Instream waterholes

A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy

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December 2013

Australian Government
Department of Infrastructure and Regional Development

OFFICE OF NORTHERN AUSTRALIA
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TropWATER
Centre for Tropical Water and Aquatic Ecosystem Research

Water for a Healthy Country Flagship Report series ISSN: 1835-095X

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Citation

McJannet D, Marvanek S, Kinsey-Henderson A, Petheram C and Wallace J (2013) Instream waterholes. A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. CSIRO Water for a Healthy Country and Sustainable Agriculture flagships, Australia.

Flinders and Gilbert Agricultural Resource Assessment acknowledgments

This report was prepared for the Office of Northern Australia in the Australian Government Department of Infrastructure and Regional Development under the North Queensland Irrigated Agriculture Strategy <http://www.regional.gov.au/regional/ona/nqis.aspx>. The Strategy is a collaborative initiative between the Office of Northern Australia, the Queensland Government and CSIRO. One part of the Strategy is the Flinders and Gilbert Agricultural Resource Assessment, which was led by CSIRO. Important aspects of the Assessment were undertaken by the Queensland Government and TropWATER (James Cook University).

The Strategy was guided by two committees:

(i) the **Program Governance Committee**, which included the individuals David Crombie (GRM International), Scott Spencer (SunWater, during the first part of the Strategy) and Paul Woodhouse (Regional Development Australia) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; and the Queensland Government.

(ii) the **Program Steering Committee**, which included the individual Jack Lake (Independent Expert) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; the Etheridge, Flinders and McKinlay shire councils; Gulf Savannah Development; Mount Isa to Townsville Economic Development Zone; and the Queensland Government.

This report was reviewed by Tim Malthus (CSIRO), and Ian Watson (CSIRO). Valuable comments were provided by the following people: Nathan Waltham (JCU) Julien Lerat (CSIRO), Ian Jolly (CSIRO) and Peter Stone (CSIRO).

Members of the SLATS program are acknowledged for their valuable assistance with processing of LandSat imagery for identification of waterholes, including Giri Khanal, Neil Flood, Nicholas Goodwin, Lisa Collette and Christian Witte. Without their help this work would not have been possible.

Director's foreword

Northern Australia comprises approximately 20% of Australia's land mass but remains relatively undeveloped. It contributes about 2% to the nation's gross domestic product (GDP) and accommodates around 1% of the total Australian population.

Recent focus on the shortage of water and on climate-based threats to food and fibre production in the nation's south have re-directed attention towards the possible use of northern water resources and the development of the agricultural potential in northern Australia. Broad analyses of northern Australia as a whole have indicated that it is capable of supporting significant additional agricultural and pastoral production, based on more intensive use of its land and water resources.

The same analyses also identified that land and water resources across northern Australia were already being used to support a wide range of highly valued cultural, environmental and economic activities. As a consequence, pursuit of new agricultural development opportunities would inevitably affect existing uses and users of land and water resources.

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agricultural Strategy. The Assessment seeks to:

- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural opportunities
- assess potential environmental, social and economic impacts and risks.

By this means it seeks to support deliberation and decisions concerning sustainable regional development.

The Assessment differs from previous assessments of agricultural development or resources in two main ways:

- It has sought to 'join the dots'. Where previous assessments have focused on single development activities or assets – without analysing the interactions between them – this Assessment considers the opportunities presented by the simultaneous pursuit of multiple development activities and assets. By this means, the Assessment uses a whole-of-region (rather than an asset-by-asset) approach to consider development.
- The novel methods developed for the Assessment provide a blueprint for rapidly assessing future land and water developments in northern Australia.

Importantly, the Assessment has been designed to lower the barriers to investment in regional development by:

- explicitly addressing local needs and aspirations
- meeting the needs of governments as they regulate the sustainable and equitable management of public resources with due consideration of environmental and cultural issues
- meeting the due diligence requirements of private investors, by addressing questions of profitability and income reliability at a broad scale.

Most importantly, the Assessment does not recommend one development over another. It provides the reader with a range of possibilities and the information to interpret them, consistent with the reader's values and their aspirations for themselves and the region.

Peter Stone

Dr Peter Stone, Deputy Director, CSIRO Sustainable Agriculture Flagship

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Shortened forms

APE	areal potential evaporation
APSIM	Agricultural Production Systems Simulator
CMIP	Coupled Model Intercomparison Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Cv	coefficient of variation
DEM	digital elevation model
EEMD	Ensemble empirical mode decomposition
ENSO	El Niño Southern Oscillation
GCMs	global climate models
GCM-ES	global climate model output empirically scaled to provide catchment-scale variables
IMF	Intrinsic Mode Functions
IPCC AR4	the Fourth Assessment Report of the Intergovernmental Panel on Climate Change
IPO	Inter-decadal Pacific Oscillation
ITCZ	Inter-tropical Convergence Zone
MJO	Madden-Julian Oscillation
NASA	National Aeronautics and Space Administration
NQIAS	North Queensland Irrigated Agriculture Strategy
ONA	the Australian Government Office of Northern Australia
PE	potential evaporation
SOI	Southern Oscillation Index
SRES	Special Report on Emissions Scenarios

Units

MEASUREMENT UNITS	DESCRIPTION
GL	gigalitres, 1,000,000,000 litres
keV	kilo-electronvolts
kL	kilolitres, 1000 litres
km	kilometres, 1000 metres
L	Litres
m	Metres
mAHD	metres above Australian Height Datum
MeV	mega-electronvolts
mg	milligrams
MJ/m^2	megajoules per metre square
ML	megalitres, 1,000,000 litres

Preface

The Flinders and Gilbert Agricultural Resource Assessment (the Assessment) aims to provide information so that people can answer questions such as the following in the context of their particular circumstances in the Flinders and Gilbert catchments:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure and values?
- What are the opportunities for irrigation?
- Is irrigated agriculture economically viable?
- How can the sustainability of irrigated agriculture be maximised?

The questions – and the responses to the questions – are highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports must be read as a whole if they are to reliably inform discussion and decision making on regional development.

The Assessment is producing a series of reports:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the 12 research activities (outlined below) has a corresponding technical report.
- Each of the two catchment reports (one for each catchment) synthesises key material from the technical reports, providing well-informed but non-scientific readers with the information required to make decisions about the opportunities, costs and benefits associated with irrigated agriculture.
- Two overview reports – one for each catchment – are provided for a general public audience.
- A factsheet provides key findings for both the Flinders and Gilbert catchments for a general public audience.

All of these reports are available online at <http://www.csiro.au/FGARA>. The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

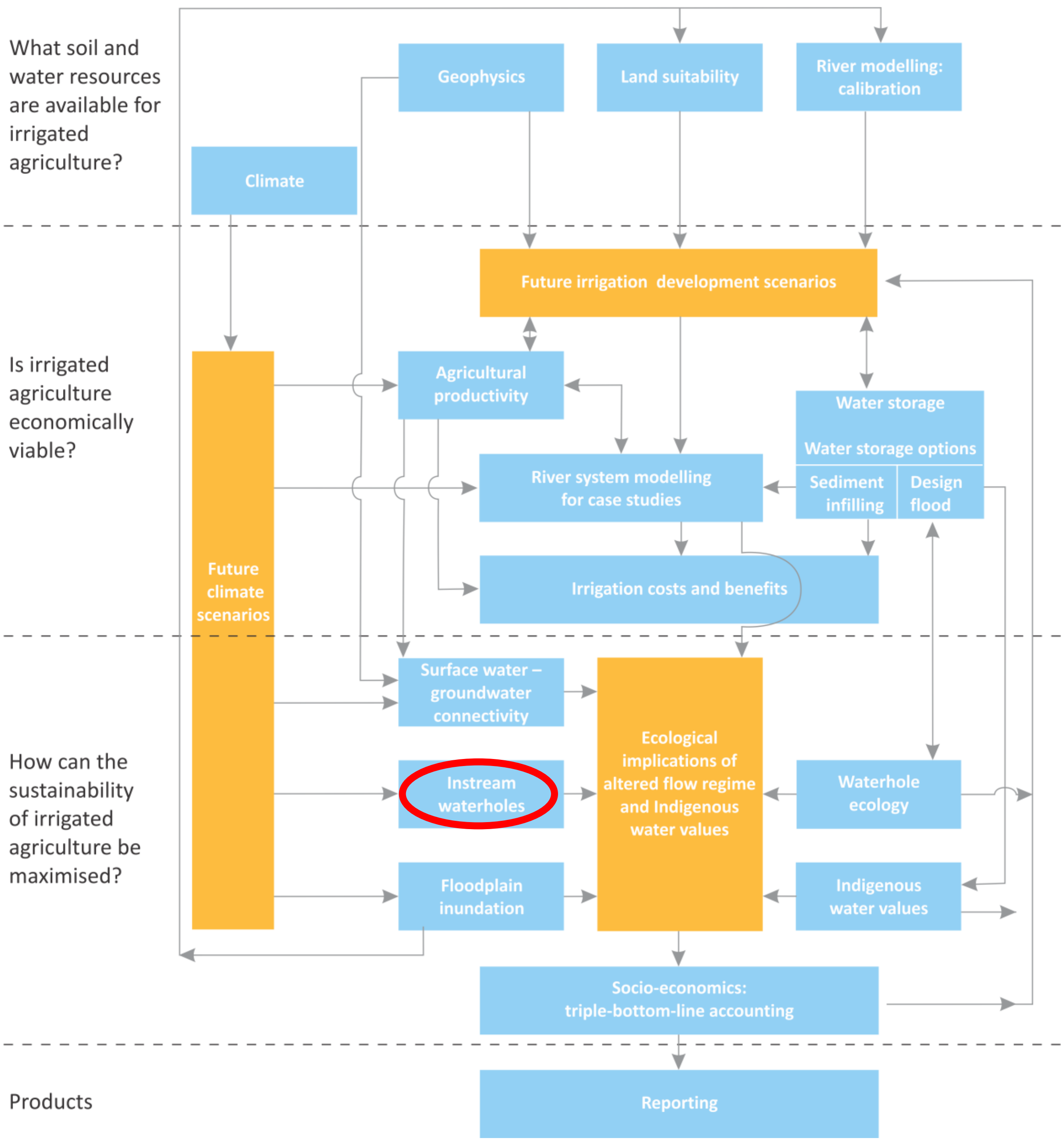
The Assessment is divided into 12 scientific activities, each contributing to a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 1 illustrates the high-level linkages between the 12 activities and the general flow of information in the Assessment. Clicking on an ‘activity box’ links to the relevant technical report.

The Assessment is designed to inform consideration of development, not to enable particular development activities. As such, the Assessment informs – but does not seek to replace – existing planning processes. Importantly, the Assessment does not assume a given regulatory environment. As regulations can change, this will enable the results to be applied to the widest range of uses for the longest possible time frame. Similarly, the Assessment does not assume a static future, but evaluates three distinct scenarios:

- Scenario A – historical climate and current development
- Scenario B – historical climate and future irrigation development
- Scenario C – future climate and current development.

As the primary interest was in evaluating the scale of the opportunity for irrigated agriculture development under the current climate, the future climate scenario (Scenario C) was secondary in importance to scenarios A and B. This balance is reflected in the allocation of resources throughout the Assessment.

The approaches and techniques used in the Assessment have been designed to enable application elsewhere in northern Australia.



Preface Figure 1 Schematic diagram illustrating high-level linkages between the 12 activities (blue boxes)

This report is a technical report. The red oval in Preface Figure 1 indicates the activity (or activities) that contributed to this report.

The orange boxes indicate information used or produced by several activities. The red oval indicates the activity (or activities) that contributed to this technical report. Click on a box associated with an activity for a link to its technical report (or click on 'Technical reports' on <http://www.csiro.au/FGARA> for a list of links to all technical reports). Note that the Water storage activity has multiple technical reports – in this case the separate reports are listed under the activity title. Note also that these reports will be published throughout 2013, and hyperlinks to currently unpublished reports will produce an 'invalid publication' error in the CSIRO Publication Repository.

