board

Seasonal watercourses or wetlands — Those watercourses or wetlands that contain water on a seasonal basis, usually over the winter–spring period, although there may be some flow or standing water at other times

Stock use — The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act)

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

WAP — Water Allocation Plan

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water-dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; the in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water-dependent ecosystems

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

REFERENCES

Billington K and Kotz S, 1999, 'Inventory of dams in the Marne Catchment, South Australia,' in *Proceedings of the Second Australian Stream Management Conference* 8-11 February 1999, Adelaide, South Australia

Boughton WC, 1966, A mathematical model for relating runoff to rainfall with daily data, in *Civil Engineering Transactions, I.E. Aust*, CE8 (1), April 1966, pp. 83-97

Champion B, Egan D, Pearce JP and Jefferies W, 1999, *The impact of farm dams on streamflow in a rural catchment,* University of Adelaide, Department of Civil and Environmental Engineering, Adelaide

Clark R, 2007, *Investigations into the cause and magnitude of flow decreases in the Clare Valley*, Northern and Yorke Natural Resource Management Board, Adelaide

Cresswell D, 1999, *Wakefield River scientific panel assessment of environmental flows: Hydrology report* [Unpublished report], Environment Protection Agency, Department for Environment, Heritage and Aboriginal Affairs, Government of South Australia

Cresswell D, 2000, *Broughton River scientific panel assessment of environmental flows: Hydrology* [Unpublished report] Department for Environment and Heritage, Government of South Australia

Deane D, 2005, *Rocky River Catchment water resources assessment,* Report DWLBC 2005/34, Department of Water, Land and Biodiversity Conservation, Government of South Australia

Deane D, Graves C, Magarey PD and Phipps L, 2008, *Preliminary assessment of the impacts of water resource development on Burra Creek catchment,* [Draft Report], Department of Water, Land and Biodiversity Conservation, Government of South Australia

Dingman SL, 2002, *Physical hydrology,* 2nd Edition, Prentice Hall, New Jersey

DWLBC, 2006, *State Natural Resources Management Plan 2006,* Department of Water, Land and Biodiversity Conservation, Government of South Australia

Grayson RB, Argent RM, Nathan RJ, McMahon TA and Mein RG, 1996, *Hydrological recipes: Estimation techniques in Australian hydrology*, Cooperative Research Centre for Catchment Hydrology, Melbourne, Victoria

Greenwood AJB, 2000, *Regionalised estimates of runoff capture by farm dams,* [Unpublished report], Department of Water Resources, Government of South Australia

Heneker TM, 2003, *Surface Water Assessment of the Upper River Torrens Catchment,* Report DWLBC 2003/24, Department of Water, Land and Biodiversity Conservation, Government of South Australia

Magarey P and Deane D, 2005, *Willochra Basin groundwater monitoring status report 2005*, DWLBC Report 2005/39, Department of Water, Land and Biodiversity Conservation, Government of South Australia

McMurray D, 2004, *Assessment of water use from farm dams in the Mount Lofty Ranges, South Australia,* Report DWLBC 2004/02, Department of Water, Land and Biodiversity Conservation, Government of South Australia

MREFTP, 2003, *Environmental water requirements of the Marne River, South Australia - Final report*, Marne River Environmental Flows Technical Panel, River Murray Catchment Water Management Board Report

Murdoch, 2002, *Light River environmental water requirements: Hydrology,* [Unpublished report], Department for Environment and Heritage, Government of South Australia

NCHE, 2004, *A Summary of published reports of transmission losses in ephemeral streams in the U.S,* A Report to the National Center for Housing and the Environment, Washington

NYNRMB, 2006, *Draft water allocation plan for the Clare Valley Prescribed Water Resource Area,* Northern and Yorke Natural Resource Management Board, Adelaide

O'Driscoll EPD, 1956, *The hydrology of the Willochra Basin,* Report of Investigations No.7, Department of Mines, Government of South Australia.

Risby L, Scholz G, Vanlaarhoven J and Deane D, 2003, *Willochra Catchment hydrological and ecological assessment,* DWLBC Report 2003/20-21, Department of Water, Land and Biodiversity Conservation, Government of South Australia

Savadamuthu K, 2002, *Impact of farm dams on streamflow in the Upper Marne Catchment,* Report DWR 02/01/0003, Department for Water Resources, Government of South Australia

Savadamuthu K, 2003, *Surface water assessment of the Upper Finniss Catchment,* Report DWLBC 2003/18, Department of Water, Land and Biodiversity Conservation, Government of South Australia

Shentsis I, Meirovich L, Ben-Zvi A and Rosenthal E, 1999, 'Assessment of transmission losses and groundwater recharge from runoff events in a wadi under shortage of data on lateral inflow', in *Negev, Israel Hydrological Processes* 13/11, pp 1649–1663

Teoh KS, 2002, *Estimating the impact of current farm dams development on the surface water resources of the Onkaparinga River Catchment*, Report DWLBC 2002/22, Department of Water, Land and Biodiversity Conservation, Government of South Australia.

Teoh KS, 2007, *The Impact of farm dam development on the surface water resources of the South Para River Catchment*, DWLBC Report 2003/19, Department of Water, Land and Biodiversity Conservation, Government of South Australia

VanLaarhoven J, Scholz G, Phipps L and Favier D, 2004, *A river management plan for the Light Catchment*, Report DWLBC 2004/17, Department of Water, Land and Biodiversity Conservation, Government of South Australia

Zhang L, Dawes WR, Hatton TJ, Hume IH, O'Connell MG, Mitchell DC, Milthorp PL and Yee M, 1999, 'Estimating episodic recharge under different crop/pasture rotations in the Mallee region, Part 2, Recharge control by agronomic practices', in *Agricultural Water Management* (42), pp 237-249