Executive summary

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. Streamflow in these rivers is strongly seasonal and the vast majority of annual flow occurs during the wet season. During the dry season the rivers tend to dry out to a series of in-stream pools. These pools provide water for native fauna and stock and provide refugial habitat for terrestrial and aquatic biota during the periods between streamflow events. The formation, size and persistence of these pools is dependent on the timing, duration and amount of streamflow in the preceding wet season. Water resource management plans should recognise any potential impacts that development and future climate may have on streamflow and duration of dry periods in the Assessment area. With this in mind the Dry-season pool activity aimed to; (i) develop techniques for identifying in-stream pools using remote sensing techniques, (ii) track the dynamics of pool evolution over time and identify key aquatic refugia and (iii) relate pool dynamics to streamflow characteristics.

In-stream pools were identified within the defined river reaches in the Flinders and Gilbert catchments by applying a water index algorithm to Landsat imagery collected between 2003 and 2010. Analysis was restricted to buffered areas around the stream network and cloud identification procedures were applied to exclude scenes affected by cloud or cloud shadow. Threshold values, below which all pixels are mapped as water, were defined for each catchment by comparing high resolution pool area estimates from Google Earth Pro. Optimising the water index threshold to best match pool area estimates from high resolution imagery produced different threshold values for the Flinders and Gilbert catchments. The resolution limitations of the technique need to be acknowledged and the results presented here should not been seen as the definitive mapping of all in-stream pools for the Flinders and Gilbert catchments.

The persistence of pools with time was estimated by calculating the percentage of time that a given pixel was mapped as water. Individual pools that existed for more than 90% of the time were considered to be 'key aquatic refugia' and as such are likely to be crucial for sustaining ecosystems in these catchments. A much greater number of key aquatic refugia were found in the Gilbert catchment than in the Flinders catchment. The most likely reason for the observed differences is the more persistent streamflow in the Gilbert catchment, however, the wider channels in the Gilbert catchment may also favour identification of pools at the resolution of Landsat pixels. There is also anecdotal evidence that groundwater inputs may play a greater role in pool persistence in some parts of the Gilbert catchment, although this is yet to be conclusively proven. The time series of processed Landsat scenes provides an ideal means by which to track the evolution of pools with time.

All river reaches except for the Lower Einasleigh in the Gilbert catchment experienced periods of zero flow during the study period. The duration of zero flow events tended to be much longer for locations in the Flinders catchment than those in the Gilbert catchment. Reasonably strong relationships between total pool area and time since flow ceased were derived for the Cloncurry, Mid-Flinders and Gilbert river reaches. The Lower Einasleigh River reach flowed continuously during the study and a strong relationship was found between pool area and streamflow. Strong relationships could not be derived, however, for the remaining three river reaches due to the short duration of zero flows and frequent cloud cover which severely restricted Landsat scene availability.

Similar rates of fractional reduction in total pool area with time since zero flow were observed for the Cloncurry, Mid-Flinders and Gilbert river reaches. This similarity enabled the development of a generalised relationship between duration of zero flow and reduction in pool area. This curve is well suited to streamflow scenario analysis and offers a potential means by which to approximate the relative reduction in total pool area for changes in zero flow duration for other river reaches which do not have detailed Landsat analysis. The relationships for predicting total pool area will be used by the river modelling activity to compute how total pool area may change under different development and climate scenarios. This will be reported in the companion technical report on river modelling simulation (see Preface Figure 1).

Development of water resources in the Flinders and Gilbert catchments needs to be cognisant of the importance of dry-season pools to both terrestrial and aquatic biota. This report describes techniques for catchment-specific identification of pools using Landsat imagery, presents detailed information regarding pool evolution and persistence, and provides key relationships linking pool area to streamflow conditions. With our current knowledge of the location of key aquatic refugia and spatial and temporal variations in pool persistence, combined with analysis being undertaken as part of the complementary studies on pool ecology and groundwater systems, our understanding of pool evolution and health in this area is greatly improved. This knowledge provides a strong basis to help guide water management decision making.

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1 Introduction

1.1 The importance of in-stream pools

Like many rivers that drain to the Gulf of Carpentaria, streamflow in the Flinders and Gilbert rivers is strongly seasonal. The vast majority (greater than 90%) of total annual streamflow in these rivers occurs during the wet season (November to April) (CSIRO, 2009) and streamflows during the dry season are very limited or non-existent. During the dry season the rivers tend to dry out to a series of in-stream pools with varying degrees of connectivity. These pools (see Figure 1.1 for an example) provide water for native fauna and stock and provide refugial habitat for aquatic and other biota during the periods between streamflow events (Davis et al., 2002; Hamilton et al., 2005; Lymburner and Burrows, 2008; Sheldon et al., 2010).

During dry periods many of the smaller pools disappear through evaporation and seepage and only a few of the larger pools will remain. These pools, which are referred to in this report as 'key aquatic refugia', are particularly important as they provide the critical habitat for aquatic biota to survive in these catchments. In some parts of catchments in the Gulf of Carpentaria, streamflow and in-stream pools can be maintained by groundwater flows, while in others in-stream pools receive insufficient or no additional water inputs during the dry season (DERM, 2011). As a result of these differences, management of these rivers and utilisation of surface and groundwater resources may need to vary from region to region. Management of these rivers also needs to be mindful of the potential impact that climate change and/or water resource development may have on streamflow and duration of dry periods in this region (Leigh and Sheldon, 2008).

The key characteristics of in-stream dry-season pools which contribute to their ability to sustain aquatic ecosystems are their persistence during dry periods and the quality of habitat which the pool provides. The identification of pools and their area using remote sensing techniques, relationships between pool area and seasonal flows and determination of the persistence of these pools is the focus of this report, while the importance of habitat quality is assessed within a companion technical report on aquatic and riparian ecology (see Preface Figure 1).

1.2 Research aims

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agriculture Strategy. The Assessment is divided into 12 scientific activities (Figure 1-1), each contributing to a cohesive picture of regional development opportunities, costs and benefits. This report describes scientific research undertaken in the Dry-season pools activity. This activity has three aims which are broadly based around (i) identification of in-stream pools using remote sensing techniques, (ii) tracking the dynamics of pool evolution over time and identifying key aquatic refugia, and (iii) relating pool dynamics to streamflow characteristics in defined river reaches. The advantage of the proposed methodology is that it can provide information about the spatial distribution of in-stream pools across large, and often inaccessible, areas. Specifically the aims of this research are:

1. Develop and test methods for the identification of in-stream pools in the Flinders and Gilbert catchments. This component is based around selection of appropriate methods for identifying in-stream pools using remote sensing. Landsat data was used for this study as it is freely available and has a reasonable temporal resolution (~16 days) for analysis to be undertaken during the dry season. The ability to accurately identify pools using Landsat data was assessed through comparison with higher resolution remote sensing images.

2. Identify key aquatic refugia in the study area and quantify the persistence of pools through time. Once appropriate pool identification algorithms have been defined for the Landsat data, a time series of scenes will be used to track the persistence of pools over time. Persistence will be defined as the percentage of scenes in which a given pixel is identified as being a water body.

3. Examine the relationships between streamflow and dry season pool development. One of the key components of the Assessment is modelling the impact of water resource development and future climate on streamflow. As the formation of dry-season pools is likely to be related to the duration of periods between streamflow events we will also seek to identify relationships between time since flow ceases and total pool area. Such relationships will be derived using modelled streamflow at gauging sites in the Flinders and Gilbert catchments. These relationships will be used in a companion technical report on river modelling (see Preface Figure 1) where the impacts of changes to streamflow under different development and climate scenarios will be assessed.

Figure 1.1 A large in-stream pool during the dry season in the Flinders catchment. Photo: Nathan Waltham, TropWATER, JCU

2 Methods

2.1 Assessment area

The Assessment area encompasses the Flinders and Gilbert catchments, which are located in the Gulf region of north Queensland (Figure 2.1). The Flinders catchment has an area of 109,000 km^2 and a population of about 6000 people. The Flinders River is the longest of the Gulf Rivers and second longest Australian river course outside of the Murray-Darling Basin, and sixth longest Australian river overall. The river rises in the Great Dividing Range north-east of Hughenden, nearly 1000 km from its entry to the Gulf of Carpentaria. The Gilbert catchment has an area of 46,354 km^2 and a population of about 1200 people. The Gilbert catchment is comprised of two major rivers, the Gilbert and the Einasleigh. The Gilbert River flows in a north-westerly direction from the Great Dividing Range, 150 km south-east of Georgetown and is joined by its major tributary, the Einasleigh River, downstream of Strathmore Station, before entering the Gulf of Carpentaria.

Both catchments have a maximum elevation of about 1050 m and do not have any mountains that provide notable obstruction to large-scale atmospheric circulatory systems. While the Gilbert catchment is undulating in its mid-to-upper reaches the Flinders catchment is predominantly flat (Figure 2.1). The main land use by area in the two catchments is extensive cattle grazing. Major population centres are shown in Figure 2.1.

Over the historical period (i.e. 1 July 1890 to 30 June 2011) the mean annual rainfall spatially averaged across the Flinders and Gilbert catchments was 492 mm and 775 mm respectively. In the Flinders catchment mean annual rainfall varies from about 800 mm at the coast to about 350 mm in the south. In the Gilbert catchment mean annual rainfall varies from about 1050 mm at the coast to about 650 mm in the southeast of the catchment. Within the Flinders and Gilbert catchments, areas have been defined where detailed assessments of the feasibility, economic viability and sustainability of water resource development will be made. For the analysis of in-stream pools for this report, three river reaches have been defined in the Flinders catchment and four in the Gilbert catchment. The location, name and extent of these river reaches, as used for in-stream pool analysis in the Flinders and Gilbert catchments, is shown in Figure 2.1. Also shown in this figure are the locations of stream gauging stations that were utilised in this in-stream pool analysis.

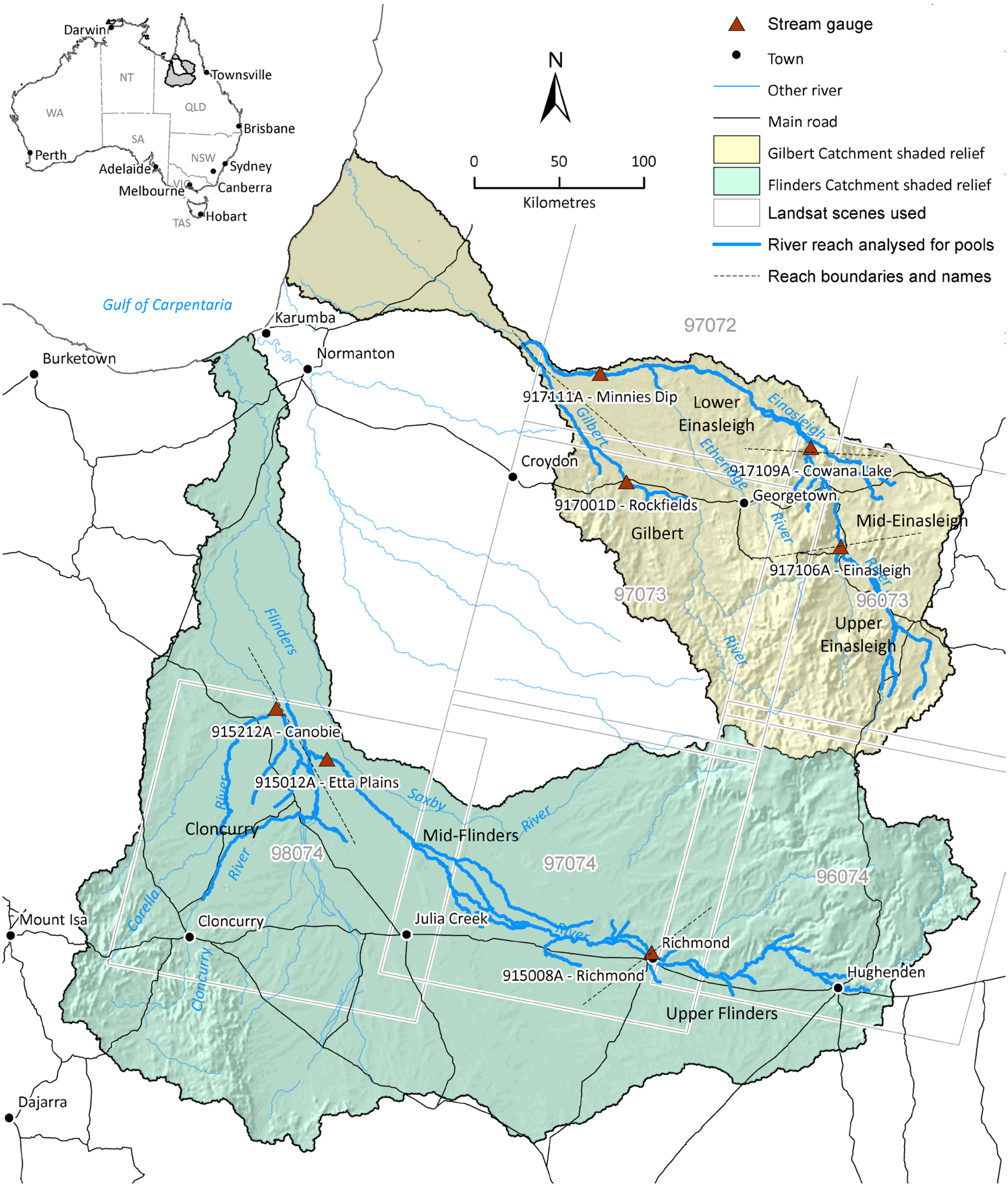

Figure 2.1 Shaded relief map of the Flinders and Gilbert catchments. The location of defined river reaches, associated stream gauging stations and Landsat scenes boundaries for each catchment as used for the dry-season pools investigation are also shown. The Flinders and Gilbert catchments and the Gulf region are shown in the small inset map in top left corner

2.2 Identification of in-stream pools

Landsat data has been used by the Queensland Government for identification of water bodies and changes in land cover since 1988 through the Statewide Landcover and Trees Study (SLATS) program. The SLATS program reports annual changes to land cover and has also developed a water-index algorithm which is able to identify the location and extent of water bodies. As part of the standard processing procedures undertaken by the SLATS program, Landsat images are orthorectified using the methodology described by

Armston et al. (2002) which utilises at least 50 ground control points to minimise image registration errors. To facilitate reliable comparison of radiance values between Landsat scenes all scenes are also radiometrically and atmospherically standardised using the procedures outlined by Danaher et al. (2001), De Vries et al. (2007) and Goodwin et al. (2013).

The water body identification process used by the SLATS program is described in detail by Muir and Danaher (2008), therefore we will only provide a summary here. The method to identify water was first developed by the SLATS program using the Canonical Variates Analysis (CVA) tool. This tool enabled identification of the best combination of Landsat bands for separating water from non-water spectral signatures using a set of training data which included a variety of water features (e.g. dams, rivers, ocean) and land uses found across the State. The highest accuracy classification used log transformations of all Landsat Thematic Mapper bands, except for band 1 (Muir and Danaher, 2008). The classification procedure results in output images with pixel values between 0 and 255. Using rank correlation the threshold at which the least number of pixels misclassified as water was found in the training data and this resulted in the selection of a single index value below which all pixels are classified as water. The SLATS program uses an index value of 68 for all of Queensland for ease of operations. For the purposes of the Assessment we selected a water index threshold best suited to each of our catchments via a calibration process (see below).

The SLATS program produces an annual ‘snapshot’ of water body extent for the State of Queensland, but, for this project we required a more detailed time series of water body dynamics for the Flinders and Gilbert catchments only. The water index algorithm was therefore only implemented for the Landsat scenes covering the river reaches of interest. These scenes are shown in Figure 2.1. Through this process a semi-continuous time series of 30 m resolution water indices was derived from Landsat 5 scenes for the period between July 2003 and December 2010. Analysis was restricted to these dates as this was when the SLATS program Landsat archive contained complete temporal coverage of processed scenes for the study area. This period includes about 22 scenes per year (based on a 16 day return interval). Landsat 7 ETM scenes were excluded from analysis due to problems associated with missing scan line data that have affected this product since 2003.

The total number of scenes included in our final analysis is shown in Table 2.1. Only scenes from the Landsat archive with less than 20% cloud cover were processed with the water index algorithm. As we were only interested in the identification and persistence of ‘in-stream’ pools we restricted the area in each scene in which we performed our pool analysis by applying a buffer to the stream network and limiting analysis to areas within this zone. The stream network was defined using 250 k topographic mapping and buffers of between 100 m and 500 m were applied depending on the width and degree of braiding of the stream. The SLATS program also produced a cloud and cloud shadow mask for each scene (see Goodwin et al. (2013)) using the methods proposed by Zhu and Woodcock (2012). This cloud mask was used in combination with the stream network buffer to identify scenes where cloud cover might influence the total area classified as water. Scenes where more than 5% of the buffered area was affected by cloud were removed from further analysis.

An initial assessment of the standard Queensland-wide water index threshold used by the SLATS program to define water bodies (water index <=68) showed that it was not capturing in-stream pools well for the Flinders and Gilbert catchments due to their limited spatial extent and narrow nature. However, the water index approach still showed potential for application if some localised calibration could be applied. Selection of a water index threshold most suited for the Flinders and Gilbert catchments was therefore undertaken by comparing the area classified as water at different index values to the area of water identified in high resolution imagery from Google Earth Pro.

Table 2.1 The Landsat TM scenes covering each river reach and the total number of Landsat scenes analysed between July 2003 and Dec 2010. Only those scenes with less than 20% cloud cover were processed (see text)

FLINDERS	LANDSAT SCENE	POOL PERSISTENCE ANALYSIS	POOL AREA TIMESERIES
Cloncurry	p098r074	94	90
Mid-Flinders*	p098r074	94	66
	p097r074	89	
Upper Flinders	p096r074	90	87
GILBERT	**LANDSAT SCENE**	**POOL PERSISTENCE ANALYSIS**	**POOL AREA TIMESERIES**
Gilbert*	p097r072	90	85
	p097r073	97	
Lower Einasleigh	p097r072	90	90
Mid-Einasleigh	p096r073	67	67
Upper Einasleigh	p096r073	67	67

*** the number of scenes processed for the pool area time series is less than for pool persistence due to the need to pair scenes acquired within 10 days of each other**

The area of individual water bodies within each of the river reaches for each catchment was manually digitised in Google Earth Pro. Pools were assigned unique Pool IDs and the date of the Google Earth image was recorded against each Pool ID. High resolution Google Earth pro imagery was available for 12 different dates between 2003 and 2006 for the Flinders catchment and for five dates between 2009 and 2011 for the Gilbert catchment. We then used Landsat water index data from the closest Google Earth date and compared total pool area for a range of water index threshold levels until the best match for total pool area was achieved. For consistency with generalised water body determination methods, only pools composed of four or more pixels were utilised (Lymburner and Burrows, 2008). Following this method we were able to derive the best water index threshold to use in each catchment to derive in-stream pool areas.

2.3 Persistence of in-stream pools

Water body extent was derived for each of the Landsat scenes identified in Figure 2.1 by classifying pixels as either water or non-water. The percentage of time (i.e. percentage of available images) that a given pixel was classified as water was then calculated. This provided a direct metric of the persistence of pools between years. Pools that were mapped as persisting for more than 90% of the time were considered to be 'key aquatic refugia'. This selected persistence level is purely an approximation for defining pools that were present for the vast majority of the time and was not informed by any ecologically significant threshold. These pools are most likely to be present during all years and are likely to be crucial for sustaining ecosystems in the river reach being studied. The time series of water body extent was also used to track the evolution of pools over time.

2.4 Streamflow characteristics and in-stream pool evolution

In order to assess the potential impacts of changes to flow on in-stream pool development, it was necessary to determine whether relationships exist between pool characteristics and streamflow. For this analysis modelled historical streamflow from key gauging stations defined for each river reach (locations shown in Figure 2.1) was used. While actual stream gauging information is available for some locations for this period, the decision was made to use calibrated river model simulations (see Lerat et al. (2013) for details) so as to better facilitate application of any derived relationships to modelled scenarios of future development and climate. As measurable streamflow ceases for large parts of the year in these catchments the time since cease to flow was tested for suitability as a predictor of total pool area. This metric may also be useful if the remnant pools are maintained by groundwater discharge from the local floodplain. A flow rate of 1 ML/day was used to represent the commencement of cease to flow. This flow rate was chosen as in most locations gauged and modelled values below this threshold have a high level of uncertainty (Lerat et al., 2013). Analysis only used data points where the number of days since zero flow was greater than 25; relationships between pool area and time since cease to flow showed a lot of variation for zero flow durations of less than 25 days. Removal of these data is justified on the basis that derived relationships are more likely to be used for estimating pool area at time-scales of months, not days, since cease to flow. In some river reaches streamflow does not cease, in these cases direct relationships between streamflow and pool area were assessed.

For river reaches where sufficient data points existed the predictive power of the derived relationships was further assessed using a non-overlapping block bootstrapping approach. This process involved systematically removing individual years of data from the analysis and using derived relationships from the remaining years to predict what pool areas would have been in the excluded year. Using this approach an entire dataset of independent estimates of pool area could be derived which could then be compared to those actually measured to get a feel for the uncertainty of the proposed method.

2.5 Assumptions and limitations

The limitations of the techniques employed in this report need to be acknowledged when interpreting results. Firstly, the analysis presented here should not be seen as the definitive mapping of all in-stream pools for the Flinders and Gilbert catchments. This is because we have focussed on selected reaches in these catchments and the Landsat product that we have used has limitations that need to be recognised. The resolution of the Landsat pixels is 30 m, therefore channels in narrow river reaches, such as heavily braided sections, are likely to be under-represented in our analysis. This limitation, as well as deliberate exclusion of off-stream pools, may mean that some permanent pools, including some that may be well known to the local people, may not be identified. Identification of pools in narrow river reaches would require the use of a higher resolution remote sensing product and would benefit greatly from local knowledge. However, for in-stream pools larger than 3600 m^2 we have confidence in the approach that we have taken within the areas we have analysed.

3 Results

3.1 Defining water index threshold values

Using Google Earth Pro we identified 73 in-stream pools in the Flinders catchment and 33 in the Gilbert catchment. The dates of Google Earth Pro estimates for different reaches were matched with Landsat image dates and then pool areas from all dates were combined to produce the total area estimate against which the water index threshold was defined. The lower number of pools in the Gilbert catchment reflects the longer pool lengths and more limited extent of high resolution imagery in this catchment. We then compared a series of water index thresholds for Landsat images looking for the best match between total pool areas identified using the two methods. For the Flinders catchment a water index threshold of 77 provided the best estimate of total pool area, underestimating the higher resolution estimate by just 3% (Figure 3.1a). Interestingly, for the Gilbert catchment a different water index threshold of 80 provided the best match to the baseline value (Figure 3.1b).

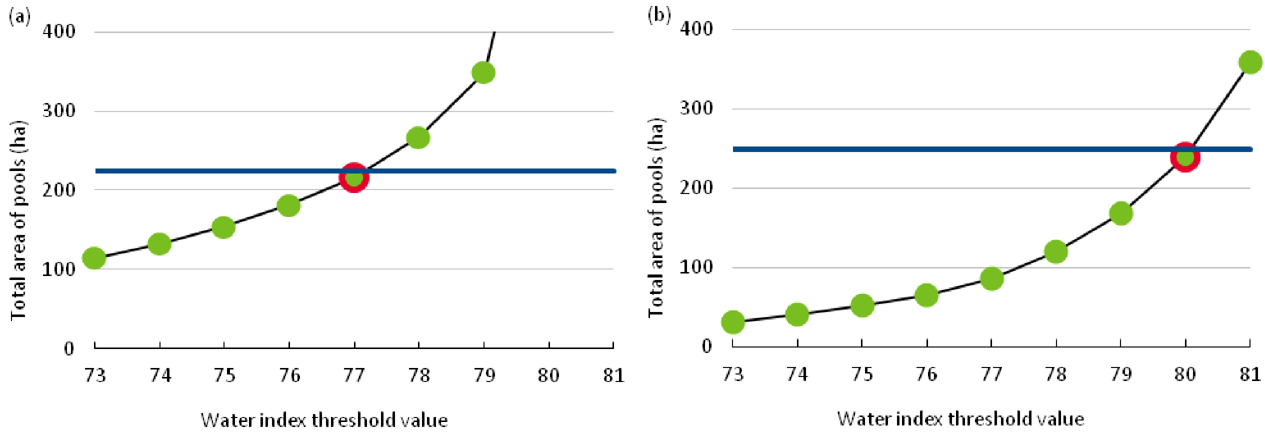

Figure 3.1 Comparison of total pool area derived for given Landsat water index thresholds against total pool area derived from high resolution Google Earth Pro imagery (blue line) in both the Flinders (a) and Gilbert (b) catchments. The water index threshold used for each catchment is circled in red

It is likely that the difference in the water index values for the two catchments reflects differences in water clarity as turbid water has a different reflectance to clear water. Lymburner and Burrows (2008) showed that water clarity across the Gulf catchments could vary markedly. Likely reasons for observed differences included local geology, stock access and whether pools were fed with groundwater. To further illustrate the point, if we apply the water index threshold of 80 to the Flinders catchment the area of pools identified is overestimated by a factor of 3. Conversely, if a threshold of 77 is applied to the Gilbert the total pool area is underestimated by 66%. The water index threshold of 68 used for image processing by the SLATS program reflects its aim to map larger and more persistent dams and water bodies, not the much smaller pools which are the focus of this study. Should the approach described here be applied to other catchments then derivation of a locally defined threshold is recommended.

A comparison of the area mapped as water using the water index for a section of Junction Creek in the Gilbert catchment and the corresponding pool extent mapped from high resolution Google Earth Pro imagery is shown in Figure 3.2. This figure shows good agreement between the two methods in wider river sections but also highlights the limitations of the approach in narrow sections where the resolution of the imagery is greater than the channel width. This comparison highlights the acknowledged resolution limitations of the method and also shows that derivation of pool numbers may be problematic. This is further demonstrated in Figure 3.3 which shows a comparison of the total number of pools identified using different water threshold index values as compared to the baseline value from Google Earth Pro. This demonstrates that the best index value for total pool area is not necessarily the best value for pool numbers. The number of pools is therefore a particularly hard characteristic to compare because of differences in image resolution. The high resolution Google Earth product will pick up narrow stretches linking larger pools and group them as one, whereas the Landsat approach will split the pool into separate water bodies because the linking channel is not identified at the coarser pixel resolution. Given the limitations in identifying the correct number of pools we will focus on using the metric, total area of in-stream pools, in this report and use the water index thresholds identified in Figure 3.1.

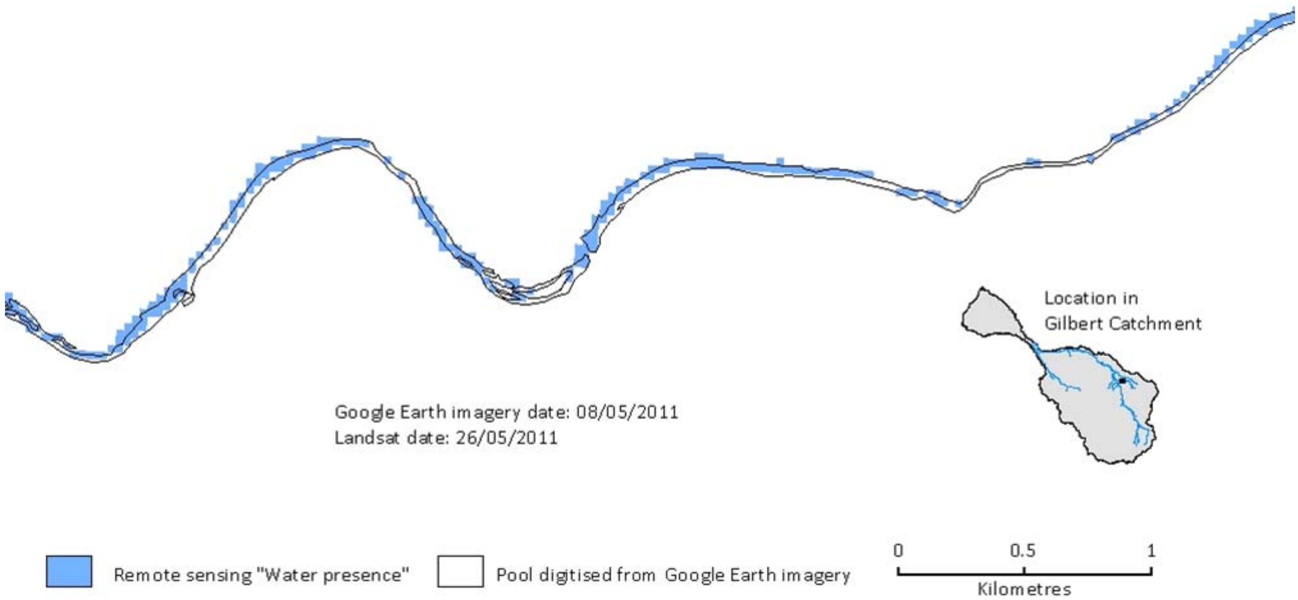

Figure 3.2 Comparison of area mapped as water using the best Landsat water index threshold and Google Earth imagery showing good agreement between the methods in wider reaches but poorer performance of the Landsat product in narrower channels

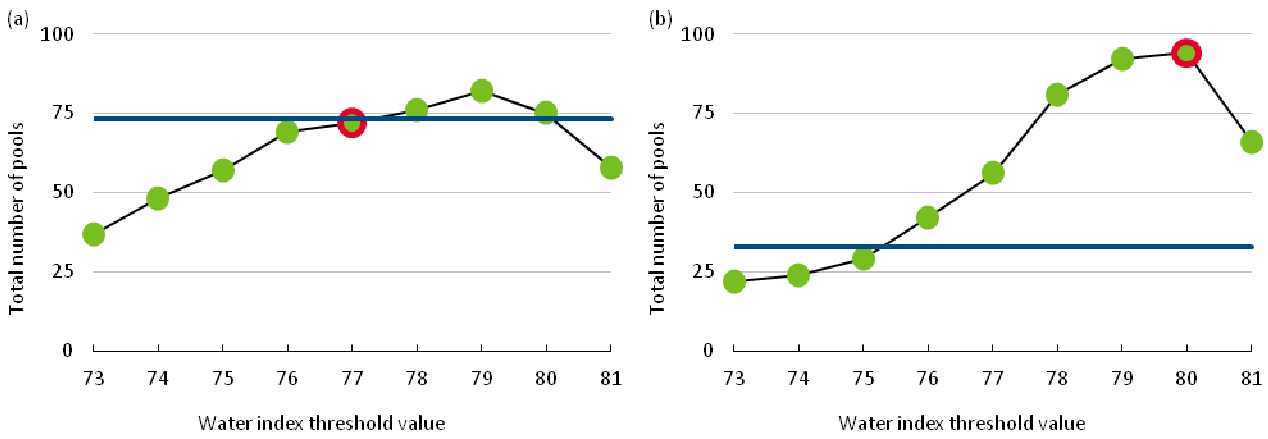

Figure 3.3 Comparison of total number of individual pools derived for given water index thresholds against total number of pools derived from high resolution Google Earth Pro imagery (blue line) in both the Flinders (a) and Gilbert (b) catchments. The water index threshold used for each catchment is circled in red

3.2 In-stream pool persistence and key aquatic refugia

Using the water index thresholds defined above, the presence of in-stream pools was determined for all suitable Landsat scenes available for the period between July 2003 and December 2010 (Table 2.1).

Interpretation of these results will be considered separately for the Flinders and Gilbert catchments in the following sections. Key aquatic refugia have been identified in this analysis as pools that persisted for more than 90% of the time and pool persistence is mapped as the proportion of time that a pixel is mapped as being water. In this case the percentage of time is represented by the percentage of available images.

3.2.1 FLINDERS CATCHMENT

The location and size of key aquatic refugia in each selected river reach of the Flinders catchment is shown in Figure 3.4. Four size classes of key aquatic refugia and the boundaries of the three defined river reaches are mapped. In the Upper Flinders reach there were no key aquatic refugia mapped at the resolution of the Landsat satellite imagery. In the Mid-Flinders seven small key aquatic refugia were mapped with the largest being less than 5 ha in area. River channels in this flat landscape are at times very complex with larger channels regularly splitting into numerous narrower channels which may then rejoin again downstream. The small number of key aquatic refugia mapped in this river reach reinforces the significant role that these systems play in the survival of aquatic species during the often extended periods between streamflow events that characterise this area. The relative scarcity of dry-season pools in the Mid-Flinders makes the region especially sensitive to potential development impacts such as erosion of proximal and upstream catchments, which can reduce water quality by increasing turbidity and by filling pools with sediment. Loss of pool habitats due to excessive erosion has been document in many locations (e.g. Bartley and Rutherfurd, 2005; Davis and Finlayson, 2000). There are three key aquatic refugia mapped at the scale of the Landsat resolution in the Cloncurry river reach (Figure 3.4). One of these refugia is particularly large (location B) and has an area greater than all the other key aquatic refugia mapped in the Flinders catchment combined. This large refugium is well known in this area and is referred to as Dalgonally Waterhole. This system supports large populations of many species (Hogan and Valance, 2005) and as a result, this is a significant refugium for this catchment. In general, large refugia are few and far between in this part of the Flinders catchment.

Confidence in our analysis technique is provided by the fact that two of our key aquatic refugia have also been the focus of field measurements which were undertaken to define factors affecting pool persistence as part of the Tropical Rivers and Coastal Knowledge (TRaCK) program. This study (DERM, 2011) identifies location A in Figure 3.4 as Stanley Waterhole and location C as Rocky waterhole.

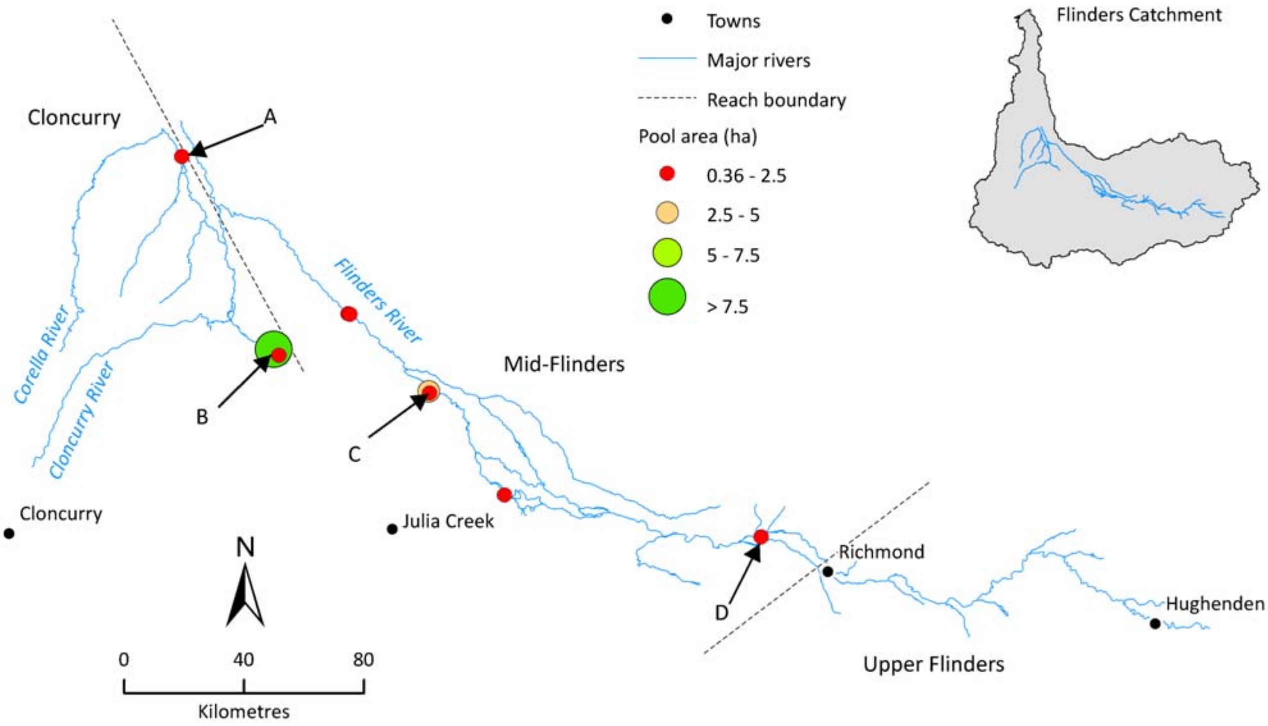

Figure 3.4 Location of key aquatic refugia identified in the Flinders catchment. Key aquatic refugia are defined as those pools which are present for more than 90% of the time. Letters represent regions which will be shown in more detail in Figure 3.6

Using the defined water threshold index it is possible to use the time series of available images to track the evolution of pools with time. This is demonstrated for a short section of the Cloncurry River reach at Location A (Figure 3.4) in Figure 3.5. This figure shows a progressive reduction in the mapped area of water during the dry season of 2005. The extent of mapped water area is shown at durations of 1, 99 and 179 days since streamflow ceased. Similar analysis can be undertaken at any area of interest along the river network.

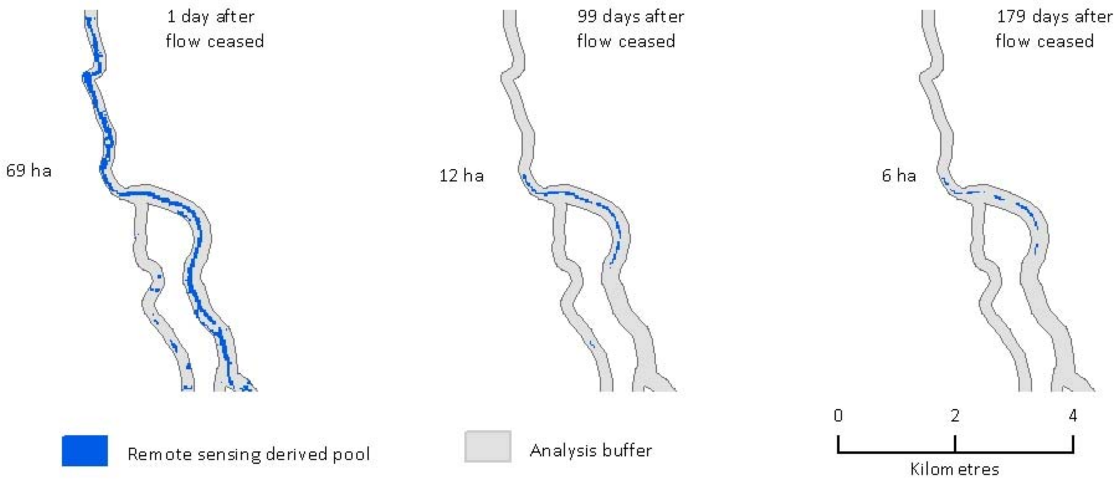

Figure 3.5 Mapping of in-stream pool evolution for at Location A (Figure 3.4) on the Cloncurry river reach showing the area of pools in the scene at a given time after flow ceased and ability of the water index threshold to track the evolution of pools

The persistence of in-stream pools at key locations identified in Figure 3.4 is shown in more detail in Figure 3.6. The percentage of time that pixels are mapped as water shows how the river channels contract to distinct pools which persist between dry seasons. Closer examination of mapped pools shows that they also tend to form at the confluence of rivers where sediment depositions can block flow, at road crossings where barriers hold back water, and on river bends where scouring leaves deeper sections of channel.

At locations A and C in Figure 3.6 it can be seen that extensive areas can be inundated during wet periods. According to the DERM (2011) report, the Stanley waterhole (location A) has a depth at the start of the dry season of around 4 m and could persist for approximately 380 days without further input. The DERM (2011) report shows that Rocky Waterhole (location C) is about 5 m deep at the start of the dry season and that this pool could persist for 640 days without further surface water input. Measurements made for this report showed that depths declined slower than expected when compared to other waterholes in the area and the likely reason was given as additional inputs to the pool from groundwater.

A report prepared by Mann and Wiebenga (1960) on groundwater levels in the Cloncurry area found that there was a lot of variability in groundwater depth and that the presence of rock bars could push water nearer to the surface in some areas. An analysis of the source of water for pools located around the Flinders catchment using radon concentrations, stable isotope and major ions data was also undertaken and is reported in a companion technical report on groundwater systems (see Preface Figure 1-1). This report identifies a couple of pools within the Flinders catchment that have a high likelihood of receiving groundwater inflows although the vast majority showed little likelihood of being fed by groundwater.

Water body clarity was also mapped in the Flinders catchment using remote sensing techniques by Lymburner and Burrows (2009). They found that most identified pools were always turbid and that in general pools in the Flinders River catchment were more turbid than those in other catchments of the southern Gulf of Carpentaria. This provides additional evidence that pools in the Flinders catchment are unlikely to be receiving groundwater discharge (which can cause suspended material to flocculate out of solution).

The size and extend of Dalgonally Waterhole (location B) is evident when compared to the other mapped refugia. The persistent pools in locations D and B suggest that these pools are formed in topographic depressions; this inference is made by observing the very narrow bands of less persistent water area around these pools. If they are in depressions, then these pools are potentially deep meaning that they can withstand longer periods without flow.

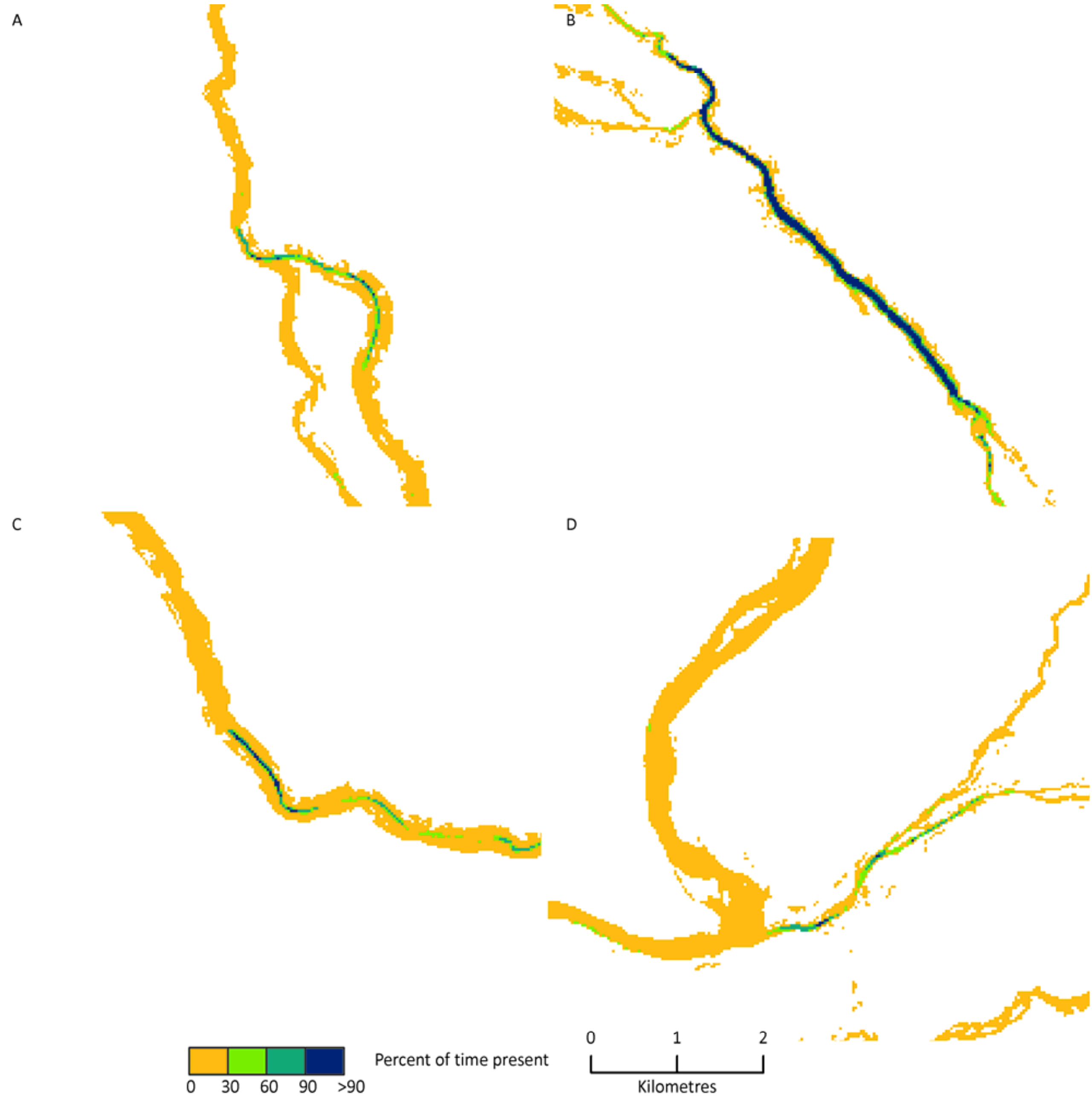

Figure 3.6 Examples of pool persistence mapping in the Flinders catchment. Letters correspond to locations shown in Figure 3.4

3.2.2 GILBERT CATCHMENT

The location and size of key aquatic refugia in each of the four river reaches in the Gilbert catchment is shown in Figure 3.7. The most obvious observation is the greater number of key aquatic refugia mapped in the river reaches of this catchment when compared to the Flinders catchment (Figure 3.4). Reasons for this are not certain but could be related to a number of factors. The most likely cause is the much greater rainfall experienced in this catchment. Average rainfall in the Gilbert catchment is 775 mm compared to 492 mm for the Flinders catchment. The river channels also tend to be wider, less braided and more defined in the Gilbert catchment and this favours concentration of streamflow in the landscape and also better enables identification using Landsat imagery. Another factor contributing to the mapping of more key aquatic refugia in the Gilbert catchment is the potential for groundwater outcropping along the river system. Analysis to ascertain the source of water for pools located around the Gilbert catchment using radon concentrations, stable isotope and major ions data are reported in the companion technical report on groundwater systems (see Preface Figure 1-1). This report has identified a few pools in the Gilbert River reach and upper areas of the Einasleigh River that have a high likelihood of receiving groundwater inflows.

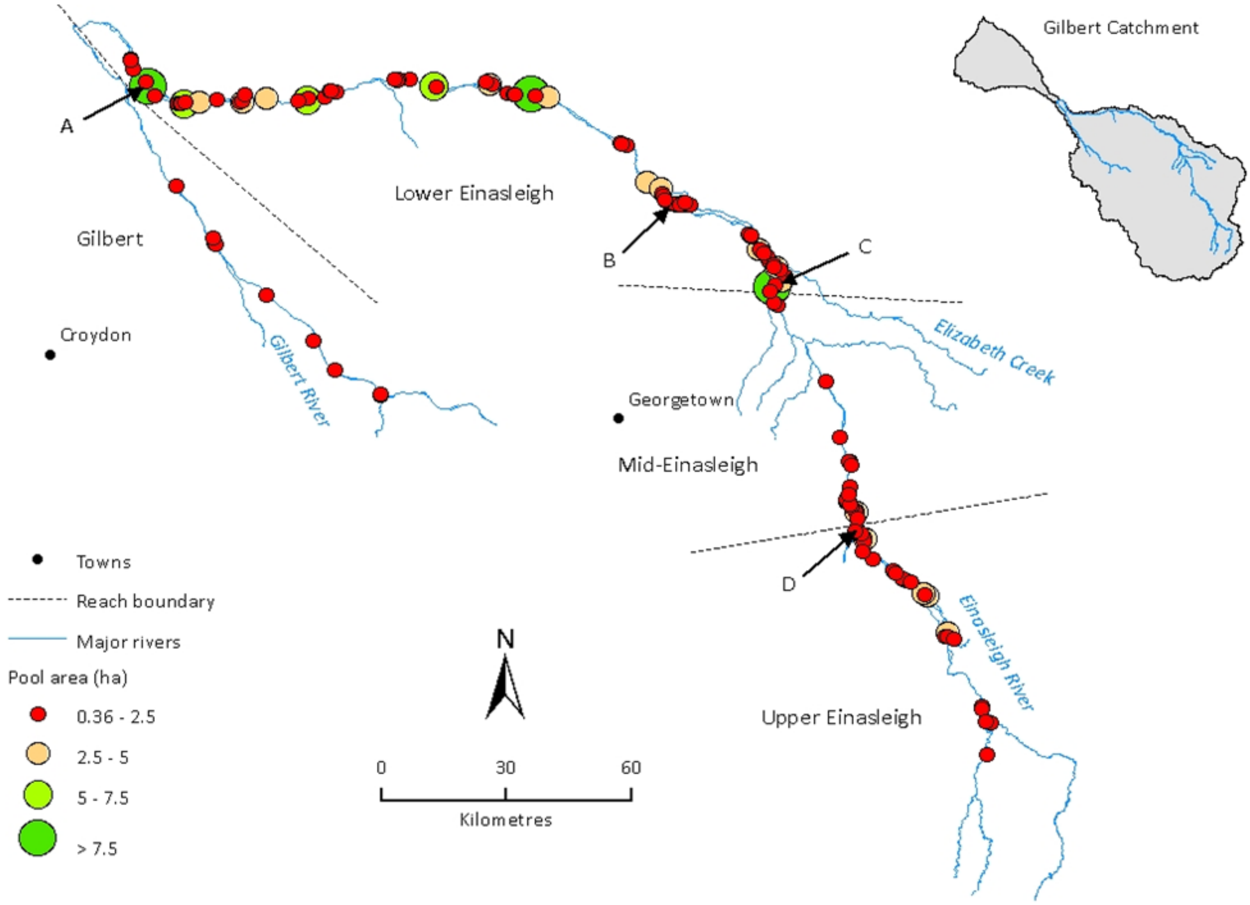

Figure 3.7 Location of key aquatic refugia identified in the Gilbert catchment. Key aquatic refugia are defined as those which are present for more than 90% of the time. Letters represent regions which will be shown in more detail in Figure 3.8

In the Gilbert River reach (Figure 3.7) there are relatively few key aquatic refugia mapped and those that do exist tend to be small. The river channel in this area is relatively straight and reasonably wide (often in excess of 300 m) and filled with coarse sand deposits. Given the conditions likely to favour pool formation discussed earlier, it is possible that large persistent pools do not form in the same locations from year to year in this reach due to mobile bed sands or that pool formation is not common in this river reach.

The Upper Einasleigh reach has numerous small and intermediate sized key aquatic refugia mapped and these tend to be more common at the downstream end of the reach near the border with the Mid-Einasleigh reach. In this area there are also a number of gorges where deep water bodies can form. Steeper catchments also feed the river systems in this section of the Einasleigh River (see Figure 2.1) which leads to more defined river channels when compared to the flatter channels in the Flinders catchment.

The Lower Einasleigh has the greatest concentration of key aquatic refugia of any river reach in this study. It also supports three refugia that fit into the largest size class (>7.5 ha). More persistent streamflow is likely to be the major cause of the dense distribution of key aquatic refugia in this reach. The persistence of streamflow in this reach could be related to groundwater inflows in this region. Analysis of radon concentrations, stable isotope and major ions were undertaken at one location on this reach and results suggested only limited groundwater input, but, measurements made on Elizabeth Creek, which feeds into this river reach, suggest that there is a high likelihood that streamflow is sustained by continuous groundwater discharge. These results are described in the companion technical report on groundwater systems (see Preface Figure 1-1). Further groundwater surveys may be needed to help elucidate whether groundwater helps sustain the large number of pools in this river reach. The key aquatic refugia mapping shown in Figure 3.7 could be used to help guide groundwater sampling design. The number and size of refugia along this reach are likely to provide many persistent aquatic habitats.

An analysis of pool water clarity in the Gilbert catchment undertaken by Lymburner and Burrows (2008) showed that pools in this catchment were predominantly of low turbidity. This could indicate greater inputs of groundwater when compared to the Flinders catchment but could also reflect differences in soil types and geology in these areas; again further research would be needed to answer these questions.

Figure 3.8 shows the persistence of in-stream pools at key locations identified in Figure 3.7 in more detail. The percentage of time that pixels are mapped as water again shows how the river channels contract to distinct pools which persist between dry seasons. Location A is within the Lower Einasleigh river reach where the channel and inundated area can be very large. The smooth boundary of the mapped persistence for this location reflects the fact the inundation occurs to the full extent of the buffer that has been applied to the river channel to limit the analysis to the vicinity of the major channels. Of particular interest at location B is the ability of the method utilised to pick up topographic effects on pool persistence. The ring of permanent water shown in this figure is a location where the river splits around a bedrock outcrop. Large pools shown for location D occur downstream of where four tributaries flow into the main channel from the surrounding catchment. Chains of persistent pool occur in this reach of the river reflecting either consistent inflows or groundwater outcropping. The narrow band of persistent pools at location D reflects the steeper topography at this location when compared to other locations.

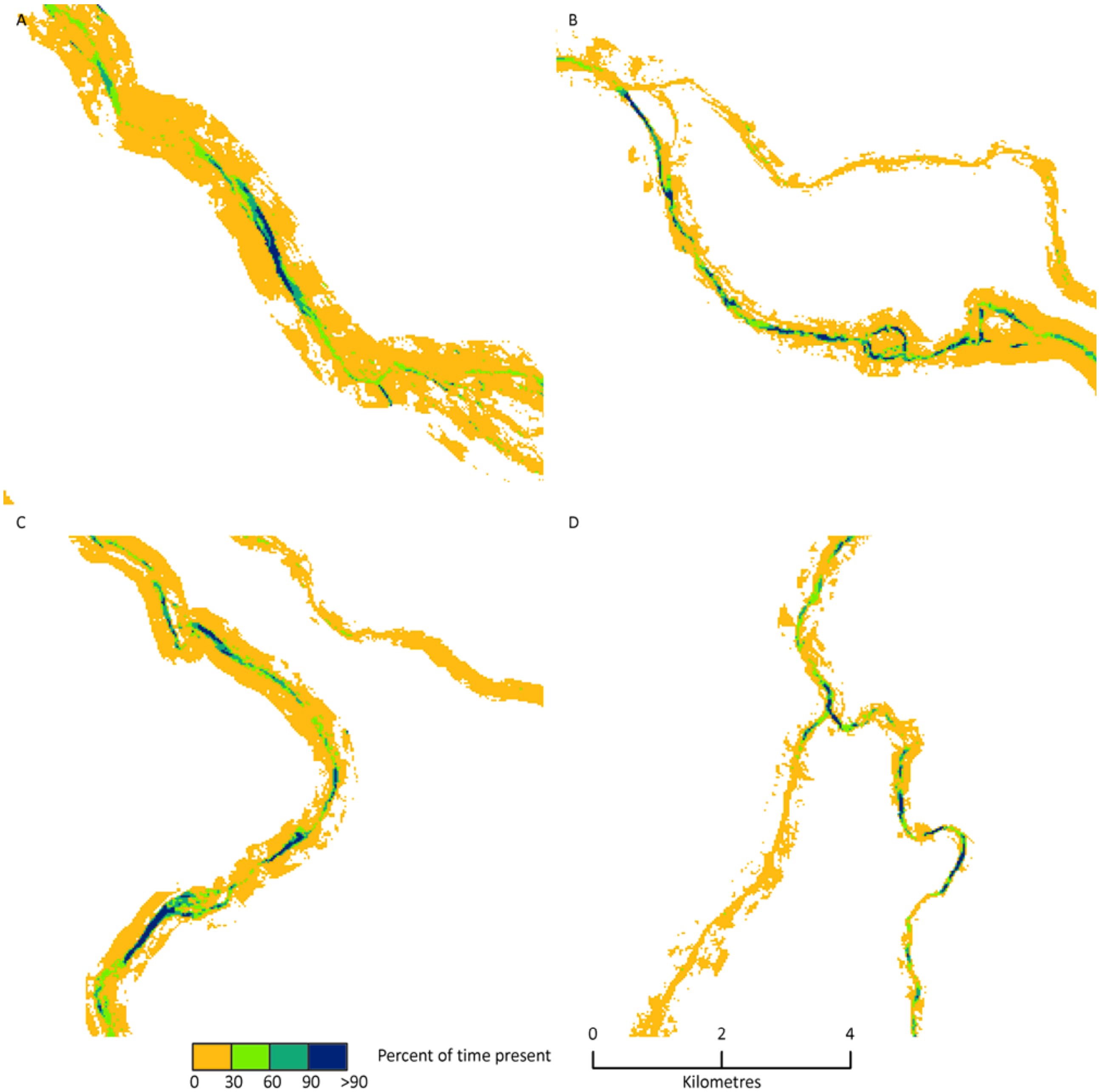

Figure 3.8 Examples of pool persistence mapping in the Gilbert catchment. Letters correspond to locations shown in Figure 3.7

3.3 Streamflow characteristics and in-stream pool evolution

3.3.1 ZERO FLOW DURATION

When considering the relationship between in-stream pool evolution and streamflow characteristics it is useful to consider the duration between streamflow events in a given reach for a given year. Figure 3.9 shows distinct differences in the duration of zero flow between the Flinders and Gilbert river reaches. (N.B. A flow rate of less than 1 ML/day was used to represent the commencement of zero flow as discussed in the methods section). Modelled streamflow for the Cloncurry reach at gauging location 915212A shows that annual maximum durations of zero flow range from 227 days to 320 days. On average there is no flow at this location for 75% of the year. Extended periods of zero flow also characterise the Mid-Flinders (915012A) and Upper Flinders (915008A) although year to year variability is much greater. Zero flow durations of as much as 330 days, or 90% of the year, have occurred during dry periods whereas during wetter periods the zero flow duration may be as little as 123 days or 34% of the year. The different zero flow durations for the Upper and Mid-Flinders reflects the spatial variation of inflows to these river reaches and differences in contributing area (i.e. larger catchment areas typically have greater streamflow and streamflow of longer duration).

In the Gilbert catchment zero flow durations are much less that in the Flinders catchment, with the Gilbert River reach (917001D) having the longest average duration of 160 days (Figure 3.9b). The Upper (917106A) and Mid-Einasleigh (917109A) river reaches have relatively short zero flow durations averaging 63 and 50 days, respectively. The modelled streamflow at the selected gauging location for the Lower Einasleigh (917111A) showed that there were no days of zero flow; streamflow continued throughout the dry season at low levels forming a series of pools connected by small streams. As the Lower Einasleigh River reach does not experience zero flow conditions it will be considered separately in the analysis of pool evolution presented below.

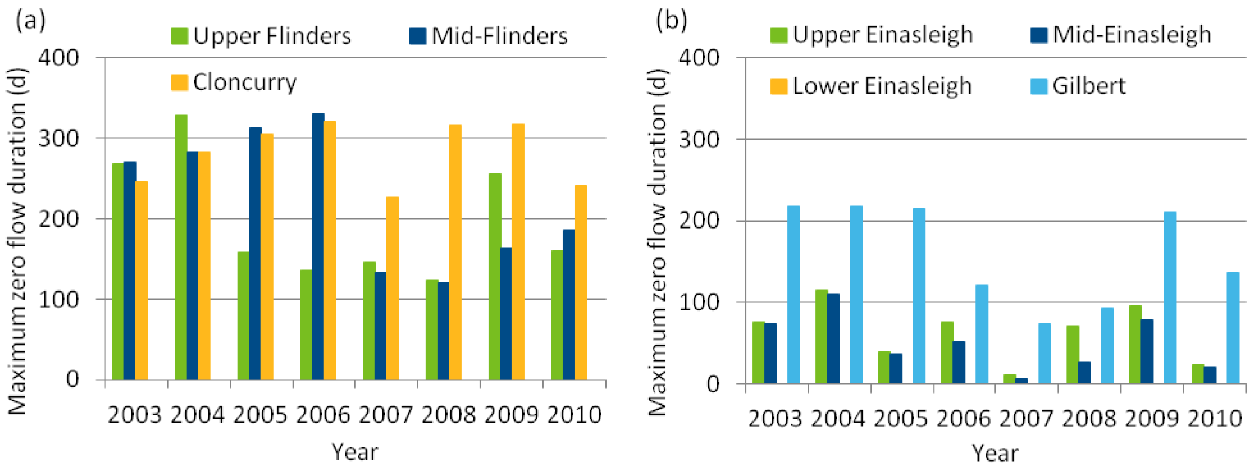

Figure 3.9 Maximum duration of zero flow for each calendar year in river reaches of the Flinders (a) and Gilbert (b) catchments

3.3.2 POOL AREA AND TIME SINCE CEASE TO FLOW

For the Upper Flinders reach, the relationship between pool area and time since flow ceased showed some interesting characteristics (Figure 3.10a). Data fell into two groups; green points that form a very strong relationship with time since zero flow, and gold points that are being plotted as outliers. For the Upper Flinders the cluster of outliers represents points in the time series where a number of small streamflow events punctuated the dry season. Closer analysis of these points shows that these small streamflow events were unlikely to fill the river channels and pools contained within them but they were big enough to reset our calculation of time since cease to flow. The end result is very small pool area values for what appears to be relatively short periods of time after cease to flow. Numerous attempts were made to develop a method to prevent small events from resetting the time since cease to flow by setting a minimum streamflow threshold that needed to be exceeded again after zero flow commenced, but a consistent streamflow level that could be used as a threshold for all years could not be defined. This is likely to be due to spatial variation in streamflow in different parts of the catchment. If the outliers for the Upper Flinders are ignored, a very strong relationship (R^2=0.89) between pool area and days since cease to flow exists. However, application of this relationship to any other streamflow scenarios is not recommended because resetting events are particularly hard to identify and eliminate. More detailed on ground studies and higher resolution imagery would be required to enable better prediction of pool area in this reach. From the derived fit to the green data points it can be observed that at periods of more than 200 days since cease to flow the area of pools in the Upper Flinders was far less than other river reaches with less than 10 ha of pools mapped.

A strong relationship (R^2=0.72) between time since zero flow and pool area was observed for the Mid-Flinders river reach (Figure 3.10b). There were only a few outliers that are related to streamflow in part of the river reach and not others. The results suggest that in this reach the number of days since zero flow can be reliably used to predict pool area, therefore, the predictive capacity of this relationship was examined using a bootstrapping approach with the results shown in Figure 3.11a. The most important observation from this figure is that the majority of the observed and predicted points are reasonably tightly clustered (R^2=0.70) around the 1 to 1 line. Interestingly the best performance of the derived relationship is at smaller pools areas, which tend to occur many days after cease to flow. This is when the ecological importance of the remaining pools is at its highest, therefore, we have confidence in the use of the derived relationship for prediction of pool area under future development and climate scenarios. When observed pool area was in excess of 200 ha, there was a tendency for under-prediction of pool area using the bootstrapping approach; this reflects the small number of data points available for constraining the fitted relationship at larger pool areas. As such, use of the derived relationship in Figure 3.10b is not recommended for pool areas in excess of 200 ha.

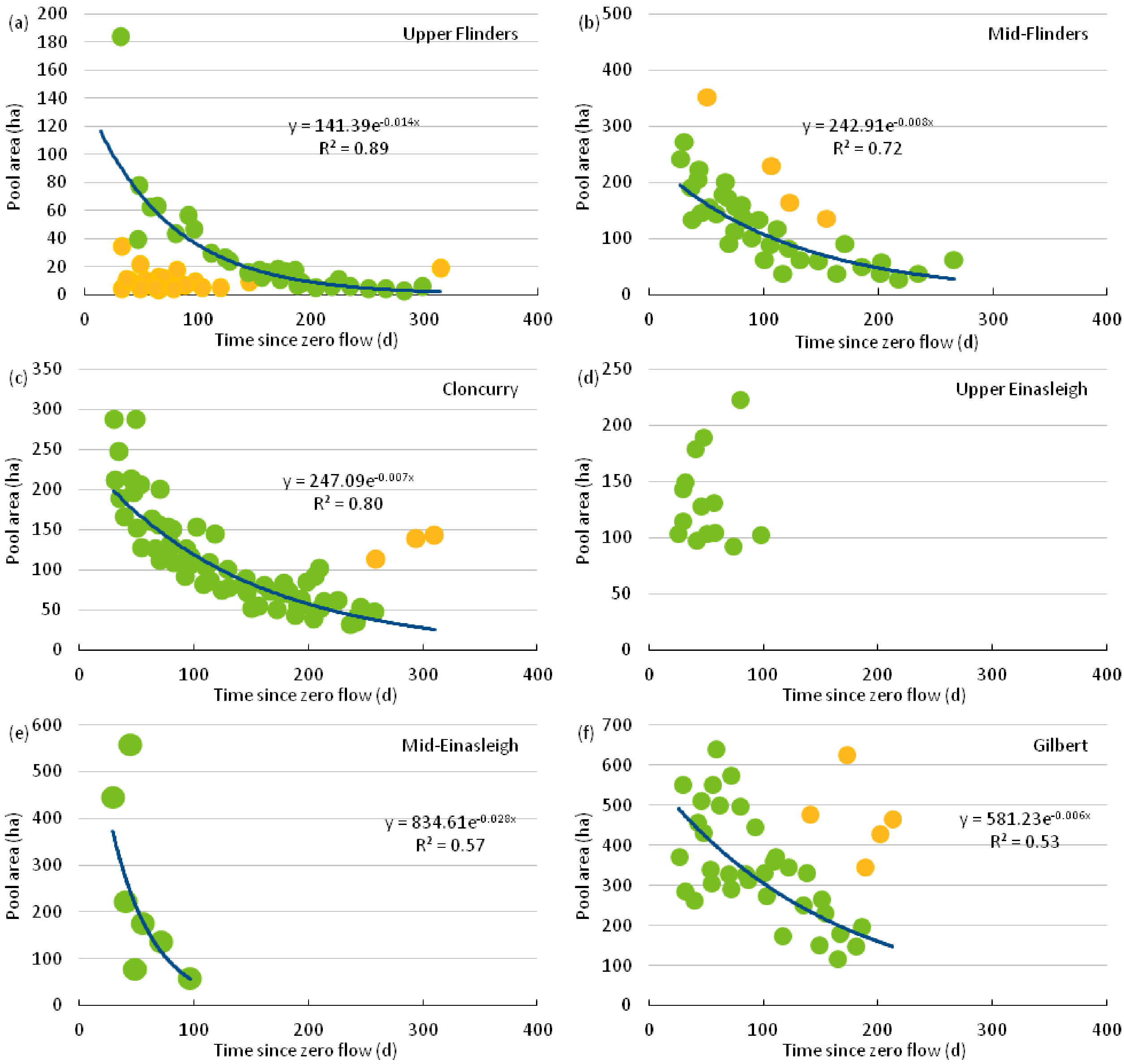

Figure 3.10 Relationship between time since zero flow and total pool area for the Upper Flinders (a), Mid-Flinders (b), Cloncurry (c), Upper Einasleigh (d), Mid-Einasleigh (e) and Gilbert (f) river reaches. Gold circles represent those identified as outliers in the dataset

A strong relationship (R^2=0.80) between time since zero flow and pool area was also observed for the Cloncurry river reach (Figure 3.10c). There were three outliers identified in the dataset and these were all found to occur during periods where streamflow was occurring in the upper part of the river reach but had not yet made it to the gauging point. Figure 3.11b shows further testing of the relationship between days since cease to flow and pool area using a bootstrapping approach. The relationship between observed and predicted values is strong (R^2=0.75) and the majority of points are clustered around the 1 to 1 line giving confidence in predicted values. However, when observed pool area was in excess of 200 ha, there was a tendency for under-prediction of pool area using the bootstrapping approach. As with the Mid-Flinders reach, this reflects the small number of data points available for constraining the fitted relationship at larger pool areas. As such, use of derived relationship in Figure 3.10c is not recommended for pool areas in excess of 200 ha.

Comparison of the days since cease to flow with total pool area for the Upper Einasleigh was limited by the small number of available data points (Figure 3.10d). This highlights problems associated with trying to develop relationships for river reaches, such as this, where the short duration of zero flow limits the availability of scenes for analysis. Cloud was also a major factor in limiting the number of available images for this river reach with 26% of scenes being excluded for cloud cover issues. While it is not possible to derive a predictive relationship for this river reach, it is interesting to note that the area of pools is consistently greater than 100 ha.

For the Mid-Einasleigh (Figure 3.10e) there were very few data points that could be used to derive a relationship between time since cease to flow and pool area. Nearly 30% of the Landsat scenes for this reach were rejected as they had cloud obscuring the area of interest. This, combined with the short periods of zero flow (Figure 3.9b), results in only seven data points being available for undertaking analysis. While there appears to be a decline in pool area with time, the relationship is not strong and there will be much uncertainty in the derived results. Further analysis of Landsat scenes may provide more data points to strengthen this relationship but until then use of the relationship in Figure 3.10e is not recommended.

The total pool area for the Gilbert River reach showed a reduction with time since cease to flow (Figure 3.10f), however, the relationship was not particularly strong (R^2=0.53). The source of the variation is not clear, but could be related to pools not forming in the same locations year after year as suggested earlier in discussions around persistence. With more data the relationship might strengthen but until such time the derived relationship should be used with caution.

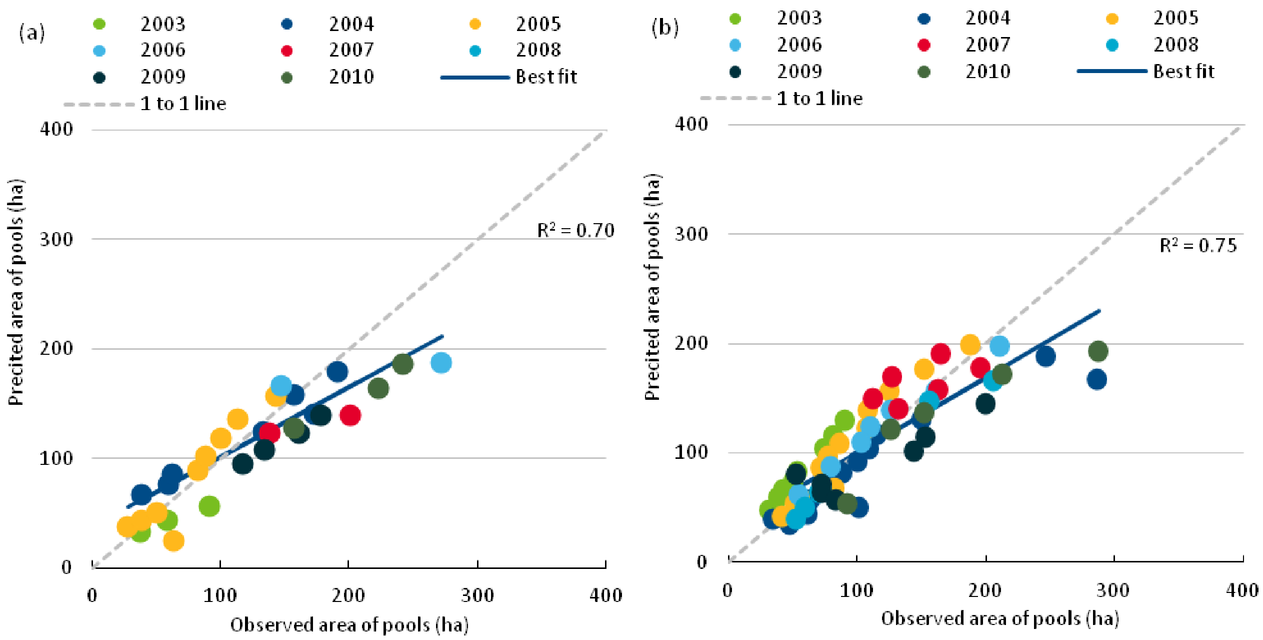

Figure 3.11 Comparison of observed and predicted pool area for the Mid-Flinders (a) and Cloncurry (b) river reaches using a bootstrapping approach. The different colours represent the year being predicted using relationships derived from the remaining dataset

Figure 3.12 illustrates a potential application of the relationships derived for the Mid-Flinders, Cloncurry and Gilbert river reaches (Figure 3.10) to a scenario of increased zero flow duration. Increases in zero flow duration could result from a future climate which is drier than present or extensive water harvesting. In Figure 3.12 the average duration of zero flow is increased from its current value of 225 days for the

Cloncurry River reach, 282 days for the Mid-Flinders River reach and 160 days for the Gilbert River reach to simulate the effect of decreased flows. A corresponding reduction in total pool area is shown on the y-axis. An increase in the average duration of zero flows of 30 days results in an approximate total pool area reduction ranging between 16% for the Gilbert River reach and 21% for the Mid-Flinders River reach. An increase to average duration of zero flow of 100 days results in a reduction of total pool area of ranging between 45% for the Gilbert River reach and 55% for the Mid-Flinders River reach. As an example, such relationships could be used to help protect a predefined minimum pool area when developing and managing water resources in this area.

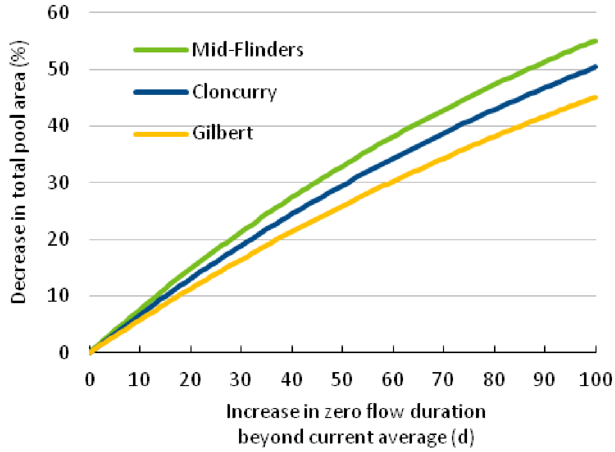

Figure 3.12 Increase in the duration of zero flow from current average conditions for the Mid-Flinders, Cloncurry and Gilbert river reaches and corresponding decrease in total pool area. The average duration of zero flow is currently 225 days for the Mid-Flinders reach, 282 days for the Cloncurry reach and 160 days for the Gilbert reach

The multiplier in the exponential relationships derived for the Mid-Flinders, Cloncurry and Gilbert river reaches (Figure 3.10) represents an approximation of the total area of pools at the time that streamflow ceases. If this multiplier is set to 1 the relationship produces curves representing the fractional decrease in pool area with time since zero flow. Such curves are shown in
Figure 3.13 where it can be seen that the fractional reduction in pool area with time for different sites is similar. The similarity comes from the closely matched exponents in all three relationships (range = -0.006 to -0.008). Taking the average of these exponents would produce the relationship $y=1e^{-0.007x}$ which is well suited to streamflow scenario analysis and offers a potential means by which to approximate the relative reduction in total pool area for changes in zero flow duration for other river reaches that do not have detailed Landsat analysis.

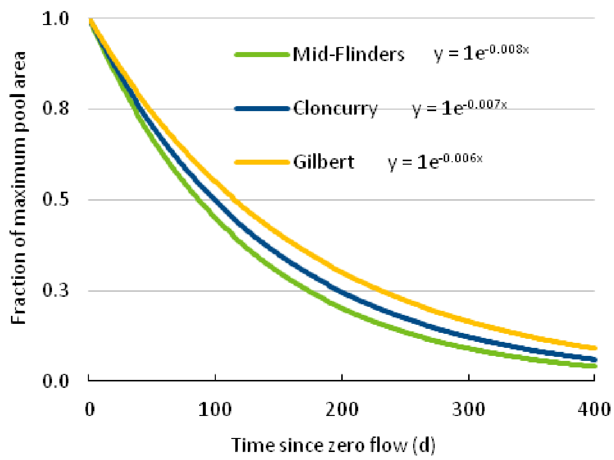

Figure 3.13 Fractional decrease in total pool area with time since zero flow for the Mid-Flinders, Cloncurry and Gilbert river reaches

3.3.3 POOL AREA AND STREAMFLOW

In the Lower Einasleigh River reach streamflow did not cease during the dry season during the period for which Landsat images were processed. As a result an alternative analysis approach was undertaken where pool area was related to the daily streamflow rate for the most downstream gauge for this river reach (917111A). From Figure 3.14 it can be seen that the relationship between pool area and streamflow is relatively strong (R^2=0.71) and thereby provides a reliable method for estimating pool area for this reach. Of particular note is the tight relationship at streamflows less than 10 ML/d, this gives confidence in pool area predictions at low flow which is particularly important for analysis of the impacts of water resource development in this area. Further testing of the reliability of the derived relationship is shown in Figure 3.15, which presents the results of a bootstrapping analysis. Most of the predicted and observed data points cluster around the 1 to 1 line but there are a few points when observed pool area was in excess of 3000 ha where predictions are poor. As in previous examples the poor predictions occur due to the small number of data points representing very large pool areas. As such, use of derived relationship in Figure 3.10c is not recommended for pool areas in excess of 3000 ha. It should also be noted that if future development and climate scenarios result in periods of zero streamflow then the derived relationship is no longer applicable.

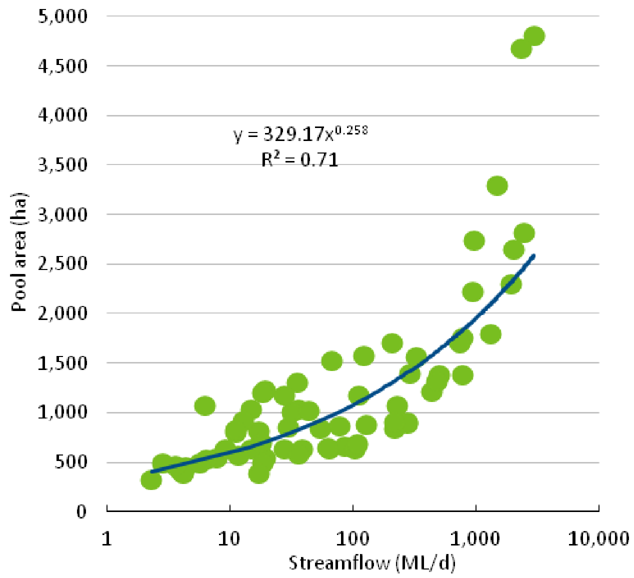

Figure 3.14 Relationship between streamflow rate and total pool area for the Lower Einasleigh River reach

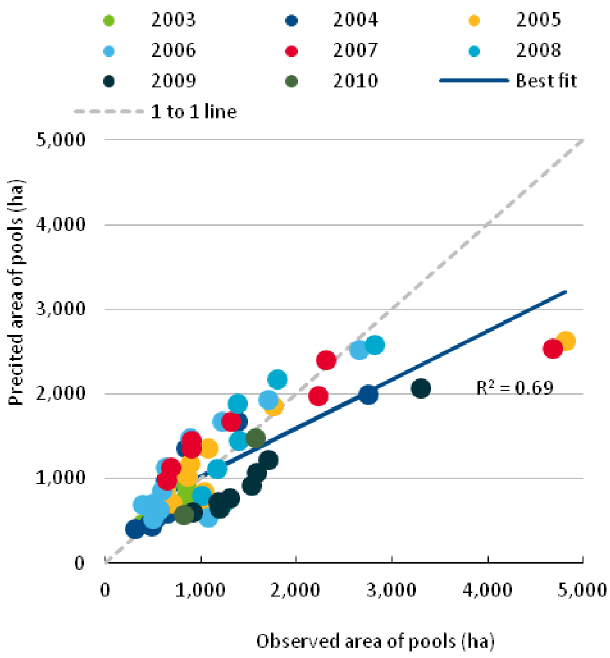

Figure 3.15 Comparison of observed and predicted pool area for the Lower Einasleigh River reach using a bootstrapping approach. The different colours represent the year being predicted using relationships derived from the remaining dataset

4 Conclusions

The strongly seasonal nature of streamflow in the Flinders and Gilbert catchments, and indeed many other catchments in north Australia, means that remnant pools provide essential habitat for both terrestrial and aquatic biota during the periods between streamflow events (Davis et al., 2002; Hamilton et al., 2005; Lymburner and Burrows, 2008; Sheldon et al., 2010). As such, water resource management plans in the Assessment area should recognise any potential impacts that development and future climate may have on streamflow and duration of dry periods.

In this report a technique has been described that enables identification of in-stream pools in the Flinders and Gilbert catchments using remote sensing approaches. The technique employs a water index algorithm in combination with a catchment-specific threshold to classify pixels in Landsat imagery as water or non-water. The water index threshold is set through comparison with high resolution imagery and varies due to differences in water clarity between catchments.

The advantage of the proposed method is that it can provide information about the spatial distribution of in-stream pools across large, and often inaccessible, areas. The approach developed can also be easily adapted for application in other catchments. The resolution limitations of the technique need to be acknowledged and the results presented here should not been seen as the definitive mapping of all in-stream pools for the Flinders and Gilbert catchments.

Applying the water index threshold for each catchment to Landsat images collected between 2003 and 2010 enabled the dynamics of pool evolution and pool persistence to be tracked over time. Pools that persisted for greater than 90% of the time were identified as key aquatic refugia that are likely to be crucial for sustaining ecosystems in these catchments. Protection of these pools should be considered in any planned development of surface and groundwater resources.

A much greater number of key aquatic refugia were mapped for the Gilbert catchment when compared to the Flinders catchment. The most likely reason for the observed differences is the more persistent streamflow which is likely to be related to higher rainfall in the Gilbert catchment. There is also anecdotal evidence that groundwater inputs may play a greater role in pool persistence in the Gilbert catchment.

Examination of mapped pools showed that they tend to form at the confluence of rivers where sediment depositions can block flow, at road crossings where barriers hold back water, in topographic depressions and on river bends where scouring leaves deeper sections of channel. The potential for some key aquatic refugia to be fed by groundwater also increases the need for careful management of groundwater extraction.

The duration of zero flow is closely tied to the persistence of in-stream pools. All river reaches except for the Lower Einasleigh experienced periods of zero flow. The duration of zero flow tended to be much longer for locations in the Flinders catchment than those in the Gilbert catchment. Relationships between total pool area and time since flow ceased were derived for the Cloncurry, Mid-Flinders and Gilbert river reaches. The derived relationships for these reaches can be easily applied to modelled streamflow for these locations to assess the potential impact of different development and climate scenarios on pool persistence. Small streamflow events insufficient to fill in-stream pools complicated relationship development for the Upper Flinders river reach, while reliable relationships could not be constructed for the Mid and Upper Einasleigh river reaches due to the combination of frequent cloud cover and the short duration of zero flow.

Similar rates of fractional reduction in total pool area with time since zero flow were observed for the Cloncurry, Mid-Flinders and Gilbert river reaches. This similarity enabled the development of a generalised relationship between duration of zero flow and reduction in pool area. This curve is well suited to streamflow scenario analysis and offers a potential means by which to approximate the relative reduction in total pool area for changes in zero flow duration for other river reaches which do not have detailed Landsat analysis.

The Lower Einasleigh river reach flowed continuously during the study period therefore the relationship between streamflow and total pool area was assessed for this location. A strong relationship was found which could easily be applied to modelled streamflow for future scenario analysis. In summary, reliable means by which to predict pool area from streamflow were produced for four of the seven river reaches studied.

While this report has focussed on water quantity and pool area it is also important to consider potential impact of development of water quality in pools. Extending the length of time between flushing events from floods could be detrimental to the temperature, oxygen and nutrient status of pools. In addition, increased disturbance of the landscape during development could lead to increased sediment and nutrient loads which can infill pools, promote algal growth and reduce water quality. Despite these concerns, there are a number of tools that can be used to help minimise impacts of development and climate on in-stream pools in the Assessment area. With our current knowledge of the location of key aquatic refugia and spatial and temporal variations in pool persistence, combined with analysis being undertaken as part of the complimentary studies on pool ecology and groundwater systems, our understanding of pool evolution and health in this area is greatly improved. This information, combined with past studies on pool clarity, persistence and productivity, gives a strong basis to help guide water management decision making in this region.

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